

Echoes of the Past, Visions of the Future: 4D digitalization of the Temple of Debod

Lucrezia Gorgoglione^{1*}, Sarah Martínez de Paz², Marina Lorne³, Luis Javier Sánchez-Aparicio²

^{1*} Dep. of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, Italy l.gorgoglione@pm.univpm.it

² Dep. of Construction and Architectural Technology, Escuela Técnica Superior de Arquitectura de Madrid, Universidad Politécnica de Madrid, Spain

³ Escuela Politécnica Superior, Universidad San Pablo- CEU, Montepríncipe Campus, Madrid, Spain

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Abstract

This paper presents an immersive 4D digital platform designed to communicate and critically explore the transformation of the Temple of Debod in Madrid while supporting public understanding of ongoing conservation debates. This platform uses 360° panoramas of strategic points of the Temple. The platform enables “time travel” through three coherent states: the Temple’s original Nubian setting, its current condition in Madrid, and a plausible future scenario in which a protective museum envelope mitigates environmental stress. Rather than offering a conventional virtual tour, the work focuses on the integration of heterogeneous temporal content, reality-based documentation, historically grounded reconstructions, and a speculative yet technically consistent conservation proposal, within a single interactive environment.

The result is a spatio-temporal narrative that makes change, relocation, and conservation choices visible and comparable. By combining immersive navigation, interpretive layers, and transparent scenario-building, the platform reframes documentation as a tool for dialogue: not only about what the monument is, but also about what it has become and what it could be.

1. Introduction

The preservation of historical heritage remains one of the most challenging tasks for disciplines that seek to connect knowledge of the past with the needs of the present. Over the past decades, the digital turn has profoundly reshaped the ways in which Cultural Heritage is documented, interpreted, and communicated, introducing new perspectives on how architecture and urban form are perceived and shared across disciplines. Historic buildings and cityscapes are no longer understood as static remnants of vanished civilizations, but as living archives of collective memory, embodying artistic intentions, construction knowledge, and social identities accumulated over time.

International conservation doctrine has long provided the conceptual backbone for acting on this “living archive”, insisting that any intervention must be grounded in rigorous documentation, respect for authenticity, and interdisciplinary cooperation. From the Athens Charter (1931) to later milestones such as the Venice Charter (1964) and Krakow Charters (2000), monuments are framed as witnesses of human traditions and as stratified outcomes of multiple historical phases, calling for conservation approaches that protect integrity while recognising temporal complexity. In parallel, UNESCO instruments reinforced heritage as a shared responsibility and broadened its scope beyond the strictly material domain (UNESCO, 1972; UNESCO, 2003).

These principles, however, are now tested by unprecedented pressures: climate change, atmospheric pollution, and rapid urban development are accelerating material decay and structural vulnerability, often exceeding the capacity of traditional conservation practices to respond effectively (Pierdicca et al., 2023). This situation strengthens the case for integrated documentation strategies that can support diagnosis and long-term planning while communicating change, risk, and uncertainty in an accessible way. Accordingly, the most recent guidelines have explicitly addressed digital mediation and virtual reconstruction, emphasising the transparency of sources, interpretative responsibility and the need to distinguish evidence from hypotheses, especially when digital models combine

measured reality with reconstructed or speculative content (Gorgoglione et al., 2024).

In this evolving scenario, digital technologies have become essential tools for understanding and safeguarding-built heritage. Advances in geomatic surveying, reality-based 3D modeling, and immersive visualization enable the generation of metrically reliable and visually rich digital representations that combine scientific rigor with experiential depth (Savini et al., 2025; Herrero-Tejedor et al., 2023). Beyond static documentation, recent research has emphasized the importance of representing heritage as a temporal process. The integration of time as a core dimension—through 4D reconstruction, HBIM, and digital twins—allows scholars and practitioners to analyze historical evolution, construction phases, and decay mechanisms within a unified spatio-temporal framework (Rodríguez-González et al., 2017; Bruno et al., 2021).

