XR Narratives from Informative Models: The Mausoleum of Cecilia Metella and the Castrum Caetani in the Appian Way (UNESCO)

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Abstract

Extended Reality (XR) is recognized as a form of cultural opportunity for transferring knowledge to the broader public through digital heritage. Mostly, it is based on models developed discreetly and with passive fruition. The growth of informative models and geo-information systems opens the door to multiple potentialities, feeding and multiplying narratives where visitors can orient their own interests. The paper explores the potential of developing interactive web models that enable users to navigate narratives and layers of information within a shared geospatial framework. It proposes a scalable methodology through which the development of XR in a complex heritage context, such as the Appian Way, could support the integration of multi-scale, multi-temporal stratified layers (e.g., ArcheoInfrastructure, ArcheoLandscape, archaeological and architectural layers), allowing for continuous future implementation by diverse subjects. The increased availability of quality models derived from rigorous multi-scale surveying, including LiDAR, Terrestrial Laser Scanning (TLS), Mobile Mapping Systems (MMS), and photogrammetry (by using different cameras and drones), represents a resource that can be reused to enrich XR content and amplify the impact of efforts made in their creation within research and conservation projects. The multiplication of diverse data sources and models necessitates the correlation of informational nodes within geographic space, an aspect still underutilized in current XR environments. This shift points toward the development of geoXR. The research investigates how content-driven informative models, such as Heritage Building Information Modeling (HBIM) nodes, Geographic Information Systems (GIS), and 3D landscape information systems, can be interrelated into an interoperable and interactive geoXR platform.

1. Introduction

Digital models that communicate information and transfer knowledge related to built heritage are increasingly developed through immersive formats. The concept of 5D culture is gaining importance, particularly in supporting the re-use of models within platforms such as Europeana (Europeana Pro, 2024). The re-use of advanced informative quality models holds great potential for disseminating aggregated knowledge, requiring the proper transfer of their feasibility, accuracy and validation (Brumana, et al., 2024). Within the domain of Digital Cultural Heritage (DCH), studies have generated virtual experiences that embed identity, cultural, historical, and architectural values. Extended Reality (XR), Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), enable novel ways to experience heritage through sensory immersion and spatial interaction (Banfi, 2021; Vasarainen et al., 2021). Consequently, many museums and galleries offer virtual access to their collections via VR headsets, web platforms, panoramic tours, and serious games. The evolution of interactivity, immersion, and interoperability in HBIM (Banfi, 2021) has fostered XR experiences across diverse user groups. Simultaneously, reflections have been emerging on realism, abstraction, and interactivity when integrating landscapes in XR spaces (Lange, 2001; Williams et al., 2007; Kühne et al., 2022), pointing to the need for hybrid approaches that combine data fidelity with narrative design. Increasingly, web-based XR applications accessible via smartphones are enabling mass personalization of cultural tours, driving demand for richer, content-driven narratives. Within this context, the integration of HBIM and GIS via XR offers a foundational framework that spans from the geomorphological, environmental, and landscape scales of heritage contexts to the detailed management of archaeological and architectural elements – organized as HBIM nodes interconnected across spatial-temporal scales.

2. Research Objectives

Building upon these premises, this research proposes an innovative and interactive method for transforming 3D HBIM models and 3D ArcheoLandscape photogrammetric models into XR narratives, engaging virtual users with built heritage through both its tangible and intangible dimensions. The progressive integration of these nodes into geoXR is envisioned as a narrative-rich pathway, anchored in a strong geographic GIS-based spatial framework of the Appian Way, tested here as the enabling infrastructure for the geoXR environment. Spatial geodata typically managed within GIS is repurposed and encoded in 3D engines such as Twinmotion and Unreal Engine (Portman et al., 2015; Ghadirian & Bishop, 2008). In this way, the research aims to implement immersive XR narratives that enhance public engagement, re-using the richness of HBIM and GIS informative systems. It proposes the development of a scalable, GIS-geoXR integrated framework for disseminating multi-temporal, interdisciplinary knowledge of complex heritage sites, enabling the correlation of informational nodes (HBIM and 3D landscape models). This study underscores the transformative potential of integrating GIS, HBIM, and 3D landscape modeling technologies to enhance the communicative capacity of geoXR in conveying the complexity of multi-stratified archaeological infrastructures, archeolandscapes, and architectural remains. The resulting narratives are grounded through multi-temporal stratification, layered onto historical cartographic sources and deployed via XR applications. By exploring new forms of interactivity and immersion for the public, the study pushes the frontier of heritage enhancement, investigating how integrating GIS, 3D modelling, and XR technologies could transform archaeological landscape management and bridge the past and envisioned futures through multi-temporal data and XR storytelling (Wang et al., 2025, de Andrade et al., 2020; Papadimitriou, 2022).

