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Enhancing archaeological knowledge dissemination: the pivotal role of digital representation and BIM interoperability for preservation, FEA, and XR of Villa dei Quintili in Rome

This research delves into the profound significance of the Science of Representation, demonstrating its pivotal role in crafting semantic and interoperable analysis. The adept application of these 'mediums' could represent a primary shift for future generations in how information is conceptualized, interpreted, represented, and communicated, ultimately fostering a deeper level of understanding and collaboration among professionals in the field. In this context, the convergence of digital representation, knowledge-driven semantic refinement, and techniques for intricate model conversion could assume a foundational role. Given these paramount considerations, the study emphasizes the urgency of establishing interoperable procedures and cultivating a comprehensive understanding of digital representation as a crucial informational medium.
The results served as vessels for disseminating archaeological knowledge and as powerful tools for dissecting the structural intricacies of ancient environments. To achieve this, a highly specialized cognitive process was required to elucidate both the tangible and intangible elements within the ontological framework. The introduction of the interoperable approach at the archaeological site of Villa dei Quintili in Rome served as a prime example of the critical function of digital models able to interpret, disseminate, and preserve our cultural heritage accurately. It proved instrumental, both theoretically and practically, in transferring geometries and information for diverse analytical purposes, significantly enhancing their effectiveness through a thoughtfully selected range of exchange formats for preservation and structural analysis. Finally, the study introduces a methodology for translating digital models into advanced mediums, including extended reality (XR), pushing the boundaries of heritage preservation in the digital age.

Keywords:
Heritage Representation, BIM Interoperability, Building archaeology, Finite Element Analysis, Virtual reality

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THE TRANSFORMATIVE POWER OF THE SCIENCE OF REPRESENTATION IN MODELLING INTEROPERABILITY

In the ever-evolving landscape of digital information dissemination, the Science of Representation stands as a cornerstone. It encompasses a rigorous inquiry into and practical application of advanced semantic representation and modelling techniques, spanning a wide array of fields such as preservation, archaeology, engineering, and their related domains (Docci & Fiorucci, 2006; Centofanti, 2018; Carbonara, 2012). By leveraging state-of-the-art digital technologies, it enables the precise capture, processing, and intricate visualisation of both tangible and abstract elements. The adept and judicious use of these tools heralds a paradigm shift in how information is conceived, interpreted, comprehended, and conveyed (Attenni et al., 2022; Rossi et al.,2021; Brusaporci et al.,2023).

This transformative process, rooted in modelling, deepens comprehension and facilitates more effective collaboration among professionals across diverse sectors. A nuanced grasp of crafting interoperable models and an extensive understanding of 3D modelling conceived broadly as an "informational medium," encompassing formal structural representation, analytical instrumentation, and a conduit for the transmission, utilisation, and dissemination of tangible and intangible values, enable the alignment and transference of heritage across a wide expanse of applications and disciplines (Banfi, 2023).

However, in practice, the flow of data from the initial phases of digital survey to the subsequent phase of digitisation into semantic models often appears disjointed, failing to seamlessly align with specific applications such as preservation, structural analysis, and the dissemination of values in intricate scenarios. This exchange primarily revolves around geometric entities and their pertinent information, potentially yielding varying results and analyses depending on the model at hand. The 3D modelling process typically demands heightened consideration for historical information and a heightened degree of customisation regarding object geometry (Giaccone et al.,2020). Moreover, alterations made to the object during modelling may necessitate enhanced communication among the various professionals involved. This can result in models tailored for specific analyses but may also lead to suboptimal utilisation. In cases of heightened complexity, distinct approaches may yield varying outcomes for identical models within a given case study.

Additionally, the inherent rigidity of database architecture and modelling tools within Building Information Modelling (BIM) platforms calls for introducing novel approaches capable of underpinning the model's Level of Development (LOD) and the modelling process itself (Hussein et al., 2020; Di Biccari et al.,2022). In this context, the confluence of digital modelling, knowledge-driven semantic discretisation of the artefact, and techniques for the conversion of complex models for diverse types of analysis assumes a foundational role within a process aimed not only at documenting heritage but also at accurately interpreting, comprehending, safeguarding, and structurally consolidating it. In this scenario, it is imperative to oversee the entirety of the process, ensuring the verification and validation of interoperability between applications, from the initial surveying phases to the ultimate stages of sharing and managing the conclusive BIM-based analysis. The harmonious integration of these domains and the mutually reinforcing nature of the information provided by each technology could lead to a renewed data flow and a comprehensive, highly detailed, and all-encompassing framework for a given project. For these reasons, the present study elucidates the methodology employed in the case of Villa dei Quintili, located at the V milestone of the ancient Appian Way in Rome (Fig. 1).

This aims to provide insights into both the ma-

Fig. 1 - The research case study: the Villa dei Quintili (left), located at the V milestone of the ancient Appian Way (right) in Rome

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terial and immaterial significance attributed to one of the foremost Roman archaeological sites under national jurisdiction.It emphasises how the central role of digital representation, much like a knowledge-based process founded on meticulous analysis of the subject of study, leads to the creation of interoperable representation.
These models are designed to support preservation efforts, facilitate structural analyses, and further dissemination initiatives throughout the preservation process. These values are subsequently revisited and adapted in the concluding sections, with the goal of developing a comprehensive process proficient in translating the richness encapsulated within digital models into cutting-edge representational mediums, including Virtual Reality (VR) and web-XR.

ARCHAEOLOGICAL INSIGHTS: DOCUMENTING THE RICH HISTORY OF VILLA DEI QUINTILI

Nestled at the fifth milestone of the Via Appia Antica lies the Villa dei Quintili, an archaeological gem of Roman antiquity. Constructed in the early 2nd century AD by the prominent Quintilio brothers, the villa boasted extensive structural additions and opulent adornments sourced from imperial quarries (Paris et al.,2019). Unfortunately, the villa's splendour was marred by false accusations of conspiracy against Emperor Commodus, leading to its confiscation along with the assets of its owners.
The Villa dei Quintili witnessed gradual abandonment and looting throughout the centuries, losing valuable materials and artworks. While 18th and 19th-century archaeological excavations yielded numerous artefacts, they provided limited insights into associated structures.
Pioneering archaeologists such as Antonio Nibby, Luigi Canina, and G.B. Guidi contributed to unravelling the architectural and historical tapestry of the villa, shedding light on artefacts from later periods that attested to its enduring use (Fig. 2 and 3). In 1909, the English archaeologist Antonio Ashby conducted a topographic survey, classifying the villa into five functional sectors and providing a crucial reference point for future excavations (T. Ashby,1909). Despite these strides, further research is needed to reconstruct the site's stratigraphy and evolution over time accurately.
Between 1922 and 1932, the reclamation of the Agro Romano unearthed significant discoveries, including the Villa dei Quintili. While some parts of the ancient residence were unintentionally destroyed, this led to the uncovering of important sculptures now showcased in the antiquarium of the archaeological site and the National Roman Museum. Subsequent excavation campaigns and research, such as the study led by Andreina Ricci's team from the University of Tor Vergata between 1984 and 1987, have contributed to a deeper comprehension of the site. This study paved the way for initial investigations of the monument and the discovery of a Theodoric-era stamp in a thermal complex (Ricci, 1998; Ricci et al.,).
Over two decades, the Villa dei Quintili has been the focal point of rigorous research, spanning four excavation campaigns from 1998 to 2018, alongside extensive restoration and enhancement efforts. These endeavours expanded the archaeological area and enriched our understanding of various sectors of the site. The imperial villa's architecture follows a "pavilion" layout, tailored to the natural terrain. It stood as a self-sufficient marvel, boasting amenities like baths, gyms, libraries, and breathtaking views towards the Appia Antica and Via Latina.
The villa's spaces comprised representative areas, private chambers, paved squares, thermal complexes, gardens, porticoed courtyards, performance venues, and an elliptical-shaped structure. Mosaic and precious marble flooring, featuring pavonazzetto, ancient yellow marble, serpentine, and porphyry were adorned with intricate geomet-

Fig. 2 - The Villa of the Quintilii. View from the Torlonia farmhouse and 3D textured model of the entire complex following the survey campaigns of 2022 and 2023. Source: author F.B.

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Fig. 3 - Carlo Labruzzi (1748-1817), Calidarium (left), Frigidarium (right), etching, 18th century. Source: Lugli, G (1967) Via Appia: Sulle ruine della magnificenza antica; Leonardo Arte: Venezia, 1997.