Several studies have demonstrated the potential of such approaches. Unified virtual models have been proposed to support real-time visualization, diagnosis, and decision-making in architectural heritage conservation (del Blanco García et al., 2024), while immersive environments and XR platforms have been explored as tools for dissemination, education, and participatory engagement (Maté-González et al., 2025). Large-scale initiatives, such as Virtual Angkor project (<https://www.virtualangkor.com/>), have pioneered evolutionary and scenario-based reconstructions to represent long-term urban transformations and interpretative uncertainty (Chandler and Clulow, 2020). Similar principles have been applied to underwater and inaccessible heritage contexts, where virtual museums enable the visualization of otherwise invisible cultural assets (Gambin et al., 2021). More recently, reality-based 3D modeling combined with virtual reality has proven effective in exploring historical change and spatial continuity in architectural heritage (Roggio et al., 2025).

Despite these advances, significant gaps remain. While numerous projects integrate photogrammetry, HBIM, and immersive visualization, relatively few explicitly address monuments that have undergone physical relocation and radical contextual transformation. Moreover, the challenge of coherently integrating reality-based models with reconstructed or

hypothetical scenarios, while maintaining interpretative transparency, remains an open methodological issue (Artopoulos et al., 2024). Automated processing of historical documentation and archival imagery further complicates this integration, although recent studies highlight promising directions for bridging analogue sources and digital environments (Roulet et al., 2019).

In response to these limitations, this research proposes a scenario-based 4D digital framework specifically designed to address the documentation and interpretation of relocated architectural heritage. To this end, it is proposed the creation of a virtual reality platform based on the use of 360° panoramas with attached information in the form of hotspots, allowing to integrate texts, pdfs and images to enrich the environment.

The building used for developing and validating the platform is the Temple of Debod. This building is an Egyptian sanctuary dating back to the 2nd century BCE and relocated to Madrid in 1972 as part of the UNESCO-led Nubian Monuments Campaign. By visualizing the Temple of Debod in three distinct temporal states—its original Nubian context, its present urban condition in Madrid, and a projected protective musealization scenario—the platform aims to support comparative analysis, preventive conservation reasoning, and public understanding.

Specifically, the work aims to: (i) formalize a 4D digital model capable of integrating heterogeneous datasets, including historical documentation, geometric survey data, and interpretative reconstructions; (ii) explore the applicability of the 4D paradigm as a decision-support tool for preventive conservation through the comparison of alternative temporal and environmental scenarios; and (iii) assess the potential of immersive 4D environments for research, education, and heritage management, moving beyond purely aesthetic visualization toward analytically grounded digital twins.

2. Case Study: the Temple of Debod

The Temple of Debod is an ancient Egyptian sanctuary originally constructed in Lower Nubia during the second century BCE and dedicated to the gods Amun and Isis (Barsanti, 1911; Säve-Söderbergh, 1987). As part of UNESCO's International Campaign for the Safeguarding of the Monuments of Nubia (1962), the temple was dismantled following principles of archaeological anastylosis and transferred to Spain in 1968 as a diplomatic donation, in recognition of Spain's contribution to the documentation and conservation of Egyptian heritage threatened by the construction of the Aswan High Dam (Okasha, 2010; Zurinaga, 2018). The reconstruction of the Temple was carried out in Madrid between 1971 and 1972, in the Parque del Cuartel de la Montaña (Almagro Basch, 1971).

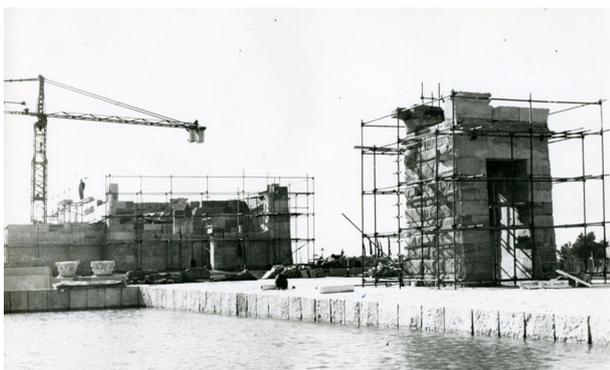


Figure 1. Reconstruction work on the Temple of Debod in Madrid, 1972. ©Memoria de Madrid, license CC BY-NC 4.0.

Unlike other relocated Nubian temples installed within climate-controlled museum environments, such as Dendur, Taffa, or Ellesiya, the Temple of Debod was placed outdoors, becoming part of the public urban space (Varagnoli, 2021; Flores, 2022). This decision substantially determined its conservation conditions, as it involved situated a monument built of Nubian sandstone, a material characterized by high porosity and marked hygroscopic sensitivity, within a climatic and atmospheric context radically different from that of its original location (Fitzner et al., 1997; Charola, 2000).

