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CONSERVING ARCHITECTURAL HERITAGE THROUGH HYBRID STRATEGIES AND OPEN TECHNOLOGIES IN THE PHYGITAL ERA

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Abstract

In the current context of digital transformation, the MATHE method proposes a phygital strategy for the conservation, documentation and dissemination of architectural heritage. Tested on the Optical Telegraph Line between Madrid and Valencia, this integrated system combines Web-GIS, Augmented Reality (AR) and Virtual Reality (VR) in a coherent heritage valorisation proposal. The MATHE-GIS platform organises georeferenced and alphanumeric data in an accessible, open format, while MATHE-AR and MATHE-VR tools extend the heritage experience beyond physical boundaries. These technologies provide a hybrid, both on-site and off-site, experience that enhances users' understanding of cultural assets. It concludes that virtualisation, far from replacing the heritage object, constitutes a strategic avenue for its study, interpretation and dissemination, enabling more democratic, participatory and sustainable access.

Keywords

Architectural heritage, augmented reality, virtual reality, Web-GIS, phygital experience, optical telegraphy,

1. *Introduction*

In the current context of digital transformation, the concept of the phygital experience, as the fusion of physical and digital, represents a strategic opportunity for the conservation, interpretation, and dissemination of architectural heritage (Sezgin & Karaman, 2022). The synergy between complementary realities makes it possible to overcome the inherent limitations of each: the physical inaccessibility of many cultural assets can be offset by the creation of digital twins accessible anytime and anywhere, while the abstraction of the digital environment gains depth when linked to the original physical context of the object (de-Dato, 2024).

From this perspective, a doctoral research project has been conducted, resulting in the development of the MATHE methodology (Mixed reality for Architectural Tours in Heritage Experiences) conceived as a versatile tool aimed at professionals from diverse disciplines, such as architecture, engineering, computer science, archaeology, cultural management, or education, for the development of products targeted at non-specialist audiences. This methodology differs from established digital workflows, such as scan-to-HBIM+XR or web geoportals, through its comprehensive figital approach, which focuses not only on digitalisation but also on the experiential enhancement of heritage. Unlike models centred on information management or geometric accuracy, MATHE proposes an open and adaptable methodological framework that integrates interoperable technologies within a conceptual structure for the creation and appreciation of heritage and social participation, prioritising technological democratisation (Najjar et al., 2025). Its purpose is to democratise access to heritage through accessible, sustainable, and technically viable phygital experiences, adapted to the asset's characteristics and the end user's expectations. With the products developed under this methodology, visitors are no longer passive spectators but active participants who interact with physical and virtual environments, thereby increasing their engagement and understanding (de-Dato, Hernández & Lasorella, 2025).

Beyond its implications for cultural mediation, this methodological proposal also offers substantial advantages for the research and dissemination of architectural heritage in complex contexts, such as economic constraints or risk situations, allowing broader and more demanding audiences to be reached (Alsadik, 2022; Lasorella, Cantatore & Fatiguso, 2021; Čejka et al., 2021; Lo Presti & Carli, 2021). Furthermore, it proves valuable for the field of restoration, enabling precise documentation of the current state of a heritage asset before any intervention, thereby supporting decision-making when faced with dilemmas such as reconstruction or conservation in a state of ruin (Monterroso-Checa et al., 2020; Lo Presti & Carli, 2021; Bruno & De Fino, 2021). The possibility of virtually interacting with digital models enables exploring different scenarios and alternatives without compromising the original object (Bernardo, Musolino & Maesano, 2021).

During the application of the method to the case study, continuous adjustments and improvements were carried out to address both technical difficulties and emerging needs during the process. This experimentation made it possible to identify limitations in the tools employed and to propose practical solutions, thus generating transferable knowledge of value to future researchers addressing similar topics.

This article summarises some of the contributions of the doctoral thesis and presents three subsystems of the MATHE methodology, along with examples of their respective products. Specifically, it will discuss the MATHE-GIS, MATHE-AR, and MATHE-VR phases. For a comprehensive overview of the MATHE system, reference is made to the proceedings of the 3rd International ICOMOS Symposium, where the complete methodology with its eight phases and seven subsystems is presented (de-Dato, Hernández & Lasorella, 2025).

2. *Objectives and methodology of the study*

Before delving into the results outlined above, it is necessary to contextualise the method employed, which stems from a joint research project on heritage virtualisation developed by the Universitat Politècnica de València and the Politecnico di Bari. The proposed workflow responds to the phygital integration needs identified during the analysis of the state of the art and of current trends in heritage management. Its goal is to establish a structured pathway for the valorisation of architectural networks conceived as interconnected systems. For this reason, the method has been tested on the Spanish Optical Telegraph Line running from Madrid to Valencia.

The methodology implemented in this research is based on two interconnected and continuously feedback-driven parts.

The first part examines the main trends in the digitalisation of heritage experiences, identifies their weaknesses and potential, and proposes a theoretical framework alongside an operational protocol that follows a logical sequence for designing phygital strategies. The second part, focused on empirical experimentation, involves testing the designed protocols through specific case studies. The outcomes obtained during this phase feed back into the theoretical model, correcting any flaws and overcoming the limitations encountered during the design stage.

The resulting outputs have been subsequently tested in an operational version to collect feedback and impressions from the end users. However, user feedback has not yet been gathered through formalised protocols, which may be addressed in a subsequent phase of the research.

3. *Theoretical context*

The MATHE methodology is conceived as an integrated workflow that combines traditional documentation with advanced digital management, offering a unified platform capable of integrating different systems and technologies applied to architectural heritage. The method brings together three-dimensional digitisation tools based on photogrammetry, relational databases for the systematisation of multidisciplinary information, Geographic Information Systems (GIS) for spatial management, as well as immersive Virtual Reality (VR) and Augmented Reality (AR) environments aimed at dissemination. All these converge in a web infrastructure that ensures accessibility both for experts and non-specialist users, broadening the reach of the heritage experience both on-site and remotely. Added to this is the design of physical routes connected to digital itineraries, allowing for the construction of a hybrid experience that links real and virtual space within a coherent, educational, and emotionally meaningful environment. In this way, a methodological framework is configured that not only preserves and organises architectural and cultural information but also projects it into interactive and collaborative scenarios.

