HERIT ADAPT

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Abstract

The overall objective of the HERIT ADAPT project is to reinforce the Sustainability and Resilience of Euro-MED Tourism Destinations by increasing the adaptation and mitigation capacity of natural and cultural heritage assets which are directly linked with their tourism attractiveness. In this context, a first output is related to a Feasibility study for the establishment of the HERIT ADAPT data-driven technology-enabled Sustainable Tourism Model. The present report is contributing towards this direction by providing a review of available technological solutions, as well as previous project outcomes with a high capacity of capitalization during the Herit Adapt pilot experimentation in its envisaged pilot sites across the Euro Med area.

Project Partners

Organization	Abbreviation	Country
Region of Western Greece	RWG	GR
ATHENA, Research and Innovation Centre in Information, Communication and Knowledge Technologies, Industrial Systems Institute	ATHENA	GR
European Public Law Organization	EPLO	GR
Sapienza University of Rome	SDR	IT
Municipality of Genoa	COMGE	IT
Dubrovnik Development Agency DURA	DURA	HR
Limassol Tourism Development and Promotion Co Ltd	LTC	CY
Old Royal Capital Cetinje	PCT/ORCC	ME
University of Granada	UGR	ES
Regional Tourism Agency Occitanie	CRTL	FR
Ministry of Tourism of the Republic of Bulgaria	MTRB	BR

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Glossary

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Cultural Heritage	CH
Territorial Working Groups	TWGs
Sustainable Tourism Model	STM

Summary

The HERIT ADAPT project places special emphasis on enhancing the Sustainability and Resilience of Euro Med tourism destinations. It recognizes the fact that tourism has shown considerable vulnerability and non-resilience in many crises. It also addresses the issue from the point of view of Cultural and Natural Heritage sites seen as indispensable assets of Euro Med territories. Helping protect such sites can significantly contribute to the overall Sustainability and Resilience of tourism destinations in the Mediterranean area.

Different technological solutions can help towards this direction. The Industry 4.0 paradigm shift and its enabling technologies can be applied also with reference to protection and maintenance of heritage sites. Sensing technologies, 3D modeling of sites, Data Analysis, AI/ML algorithms, XR technologies can all drive towards more efficient monitoring, and more informed decision making and interventions in Cultural and Natural heritage sites.

Furthermore, technologies for tourism flow monitoring can help address the effects of over tourism and enhance overall sustainability of tourism destinations. Adaptation of climate crisis is also critical in the context of tourism destination resilience.

The present report performs a state of the art review on aforementioned technology solutions with applicability in the HERIT ADAPT context, and especially with reference to its pilot experimentation. The set of technologies, solutions and methodologies investigated can provide the pilot sites with adequate knowledge to be exploited in the context of the project.

The project partnership engages into an investigation of the available solutions already applied in the pilot sites, as well as outcomes of projects that could be capitalized by HERIT ADAPT. A set of solutions complements the wider technology offer, offering a set of tools, solutions, applications and methodologies that could be part of the pilot experimentation in HERIT ADAPT.

An analysis of the pilot sites is also done with reference to their anticipated objectives and goals, activities, infractructures and resources to be engaged, and expected outcome leading to increased sustainability and resilience.

The report is part of the methodology for the provision of a Feasibility study for the establishment of the HERIT ADAPT data-driven technology-enabled Sustainable Tourism Model.

Introduction

The present report is related to Activity 1.3 "Mapping of existing technological tools for destinations' management and monitoring in regards to Sustainability & Resilience" of WP1 "Methodology for monitoring & management of tourism & climate change related risks in touristic areas" of the EuroMed HERIT ADAPT project.

The Activity 1.3 runs in parallel with Activities 1.1 and 1.2 that relate to the activation of Thematic Working Groups in the pilot territories, and elaboration of SWOT Analyses per pilot. Its main focus is on the identification of adequate technological solutions that can be applicable in the context of the pilot experimentation targeting the enhancement of sustainability and resilience of pilot destinations, focusing primarily on their heritage sites.

The methodology that was followed in Activity 1.3 involved primarily the 3 academic partners of the consortium, i.e. ATHENA leading the activity, University of Sapienza and University of Granada in compiling a review of the current state of the art, forming the baseline for the project pilot experimentation. The three academic partners reviewed different types of technologies related to 3D modeling of sites, sensing, AI/ML, XR, tourist flow monitoring, and climate adaptation methodologies.

The entire consortium was involved in order to collect useful information on the pilot sites, the envisaged pilot experimentation, its individual activities and expected resources. Focus was placed on previous projects that could be capitalized in the context of the pilots, as well as existing infrastructures and solutions applied already in the pilot sites. To this end a questionnaire has been compiled and been completed by the partners associated with the pilot testing.

The rest of the report is structured as follows:

- A first chapter presents the rationale for the overall report and the review work included in the report.
- Then, Technologies and Application Domains are presented. This chapter comprises review of technologies related to a) application of Artificial Intelligence, b) Sensing technologies, c) use of Extended Reality, d) tourism flow monitoring, e) climate adaptation methodologies, f) generation of 3D digital models driving towards digital twin solutions for heritage sites.
- A number of solutions that could be applied in the pilot sites is presented. Such solutions stem from previous projects applied on the sites or that could be capitalized in the context of Herit Adapt.
- Finally, the pilot experimentation characteristics are detailed mapping each pilot site to envisaged solutions and addressing sustainability aspects pursued.

The report intends to provide coherent input for the production of Output 1.1 "Feasibility study for the establishment of the HERIT ADAPT data-driven technology-enabled Sustainable Tourism Model".

Rationale

As a number of different crises have shown, the tourism sector remains significantly vulnerable and non-resilient mandating new approaches to help adapt to and mitigate risks. Furthermore, the traditional model followed in many Mediterranean territories is characterized by seasonality and concentration around the coastal zone, thus resulting to a largely non-sustainable tourism.

Cultural and Natural Heritage is increasingly recognized not only for its intrinsic worth but also as for its role towards achieving a more sustainable, equitable and green economy. Specifically with reference to sustainability they contribute significantly to all of its three pillars, offering territorial assets that enhance the destination attractiveness and thus contribute to territorial competitiveness, being quite important for people at local, regional, national and EU level, promoting EU values, linking to the past and offering visions to the future, and integrating harmoniously with the natural and built environment.

Cultural and Natural Heritage protection and conservation is of great importance, allowing territories to continue reaping the benefits of their presence. Different technologies may contribute to this end. Sensing technologies are necessary to allow the collection of data from heritage sites and provide data driven decision making. Such technologies comprise remote sensing, proximal sensing, contact sensing but also wearables. Digital twins stemming from other application domains can help monitor heritage sites in real time but also record interventions throughout the site lifecycle. Creation of 3D Digital models of heritage sites is a first step towards this direction of creating the site Digital Twin. Machine Learning and Artificial Intelligent algorithms can be utilized on top of the data collected for heritage sites offering aid to a bunch of operations including conservation and restoration, research and documentation, public engagement, accessibility and inclusion. Extended Reality also provides technologies to allow engagement of the visitor, including Virtual Reality and Augmented Reality, and making possible increased authenticity via immersiveness. All these technological solutions contribute to better highlighting the heritage sites of tourism destinations and enhancing their visibility whether they are of greater or lesser importance.

Furthermore, addressing the main risks for heritage sites and monuments is of paramount importance. Such risks comprise for instance the flow of tourists, creating the need for tourism flow monitoring and devising adequate strategies to this end. Climate crisis poses a much greater risk as it affects heritage sites through its contribution to adverse weather phenomena. Climate adaptation methodologies need to be applied so that such risks are efficiently dealt with.

Finally, a number of projects and their outcomes are envisaged for capitalization in the context of the HERIT ADAPT project. These projects make use of a number of technological solutions that drive along the above directions. It is envisaged that some of their results will be capitalized during the project pilot experimentation.

Technologies and Application Domains

Artificial Intelligence

The field of **Artificial Intelligence (AI**) focuses on creating computer systems that can perform tasks traditionally associated with human cognitive abilities. These include recognizing patterns and speech, playing games, making decisions, solving problems, and extracting insights from data. AI is a broad domain that incorporates various specialized areas such as machine learning, natural language processing, computer vision, and robotics. Its applications have expanded to numerous scientific disciplines, including information science, mathematics, medicine, geoscience, physics, chemistry, and of course cultural heritage.

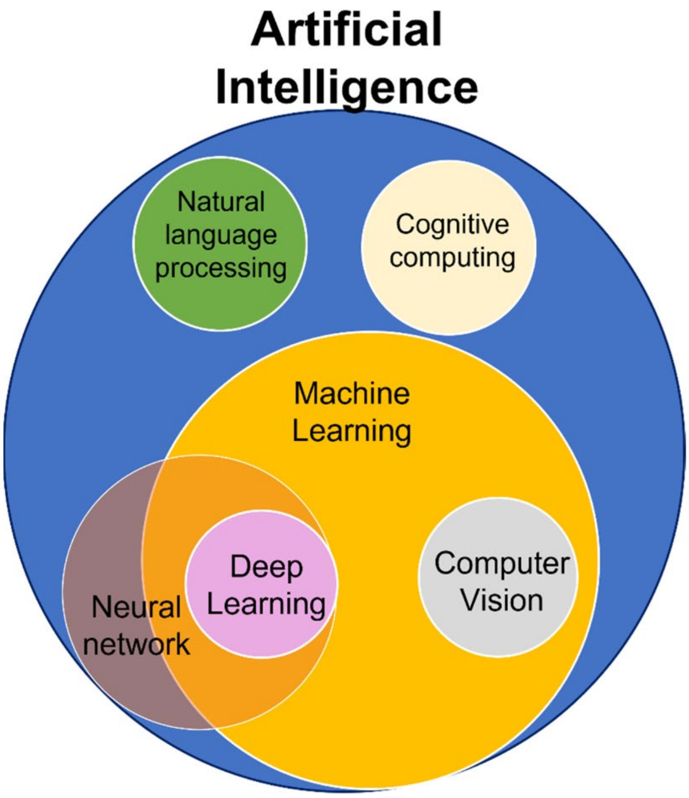

Figure 1 Key components of AI used in CH applications

Cultural heritage (CH) encompasses the tangible and intangible legacy of a society, including artifacts, monuments, traditions, and knowledge passed down through generations. As custodians of this rich tapestry of human experience, cultural institutions face the ongoing challenges of preservation, accessibility, and engagement in an increasingly digital world.

The intersection of AI and CH represents a fascinating frontier where cutting-edge technology meets the preservation and exploration of human history and creativity.

In the context, the following AI fields, as depicted in (Figure 1) play a significant role in the preservation, restoration, and analysis of historical artifacts, art, and other cultural materials:

- Machine Learning (ML): ML techniques are used to analyze patterns in digitized cultural assets (e.g., images of artworks, ancient manuscripts) and improve tasks like categorizing or identifying objects and styles in artworks, restoring degraded materials, or even predicting missing elements in a damaged artifact.
- Deep Learning (DL): A subset of ML, deep learning uses more complex neural networks to perform intricate tasks like inpainting (filling in missing parts of images), recoloring black-and-white photos, or enhancing the resolution of old photographs or films. These techniques can be particularly useful in the digital restoration of cultural artifacts, such as restoring faded paintings or reconstructing broken sculptures.
- Neural Networks: The foundation of deep learning, neural networks simulate the human brain to "learn" from visual or textual data related to cultural heritage. For example, neural networks can be trained to recognize historical patterns, artistic styles, or specific features of archaeological artifacts.
- Computer Vision (CV): CV focuses on enabling machines to interpret and understand visual data from the world. In Cultural Heritage, computer vision is crucial for digitizing and analyzing visual content, such as paintings, sculptures, and architecture. Applications include detecting cracks in paintings, generating 3D models of historical sites, and even identifying forgery in artworks.
- Natural Language Processing (NLP): NLP enables the processing of historical texts, manuscripts, and inscriptions in ancient languages. It is used to digitize and analyze large volumes of textual data in archives and libraries, translate ancient documents, or extract information from handwritten or printed materials.
- Cognitive Computing: In the cultural heritage domain, cognitive computing can simulate human thought processes to help interpret the meaning of complex or abstract historical data, aiding historians and archaeologists in understanding artifacts or documents that require contextual analysis.

The key CH areas where AI make significant impact are described in the following sections.

Conservation and Restoration

Cultural Heritage **Conservation** refers to all actions and strategies implemented to ensure the longevity of cultural heritage, while reinforcing the preservation of its inherent messages and values. Cultural heritage preservation encompasses both tangible elements, like historical artifacts and monuments, and intangible aspects, such as traditions, languages, and rituals [1].

Cultural heritage **Restoration** involves a variety of activities aimed at protecting and maintaining cultural assets. This goes beyond the physical repair of artifacts to include documentation, research, and preventive measures designed to extend their lifespan and significance. The primary objective is to preserve the authenticity and integrity of cultural heritage, ensuring that it continues to convey its historical and cultural meanings effectively. While conservation focuses on stabilizing and maintaining artifacts, restoration involves more direct interventions to return an object to a specific historical state.

Restoration and Enhancement

AI technologies are transforming the preservation of historical images through techniques such as denoising, inpainting, and super-resolution. These methods repair damaged or degraded photographs, paintings, and other visual artifacts, restoring them to their former clarity and detail. By removing noise, filling in missing or deteriorated parts, and enhancing resolution, AI-based image restoration ensures that these cultural treasures can be studied and appreciated by future generations. This digital restoration process is crucial for maintaining the integrity and authenticity of historical images that have been affected by time or environmental factors.

In [2] the authors propose a framework for a generative experience for creating 3D models of CH object, where a neural radiance fields (NeRF) model for 3D rendering has been integrated with the Stable Diffusion (SD) architecture for image inpainting and adapted to address the specific characteristics of archaeological objects.

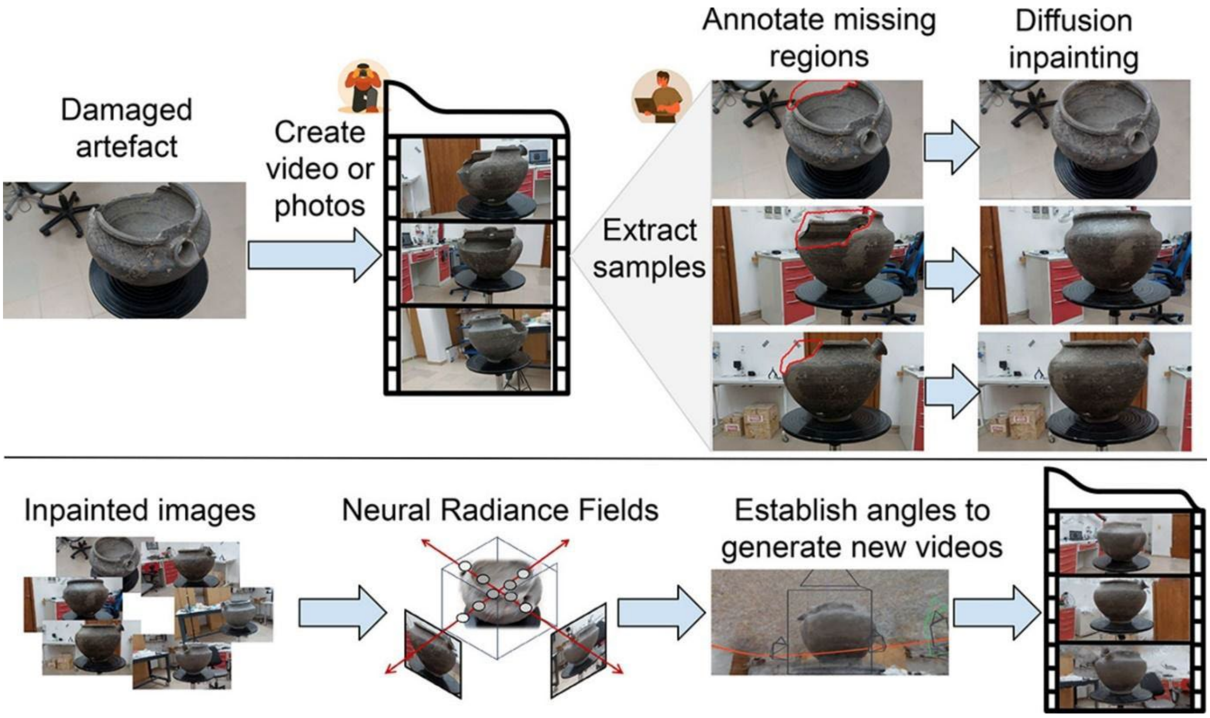

Figure 2 A neural radiance fields (NeRF) model for 3D rendering has been integrated with the Stable Diffusion (SD) architecture for image inpainting **[2]**

Gupta et al. [3] propose a method based on deep neural networks for the virtual restoration of digitized artworks. The approach introduces a hybrid model that combines automatic mask generation using Mask R-CNN with image inpainting through a U-Net architecture featuring partial convolutions and automatic mask updating. The proposed method is evaluated both qualitatively and quantitatively. For qualitative assessment, three art domain experts were consulted, while quantitative validation was conducted on a dataset of images with artificially created irregular holes, using mean square error (MSE) and structural similarity index (SSIM) metrics. The results (demonstrate the effectiveness of the approach for virtual restoration of digitized artworks.

Figure 3 Top row: damaged painting, Bottom row: restored painting [3]

In [4] the authors present the results of the AIRES-CH project, which aims to develop a web-based application for the digital restoration of pictorial artworks using Computer Vision technologies applied to physical imaging raw data. A set of 1D and 2D models for automatic recoloring have been developed, trained, and tested on a relatively small dataset of X-ray fluorescence (XRF) imaging data from various pictorial artworks, including medieval illuminated manuscripts, Flemish and modern multi-layered paintings, and Renaissance drawings. These models are integrated into the web application for online analysis of XRF raw data, hosted on the CHNet cloud. The models used are slight variations of well-known models from the literature, adapted to this specific task. Additionally, we tested a custom model designed based on insights from the physical imaging technique employed. The results of these models are highly promising, providing a solid foundation for future refinements.

AI-based Computer Vision can assist in restoring heavily degraded old films and pictures. Like in the work presented in [5], where the authors propose a learning-based framework, , recurrent transformer network (RTN) to restore and colorize films by eliminating scratches through the temporal coherence of neighboring frames (Figure 4). In the same context, [6] presents a system that employs a multi-frame approach using a Swin-UNet-based architecture. The results of this work are highly promising, and a web application has also been developed as part of the project.

Figure 4 Top row: original input, Bottom row: result of restoration **[5]**

3D Model Creation from 2D images

AI-based algorithms are instrumental in the creation of 3D reconstructions of cultural heritage objects, buildings, and sites. Techniques such as generative adversarial networks (GAN) and neural radiance fields (NeRF) allow for the modeling of objects even from incomplete or sparse data, generating detailed and accurate 3D representations. This process facilitates the virtual preservation of heritage sites, enabling researchers and the public to explore and study these cultural assets in a digital environment. These 3D models also support physical conservation efforts by providing detailed references for restoration work and creating digital archives that can be used to monitor changes over time.

In [6], volume is employed to transform the input image into a flat bas-relief. Common components of the input image include logos, stems, human faces, and figures that are projected from the background of the image. While these techniques can extract 3D information from 2D images, their primary applications are in the creation of logos, coats of arms, and numismatics. Moreover, they heavily depend on Shape from Shading (SFS) techniques [7], which begin with shaded images and use reduction methods for 3D reconstruction. An example of this method can be found in Figure 5.

Heritage Digitization

Audiovisual materials, such as films and recordings, are at risk of deterioration due to their physical nature. AI plays a pivotal role in digitizing and restoring these materials, converting them into digital formats that preserve their content while mitigating further decay. Advanced algorithms help in enhancing audio and visual quality, correcting imperfections, and bringing deteriorated audiovisual content back to life. This digitization process not only preserves the historical and cultural significance of these materials but also makes them more accessible for educational and research purposes, ensuring that valuable cultural narratives are not lost to time

AI is revolutionizing the digitization of ancient texts by utilizing technologies like natural language processing (NLP) and computer vision. High-resolution scanning combined with AI-enhanced image preprocessing improves the readability of faded manuscripts, while Optical Character Recognition (OCR) systems convert handwritten or printed characters into machine-readable text [8]. These systems also provide text segmentation, isolating the text from surrounding images or decorations for more accurate processing. Powered by AI and trained on vast datasets of digitized texts from various historical periods and languages, OCR systems can recognize and interpret different scripts, enabling precise translations. Additionally, AI plays a critical role in reconstructing missing or damaged sections of ancient texts, much like in artwork restoration. By analyzing similar texts from the same period, language, and style, AI learns linguistic patterns and stylistic nuances, allowing it to generate plausible reconstructions of missing content. This process not only enhances preservation but also facilitates research and ensures the long-term protection of cultural heritage, making these invaluable documents accessible to scholars and the public worldwide.

Figure 5 Masolino da Panicale's "The Healing of the Cripple and the Raising of Tabith **[6]**

Defect Detection

Machine learning algorithms are crucial in analyzing 3D models of cultural heritage sites to detect patterns, anomalies, or changes over time. This analysis aids in identifying signs of deterioration, structural weaknesses, or other potential threats to the integrity of these sites. By detecting changes early, conservationists can take proactive measures to preserve these valuable cultural assets. AI-based change detection supports ongoing conservation efforts, providing a data-driven approach to maintaining the condition of heritage sites and ensuring their longevity for future generations.

In [9], the authors propose a framework that utilizes 3D point clouds and 2D visual data for detecting structural damage on the surfaces of several cultural heritage (CH) structures. Their framework is based on a semantic segmentation approach for preprocessing the data and removing additional components that act as noise. Subsequently, they leverage a Faster-RCNN-based neural network, train their model using data from a temple in Ayutthaya, Thailand, and test it on images taken from Hampi, a UNESCO World Heritage site in India.