Today, the temple stands in the open air at the Parque del Cuartel de la Montaña, where continuous exposure to rainfall, thermal fluctuations, and urban pollution has intensified deterioration processes. This condition has revived critical debate among scholars and conservators regarding the need for protective measures, including possible musealization strategies. Madrid's continental climate, characterized by pronounced seasonal thermal fluctuations, episodes of frost, periods of intense solar radiation, and an urban atmosphere with significant levels of pollutants, generates particularly unfavorable conditions for the physicochemical stability of the stone material (Cassar, 2005; García-Talegón et al., 2015).



Figure 2. Detail: a) vandalism by visitors; b) mapping of salts and humidity. ©Fundación de Santa María la Real y Ayuntamiento de Madrid

Systematic environmental monitoring campaigns and diagnostic studies conducted since 2016 have documented active deterioration processes affecting the Temple of Debod, including granular disintegration, surface exfoliation, crust formation, biodeterioration, and localized loss of mechanical strength (Fort et al., 2013; Ayuntamiento de Madrid, 2022). These findings have raised growing concerns regarding the long-term sustainability of conserving the monument under conditions of direct exposure to the urban environment (Almagro Gorbea, 2021).

The monument not only exemplifies the challenges arising from the physical displacement of a historic structure, but also the material consequences of its adaptation to a new climatic and urban context. Its current condition makes it an ideal case study for the application of 4D digital heritage approaches, aimed at documenting, simulating, and comparatively evaluating temporal, environmental, and intervention scenarios, in order to support decision-making processes in preventive conservation, long-term management and public valorisation.

3. Methodological proposal for the creation of the platform

The following figure summarized the methodology followed to create the 4D platform.

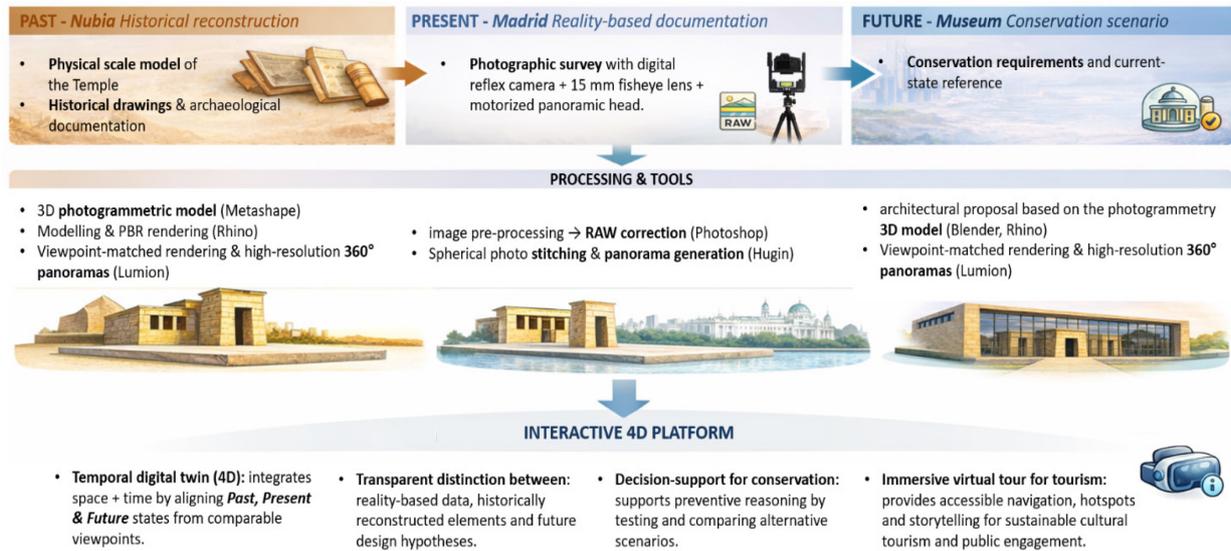


Figure 3. Proposed workflow for generating the 4D environment ©L.Gorgoglione

3.1 Reconstruction of the past: Nubian context

The past state of the Temple was obtained by digitalizing the physical scale model of the Temple based on the studies performed by Franz Christian Gau in 1819 (Figure 4).