3. Research Case Study

The Appian Way site, “Via Appia Antica, Regina Viarum,” was officially inscribed on the UNESCO World Heritage List on 29 July 2024, becoming Italy’s 60th recognized site. Initially designed for military purposes by Appius Claudius, Censor of Rome in 321 B.C., the Appian Way was built to connect Rome to Capua and later extended to Brindisi. From its inception, it served as a major commercial and cultural communication route, conceived as a *via publica*, a public road accessible to all, constructed on land expropriated by the Roman State. Today, the Appian Way stands as a unique example of archaeological heritage infrastructure, with its mausoleums, sepulchers, ruins, remains and museums (Paris, 2000). This living palimpsest, deeply stratified over two millennia, demands a new narrative approach, one that transcends conventional storytelling by integrating multiple levels and scales of historical and spatial information. The first 12 km of the Appian Way, managed by the Parco Archeologico dell’Appia Antica (PAAA), have undergone a progressive digitization and detailed surveying aimed at supporting research, conservation, design projects, and public communication. The significance of this infrastructure is exemplified by monuments such as the Mausoleum of Cecilia Metella, built as a commemorative funerary monument between 30 and 20 B.C. A milestone in this SCAN-to-BIM-to-XR digitization was the virtual multimedia exhibition, launched on 22 December 2023 (Brumana et al., 2024), featuring 10 Oculus visors within the Cecilia Metella Mausoleum (PAAA MuviAppia, 2025; PAAA, 2024; Katatexilux, GIcarus Lab). The significant increase in visitor engagement at the Mausoleum of Cecilia Metella, previously under-visited, highlights the power of high-quality, immersive information models and the necessity of communicating the provenance of the data, including survey methodologies and the authorship of the 3D models that is generally missed. Moving from this result, the paper presents the experimentation of new narratives deployed on information models through the SCAN-to-BIM-to-geoXR within the common framework of geoXR pipeline.

4. Research Methodology & Materials: ArcheoLandscape Data Management System toward a geoXR interoperability (GIS, 3D Photogrammetric models, and HBIM).

The data acquisition was conducted through a multi-sensor 3D survey approach, forming the reference database that supports the proposed enhancement. The digitization of the 12 km of the Appian Way (Brumana et al., 2023), involved the use of Mobile Mapping Systems (MMS), terrestrial and UAV aerial photogrammetry, and 360° spherical imaging (Brumana et al., 2023). Building on this foundation, three primary integration paths are proposed:

a) GIS-to-geoXR – Enables the geographic contextualization of heritage assets by anchoring SHP and GeoTIFF layers within immersive XR environments, preserving semantic layering.
b) OBJ-to-XR – Focuses on the immersive visualization and interaction with 3D ArcheoLandscape models, derived from photogrammetric campaigns. This supports the exploration of terrain, ruins, and environmental-landscape features as the uniqueness of the vegetation layer.
c) SCAN-to-HBIM-to-XR – Enhances the approach of singular architectural-archaeological elements through implemented textual and visual data about construction phases, materials, techniques.

A common framework has been implemented to support the integration of geographic scale with modular architectural nodes, designed to be progressively expanded over time within the XR platform. This is operationalized through the creation of a Multi-Temporal Geographical Atlas, which encodes geographic layers – including shapefiles (SHP), historical cartography, and, in the future, Earth Observation datasets – as multi-scalar environmental, infrastructural, and cultural information. The atlas is conceived to facilitate advanced interoperability workflows, particularly GIS-to-XR, in support of the management and communication of complex archaeological infrastructures. The proposed system is structured as a network of spatial-temporal nodes, each developed through high-quality, updatable, and reusable information models. The XR is designed to address academic research and public engagement goals. Furthermore, the inclusion of paradata ensures full documentation of the SCAN-to-HBIM-to-XR workflow, detailing specifications such as Levels of Development (LOD) and Levels of Accuracy (LOA) keeping the source accuracies. This contributes to transparency and traceability throughout the entire pipeline – from initial data acquisition to the deployment of immersive experiences – ensuring all derived outputs are validated and technically coherent (Brumana et al., 2023). A mind map of the multiple layers managed through XR has been implemented to include and correlate the stratified components of the Appian Way. These include environmental and geomorphological features, multi-temporal atlas layers, archeo-landscape dimensions, architectural and archaeological elements, as well as sculptural remains (Figure 1). At the core of the interoperability framework lies a hierarchical, layered structure – beginning with the Geodata-Infrastructure layer (Hahmann & Burghardt, 2013). This foundational level encompasses Geographic, Environmental, and 3D Landscape data, followed by ArcheoLandscape and Multi-Temporal Stratification layers, which connect historical and spatial nodes. The upper tier consists of ARCH-Layers, subdivided into archaeological and architectural subsets. Together, these interconnected layers constitute a scalable framework that enables the integration of heterogeneous data types into immersive XR environments, effectively transforming XR into geographically grounded narratives for heritage applications in complex contexts: the geoXR. The GIS-to-geoXR infrastructure integrates Multi-Temporal Geographical Atlas layers with GIS data management processes, leveraging photogrammetric high resolution 3D textured models. These models form a foundational layer for the development of detailed XR narratives, enabling advanced visualizations of sculptures, archaeological remains, and environmental contexts through the OBJ-to-XR layer. In parallel, the HBIM node, enriched with both ARCHaeological and ARCHitectural layers, manages detailed building-scale information. This structured data approach supports the accurate representation of historical thresholds, construction phases, and material characteristics – critical for creating informative and immersive XR experiences. The GIS-to-geoXR interoperability is crucial in translating complex spatial datasets into interactive environments. This is exemplified by case-specific applications such as the 12 km shapefile of the Appian Way, the photogrammetric 3D textured model of the Marco Servilio Quarto transects, and the HBIM reconstructions of Cecilia Metella and the Castrum Caetani. These datasets will further enhance environmental precision and enable dynamic monitoring capabilities. Ultimately, this integrated system contributes to the development of a comprehensive XR environment, envisioned as the foundational infrastructure for a Future Digital Twin. This Digital Twin will function not only as a validated data repository but also as an evolving, collaborative platform supporting multi-user interaction. It offers both the public and researchers an opportunity to explore detailed, historically grounded narratives, thereby amplifying engagement and deepening cultural understanding (Hahmann & Burghardt, 2013). The proposed interoperability scheme thus offers a scalable, holistic solution, integrating rigorous, multidisciplinary scientific data into accessible, interactive, and immersive XR experiences.