Research and Documentation

AI helps in organizing and interpreting cultural heritage data, enabling researchers to study and document artifacts more effectively. AI-powered tools can automate labor-intensive tasks like categorizing collections and analyzing historical data

Object Detection and Classification

Over the last years, CH scientists have adopted Machine Learning-based workflows for the automatic detection of archaeological objects in remote sensing data [9]. Early applications of Machine Learning (ML) primarily focused on object detection methods [10], [11], but recent studies have shifted toward more detailed approaches using semantic segmentation techniques [12]. These approaches include various implementations of VGG-19 CNN [13], U-Net [14], and Mask-RCNN [15] architectures, which require additional effort in preparing training sets due to the need for pixel-level labeling.

AI-driven computer vision technologies allow for the automatic recognition and classification of cultural objects. By examining visual characteristics and patterns, AI algorithms can identify and categorize items such as artifacts, sculptures, and architectural elements [16], aiding in the organization and cataloging of museum collections [17]. Examples include predicting color metadata for textile objects [18], as well as metadata related to technique, period, material, and location for European silk [19]. The authors in [20] use pretrained semantic segmentation networks for detecting archeological sites in the Mesopotamian floodplains environment. The modes were fined utilizing data from open sources like satellite images and already annotated sites. The authors of [21] adopt a similar method by leveraging CNN networks for simultaneously perform detection and segmentation on archeological sites by utilizing transfer knowledge techniques on pre-trained networks. The results compared to archeological reference data show an increase in detection accuracy and offered new insights into archaeological documentation and interpretation through morphometric analysis and contextual characterization using object segmentation. Following the same pattern, the work in [22] presents a method for extracting ancient city wall sites at the pixel level from LiDAR remote sensing data using deep learning. The method utilizes airborne laser scanning data, processed into Digital Elevation Models, combined with archaeological surveys. A U-Net semantic segmentation model is trained to predict wall sites, achieving high precision and accuracy. Post-processing with connected component analysis further optimizes the results, demonstrating the method's effectiveness in archaeological site detection. The work in [23], presents AutArch, an AI-driven workflow for detecting and recording objects in archaeological catalogues. It automates data extraction from large, unsorted resources like PDF files using deep learning models for object detection and classification.

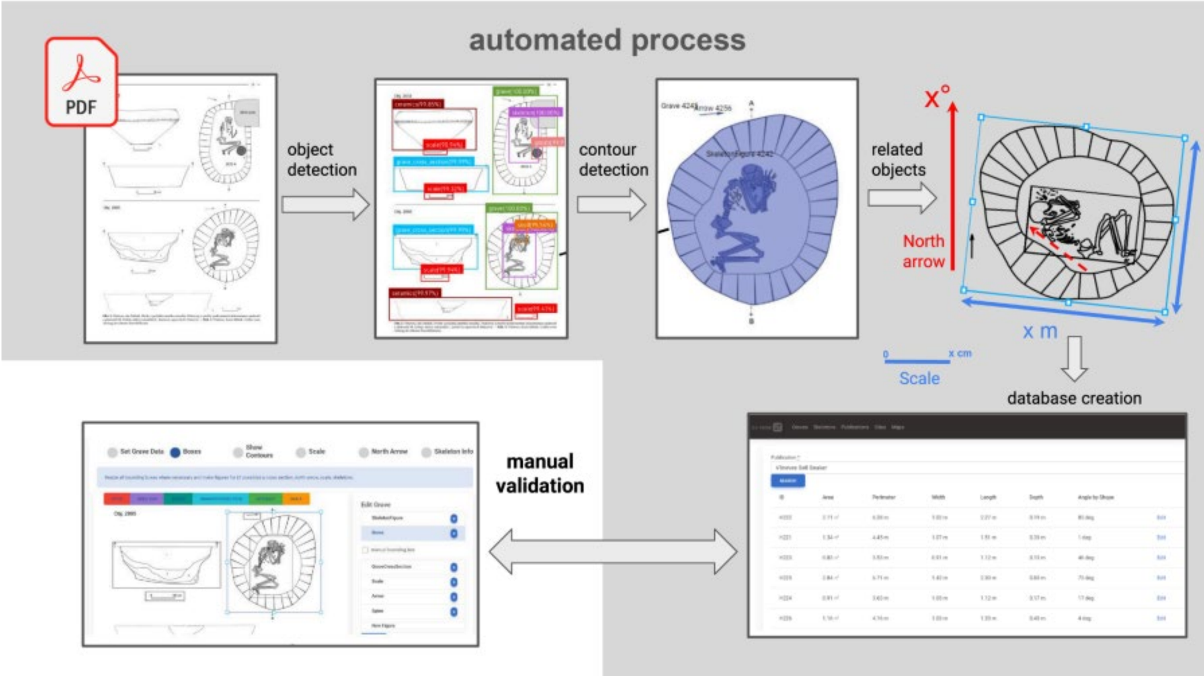

Figure 6 Overview of the workflow in AutArch **[23]**

The AI-assisted workflow (Figure 2) is consisted of six steps and supported by a Graphical User Interface. Key features include processing archaeological drawings and photographs to identify artifacts such as graves, ceramics, and stone tools, and extracting attributes like size and orientation. The method is evaluated using European archaeological datasets from the third millennium BC, enhancing the efficiency of archaeological cataloguing.

Content-based Image Retrieval

Digital or digitized cultural collections present the challenge of managing diverse types of images, including a mix of photographs, hand-made content, black-and-white and color images, as well as low-quality scans, blurry photos, and high-quality digital pictures. In this context, content-based image retrieval (CBIR) serves as a powerful tool for identifying connections between images, regardless of their original organization within collections. However, due to the diverse nature of these images—stemming from differences in acquisition sources, changes in viewpoint and lighting, and the evolution of content over time—heterogeneity is a defining characteristic of these collections. These factors pose challenges in developing efficient and robust content-based descriptors, ranging from pixel-level issues (such as alterations caused by digitization or aging of photographic chemicals) to semantic-level complexities. CNNs have demonstrated their effectiveness as powerful feature extractors. Unlike traditional hand-crafted methods, where descriptors were meticulously designed to optimize invariance and discriminability (such as SIFT, ORB, SURF), deep learning allows an optimization algorithm to automatically learn how to capture these features. In [24] the authors propose a new benchmark for evaluating deep features on heterogeneous data, and an analysis was conducted on how the most recent and efficient features respond to the range of variations encountered.

Accessibility and Inclusion

AI can make cultural heritage more accessible and inclusive by overcoming language barriers, providing digital access to rare artifacts, and enabling people with disabilities to engage with cultural heritage.

Transcription and translation: AI-powered speech-to-text transcription and translation services make audiovisual content more accessible and understandable to a wider audience.

- **Transcription of Historical Texts**: AI transcription services can convert ancient texts, inscriptions, and manuscripts into modern languages, facilitating easier access and analysis.
- **Translation Services**: These services can translate metadata or full-text content of heritage objects, making them accessible to non-native speakers. Platforms provide translation capabilities in over 50 languages, allowing users to reach a global audience with their content.
- **Handwritten Texts**: AI tools can transcribe handwritten texts, which are often difficult to read and analyze manually. This automation not only speeds up the process but also enhances the accuracy of the data captured from these documents.

Public Engagement

AI enhances public interaction with cultural heritage through immersive experiences, personalized engagement, and creative expressions, making heritage more engaging and understandable for a broader audience.

Recommender Systems for Personalized Experiences

AI technologies also enable personalized experiences in cultural heritage contexts:

- **Interactive Chatbot Systems**: Museums are increasingly employing dialogue systems and chatbots to guide visitors. These AI-driven tools offer interactive information, enhancing the educational experience by responding to visitor queries in real-time.
- **Customized Recommendations**: Recommender systems can suggest relevant exhibits or tailored tours based on visitor preferences. This personalization enhances user engagement and satisfaction by providing targeted experiences that resonate with individual interests.

Virtual Reality (VR) and Augmented Reality (AR)

Virtual Reality (VR) and Augmented Reality (AR) are transforming the way cultural heritage sites and museums are experienced, creating immersive environments that allow visitors to engage with history in innovative ways. VR enables users to explore ancient ruins or historical sites virtually, offering a lifelike experience that would otherwise be inaccessible. AR, on the other hand, enhances real-world museum exhibitions by overlaying digital content onto physical displays, providing deeper insights and interactive elements.

AI-generated virtual characters or objects can further enrich these experiences by offering contextual information, guiding visitors through historical events, or recreating moments from the past. For example, visitors could virtually interact with historical figures or objects, learning about the cultural significance or the events that shaped a particular period. These technologies allow for a more engaging and educational experience, making history come alive in a dynamic and interactive way.

Examples include virtual tours of ancient ruins where users can "walk" through historical landmarks, or AR-enhanced exhibits that bring artifacts to life, providing additional layers of storytelling and information. Visitors might also interact with AI-driven virtual characters, who can answer questions or narrate historical events, offering a personalized, immersive learning experience.

Challenges

- **Quality**: AI models face challenges from source degradation (e.g., fading, noise, damage), handling diverse formats, and the scarcity of historical data.
- **Quantity and Historical Uniqueness**: Cultural heritage datasets are often limited and incomplete, making it difficult to train AI models and validate their accuracy, unlike other fields where data is more abundant.
- **Time and Temporal Complexity**: Historical images are often captured at different points in time, complicating the reconstruction of accurate timelines, and metadata may be missing or unreliable.
- **Transparency and Interpretability**: AI models in heritage must be explainable and interpretable, as many existing systems still operate as opaque "black boxes" with unclear decision-making processes.
- **Ethical Considerations and Bias**: AI must address issues like privacy, cultural sensitivity, and bias to ensure equitable representation and interpretation in cultural heritage applications.
- **Data Availability and Access**: Access to high-quality datasets is hindered by legal restrictions, ownership, and poor tagging or indexing, limiting the potential for AI in heritage.
- **Interdisciplinary Collaboration**: Close cooperation between AI experts, historians, archaeologists, and cultural specialists is essential to ensure AI solutions are contextually relevant and effective for cultural heritage.
- **Customization and Flexibility**: Humanities scholars require adaptable AI tools that allow for model customization and refinement, enabling them to tailor AI techniques to their specific research questions and needs.
- **Education and Training**: There is an increasing need for interdisciplinary education and ongoing professional development in AI and digital heritage, spanning both traditional academic fields and vocational programs.

Sensing

The use of sensing technologies and sensor devices within Cultural Heritage sites is currently common practice among experts and researchers. Overall, sensing used in Cultural Heritage applications fall within three broad categories:

- **Remote Sensing,** with sensors that operate from a long distance, such as RGB cameras, multispectral cameras, and LiDAR sensors, and can be mounted on an airborne or spaceborne platform, such as drones or satellites, or they can be utilised from the ground, in cases where high data fidelity is required, such as when performing terrestrial laser scanning using LiDAR.

- **Close-Proximity Sensing or Proximal Sensing**, with sensors that operate on site from a close distance. These include microwave sensors, ground penetrating radars, thermal cameras and more.

- **Contact sensing**, which requires contact with a surface on the cultural asset, or close to it. These include strain gauges, temperature and humidity sensors, soil moisture sensors, and weather stations.

There is a fourth category of sensing utilised in cultural heritage applications, specifically used for visitor and crowd control, but not for acquiring data on the state of the cultural asset per se, which mainly utilizes Wearable and Mobile Sensors. These often include Bluetooth Low Energy (BLE) beacons, WiFi-compatible devices such as smartphones, visual Markers like QR codes and more.

In this context, recent research in the field has largely identified the key techniques and technologies to take advantage of the aforementioned sensing categories used for cultural heritage preservation and sustainability.

Photogrammetry, either terrestrial or airborne/spaceborne, creates a high-fidelity 3D reconstruction of cultural heritage sites while matching the details of a real surface to its 3D reconstructed counterpart, a capability which is lacking in other more powerful tools for 3D reconstruction such as point-cloud generating LiDAR devices. On the other hand, the advantage of LiDAR is the more accurate depiction of three-dimensional geometric details, which may be omitted by photogrammetric methods, always subject to the quality of data inputs in both cases. Therefore, laser-scanning techniques and photogrammetry complement each other, and most recent use cases resort to the utilization of both techniques, in order to provide the highest available fidelity. LiDAR often performs the heavy lifting of the 3D geometry depiction, while photogrammetry can relate the surface texture to that depiction.

In addition, three-dimensional reconstruction of cultural heritage sites, when coupled with geolocation, can prove to be a powerful tool for mapping all sensitive points in a single cohesive and comprehensive Digital representation of the asset. As an example, after the 3D framework is created, detecting moisture inside walls, can be precisely geolocated on the 3D model, facilitating its visualisation and to devise methods to mitigate its effect. Such a process closely resembles Digital Twin (DT) practices, which are now followed in a multitude of sectors, ranging from industry to smart cities. Overall, many facets of a DT can be applied to cultural heritage sites, bridging the physical and digital worlds.

In this context, recent research on the use of sensors for cultural heritage sustainability was reviewed, and summaries of these works are subsequently presented based on sensing category, helping to put into context the current discourse.

Remote Sensing

Regarding remote sensing, [25] broadly reviews the different remote sensing technologies available for cultural heritage applications. These include passive sensors such as:

· Photographic sensors (aerial or spaceborne), which help in revealing surface anomalies like crop, soil, and shadow marks that indicate buried structures.

· Multispectral and Hyperspectral Imaging sensors, which allow the detection of archaeological features like buried structures through variations in vegetation or soil.

· Thermal Sensors which allow the measurement of temperature variations and are also useful for the detection of subsurface structures

In addition, types of active sensors are used, such as:

· Synthetic Aperture Radar (SAR), which transmits radar signals and receives the reflected radiation. Useful for detecting buried features, as well as for detecting microrelief and structural stability.

· LiDAR, which is especially effective in overgrown vegetation areas.

With respect to managing cultural heritage site analysis, [26] describes three key methodologies: Multitemporal Land Cover Analysis, Urban Heat Island (UHI) Effect Analysis, and Persistent Scatterer Interferometry (PS-InSAR). Multitemporal Land Cover Analysis uses satellite RGB imagery to monitor land use changes over time, particularly focusing on urban expansion that may threaten cultural heritage sites. UHI Effect Analysis involves assessing temperature variations within urban areas using thermal infrared satellite data. This can identify areas with increased temperatures, which can lead to increased thermal stress on heritage structures, thus helping in damage prevention. Finally, PS-InSAR is used for structural monitoring by detecting minute ground movements over time. This method provides high-precision data on ground and building stability, which can be utilised for early detection of potential structural issues.

[27] utilizes Ground Penetrating Radar (GPR) and Synthetic Aperture Radar (SAR) from satellite, for heritage. The process involves using SAR to identify points of maximum surface displacement, which are then investigated more closely using GPR to detect subsurface anomalies. The goal is to provide a multi-layered view of the site, in order to identify potential threats of a structural nature as well as to improve the accuracy of boundary delineation and protective zone establishment. The methodology is supported by software modules that facilitate data integration and automate the boundary correction process.

Proximal Sensing

Regarding proximal sensing, summarizes current sensors used for cultural heritage sites. Terrestrial laser scanning, in contrast to aerial and space, is widely used for deformation monitoring and structural health analysis, via creating a high-fidelity 3D digital copy of the cultural asset. Similarly, terrestrial photogrammetry provides a higher fidelity result, when compared to its aerial and space counterpart. It is also a cost-effective method for generating 3D reconstructions, when compared to laser scanning. Close-range multispectral imaging is very useful when identification of specific materials, as well as the determination of the condition of certain surfaces, are needed. Close-proximity Infrared Thermography (IRT) detects infrared radiation emitted from surfaces, allowing for the identification of temperature differences that may indicate underlying issues such as moisture, cracks, or material deterioration. Ground-Penetrating Radar (GPR) is a geophysical method that utilizes radar pulses to detect subsurface features. It is used to locate anomalies such as hidden structures or voids within, or beneath, historical buildings. The last close-proximity sensing category described are sonic and ultrasonic techniques. These, based on the propagation of elastic waves through materials, allow the detection of internal flaws and changes in material density. They are often used in the structural assessment of historic buildings, or assessing the integrity of columns, or walls.

The other half of the paper is dedicated to data fusion from multiple sources, such as the plethora of the aforementioned sensors. It emphasizes the need for a multidisciplinary approach to attack cultural heritage related challenges from multiple angles and devise well informed solutions. [28] describes a methodology of proximal sensing, utilising terrestrial laser scanning, photogrammetry and microwave electromagnetic measurements, to create a geolocated 3D reconstruction of a heritage building, and provide an assessment of both surface and subsurface conditions. TLS provides an accurate 3D point cloud, while photogrammetry utilising structure from motion and multi-view stereo techniques, provides details on the colours of the surfaces as well as the reflection. Differences in surface RGB (colours) can reveal problematic areas, that have suffered damage, or corrosion. On the other hand, the Electromagnetic Conductivity (EC) Measurement performed with the electromagnetic sensors, can testify to internal problems such as moisture content, density variations, or the presence of voids or cracks.

[29] presents a non-destructive system for assessing in-wall moisture content in cultural heritage buildings using a combination of microwave spectroscopy, photogrammetry, and terrestrial laser scanning. Therefore, the sensors used were microwave sensors, 2D photos, and laser scanners (LiDAR). The methodology involves using microwave sensors to penetrate the building materials and detect moisture levels within walls, complemented by photogrammetry and TLS to precisely geolocate the sensors in the 3D model of the structure. In this way, the detected moisture points can be geo-located in the 3D reconstruction of the structure, providing a pinpointed record of the problematic point, in 3D coordinates.

Contact Sensing

[30] reviews the application of electrochemical and Surface-Enhanced Raman Scattering (SERS) sensors in the diagnostics and conservation of cultural heritage, mainly artworks, such as paintings on canvas, or murals. Electrochemical Sensors are particularly useful for analysing the chemical composition of artworks, in order to detect degradation, and then decide on suitable conservation actions based on such data. Applications of voltammetry and immunosensors are detailed, putting an emphasis on their ability to perform minimally invasive analyses on cultural heritage materials. In addition, SERS Sensors can detect and analyse pigments and binders in artworks with high sensitivity.

Moreover, SERS are especially useful in studying organic colorants and complex paint matrices. Limitations of the aforementioned sensors include the need for more robust, portable devices and the challenges in analysing complex multilayered structures in artworks. Despite these challenges, the potential for further developments in sensor technology, particularly in combining SERS with electrochemistry, offers promising prospects for the field of cultural heritage conservation.

[31] presents an IoT-based solution for the preservation of cultural heritage sites, utilizing a three-layer architecture. The Perception/Sensing Layer integrates the sensors, including temperature, humidity, gas, vibration, ultrasonic, and xylophage detectors, strategically deployed around the heritage site to monitor environmental and structural conditions. Most of these sensors are utilised for the immovable cultural asset (the church) but environmental sensors can also provide alerts for movable cultural assets (such as relics and manuscripts). The Network/Transmission Layer transmits the collected sensor data to a central system via low-power communication technologies like ZigBee, Bluetooth, or Wi-Fi, with options for local processing through fog computing or cloud-based analysis. Finally, the Application Layer handles the storage, processing and analysis of the gathered data, thus enabling intelligent decision-making and most importantly, constant remote monitoring.

[32] explores how IoT, combined with artificial intelligence (AI), particularly deep learning models, can predict future degradation processes by analysing time-series data from IoT sensors. A bridge in Korea was used as a case study to demonstrate the practical application of IoT and AI in cultural heritage conservation. The sensors deployed on the bridge monitor structural integrity parameters such as vibration, distortion, resistance, slope and load on the structure. The Deep Learning models which utilise this gathered time series data are based on Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU).

[33] presents a deployment of a network of sensors, including temperature and humidity sensors, soil moisture sensors, thermal cameras, and weather stations, the system continuously monitors environmental conditions that could impact the structures. Data collected from these sensors is analyzed using a Generative Adversarial Network (GAN) to predict rising dampness in masonry. The sensor collected data is used to train the GAN so it can generate images resembling thermal camera scans of the structures, focusing on areas of rising dampness. The generator part of network learns to produce these images based on the input data, while the discriminator part learns to differentiate between actual thermal images and the generated ones. This approach was tested at the Archaeological Park of Pompeii.

[34] presents an IoT-based framework designed for the preservation of cultural heritage buildings through monitoring and predictive maintenance. This system integrates various sensors to collect real-time data on environmental and structural conditions, which is then processed using machine learning techniques to detect and classify potential damages. The framework consists of several layers, including a Sensor Layer for data collection, a Knowledge-Base Layer for data management, an Inference Engine Layer for predictive analytics, and an Application Layer for user interaction and decision-making support. The

sensors utilised include temperature and humidity monitors, air quality sensors, thermal cameras, vibration sensors, soil sensors (for moisture) and light sensors.

Wearable Sensors

[35] introduces the "Visitor-Sensing" framework, which integrates GPS tracking, surveys, and wearable devices such as portable electroencephalography (EEG) helmets to gather and analyse data on visitor behaviours within cultural heritage sites. This approach aims to enhance visitors' experience by providing insights into their engagement. By drawing on concepts from open innovation, crowdsourcing, and citizen science, and combining them with the data gathered from the aforementioned sensors, visitors are treated as active participants in cultural heritage management.