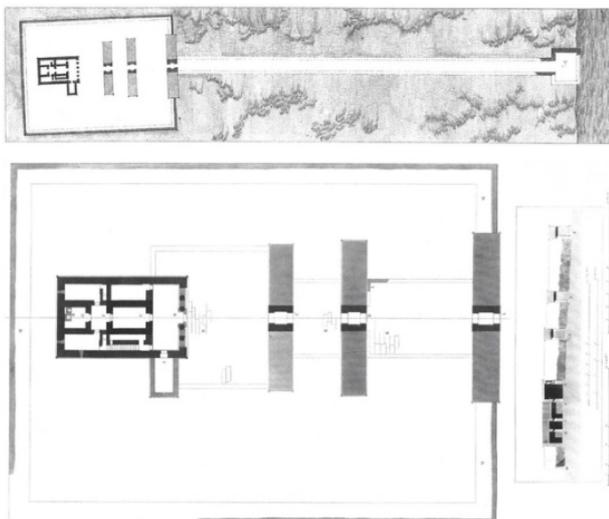


Figure 4. Plans of the Temple of Debod in 1819.
 ©Christian Gau. F.

The virtual reconstruction was obtained by using the Structure from Motion approach. To this end the Canon EOS 800 D equipped with a 15-55 mm rectilinear lens was used. The images were captured by following a convergent protocol, requiring a total of 138 positions, ensuring an overlap between 80-90 %. Finally, the 3D model was obtained by processing these images into the photogrammetric software Metashape (<https://www.agisoftmetashape.com/>) (Figure 5).

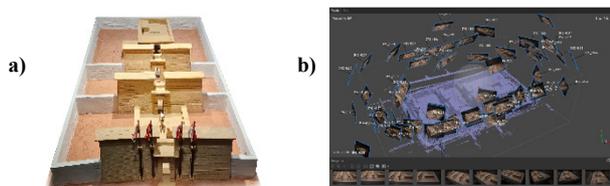


Figure 5. Past model: a) Model scale of the Temple of Debod in Nubia. ©Madrid City Council. b) 3D modelling in Agisoft Metashape.

The 3D mesh obtained from the photogrammetric reconstruction was optimized within the 3D modelling software Rhinoceros (<https://www.rhino3d.com/es/>). In this software the photogrammetric model was used as the base for the 3D model of the construction. Missing architectural elements, such as the processional and the river quay, were modelled according to the historical drawings to restore the Temple's original connection to the Nile. The texture of the 3D models was improved by using Physically Based Rendering (PBR) materials enabled realistic simulation of light-material interactions, ensuring visual coherence (Figure 6). The transformation from the 3D model to a 360 image was performed by using the software Lumion (<https://lumion.es/>). These panoramas were created with the same point of view than the panoramas captured to render the current state of the Temple (Figure 7).

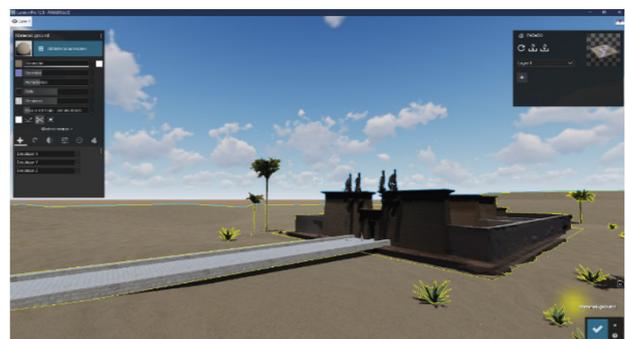


Figure 6. 3D modelling and texturing of the Temple of Debod in the past.



Figure 7. 360° panorama reconstruction of the Temple in the past (using Lumion).

It is worth mentioning that the Adijalamani Chapel was digitally restored adapting the 360° panorama provided by the Madrid City Council, which was enhanced with hypothetical polychromy and reliefs based on iconographic parallels with the Temple of Philae.

3.2 Reconstruction of the present

The current state of the Temple was recreated by using 360° images taken from a total of 15 places along the Temple (Figure 8).

