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Virtual Reconstruction as a Scientific Inquiry Tool: the Late-Antique Wall of Aquileia (M2) Using the Extended Matrix

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***Abstract* – This paper focuses on the implementation of virtual reconstruction as a scientific research tool within the traditional workflow of universities. The case study revolves around the late Roman defensive wall of Aquileia, known as M2, in the city's Southeast sector, where the University of Verona conducts research. The paper demonstrates how virtual reconstruction serves as an additional tool for researchers engaged in archaeological investigations, providing scientific inquiry and transparency in reconstruction models. The formal language known as Extended Matrix (CNR) is utilised in this project to enhance scientific mapping and transparency. It outlines the stages of study, including archaeological investigations, comparative and typological studies, and the virtual reconstruction using three-dimensional surveys, digital replicas, scientific backend through Extended Matrix, and photorealistic modeling. The study argues that virtual reconstruction can contribute to research, dissemination, and public archaeology activities, and it holds potential as an established tool in future research phases.**

Keywords: Aquileia; late-antiquity; virtual archaeology; Extended Matrix; virtual reconstruction.

I. INTRODUCTION

This contribution aims to demonstrate how virtual reconstruction can be implemented as a tool for scientific research within the traditional workflow of study and research conducted by universities. The case study in question is the late-3rd to early-4th century AD defensive wall of Aquileia, referred to by scholars as M2, in the preserved section of the city's Southeast sector where the University of Verona has been conducting archaeological investigations since 2018. Specifically, this study will show how virtual reconstruction has served as a scientific inquiry tool, utilised by the university researchers that are involved in the archaeological investigations, thus providing an additional instrument to traditional research.
Notably, this accomplishment has been achieved through the use of the formal language Extended Matrix and the associated workflow developed at the CNR-ISPC [1]. In recent years, virtual reconstruction has become an indispensable tool in the archaeologist's repertoire, and it is primarily used for public outreach and museum exhibitions. Nevertheless, despite its growing usage, there continues to be a lack of scientific publications explicitly delineating the motivations behind the development of reconstruction hypotheses [2]. Various efforts have been made to enhance the scientific transparency of virtual reconstructions and surmount the "black-box effect" inherent in reconstruction models [3].
Among these, the Extended Matrix has been forming a vibrant scientific community over the years. Notably, this approach has been employed in various virtual reconstruction projects [1]. Specifically, the e-Archeo project (Ministero della Cultura, ALES S.p.A.) [4] stands out as exemplary for the application of this methodology. The project entailed the virtual reconstruction of eight Italian archaeological sites, in partnership with CNR-ISPC and multiple Italian universities, including the University of Verona. The University of Verona has independently applied the same approach in the case study of Aquileia's late-antique defenses, utilising the newly acquired skills from the project.
In this contribution, we will therefore illustrate the various stages that have characterized this work, from archaeological investigations to virtual reconstruction.
Following this brief introduction, Section II of this contribution contextualizes the case study, describing the defensive system of Aquileia throughout the centuries.
Section III delves into the details of the archaeological investigations conducted in the Fondo ex Pasqualis area, from the 1950s to the most recent ones carried out by the University of Verona. The focus is on the most significant discoveries related to “M2”.
Section IV is dedicated to the comparative and typological study of the late-antique defenses under consideration, crucial for the formulation of a reconstruction hypothesis.
Section V briefly introduces the formal language Extended Matrix, used within this project.

Section VI presents the virtual reconstruction obtained. Section VII is dedicated to the conclusion, which is accompanied by reflections on the work carried out and prospective analyses for future research.