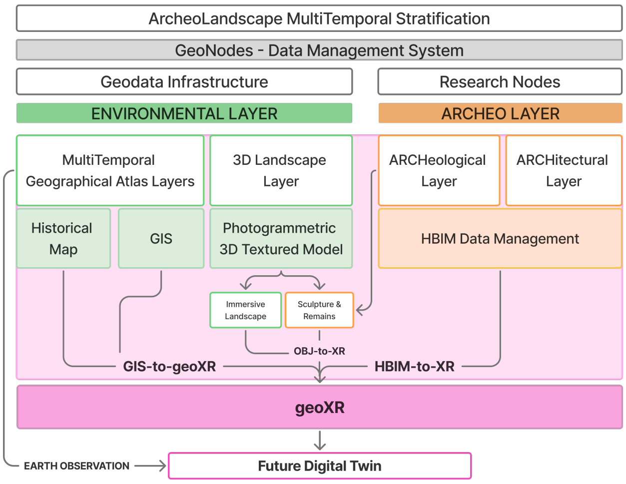

Figure 1. Mind map of the multiple stratified Appian Way layers managed implemented through geoXR.

4.1 From GIS Data Management Infrastructure to geoXR

The workflow shows how GIS data layers can be repurposed into 3D engines like Twinmotion to enable interactive, spatially contextualized XR experiences. It marks a shift in GIS use – from spatial analysis to storytelling medium – supporting the interpretation of multi-temporal, stratified spaces like the Appian Way. Through geometric semantics, GIS datasets become interactive elements in virtual environments, enhancing narrative immersion and allowing exploration of historical transformations. The use of georeferenced historical cartography further anchors digital reconstructions in their geographic context. The geospatial data infrastructure for the Appian Way was not derived from traditional urban-scale cartography (e.g., 1:1000, 1:2000) or from DBGT (DataBase GeoTopographic) sources, but was instead generated through high-resolution survey campaigns, including Terrestrial Laser Scanning (TLS), Mobile Mapping Systems (MMS), and photogrammetry. The specific surveying accuracies and resulting outputs are summarized in Table 1. The datasets have been generated on a GNSS-RTK (real-time kinematic) (RDN2008) reference system, with an accuracy of ±2.0 cm in planimetry and ±3.0 cm in altimetry and managed in a GIS environment (EPSG: 7792/RDN 2008). TLS point clouds acquired with Faro Focus 3D achieved a local accuracy between ±3 and ±5 mm, and were georeferenced on GNSS Ground Control Points (GCPs) with an error range of ±1 to ±3 cm. The MMS surveys (GeoSLAM Zeb Horizon) were registered within the same reference system with an average spatial accuracy of ±5 to ±10 cm on GCPs. The 3D textured models and orthophotos were derived from photogrammetric processing at scales ranging from 1:50 to 1:100, with terrain pixel resolutions 5 – 10 mm documenting the richness and state of the art for the PAAA maintenance plans. From these data sources, SHP vector layers were generated at a 1:100 scale resolution, with geometric errors ranging from 2 to 1 cm and tolerance levels between 5 and 2.5 cm, depending on detail complexity and the availability of TLS/MMS datasets (Figure 2). The native SHP dataset retained geodetic precision based on the RDN2008 reference system, defined on the National Dynamic Grid Datum (Rete Dinamica Nazionale 2008). To ensure seamless integration into XR within the GIS-to-geoXR workflow, the SHP dataset was transformed into the EPSG:3857 (Pseudo-Mercator) coordinate system, supporting the interoperability in BlenderGIS environment. The conversion preserved metric accuracy (float32) referenced to the World Geodetic System 1984 (WGS 84) Datum. Adopting EPSG:3857 guaranteed interoperability with web-based geodata (2D/3D), enabling consistent rendering of the SHP vector dataset within the BlenderGIS scene and ensuring alignment with OSM-derived layers.