The method is structured into eight successive phases that feed into one another. In the first stage, documentary and technical foundations are established through historical research, photogrammetric surveys, and standardised data capture protocols. Next, precise three-dimensional models are developed, considered digital twins, which are optimised for applications in conservation and dissemination. The intermediate phases focus on the setup of relational databases and GIS platforms (refer to section five) that ensure interoperability and scalability, while the subsequent stages introduce interactive AR and VR experiences (refer to sections seven and eight), accessible via mobile devices or immersive headsets, based on the outcomes of the preceding phases. Finally, the methodology culminates with the planning of phygital itineraries, where the interconnection of physical routes with digital content enhances a comprehensive understanding of heritage and reinforces its cultural, social, and economic value. Among many results derived from the application of the MATHE methodology, this article focuses on presenting the Web-GIS container and the AR and VR tools integrated within this system.

The Web-GIS was conceived as an open-access platform that allows the organisation, visualisation, and interrelation of the elements that make up the systemic architectural network under study. It overcomes territorial dispersion by providing a georeferenced and navigable representation. This approach is in line with the literature, which underlines the need for new methodological approaches, especially for systemic architectures, within the slow digitalisation process of existing historic heritage (Currà, D'Amico & Angelosanti, 2021, Banfi, Brumana & Stanga, 2019; Benavides, Martín & Rouco, 2020; Costantino, Pepe & Restuccia, 2023).

Applications of AR and VR in the heritage sector encompass a wide spectrum of possibilities and objectives, ranging from dissemination and interpretation (Bec et al., 2021; Brusaporci, 2020), to accessibility (Barbara et al., 2020; Izkara, 2010), reconstruction of ruins (Adão et al., 2019; Evangelidis, Sylaiou & Papadopoulos, 2020), and assessment of restoration options (Escriva & Madrid, 2010).

In this work, the proposed digital environment not only facilitates the structured consultation of spatial and alphanumeric data but also acts as the technological foundation for the development of immersive experiences aimed at interpreting and enhancing the value of heritage. The following sections provide a detailed description of the system architecture, its functionalities, and the interaction possibilities offered to users through the integrated AR and VR tools. The proposed methodology is grounded in the recommendations of the Europeana Network Association Task Force 3D concerning the selection of 3D formats, viewers, interoperability, and quality standards (Fernie, 2024). In particular, it adheres to the guidelines on metadata, descriptive protocols, and standardised formats (obj for three-dimensional models and HTML5/WebGL for the GIS viewer), among others, ensuring potential integration in repositories such as Sketchfab and 3DHOP.

4. *Presentation of the case study*

The experimental field chosen for this research, due to its suitability, was the Spanish optical telegraph towers. These structures constitute a systemic network which, although dispersed across the territory, is unified by a single function (Lasorella, Cantatore, de-Dato & Fatiguso, 2022): the long-distance transmission of messages during the 19th century. Although the use and experimentation of optical telegraphy began a century earlier in France, this system materialised through the project of Colonel José María Mathé Aragua into three major lines in Spain: Madrid–Irún, Madrid–Barcelona, and Madrid–Cádiz, totalling 196 towers. The Madrid–Valencia section of the second line, consisting of thirty towers built between 1848 and 1850 (Olivé, 1990), represents a paradigmatic example, both for its state of conservation, with nineteen structures still standing, and for the homogeneity of its typology.

Leaving aside the telegraphic system itself, which has been studied in depth by authors such as Romeo López (1980) and Olivé Roig (1990), the architectural design of these towers responded to technical and defensive requirements. They were located on natural or artificial elevations, prioritising visibility between stations, which were generally positioned two to three leagues apart. These conditions often made access and an overall perception of the network difficult. Their square floor plan contained three levels: the ground floor was used for storage and services; the intermediate floor for the garrison; and the top floor housed the telegraphic apparatus, which projected above the roofline. The masonry and lime mortar walls, with thicknesses ranging from 95 cm at the sloping base to 55 cm at the upper levels, ensured great resilience. Perimeter loopholes and a raised entrance at the first floor, accessible by retractable ladder, reinforced their defensive function.

In terms of materiality and construction solutions, these towers combined local stone and/or brick in reinforcement elements, resulting in three defined construction configurations, CT1, CT2, and CT3: the first included towers built entirely of stone with occasional use of brick in cornices, jambs, and architraves; the second, the most numerous, consisted of masonry towers with solid brick structural joints and construction details; the third, a smaller group, was built entirely in stone. Thanks to their robust structure, many remained standing despite abandonment since 1857, when the electrical telegraph replaced the optical system (Olivé, 1990), although with varying degrees of deterioration.

The most frequent pathologies include mortar erosion, loss of renderings, partial collapses, vegetation colonisation, and more or less severe structural failures depending on the case. The conservation status has been classified into five categories: from total disappearance to a ruined state, to towers with partial collapses, consolidated structures, or restored ones.

From a heritage perspective, these towers constitute a unique architectural ensemble: repetitive in their typological conception, yet with variations adapted to the terrain and local construction conditions. Due to their systemic network character, their study requires a dual approach: the micro-scale, focused on the architectural unit, and the macro-scale, which considers the network as a territorial system articulated by visibility and function (Fatiguso, De Fino, Cantatore & Caponio, 2017).

The conservation of this heritage demands strategies that combine precise documentation, material conservation, and interpretative valorisation, with solutions that consider not only the individual building but the entire network. The phygital approach, integrating centralised digital recording, 3D modelling, and immersive experiences, emerges as a key tool for their preservation and dissemination, articulating their historical and architectural relevance with new forms of public access.