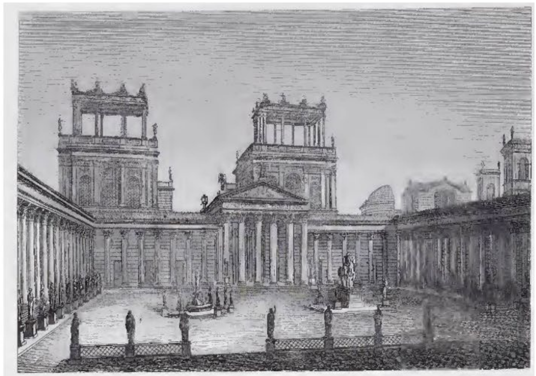

Fig. 4 - Luigi Canina (1795-1856), Ruins of the Villa dei Quintili (left), reconstruction of the great atrium (right), 1853. Source: Canina, L. La prima parte della Via Appia dalla Porta Capena a Boville: Monumenti; G.A. Bertinelli: Roma, 1853.

ric patterns. The spaces were embellished with polychrome stucco, painted plaster, and panels depicting naturalistic and mythological motifs.
Within the elliptical structure, a small amphitheatre once served as a gymnasium before transforming into a garden. Porticoed gardens, thermal halls, and structures like the frigidarium and calidarium defined the area (Fig. 4). The thermal sector boasted polychrome marble flooring with geometric patterns and a base for architectural ornamentation. The representative area included a grand porticoed exedra and a circular space for a summer triclinium. Throughout history, the villa saw alterations, fortifications in the Middle Ages, and the establishment of productive and artisanal activities.

The Villa dei Quintili bears witness to ancient Roman architecture and life, narrating a tale of splendour, decline, adaptation, and modification over the centuries (Fig. 5). It remains a beacon of study and discovery, offering fresh insights into its history and significance.

REPRESENTING VILLA DEI QUINTILI

In the realm of virtual heritage, the accessibility of data and technological advancements has played a pivotal role in creating models that faithfully represent historical forms. Achieving precision and accuracy in capturing and sharing the historical forms ingrained over the centuries has emerged as a primary research objective. The accessibility of data and technological developments have played a fundamental role in creating models that represent architectural heritage. Precision and accuracy in capturing and sharing the historical forms inherited over the centuries have become a priority for research objectives.
The choice of tools for the three-dimensional survey of the archaeological site depends on the characteristics of the object, such as its size, material, and complexity of form. In addition to terrestrial digital photogrammetry, total station (TS), terrestrial laser scanning (TLS) and drones have been used to obtain aerial photogrammetric data. Figure 6 shows the main operations for the digital survey of the Villa dei Quintili and the corresponding outputs. Three-dimensional scans achieved a resolution between 100 and 200 million points per scan, capturing the geometries of architectural, structural, and natural elements and completing the large-scale photogrammetric survey. Terrestrial photogrammetry involved capturing numerous photographs from a fixed position on the ground using a tripod and a digital camera. Subsequently, the pictures were processed with photogrammetry software to obtain 3D models of each archaeological element in the area of interest. Aerial photogrammetry allowed for coverage of larger areas, collecting data from difficult-to-access zones and ensuring greater surface coverage in shorter timeframes compared to terrestrial

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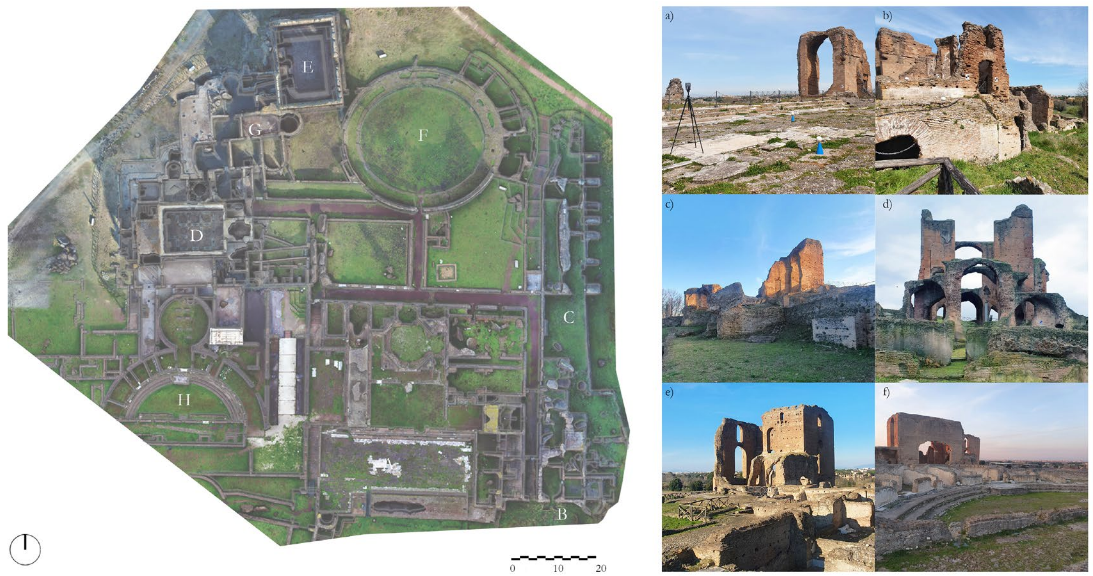

Fig. 5 - Geometric and photogrammetric restitution of the archaeological area. Site plan and orthophoto (February 2023): a) Residences - Representative Area, b) Residences - Private Area, c) Service Area, d) Frigidarium, e) Calidarium, f) Theater, g) Tepidarium, h) Small amphitheatre. Source: author F.B.

photogrammetry.

Integrating total station, laser scanning, and photogrammetry represents a significant advancement in digitisation, as it allows for greater precision and reliability in recording topographic data. The total station created a geodetic network consisting of precise control points distributed over a wide area, providing a reference base for surveying. The network was measured with Leica TPS1200 total station and a final least-squares adjustment provided an average precision of ±2.0 mm. The scans' final registration provided an average target precision of ±4.5 mm. Furthermore, integrating total station with other surveying techniques, such as laser scanning and photogrammetry, eliminated manual errors, improved speed and accuracy in calculating (x, y, z) coordinates and optimised data management for HBIM model generation (Fig. 7).

The scan-to-BIM process for the archaeological site initially involved creating complex curves, surfaces, and solids, then enhancing the semantic value of the three-dimensional reconstructions through object-oriented HBIM modelling. In this context, the "representation model" in the activities of surveying, documentation, analysis, interpretation, design, and dommunication in the fields of architecture and archaeology plays a crucial role. This model can be restitutive, reconstructive, or predictive. Surveying, an integral part of the historical-critical analysis process, requires a thorough understanding of the object under study. In addition to surveying, the researcher collects archival documents, analzes degradation, documents construction details, and conducts critical elaborations. The result is a "complex representative model" that allows for an increase in initial

Fig. 6 - 3D survey operations and laser scanning data of the Villa dei Quintili archaeological site. Survey campaign March 2022.
Source: author F.B.

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knowledge [Centofanti 2018]. This model is essential for drafting restoration projects and designing new constructions, requiring a detailed understanding of the reference context. On the other hand, the effectiveness of different 3D modelling techniques varied depending on specific contextual requirements, with certain representations being better suited for applications. Therefore, understanding the generative logic, advantages, and disadvantages of each type of 3D modelling and the interoperability of major geometric entities such as curves, surfaces (mesh and NURBS), solids, and HBIM objects is crucial.

In HBIM model of Villa dei Quintili, the information level of the model determined its semantic value, which was directly linked to the information associated with the model. Data collected during the artefact study and analysis were connected, inserted, and mapped to the previously generated objects, establishing a bidirectional relationship between objects and information. This characteristic distinguished HBIM projects from digitally modelled free-form representations. Using wall stratigraphy functions, HBIM models were enriched with detailed information on materials, including their geometric and physical properties such as thickness, height, width, density, mechanical information, and historical significance. Once the model was created, schedules listing the mapped alphanumeric information could be automatically generated and extracted. The model mapping phase also involved defining HBIM parameters to enhance semantic enrichment beyond the requirements of newly constructed buildings, encompassing the value of historical heritage and the transmission of intangible values specific to the archaeological site. Recognising the value of HBIM models, increased attention has been given to developing proprietary and open formats capable of representing the geometric information of built heritage and facilitating communication and sharing of its semantic richness. This attention aligns with identifying a generative approach that fully captures the value of "Drawing" as a knowledge tool, promoting the creation of comprehensive, precise, and interoperable HBIM models.