[35] provides an extensive overview of Digital Twins (DTs) and Virtual Museums (ViMs) in the cultural heritage sector. Concerning the use of sensors, the paper highlights their role in the development and operation of Digital Twin (DT) museums, emphasizing their use in areas such as museum management and visitor experience. Environmental sensors can be used to maintain optimal conditions for artifact preservation, with real-time data feeding into the DT to simulate potential impacts and inform preservation strategies. Terrestrial laser scanners and photogrammetry tools, create detailed 3D models of museum spaces and artifacts, forming the foundation of the digital twin. Wearable sensors such as motion and proximity sensors track visitor movements and interactions, enabling the DT to deliver personalized and dynamic experiences by adapting content based on visitor behaviour. For security and asset management, RFID tags and surveillance sensors can be deployed for real-time tracking and monitoring of museum assets.

[36] utilises Bluetooth Low Energy (BLE) signal receivers to determine the proximity of visitors from cultural heritage art pieces inside a museum. The paper also performs a literature review on wearable sensors that can be used for the same application. Bluetooth Low Energy (BLE) beacons are small, wireless devices that broadcast signals to BLE-enabled devices like smartphones, allowing proximity detection based on the Received Signal Strength (RSS) of the beacon's signal. Alternatively, existing WiFi access points and techniques like lateration and fingerprinting can be used to estimate user location, avoiding additional infrastructure but sometimes lacking precision due to signal interference and variability. Another technique is using ultrasonic wavelengths by tracking mobile devices indoors using audio signals generated by standard speakers, requiring dedicated infrastructure for signal emission but no special hardware on the user's device. Additionally, Infrared (IR) uses beacons that emit modulated IR light signals with unique identifiers, which is cost-effective but requires direct line of sight and is limited by the lack of IR transceivers in many modern devices. Visual detection techniques are another alternative. By employing camera-based systems to detect visual markers like QR codes or image patterns, visual detection provides intuitive user experience but requires significant computational resources and is prone to errors from occlusion and lighting variations. A different solution is also provided by Ultra-Wideband (UWB), which measures the time-of-flight of radio signals to provide high precision indoor localization with centimeter-level accuracy but requires specific hardware and infrastructure. Finally, Near Field Communication (NFC) enables short-range

communication between devices when they are in close proximity, highly available in consumer devices but limited to very close interactions.

Challenges and Limitations

The analysis of aforementioned literature produced a number of challenges going forward. [29] provides deep insight into the challenges faced by remote sensing for cultural heritage purposes:

Passive multi- and hyperspectral remote sensing can be confronted with challenges particular to the nature of image sampling from a long distance. In broadband multispectral imagery, subtle spectral details can be lost due to averaging. This can limit the ability to accurately detect and differentiate archaeological features. Moreover, the visibility of crop and soil marks, commonly used in archaeological prospecting, depends on several factors including crop type, soil conditions, and phenological cycles, making consistent detection challenging. Generic detection of archaeological features through multi- and hyperspectral images is also limited since they do not exhibit specific or special spectral signatures which can be standardized.

As for LiDAR remote sensing for cultural heritage purposes, [25] identifies more shortcomings. Namely, the lack of multispectral LiDAR systems limits the arsenal of tools at our disposal, since most existing LiDAR systems operate at single wavelength. It also highlights semantic segmentation as an important future challenge which serves as a novel classification method to 3D LiDAR point clouds and is mostly used in urban or indoor spaces. Semantic segmentation is the process of determining automatically the purpose of certain rooms or spaces in a 3D environment, that was created through a point-cloud, or even photogrammetry. By creating a 3d plan of a CH structure, for example a palace, semantic segmentation allows the identification of its spaces, such as the stables, the baths, the throne room, etc. The field archaeological environment is generally complex, and semantic segmentation is difficult to be applied at present. However, with the development of artificial intelligence (AI) and big data, it is possible migrate it to archaeological scenes in the future.

SAR challenges identified in [25] concern its lower resolution data when compared to very high-resolution optical imagery at bands with greater penetration capabilities (i.e., L- and P-band), for detecting semi-buried remains. Specific features can also pose challenges to SAR in their identification due to its lower resolution, while SAR imagery can also suffer from speckling effects. Moreover, moisture content can heavily limit the penetration capability of SAR, curtaining its use in certain environments like arid areas. [26] mentions a limitation faced by the PS-InSAR technique which utilises SAR imagery. While it can signal the potential susceptible areas of CH structures, ground proofing needs to be performed to validate or deny its indications, especially for an area as sensitive as cultural heritage.

[26] also identifies challenges faced by historical satellite imagery. Satellite images, especially historical ones (meaning pictures taken many years ago), have a spatial resolution that is not fine enough to detect small-sized archaeological features within the cultural heritage site. This limitation affects the ability to monitor detailed changes and manage small-scale archaeological sites effectively. Since historical images can be

employed to detect new illegal constructions inside the archaeological site, the satellite resolution poses a significant challenge when comparison of current images with historical ones is required.

As for challenges concerning proximal sensing, many are mentioned in the literature. Regarding terrestrial laser scanning, which is widely used in cultural heritage sensing. [37] mentions the need to be pedantic, when employing it, because TLS sensors are line-of-sight and, therefore, multiple scans are required to scan an entire structure's surface. The variance of surface reflectivity encountered in CH, complicates TSL application. The main drawback is the problem of measuring the reflective objects, which can affect the quality of the point cloud or completeness of the measured object. The laser beam is fully absorbed by elements of too-low reflectivity; this results in data gaps within the point cloud. In the case of high-reflectivity surfaces, the reflected laser beam does not reach the detector and therefore the locations of points are incorrectly determined [28]. Photogrammetry, which often is the alternative or complementary technique to terrestrial laser scanning, encounters illumination and texture-based challenges. Occlusions, blank or poorly textured areas and repetitive structures hinder applications of photogrammetry [28]. Finally, it only provides surface level analysis, the structural health inside the object needs different sensors, and more labour. In [29] TSL, photogrammetry and microwave spectroscopy are combined. The paper notes that the microwave moisture sensing system used in the study "did not fully align with the pin-type moisture meter data," suggesting a limitation in ensuring consistency and reliability between different measurement techniques. A similar conclusion is drawn by [37] when discussing the combination of ground penetrating radar with photogrammetry and tsl. It presents exiting potential, but it becomes more complicated because of its multi-sensor approach. Moreover, ground penetrating radar, unlike thermography is more challenging to interpret and has lower spatial resolution than TLS and close-range photogrammetry. For the last proximal sensing technique discussed in [37], namely the Elastic Wave Technique, the paper notes that its application is based on the principle that wave propagation velocity is associated with measurable parameters of the material through which it travels. The presence of damage (voids, cracks, defects) changes the material's physical properties, affecting propagation. There is a great number of parameters influencing the correct calculation of wave propagation velocity. Roughness and defects of the historical surface under examination, and subsurface small cavities affect the results.

The literature provides further insight upon the limitations and challenges of contact sensors, especially when they are interconnected in a network, following the IoT example, thus enabling all its amenities for a CH context. To start with CH applications can prove to be too difficult for proximal sensors to handle, therefore the use of contact sensors that cause micro-damages, in the form of sampling, might be necessary [30]. When IoT communication is to be established, range and battery longevity prove to be two of the most important hindrances [12]. Devices placed inside structures that utilise radio waves for communication, such as ZigBee, have a severe reduction of their range, because of interference from the structure itself [32]. From approximately 100m in open space, stable data transmission is only realistically attainable in a range of 20–30m in a structure. Moreover, non-intrusiveness of both proximal and physical sensors is another important liability [33]. [36] presents the drawbacks of various IoT communication technologies that can be used in the CH context. Bluetooth Low Energy (BLE) necessitates the physical deployment of tags, and its received signal strength (RSS) can be affected by crowd density and signal reflections. WiFi offers low proximity detection accuracy, making it less reliable for precise localization. Ultra-Wideband (UWB), while offering high accuracy, requires extensive infrastructure and is limited by the current diffusion of compatible end-user devices. Near Field Communication (NFC) has restricted interaction capabilities in crowded environments. Visual detection systems demand extensive training phases and are vulnerable to issues like partial visual occlusion. Barcodes and QR codes could interfere with the aesthetic of artworks and photographing them might be restricted in places like museums. Ultrasonic technology, while able to provide some level of proximity sensing, requires significant infrastructure and has low accuracy. Lastly, infrared technology relies on highly directional beams and line-of-sight, which can be problematic as many modern devices lack IR transceivers.

Finally, some general challenges associated with the use of sensors will be presented from the scope of CH application. Sensors can generate huge quantities of data, making it challenging to handle, store and process the generated data [38]. Currently, more methods need to be developed in order to acquire universal datasets for CH applications [33], due to the scarcity of related datasets required to train large models.

Mapping of existing Extended Reality (XR) technological tools for enhancing cultural heritage sites visitor experience, sustainability, and resilience

This section delves into the use of technological tools that enhance visitor experiences at cultural heritage sites, while promoting sustainability and resilience. It specifically examines applications within the Extended Reality (XR) spectrum, showcasing how these technologies can transform interactions with heritage sites. The section provides detailed use cases involving both immersive and non-immersive formats of Virtual Reality (VR) and Augmented Reality (AR), highlighting their integration into real-world cultural heritage experiences. By employing these XR tools, cultural heritage sites can offer more engaging, educational, and interactive experiences for visitors, while also ensuring the long-term preservation and relevance of cultural assets. Finally, this section discusses trends in technological solutions, narrative design, and evaluation methodologies of such applications, providing a clear overview of the field.

Immersive AR

Martí-Testón et al. [39] (2021) designed and developed an immersive AR application for enhancing visitor experience at the Almoina Museum. The primary objective of this study was to determine what type of storytelling could meet the requirements of Museology 4.0, which call for an application to be immersive, experiential, naturalized, narrative, interactive, intelligent, gamified, transmedia, and social.

The goals were to design a general methodology for producing a more emotive, intuitive, and natural way to explore heritage, to develop a methodology for presenting content through AR HMDs, and to integrate virtual and physical information about objects in a user-friendly environment. The project also aimed to document all the steps taken to develop a functional prototype for the Almoina archaeological museum based on the proposed methodology. Additionally, the usability and effectiveness of the developed prototype were evaluated based on feedback from the museum's visitors. After several meetings with the museum's director, the decision was made to recreate the virtual city during the republican period and the first settlement of the city in the 2nd century BC. The design methodology of the application included:

- Analysis: Analyze the content to be represented and determine how it will be presented.

- Design: Create a narrative script that meets Museology 4.0 requirements with appropriate interactivity. Design the environmental sound, architectural elements, and objects to be recreated in 3D and 2D, as well as human figures.

- Development: Develop a technical script for the storytelling. Create 3D assets, images, and videos. Select and prepare an actress to act as a guide. Record the scripts using a chroma key set. Post-produce the videos for integration into the program. Choose music and sound effects.

- Implementation: Coordinate and guide the programming of the application with the developer. Perform initial integration and functionality tests. Draw conclusions and analyze the results, providing participants with an immersive and interactive experience.

The storytelling approach used was non-linear: users could roam the museum, focus on certain areas, and interact with specific coins to receive information at will, naturally engaging with the content. The interaction was interactive, utilizing user gaze and position to initiate experiences and provide information about museum areas. The guide was introduced using banners, followed by coins that triggered short stories when gazed upon. The equipment used was Microsoft HoloLens.

The experimental design involved invited participants, and feedback was collected using post-experience questionnaires, the SUS Scale, and the Presence Questionnaire. The study included 10 participants who engaged with the system as single users. The results showed that the attractiveness of the AR application was based on media understanding and its ability to provide context alongside the museum exhibits. Users found the interaction with the virtual parts of the AR experience intuitive, although the HoloLens' narrow field of view reduced the quality of the experience, and users reported feeling fatigued from wearing the headset. This study demonstrated the potential of immersive technologies to enhance cultural heritage experiences, highlighting how interactive tools can create educational and engaging environments in museums [39].

Figure 7: AR application at the Almoina Museum

Hammady et al. [40] (2021) evaluated the role of AR as a Holographic Virtual Guide at the Egyptian Museum in Cairo. The primary objective of this study was to introduce a theoretical framework that assesses the potential of an AR guidance system in terms of usefulness, ease of use, enjoyment, interactivity, multimedia, user interface, the role of the guide, and the intention to use.

The study involved tutorials on using the HoloLens, interactive points, and preloaded content. Two types of museum visitors participated in this experiment. The first group consisted of participants who accepted the invitation through a promotional video about the MuseumEye system, which was published on social media. The second group volunteered to participate after seeing other visitors experiencing new ways of touring the museum. This provided participants with an immersive and interactive experience. The storytelling approach used was non-linear, where a virtual guide walked alongside the visitors, providing information about specific artifacts. The interaction was interactive, allowing users to manipulate the artifacts and use a UI to navigate through the application. The equipment used in the study was the Microsoft HoloLens.

The experimental design involved volunteers recruited via a social media video as well as regular museum visitors. Feedback was collected using open and closed-ended questionnaires. A total of 171 participants engaged with the system as single users.

The study revealed the potential future use of AR in museums and demonstrated its capacity to ensure sustainability and engagement beyond the traditional visitor experience, which could enhance the economic state of museums and cultural heritage sectors. This study also proved that designing the guide system according to the main roles of guides, as stated in the most cited museum studies, can stimulate visitors' intention to use the system in the future. This demonstrates the potential of immersive technologies to transform cultural heritage experience [40].

Figure 8: MuseumEye system

Hammady et al. [41] (2020) also investigated visitors' technology acceptance of AR in museums by designing and integrating a relevant application at The Manchester Museum. The primary objective of this study was to introduce the Ambient Information Visualization Concept (AIVC) as a new form of storytelling that enhances communication and interactivity between museum visitors and exhibits by optimizing the spatial environment around the user. The study also investigates how AIVC influences user engagement in the museum. Using Microsoft HoloLens, the AIVC was deployed in a historical storytelling scene, "The Battle", in the Egyptian department at The Manchester Museum. The research measured user acceptance of the AR prototype through the Technology Acceptance Model, evaluating personal innovativeness, enjoyment, usefulness, ease of use, and willingness for future use.

The study design consisted of four layers: controls, a virtual narrator, virtual supplementary characters, and a battle scene for users to observe. The ambient information visualisation system created an interactive environment where visitors were at the center of a multilevel globe, surrounded by physical and virtual objects to guide them through the museum. The non-linear storytelling allowed users to focus on specific parts of the application or select different scenes to explore. Interaction was interactive: users manipulated artifacts, using gaze to focus and hand gestures to trigger actions. The equipment used was the Microsoft HoloLens. Social media invitations brought museum visitors to participate daily, and feedback was collected via post-experience questionnaires. A total of 47 participants engaged with the system, either as single users or in multi-user mode, where visuals and interactions could be shared in real time.

The results showed that personal innovativeness influenced enjoyment, ease of use, and usefulness. Perceived enjoyment, in turn, influenced ease of use. Participants expressed a willingness to adopt the system in the future, indicating the potential for MR and AIVC in museums. This study demonstrated how MR, combined with AIVC, can enhance and enrich the museum experience, offering a glimpse into the future of cultural heritage spaces.

Figure 9: Historical storytelling scene, "The Battle".

Bekele et al. [42] (2021) examined the influence of collaborative and multi-modal AR for cultural learning in virtual heritage at the Western Australia Shipwreck Museum. The primary objective of this study was to validate whether collaboration, engaging experiences, and contextual relationships enhance cultural learning in a collaborative and multi-modal AR heritage environment.

The study introduced controls and the story of the Xantho, along with a mixed reality map projected on the floor for users to walk on. The design methodology incorporated collaborative interaction, multimodal interaction, social interaction, and contextual relationships, all aimed at enhancing cultural learning. This provided participants with an immersive and interactive experience. The non-linear storytelling allowed users to interact with different parts of the AR map. The interaction was interactive: users could manipulate virtual components through speech, gaze, gestures, and movement, with the ability to change interaction modes at will. The equipment used was the Microsoft HoloLens. The experimental design involved a guided tour with free exploration points, allowing users to experience different modes of interaction. Feedback was collected using post-experience questionnaires and interviews. A total of 11 participants —experts, archaeologists, curators, and museum researchers—engaged with the system, either as single or multi-users.

The results demonstrated that multimodal interaction and user collaboration enhanced the quality of the experience (QoE). Collaborative interaction also strengthened the contextual relationship between the user and the museum exhibits. Additionally, the learning experience was influenced by the quality of the content, such as the fidelity of the 3D models. Usability improvements, including tutorials and feedback on user progress, were recommended to support the AR application.

This study highlights the potential of immersive technologies to transform cultural heritage experiences, showing how collaborative and multimodal MR environments can create engaging and educational experiences in cultural heritage settings.

Figure 10: Milti-user AR Application

O'dwyer et al. [43] (2021) used volumetric video in an AR Application designed to provide visitors with an engaging experience at the Library of Trinity College Dublin. The primary objectives of this study were to test three hypotheses: (H1) the use of volumetric video (VV) in cultural heritage (CH)-oriented AR applications raises specific areas of interest for information communication; (H2) humorous and playful anecdotes may be effective vehicles for curatorial information disclosure; and (H3) the combination of H1 and H2 presents an appealing format for AR museum guides, deserving further development.

The study involved viewing a bust and a virtual human presenting information about the space of the library. The design methodology simulated Jonathan Swift imparting a whimsical anecdote linked to the Long Room, providing participants with an immersive but non-interactive experience. The storytelling approach used was linear, and the equipment employed was the Microsoft HoloLens.

The experimental design featured a volumetric video (VV) model presenting information, and feedback was collected through post-experience questionnaires. Seventeen participants, including librarians, administrators, researchers, humanities staff, and graduate students of arts-related subjects, engaged with the system as single users.

The results showed that humorous content enhanced the experience, while the ease of use of AR technology improved the QoE. Additionally, there was no significant difference in user experience between the HMD and a tablet. The study recommended further investigation into the combined effects of volumetric video and humorous anecdotes in cultural heritage applications, given their potential to create unique and engaging experiences.

This case study demonstrates the potential of immersive technologies to transform cultural heritage experiences, highlighting how tools like volumetric video in AR can provide educational and engaging narratives in cultural heritage environments.

Figure 11: Jonathan Swift simulation

Dima et al. [44] (2021) investigated the integration of Affectual Dramaturgy with an AR application for immersive heritage performance at Sutton House. The study explored how AR can be used in heritage performance, although specific objectives were not listed. The study involved viewers walking around the Great Chamber, guided by three voices representing key historical figures who lived in the house across four centuries. Professional voice actors performed monologues as if speaking directly to the viewer. As participants listened, they saw and heard superimposed content, which sometimes aligned with the narration and other times did not. At certain points, viewers had opportunities to interact, though this was not explicitly communicated.

The design methodology was based on curatorial requirements, with much of the content drawn from the house's archives. This provided participants with an immersive and interactive experience. The non-linear storytelling allowed users to engage naturally with the content. Interaction was gesture-based, and the equipment used was the Microsoft HoloLens. The experimental design involved volunteer visitors who used the application, and feedback was gathered through observations and freely asked questions. The number of participants was not specified. The study highlighted that proper guidance is crucial during AR applications. Participants felt that scripted tutorials should be provided to familiarize users with the equipment and experience.

The results indicated that integrating dramaturgy into AR experiences should involve time-space storytelling, connecting both time and space for maximum impact. Additionally, live performances can be integrated with interactive content to enhance the QoE during visits to cultural heritage sites. This study demonstrated the potential of immersive technologies to transform cultural heritage experiences. It highlighted how interactive and immersive tools, combined with performance elements, can create educational and engaging experiences in cultural heritage environments.

Figure 12: AR dramaturgy at Sutton House.

Aoki et al. [45] (2023) conducted a study at the Mizuki Shigeru Museum evaluating an AR guide application. This study assessed the usefulness of the AR experience and its impact on visitors' willingness to pay more for their visit. The study involved the digital placement of audio guides, 2D and 3D Yokais, gates, and text explanations of Yokais throughout the museum.

The design methodology involved discussions with curators and the strategic placement of digital content on physical exhibits, providing participants with an immersive, though non-interactive, experience. The storytelling approach was non-linear, allowing users to explore content naturally at their own pace. The equipment used for the experience was the Microsoft HoloLens. The experimental design involved volunteer visitors using the application, with feedback collected through freely asked questions. A total of 93 participants engaged with the system as single users.

The results showed that visitors felt the AR application significantly enhanced their museum experience, with many stating they would be willing to pay double to visit the museum with enhanced AR experience. This feedback highlights the potential for mixed reality to enrich cultural heritage tours and improve visitor satisfaction. This study demonstrates the transformative potential of immersive technologies in cultural heritage settings. It showcases how AR can be integrated into museum experiences to create engaging, educational, and interactive environments that add value to the visitor experience.

Figure 13: AR experience a Mizuki Shigeru Museum

Liu, et al. [46] evaluated interaction challenges of immersive AR applications for first-time users at museums and exhibitions'. The study was conducted at the Natural History Museum and its goal was to test the usability of immersive AR applications by first-time users. The study guided visitors to specific locations within the museum, allowing them to experience holographic exhibits.

The design methodology involved studying visitor routes and iteratively designing AR content accordingly. This provided participants with an immersive and interactive experience. The non-linear storytelling allowed users to engage naturally with the content. Interaction was gesture-based, and the equipment used was Microsoft HoloLens.

The experimental design involved recruiting participants, primarily university students, with feedback collected through post-test interviews and questionnaires. A total of 10 participants engaged with the system as single users. The results highlighted the importance of pre-planned paths to guide visitors, particularly due to the limited space in the museum. The study noted that environmental factors, such as high-traffic times, impacted on the testing process, requiring additional support for visitors. Since all participants were first-time users, it was essential to accompany them throughout the test to ensure their safety and provide guidance on the unfamiliar exhibition layout and HMD interactions.

Key challenges included novel interaction patterns, inappropriate user interface parameters, and insufficient feedback, which posed obstacles to the user experience. The study underscores the potential of immersive technologies to transform cultural heritage experiences, illustrating how AR can offer engaging and interactive tools in museum settings. It highlights the need to address interaction challenges, especially for first-time users, to optimize the visitor experience.