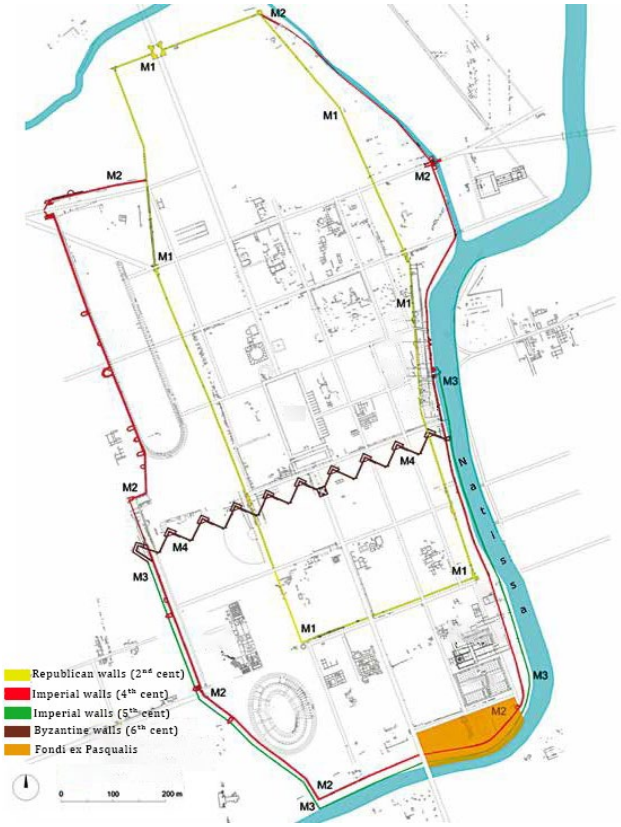

Figure 1: Aquileia: map of the ancient city indicating the urban fortifications and the Fondo ex Pasqualis area (image adapted from: Basso et al. 2022a, p. 88, fig. 1).

II. DEFENSIVE WALLS OF AQUILEIA

The colony of Aquileia, founded in 181 BC, is located approximately 11 km from the Adriatic Sea, along the *Natiso cum Turro*, which flowed through the Southeastern side of the city. The initial phases of the city's existence witnessed the construction of the first fortification, referred to as M1. This fortification, approximately 3000m long, consisten in an elongated rectangle in a North-South direction, enclosing an area of 42 hectares [5]. Towards the end of the 1st century AD and the beginning of the 2nd century AD, certain sections of the defensive walls were demolished, following a decline in their importance, [6, 7]. The state of abandonment in which they languished is well-documented in a famous passage by Herodian (VIII, 2, 4-5), which recounts the siege of the city by Maximinus Thrax in 238 AD. Herodian remarks that the city was defended by a very ancient wall, largely in ruins. This passage also serves as an important *terminus post quem* for the erection of the defensive walls referred to as M2, the case study considered in this contribution. The construction of the new fortification nearly doubled the size of the city, expanding it to 82 hectares. Specifically, the city expanded westward, incorporating the circus, theater, and amphitheater, and southward along the river, where the section subject to virtual reconstruction presented here is preserved. Another defensive wall, M3, was built in the 5th century AD, serving as an additional layer of protection alongside the previous one [5]. The final defensive phase of the city during the 6th century AD sees the construction of another city wall, M4, that narrows the inhabited area in the Southern sector.

For the scope of this present contribution, we will focus on the late-3rd to early-4th century phase, with the virtual reconstruction of M2.

III. ARCHAEOLOGICAL RESEARCH IN FONDO EX PASQUALIS

The contribution focuses on the so-called Fondo ex Pasqualis, located in the Southern sector of the city (fig. 1). This area lies between the Paleochristian Basilica and the present-day Natissa River. Three late-antique market squares and two long stretches of the defensive walls M2 and M3 are preserved here. Two of ther squares and the walls were discovered in the 1950s by Giovanni Brusin [8]. New excavation campaigns, directed by Patrizia Basso and Diana Dobreva from the University of Verona, in collaboration with the Soprintendenza Archeologia Belle Arti e Paesaggio of Friuli Venezia-Giulia and Cristiano Tiussi, Director of Fondazione Aquileia, have been ongoing since 2018 [9, 10, 11], which led to the discovery of a new square in 2020.