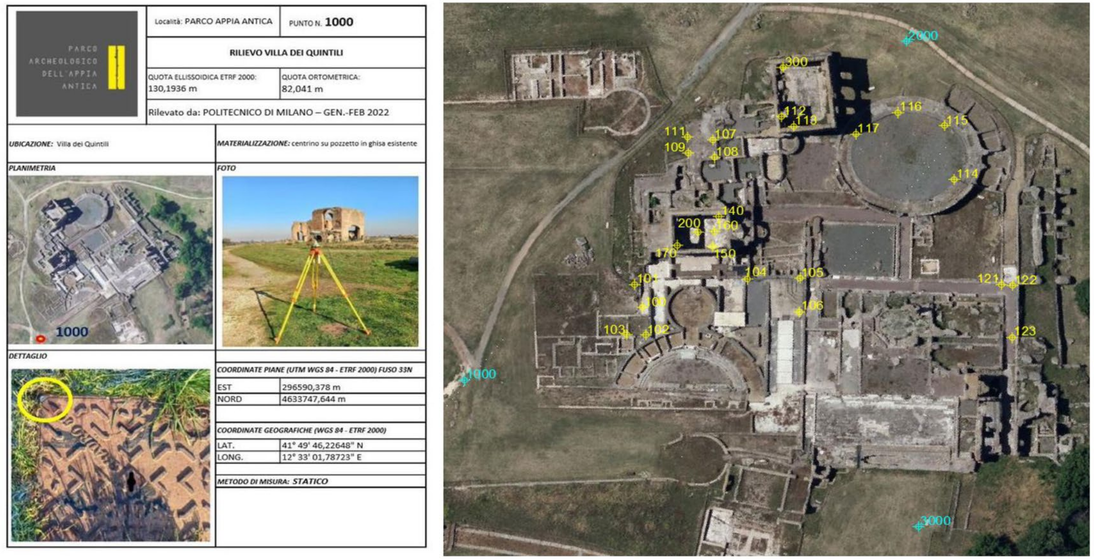

Fig. 7 - Planimetric and altimetric framing network. Source: F.B.

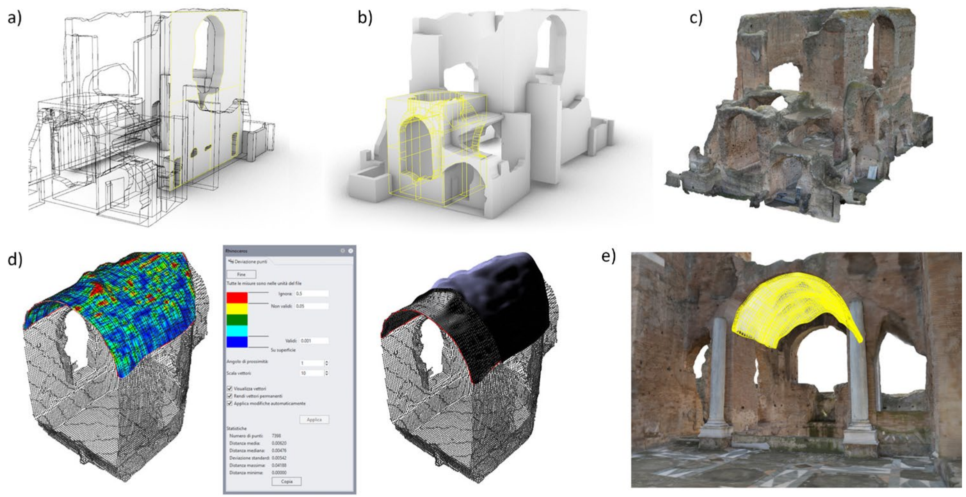

Fig. 8 - 3D modelling process of frigidarium: a) 3D drawing, b) NURBS model, c) textured model, d) AVS and grade of accuracy of complex elements, e) HBIM model object. Source: author F.B.

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Geometric verification of the model required specific Non Uniform Rational Basis-Splines (NURBS) modelling techniques to account for the morphological complexity of each element identified during the generative process. An Automatic Verification System (AVS) assessed the standard deviation between point clouds and the HBIM model (Fig. 8). The geometric reliability of each model depended not only on the accuracy of the survey but also on the interpretation and modelling phase of individual elements.
The study achieved highly accurate results within the established representation scale, with each component having a grade of accuracy (GOA) of approximately 2/3 mm, starting from an error value of about 1/2 mm relative to the survey's precision. Geometric reliability was conveyed within the HBIM project through the development of specific parameters, where the identification of individual data and their achieved GOA were specified in the property windows. Adopting and defining new exchange formats has enhanced model-sharing practices and orientation within the context discussed. The success of these novel representation forms relied on their ability to transfer both geometric and semantic information, facilitating a better comprehension of the research case study and more efficient management of analysis, maintenance, and restoration activities (Fig. 9). Rather than viewing the definition of suitable methods and formats as solely a technological challenge, a broader and interdisciplinary approach was adopted, involving professionals from diverse fields and integrating innovative approaches to communication and information sharing.

ADVANCING INTEROPERABILITY AND DATA TRANSFORMATION IN HERITAGE REPRESENTATION

In the early 2000s, the term "BIM interoperability" emerged, emphasizing the imperative need

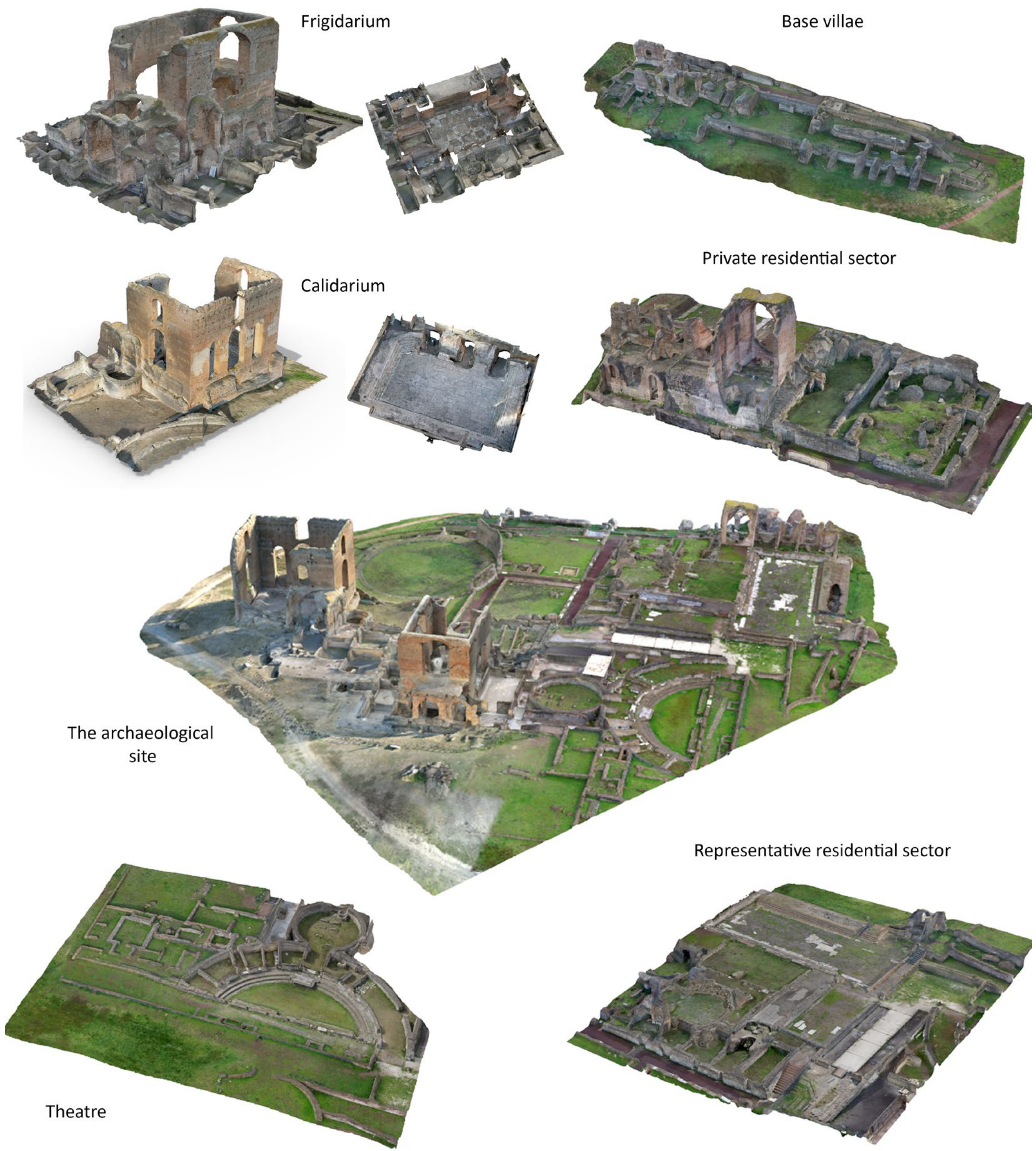

Fig. 9 - High-resolution textured models of the main areas of the archaeological sites: a) Residences - Representative Area, b) Residences - Private Area, c) Service Area, d) Frigidarium, e) Calidarium, f) Theater, g) Tepidarium, h) Small amphitheatre. Source: author F.B.