5. *Presentation of the case study*

At present, the market offers a wide range of Web-GIS tools that provide different types of services, from simple static map visualisation or data download to advanced geospatial queries and analyses. The choice of technology depends on the nature and scope of the services to be fulfilled (Agrawal & Gupta, 2017; Netek, Pohankova, Bittner & Urban, 2023; Palestini et al., 2025).

The MATHE-GIS system is structured around the basic functions of Geographic Information Systems (GIS), such as attribute queries and spatial analysis, managed through preconfigured forms and maps on the server. These elements are processed server-side and presented to the user via a client-side web interface.

The adopted strategy allows data to be provided dynamically from a robust server, which also hosts the necessary software for its processing. This approach frees heritage managers from the need to maintain their own technological infrastructure, while facilitating access for non-specialist users, who require only an internet connection to consult the information. Thus, the system contributes to the democratisation of access to geospatial technologies.

Interaction begins when the user accesses the interface, designed during a separate project phase, through a web browser. The request is transmitted via the internet to the cartographic server, where the software managing the data and

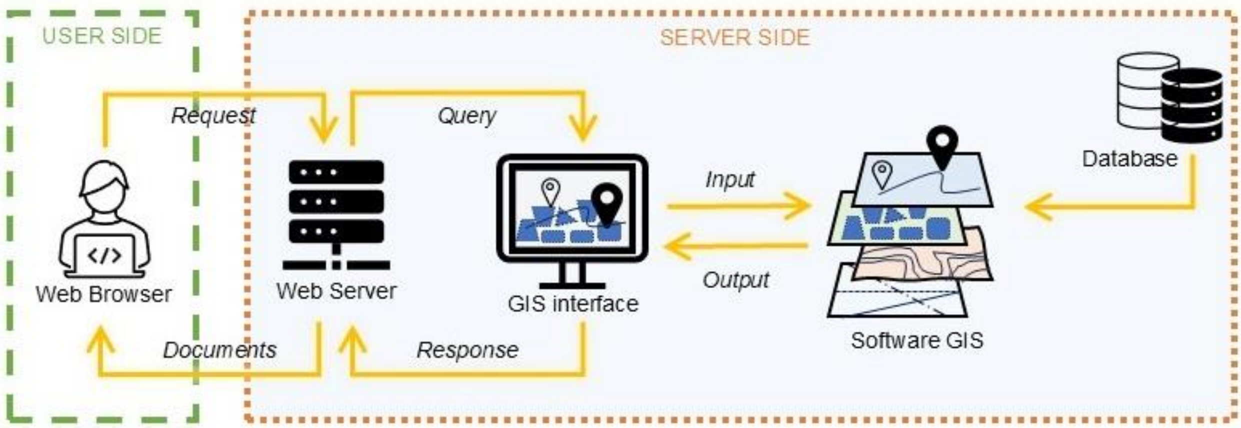


Fig. 1: Workflow of the Web-GIS

generating the maps is located. The processing results are then sent back to the user's browser for visualisation (Fig. 1). The resulting maps enable the precise geographical location of the architectural units belonging to the network under study, using latitude and longitude coordinates obtained during a preliminary study phase, and represented in the WGS84 geographic reference system. Access to information is provided through queries and filters applied to the structured database.

With regard to the algorithms implemented within the GIS system, several have been employed either directly or indirectly through the import of content from external tools. These include the "A-star Search Algorithm" for optimal route calculation, "Attribute Join" for the merging of layer attributes, and the "Voronoi" algorithm for the delineation of areas of influence, among others. However, the use of these specific algorithms is not of primary significance to the methodology itself, as different algorithms may be more appropriate depending on the type of architectural network and the ultimate purpose of the web-GIS. The geographic layers have been enriched with alphanumeric information that facilitates the identification of each building, including data such as name, position within the line, and address. For unambiguous identification, the code assigned to each architectural unit in the catalogue and survey sheets has been used as a label in the system.

The Web-GIS platform developed within the MATHE methodology is structured around several components designed to ensure an intuitive and comprehensive browsing experience. First, an interactive cartographic viewer has been implemented to display the entire architectural network (Fig. 3). This viewer is complemented by a fixed control panel for customised content selection, a lateral popup panel offering detailed information on each unit, a dynamic legend module that adapts to the selected contents, and a set of tools for changing the base map, as well as measuring distances and areas.

The side panel is organised into three main sections (Fig. 4), although its design allows future expansion depending on user profiles and the system's specific objectives. These sections enable:

i) visualisation of general information on each building, including links to AR/VR applications together with a representative image;
ii) exploration of a graphic gallery with general and detailed images of the selected element;
iii) access to relevant documentation for historical analysis or research support.

The incorporated data cover: building identification; positioning through geographic coordinates obtained in situ via GPS devices over Google Maps cartography, using WGS84 as the reference system and expressing latitude and longitude in decimal degrees; administrative location (address and municipality); construction and demolition dates (if applicable); architectural features such as materials and conservation status; technical information on risks and vulnerabilities (of interest to specialist profiles); and, finally, links to external functions such as route calculation or access to AR/VR experiences.

For system development, various platforms, both commercial and open source, were tested to find a solution combining usability, performance, and accessibility. ArcGIS®, Felt®, and QGIS were trialled: the first was rejected due to high licensing costs despite its operational efficiency; the second, although visually appealing and easy to use, was limited in functionality. ESRI's ArcGIS Online initially allowed effective data management and an intuitive interface layout, facilitating collaborative work and interoperability with other digital environments.

However, the final version of the system was built on the open-source software QGIS (v. 3.28.8) (Fig. 2), a recognised reference tool in the GIS field (Dmytro, Arkadii, Tetiana, Dmytro & Denys, 2023). From a table of geographic coordinates, a spatial file in GeoJSON[1] format was generated and normalised to ensure correct visualisation. This format was chosen for its structural simplicity and interoperability with most GIS platforms.