Data Source			
Sensor	**Accuracy / Resolution**	**Output**	**Reference System**
GNSS (RTK)	±2.0 cm planimetry; ±3.0 cm altimetry	GCPs	RDN2008
MMS (GeoSLAMZeb Horizon)	±5–10 cm on GCPs	Point cloud	
TLS (Faro Focus 3D)	± 3–5 mm locally; ±1–3 cm on GCPs registration	Point cloud	
Ground 360° camera (Insta360 ONE X)	±2–7 cm on GCPs	3D textured mesh model, Orthophoto (1:50–1:100), 5–10 mm Pixel Terrain	
UAV test (DJI Mini 2)	±2–7 cm on GCPs		
Native SHP Dataset			
	Accuracy / Resolution	**Reference System**	
Native SHP from 1:100 survey (TLS, MMS, photogrammetry)	1:100 (geometric error=2cm, tolerance =5cm)	EPSG:7792 Geodetic CRS: RDN2008 / Datum: Rete Dinamica Nazionale 2008 / UTM zone 33N	
GIS-to-geoXR conversion			
XR SHP Encoding / BlenderGIS Export	Preserve linear metrics in float32 precision	EPSG:3857 Geodetic CRS: WGS 84 / Datum: World Geodetic System 1984 ensemble / Pseudo-Mercator - Spherical Mercator, Google Maps, OpenStreetMap, Bing, ArcGIS, ESRI	
Historical Map (resolution 1m=1pixel) / Georeferenced Raster (geoTIFF)	First-order polynomial Residual error <1 pixel		

Table 1. The 12km survey of the Appian Way: Data Sources, Reference Systems, Accuracies, Outputs, SHP, GIS-to-geoXR.

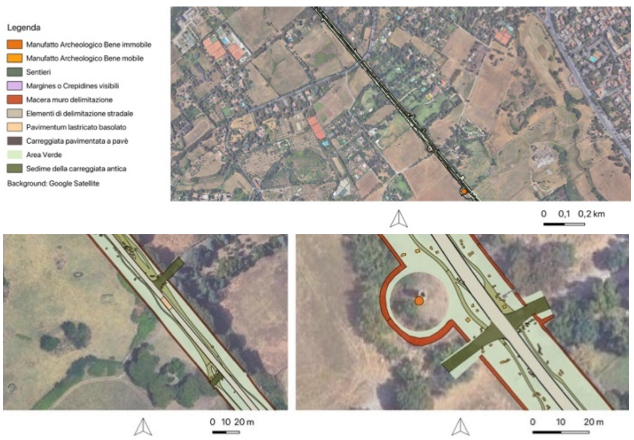

Figure 2. QGIS – SHP Geospatial data management.

Figure 3. 1st order polynomial georeferencing: the 3 Canina’s Historical Section Maps of the Appian Way (Canina, L. 1853b).

A first-order polynomial georeferencing (EPSG:3857) was applied to historical imagery scanned from Luigi Canina's maps of the Appian Way (three sections from Rome to Frattocchie) (Figure 3), with approx. 1 m/pixel resolution influenced by the limitations of original maps, source distortions, and conservation status. The resulting geoTIFF (residual values <1 pixel) was imported into the BlenderGIS scene, where all spatial features (SHP and GeoTIFF datasets) were semantically mapped. Finally, the completed scene was exported as a glTF (GL Transmission Format), a compact format facilitating integration into XR environments such as Twinmotion (Della-Bosca et al., 2024).

4.2 From Photogrammetric 3D ArcheoLandscape Textured Model to XR

To shift geographic data management within the XR environment into a fully three-dimensional representation, an additional experimental step has been implemented. 3D photogrammetric models have been deployed on 100m length sections (Figure 4). The models were tailored for 3D ArcheoLandscape representation and fruition. Each section is potentially scalable to other segments digitization – beyond the 12 km surveyed so far – along the whole Appian Way length from Rome to Brindisi. This is contingent upon further future research developments and preservation projects funding. The transition from the photogrammetric 3D ArcheoLandscape model to the XR system followed a structured workflow in Agisoft® Metashape via Structure-from-Motion (SfM) photogrammetry, integrating multiple blocks oriented together within a unique SfM project (Genzano et al., 2024). Multiple survey campaigns comprised both terrestrial and aerial acquisition systems. Aerial-drones photogrammetry was performed using a DJI Mini 2 UAV, with terrain pixel resolutions ranging from 5 to 10 mm, with spatial accuracy of ±2 to ±4 cm on GCPs. Additionally, 360° ground-level imagery acquired via Insta360 ONE X was processed and georeferenced, achieving an average accuracy between ±2 and ±7 cm on GCPs. Dense Cloud was generated from drone imagery using a compact setting with 0.003 m point spacing, resulting in a Raw Dense Cloud of 33,180,126 points. The second Dense Cloud was produced from 360° images. The two datasets were aligned using Point Cloud assets settings. Filtering by highest confidence removed sky coverage and vegetation-related noise. The unified Dense Cloud composed of 52,448,310 points, was generated with medium-quality and mild filtering to ensure balance between model accuracy and computational efficiency, with a final file size of 689.51 MB. The output is an immersive 3D textured mesh model of the Appian Way landscape infrastructure, detailing historical elements such as *Basolatum* paving, *Crepidines*, and Canina's *Macere* masonry borders.