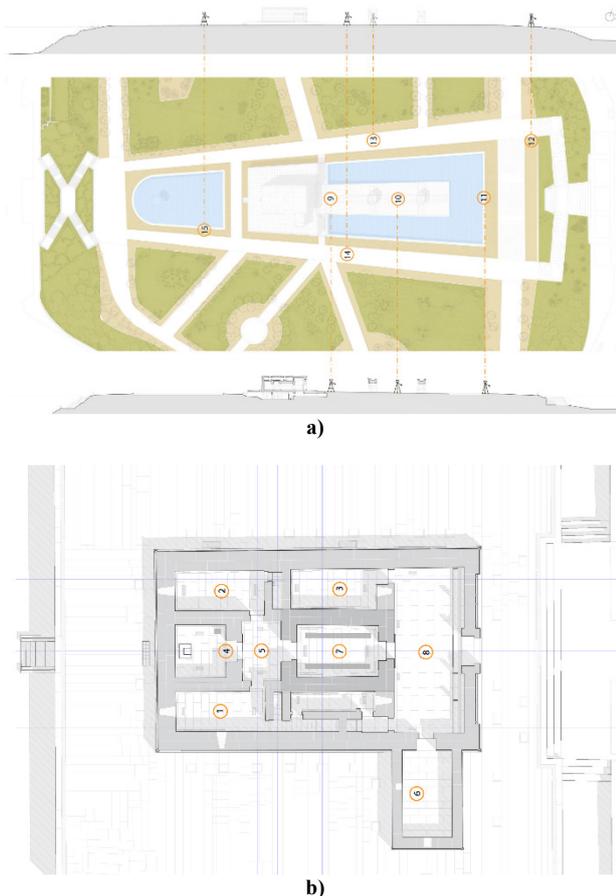


Figure 8. Data collection plan for panoramas: a) outside and b) inside the temple.



Figure 9. Equipment used for acquisitions: Canon EOS 850D and GigaPan Epic Pro.

The photographic survey was conducted using a Canon EOS 850D digital reflex camera equipped with a 15 mm fisheye lens, mounted on a GigaPan Epic Pro motorized panoramic head fixed to a levelled tripod (Figure 9). This configuration allowed precise control of camera orientation and ensured repeatable angular steps during image capture, a critical requirement for the generation of high-quality spherical panoramas.

For each panorama were taken 30 photos, distributed across five horizontal rings at different elevation angles to fully cover the spherical field of view. A lateral overlap of approximately 30% was maintained between consecutive images to facilitate robust feature matching during the stitching process and to ensure complete equirectangular coverage. In total, 15 panoramic stations were surveyed, corresponding to strategically selected interior and exterior viewpoints that capture both the architectural articulation of the temple and its surrounding landscape context. The full acquisition was completed within a single working day by coordinating interior and exterior captures according to natural lighting conditions. Interior stations were prioritised during periods of lower outdoor glare, while exterior viewpoints were acquired in time windows that reduced radiometric artefacts and preserved material readability on façades and stone surfaces. This coherent scheduling improved the visual consistency of the dataset and reduced the need for aggressive post-processing corrections.

RAW image files were processed in Adobe Photoshop to perform basic radiometric correction and white balance adjustment. The panoramas were subsequently stitched using the open-source software Hugin (<https://hugin.sourceforge.io/>), employing automatic feature detection, lens distortion correction, and multi-band blending algorithms. This workflow ensured geometric coherence between panoramas while preserving high radiometric quality, in line with established best practices for heritage-oriented spherical photogrammetry.

From a methodological perspective, the use of spherical photogrammetry was not intended as a standalone documentation technique, but as a bridge between reality-based acquisition and immersive interpretation. Unlike conventional image-based modeling workflows focused on dense surface reconstruction, the adopted approach prioritizes visual continuity, spatial orientation, and temporal comparability, making it particularly suitable for the integration of present-day panoramas with reconstructed past and speculative future scenarios within a unified 4D environment.

The resulting panoramic dataset constitutes the reality-based foundation of the immersive platform, onto which reconstructed historical contexts and scenario-based musealization models are subsequently integrated and spatially aligned, as described in the following sections.

3.3 Reconstruction of the future: musealization scenario

A plausible future scenario was reconstructed by using the 3D model obtained during the reconstruction of the past. In this sense it was used the software Rhinoceros to make an architectural proposal that musealize the Temple.