The MATHE-GIS viewer was developed using the JavaScript library Leaflet[2] (v. 1.9.4), known for

[1] GEOJSON (Geographic JavaScript Object Notation) is a format for exchanging geographic data and their spatial attributes between different applications and systems. It is lightweight, open-format, programming-language independent, and was standardized by the Internet Engineering Task Force (IETF) in 2015.

[2] Leaflet was developed eleven years ago by the Ukrainian programmer Volodymyr Agafonkin as a response to the complexity and exclusivity of the GIS field, with the aim of promoting the democratization of geospatial digitalization.

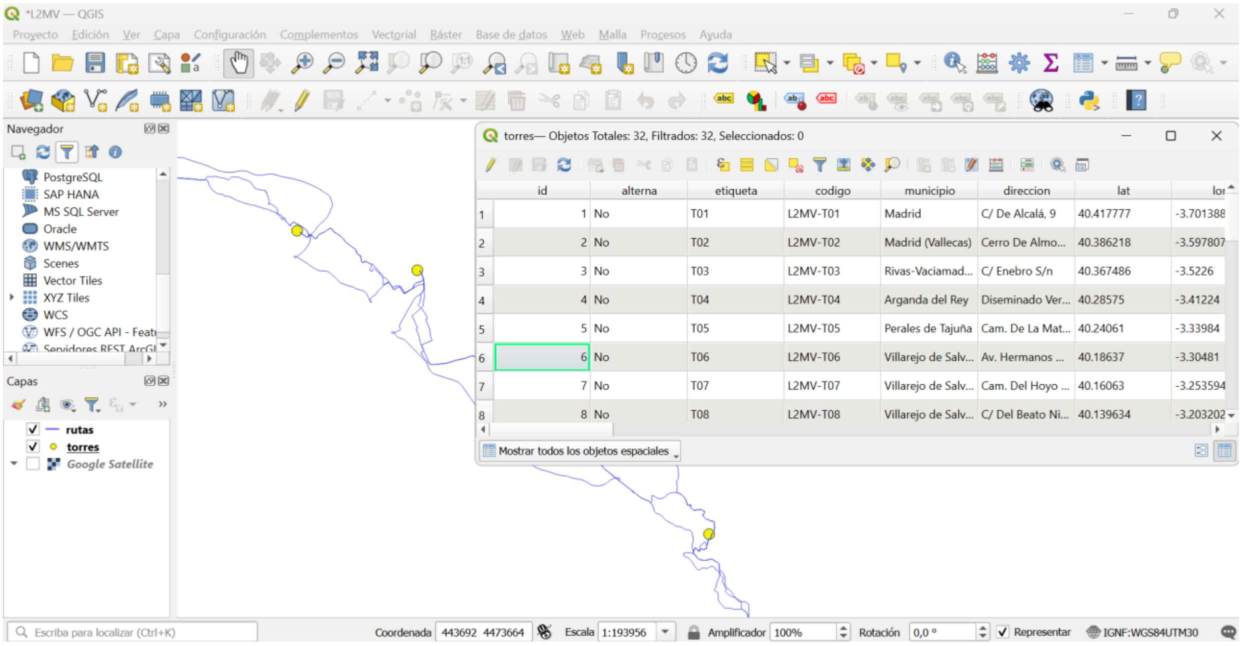


Fig. 2: Development fase of the layers in the GIS software QGIS

its lightness (only 38K), modularity via plugins, ease of use, and good performance (Netek, Brus & Tomecka, 2019) as it employs a smaller number of distinct objects (classes) used in each case compared with other APIs.

As an open-source project, Leaflet benefits from an active community that ensures constant updates and the incorporation of new functionalities, making it a solid and scalable option for interactive mapping projects. MATHE-GIS, based on Leaflet, uses HTML for structure, CSS stylesheets for visual design, and JavaScript for dynamic functionalities. Specific plugins were integrated to add tools such as area and distance measurement (Leaflet Measure), full screen visualisation (Control Full Screen), sidebar information display (Leaflet Sidebar), and legends with colour codes associated with geographic markers (Leaflet Control HTML Legend).

The viewer was developed using Visual Studio Code (version 1.84.2), a free and open-source code editor distributed under the MIT licence, which facilitates writing and managing code in various programming languages.

Through the MATHE-GIS platform, users can visualise key data relating to location, geophysical characteristics, and conservation status, among others, accompanied by both current and archival images when available. The system also allows the download of historical documents and provides direct links to augmented and virtual reality applications accessible online. Another important functionality is its integration with Google Maps, enabling users to calculate routes from their current location to points of interest in the architectural network. In addition, MATHE-GIS ensures data interoperability by allowing export and exchange in GeoJSON format, thus ensuring compatibility with other GIS systems and applications. Its modular design and use of open technologies make the platform scalable and adaptable to any type of systemic architectural network. The system is available through a web geoportal and a WebMap client, connected to a web server supporting remote and collaborative access for diverse users.

As noted, the GIS system integrates a main cartographic viewer that displays the entire network of towers stretching from Madrid to Valencia via positional markers (Fig. 3). Each marker, although individually represented, contributes to a clear overall visual understanding of the network, while the sequential numbering of labels (T01, T02, T03, etc.) facilitates the identification of spatial link among towers.

By default, marker visualisation employs a colour code indicating the conservation status of each tower: black for disappeared towers; red for those in ruin; orange for towers with significant partial collapses but not entirely ruined; yellow for consolidated towers with partial interventions; and green for restored towers. This classification does not imply professional judgement from a restoration perspective. On the right side of the

Fig. 3: Main map viewer of the MATHE-GIS system, displaying the tower indicators in different colours according to their conservation status.