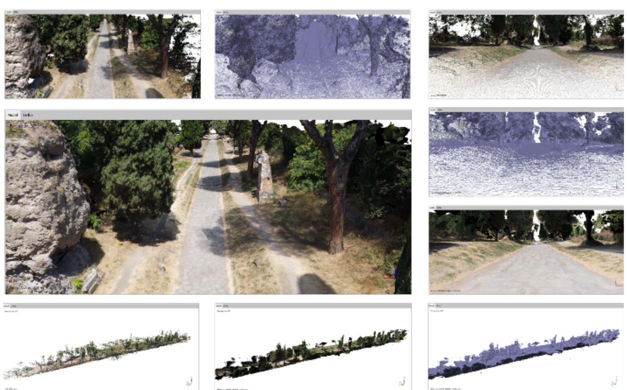

Figure 4. OBJ-to-XR ArcheoLandscape Workflow sequence of photogrammetric 3D textured model reconstruction.

4.3 From Scan-to-BIM model to XR

The transformation of complex heritage buildings from laser scanning data to immersive XR experiences requires a multi-software workflow, where the case study of the Mausoleum of Caecilia Metella and the Castrum Caetani demonstrates both the potential and limitations of current HBIM-XR integration processes. The workflow started with high-resolution point cloud data acquired by laser scanning, containing millions of spatial coordinates. Once cleaned up and decimated (Recap Pro), were then fed into AutoCAD software where the wall profiles were extracted and then imported into Autodesk Revit where an initial modelling of basic elements was carried out. However, this process sometimes can require significant interpretation, both in the extraction of profiles and in the subsequent modelling, as laser scanning is not always able to automatically recognise complex architectural features or construction techniques.

For intricate decorative elements such as the marble frieze and the 'diatoni' system still present in the basement of the mausoleum, the workflow necessarily switched to Rhinoceros, which offers more refined NURBS modelling capabilities for complex geometries than Revit. This software transition, while technically necessary, introduced some important interoperability challenges, as models created in Rhinoceros must be manually integrated into the Revit environment, as there is no direct working plug-in between the two software. For the identification of the historical phases and data on the construction techniques and materials of the historical complex, both customised parameters and colour coding directly incorporated into the 3D geometry of the model were used. The second approach, while visually effective, represents a compromise solution necessitated by the limitations of current BIM software in handling complex cultural heritage data structures. Subsequently, since the point cloud does not return the texture of the objects, in order to give a complete picture of the mausoleum and the Castrum, it was decided to apply photogrammetric data by using the 'Decals' function in Revit on the various surfaces of the model, thus improving the visual fidelity and scientific value of the model and proving the potential of the combination of geometric accuracy and photorealistic visualisation in cultural heritage documentation (Figure 5).

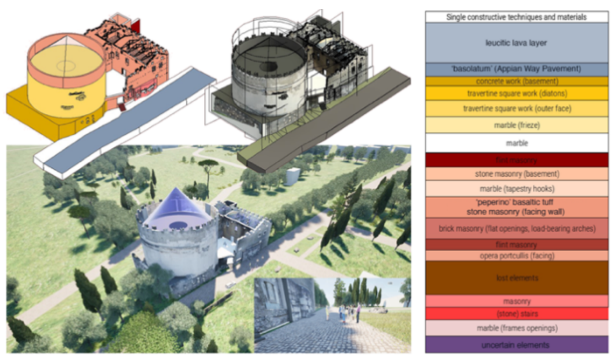

Figure 5. The HBIM model objects managing the construction technologies and phases of the Cecilia Metella Mausoleum and Castrum Caetani.

5. Research results

5.1 XR fed by GIS: the Appian Way 12 km Polygons at 1:100 Scale

The integration bridge in BlenderGIS established the foundational framework for the XR environment.

Firstly, a custom base map from OpenStreetMap (OSM), focused on the Appian Way route from Rome to Brindisi (Figure 6), was retrieved in BlenderGIS (EPSG:3857) to ensure a navigable spatial reference. This step provided a visual and geographic scaffold onto which SHP and geoTIFF data could be anchored.