Figure 14: Visitor following a virtual butterfly guide at the National History Museum.

Immersive VR

Bertoméu et al. [47] (2022) explored immersive VR for heritage education in museums. This study involved an immersive VR application used to compare user experiences and knowledge acquisition between groups of students using mediated technologies versus traditional methods at the Santa Pola Sea Museum.

The study involved both guided tours and VR/AR applications that focused on a Roman House and the production of salted fish and fish sauces. The design methodology included documenting content and developing the VR application based on research material about the site. The experience was non-linear, allowing users to freely move around virtual space. Interaction was teleport-based, where users could explore the virtual environment and observe the fish production process. The equipment used was an HTC Vive HMD.

The experimental design involved two groups: the first group visited the site with their teacher, while the second group experienced the site with an AR guide and a VR reconstruction. Feedback was collected through questionnaires, focus groups, and methodological triangulation, gathering data at different stages of the experience. Thirty secondary school students participated, split into two focus groups, engaging in a co-visit setting.

The results indicated that VR provides rich educational experiences that benefit both students and teachers. However, the content needs to be properly contextualized to prevent a focus on the technology itself, which could hinder knowledge acquisition. Additionally, the introduction to the technologies should be done prior to using VR applications to ensure a smooth and effective learning experience. This case study demonstrates the potential of immersive technologies to enhance cultural heritage education. It highlights how interactive VR/AR tools can create engaging and educational experiences, providing valuable insights into the effective use of virtual archaeology in museum settings.

Figure 15: Virtual Roman House Reconstruction.

Pedersen et al. [48] (2024) created an immersive VR application allowing visitors to interact with a Glass Harmonica instrument at the Danish Music Museum, to familiarize visitors with the historical background and interaction of the glass harmonica.

The study involved a VR application where users could either freely interact with the virtual instrument or follow a predefined narration providing information through multimedia sources. The design methodology followed four stages: initial consultations with museum staff, ideation and prototyping, informal testing at Aalborg University, and final implementation at the museum. The installation was evaluated through observations and interviews with museum guests, with feedback documented by museum personnel.

The storytelling approach combined linear narration through audio clips, talking paintings, and animated figures (such as ghosts, since the instrument was historically considered haunted), with a non-linear option allowing users to deactivate the narration and explore the instrument interactively. The interaction was gesture-based, with users manipulating the virtual glass harmonica and other elements through hand tracking. The equipment used included Oculus Quest 2, Unity, Blender, and ghostly hand representations.

The experimental design involved volunteers recruited during museum visits, with feedback collected through open-ended interviews and observations. A total of 22 participants engaged with the system as single users. The results revealed that staff familiarity with technology is crucial for successful implementation. Users enjoyed standing and exploring the virtual space, though bystanders sometimes affected the hand-tracking functionality. Additionally, dedicating physical space to such an experience improved engagement, and asymmetrical interaction using large displays attracted bystanders and added to the experience. Users appreciated the storytelling design, which was seen as an essential aspect of the application. It was also suggested that physical artifacts be connected to virtual experience, and that haptic feedback could enhance user perception. However, the "wow" effect of VR was short-lived for some participants. This case study demonstrates the potential of immersive technologies to transform cultural heritage experiences, highlighting how interactive and immersive tools can create engaging and educational experiences in museum settings.

Figure 16: Virtual Glass Harmonica.

Varelas et al. [49] (2023) explored how VR enhances cultural heritage through immersive game experiences at the Noesis Science Center & Technology Museum.

The study involved three VR game scenarios:

- The Siege of Rhodes – users could act as defenders or attackers, using the Korax and catapult.
- The Antikythera Mechanism – users interacted with the mechanism, explored the shipwreck discovery, and learned about the role of astronomy.
- The First Settlement of Europe – users experienced the settlement at Akrotiri Thira and observed changes due to natural phenomena, such as a volcanic eruption.

The design methodology included documenting historical information and designing virtual artifacts and actions based on this data. The storytelling approach was linear, with each game following a predefined scenario that evolved based on user actions. Interaction was interactive: users could pick up items, navigate through the VR space, and perform actions to achieve the goals of each game scenario. The equipment used included a motion simulator and the HTC Vive.

The experimental design and feedback collection methods were not specified. Participants engaged with the system as single users. The results demonstrated that VR can effectively reconstruct damaged or lost historical artifacts, structures, and environments. VR also facilitates the communication of historical knowledge through sensory methods, making it accessible to both specialized and general audiences without relying on linguistic codes. Additionally, VR games can contribute to the sustainability of cultural heritage by engaging users in immersive, educational experiences.

Figure 17: The Siege of Rhodes Game.

Clini et al. [50] (2023) created a temporary exhibition, at the new premises of Sale Betto Tesei, using immersive VR technologies and explored digital solutions that support both onsite and online museum experiences. The study provided visitors with an immersive digital storytelling experience focused on The School of Athens. Using a VR headset, the Oculus Quest 2, the visual and auditory elements combined to immerse users in a virtual reconstruction of the painting, with characters guiding them through the exploration.

The design methodology involved a 3D reconstruction of the School of Athens, not as an exact representation but as an interpretation aiming at believability and completeness. The addition of philosophers and narration based on historical data enhanced the experience. The storytelling was divided into four parts: (1) an introduction where users observed The School of Athens alongside other Raphael frescoes, (2) users entered the painted space and met actors portraying Raphael and Angelo Colocci, who explained the allegorical meanings, (3) the philosophers gradually appeared in the grand temple, and (4) a transition returned users to the physical space of the Stanza della Segnatura.

The storytelling approach was linear, where users viewed the 360° movie, while interaction remained non-interactive. The experimental design involved visitors interacting with the application while researchers observed and gathered feedback through think-aloud and observation. Although the number of participants was not specified, they engaged with the system as single users.

The results showed that users preferred VR devices over large displays, though low lighting affected system functionality. Users expressed a desire for greater interaction and exploration. The importance of storytelling was emphasized, with some users requiring staff assistance to initiate the experience.

Figure 18: The School of Athens.

Puig et al. [51] (2020) designed, developed, and evaluated an informal blended learning experience and to use data analytics to study user profiling in VR heritage projects at the Museu d'Arqueologia de Catalunya. The study featured a cinematic and interactive 3D reconstruction of the Neolithic settlement of La Draga, where visitors played the role of time travelers. Participants had 5 minutes to identify non-Neolithic objects and throw them into a time portal.

The design methodology involved consulting the archaeological community for location requirements and creating two different experiences: one providing introductory information and another offering a rich, interactive experience. The storytelling approach was linear in the 360° movie, and non-linear in the VR game, where users could freely explore the virtual space and collect objects. Interaction was non-interactive for the 360° movie, while the VR game was interactive, using HTC Vive controllers.

The experimental design involved museum visitors invited to participate in the La Draga VR experience and informed them about the research and anonymity of the data collected. Participants navigated the virtual environment, identified objects, and discarded non-Neolithic items. Feedback was collected through post-experience questionnaires. A total of 42 volunteers participated in the initial evaluation of both the 360° movie and VR game, while 262 volunteers participated in the formal evaluation of the VR game.

The results revealed that users were categorized into Strugglers, Engaged, Explorers, and Late-Explorers, depending on the difficulties they faced. Key findings showed that VR provides multimodal and enhanced learning experiences, encourages self-awareness about knowledge acquisition, and requires a dedicated physical space. The study noted that VR could sometimes distract from content (the "Guggenheim effect") and suggested that the virtual world should include activities around points of interest. Introduction tutorials, user categorization, varied difficulty levels, and additional guidance, such as mini maps, were recommended to improve user experiences.

Figure 19: La Draga VR.

Tennent et al. [52] (2020) designed and developed "Thresholds", an immersive VR experience presented at various locations: Somerset House, London (18th May–11th June 2017, ~5,000 visitors); Birmingham Museum and Art Gallery (24th June–6th August 2017, ~1,200 visitors); Lacock Abbey, Wiltshire, UK (16th September–29th October 2017, ~800 visitors); and the National Science and Media Museum, Bradford, UK (2nd March–7th May 2018, ~2,600 visitors).

The primary objective of the study was to explore how museum professionals could integrate VR into their exhibits in a scalable, flexible way that delivers compelling experiences. Thresholds was inspired by the "Model Room," an 1839 exhibition by photography pioneer Henry Fox Talbot, which displayed 93 "Photogenic Drawings" (early photographs). The VR application allowed visitors to explore a recreation of this historical exhibit, providing them with an immersive and interactive experience.

The storytelling approach was non-linear, allowing users to freely roam the virtual space and interact with VR objects. Interaction was facilitated through Leap Motion, with users employing hand gestures to interact with objects, creating an engaging experience. The equipment used included a backpack PC, HTC Vive, Leap Motion, and hand-tracking technology for ghostly hand representations.

The experimental design involved museum visitors experiencing the application, with feedback collected via log data, questionnaires, interviews, and pre- and post-experience questionnaires. A total of 2,349 participants contributed to heatmap data on movement and object viewing, while 12 volunteers participated in the formal evaluation. The results highlighted that overlaying real-world spaces with VR content creates engaging experiences. Recommendations included providing ghost-like avatars in multi-user applications to improve social presence, ensuring that VR content aligns perfectly with the physical environment, and addressing tracking jittering. The importance of clear barriers between accessible and inaccessible spaces and scripted tutorials to guide users was also emphasized.

Figure 20: Thresholds application.

Rizvić et al. [53] (2021) designed and developed a virtual time travel to the past of Bosnia and Herzegovina and evaluated it at the Offices of Sarajevo Tourist Organization. The objective of the study was to demonstrate how VR and AR technologies can be combined with storytelling to create immersive experiences.

The study involved several applications:

- Nine Dissidents: A 360° movie that aimed to rehabilitate writers, poets, and intellectuals persecuted by the socialist regime for not joining the Communist Party.

- Old Crafts Virtual Museum: A 360° movie consisting of four virtual environments, where actors in traditional costumes tell stories about crafts, with users entering workshops to see real craftsmen at work.

- The Battle on Neretva: A VR application combining storytelling and gameplay. Users learn about the battle and receive a virtual reward from Supreme Commander Tito upon completing their mission.

The design methodology was divided into three phases:

- Preproduction: Concept design, historical research, scenario writing, casting, and set design.

- Production: Filming 360° video, composing music, drone photogrammetry, and graphic design.

- Postproduction: Sound production, color correction, editing, and programming the VR applications.

The storytelling approach was linear in the 360° movies and interactive in the VR game, where users made choices to proceed. Interaction ranged from non-interactive in the 360° movies to interactive in the VR game, with equipment such as the Oculus Quest and controllers used for gameplay.

The experimental design involved museum visitors experiencing the applications, with feedback collected through post-experience questionnaires, semi-structured interviews, and open-ended questions. A total of 12 participants engaged with the system as single users.

The results demonstrated that both VR videos and applications can provide rich educational experiences. Interactive storytelling, through virtual actors, enhances user engagement, edutainment, and emotional responses. The study also emphasized that these applications promote physical museum visits and motivate users through gamification, though the level of gamification should be carefully balanced to maintain historical integrity. VR technology allows for the reconstruction of fragmented history and the interaction with virtual counterparts of real exhibits, adding to the museum experience. However, challenges such as the cost of VR headsets and user familiarity with the technology still remain.

This case study highlights the potential of immersive technologies to transform cultural heritage experiences, illustrating how VR can create engaging, educational, and emotionally impactful tools in museum environments.

Figure 21: Nine Dissidents.

Soga and Suzuki [54] evaluated a VR appreciation system for fountain pens at the National Museum of Japanese History, evaluating the system's usefulness and usability.

The system allowed users to preview 3D CG models of fountain pens in a VR space using a HMD while interacting with a pen-type device. Due to the sensitivity of Maki-e fountain pens to light and humidity, they are unsuitable for permanent exhibitions, and some intricate patterns are difficult to see with the naked eye. The VR system offered a solution by providing a detailed, immersive view of these artifacts.

The storytelling approach was non-linear, with visitors focusing on virtual elements using gaze. The interaction was facilitated through the Oculus HMD and a Wii remote, allowing users to engage with the content naturally. The experimental design involved museum visitors, and feedback was collected through questionnaires and log data. A total of 134 participants engaged with the system as single users.

The results indicated that users tended to browse fountain pens displayed in the center of the VR screen more frequently, likely due to their unfamiliarity with the technology. This suggests that a detailed user manual or demonstration might be beneficial for enhancing the user experience. The proposed VR system for viewing fountain pens was a highlight of the special exhibition, demonstrating the potential of immersive technologies to transform cultural heritage experiences. This case study highlights how interactive and immersive tools can create educational and engaging experiences in museum environments, offering an effective way to display delicate artifacts like Maki-e fountain pens.

Figure 22: User viewing fountain pens using VR.

Non-Immersive AR

Mulyadi and Kusumawati [55] (2024) evaluated AR technology integration with visitor experience at the Panji Museum. The AR-based application in the museum was designed to be simple, with minimal functions, making it accessible for users of various age ranges. The application used ARtechnology to display three-dimensional representations of museum objects. Users activated AR by scanning QR codes available on each museum object's description, providing an immersive and interactive experience.

The storytelling approach was non-linear, allowing users to explore the content at their own pace. Interaction was facilitated through mobile device touchscreens, and the equipment used was smartphones. The experimental design and feedback collection methods were not specified. Participants engaged with the system as single users.

Although specific results were not provided, the study demonstrated the potential of AR technology to enhance museum experiences, offering a glimpse into how digital tools can make cultural heritage more engaging and accessible.

Figure 23: AR content displayed after QR-Code scanning.

Shah et al. [56] (2023) integrated an AR application at the Terengganu State Museum to investigate visitor experiences using the Museum Experience Scale (MES). The application was developed to preserve an ancient manuscript while making it accessible to the public through AR. This provided participants with an immersive and interactive experience. The storytelling approach was non-linear, allowing users to engage naturally with the content. Interaction was facilitated through tablet touchscreens, enabling users to explore the AR content.

The experimental design involved museum visitors using the application, and feedback was collected using the MES. A total of 31 participants engaged with the system as single users. The results showed a positive experience across all MES components, with the highest score for engagement, followed by knowledge and learning. The study demonstrated the potential of immersive technologies to enhance cultural heritage experiences, showing how interactive and immersive tools can create educational and engaging experiences in museum environments [18].

Figure 24: AR application showcasing ancient manuscript.

Teixeira et al (2022) enhanced the museum visitor experience at the Ecomuseu through AR. The study involved developing an AR-based virtual guide that enabled visitors to interact with signpost content in a gamification-based way. The application featured six interaction points across different locations in the museum, providing detailed explanations about the environment and its history. Visitors could interact with textual information in a unique format and receive feedback from the application, allowing them to explore the museum at their own pace while being guided by the application.

The storytelling approach was non-linear, designed to naturally engage users with the content. Interaction was facilitated through mobile device touchscreens, with visitors using their smartphones to access the AR content. The experimental design involved invited participants, and feedback was collected through a questionnaire. A total of 15 participants engaged with the system as single users. The results showed that it is possible to develop a high-quality AR solution using available free tools and resources. Although the app was designed as a virtual guide for exhibitions, the study highlighted that the possibilities with this technology are endless.

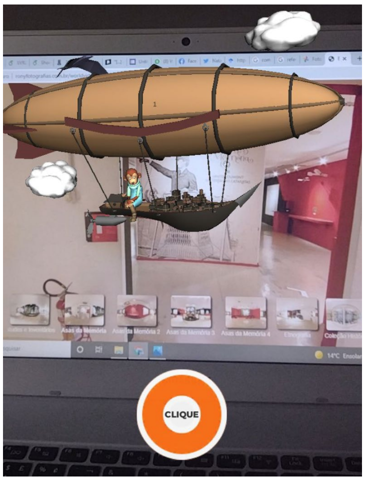

Figure 25: AR content at Ecomuseu.

Geigel et al. [57] (2020) applied AR technologies to enchance visitor experience at the Genesee Country Village & Museum. The study featured a digital docent with a historical connection to a specific museum space. The docent delivered a welcoming monologue and encouraged users to interact by asking predefined questions. These questions could be asked aurally or selected from a visual list, providing alternate means of interaction through gestures, mouse clicks, or screen taps. This setup created an immersive and interactive experience for museum visitors.

The storytelling approach was non-linear, allowing users to engage naturally with the content. Interaction was facilitated through mobile device touchscreens, with the equipment used including smartphones, Hololens, and web-based platforms. While specific details on experimental design and feedback collection methods were not provided, the application successfully enabled a common visitor experience through both on-site AR and off-site VR viewing. The results demonstrated the potential of conversational digital avatars to engage visitors in a living history museum setting, highlighting how AR and VR technologies can create educational and interactive experiences both on-site and remotely [20].

Figure 26: Virtual character providing information through AR application.

Cesário et al (2020) developed the AR application "Turning Point" and evaluated at the History Museum of Funchal, studying its efficiency to enhance the museum visitor experience. In the Turning Point experience, users were encouraged to visit specific physical locations in the museum to unlock story plot points and solve a mystery. The core mechanic involved finding AR markers, which indicated the presence of story content and unlocked fragments that progressed the plot. This provided participants with an immersive and interactive experience.

The storytelling approach was linear, guiding users through the story step by step. Interaction was facilitated through mobile device touchscreens, with visitors using their smartphones to engage with the AR content. Details on experimental design and feedback collection methods were not specified, and information about the number of participants is not provided. Although specific results were not mentioned, this case study demonstrates the potential of immersive technologies to transform cultural heritage experiences. It highlights how AR tools can create educational and engaging experiences for museum visitors.

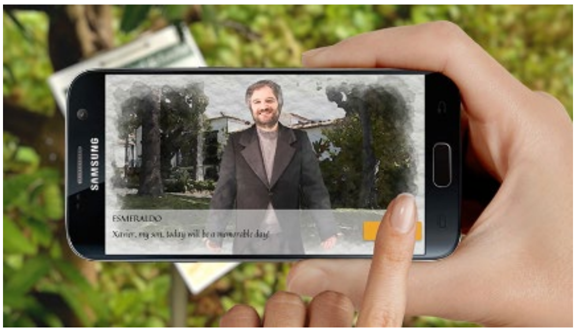

Figure 27: Turning Point.

Bernarduzzi et al. [58] (2021) enhanced Pavia University History Museum visitor experience through the use of AR. The authors and the museum staff critically analyzed the best approaches for implementing AR technology in the museum and formulated new ways to introduce the collections. The project involved storytelling videos promoted through an AR application that activated by scanning AR markers within the museum. This provided participants with an immersive and interactive experience. The storytelling approach was non-linear, allowing users to explore content at their own pace. Interaction was facilitated through mobile device touchscreens, with visitors using their smartphones to engage with the AR content.

The experimental design involved visitor volunteers using the application, and feedback was collected through short interviews. Although the exact number of participants is not specified, the results indicated that while the application successfully enhanced the visitor experience, some technical improvements were needed. This case study highlights the potential of immersive technologies to transform cultural heritage experiences, demonstrating how AR can create interactive and engaging tools in museum environments.

Figure 28: Pavia University History Museum AR application.

Li [59] (2021) created an AR application entitled CubeMuseum. The primary objective of the study was to use a cost-effective cube and a smartphone application to promote cultural heritage. The study involved creating digital copies of museum collections using close-range photogrammetry. Once reconstructed, the virtual objects were imported into Unity for AR interaction design. Users interacted with the virtual objects via a smartphone AR application and a physical cube, with each face of the cube containing a 2D image target. The smartphone camera tracked these images, allowing the user to view and interact with virtual objects. Information labels and photos of the objects in the museum were also used as image targets. The storytelling approach was non-linear, allowing users to explore the content at their own pace. Interaction was facilitated through mobile device touchscreens, with visitors using their smartphones to engage with the AR content.

The experimental design involved visitor volunteers using the application, and feedback was collected through a questionnaire. A total of 112 participants engaged with the system as single users. The evaluation was conducted at the UKRI Impact Festival, Beijing (November 8, 2018); SPARK: The Science and Art of Creativity, Hong Kong (January 19, 2019); and the AHRC UK-China Creative Industries, Shanghai (December 2, 2019).

The results indicated that the embodied interactions supported by CubeMuseum enhanced users' learning experiences of cultural heritage by combining physical embodiment with digital interactivity. This case study demonstrates the potential of immersive technologies to transform cultural heritage experiences, highlighting how AR can create engaging and educational tools in museum settings.

Figure 29: CubeMusem.

Paliokas et al. [60] (2020) developed the e-Tracer AR application, an educational guide that allows museum visitors to navigate exhibits using their own smartphones or tablets. The application was designed to support the museum’s mission of preserving the technical knowledge of Epirote silversmithing artists, at the Silversmithing Museum, located in the castle of Ioannina, and disseminating information about the tradition to the public.

The AR functionality was triggered by sensing a museum artifact through the mobile device’s built-in camera. The marker-based object detection mechanism projected additional information, such as a short description, or allowed for the virtual projection of animated 3D objects when available. This provided participants with an immersive and interactive experience. The storytelling approach was non-linear, allowing users to explore content at their own pace. Interaction was facilitated through touchscreens on mobile devices.

The experimental design involved experts, and feedback was collected through a questionnaire. A total of 4 participants engaged with the system as single users. This case study demonstrates the potential of immersive technologies to transform cultural heritage experiences. It highlights how AR can create engaging, educational tools that enhance museum visits and promote cultural heritage.