Focusing on the results related to M2, recent investigations first involved a detailed reassessment of the section of the walls uncovered in the 1950s. The masonry has a variable width of approximately 3m and has been unearthed for a length of about 100m. Up to five courses of the elevation have been preserved, showcasing a notable pattern of material reuse, including honorary inscriptions from the 2nd century AD, particularly prominent in the outer face. New investigations have revealed that M2 was constructed on the riverbank of the Natissa River, in the Eastern sector of the city. The river was wider during this phase, reaching approximately 30m.

Undoubtedly, the most remarkable finding for comprehending the inner wall's structure is a substantial section of the collapsed outer face (Fig. 2), unearthed during the 2018 excavation campaign. This section, measuring 5.50m x 5.30m, exhibits a well-organized arrangement of 30 rows consisting of bricks, pebbles, and roughly squared stones. Fragments of mortar, composed of sandy-silt sediment with mortar clumps, are still evident between the stones. Notably, a rectangular loophole with a semicircular brick surround holds

particular significance.

Figure 2: Aquileia, ex Fondo Pasqualis, collapsed outer face of M2 (image from: Basso et al. 2022, p. 92)

IV. COMPARATIVE STUDIES

The current case study lies within the broader context of late-Roman defenses, an area that has been at the centre of scholarly attention throughout the years [12, 13, 14, 15, 16].

From a stylistic standpoint, the defensive wall M2 presents interesting analogies, particularly with the walls from the tetrarchic period regarding the architecture of the towers [17]. In fact, during the period between 265-285 AD, several Italian centers, such as Rome, Verona, and Milan, were fortified in response to the crisis at the Northern borders of the Empire [18]. In particular, Milan's city walls exhibit several similarities with those of Aquileia. Aquileia and Milan represent the two main poles of the Diocletian organization in Northern Italy, which is also evident through the similar urban choices between the two cities [17]. Milan's Massimian Walls were built between the late-3rd and the early-4th century AD. The most interesting section for the study at hand is currently preserved in the area of the Archaeological Museum, where a tower and a section of the wall measuring almost 20m in length and 12m in height are preserved [19]. The primary interest within this project lies in the evidence of a covered walkway located approximately 7m above the Roman ground level. The upper level of the walkway is not preserved, but its elevation has been determined by the opening of the entrance door on the north side of the tower, at a height of about 12m.

The case of Milan represents the most significant comparison in terms of chronology, geography, and close relations between the cities at that time. Other cases have been considered for the hypothetical reconstruction of the M2 wall, particularly regarding the covered walkway, the uncovered walkway, and the battlements. In particular, the case of Rome's Aurelian Walls [20] specifically the Aurelian *cornice* on the battlements and the Honorian phase for the covered walkway, as well as the Roman walls in Barcelona, without going into detail [21].

In addition to researching comparisons with other archaeological sites, other sources have been considered, like ancient treatises (*Epitoma rei militari* by Vegetius and The Anonymous Byzantine's *De re strategica*), bibliographical research, and iconographic investigations (mosaics, bas-reliefs, sarcophagi, and paintings).

The combination of these various sources has led to a definitive reconstruction hypothesis. The height of the wall is hypothesized to be approximately 9m, based on the dynamics of collapse, ascribed to simple overturning [22], the exportation of rows of blocks from the base of the wall, comparisons, and poliorcetic observations [23]. The discovery of a loophole in the collapsed wall surface has allowed for the hypothesis of the existence of a covered sentry walkway, which is rarely preserved. Based on a comparison with the Milanese context, a narrow corridor covered by a barrel vault and interspersed with niches at the loopholes has been postulated. The height of the internal walkway's ground level is hypothesized to be approximately 4m above the ancient ground level.

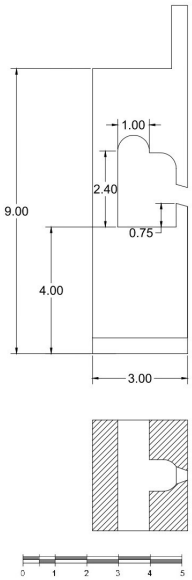

Figure 3: Reconstructive section of M2 (graphic elaboration by the author).