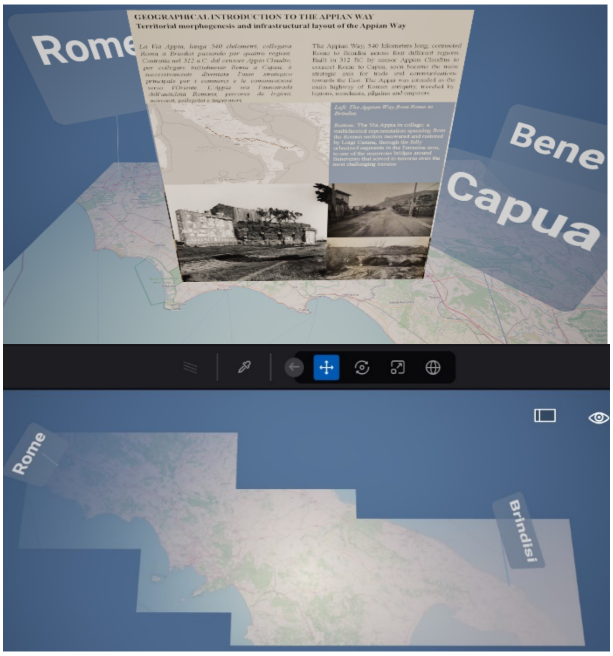

Figure 6. Twinmotion – “geoXR, The Appian Way, from Rome to Brindisi.

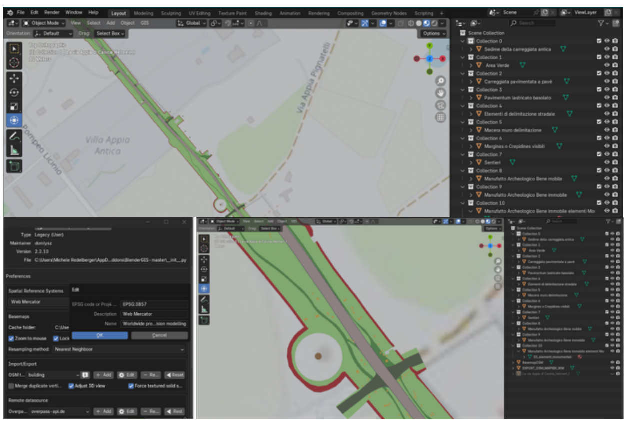

Figure 7. BlenderGIS – Parameters for glTF exportation.

Figure 8. Twinmotion – “geoXR”, The MultiTemporal Geographical Atlas.

Then, the XR-encoded SHP features (EPSG:3857 – Pseudo-Mercator) were imported as individual objects, allowing the retention and mapping of attribute data onto corresponding BlenderGIS elements. Coordinates were preserved within Blender’s internal floating-point precision. Structuring BlenderGIS project in individual objects enhanced semantic granularity, mirroring the hierarchical structure of the original PAAA GIS environment. The geoXR semantic structure is based on the Multi-Temporal Geographical Atlas Layers (Figure 7), and is organized following the legend classification categories defined with PAAA: the Carriage Pavimentum: the original Roman paved surface (*Basolato*); Cobblestone paving: later additions not directly linked to the Roman infrastructure; the Roman sidewalk (*Crepidines*); *Macere Margines*: lateral walls defining the park's boundaries; Archaeological artefacts: dispersed remains and stones along the route; Monuments: remnants of funerary and architectural structures; Paths: pedestrian and cycling trails; Green areas: zones designated for ongoing maintenance. The Blender scene was exported in glTF format to ensure XR interoperability. The resulting glTF file was integrated into Twinmotion, enabling real-time rendering and interactive storytelling within immersive XR environment. This workflow established the geospatial scaffold of the geoXR system, laying the foundation for the integration of landscape and cultural heritage elements, including photogrammetric 3D models and HBIM components (Figure 8).

5.1.1 Expanding geoXR Narratives: from GIS to Immersive Heritage Storytelling

The following examples illustrate samples of the development of geoXR narratives through the integration of GIS frameworks with HBIM and 3D textured models. HBIM nodes are managed within Geographic Information Systems (GIS) and experimentally combined with high-resolution 3D landscape textured models. Shared geographic layers ensure scalability and replicability of these approaches, especially within complex heritage contexts, and support the further extension of XR applications built upon HBIM-GIS models. The objective is to amplify the interpretative horizons of the monumental complex, using XR to narrate multiple micro-stories that can be accessed intuitively by the public. The XR platform remains dynamically expandable: as new research unfolds, exploring hidden elements, archival documents, surveying data, and construction techniques, the platform enables the continuous enrichment of heritage narratives built on structured informative models. A compelling example is the development of multi-temporal geoXR narratives, anchored to georeferenced historical raster maps, such as Luigi Canina’s 19th-century Map (Figure 9). The historical map serves as a precursor analogic geographic system, where Canina meticulously plotted the monuments and sepulchers documented in his volumes on the Appian Way (Canina, 1853a, b). Luigi Canina, in fact, established the first open-air museum of the Appian Way to preserve it from neglect and theft. He designed and built up the ancient Macere (lateral Appian Way boundary walls) flanking the Roman sidewalks and carriages, which are partially visible today. Each historical node, representing a past or present condition, can be explored through the immersive geoXR experience. The envisioned geoXR interactive map supports the outdoor web interactive engagement, where unaware visitors biking or walking across the Appian Way, will discover the multistratified contest, with the sepulchers along their route, accessing contextual explanations, and engaging with the digital content aligned to present-day surveys (Althoff et al., 2016; Gryl, 2022). The immersive heritage storytelling is directly linked to the user's visual field, and its fruition is made possible through a web-based, smartphone-accessible immersive XR environment. This allows visitors to rediscover the Appian Way's layered history, recognize archaeological remains in situ, and, while walking, interactively explore the narratives embedded in its landscape (Horbiński & Zagata, 2022; Carbonell-Carrera et al., 2021). The integration of geolocation codes is currently in progress to enhance spatial orientation.