Fig. 4: Main map viewer of the MATHE-GIS system, showing the available route options.

viewer, a thematic panel enables users to select alternative categories to "Conservation status," such as "Materiality" and "Ownership," as well as to activate route visualisation and consult an adaptive legend. When "Materiality" is selected, marker and legend colours change to reflect the three constructive categories described previously (section 4): blue (CT1), green (CT2), and red (CT3), while disappeared towers remain indicated in black. The legend specifies the material

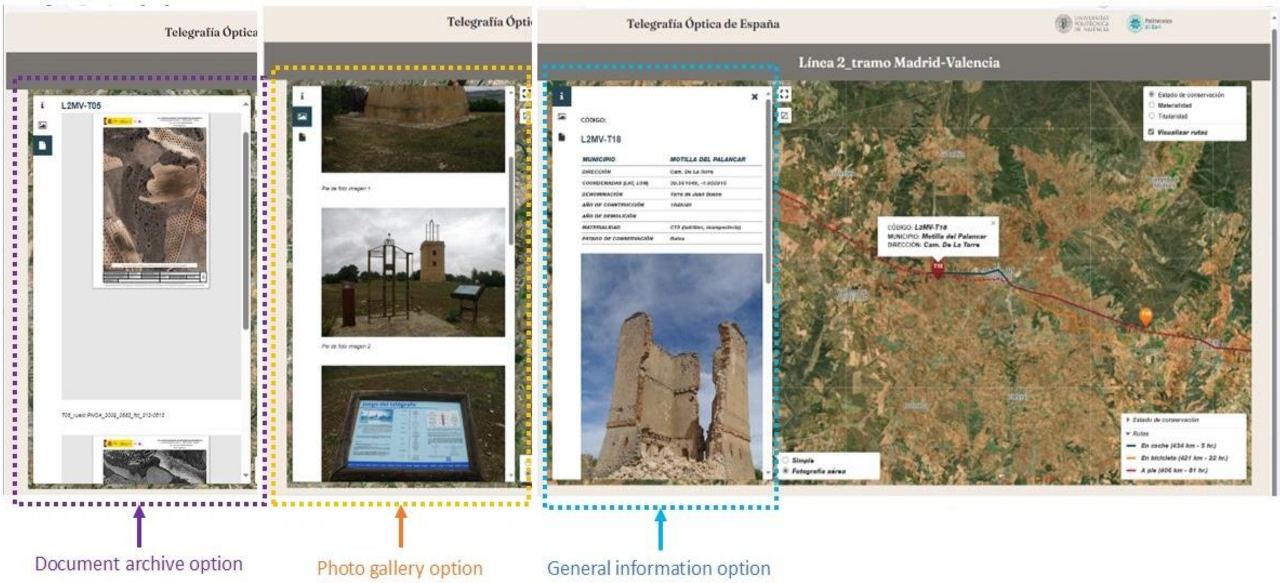


Fig. 5: Side panel with three different information options (document archive, photo gallery and general information) and pop-up windows showing basic information about the selected tower.

composition corresponding to each category. The "Ownership" option distinguishes public and private towers using cyan and magenta, respectively, while black continues to indicate disappeared towers. Routes can be displayed in three modes, car (on blue), bicycle (on yellow), and walking (on red), similar to Google Maps. These routes are shown simultaneously, allowing users to compare distances and estimated times, displayed alongside each route (Fig. 4). The viewer's default base map is a retro-style relief map developed by Mapbox and available under an open-source licence. It is centred on the telegraph line, but zoom levels range from a panoramic view of the Iberian Peninsula, ideal for appreciating the network's extent or comparing it with other systems in future studies, to detailed urban street-level views for evaluating accessibility to each tower. Users may also choose an "Aerial Photograph" view, based on OpenStreetMap satellite maps, also open source, to observe the immediate physical surroundings of each tower as well as the landscapes traversed by the systemic network and its routes.

Finally, the viewer incorporates a tool for measuring distances and areas, which is particularly useful for quickly estimating partial route lengths or direct distances between towers. This feature helps better understand the advanced nature of Mathé's telegraphic system within the technological context of 19th-century Spain, as well as evaluate the influence of geographical relief on the line's layout. When interacting with a marker in the viewer, a pop-up window enables showing basic information, including the tower's ID, municipality, and address. By clicking on the marker, the viewer zooms in to level 13 (approximate scale 1:68,247), centring on the tower's immediate environment to reveal its spatial relationship with adjacent units. At the same time, a sliding side panel (Fig. 5) opens to provide detailed information. This side panel is structured into three sections:

i) General information;
ii) Photographic gallery;
iii) Document archive.

The first section presents a wide range of data drawn from the catalogue, including identification, geographic location, material and construction features, conservation status, potential risks, among others, along with direct links to a virtual tour and to the route calculation function from the user's position to the tower. The second section hosts a carousel-style gallery of images, showcasing overview photographs and detail shots obtained during survey campaigns.

Finally, the third section gathers historical documentation and related files, available for download or printing, thus facilitating access to sources that would otherwise be difficult to compile. This last area, designed particularly for researchers, makes a significant contribution by centralising and democratising access to lost historical info.

6. On the virtualisation of physical reality

In the experimentation of the MATHE method, different strategies (both on-site and off-site) for the virtualisation of heritage have been tested and proposed. Starting from the lowest level of virtualisation, an AR application was developed using Unity software (version 2021.3.28f1), experimenting with holograms activated by visual markers, which may be QR codes or specific images. Following the creation of different AR proposals, more complex VR applications were also tested, such as serious games for desktop, immersive games for HMD headsets, and 360º tours. Once again, in the interest of democratising the digital heritage experience, the applications have been made available for download from the web platform (MATHE-WEB) or via direct access through the Web-GIS (MATHE-GIS).

7. Development of AR content

Phase 5 of the MATHE method, known as MATHE-AR, relates to the enrichment of the physical experience through the incorporation of digital content and applications. In the field of Augmented Reality (AR), two main strategies can be identified: an off-site modality and an on-site modality.