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for seamless integration of various BIM software and systems within the realm of construction and design. Interoperability entails the smooth exchange of data between disparate systems or components, ensuring optimal functionality (Ren & Zhang, 2021). This concept holds particular significance in technological contexts, especially in the domain of digital modelling, as it denotes the seamless communication and integration of diverse software, hardware, or systems without encountering impediments. Recent advancements in GBXML and Industry Foundation Classes (IFC) specifications have revolutionized the flow of information in the stages following the initial BIM modelling process (Laaks & Kiviniemi, 2012; Pazlar & Turk, 2008).

This has eradicat ed the laborious tasks of re-modelling, redundant data entry, and reliance on specialized plug-ins or custom interfaces. Within BIM applications, well-defined data sets can now be effortlessly directed towards a diverse range of analyses, thanks to semi-automatic export methods. Tools such as Solibri and other IFC viewers empower professionals to assess model quality in semantic terms by astutely interpreting pre-mapped parameters (Muller et al., 2017; Lai & Deng, 2018).

IFC stands as an "open life cycle" BIM data format, garnering widespread support from major software players including Autodesk, Graphisoft, and Bentley. Its popularity often surpasses that of GBXML, particularly in the field of energy analysis. This emphasis on interoperability has even prompted entire governments, such as those of Denmark, Finland, and Norway, to mandate the use of IFC formats across all projects. This not only establishes a unified communication standard but also fortifies collaboration among private enterprises, public authorities, contractors, and designers (Elagiry et al, 2020).

The IFC schema has undergone several iterations, with IFC 2x3 and IFC 4 being the most significant. Currently, a plethora of ongoing projects predominantly favor IFC2X3 as the preferred exchange format. Nevertheless, it's worth noting that integrating BIM with building performance simulation and diagnostics can present challenges, particularly for buildings with intricately detailed models composed of numerous polygons.

To ensure seamless interoperability and maximize the utility of these models, it's vital to acknowledge that results may be contingent on proprietary formats, potentially rendering them susceptible to obsolescence. Additionally, in collaborative endeavours encompassing diverse disciplines, conflicts between different applications may arise. For instance, structural or energy-specific software may grapple with accurately interpreting the properties of the generated model. Addressing these challenges proactively is of paramount importance, ensuring the effective management of BIM data within the context of our built heritage.

This impetus has driven research efforts aimed at formulating sustainable processes where the value of Drawing, as a knowledge-generating process, enables the creation of semantic models proficient in conveying both tangible and intangible heritage values. To uphold the informative value of each element, parameters have been incorporated to accommodate alphanumeric values, which can subsequently be utilized by BIM-based analysis software.

Currently, a professional must acquaint themselves with over 130 digital formats (McHenry, & Bajcsy, 2008) to transfer the semantic and geometric richness of HBIM models during a digitization process. The simultaneous use of different modelling software presents a significant challenge, leading to the utilisation of a substantial number of formats. If employed inadequately, this can lead to exponential loss of both geometric and informational data. In this context, a holistic approach leveraging 3D tools, with the aim of minimizing the use of exchange formats (both proprietary and open), can represent an effective solution for representing and sharing the values of built heritage. This makes the process itself as sustainable as possible while minimizing the loss of information between stages.

The paradigms of interoperability and real-time sharing have been investigated to disseminate geometric and alphanumeric values to a wider audience, not limited solely to the professionals involved in the process. One of the main difficulties of this process is the simultaneous use of different modelling software, leading to the utilization of a large number of formats, which, if used inadequately, can result in the exponential loss of both geometric and informational data.

For this reason, this study compares the limitations related to these software differences, which in many cases, despite having the same input data (point clouds), can generate different outputs, especially in the field of HBIM.

It was possible to identify the necessary exchange formats to improve the dialogue between NURBS modelling applications like MC Neel Rhinoceros and BIM software like Autodesk Revit and Graphisoft Archicad. In particular, the proposed research approach is based on the following steps and exchange formats:

- Laser scanner output: las, e57, pts;
- Photogrammetry output: pts, jpg, png;
- AutoCAD and Recap Pro output: dxf, dwg, rcs, rcp;
- NURBS modelling output: 3dm, dwg (2007 solids schema), ACISsat;
- HBIM output: rvt, ifc, excel, ODBC, and fbx.;
- XR outputs: web-VR, mobile and desktop VR-AR apps, Images and Renderings, Videos and Animations, 360° Panoramas and VR, Standalone Executable Files, Interactive Experiences, Flow Diagrams and Floor Plans, Recording of Actions and Animations, Export in Standard Formats (FBX and OBJ), Customized Materials and Textures, Lights and Lighting Environments.

Through this selection, it is possible to transform simple points into HBIM objects capable of communicating various types of information in an open language. It was found that the most efficient format and schema for dialogue between NURBS modelers and BIM software is the DWG format. However, it should be emphasized that the DWG format, in turn, must be based on a specific export schema capable of transforming primitives, surfaces, and solids into entities recognizable by the BIM application.

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The transformation of point clouds into NURBS models composed of complex surfaces occurs directly in free-form modelling software like Rhinoceros.
AutoCAD can support the representation and modelling process when the user does not prefer the 2D vector representation tools of modelling software. The dialogue between these two applications can be accomplished using the DWG format without incurring data loss in geometric terms.The next step, once the NURBS model has been created, is to transfer it to the parametric software (in this case Autodesk Revit) in the correct manner. In particular, to prevent the model or drawings produced in MC Neel Rhinoceros or Autodesk AutoCAD from becoming basic uneditable 'blocks', the traditional import functionality of Revit should not be used (Insert/Import CAD). From a computational perspective, the architecture and logic of the software must be "bypassed" using the DWG format defined by the proposed method and imported into Revit through the Volume and Construction/Mass Local/Insert/Import CAD function.
The final step, once the typology of the BIM-wall object (materials, wall stratigraphy, etc.) has been defined, consists of the automatic or semi-automatic transformation of CAD/NURBS elements into BIM objects capable of being linked to alphanumeric information and new HBIM parameters. In most cases, users who are new to applying the proposed process may encounter misleading visualizations, which may lead them to believe that the process is not actually applicable. Before reaching the final step, the user must acquire knowledge and modelling skills in both software applications.
Only through this comprehensive approach has it been possible to fully exploit the advantages offered by HBIM models and effectively leverage technology to enhance quality and interoperability across various disciplinary sectors. To this end, the scan-to-BIM process employed advanced modelling techniques, enabling the conversion of 3D drawings into NURBS mathematical models for enhanced usability in different types of analysis. Creating architectural and structural elements, such as vaults, arches, damaged walls, and decorative features, necessitated a reliable geometric transposition based on a deep understanding of the artefact and accurate interpretation of each element.

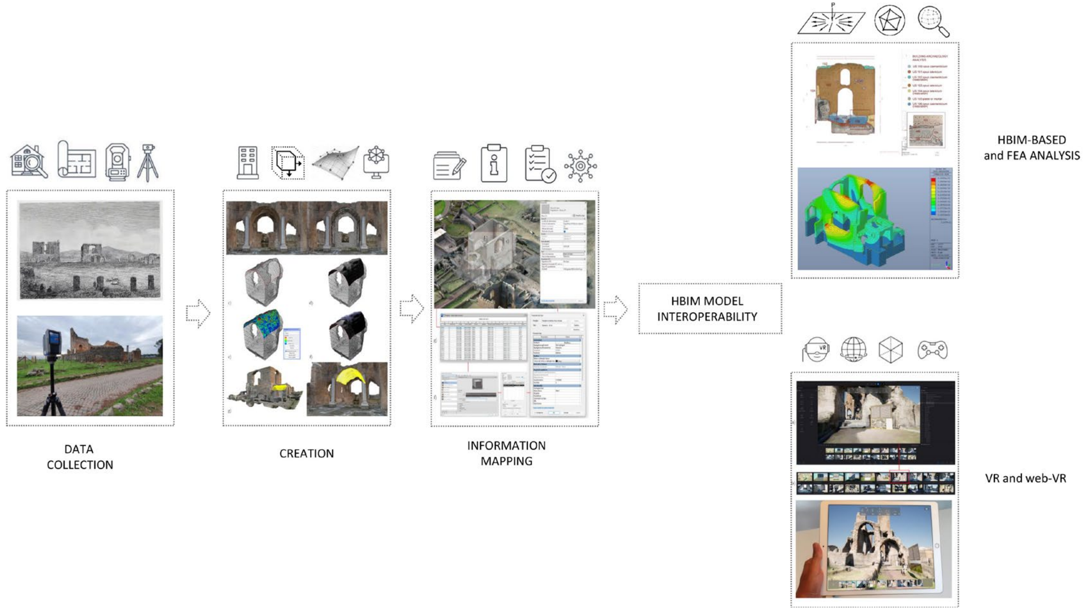

Fig. 10 - HBIM model interoperability: from data collection to HBIM-based and FEA analysis to VR and wev-VR.