The proposal, a climate-controlled museum enclosure, draws architectural inspiration from the Temple of Dendur pavilion (Metropolitan Museum of Art, New York) and adapts a self-developed design proposal for the Solar Boat Museum in Giza. The workflow employed Blender for the fine detailing of the temple's masonry textures and Rhinoceros for the design of the architectural envelope.

The design prioritizes the recovery of the Temple's original axial orientation and simulates controlled temperature and humidity conditions, providing a speculative yet technically plausible framework for preventive conservation.

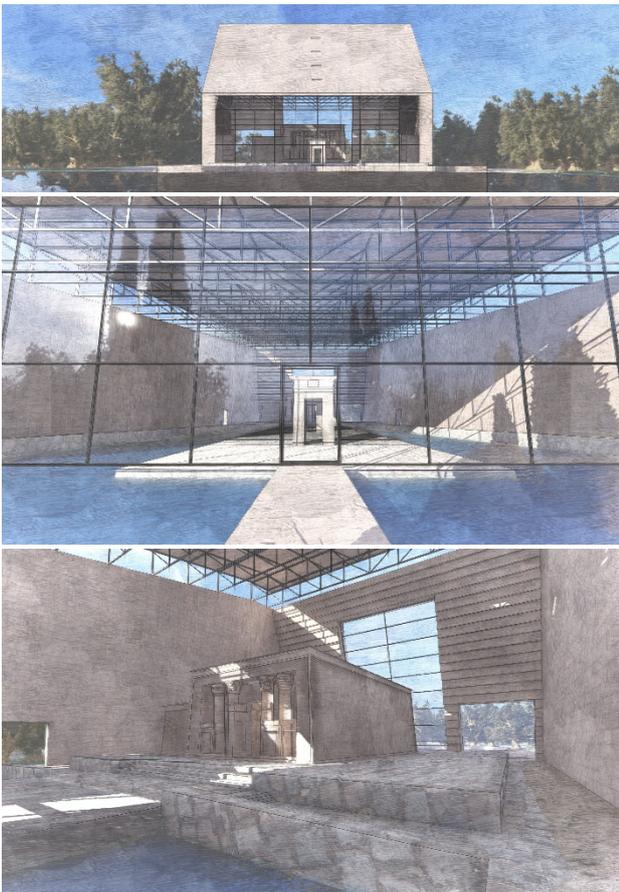


Figure 10. Rendered sketch of the main facade for the museum project. ©S.Martínez

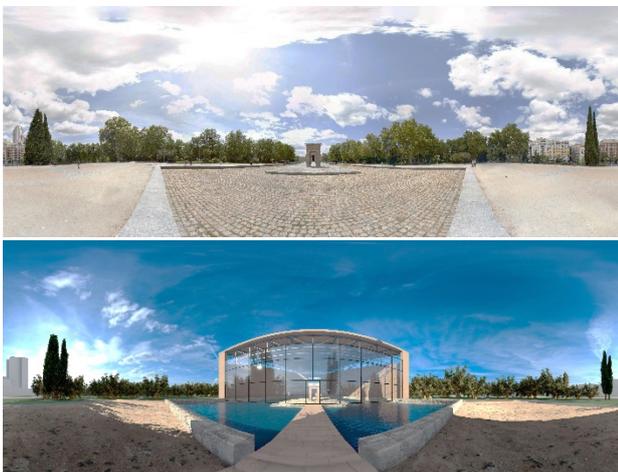


Figure 12. Example of comparative overviews: current state and future state of the building.

From these renderings, 360° panoramas were created using Luminon software, which were then positioned in the same location as those acquired for the representation of the current state (Figure 11).

3.4 Integration into the 4D Environment

The final immersive assembly was constructed using Pano2VR software (<https://ggnome.com/pano2vr/>), integrating different panoramic views. The system aggregates a total of 26 spherical

nodes (10 representing the Present, 10 the Past, and 6 the Future) linked via a custom logic that permits seamless temporal switching from identical spatial coordinates. These views were complemented with a proper interface made up by different buttons that allow to navigate along the Temple not only spatially but also in a temporal way (past-present-future) (Figure 12).