In the off-site modality, the MATHE methodology proposes the integration of multimedia elements that can be linked to external web resources or activate pop-up windows within the main phygital tour, either through the Web-GIS or by means of virtual experiences. Digital AR content covers a wide spectrum, including explanatory audio guides, three-dimensional diagrams, historical videos showing the evolution of the building, reconstructions of disappeared parts, aerial views captured by drones, 3D representations of significant elements, historical images, as well as games and interactive challenges designed to make the experience more engaging or to unlock additional levels of information or rewards. Furthermore, informative texts, purchasing recommendations, and other types of content may be incorporated depending on the creativity of the manager.

An interesting and easy-to-manage off-site alternative is the generation of 3D digital holograms, which can be projected onto specific surfaces or viewed through mobile devices. It is common to find mobile applications for iOS and Android that allow the projection of AR holograms onto surfaces with QR codes (Fig. 7) or onto physical three-dimensional objects, such as the Merge Cube®, which uses markers on its faces to facilitate the visualisation of digital models (Fig. 8).

Fig. 6: AR application using Image-Target technology

Fig. 7: AR application using QR code technology

In contrast, the on-site modality is based on the development of AR filters for mobile devices that allow three-dimensional elements, sounds, or other content to be displayed on a target image captured by the smartphone camera (Fig. 6). This strategy is more visually impactful and intuitive for the end user. However, the literature reports a variety of outcomes, with successful cases showing positive impacts on the local community (Xian & Shen, 2020; Xiao, 2022), and others where technical difficulties compromised the quality of the final product (Ghani, Rafi & Woods, 2020; Liestøl & Hadjidaki, 2020; Nevola, Coles & Mosconi, 2022). In this context, the quality of the visual marker (target) is crucial to ensuring correct activation of AR content on the user's device. Physical variation caused by interventions on the asset, or even chromatic changes due to weather conditions, may interfere with the application's functionality. However, the application has been optimised to ensure maximum performance, regardless of external factors. The 3D model explored within the application is stored locally in the device's memory and downloaded together with the app. This configuration prevents potential issues related to Wi-Fi or mobile network coverage and enables instantaneous loading of the model once the marker is detected.

Model rendering depends exclusively on the processing capacity of the device, although it has been specifically optimised for mobile platforms. Furthermore, parameters such as GPS accuracy do not influence the application's functionality, as it does not rely on geolocation technologies; the tower image alone serves as a sufficient marker for accurate recognition and operation.

With respect to marker detection, the image employed has been rated four out of five stars by Vuforia, the software responsible for marker recognition. This rating ensures robust tracking performance under most common lighting and viewing angle conditions.

As a complementary alternative, it has been suggested that on-site interpretative panels could be enriched through the inclusion of QR codes or markers linking to digital content (Fig. 7). Likewise, the simultaneous use of GPS-based AR experiences is proposed, allowing additional information to be displayed to the user once they are located at the heritage site. In this case, the data appear on the mobile device screen when the camera is directed at the building and the GPS is activated, although the precision depends on satellite signal quality, which typically has an error margin of between 5 and 10 metres.

For the development of such content, several free and commercial applications are available, e.g., SparkAR, Unity, Vuforia, ActionBound, Roar,

a) b) c)

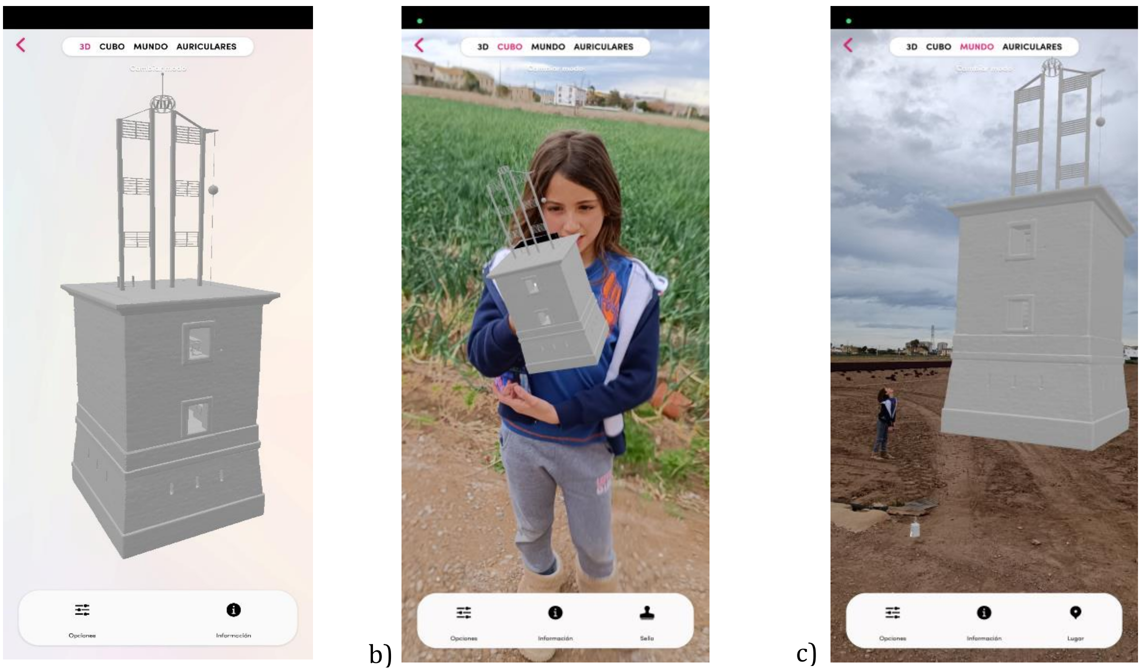


Fig. 8: Screenshots of the holographic visualisation of the tower by Merge Cube: a) 3D mode; b) Cube mode; c) World mode.