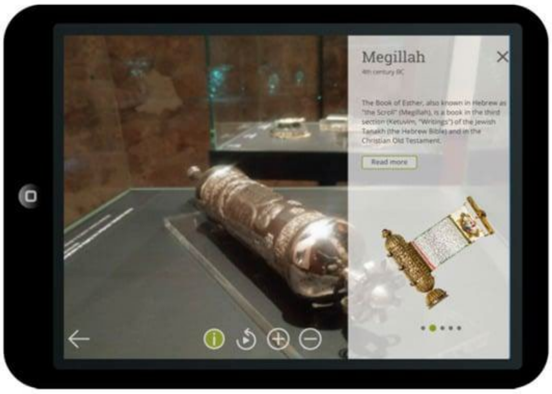

Figure 30: CubeMusem.

Non-Immersive VR

Pattakos et al. [61] (2023) designed, developed and evaluated a novel display installation to enhance user interaction and experience, as exemplified by several use cases in the cultural and educational fields. The display was implemented in the National Historical Museum, allowing users to engage with digital representations of physical artifacts using touch glass and raycasting technology. This immersive yet non-physical experience enables users to visualize historical pieces, fostering greater interaction and educational value. Feedback from participants was largely positive, highlighting the successful integration of ICT components in enhancing museum experiences [25].

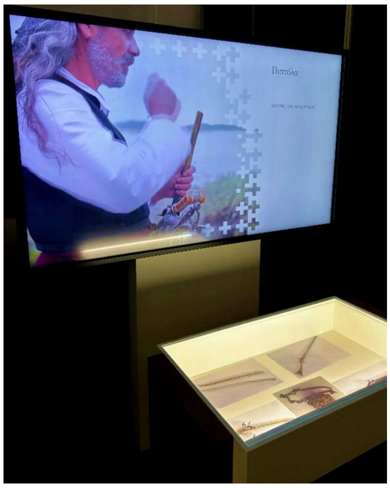

Figure 31: Touch glass display.

Similarly, Meier et al (2021) focused on offering users a virtual platform to explore cultural content and in this case traditional clothing. Accessible through a PC with simple keyboard and mouse controls, this online museum provides users the freedom to explore various exhibitions interactively. Although lacking in-depth participant feedback, the project demonstrates the ability of non-immersive VR to democratize access to cultural heritage, enabling users to engage from anywhere in the world.

Figure 32: Virtual clothing museum.

Comes et al. [62] (2022) used multi-touch tables and leap motion technology to facilitate interaction with digital artifacts. This setup allows users to explore ethnographic content in an engaging manner, bridging the gap between traditional exhibitions and modern digital engagement [27].

Figure 33: Mutli-touch display.

Lastly, ZILIO et al. [63] (2021) designed, developed, and evaluated FakeMuse, a serious game about authentication of artifacts, utilizes smartphones and tablets to provide users with an educational gaming experience. While participant feedback indicated that the quiz sessions were engaging, some noted difficulties in retaining complex information, underscoring both the advantages and limitations of non-immersive VR in educational contexts.

Figure 34: FakeMuse.

Technological Trends, Narrative Design, and Evaluation Methodology

Table 1 summarizes the different immersive and non-immersive technologies used in museum settings, their associated equipment, types of narrative design, methods of evaluation, types of user experiences, and estimated cost ranges.

As shown in the table, common uses of XR technologies in museums include Immersive VR and AR, along with Non-Immersive VR and AR solutions. Regarding equipment, Immersive VR solutions commonly utilize popular HMDs such as Oculus and HTC Vive. However, when minimizing costs is a priority, solutions like Gear VR can also serve as adequate alternatives. Non-Immersive VR applications, on the other hand, are mostly based on PCs as part of installations, which can include supplementary equipment such as customized controllers and touch screens. As for Non-Immersive AR applications, these are commonly accessed using smartphones and tablets, making them less immersive but more easily available to general users.

Across all categories, experiences can be interactive or non-interactive, with the technology and design influencing the level of user engagement. Immersive VR and AR offer a mix of interactive and non-interactive experiences, as well as specific interactive games, indicating a focus on user engagement and dynamic interaction. Non-Immersive VR and AR primarily focus on interactive experiences and games, showing that even less immersive technologies still prioritize user interaction.

Furthermore, narrative design can be categorized as linear or non-linear. Linear narratives guide users along a set path, while non-linear narratives allow for more exploration and varied outcomes. In the Immersive VR applications examined here, there is a balance between linear and non-linear narrative design approaches. However, in Immersive AR applications, non-linear narrative design is more popular, as these applications allow users to explore real museum spaces augmented with digital information without being confined to a specific physical area, as is common in Immersive VR applications. Non-Immersive VR applications primarily use a non-linear narrative, suggesting a more exploratory form of engagement, while Non-Immersive AR combines both linear and non-linear approaches, providing more flexibility depending on the application. Here it must be mentioned that many

Regarding evaluation, across all technologies, questionnaires and interviews are common methods, allowing users to provide feedback on their experiences. For Immersive VR and AR, more direct methods such as observation and log data (tracking user activity) are used. Evaluations of Non-Immersive VR applications also include think-aloud protocols, where users verbalize their thoughts during the experience, providing real-time feedback.

The cost estimates are divided into three categories. Immersive VR and Non-Immersive VR have relatively moderate entry costs for institutions. Immersive AR is more expensive, which is expected given the advanced equipment (e.g., Microsoft Hololens) and the complexity of the content. Finally, Non-Immersive AR applications have lower costs, as smartphone- and tablet-based AR experiences are the most affordable options for museums and exhibitions.

In conclusion, Immersive VR and AR technologies offer more engaging and interactive experiences but come with higher costs, especially for AR. Non-Immersive AR offers a budget-friendly alternative while still providing interactive, albeit less immersive, experiences. Finally, different narrative structures (linear vs. non-linear) and evaluation methods reflect the varying goals and flexibility of these technologies in museum and exhibition contexts.

Technology	**Equipment**	**Narrative Design**	**Type**	**Evaluation**	**Cost**
Immersive VR	Oculus HMD [48], [50],[53], [54] HTC Vive HMD [47], [49], [51], [52] Gear VR [51]	Linear [47], [48], [51], [52], [54] Non-Linear [48], [49], [50], [51], [53]	Interactive Experience [47], [48], [52], [54] Non-Interactive Experience [50], [51], [53] Interactive Game [49], [51], [53]	Questionnaires [47], [51], [52], [53], [54] Interviews [46], [46], [47], [48], [52] Observation [48], [50], [53] Log Data [47], [54]	Medium (1000-2000 €)
Immersive AR	Microsoft Hololens [39], [40], [41], [42], [43], [44], [45], [46]	Linear [43] Non-Linear [39], [40], [41], [42], [44], [45], [46]	Interactive Experience [39], [40], [41], [42], [44], [45], [46] Non-Interactive Experience [43], [45]	Questionnaires [39], [40], [41], [42], [43], [46] Interviews [42], [44], [45], [46]	High (>2000 €)
Non-Immersive VR	PC/Installation [61], [62], [63], [64]	Non-Linear [61], [62], [63], [64]	Interactive Experience [61], [62], [63], [64] Interactive Game [64]	Questionnaires [64] Think-aloud [62]	Medium (1000-2000 €)
Non-Immersive AR	SmartPhone/Tablet [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66]	Linear [66] Non-Linear [55], [56], [57], [58], [59], [60], [65]	Interactive Experience [56], [57], [58], [59] Interactive Game [[57], [60], [66]	Questionnaires [56], [59], [60], [65] Interview [58]	Low (<1000 €)

Table 1: Existing XR technological solutions tools for enhancing cultural heritage sites visitor experience, sustainability, and resilience

Flow Monitoring

Analysis of the tourist flows and technological applications

In this section, we carry out a review of the technological proposals that the academic community has made to contribute to the management of tourist flows. In this context, the purpose is to identify, on the one hand, what the proposed technologies have been so far, and, on the other hand, the benefits and limitations of these. The 21st century has brought the expansion of the tourism sector internationally, and, with it, the emergence of a global phenomenon that has a very important effect on the economic development and reputation of a large number of countries around the world [67]. In this context, part of the academic literature has focused on the study of tourist flows, defined as collective spatial displacement motivated by the similar tourist needs of tourists [68]. However, more modern definitions consider it essential to consider within tourism flows not only the displacement of people, but also very relevant information such as its impact on the environment, that is, the flow of energy and materials, among others [69].

In this way, tourism flows carry risks, which are not only important to identify, but it is also essential to propose tools to mitigate them or reduce their impact. Carballo et al. [70] identified 5 types of risks, which have been generally accepted by the academic community, governments and tourism managers: health, crime, accident, environmental and natural disaster risks. In our case, this report is based on environmental risk, i.e. the risk that tourism flows have for the environment, and how technologies can contribute to reducing the impact of their impact on the economic, social and environmental dimensions.

Traditionally, tourism has had a strong environmental impact. In 2013 it accounted for 8% of global greenhouse gas emissions, assuming four times the initial estimates [71], while by 2025 CO2 emissions are expected to exceed 6.5 billion tonnes [72]. Among other issues, this is motivated by the use of a large amount of fossil fuels [73], which in turn contributes significantly to global warming. Other environmental impacts caused by tourism are excessive water use, changes in soil as a result of infrastructure investments [74] or the generation of huge amounts of solid waste [75]. Awareness of the availability of natural and cultural resources, as well as the negative impact of tourism on the environment and society [76], have led to an increased concern to propose instruments to improve the impact of tourism [77], and important contributions are being made to assess the carrying capacity of destinations, reduce the carbon footprint, generate and use cleaner energy and protect the environment [72], among others.

In this context, information and communication technologies are playing a fundamental role in a globalized world [78]. The technological development of recent years could have a significant effect on sustainability [79], and the tourism sector has not remained oblivious to it. Thus, various technologies are being applied to the tourism sector in the hope of achieving lower impacts, such as virtual reality, augmented reality, artificial intelligence or mobile interactivity, as well as other more recent technologies whose benefits are still being tested.

Consequently, based on the recognition that the tourism sector, in particular, and tourism flows, in general, must improve their impact on the environment, as well as knowing the potential that technological development can promote in improving impacts on the environment, the objective of this report is to identify the technologies that have been evaluated in the academic literature to manage tourism flows, as well as the benefits and barriers they present.

To respond to the proposed objectives, the methodology of systematic literature review has been used, according to which it is possible to investigate, examine and synthesize the academic literature, especially in areas of recent knowledge or that have been little explored. In this way, this methodology allows to deepen in novel or little studied aspects, allowing to identify the most significant contributions. The literature review was conducted using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, which consists of a set of checklists that follow a flowchart. In this way, first of all, it is necessary to identify the keywords related to the aspects that you want to evaluate. In our case, a subset of keywords related, on the one hand, to tourist flows, and, on the other, a subset related to the technologies for the management of these have been identified. Both sets of words are available in Figure 1.

The search string used to identify the documents that were finally evaluated is as follows: (TITLE-ABS-KEY ("technologies" OR "Virtual Reality" OR "Augmented Reality" OR "Digital Technologies" OR "Information And Communication Technology" OR "Virtual Tourism" OR "Internet Of Things" OR "Information Systems" OR "GIS") AND TITLE-ABS-KEY ("tourism flow*" OR "International Tourist Flow*" OR "International Tourism Inflow*")) AND (EXCLUDE (PUBYEAR , 1997)) AND (EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "MEDI")). The documents were searched in September 2024. Appendix I includes a table with all the documents analyzed, as well as for each of them information on: the dimension in which it was evaluated, as well as the regions in which the research was conducted.

Results

This section shows the results related to the application of the methodology of academic literature review. The findings are shown in two distinct subsections: (a) on the one hand, the general characteristics of academic production are shown, showing the results of the evolution of the number of documents published annually, the typology of documents, the most productive countries and their international cooperation networks, as well as the co-occurrence networks of keywords or most relevant topics within the line of research; and (b) on the other hand, a second subsection in which the content of the documents is analyzed based on the dimensions that are under study.

General characteristics

Figure 35 shows the number of documents published annually for the period under study (2006 – 2024).

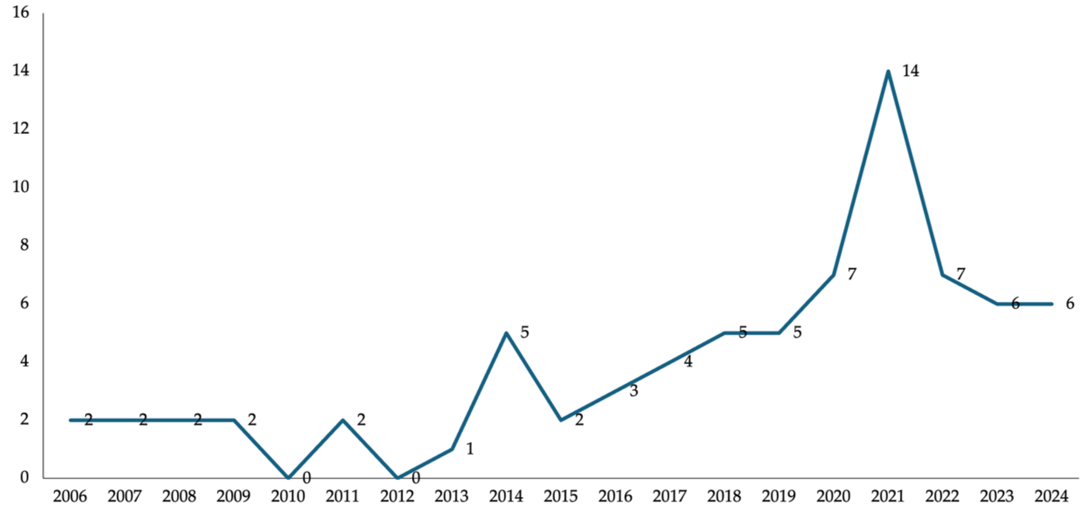

Figure 35 Evolution of the number of documents published

Although the first documents were actually published in 1997, it can be considered that this line of research does not begin to develop until 2006. Since then, it has experienced linear growth, with periods of increased academic activity. In this way, two clearly differentiated subperiods can be distinguished: (1) a first period from 2006 to 2015 (both inclusive), in which a total of 10 documents were published; and (2) a second sub-period covering the years 2016 – 2024, with a total of 65 documents, i.e. more than 86% of total academic output. Within this subperiod, the number of publications in 2021 stands out, which, with 14 publications, is the most productive of the entire period analyzed. However, due to COVID-19, this significant increase in publications could be in line with the increase in general academic production, since in the following three years the publications are located in the average of the subperiod (6).

Figure 36 shows the typology of published documents, both in absolute and percentage numbers. Clearly, research articles are the most representative, with 68% of total academic output. This, in itself, is a very relevant fact, given that research articles are valued based on novelty, scalability of results and the generation of new knowledge, in addition to being reviewed by blind peers, which are clear indications of high quality [80], [81].

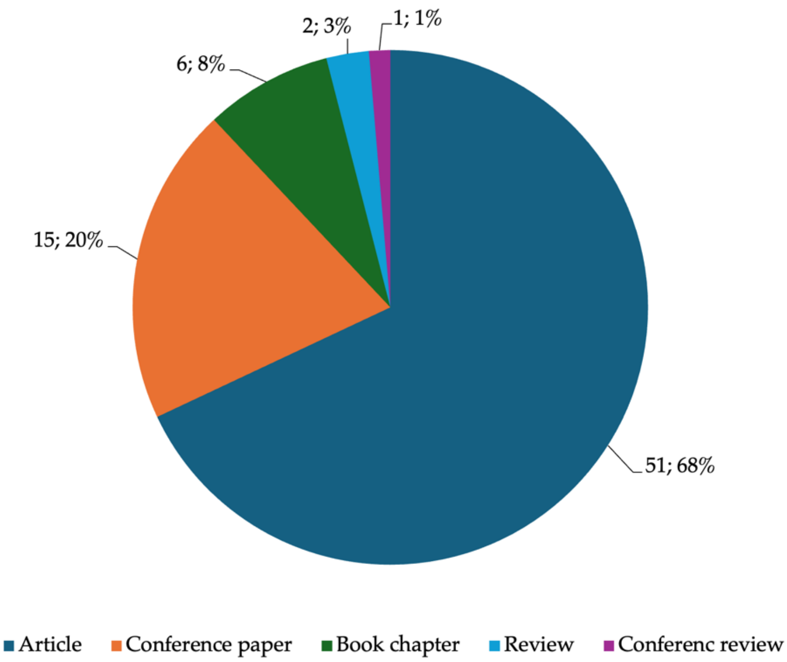

Figure 36 Type of documents published

As for the most productive countries in the academic literature on technologies for the management of tourism flows, Table 2 presents those countries that have published at least 3 research papers.

Table 2 Main producer countries and cooperation networks

Country	Documents	TC	H index	Main collaborators
China	23	301	7	Canada, Mongolia, United States
Italy	10	107	5	Denmark, Finland, Ireland, Norway
Spain	8	186	5	United Kingdom
United States	3	204	3	Canada, China, Hong Kong, Mongolia
Romania	3	45	3	Singapore
Portugal	3	52	2	-

(TC): total citations.

In total, Scopus identified authors from a total of 35 countries, of which 10 have published two papers and 19 have published a single research paper. The three most productive countries have published 54.7% of the academic production, so there is a high concentration of publications regarding the nationality of research institutions (Scopus considers the nationality of the institution, regardless of the nationality of the authors). In fact, as shown in Figure 37, these countries are some of the countries where tourism has the greatest impact on Gross Domestic Product.

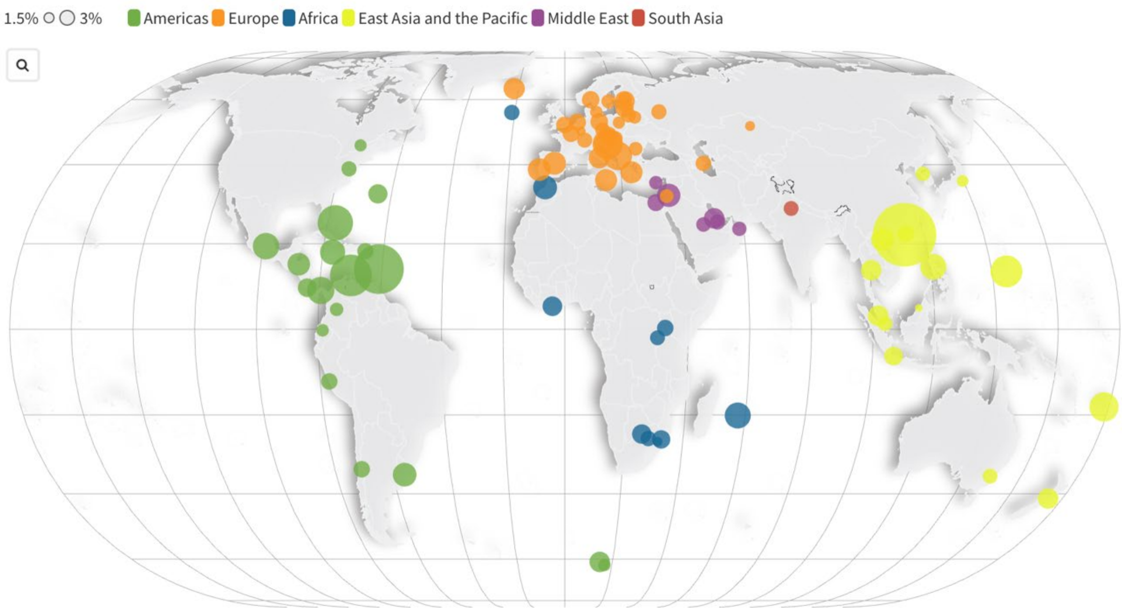

Figure 37 Contribution of tourism to GDP (**Source: UN Tourism (2024)**)

For its part, Figure 37 shows the distribution of the continents in which the research that is being studied has been carried out.

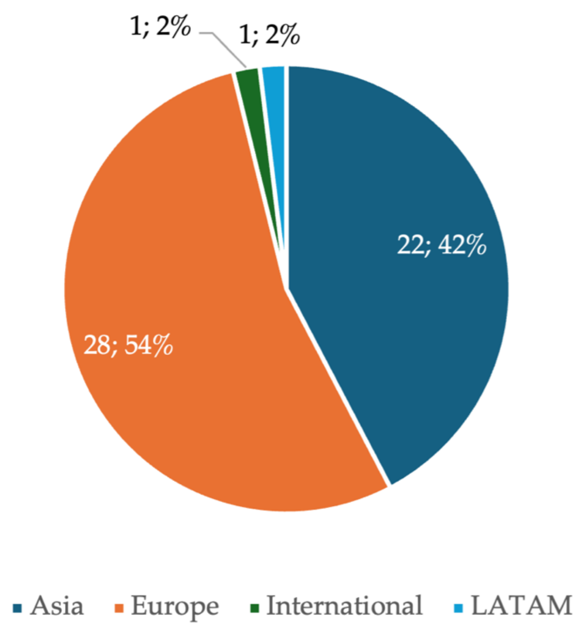

Figure 38 Distribution of the application of research by continents

Clearly, as already identified in Figure 38, the continents with the highest tourist flows are those on which most of the research is being carried out. In fact, only in Europe and Asia is there a relevant number of studies on the management of tourism flows, at least from the point of view of academia. Moreover, in Asian countries, most research has focused on China (19), with a residual study in countries such as India (1), Kazakhstan (1) and Israel (1). For its part, in Europe the research has been much more decentralized, with studies carried out in France, Spain, Italy, Portugal, United Kingdom, Bosnia-Herzegovina, Albania, Greece, Russia, Croatia, Estonia, Ukraine, Hungary or Romania.

Finally, the analysis of co-occurrences of the keywords contained in the documents was carried out. This analysis is relevant because the keywords are representative of the content of the documents [82]. Co-occurrence is based on keywords referring to similar topics [83], [84], so this method allows to create an image of the research line as a whole [85], as well as to analyze its evolution over time [86].