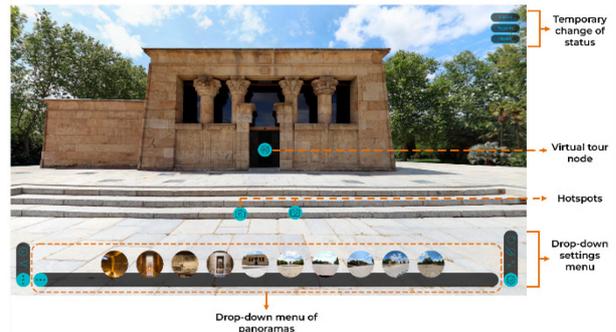


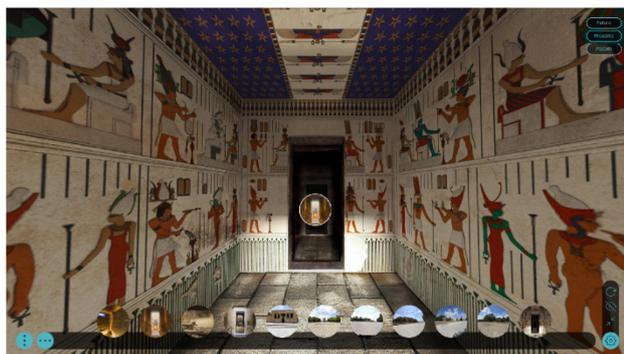
Figure 11. Virtual environment interface (Pano2VR).

Thanks to this interface, the platform enables interactive exploration of the Temple's three temporal configurations, featuring dynamic timelines, spatial orientation aids, and key contextual information (Figure 13).

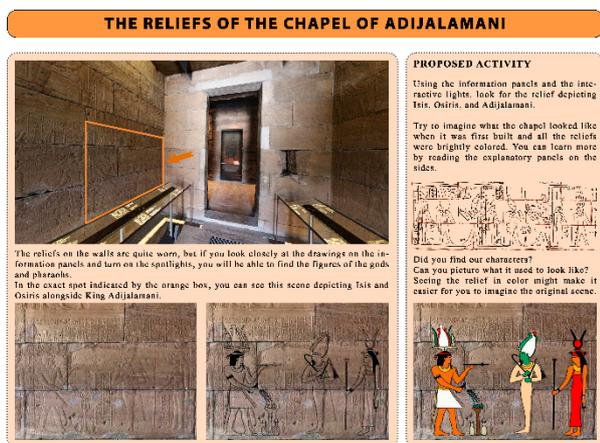


Figure 13. 360° virtual tour showing the same viewpoint in three temporal states (Past, Present, Future), developed with Pano2VR.

The panoramas were enriched with information in the form of texts, graphs and pdf files that allow to improve the user experience (Figure 14).



a)



b)

Figure 14. Chapel of Adijalamani's: a) panoramic view; and b) information showed when the user clicks on a hotspot of the chapel. ©S.Martínez adapted from

<https://www.recursoesconde.org/difusion/360/TemploDebod/Adijalamani.html>

To ensure broad accessibility and technical reproducibility, the system was exported as a responsive HTML5 package.

4. Conclusions and Future Work

This study demonstrates how immersive 4D environments can move beyond purely visual documentation to become structured tools for understanding, communicating, and critically reflecting on the temporal complexity of architectural cultural heritage. By integrating reality-based data with historically grounded and scenario-driven reconstructions, the proposed platform offers a coherent representation of the Temple of Debod across past, present, and possible future conditions, supporting both interpretative clarity and comparative analysis.

The results confirm the potential of time-aware digital frameworks to enhance heritage interpretation, particularly for relocated and environmentally vulnerable monuments. The platform provides a shared reference space in which conservation hypotheses, musealization strategies, and environmental impacts can be explored in a transparent and accessible manner, reinforcing its role as a decision-support and communication tool.

Future developments will focus on extending the platform's analytical capabilities. These include the refinement of 3D models and contextual environments, the introduction of guided

and adaptive immersive experiences, and the integration of advanced diagnostic and predictive approaches. In particular, coupling the 4D environment with AI-based degradation analysis, XR-driven accessibility solutions, and FAIR-compliant data structures would enable a transition toward intelligent digital twins for long-term heritage management.

Overall, this research highlights the value of immersive, time-based digital platforms as a bridge between documentation, conservation planning, and public engagement, contributing to a more resilient and forward-looking approach to cultural heritage preservation.

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