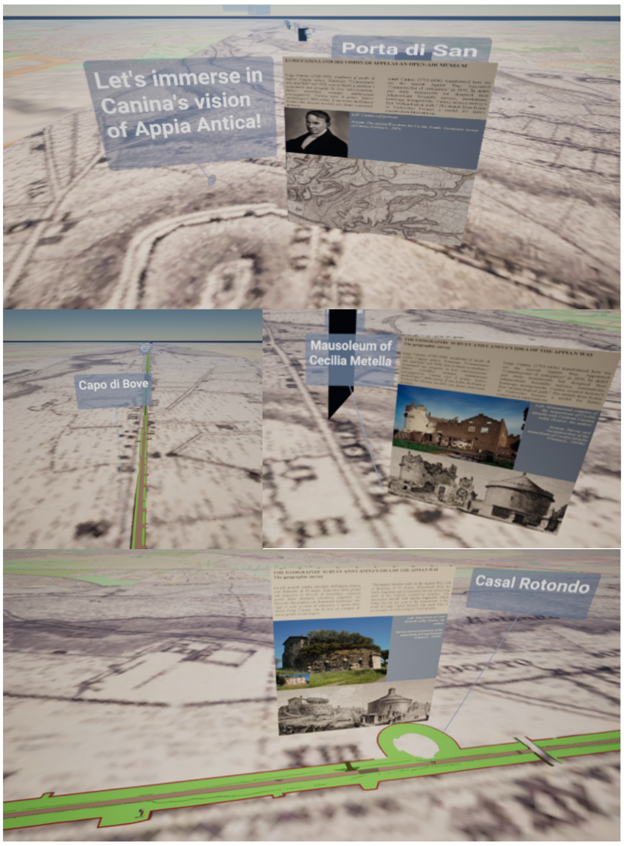

Figure 9. The geoXR interactive immersive journey within the current GIS surveys of the 12 km Appian Way section and the past Luigi Canina map with all the monuments documentation.

5.2 XR fed by 3D ArcheoLandscape Models

The implemented workflow transformed high-resolution photogrammetric data into an immersive 3D landscape environment, fully integrated within the XR framework. The textured OBJ mesh was georeferenced and aligned with GIS-based basemaps in the geoXR environment using Twinmotion.
This alignment enabled real-time navigation and interaction, preserving both morphological accuracy and heritage-specific visual fidelity. The resulting geoXR environment replicates the spatial complexity of the archaeological landscape, allowing users to recognize the paving, the infrastructure, the morphology, the historical features, and site context, with the Agro-Romano fruition (Figure 10). Semantic consistency with GIS layers was carefully maintained, ensuring that reconstructed features correspond accurately to the original surveyed data. The visual outputs display textured terrain models and archaeological remnants, rendered in a fully navigable XR interface. This enables both expert and non-expert audiences to explore the site in a spatially coherent and user-friendly manner (Stintzing et al., 2020). The narrative developed for the VR room focused on the construction technologies of Basolatum artefacts extracted from the volcanic lava and used for the paving. The XR highlighted the eruption that generated the Appian Way geomorphology in the section going from Albani Mountains to Rome. The XR has been enhanced by integrating high-resolution 3D landscapes (Figure 11) (Kühne et al., 2022). The workflow supports interpretive and didactic applications in landscape archaeology, and cultural heritage communication, through on-site user engagement and immersive comprehension (Koegst et al., 2022; Prisille & Ellerbrake, 2020).

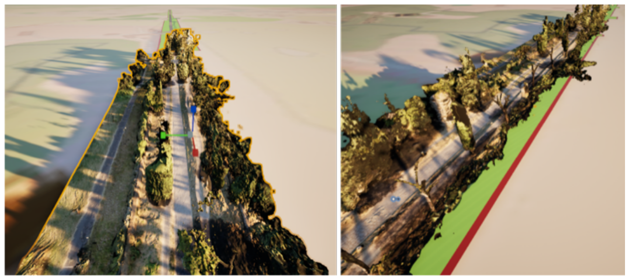

Figure 10. The 3D ArcheoLandscape model and GIS layers into Twinmotion.

Figure 11. The immersive XR explanation of the Appian Way, the ArcheoLandscape layers: Basolatum, Crepidines, Tombs, and Vegetations layers.