For a total of 582 identified keywords, an interaction of at least 2 co-occurrences was selected, obtaining a total of 84 keywords. On these, those that were included in the search chain were eliminated, as well as others that had no relation to our objectives, so finally, in Figure 39, 54 keywords are shown. The colors refer to the groupings of the keywords, the size of the circles represents the number of times that keyword appears in the analyzed documents, as well as the distance between the lines and the frequency with which they appear.

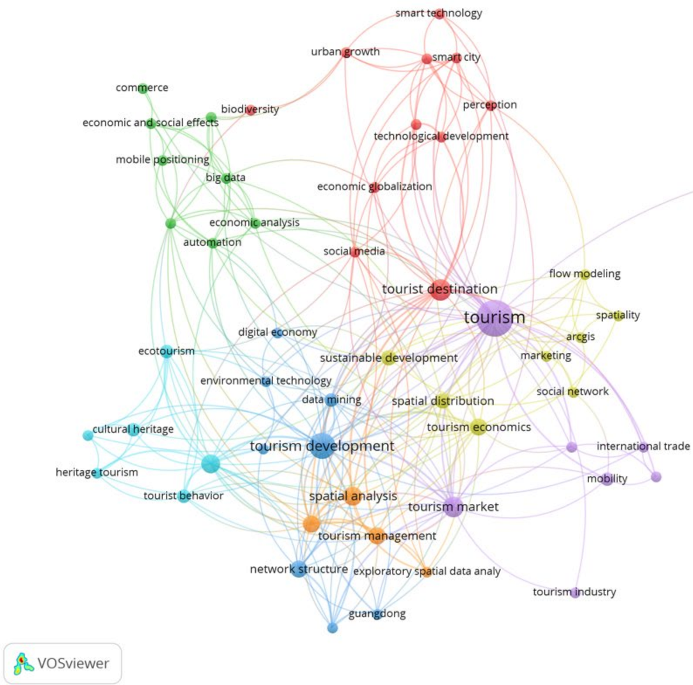

Figure 39 Most relevant research topics

The low dispersion between the keywords represented indicates that there is a great correlation between all of them, so, although 8 clusters can be identified, the topics that are addressed within these are very related to each other, as one would expect when it comes to such a specific line of research. Thus, the largest cluster is the red one, with 11 keywords, which mainly refer to the development of smart cities for the management of tourist flows. The green, dark blue and yellow clusters are all composed of 8 keywords. Green refers to technologies oriented to the analysis of the economic impact of tourist flows, while blue and dark yellow refers to the data analysis technologies used, especially quantitative ones, which are applied to the management of tourist flows in a more generic dimension. Clusters with fewer keywords are purple (7), light blue (6), orange (4) and brown (2). The first addresses the tourism model from a global dimension, light blue and brown to the proposal of a more sustainable tourism model, while orange is focused on the evaluation of the impact of tourism in urban areas.

Content analysis

In the content analysis, a total of 56 documents were considered, since the remaining 19 did not allow to identify the benefits and limitations of the technologies applied for the management of tourist flows. Consequently, although they were considered for the analysis of the general characteristics, in the content analysis they were not taken into account. In this way, two dimensions were identified, which are: (a) Geographic Information Systems (GIS); and (b) Information and Communication Technologies. The content analysis is then performed.

Geographic Information Systems (GIS)

In relation to the application of GIS tools and applications, in the studies related to the analysis of tourist flows, there is a greater scientific production during the last 5 years, having published 16 of the 25 articles identified in this dimension, between 2020 and 2024.

Most of the identified studies use GIS tools for the analysis of tourist flows and their impacts, at the level of city or tourist place ([69], [87], [88], [89], [90]), at regional level ([91], [92], [93], [94], [95]), or nationally or internationally ([96],[97], [98], [99], [100]), to provide tools to support the decision-making process for tourism development planning.

The combination of GIS tools with the application of social network theory and analysis allows exploring the characteristics of the spatial network structure of tourism flows and the balance between tourism supply and demand. Thus, Han et al. [101] show in their work how the driving mode of tourism economic growth and the tourism economic flow network in Yunnan Province is gradually shifting from the supply-driven pattern to the demand-driven pattern. Borowiecki and Castiglione [102] investigate the association between participation in leisure activities and tourist flows in the Italian provinces, showing that theatrical activities increased the number of domestic tourists, while museums or concerts increased the number of foreign tourists. Yan et al. (2021) provide an example to explore the analysis of spatial characteristics of tourism flow networks by using travel note data on the Internet and optimising the spatial structure of tourist destinations in metropolitan areas. Liu et al. (2020) analyzes in depth the change of the tourist flow network, in the agglomeration of Chengdu-Chongqing, under the influence of high-speed rail.

In addition, the exploratory analysis of spatial data allows the analysis of tourist flows and their impacts, in relation to the offer of accommodation and the size of the local population, as shown by Sarrión-Gavilán et al. [94], which highlight a persistent imbalance between coastal and inland areas in the Autonomous Community of Andalusia (Spain), through the Moran index and the LISA (Local Index of Space Association) conglomerate maps. Yang and Wong [100] investigate the spatial distribution of incoming and outgoing tourist flows to Chinese cities and their growth rates, also through the exploratory analysis of spatial data and show, with Moran's significance maps, the existence of four important areas of international tourism and five other relevant ones in national tourism in the analyzed period. Xing-zhu and Qun [87] apply spatial-temporal exploratory analysis to better understand the flow patterns of receiving tourism in Chinese cities during the period 2000-2009, using GIS datasets at the city level.

On the other hand, the development of spatial information technology and the availability of data from multiple sources have broadened the perspectives for the investigation of spatial correspondence between the supply and demand of tourism resources and their interaction [93]. In this sense, Zhu and Cao (2020) are based on geotagged photos from Flickr, applying various analytical methods, such as the social network, geographic information systems and Markov transition probability, to analyze the characteristics of the structure of the tourist network in the cities of the Yangtze River and highlight the internal discipline of the flow of tourists from the urban group. Similarly, Qin et al. [89] analyze the tourist flow, connections between tourist spots and spatial organization, as well as their influence on urban traffic organization, utilities facilities and the disposition of the leisure tourism industry in the city of Beijing, between 2004 and 2015, from the Flickr API interface using data mining technology. In addition, they analyze the spatial patterns of incoming tourist flows and the spatial characteristics of the areas of interest using various methods, such as P-DBSCAN (Density-based spatial clustering of applications with noise) and the Markov chain.

On the other hand, in some works, the analysis of georeferenced information of tourist flows is used to investigate the consequences of tourist pressure on sustainability and the environment. In this sense, Gómez López and Barrón Arreola [96], who have carried out an investigation on the relationship of tourist flows with certain environmental variables, such as the volume of water and waste treated, the trees planted, the environmental licenses granted or the irrigation of plants and gardens, do not appreciate conclusive evidence regarding the impact of tourism activity on the environmental variables considered in the 32 states of Mexico, for the period between 1999 and 2019.

Cillis et al. [103] consider the GIS approach as a fundamental tool to quantify the surface and evaluate the spatial and qualitative characteristics so that, using different integrated tools, such as satellite images and landscape metrics, they have carried out a complete study of the conditions of the ecological network in the Italian city of Matera, assessing the state of potential biodiversity in the urban area, concluding that the values of the landscape metric represent the basis of information on which it will be possible to plan the future development of urban green spaces.

Finally, Zubiaga et al. [104] provide a methodology for the management of tourist flows that is designed to promote sustainable tourism in historic centers through intelligent support mechanisms. The proposed methodology allows to develop a sustainable management strategy for cultural circular tourism in the historic center of cities, with tools through which city managers can interact to increase flows to less visited areas and encourage economic activity, as well as to safeguard crowded areas and threats to heritage. Thus, visitors can adapt their visit to the needs and situation of the historic center, in terms of the number of people who are likely to be in one place or another.

Information and Communication Technologies (ICT)

Regarding information and communication technologies, technological evolution has been remarkable during the period of time studied, leading to the emergence of new more sophisticated tools, or simply to greater use of those already available.

Digitalization, through different tools and levels of sophistication, is one of the most powerful tools for the management of tourist flows, especially to preserve cultural heritage [105]. In this way, we find elements for the management of tourist flows such as the transmedia system, which is based on the use of websites, mobile devices and stereoscopic technologies to create immersive and more exciting virtual experiences for tourists, often causing physical displacements later [106]. In this regard, one aspect that deserves to be highlighted is that information on websites should be available in multiple languages, which is particularly relevant for small and medium-sized enterprises to expand the reach of international tourists [107], [108]. However, if we focus on a younger target audience, the ideal would be to use other communication tools, especially mobile applications, which should also incorporate functionalities that allow potential tourists to plan the trip, book, develop the trip and write reviews, the latter especially stimulating to attract others in the future [109]. This is giving rise to so-called *smart tourism*, which has two key advantages: on the one hand, it contributes to the improvement of sustainability in heritage spaces, and on the other hand, it allows to obtain information from tourists about their perception [110]. For Marchesani et al. [111], cities that adequately integrate digital technologies will be those that achieve the greatest interaction with tourists, and thus the greatest ability to attract them.

Parallel to apps, social networks have progressively gained prominence in recent years, which, obviously, has an important impact on the management of tourist flows. In this way, it is common for tourists to share large amounts of information on their social network profiles (photos, videos, opinions, among others), as well as on many occasions share the geolocation of their mobile devices (Kovács et al., 2021). In the case of data provided by the geolocation of mobile devices, they provide information on the timing, seasonality and dynamics of visits, meet tourists who repeat experiences [95], [95], and managing gateways to countries [113]. In this context, tourism operators and governments must have data analysis and interpretation tools to be able to draw valuable conclusions from the data provided by tourists, being, so far, the Big Data tools the most appropriate for this purpose [114], [115]. Other tools for processing these data are currently being proposed, such as spatiotemporal modelling [116], but they still experience important challenges such as high sampling costs or low accuracy [93]. Multilevel modeling has also been proposed, which presents as main advantages in the application to the management of tourism flows that is open and extensible to other Internet of Things scenarios [117]. And finally, the academic community proposes the use of Long-Term Memory Neuronal Networks (LSTM) to predict tourist flows, as they seem to show better results compared to other methods such as the Autoregressive Integrated Mobile Average (ARIMA) model and the Retropropagation Neuronal Network (BPNN) [118].

On the other hand, some other experiences should be highlighted, such as virtualization [119]. One of the technologies being tested is augmented reality, which is allowing the development of fully virtual tour packages that do not require physical travel. However, the high amount of financial resources required to develop real and exciting experiences means that for the moment the technology is still in a phase of experimentation [120]. Finally, recently Qian & Luo [121] have proposed the application of virtual reality to tourism, although they point out important challenges such as the selection of tourist routes oriented to the needs of users and the design of an adequate experience with the smart tourism system.

Conclusions

This report aimed to carry out a review of the technological applications that the academic community has evaluated to improve the management of tourist flows, in order to identify the proposed technologies, as well as their benefits and limitations. To meet this objective, a systematic review of the literature was carried out, through which a total of 76 documents related to the subject were identified in the academic repositories considered most relevant by the academic community, such as Scopus and Web of Science. From these, the general characteristics were obtained, through which the annual evolution of the number of scientific publications is shown, the typology of the published documents, the most producing countries, the countries and continents in which the technological applications were evaluated and the grouping of the keywords. In the results, the content analysis of the documents has also been presented, which has ultimately allowed to respond to the research objective. Consequently, we can draw some conclusions that may be useful, and which are listed below:

- The annual evolution of the number of publications (Figure 35) allows two important conclusions to be drawn: (1) The publication of the Sustainable Development Goals (SDGs) in 2015 led the academic community to focus on technologies for the management of tourism flows, although this growth has been sustained to date; and (2) The trend of linear growth shows that, predictably, the academic community will continue to make contributions in this line of research in the coming years, responding to some of the current challenges that are emerging. Although it is a line of research that has not been very productive (only 76 documents in the period of 18 years evaluated), the growing concern of governments and the population in general about the negative externalities of tourism flows, as well as the commitment of national and international funding agencies of research activity in the establishment of a more sustainable tourism model, it is very likely that there will be a remarkable growth of research in the coming years.

- The most productive countries are mainly of Asian (China) and European (Italy, Spain, Romania and Portugal) origin (Table 2), with these countries having the highest contribution of the tourism sector to their Gross Domestic Product (Figure 37). In fact, a large number of publications have been based on case studies, that is, evaluating the application of tools for the management of tourism flows in certain geographical contexts, which have focused mainly on Asia (mostly in China) and Europe (in this case, a wide diversity of countries is observed) (Figure 38). This clearly indicates that there is an alignment between the social/political reality of the management of tourist flows and the academic community in these geographical areas, providing solutions that hope to contribute to improving the management of tourist flows (both inbound and outbound).
- The use of Geographic Information Systems and data from diverse sources, as well as the growth of data from IoT (Internet of Things) and digital social networks have allowed a considerable increase, in recent years, of studies related to the behavior of tourist flows, both at the level of city or tourist place, as well as at regional, national or international level, with the fundamental objective of providing information to support the decision-making process for tourism development planning.

Finally, it is important to recognize the main limitations of this report, which focus mainly on the methodology used and the procedures applied to respond to the research objective. Firstly, the limitation of the selected academic repositories (Scopus and Web of Science), which, while considered by the academic community to be the highest quality scientific databases, is likely that some high-quality research papers have not been indexed in these repositories, and therefore some key issues have not been considered. To avoid this, it is proposed to expand the number of academic repositories evaluated in the future. Secondly, the selection of keywords results in a bias in the identification of documents. It is very likely that other documents that contributed to the fulfillment of the research objective were not identified, among others, for two reasons: (a) did not incorporate the selected keywords into the title, abstract or keyword section; and (b) although a significant effort was made by all members of the research team to identify all the keywords linked to the management of tourism flows, it could happen that some were not identified and, therefore, those research documents could not be identified. Third, the growth trend shows that there is likely to have been some additional publication during the reporting period, which could not be assessed. For this report to fulfill the ultimate purpose within the research project, it is recommended that it can be periodically re-evaluated, which will predictably lead to the identification of new computer applications, or simply, the improvement of those already evaluated. Finally, the report was based solely on the academic dimension, not considering practical applications, good practices or projects and experiences developed by tour operators, so complementing this report with quality information in specialized journals, industry reports or successful practices could expand the wealth of information.

Appendix 1. Research papers analysed.

ID	Authors	Title	Year	Dimension	Country	Continent
1	Terrier C.	Tourist flows and inflows: On measuring instruments and the geomathematics of fluxes; [Flux et afflux de touristes: Les instruments de mesure, la géomathématique des flux]	2006	ICT	Francia	Europe
2	Paulino I.; Prats L.; Domènech A.	Breaking brands: New boundaries in rural destinations	2021	GIS	España	Europe
3	Terrier C.	Tourist flows and inflows: On measuring instruments and the geomathematics of flows	2008	ICT	N/A	N/A
4	Sarrión-Gavilán M.D.; Benítez-Márquez M.D.; Mora-Rangel E.O.	Spatial distribution of tourism supply in Andalusia	2015	GIS	España	Europe
5	Liu J.; Ji X.; Lu J.; Zhang T.	Research on Matching Supply and Demand of Tourism Resources in Jiaodong Economic Circle Based on Multi-source Heterogeneous Data; [基于多源异构数据的胶□□□圈旅游□源供需匹配□空特征]	2024	GIS	China	Asia
6	Cillis G.; Statuto D.; Picuno P.	Restoring biodiversity in a highly-intensive touristic urban area: A case study in the city of matera (southern Italy)	2019	GIS	Italia	Europe
7	Pardo M.ª.C.; Silva G.; Paiva S.	The role of big data in monitoring sustainability of tourism destinations: The case of north portugal region	2021	N/A	Portugal	Europe
8	Ammirato S.; Felicetti A.M.; Gala M.D.; Aramo-Immonen H.; Jussila J.	Knowledge management and emerging collaborative networks in tourism business ecosystems	2015	ICT	N/A	N/A
9	Di Pietro L.; Mugion R.G.; Renzi M.F.	Cultural technology district: A model for local and regional development	2014	ICT	Italia	Europe
10	Zhao J.-Y.	Research on the Evolution of the Quantity and Quality of Inbound Tourism Flow in Henan Province	2017	ICT	China	Asia
11	Nistor M.-M.; Nicula A.-S.	Application of gis technology for tourism flow modelling in the united kingdom	2021	GIS	UK	Europe
12	Zhu H.-Z.; Cao F.-D.	Tourist Flow Network Structure Characteristics and Its Flow Pattern Based on Geo-Tagged Photos: Taking the Yangtze River City Group as An Example; [基于地理□□照片的游客流□网□□构特征及其流□模式-以□子江城市群□例]	2020	GIS	China	Asia
13	Park C.; Kim Y.-R.; Yeon J.	Stronger together: International tourists "spillover" into close countries	2023	GIS	N/A	N/A
14	Li Y.; Cao H.	Prediction for Tourism Flow based on LSTM Neural Network	2018	ICT	N/A	N/A
15	Han J.; Ming Q.; Shi P.; Luo D.	Analysis on structural characteristics of regional tourism network and its influence mechanism from the perspective of multi-dimensional flow - Taking Yunnan Province as an example; [多□"流"□角下区域旅游网□□构特征及其作用机制分析——以云南省□例]	2021	GIS	China	Asia
16	Yu F.	Integrated operation path of the tourism products supply chain in China: Online intelligentization	2018	ICT	China	Asia
17	Rossi M.T.; De Sanctis M.; Iovino L.; Rutle A.	A multilevel modelling approach for tourism flows detection	2019	ICT	N/A	N/A

ID	Authors	Title	Year	Dimension	Country	Continent
18	Borowiecki K.J.; Castiglione C.	Cultural participation and tourism flows: An empirical investigation of Italian provinces	2014	N/A	Italia	Europe
19	Shao H.; Jin C.; Lu Y.; Du J.	Response pattern and driving mechanism of virtual tourism flow to high-speed rail construction in the Yangtze River Economic Belt; [□江□□□虚□旅游流□高□建□的响□格局及其□□机理]	2024	GIS	China	Asia
20	Pardo C.	Managing tourism development: a kit for action	2018	ICT	N/A	N/A
21	Glamuzina N.; Madžar I.; Putica J.	Regional aspects of modern tourism development of Bosnia and Herzegovina; [Regionalni aspekt suvremenoga turističkoga razvoja Bosne i Hercegovine]	2017	GIS	Bosnia-Herzegovina	Europe
22	Yang Y.; Wong K.K.F.	Spatial Distribution of Tourist Flows to China's Cities	2013	GIS	China	Asia
23	Kordha E.; Gorica K.; Sevrani K.	The Importance of Digitalization for Sustainable Cultural Heritage Sites in Albania	2019	ICT	Albania	Europe
24	Zhang J.; Jensen C.	Comparative advantage. Explaining Tourism Flows	2007	N/A	N/A	N/A
25	Carciotti S.	Co-designing a smart tourist destination: An innovative governance method	2021	ICT	N/A	N/A
26	Karipis K.I.; Tsimitakis E.N.; Skoultsos S.G.	Contribution of Visitor Information Centres to promoting natural and cultural resources in emerging tourism destinations	2009	N/A	Grecia	Europe
27		ACM International Conference Proceeding Series	2016	N/A	N/A	N/A
28	Li D.; Deng L.; Cai Z.	Statistical analysis of tourist flow in tourist spots based on big data platform and DA-HKRVM algorithms	2020	GIS	N/A	N/A
29	Cazzari C.; Martellozzo F.; Randelli F.	Evolution of built-up along the Sardinian coastal areas. Between economic development and ecological vulnerability; [Evoluzione del costruito nelle aree costiere della Sardegna. Fra sviluppo economico e vulnerabilità ecologica]	2022	GIS	Italia	Europe
30	Xing-zhu Y.; Qun W.	Exploratory space-time analysis of inbound tourism flows to China cities	2014	GIS	China	Asia
31	Qin J.; Li L.; Tang M.; Sun Y.; Song X.	Exploring the spatial characteristics of Beijing inbound tourist flow based on geotagged photos; [基于地理□□照片的北京市入境旅游流空□特征]	2018	GIS	China	Asia
32	Trunfio M.; Pasquinelli C.	Smart technologies in the covid-19 crisis: Managing tourism flows and shaping visitors' behaviour	2021	ICT	N/A	N/A
33	Du J.-Z.; Xv J.; Jin C.	Regional Virtual Tourism Flow and Its Influencing Factors Based on Baidu Index: A Case Study in Yangtze River Delta; [基于百度指数的□江三角洲虚□旅游流流□特征和影响因素分析]	2021	ICT	China	Asia
34	Belova A.V.; Belov N.; Gumeniuk I.	Modern Technologies in Tourism as a Tool to Increase International Tourism Attractiveness and Sustainable Development of the Kaliningrad Region	2021	ICT	Rusia	Europe
35	Michael Hall C.; Seyfi S.	Tourism and sanctions	2021	N/A	N/A	N/A
36	Khoo-Lattimore C.; Prideaux B.	ZMET: A psychological approach to understanding unsustainable tourism mobility	2014	N/A	N/A	N/A
37	Yang Y.; Sui X.; Liu Z.	Spatial pattern change of the network structure of China's inter-provincial virtual tourism flow	2022	TIC	China	Asia