WallaMe, Aumentaty, Augmented Class, Layar, or ZapWorks, differing in capabilities coherently with the complexity of the digital functions to reach.
In the case study presented, the MATHE-AR system was tested using Unity, complemented by scripts programmed in Vuforia, which employs visual marker technology to activate 3D models of the building in its original state, including interiors, furnishings, and apparatus. These scripts make it possible to customise and automate features not natively supported by Unity. The Merge Cube® was also used as a tool for an off-site strategy with dissemination and didactic purposes (Fig. 8). Merge Cube® is a holographic cube that can be held in one hand and, through a smartphone or tablet, allows the visualisation, in this case, of a virtual reconstruction of the prototype tower designed by Mathé. The previously generated 3D model was uploaded to the MergeEdu® platform, which assigns a unique identifier and QR code to facilitate its access and use. This code can be contained in exhibition panels located next to the towers (on-site strategy) or into digital platforms (i.e., the project's Web-GIS viewer) enabling users to interact with the model anywhere.

Visualisation is possible through the MergeEdu ObjectViewer application, available free of charge for mobile devices. This tool offers four modes: 3D, Cube, World, and Headset. The default "3D" mode allows users to explore the model directly on the screen without requiring a camera (Fig. 8a). In this mode, the model can be rotated, enlarged, or entered to examine interiors or distant details, depending on the possibilities of the previously generated 3D model. The "Cube" mode offers a more immersive interaction, manipulating the model with the physical cube (Fig. 8b). In this case, the user experiences more intuitive control over the model. The "World" option makes it possible to project the model into the physical environment at real scale through its visualisation on the smartphone screen (Fig. 8c), while the "Headset" option provides immersive experiences by devices such as Merge Goggles or Google Cardboard.

Although the free versions of MergeEdu have limitations, their interactive potential can be expanded with complementary platforms such as CospaceEdu®, which is useful for educational purposes through block programming, or with more advanced environments such as Unity, which allow for the development of more personalised and complex experiences.

8. Development of AR content

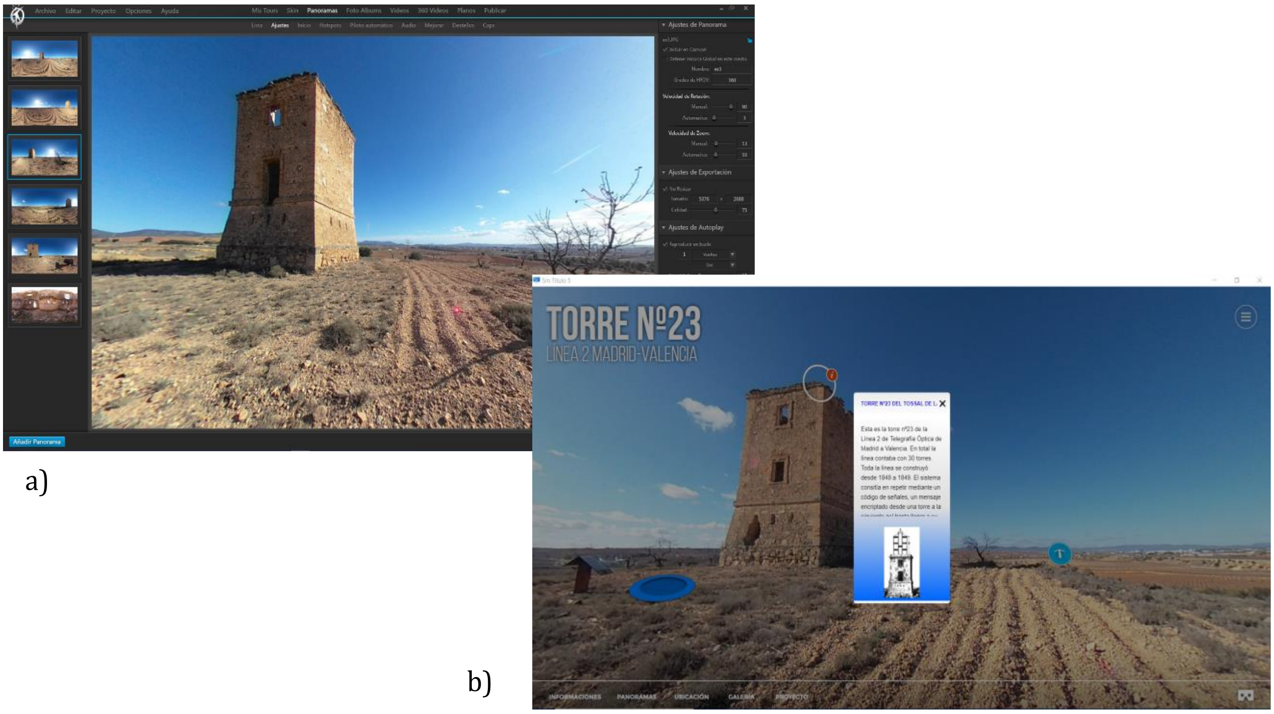
At present, two main approaches can be distinguished in the use of Virtual Reality for heritage experiences:

i) VR experiences generated from three-dimensional models produced specifically or via photogrammetry;
ii) VR experiences that recreate real environments using linked 360° spherical panoramas.

As in the previous phase dedicated to AR, VR admits different strategies for creating digital content. From the analysis of the state of the art, immersive off-site strategies were identified, employing display devices such as HMD headsets (e.g., Meta Quest), CAVE systems, or stereoscopic viewers via virtual tours, as well as non-immersive strategies that use screens for projecting first- or third-person videogames. There are also on-site strategies using portable HMDs or mobile devices, although these require suitable physical spaces for the installation and management of immersive VR tools. In this work, the second approach has been presented due to its ease of execution, requiring minimal technical expertise from the heritage manager, and in order to offer the end user an enriched experience that allows immersion and interaction within the virtual environment.