Additionally, the HBIM objects, as elaborated in subsequent paragraphs, served various purposes, including evaluating the archaeological site's conditions, structural analysis, and disseminating information by creating virtual environments and multimedia materials, thereby enhancing the overall experience of the archaeological site.

BUILDING ARCHAEOLOGY: EVALUATING OF THE CONDITIONS OF THE ARCHAEOLOGICAL SITE

Research on BIM in the context of built heritage focuses on developing strategies to integrate material and decay analyses into informative platforms, aligning HBIM with knowledge and preservation requirements. Building archaeology analysis, dedicated to reconstructing the historical context of existing structures through direct observations, offers a potential methodology to achieve this objective (Boato & Pittaluga, 2000). By examining various data, including materials, construction techniques, and interconnections between elements, archaeologists can uncover the building's past (Schuller, 2002; Hodder, 2022). Similar to architectural conservation, building archaeology employs scientific and analytical methods to describe, evaluate, and date these structures. The building stratigraphic unit (SU) serves as a valuable tool in this field, representing a segment of the building resulting from a single construction activity. In the HBIM model, stratigraphic units are crucial in meeting geometric and informational reliability requirements.The reliability of the HBIM model is closely linked to the concept of "transparency," which has been addressed in the literature since the introduction of the London

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Charter in 2009 (Denar D. H. 2012; Carrillo Gea et al., 2013; Brusaporci & Trizio, 2013).
The Seville Principles, expanded upon in 2012, further emphasise this concept, particularly in archaeology (Bendicho, 2013). The London Charter focuses on computer-based visualisation of Cultural Heritage, highlighting the importance of communicating utilised sources through the model as a means of data transmission in cultural asset research. In the context of three-dimensional archaeological reconstructions, "intellectual transparency" involves transparently presenting the sources used. Conversely, the Seville Charter addresses "scientific transparency," aiming to make three-dimensional visualisations accessible and usable for other experts to verify or challenge the obtained results. These principles introduce the concept of paradata alongside metadata. Metadata provides ancillary data that describes the object or subject in detail, including indirect sources utilised in construction of parametric model. Paradata, on the other hand, relates to the data collection process, which is particularly relevant in built heritage and encompasses methods of acquisition and survey, such as direct methods, laser scanning, and photogrammetry. The analysis resulting from building archaeology integrates both direct and indirect sources, with direct sources including surveys, on-site inspections, and material/decay analysis, while indirect sources consist of reconstructions based on primary and/or other indirect sources (Fig. 9).
Building archaeology contributes to the subdivision of walls into stratigraphic units (SUs), differentiated based on construction techniques and stratigraphic relationships.
The HBIM model of the site is then constructed using these SUs, ensuring that each wall layer has its own consistency and properties. HBIM properties are added, encompassing materials, observations, and documentation for each SU, aiming to convey hypotheses regarding construction phases or materials and the reliability of the sources. Building archaeology thus captures the geometric and semantic complexity of the site, offering an overall view of the data used and the level of

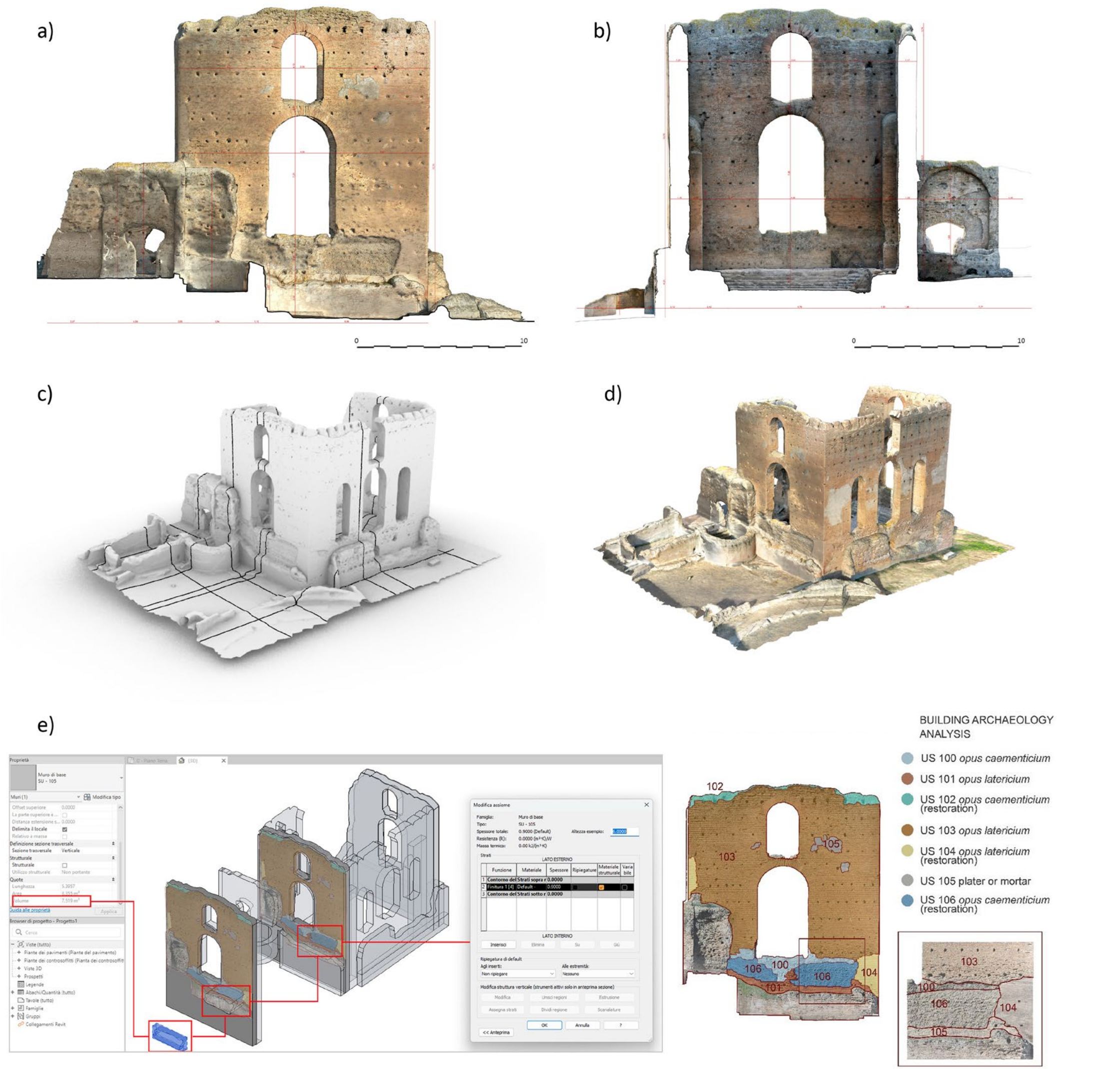

Fig. 11 - Southern façade – Preliminary Building Archaeology analysis: from a-b) measured drawings (elevations and sections), c) NURBS models and section planes, d) textured model to e) HBIM model for building archaeology analysis: from NURBS model to HBIM objects (Customizable and computable stratigraphic units). Source: author F.B.

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knowledge attained for each individual HBIM object. The analysis focused primarily on the southern facade of the calidarium (Fig. 11), selected as a representative sample for examining materials, construction phases, techniques, and structural conditions.

To enhance the Level of Development (LOD) and Level of Information (LOI) of HBIM models, they were decomposed into sub-elements capable of representing semantic structures beyond mere geometry or construction logic. Establishing intelligent parametric objects and their bidirectional relationships were crucial for subsequent information mapping and sharing complex analyses. A more detailed analysis will involve utilising archival documentation to reconstruct the construction and restoration sequence in greater detail. The exercise aims to comprehend the complex construction history of the calidarium, including recent and older transformations and restorations over the centuries.

At approximately 2.70m above ground level, the facade's visible cementitious core (SU 100) is partially restored (SU 106) due to loss or lack of integration of the brick facing during the preservation phases. Towards the east, a stratigraphic unit with recently restored brick masonry (SU 104) is discernible, also appearing higher on the left side, indicating specific restoration interventions. The foundation is marked by SU 101, which likely covered the underlying cementitious core, distinguishable by the different color of bricks in the masonry characterising the facade (SU 103). Further insights into these two layers of masonry can be gained through a chronological analysis of the bricks combined with archival research.

The foundation also features a brick masonry extending approximately 0.80m from the ground, with openings displaying two arch rings in SU 103, where the larger one is positioned below, the smaller one. Traces of mortar or plaster (SU 105) are observable in some areas of the facade, requiring diagnostic investigation for composition analysis. At the upper part (summit), SU 102 is visible, corresponding to the restoration of the upper sections of the walls, as seen on other fronts of the calidarium. Spaced pontai holes are visible at various levels on the brick and opus caementicium stratigraphic units, indicating a height difference of approximately 1.30m.