5.3 XR fed by informative models and HBIM: a journey across transformations and construction technologies

The 3D HBIM model of the Mausoleum Lava Room, along with the 'Peperino' basalt rocks used in the construction of the Castrum Caetani (Paris, 2000), represents a significant opportunity for further exploitation of HBIM content within immersive narratives. The historical complex, composed of the Mausoleum of Cecilia Metella and the adjacent Castrum Caetani – constructed in the early 14th century by order of Pope Boniface VIII – embodies centuries of layered architectural evolution.
The documentation of historical thresholds and construction techniques through HBIM, derived from the SCAN-to-BIM-to-XR process, enables the generation of new narratives. These narratives trace the construction phases that shaped the complex over time, supported by the integration of material and technical data tied to distinct historical periods (Figure 12). In the final stage of the workflow, Twinmotion was used to structure

thematic content related to the Cecilia Metella and Castrum Caetani complex. This included the use of various interactive tools, such as animated 3D elements, LED wall simulations, and custom animators, to enhance the immersive storytelling and visual engagement within the XR environment. However, the transition from Revit to Twinmotion for XR visualization revealed a critical limitation of the current workflow. Although Twinmotion successfully imported the geometric model and preserved colour-coded semantic classifications, it failed to transfer most of the embedded object parameter data and did not retain the accurately applied photogrammetric textures originally defined within Revit. This gap in interoperability highlights a major challenge in the XR pipeline: the difficulty in preserving both semantic richness and material accuracy during the migration between modeling and visualization environments.

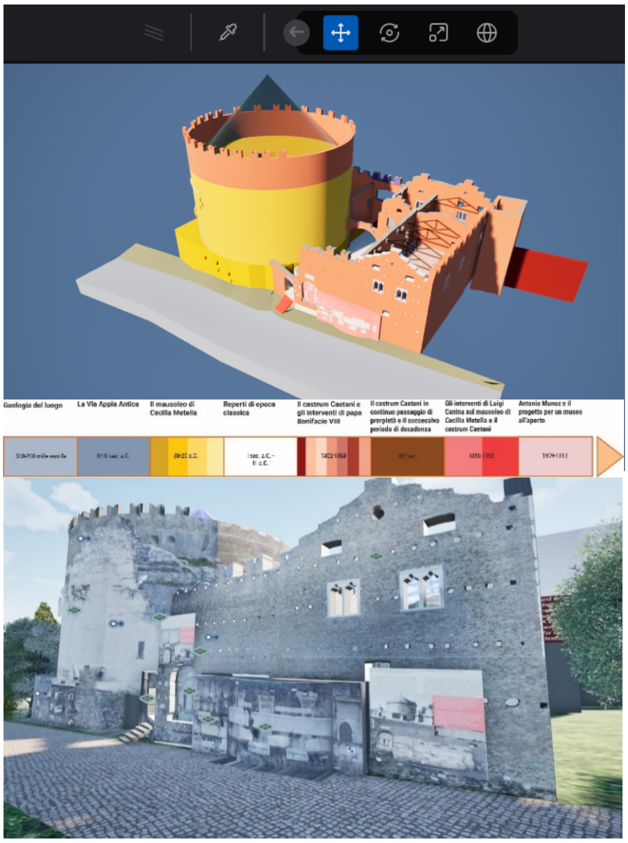

Figure 12. HBIM model imported into Twinmotion retained only object colors; photogrammetric textures were reinserted with interactive objects in the XR scene.

6. Further Development: EO-Based Digital Twins into XR

Satellite-based monitoring efforts, such as those in Lombardy (Villa Arconati Park) and Murcia (Camp Altiplano), demonstrate the power of Earth Observation (EO) data to inform on land degradation and regenerative practices, while expanding user engagement and awareness of climate change at local scales (Gabriele et al., 2023; 2025). Multi-temporal NDVI/EVI analyses in the Agro Romano–Appian Way area further revealed patterns of degradation and regeneration (Brumana et al., 2023), supporting the management of green-archaeological areas. In the future, the geoXR framework could effectively integrate EO-derived layers to promote biodiversity and health-based conservation values (Eskandari et al., 2024). This would need an experimental phase to create interoperable codes allowing dynamic satellite monitoring within immersive Digital Twins, to enhance public understanding of environment through bio-physical indicators anchored into the geospatial context of eXtended-landscape-Realities.

7. Conclusions

The paper proposed a multi-temporal, multi-spatial layered environment to support the immersive exploration of archaeological contexts, enabling nuanced storytelling grounded in metric precision, preserving the accuracies of the source models, and the semantically enriched data from the informative models, all anchored within a geographic background. The proposed interoperability framework addresses technical issues, such as the limitations of XR platform coordinate transformations and the semantic loss that can occur when transferring data. Ensuring spatial accuracy is essential to guarantee the reusability of models like HBIM nodes, 3D ArcheoLandscapes, and GIS-based multi-temporal layers within a unified geoXR ecosystem. Current integrations are hindered by how information is transferred and encoded into XR, but the content can still be made accessible in immersive environments. Through user-driven keyword selection and interactive interfaces, the system enables content retrieval, suggesting a pathway toward the development of informative XR systems tailored for cultural heritage fruition and archaeological research.

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