ID	Authors	Title	Year	Dimension	Country	Continent
38	Leitis E.	The Role of Ecotourism in the Reduction of Anthropogenic Load on Natura 2000 Territories throughout Latvia	2011	N/A	N/A	N/A
39	Guedes A.; Faria S.; Gouveia S.; Rebelo J.	The effect of virtual proximity and digital adoption on international tourism flows to Southern Europe	2023	ICT	N/A	N/A
40	Liu S.; Zhang L.; Wu C.; Ge J.; Long Y.	Fine-grained spatiotemporal estimation of tourism flows leveraging cross-video collaborative perception	2024	ICT	N/A	N/A
41	Franco I.N.; Foronda-Robles C.; Rollán F.; Canales P.	Tracking Tourist Flows Through Wi-Fi Sensor Technology in Seville	2024	ICT	España	Europe
42	Casado-Díaz M.A.; Casado-Díaz A.B.; Casado-Díaz J.M.	Linking tourism, retirement migration and social capital	2014	N/A	España	Europe
43	Alfano I.; Bertacchini P.A.; Pantano E.	Promotion of cultural heritage: Bronzes of Riace in a cross-media approach	2008	ICT	Grecia	Europe
44	Qian D.; Luo W.	Design of Smart Tourism System in Urban Scenic Spots Based on Computer Virtual Reality Technology	2022	ICT	N/A	N/A
45	Siano A.; Confetto M.G.; Siglioccolo M.	A study on the services offered by three categories of Italian museums via their web sites	2009	ICT	Italia	Europe
46	Bera S.; Majumdar D.D.	Assessment of Tourism Carrying Capacity for the Sustainable Tourism Development of South Andaman, India	2023	N/A	India	Asia
47	Nurmagambetova A.; Baimukhanova S.; Pukala R.; Kurbanova K.; Kidirmaganbetova A.	Improvement of accounting in the hotel business in the transition to a digital economy	2020	N/A	Kazajstán	Asia
48	Javor A.	Statistical indicators on the relationship between croatian tourism and retail trade	2007	N/A	Croacia	Europe
49	Kuusik A.; Tiru M.; Ahas R.; Varblane U.	Innovation in destination marketing: The use of passive mobile positioning for the segmentation of repeat visitors in Estonia	2011	ICT	Estonia	Europe
50	Boiko V.O.; Boiko L.O.	PROBLEMS AND PROSPECTS FOR INNOVATION-DRIVEN DEVELOPMENT OF THE TOURISM INDUSTRY IN UKRAINE; [ПРОБЛЕМИ ТА ПЕРСПЕКТИВИ ІННОВАЦІЙНОГО РОЗВИТКУ ТУРИСТИЧНОЇ ГАЛУЗІ В УКРАЇНІ]	2022	N/A	Ucrania	Europe
51	Zhang Y.; Du J.	An Impact Study of the Hong Kong-Zhuhai-Macao Bridge on Regional Tourism Integration Development in the Guangdong-Hong Kong-Macao Greater Bay Area; [港珠澳大□□粤港澳大湾区区域旅游一体化□展影响的□量研究]	2023	GIS	China	Asia
52	Wang Y.; Xi M.; Chen H.; Lu C.	Evolution and Driving Mechanism of Tourism Flow Networks in the Yangtze River Delta Urban Agglomeration Based on Social Network Analysis and Geographic Information System: A Double-Network Perspective	2022	GIS	China	Asia
53	Sofield T.H.B.	Border tourism and border communities: An overview	2006	N/A	International	International

ID	Authors	Title	Year	Dimension	Country	Continent
54	Methi P.; Fatma A.; Bhatt V.; Pathak P.; Sinha B.; Ravi Kumar V.V.	Assessing the Perception of Consumers Towards Smart Tourism Destination	2023	ICT	India	Asia
55	Marchesani F.; Masciarelli F.; Ceci F.	Digital trajectories in contemporary cities: Exploring the interplay between digital technology implementation, the amplitude of social media platforms, and tourists inflow in cities	2024	ICT	Italia	Europe
56	Liu J.; Ma Y.	A study on the coupling process and pattern of tourism flow and regional traffic in five provinces of Northwest China from 1995 to 2014	2017	GIS	China	Asia
57	Şchiopu A.F.; Pădurean A.M.; Ţală M.L.; Nica A.-M.	The influence of new technologies on tourism consumption behavior of the millennials	2016	ICT	Rumanía	Europe
58	Gao X.; Gu Z.; Niu S.; Ryu S.	Effects of International Tourist Flow on Startup Financing: Investment Scope and Market Potential Perspectives	2022	N/A	N/A	N/A
59	Yan S.; Zhang H.; Jin C.	Space Association Features of Domestic Tourist Flow Network in the Shanghai Metropolitan Area; [都市区国内旅游流网口空口关口特征]	2021	GIS	China	Asia
60	Gómez López C.S.; Barrón Arreola K.S.	Tourism and the environment in Mexico: evidence of the relationship in the short and long term	2024	GIS	México	LATAM
61	Berzina I.; Lauberte I.	The model of automation and extension of tourism economic impact assessment in specific regions	2018	ICT	N/A	N/A
62	Raun J.; Shoval N.; Tiru M.	Gateways for intra-national tourism flows: measured using two types of tracking technologies	2020	ICT	Estonia e Israel	Europe and Asia
63	Xuelan C.; Yelin F.; Xueqing S.; Jinglong L.	Spatial distribution characteristics of network structure of tourism flow in five major urban agglomerations of coastal China	2021	GIS	China	Asia
64	Gouveia J.P.; Seixas J.; Palma P.; Duarte H.; Luz H.; Cavadini G.B.	Positive Energy District: A Model for Historic Districts to Address Energy Poverty	2021	N/A	N/A	N/A
65	Gao H.	A study on the spatio-temporal evolution of Tibetan inbound tourism flow network based on social networks	2021	ICT	China	Asia
66	Kyrylov Y.; Hranovska V.; Boiko V.; Kwilinski A.; Boiko L.	International Tourism Development in the Context of Increasing Globalization Risks: On the Example of Ukraine's Integration into the Global Tourism Industry	2020	N/A	Ucrania	Europe
67	Kovács Z.; Vida G.; Elekes Á.; Kovalcsik T.	Combining social media and mobile positioning data in the analysis of tourist flows: A case study from Szeged, Hungary	2021	ICT	Hungría	Europe
68	Skolilova P.; Riha Z.	Emerging markets for an air transport	2016	N/A	N/A	N/A
69	Liu D.; Chen J.; Jia Y.	Characteristic of tourist flow network in Chengdu-Chongqing urban agglomeration under the influence of high-speed railway; [高口影响下成渝城市群旅游流网口的口化特征]	2020	GIS	N/A	N/A
70	Wang L.; Wu X.; He Y.	Nanjing's intracity tourism flow network using cellular signaling data: A comparative analysis of residents and non-local tourists	2021	ICT	China	Asia

ID	Authors	Title	Year	Dimension	Country	Continent
71	He J.; Wang M.; Xi G.; Zhu H.; Dai J.; Zhang X.	Research Progress and Prospects of Chinese Cybergeography Against the Background of the Digital Transition; [数字化□型背景下中国网□信息地理研究□展与展望]	2023	N/A	China	Asia
72	Domènech A.; Gutiérrez A.	A GIS-Based evaluation of the effectiveness and spatial coverage of public transport networks in tourist destinations	2017	GIS	España	Europe
73	Nistor M.-M.; Nicula A.-S.; Dezsi Ş.; Petrea D.; Kamarajugedda S.A.; Carebia I.-A.	Gis-based kernel analysis for tourism flow mapping	2020	GIS	Rumanía	Europe
74	Zubiaga M.; Izkara J.L.; Gandini A.; Alonso I.; Saralegui U.	Towards smarter management of overtourism in historic centres through visitor-flow monitoring	2019	GIS	N/A	N/A
75	Yang Y.; Liu H.; Li X.	The World Is Flatter? Examining the Relationship between Cultural Distance and International Tourist Flows	2019	N/A	N/A	N/A
76	Rivera-Trigueros I.; Gutierrez-Artacho J.; Olvera-Lobo M.-D.	Corporate Websites and their Multilingual Dissemination. An analysis of Southern Spain Tourism Sector	2022	ICT	España	Europe

Climate Adaptation in the Context of Cultural Heritage

The discussion around climate change more often than not centers around threats to human communities and their way of living, as well as ecosystems, regarding threats to fauna and flora. However, another area that has known the effects of climate change is tangible cultural heritage, buildings and sites in particular, as they are the most exposed pieces of those that form what is called human heritage and identity. Such artifacts are under stress from climatic change and the extreme weather phenomena that it brings. In this section, we synthesize two literature sources, *The future of our pasts: Engaging cultural heritage in climate action outline of climate change and cultural heritage* [122] from ICOMOS, and a thorough review of climate change impacts and practical ways of adapting heritage buildings to it, named *Adaptive measures for preserving heritage buildings in the face of climate change: A review* [123]. The ICOMOS report provides a methodological approach to adaptation planning, presented in the following subsection. The subsequent subsection summarises ICOMOS report's three stages of carrying out the adaptation which include the stage of Knowledge and Understanding, then the stage of Planning and Implementation, and finally the identification of Opportunities, Constraints and Challenges. We briefly present adaptation solutions as discussed in [123], in an effort to provide the whole scope of adaptation of heritage buildings to climate change.

A methodological approach to adaptation planning

ICOMOS' methodological approach establishes a comprehensive framework for preparing the adaptation process for cultural heritage. Eleven successive steps are described, which take a multi and interdisciplinary approach, combining technical and social sciences.

Step 1. Heritage inventory and documentation Inventory preparation is a fundamental step in heritage management and climate strategy. Developing a comprehensive inventory serves as the basis for subsequent methodological advances. An effective inventory should be tailored to reflect the scale, nature, and complexity of the heritage resource. To enhance the inventory's value in the context of climate change, it should account for heritage Values as assets for climate action and include considerations of climate vulnerability and Adaptive Capacity[1].

For a nuanced and inclusive approach, the inventory process may integrate participatory cultural mapping techniques, which involve identifying, documenting, and recording both tangible and intangible heritage elements. This approach should emphasize place-based narratives of change and local knowledge, considering their role in maintaining and adapting heritage values over time. Documenting these elements ensures that the inventory is sensitive to local cultural contexts and establishes a foundation for climate-resilient management.

Step 2. Heritage values assessment Taking a values-based approach is essential to understanding the significance of heritage in a changing climate. This involves assessing both tangible and intangible heritage values and incorporating them into the inventory. The assessment should go beyond statements of Cultural Significance, focusing on local current heritage values and knowledge systems as assets for climate adaptation. For World Heritage

[1] *Adaptive capacity* - The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. This glossary entry builds from definitions used in previous IPCC reports and the millennium.

Sites, this process should include statements of Outstanding Universal Value. An effective assessment of current heritage values sets the groundwork for a more targeted climate change risk evaluation.

Step 3. Impact assessments Conducting Heritage Impact Assessments (HIA) is a critical step in determining the potential impacts of climate change on cultural heritage sites. Existing HIA methodologies should be adapted to address climate change-specific factors, considering not only direct impacts on the physical site but also the broader implications for associated communities. The ICOMOS framework from 2011 can be revised to incorporate a circular economy perspective, thereby enabling a more holistic evaluation of heritage conservation in the face of climate change.

Step 4. Development of a vulnerability matrix A Vulnerability Matrix should be constructed to systematically evaluate potential climate change impacts based on the best available climate science. This matrix should include variables such as climate sensitivity, exposure to hazards, and the established heritage value or Cultural Significance of the site. The matrix provides a structured approach to categorizing risks and helps in prioritizing sites and heritage elements that are most at risk.

Step 5. Vulnerability indicators A range of vulnerability indicators should be selected, that can be used to quantify the aspects of heritage most affected by climate change. These indicators serve as measurable proxies to gauge levels of vulnerability, providing critical reference points at various scales (site, regional, national) to guide policy and planning decision-making processes. The selected indicators should be adaptable to both tangible and intangible heritage and be integrated into broader climate vulnerability assessment frameworks.

Step 6. Heritage documentation and monitoring Heritage documentation and monitoring are vital components of an adaptive heritage management strategy. Standardized data collection methods should be employed nationally and internationally to enable comparative analysis and informed decision-making. A combination of traditional documentation techniques and new technical solutions, such as GIS mapping and remote sensing, can support a multi-scale analysis of the progression of climate change impacts.

Step 7. Conservation management planning Develop a conservation management plan that integrates climate adaptation strategies. This plan should be structured with short, medium, and long-term objectives to manage, adapt, and mitigate climate change impacts on heritage sites through integrated Policies.

Step 8. Risk assessment at macro scale Perform a risk assessment at a national or regional scale by analysing the likelihood and severity of potential climate hazards. This assessment can utilize data from other sectors, such as flood management and biodiversity, to gain a comprehensive understanding of the risks. The insights from this risk assessment should inform the prioritization of heritage sites and the development of national or regional Disaster Risk Management plans.

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Step 9. Vulnerability assessment at micro scale At a local/site level, conduct a detailed vulnerability assessment that considers the sensitivity, exposure, Adaptive Capacity, Impacts, and Resilience of both tangible and intangible heritage. This micro-scale analysis should view heritage as part of a human-environment system, where Adaptive Capacity and Resilience largely reside in the human element. Assessing Adaptive Capacity involves understanding community responses, local knowledge, and the resilience of heritage management practices in mitigating and adapting to climate impacts. Additionally, the assessment should evaluate the specific climate change impacts on the site and the ability of the heritage and its associated community to withstand, recover, and adapt to these changes.

Step 10. Application of the climate vulnerability index (CVI) Utilize the Climate Vulnerability Index[2] (CVI) to perform rapid assessments of climate Impacts on the cultural significance of a site. Assessment can be performed for a particular site, as well as a "thematic group" of sites, that belong to the same category or have particular characteristics in common.

Step 11. Adaptation planning Based on an informed assessment of Vulnerability, develop adaptation strategies at the site level to design Adaptation Pathways that best protect the identified Cultural Significance. Adaptation planning should be multi-scalar, with site-level actions feeding into regional and national Adaptation strategies in response to the broader macro assessment of Risk. Planning methodologies should follow a multi-sectoral, interdisciplinary approach to ensure heritage considerations are included within strategies for cross-cutting sectors such as agriculture, tourism, and land management. This comprehensive planning framework helps safeguard cultural heritage and enhances its resilience, ensuring it contributes to sustainable development goals and remains integral to climate action strategies at all scales.

Knowledge and Understanding, Planning and Implementation, Opportunities, Constraints and Challenges

This section explores the critical elements necessary for an effective cultural heritage adaptation strategy in response to climate change. It begins with building a comprehensive knowledge base through values-based approaches, participatory governance, and data collection. It then addresses the technicalities of planning and implementation, followed by the exploration of opportunities, constraints, and challenges in integrating cultural heritage into broader climate adaptation frameworks. Each stage is crucial for ensuring that cultural heritage resilience is achieved and maintained in the face of evolving climate risks.

Knowledge and Understanding

1. Values-Based Approaches and People-Centered, Participatory Governance

[2] Climate Vulnerability Index (CVI) - A rapid assessment methodology that focuses on climate risks to the Outstanding Universal Value (OUV) of World Heritage sites, and is being developed with the support of ICOMOS. The CVI is a transparent, repeatable methodology that uses best available information and can be undertaken in a two-day workshop and is applicable across all types of heritage sites.

Cultural heritage can support adaptation when Cultural Values are integrated into adaptation Governance, helping to guide adaptation Options and strengthen Enabling Conditions. Values-based Approaches should explore the concept of cultural and natural commons and recognize that different levels of Cultural Significance do not necessarily prioritize heritage effectively in the adaptation context. It is essential to consider various types of Cultural Significance and heritage, ensuring under-represented sites, such as indigenous heritage in colonized regions, are included to promote social cohesion and facilitate adaptation. Using what people value about places can guide Resiliency planning by leveraging heritage communities, methodologies, and Values assessment methods (e.g., World Heritage and ICOMOS) for adaptation planning and capacity building. Heritage plays a critical role in promoting social cohesion, integration, and equity by conserving the sense of Place and enabling inclusive community stewardship. Adaptation Pathways should include participatory and transparent inventorying and cultural mapping to mobilize communities and inform Climate Governance. Social psychology can contribute to building acceptance of Policy or systemic change and enhancing Adaptive Capacity by addressing how communities perceive and respond to Risk and Climate Variability. Heritage methodologies should support people-centered approaches for adaptation Governance by following a country-driven, gender-responsive, and participatory approach, considering vulnerable groups and integrating Local Knowledge and Indigenous Knowledge into policies and actions, as stipulated in Article 7 of the Paris Agreement. Improving and adapting existing methodologies or developing new approaches is necessary to ensure effective citizen participation, aligning with the European Cultural Heritage Strategy for the 21st century (CM/Rec(2017)1).

2. Using the Data-Collection Aspects of Heritage to Support Effective Adaptation

Before implementing adaptation actions, baseline information is needed, including knowledge of projected climate change Hazards, understanding potential direct and indirect Impacts, and an assessment of the vulnerability of heritage at Risk and its Cultural Significance (movable, immovable, and intangible). Adaptation planning must consider both slow onset (e.g., sea level rise) and rapid onset (e.g., extreme weather events) Impacts, as well as those in between (e.g., multi-year drought). The specific baseline data required will vary based on the prioritization of Impacts and heritage types/Values, and regions like island states may prioritize coastal sites. Acquiring, managing, and consolidating data related to climate Risks and vulnerabilities is essential, and existing datasets from other sectors (e.g., tourism, agriculture) may be valuable for cultural heritage. Methodological approaches for Risk and vulnerability assessments should be selected based on local conditions, using macro-scale assessments for broad regional overviews and micro-scale assessments for holistic, site-specific evaluations. Sensitivity, Exposure, and Adaptive Capacity of Cultural Significance should be analyzed, considering factors like physical characteristics, community Resilience, and traditional Livelihoods. Detailed mapping of Hazards, including direct and indirect Risks, and creating predictive methods for future projections are crucial. Additionally, Adaptive Capacity at the Human System level should be evaluated, considering human and financial resources, legislation, and infrastructure. Understanding the Impacts of recent or historical climate events (e.g., damage,

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costs, effects on Livelihoods) and learning from global experiences are vital to inform adaptation and identify potential Tipping Points.

3. Using Heritage Monitoring to Support Effective Adaptation

Collecting data using diverse monitoring techniques is essential for understanding climate change, supporting decision-making on adaptation actions, and evaluating the effectiveness of interventions. Long-term monitoring (over 30 years) is crucial due to the nature of climate change. It should cover climate Impacts on heritage places, artefacts, communities, and traditional ways of life, with new and low-tech methods explored to address data gaps. Success of adaptation actions should be measured with indicators, and data should be widely disseminated through networks and platforms despite challenges with long-term data management and archiving. Solutions include open data, inter-sectoral approaches, and capacity building. Sharing data between similar climates or heritage types, citizen science, and community-based programs can be effective, although they require support. Standardizing methods is necessary for consistency, and diverse sources of knowledge—including Local Knowledge, Indigenous Knowledge, and institutions—should be integrated, along with training professionals in the traditions of the indigenous communities.

4. Harnessing Heritage as an Asset for Climate Change Adaptation; Past, Present and Future

Identifying examples of past social adaptability to environmental change, such as traditional spatial Land Use and architecture adapted to local climate conditions, can provide valuable insights for current adaptation strategies. Understanding how communities responded to human and natural catastrophes, like war or colonization, helps examine resilience and sustain cultural heritage even through radical losses. Cultural heritage serves as inspirational evidence of human adaptation and can support the development of a common Risk culture for climate Extremes, using historical events as lessons for future Disaster Risk Reduction. Valuing Local Knowledge, Indigenous Knowledge, and endogenous ways of Knowing, such as fire regimes for biodiversity in Australia or forest management in Sweden, is crucial for Ecosystem-based adaptation. These knowledge systems are dynamic and can be integrated into modern resource management practices, but must be used with free, prior, and informed consent. Sharing heritage science and Conservation methodologies with other sectors can also support sustainability efforts, including creating a database of embodied energy for traditional materials to compare their environmental impact against modern alternatives.

5. Sharing Good Practice Examples

Sharing knowledge and information on climate change Impacts and adaptation solutions across the heritage profession and other sectors (e.g., agriculture, tourism, biodiversity) is crucial at local, national, and international levels. A thematic approach, such as focusing on physical characteristics, heritage type, or specific climate Risks, can facilitate effective exchanges of best practices. Multi-disciplinary approaches and cross-sectoral collaboration are needed to promote shared data sources, establish new networks, and enhance public outreach and education. Developing a toolbox of actions that addresses climate uncertainty, harnesses technological developments, and considers environmentally sustainable options is essential.

Dissemination, communication, education, and training should be integrated into these strategies to effectively build resilience and adapt to climate change.

Planning And Implementation

6. The Role of Heritage in Supporting Disaster Risk Reduction (DRR)

Linking climate change and Disaster Risk Reduction (DRR) is essential, as climate Impacts on cultural heritage are often experienced through Climate Variability and Extremes. There is a need to address disconnects between Policies for climate change adaptation and DRR, which are often managed by separate agencies with little coordination. Effective Disaster Risk Reduction Planning should include prevention, preparedness, response, and recovery through integrated multi-Hazard Risk Assessments that incorporate cultural heritage. This approach can transform communities from being recipients of salvage efforts to active protectors of their heritage. Local Knowledge and responses to recent Extreme Weather Events should inform new DRR policies. Integrated approaches like Ecosystems-Based DRR can enhance Adaptation Pathways for both natural and cultural heritage. The Sendai Framework for Disaster Risk Reduction[3] emphasizes integrating climate change adaptation into DRR strategies, building resilience, and reducing vulnerability while minimizing the impact on Cultural Significance. International coordination is crucial to ensure protection for poorer nations and share expertise in DRR and cultural heritage management.