Elucidating these aspects makes the relationship between sources, interpretation, and the three-dimensional model comprehensible, facilitating transparent communication of the results to individuals not directly involved in the research. The transmission of specific information for each individually modelled element ensures the "transparency" of the intrinsic parameters of each data source And at the same time, lay the foundation for the preservation process based on specific quantities (Bidirectional information-object relationship typical of parametric HBIM objects). Various modelling approaches have been employed to demonstrate how the generation of stratigraphic units, identification of materials, construction techniques, and historical phases can be transformed into tangible BIM parameters shared among all users involved in the preservation process. Advancements in programming languages, such as blueprints, have facilitated the transition from static representation of digitised elements. This process enables the management of interactive virtual objects (IVOs), enhancing interactivity and immersion in accurate scan-to-HBIM projects for VR and Finite Element Analysis (FEA).

MODEL INTEROPERABILITY FOR FEA

Due to the integration of NURBS modeling and the precise application of specific Grades of Generation (GOG) (Banfi, 2017), an extensive workflow encompassing scanning, BIM, and FEA, was established. This facilitated the accurate representation of both morphological and typological intricacies within the thermal area of the villa, seamlessly transferring this data to the Midas structural analysis software. This enhancement significantly augmented the analysis and simulation capabilities, harnessing highly detailed geometric models of the frigidarium and calidarium. Specifically, the process enabled the detection, interpretation, and visualization of wall irregularities (Fig. 12).

This information seamlessly transitioned from Autodesk Revit to Mc Neel Rhinoceros before

a). b). c)

Fig. 12 - Flat jacks, single and double, on the a) north and b) east walls and c) subvertical survey in the foundations of the calidarium. Source: authors A.V. and A.L.

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reaching the Midas software, transforming the complex model into a mesh format optimized for Finite Element Analysis (FEA).
In effecting the transfer of a model from Revit or Rhino to Midas, a file format endorsed by both platforms was employed. Among the prevalent formats utilized for this objective, the IGES (Initial Graphics Exchange Specification) stands as a prominent choice. IGES, functioning as a neutral file type, facilitates the seamless interchange of geometric data across a spectrum of CAD modeling applications, encompassing Rhino, Revit, and Midas.
During this transitional phase, it proved imperative to fine-tune specific export parameters, encompassing tessellation precision and other geometric configurations. Notably, tessellation emerges as a critical operation for facilitating the accurate transfer of intricate geometries between the utilized software platforms. This process entails the transformation of solids into meshes, rendering them amenable for subsequent interpretation and computation by structural analysis software.
Tessellated 3D models have demonstrated reduced computational complexity in processing when compared to their original solid counterparts. This transformation necessitated fewer computational resources for conducting structural analyses, thereby enabling a swifter and more resource-efficient simulation.
In the initial phase, a diagnostic analysis was imperative to integrate material properties and geometric data derived from the models. Non-invasive tests were meticulously conducted to scrutinize and characterize materials and construction methodologies, evaluate the conservation status, ascertain the mechanical attributes of the masonry, inspect foundation levels, and determine the vaults' and supporting walls' thickness. Specifically, both single and double flat-jack tests were employed to define the mechanical properties of the wall surfaces. Additionally, endoscopic examinations were carried out to investigate the composition and thickness of layers within the wall surfaces. Sub-vertical coring techniques were utilized to establish the depth of the foundations (Fig. 12).
The uniqueness and authenticity of the HBIM models were preserved to enable a more detailed simulation. While a proper interoperabilty using specifc formats and modelling techniques were

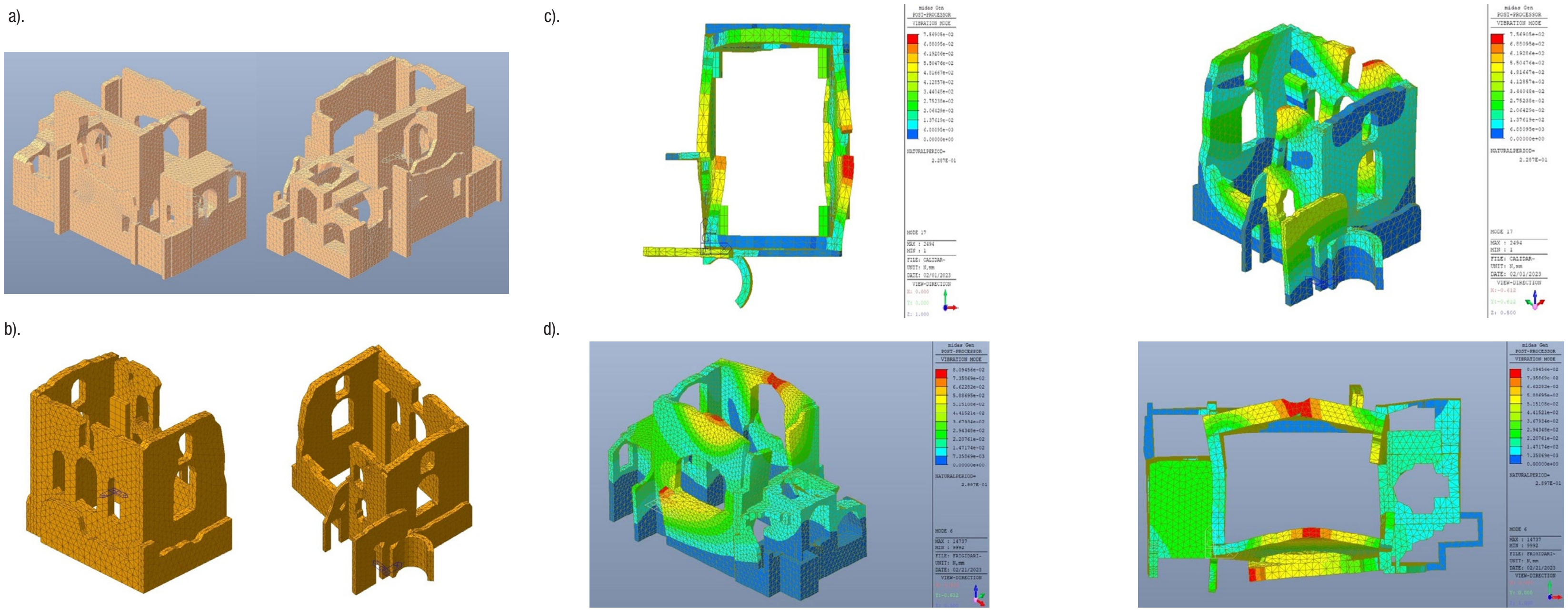

Fig. 13 From HBIM to FEM: MIDAS models of a) frigidarium and b) calidarium and modal dynamic analysis of the c) calidarium (mode of vibration No. 17 in axonometric and plan view) and d) frigidarium (mode of vibration No. 6, axonometric and plan view). Source: authors A.V. and A.L.

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necessary to obtain a coherent mesh for structural simulation, the performance of the scan-to-BIM-to-FEM methodology was remarkable and allowed for the achievement of specific structural results.
The third phase involved studying the overall behavior of both the calidarium and frigidarium through finite element analysis (refer to Fig. 13). Concurrently, analyses were also conducted using local collapse mechanisms derived from the 3D survey. The finite element analyses were performed in both linear dynamic (modal dynamic analyses with response spectra) and linear and nonlinear static (gravity static analyses and equivalent static nonlinear seismic "pushover" analyses) fields.
The analyses of the overall behavior revealed a tendency for numerous relative movements between different parts of the structure due to discontinuities within the structure itself. Although both the calidarium and frigidarium have a substantially box-like appearance, they lack horizontal closures, and both exhibit significant horizontal discontinuities at the top of the perimeter walls. The modal analysis images clearly show these relatively disordered movements (refer to figures 13c and 13d). Consequently, the modeling of the overall behavior highlights very low safety coefficients in the presence of horizontal actions (around 0.39 to 0.48). The analyses evaluating the collapse mechanisms of individual walls demonstrate even higher local risk situations, including horizontal bending mechanisms.