8.1 360º virtual tour

In this option, the virtual experience is based on a "visit" undertaken by the user in an artificial but faithfully reproduced environment, created using 360° images (spherical panoramas) interconnected through hotspots that allow transition from one image to another. These connections may be organised following a sequential itinerary or according to specific criteria of interest, such as construction elements, orientations, or typologies. Unlike cylindrical panoramas, which are obtained from two- dimensional photographs perpendicular to the lens and projected 360° around the user, spherical panoramas include both ground and ceiling, since the projection is made onto a sphere that fully envelops the observer, creating an immersive environment (Napolitano, Scherer & Glisic, 2018). Planning of the photographic shots and of the connections between them, using specialised virtual tour software, makes it possible to design optimised itineraries that ensure a realistic and fluid experience. Preliminary planning



a)

b)

Fig. 9: Development (a) and testing(b) of the 360° Virtual Tour enriched with AR information on the L2MV-T23 tower in Requena (Spain).

on a map or plan helps to optimise capture time, ensures the coverage of all spaces of interest, and allows the integration of the map as an interactive navigation element for the user, directly linked to the panoramic views.

To enhance immersion, real soundscapes may be added, while the experience can also be enriched with complementary augmented reality information such as photographs, technical sheets, hyperlinks, or informational models. Among the commercial and open-access software available for the creation of virtual tours are Tourweaver and VRTourMaker by Easypano, Panotour by Kolor, Lapentor, My360, EyeSpy360, and 3DVista.

Mobile applications likewise offer high mobility and ease of use for these experiences, facilitating their implementation even with HMD devices and thus enabling an immersive modality.

The main advantage of tours based on spherical panoramas lies in the speed and simplicity of generating content: within minutes, photographs can be taken and a tour assembled, in contrast to traditional 3D modelling. Conversely, 3D models provide a greater level of detail, enable variations in scale and perspective, and offer more flexibility in management and visualisation, unlike the more static spherical panorama (Napolitano, Scherer & Glisic, 2018). From an economic perspective, virtual tours using spherical panoramas are significantly more affordable than producing 3D models with a similar level of realism, making them an ideal solution for experiences with less stringent detail requirements, such as those oriented towards tourism. For the creation of the immersive virtual tour, a photographic campaign was designed following specific criteria of approximation and contouring of the towers' exteriors, and accessibility within the interiors.

Given the modest dimensions of the towers, the immediate surroundings and the interior areas have been covered, with a minimum of five shots: four exterior panoramas from the corners at a sufficient distance to also record the immediate context, and one interior shot encompassing the full volume of the building, which, as noted, lacked intermediate floor structures.

For the capture of the spherical panoramas, a 12-megapixel RICOH THETA S camera was used, incorporating noise reduction and HDR rendering. This camera automates the process of panoramic image capture without requiring manual stitching operations, thereby significantly streamlining the workflow. Among the programmes tested for producing the tour, 3DVista Virtual Tour proved the most effective, although its use was limited to the trial version. The virtual tour consists of multiple 360° panoramas interconnected through hotspots, i.e. interactive buttons superimposed on the images that allow navigation between them (Fig. 9). The user can control the point of view within each scene by using the mouse to rotate in all directions and to zoom in or out of the standard view. The user interface is customised to facilitate navigation: from the first image, the user can move through directional indicators (arrow-shaped hotspots) or by means of an interactive map showing the camera position and available routes. On this map, each red dot indicates a location where a spherical panorama was taken, while an orange radar highlights the current viewing direction of the user. In addition, content hotspots were implemented to provide access to further information within the same tour. In the specific case of L2MV-T23, the included contents are:

- a 3D model of the virtual reconstruction of the tower, created with 3D modelling software, showing constructional details;
- explanatory audio content on the functioning of optical telegraphy, similar to an audio guide;
- a video recorded with a FIMI X8 SE drone during the survey phase, showing from above areas with limited visibility, such as the roof and surrounding environment;
- short texts with information on details difficult to perceive in situ;
- technical information on the mainly for technicians or researchers, though included here for experimental purposes.

This virtual tour is available on the web platform (MATHE-WEB) and can be accessed via the link located in the information side panel of each tower within the MATHE-GIS system.

9. Conclusions

The application of the MATHE methodology has demonstrated the feasibility of a phygital strategy for the conservation, documentation, and dissemination of architectural heritage, combining accessible digital tools with meaningful immersive experiences. Based on a specific case study, the Madrid–Valencia Optical Telegraph Line, an integrated system has been developed that combines, among other elements, Web-GIS, Augmented Reality, and Virtual Reality within a coherent proposal for heritage valorisation grounded in physical–digital interaction.

Among the main results achieved are:

- the consolidation of a methodological structure that can be replicated in other heritage contexts;
- the effective integration of open and low-cost technologies;
- the improvement of accessibility, understanding, and enjoyment of heritage through hybrid experiences adapted to different user profiles.

The MATHE-GIS system has proved effective as a digital repository for a dispersed heritage network, facilitating structured consultation, georeferenced visualisation, and the interconnection of alphanumeric, visual, and historical data, for example, in its side panel sections dedicated to the document archive and the photo gallery.

Likewise, AR and VR tools have expanded the perception of the cultural asset beyond its physical boundaries, offering an enriched experience both on-site and off-site. In this case, the applications serve a dual function, supporting both interpretative and touristic dissemination, as well as educational purposes (edutainment).

From a disciplinary perspective, the proposal also contributes value to the fields of restoration, cultural management, and heritage education by providing new ways of documenting, interpreting, and communicating heritage. The work has also shown that virtualisation can be not only a complement but also a strategic pathway to address challenges such as inaccessibility, documentary fragmentation, or a lack of material resources. Nevertheless, the experience has also highlighted certain technical and operational limitations, opening avenues for future research focused on:

- assessing the long-term impact of these experiences on non-specialist audiences;
- evolving towards participatory models that integrate local communities into the design of phygital experiences, thereby reinforcing their social and cultural sustainability;
- and expanding or refining the method through its application to other heritage typologies or territories.

Taken as a whole, the MATHE method represents a significant contribution to the field of heritage digitalisation, offering an operative pathway for the creation of phygital experiences that combine documentary rigour, technological accessibility, and communicative potential. For now, the experimentation carried out has served as a useful proof of concept, but it requires continuity and comparative studies in diverse contexts to validate its generalised effectiveness.

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