V. EXTENDED MATRIX

The Extended Matrix (EM) is a visual node-based formal language [1] developed at CNR-ISPC to enable the scientific mapping of virtual reconstruction. Building upon the concept of Harris's matrix, the Extended Matrix proposes an extended version that includes Virtual Stratigraphic Units (USVs) [2,3]. A specific color is associated with different types of VSUs based on the level of certainty regarding their existence:

- Red for preserved elements.
- Blue for virtual reconstructions derived from physical evidence.
- Yellow for elements not found *in situ* and repositioned; dark yellow for anastylosis of

missing parts.

- Green for elements reconstructed based on deductive processes.

The graph of the Extended Matrix is created within the software yEd, using a specific palette. Several nodes are associated with each unit, specifying their properties (geometry, material, position, etc.), which are further linked to all the sources used for validation (fig. 4). Indeed, all the data obtained from the research described in the previous paragraph (excavation data, comparative case studies, ancient iconographic and literary sources) has been organized into a file and associated with a code, making them directly accessible within the model.

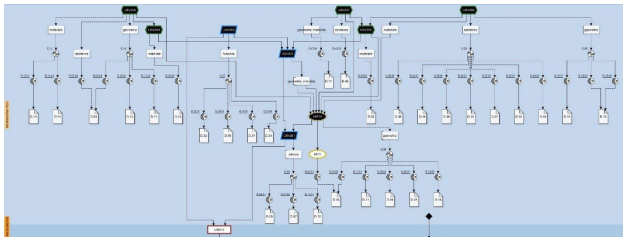

Figure 4: Graph of the Extended Matrix.

VI. RESULTS ACHIEVED: VIRTUAL RECONSTRUCTION

The first phase of the reconstruction work involved creating three-dimensional surveys of the preserved wall sections. During the 2021 excavation campaign, drone photographs (Mavic 2 Pro, DJI) were taken from nadiral, frontal, and oblique angles, with a resolution of 5472x3648, resulting in a total of 499 photographs for M2. The images were then processed using Agisoft Metashape software (Structure-from-Motion). The models serve for direct volumetric reconstruction based on actual data, eliminating the need for a high level of detail. A low-quality setting was employed, resulting in a dense point cloud consisting of 6,540,273 points and a 3D model comprising of 145,338 faces.

The drone photographs were captured two years after the removal of the collapsed wall face. Subsequently, the three-dimensional survey conducted during the 2018 campaign was adopted.

Using Blender software, the reconstruction hypothesis was modeled by employing the digital replicas obtained. The initial model was constructed using simplified volumes, employing low-poly geometry that can be easily created and adjusted. These geometries represent the USVs and are directly linked to the Extended Matrix, allowing the sources used for validating the reconstruction hypothesis to be accessed within the model. These reconstruction hypotheses were extensively discussed and validated within the university research team until a definitive hypothesis was established. Significantly, virtual modeling played a crucial role in raising questions that had not been previously considered.

In Figure 5, the reconstructive *prospectus* of M2 is shown along with its corresponding Virtual Stratigraphic Units (USVs). Starting from the bottom, USM 01 (Figure 05, red) corresponds to the previous riverside bank, along with its virtual reconstruction (Figure 05, USV101, blue). Upon this, the construction of the wall is set, characterized by large reused blocks (Figure 05, USM11, red). Traces of removal suggest the presence of at least one additional course (Figure 05, USV201, blue).

As previously established, a pivotal role in the virtual reconstruction was played by the discovery of a collapsed portion of the outer face of the wall (Figure 05, SF01, yellow). Its presence has provided definite insights into various features of the wall, such as the materials used in its construction, its height, and the presence of an arrow slit, indicative of a covered walkway. The level of reliability of the virtual reconstruction of the exterior face, therefore, can be deemed high, as it involves a virtual reconstruction of an element not found in its original location (Figure 05, VSF01, dark yellow). The only element of the virtual reconstruction whose existence is uncertain is the crenellation, represented as a non-structural USV (Figure 05, USV208, green). Its presence, in fact, has been postulated based on comparisons with other archaeological sites, mosaic depictions, paintings, and numismatic evidence.