EXPLORING ANCIENT WORLDS: VR TECHNOLOGY IN ARCHAEOLOGICAL PRESERVATION

One of the key advantages lies in the immersive experience that VR offers to visitors, enabling them to fully immerse themselves in a virtual environment and experience the sensation of being present in a place or interacting with objects and artworks (Ferretti et al., 2022; Giordano et al., 2023). Through the capacity to interact with objects, view them from various angles, and gain a deeper understanding of the details, VR enriches visitor learning and experience. It also provides an interactive representation for restoration professionals focused on analyzing their geometric and material complexities along with associated deteriorations. A meticulous observation of the mosaic surfaces underscored the necessity for advanced digital survey techniques and the application of more specific and accurate tools and procedures compared to traditional surveying and representation methods. Notably, the integration of terrestrial photogrammetry and advanced modelling techniques laid the groundwork for a process aimed at capturing elements of varying sizes, damaged and irregular, characterized by non-coplanarities and occlusions.
Beyond these geometric considerations, an additional challenge arose in interactive representation. In addition to conventional outputs like orthophotos and vector drawings (plans, elevations, and sections), digital outputs were developed to effectively convey high levels of detail (LOD) and information (LOI) through the integration of computer languages capable of animating the modelled objects. This process involved the utilization of open formats such as .fbx and .obj, facilitating the transfer of not only the complex geometry of the sculpture but also high-resolution textures obtained through digital photogrammetry. The process encompassed a refinement stage within the Mc Neel Rhinoceros software, enhancing the model's geometry and aligning the intricate surfaces of the frigidarium and calidarium for implementation in virtual reality (VR) software such as Unreal Engine, Twinmotion, and Unity (Fig. 14). The output formats encompassed a meshing process capable of transforming the mesh entities from Agisoft Metashape software into NURBS mathematical models. This process facilitated improved interoperability between software platforms and the transfer of high-resolution textures throughout the workflow from the mesh model to

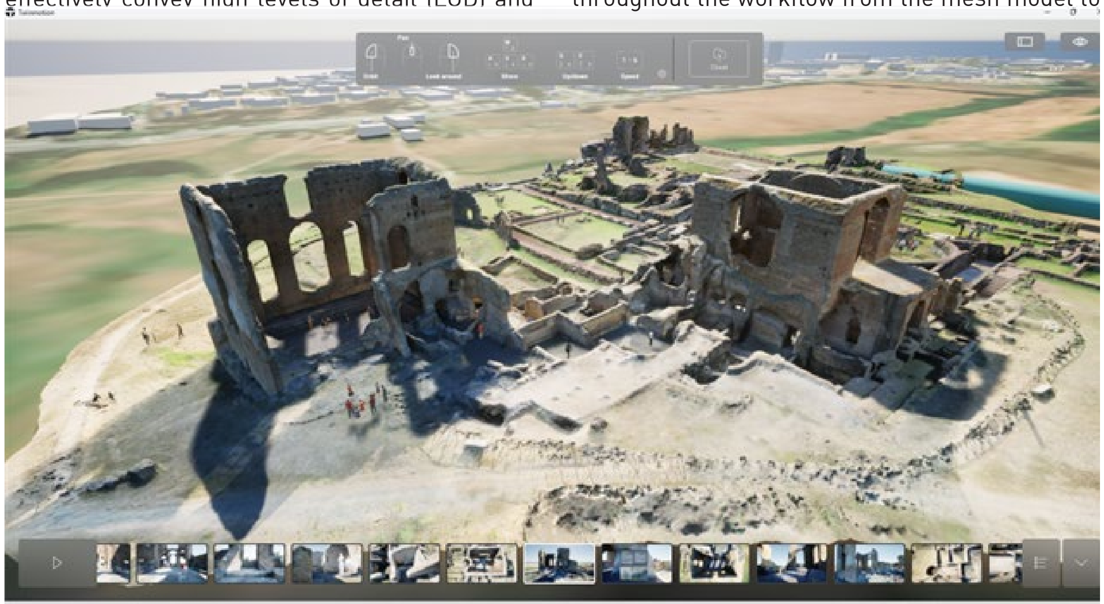
Fig. 14 - VR of the archaeological site (general view). Source: authors.

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the VR model in UE5.
The conversion process from the 3D model to the virtual environment involved the reprocessing, analysis, and interpretation of a large amount of data aiming to develop environments that could be navigated in traditional VR forms using VR headsets, commands, and web-VR forms through which virtual content and information can be accessed via mobile devices. This approach avoids the need for specific hardware and facilitates the overall experience.Using the visual programming language (VPL), it was possible to associate specific behaviours with the objects, digitized drawings, and texts imported into the VR development environment. This transformed the experience from virtual to interactive, promoting learning through a strategy based on eight essential requirements (Banfi, 2023):

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

These eight steps allowed for the application of a process that creates an immersive, interactive, and informative environment capable of representing and communicating content in a simplified and innovative manner, even through web-XR. The latter development was undertaken to simplify access to virtual content for all types of users, from professionals and experts in VR tools (such as headsets) to non-experts and virtual tourists who can only interact with mobile devices, thus avoiding the need for additional hardware integrations (Fig. 15).
While the constraints identified during the testing phase of the web-XR application may not be of paramount concern, they warrant attention for a comprehensive understanding of the current state of this specialized technology and to proactively address potential future developments.
In terms of computational capacity, contingent upon the availability of cloud-based GPU instances, the system allows for the concurrent visualization of up to a maximum of one hundred presentations. In scenarios where an insufficient number of GPU instances are available, a queuing system is established, awaiting allocation of an accessible GPU instance.
Furthermore, the calibration of presentation quality settings dynamically adapts, contingent on benchmark assessments during processing. Typically, presentations are rendered at the highest achievable quality level, denoted as 'Ultra'. However, circumstances may arise wherein a resource-intensive presentation necessitates a reduction in rendering quality to ensure a seamless viewing experience. For an optimal viewing experience, it is advised to maintain an internet connection with a bandwidth threshold of no less than 25 Mbps. Regrettably, auditory elements are not supported within presentations and panorama sets, constituting an inherent limitation.
Moreover, there exists a specification on the file size of presentations eligible for upload onto the Twinmotion Cloud, capped at 2 GB. This encompasses both the file dimensions of the Twinmotion scene itself and the associated scene assets.
Due to current constraints associated with cloud-based GPUs, presentations must operate within a threshold of 21 GB of video memory (RAM) to ensure compatibility with the cloud infrastructure. In the event of an attempt to upload media surpassing this limit, a notification will promptly inform the user of the excess.
It is possible to mitigate video memory requirements by simplifying scenes, such as removing intricate textures or geometric elements. When

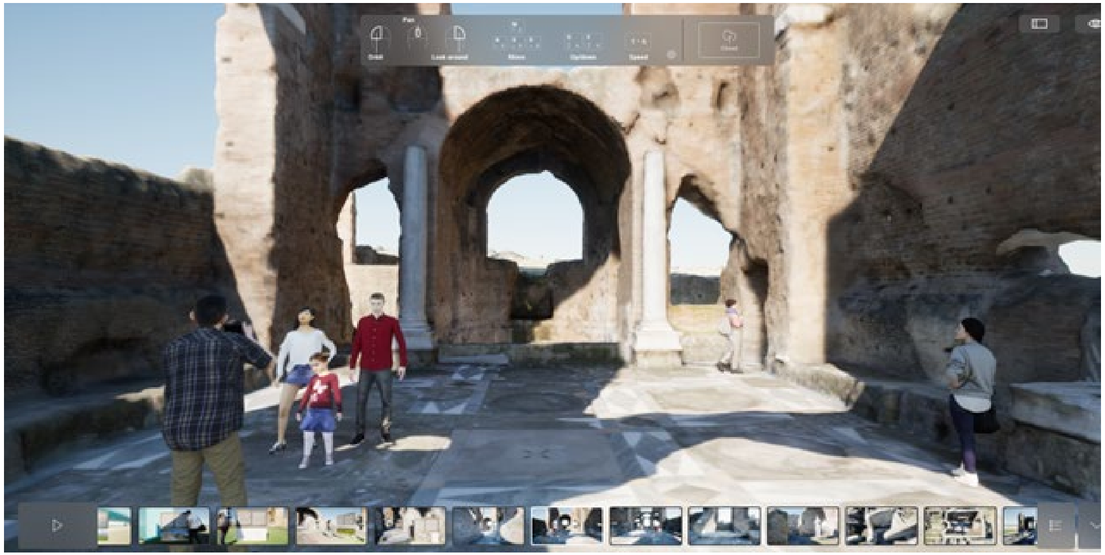

Fig. 15 - VR of the archaeological site (frigidarium view).The experience can be enjoyed using a range of devices tailored to individual navigation and interaction capabilities. These include VR headsets, mobile devices such as tablets and phones, and desktop applications accessed through a web browserSource: authors.

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uploading content onto Twinmotion Cloud or browsing content through a web browser interface, it is imperative to acknowledge that Twinmotion Cloud services may face potential obstructions from antivirus software or ad blockers. To circumvent such impediments, it is incumbent upon the user to deactivate ad blockers and authorize Twinmotion within the purview of their antivirus software.
Furthermore, it is pertinent to underscore that the dimensions of textures within presentations designated for upload onto Twinmotion Cloud are confined to 2K. Lastly, presentations are subject to temporal constraints on two fronts.
As these limits are approached, precautionary advisories are promptly issued: a presentation may not remain open for a duration exceeding 90 minutes.In the absence of any user-initiated interaction or movement within a presentation for a period of 30 minutes, automatic disconnection occurs due to perceived inactivity. A straightforward means to re-establish the connection is provided by the 'Reconnect' button, conspicuously located within the browser interface.
In light of these purely technical limitations, which do not impact the virtual experience, an additional initiative was undertaken to augment the accessibility of the mosaic structures on the site As briefly mentioned, the open-air mosaics are covered during the winter months to best preserve them from the elements. In order to provide a complementary experience to an actual visit on-site, a further application was developed to afford visitors virtual access to the most significant mosaics in the thermal and representative areas. Figure 16 shows how, through web-XR development, the mosaic floors of the archaeological site can be navigated, providing an integrative experience to the site itself.
In the winter, site visitors will not be disappointed with the tour offered, thanks to the integration of web-XR, which will allow them, both on-site and off-site, to appreciate the uniqueness of the mosaics throughout the archaeological site. Through a cloud service, it's possible to share the VR project online. With an intuitive interface and integrated guidelines, the user can quickly acquire the skills needed for simplified touch screen navigation via a web browser. In addition to avoiding the use of complex VR headsets, virtual accessibility is enhanced through a methodological approach that doesn't require the installation of additional software. Through the web, any type of user can access without worrying about having login credentials or licenses.
Using a QR code and a link provided directly by the administration, every visitor can access interactive content, exploring multimedia files that provide accurate descriptions of the mosaics and temporarily inaccessible structures.

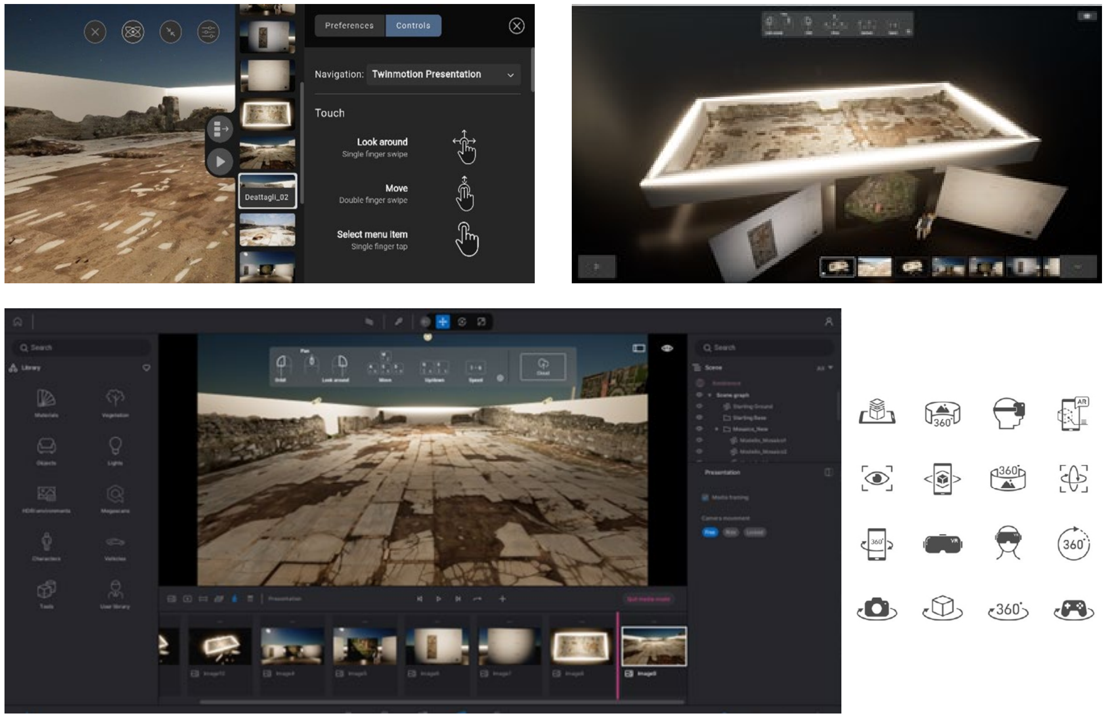

Fig. 16 - Web- VR focus on the mosaics for mobile, VR and desktop devices.

CONCLUSION

Digital representation techniques have encountered their fair share of challenges, primarily stemming from the evolution of methodologies and the introduction of model interoperability, alongside advancements in surveying techniques. These strides forward have ushered in a paradigmatic shift in how professionals in the fields of architecture and archaeology approach heritage preservation.
The seamless integration of digital models and datasets serves as a linchpin for gaining a comprehensive understanding of historical sites, offering profound insights into their spatial, structural, and

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chronological dimensions. This holistic approach underpins the decision-making processes crucial to restoration and conservation endeavours.
Therefore, engaging in theoretical inquiries into the interoperability of cutting-edge digital representation forms became pivotal.
The primary objective was to discern, within an interdisciplinary context, how the efficacy of these emerging mediums can impact subsequent analyses and endeavours directed towards architectural archaeology, safeguarding archaeological sites, conducting structural investigations, and advancing immersive environments.
The role of interpretation in 3D modelling, utilizing point clouds and archival research, was crucial. This method involved a detailed analysis of data obtained through laser scanning or photogrammetry, creating accurate point clouds representing object and structure surfaces. Interpretation went beyond visualizing points, demanding a deep understanding of the inherent characteristics and spatial relationships among acquired elements.
Interpretation allowed for discerning and categorizing various components within the point cloud, including surfaces, architectural details, and other relevant features. This led to identifying buried structural elements and a better understanding of artefacts. Additionally, interpretation played a vital role in virtual reconstruction. Interpreters generated precise models by recognizing key points and understanding their spatial arrangement. This was particularly significant in disciplines like archaeology, architecture, and heritage conservation, where faithful representation of acquired objects was crucial for research and documentation.
Interpretation's ability to integrate data from diverse sources was another important aspect, especially when combining point clouds and digital models with archival or documentary information. It facilitated establishing correlations between gathered data and historical documentation, enhancing understanding the context and object under study.
Ultimately, interpretation acted as a corrective measure for potential limitations or inaccuracies in the scanning data. By identifying and rectifying disparities or gaps, interpreters ensured the precision and reliability of the final 3D models, strengthening the scholarly integrity of the analytical outcomes.
Moreover, the digital representations derived from digital surveys significantly enhance the precision and efficacy of analytical and interventionist procedures. Within the proposed interoperable workflow, intricate HBIM models provide the foundation for generating finite element models, thereby amplifying the accuracy of structural analysis.
Incorporating historical data into digital representations further bolsters the credibility of outcomes, facilitating a more nuanced understanding of structural dynamics and ensuring steadfast preservation.
In the realm of museums, immersive virtual experiences constitute a paramount advancement in enhancing the exploration and comprehension of archaeological sites. By harnessing virtual reality headsets and augmented reality devices, visitors can engage with meticulously reconstructed historical artefacts, allowing them to immerse themselves in the grandeur of ancient architectural remnants virtually. This approach upholds authenticity while broadening global accessibility to our shared cultural heritage. Regardless of physical constraints, individuals worldwide can appreciate these invaluable treasures through the immersive potentialities offered by VR and webXR technologies.
This marks an integrative leap forward in the current museum milieu, ushering in novel prospects for implementation and interactive representation techniques. The overarching aim was to cultivate immersive experiences capable of bolstering the transformative potential of museums in the digital era.
As emphasised, the Science of Representation has emerged as a highly efficacious communication tool, providing a means to apprehend the plurality of forms that constitute the very essence of material reality. Simultaneously, they cultivate a profound appreciation for the tangible and intangible values enshrined within the archaeological expanse of Villa dei Quintili.
Notably, model interoperability, drawing, and 3D modelling have assumed a pivotal role, serving as both a space and a moment for erudition critical deliberation and as a tool for fostering interoperability with diverse analytical methodologies.
This approach has facilitated the systematic updating of knowledge, the comprehensive representation, and the meticulous analysis of one of Italy's paramount Roman archaeological sites within the broader cultural milieu.
In conclusion, consistently enhancing competencies is paramount, especially in domains marked by swift evolution, such as digital representation and communication.
This is vital for proficiently supervising a digitization process intended to distribute a wide array of content. Merely acknowledging the risks linked with technological progress falls short, as technology will inevitably forge ahead, and individuals will persist in its application. Understanding how these strides will influence our day-to-day activities across a worldwide web of connections encompassing all academic disciplines is crucial. Striving for a comprehensive understanding is paramount for effective management.

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NOTE

[1] This research represents a collaborative and meticulously coordinated effort among the authors, building upon subsequent outcomes reported in Banfi 2023. F.B. took the lead in composing all paragraphs, ensuring coordination across all sections, particularly in relation to the definition of the proposed approach. A.V. and A.L. meticulously revised paragraph 6, integrating their structural analysis findings. F.R.P. and C.S. took charge of paragraph 2 and played a pivotal role in tandem with F.B. to oversee the entirety of the content.

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