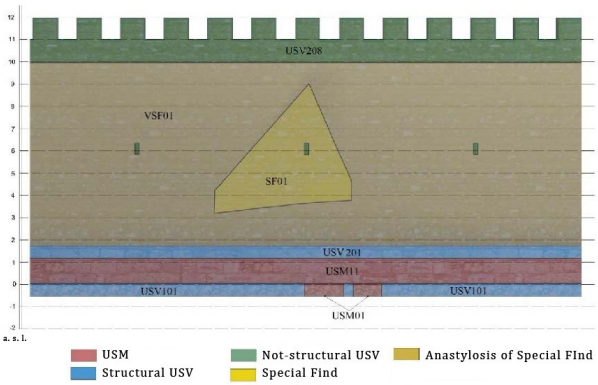

Figure 5: Reconstructive prospectus *of M2 with USVs (graphic elaboration by the author).*

After confirming the scientific validity of the proposed reconstruction hypothesis, Blender software was used to further develop the hypothesis, focusing on modeling the representation model to achieve photorealism in the reconstruction (Fig. 6).

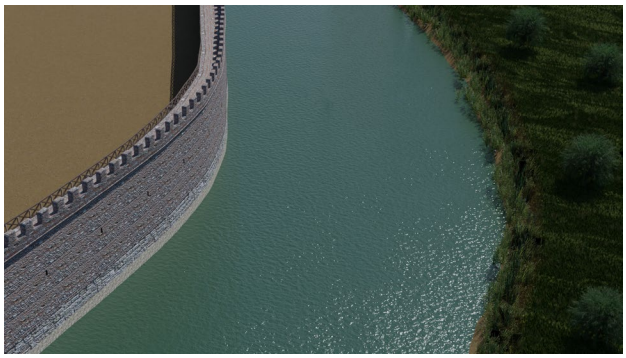

Figure 6: Reconstructive model of M2 (graphic elaboration by the author).

VII. CONCLUSIONS

This contribution has presented the study of M2 through the analysis of archaeological data, comparative studies, and literary and iconographic sources aimed at its virtual reconstruction.

The application of Extended Matrix methodology has proven crucial from multiple perspectives. The subdivision of the elevation reconstruction hypothesis into virtual stratigraphic units has enabled research and in-depth analysis of aspects that had not been previously investigated in detail. The virtual reconstruction has avoided the "black box effect" and is fully navigable and queryable in every aspect. Further excavations can also contribute to updating the reconstruction hypotheses and the corresponding matrix while maintaining scientific accuracy. Thanks to this methodology, three-dimensional reconstruction not only serves as an immediate tool for dissemination, as demonstrated by its successful use during the 2022 European Archaeology Days at the excavation site but also as a source of updated and accessible data for research.

The study and reconstruction work has also encompassed the M3 wall, which could not be addressed here. The aim is to renew and update the hypotheses.

as the excavation campaigns progress, while also enhancing the use of the reconstructions in Public Archaeology and exploitation activities. The virtual reconstruction using the Extended Matrix will then be expanded to encompass the market squares adjacent to the fortifications, ultimately leading to the virtual reconstruction of the entirety of the archaeological area in question.

Undoubtedly, virtual reconstructions can become an established tool within the research phases conducted by the University itself and by the researchers directly involved in the archaeological investigations and study. The implementation of virtual reconstruction through the Extended Matrix into the research workflow carried out within the archaeological investigations conducted by the University of Verona is already being applied, even in contexts outside Aquileia. For instance, it is used in a doctoral project by the author focused on the late-antique villa in Negrar di Valpolicella (VR).

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