7. Adaptation Planning for Heritage – Policy and Actions

Heritage must be integrated into Adaptation Pathway planning at all levels, from national policies to site-specific Management Plans, alongside other community assets. This involves adopting Risk and vulnerability assessments, such as the Climate Vulnerability Index (CVI), and prioritizing Risks and responses based on Impact and severity. An inter-sectoral approach is essential to ensure heritage is a key component in urban and territorial planning and contributes to social and institutional reconstruction after Disasters. Effective adaptation policies should be developed at both macro (strategic) and micro (site-specific) levels, with Multi-level Governance to avoid conflicts and identify mutual benefits. Evaluating adaptation plans should include metrics for reducing vulnerability, transparent reporting, and learning from success and failure. Training and education are necessary for implementing and monitoring adaptation actions, fostering inter-disciplinary cooperation, and ensuring that heritage is considered in Disaster planning and recovery strategies. Managing threats from Maladaptation is crucial by considering heritage and Cultural Significance results in climate adaptation works (e.g., flood defenses, retrofitting for Energy Efficiency).

8. Coordination of Heritage Adaptation within wider National/ Regional/International Policies

[3] *Sendai Framework for Disaster Risk Reduction* - The Sendai Framework for Disaster Risk Reduction 2015–2030 outlines development for all countries established by the United Nations through a participatory process and elaborated in the 2030 Agenda for sustainable development, including ending poverty and hunger; ensuring health and well-being, education, gender equality, clean water and energy, and decent work; building and ensuring resilient and sustainable infrastructure, cities and consumption; reducing inequalities; protecting land and water ecosystems; promoting peace, justice and partnerships; and taking urgent action on climate change.

Cross-cutting issues between the Paris Agreement, Sustainable Development Goals, and the Sendai Framework for Disaster Risk Reduction highlight the need to integrate climate change Mitigation Policy and adaptation planning at national levels. Key concerns include the Energy Efficiency of historic buildings, cultural landscape transformation, and safety of heritage under Climate Extremes. Benchmarking and sharing best practices can enhance coordination of heritage adaptation across sectoral Policies. Special attention is required for areas with shared values or sensitive information, such as Indigenous heritage or transboundary properties. Heritage considerations should be integrated into building and planning Policies, national building codes, and Sustainability rating schemes to recognize the environmental benefits of conserving cultural heritage.

9. Managing Change

The dynamic nature of the Values that contribute to Cultural Significance poses a challenge for Conservation practices, particularly as climate change may necessitate radical interventions. The Sendai Framework's emphasis on "Build Back Better" in post-Disaster recovery raises concerns for heritage professionals regarding the loss of Authenticity and Integrity, such as replacing traditional materials with modern alternatives. Taking a flexible, community-driven approach to Conservation can help the sector adapt and create new ways to engage people. Addressing how change and Conservation can be reconciled requires a participatory approach to decision-making, with guidance for site managers and the use of UNESCO World Heritage Sites as testing grounds for updating approaches to Integrity and Authenticity. When Adaptive Capacity is exceeded and loss is inevitable, strategies should be developed for Interpretation, Presentation, and Preservation of memory, such as farewell ceremonies or maintaining traditions even as communities face displacement. Expanded use of removal, relocation, and ex-situ Preservation may be necessary, but these decisions must be transparent, people-centered, and involve local communities in deciding which losses are acceptable. Heritage sites could also be valued as exemplars of climate change Impacts, reflecting a significant stage in human history. Raising awareness, disseminating knowledge, and building capacity among stakeholders are essential, along with recording and archiving at-risk sites, and promoting adaptive re-use to ensure historic sites retain their relevance and use value over time.

10. Opportunities

Adapting to capitalize on positive Impacts from climate change involves harnessing diverse knowledge systems, including traditional, indigenous, spiritual, and research-based approaches, as outlined in the Paris Agreement (Article 7.5). These knowledge systems can serve as tools for climate response and provide guidance for integrating adaptation into socioeconomic and environmental policies. New technologies can enhance adaptation strategies through research and experimentation, while iconic spiritual, cultural, and natural values can promote social cohesion and public engagement, highlighting the relevance of heritage in climate adaptation. Heritage sites can foster dialogue within communities and be used to educate the public on climate change, while also offering ecological benefits and potentially becoming more appreciated and visited due to changing climates.

Heritage can stimulate development sectors when integrated into post-disaster and post-conflict reconstruction and recovery efforts, as noted in the UNESCO and World Bank Group's CURE Position Paper (2018). Climate change may also lead to new discoveries or appreciation of culture, such as the exposure of sub-surface archaeology due to dry weather or soil erosion. Engaging with citizen science allows communities to actively participate in adaptation, monitoring, and recording activities, which builds awareness and promotes community involvement in developing effective climate responses.

11. Uncertainty Uncertainty is inherent in climate change due to varying Emission scenarios and climate responses, but it should not be an excuse for inaction. Flexible Policies and resilient management systems are needed to address uncertainty, along with transparent communication about the degree of uncertainty. Leadership and a clear vision are essential to overcome barriers to engagement and action. Implementing adaptable solutions, planning for multiple emissions scenarios, and using holistic decision-making can help manage uncertainty. Where knowledge gaps exist, the risks of uninformed action versus inaction should be clearly communicated to guide research and support community-based decision making.

12. Costs and Benefits of Adaptation Activities Effective adaptation for heritage requires financial and human resources, with a focus on Cost-effectiveness and responsible resource allocation to prevent waste. Heritage adaptation offers Co-benefits such as building resilience, Poverty Eradication, and sustainable management of resources, as outlined in the Paris Agreement. Cost-effectiveness methodologies, life cycle assessments, and Circular Economy models should be applied to optimize heritage Conservation. Empowering indigenous communities and considering tourism as both a Risk and funding source are essential. Existing Conservation methods may need to adapt to address new climate challenges, including supporting communities in preparing for inevitable Losses and Damages. Flexibility in building elevation, relocation, and use of innovative Policy tools like rolling conservation protections may be necessary. Conservation materials may need to be replaced with more sustainable options, emphasizing preventive Maintenance and local materials. Conservation practices must integrate tangible and intangible heritage, considering traditional skills and safe practices for cultural bearers, as increased Climate Extremes require fast and effective repairs, highlighting the urgency of preserving traditional trades and adapting heritage management systems.

13. Existing Barriers to Adaptive Management of Heritage That May Limit Attempts to Address Climate Change Recognizing and addressing institutional, financial, technical, and social barriers is crucial for effective heritage adaptation. Barriers include differing stakeholder interests, inadequate sectoral engagement, limited understanding, ineffective technical approaches, lack of resources, and insufficient political will and public awareness. Poor communication between groups and decision-makers can exacerbate these issues. Open dialogue is needed to acknowledge how the complexity of heritage Values and Cultural Significance can impact adaptation efforts, and how existing Policies and regulations, including those focused on heritage protection or mitigation (e.g., Energy Efficiency, building codes, planning Policies), can pose additional barriers, especially for cross-border heritage subject to multiple jurisdictions.

14. Sustainability Sustainability is crucial for addressing climate change and intersects with heritage through Sustainable Development Goals, emphasizing the sustainable reuse of structures for economic and social benefits. Heritage adaptation involves raising awareness of the sustainability of traditional and historic ways of living and ensuring that conservation actions are sustainable. This includes valuing long-term stewardship traditions, calculating the carbon benefits of historic buildings, and researching traditional adaptation pathways for modern lessons in sustainability. Heritage methodologies should support community-centered adaptation, while tried-and-tested approaches should be prioritized. Sustainable tourism development and responsible management of collections and data are also essential components.

Climate change Risks to Cultural Heritage and Practical Adaptation Measures

Impacts to cultural heritage linked to climate change have been thoroughly catalogued in [123], with five categories including temperature, moisture, precipitation, wind and solar radiation. Some more specific risks can be classified under these general categories into two further categories: a) Direct impacts and b) Indirect impacts. Under Direct impacts from temperature, [123] classifies thermoclasty, cryoclasty, haloclasty, biodeterioration and biodeterioration decay. Indirect impacts from temperature include structural instability from thawing permafrost, biodeterioration from thawing permafrost and erosion from bioprotection decay.

For moisture, classified direct impacts are haloclasty, cryoclasty, (sub-)efflorescence, biodeterioration and corrosion of metal, differential expansion in hygroscopic materials, excessive swelling and shrinkage of hygroscopic materials which can all be attributed to rising damp from soil. Further direct impacts from air moisture include leaching and cracking of glass, darkening and loss of transparency of the stained glass, corrosion of metals again, differential expansion in hygroscopic materials, excessive swelling and shrinkage of hygroscopic materials. Indirect impacts from moisture include structural instability from high-absorbing trees and structural instability from clayish soil.

Direct precipitation impacts include haloclasty, cryoclasty, polishing,pitting and slurry, chemical decay, biodegradation, ponding phenomenon, roofing elements dislocation, bulging and collapse, hygrothermal inefficiency, corrosion, infiltration and related damages, while indirect impacts only include structural instability from high-absorbing trees.

Direct impacts attributed to wind include structural destabilization, guttering failure, alveolation, denudation, soiling pattern, deep-seated moisture. Classified as indirect impacts from wind are storm tree damages, biological growth from Wind-Driven Rain (WDR), hygrothermal inefficiency of envelopes from WDR, erosion from bioprotection decay, frost damages from WDR, crystallization processes from WDR, polishing, pitting and slurry from WDR.

Finally, direct impacts from solid radiation are thermoclasty, mechanical biodegradation, chemical biodegradation and photoxidation. Indirect impacts include dust deposition from photophoresis, and discolouration from carbon particles.

[123] highlights certain practical adaptation measures to combat the aforementioned impacts. With respect to temperature adaptation measures, in order to combat cryoclasty (freeze-thaw cycles) and thermoclasty, several measures apply such as soft caping, casing, vegetation cap, shading shelters, and membrane enclosure which unfortunately are situational, while regular façade cleaning is a welcome addition. Bioprotection decay can be combated by the planting of vegetation. Biodegradation due to thawing permafrost is an issue that can be addressed by specialised coatings, structure elevation to avoid permafrost, and improving upon the drainage systems. Passive solutions to mitigate differential settlements due to thawing permafrost include strategic vegetation planting, seasonal insulation, solar refrigeration technologies, underfloor ventilation and structure elevation based on modern techniques such as stilts/piles, pads and wedges, screw jack foundations, spaceframe system foundations, pad and post surface foundations. Thermosyphons also help in combating permafrost as well as thermopiles to conduct thermal energy.

As regards adaptation measures to combat moisture, rising damp must be reduced in order to avoid its impacts. Measures include impermeable to permeable landscaping, redesign and installation of ground drainage systems, lowering ground level, cleaning of façades, mechanical interruption (DPC), chemical interruption, electro-osmatic systems and electromagnetic processes, clay barriers, breathable paint and ventilation systems including wall-based, Knapen siphons, Shrijver stones and sub-floor ventilation. A chemical way to combat rising damp effects would be to resort to changing solubles present in moisture and applying crystallisation modifiers/inhibitors. Measures to combat lixiviation and glass corrosion from air moisture include external protective glazing (EPG) and sol-gel coatings. Antioxidation coating can be used to combat corrosion of metals from air moisture, while degradation of stone can be combated with an appliance of waterproof coating. Structural impacts due to soil moisture can be combatted with underpinning, documentation of vegetation around buildings, watering closely located trees, vertical cut-off walls, expanding resin injection and lime piles.

Measures to combat precipitation include improvement of the roof system, such as improvement of verges and edges, cut slate edges, lead skew, installation of watergates, storm roll, augmentation of original details, adding new details. Another helpful improvement is that of the drainage system, by creating soakaways, installing wire balloons, rodding point/eye, anti-backflow valves, grill covered gulley traps and french drains. Measures against WDR damages include application of EPG and storm glazing, sealing to prevent infiltration of water, waterproof coating, and applying coats on metals. Flooding related issues can be combatted with impermeable to permeable landscaping, sealers, permanent and temporary barriers (such as floodgates, bladders, sandbags, wrappings), pumps, snap-on cover, anti-backflow valve, elevation of utilities systems, elevation of building through rigid or adaptive elevation (buoyant foundation or hydraulic lift and anchoring system). Roof element detachment can be combatted by mortar application, cheek nails and snow board placement. Finally bulging can be addressed by soft capping and strengthening by utilising injections and connectors.

Regarding measures against wind, material decay caused by wind can be identified and mitigated by windbreak or strategically placed vegetation or specific protective coating that addresses the particular problem the presence of the wind exacerbates, such as salt crystallisation or deposition of pollutants. Areas which frequently suffer from storms, may need protection by storm panel system, including shutters, solid storm panels, flexible wind abatement systems and perforated metal panels. Tree removal may be needed in order to avoid falling trees structural damage. Structural damage from wind often concentrates on roof elements due to uplift and shear pressure as well as lateral load, therefore measures to address roof tile detachment include cheek nails, fixing roof tiles with mortar, hooking reinforcement, taping the roof deck seams, using tighter nail spacing, fasten drip edges and gutters. Struss addition can help with roof component overload, truss element connection reinforcement can mitigate roof component tilting, and roof element anchorage reinforcement can help with roof element displacements.

Finally, measures against solar radiation can be broken up in measures against UV photodegradation, against biodegradation, thermoclasty and cracking, and against IR radiation. Against UV photodegradation a UV opaque layer can be applied on wood surfaces. Moreover, UV absorbers and stabilising agents can also be applied on wood. Protective plastic film with UV absorbing nanofillers can be applied on glazing historical surfaces to combat UV photodegradation. Vegetation can shield historical materials form solar radiation caused biodegradation, thermoclasty and cracking. Thermoclasy and cracking caused by IR radiation can be addressed by high albedo coating for roofing, and reflective coating for porous materials. Photophoresis caused by IR can be addressed by applying adhesive low-emissivity plastic films on glazing, as well as low emissivity glass replacements. Curtains and draperies and planting vegetation are two further non-destructive ways of reducing solar radiation caused photophoresis effect.

Generation of 3D Digital Models

Heritage structures and artifacts play a vital role in the modern world, acting as links between the past and present while illustrating the evolution of human civilization over time. The architecture, materials, and accessibility of each heritage building tell a story about the geopolitical, sociocultural, and economic conditions of the era in which it was constructed. As a result, documenting, conserving, and restoring these components is essential for learning from the triumphs and challenges of the past, helping us shape a stronger future. Documentation involves the systematic process of capturing, recording, and preserving detailed information about heritage sites and building. The generated information can include detailed measurements and drawings, high-resolution photographs, historical records and descriptions, as well as 3D digital models.

3D digital models represent the most advanced form of heritage documentation, providing a virtual replica of the structure. Created using specialized software that processes data from 3D laser scanning or photogrammetry, these models offer several key benefits. They ensure spatial accuracy by capturing the exact dimensions and proportions of the heritage site, enabling precise measurements and analysis from any perspective. Additionally, 3D models provide a highly detailed representation, capturing intricate features like carvings, textures, and surface imperfections that go beyond traditional documentation methods. Moreover, they enhance accessibility and interactivity, as these models can be easily shared online, allowing both researchers and the public to explore the site virtually from anywhere. Furthermore, they can be integrated into virtual reality and augmented reality experiences for immersive learning and engagement.

Photogrammetry

Photogrammetry involves extracting information from images to derive 3D measurements and is typically categorized into aerial and terrestrial types, based on the camera's position relative to the object of interest. Aerial photogrammetry often leads to the creation of maps and terrain models, whereas terrestrial photogrammetry generates 3D models and point clouds. The advent of Unmanned Aerial Vehicles (UAVs) has blurred the distinction between these categories by combining features of both approaches.

Photogrammetric Process

The fundamental steps of a photogrammetric process can be outlined as follows.

Image Capture

Acquiring photogrammetry footage involves a structured process that varies depending on the specific application and tools used. However, certain core principles must be followed, as the quality of the captured data greatly influences the final 3D model. Effective planning is the cornerstone of a successful photogrammetry project. This begins with identifying the target area or object, determining optimal camera positions, and accounting for factors like lighting and shading. This planning stage is crucial to ensure conditions are ideal for accurate and comprehensive data collection. The next step is selecting the appropriate image capture method, which can vary based on the application, such as using handheld cameras, UAVs, or turntables.

In photogrammetry, images must overlap to ensure accurate alignment and create a detailed 3D model. When shooting outdoors, managing lighting conditions is crucial, as very bright or dark light can present challenges. Hard shadows or changing light sources, such as a setting sun, can complicate photo alignment by requiring the camera to adjust to multiple light settings. To avoid these issues, photographers should aim to capture scenes when the light is more diffused, such as on cloudy days or during early morning hours. For indoor shoots, lowering the shades helps reduce strong shadows and creates a more evenly lit environment. Diffused indoor lighting from overhead fixtures or shaded lamps is ideal, as long as it doesn't cast harsh shadows. It's also important to minimize the presence of reflective or transparent surfaces, which can be difficult to align in a 3D scene. Wet surfaces should also be avoided due to the reflections they may create. Finally, the scene must remain still throughout the capture process. Any movement, such as a bumped chair or a new footprint in a dusty area, can result in blurring and disrupt the quality of the capture. To prevent this, it’s advisable to tidy the space beforehand and eliminate any potential for mid-process changes.

In addition, consistent camera settings are essential for producing high-quality, aligned images. It is recommended to shoot in manual mode to control the camera’s ISO, aperture, shutter speed, and white balance, ensuring that these settings remain the same for every shot. If using more than one camera or phone, make sure all devices use identical settings throughout the shoot to maintain uniformity.

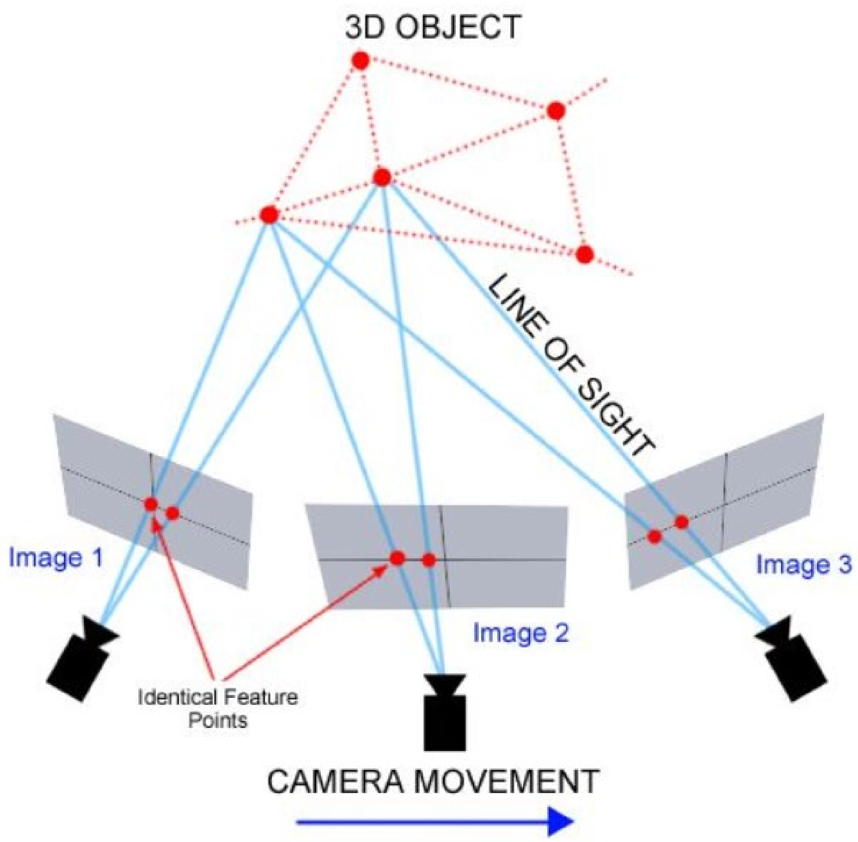


Figure 40 Camera movement during the photogrammetry process

Here are the key camera settings to consider:

- **ISO**: To avoid grainy images that can interfere with alignment and texturing, it's best to keep the ISO as low as possible. An ISO of 100 is ideal, though settings up to 800 may be used if necessary.
- **Aperture**: A large depth of field is important to ensure that everything in the scene remains in focus. An aperture between f/9 and f/13 generally works well for most photogrammetry projects.
- **Shutter Speed**: To avoid motion blur, a shutter speed of 1/200 or faster is recommended. If lower shutter speeds are required due to low light, the camera should be mounted on a tripod for stability. Once set to properly expose the main subject, the shutter speed should not be adjusted further.
- **White Balance**: The white balance must be set manually to maintain a consistent color temperature throughout the shoot. The use of white balance must be avoided. In scenes with mixed lighting, such as multiple rooms or rooms with both natural and artificial light, it is recommended to use a color chart passport to calibrate the white balance consistently across all shots.
- **File Type:** For most cases, JPG format is sufficient. However, for more advanced color correction during post-processing, RAW or TIFF files can be used to avoid compression artifacts and better preserve true colors.
- **Focus**: Using autofocus is generally acceptable, but it must be ensured that the focus is properly set for each shot. With a smaller aperture, most elements in the frame should naturally be in focus.
- **Flash**: It is recommended to keep the flash turned off to avoid inconsistent lighting and shadows.

Matching images

In this step the points extracted from the images are matched (Figure 8) and the poses of the camera are estimated (Figure 9). The main challenge in image matching lies in selecting an appropriate matching entity (a feature or element compared between images) and a similarity measure (a quantitative method for evaluating how well entities match). Performing a "pixel-by-pixel" comparison across the entire overlapping area of images requires an immense amount of computation and often results in ambiguity, due to repetitive grey values and image noise. As a result, image matching is generally considered an ill-posed problem because it does not satisfy the conditions for a stable, unique solution that is consistent with small variations in the input data. To make image matching a well-posed problem, it is necessary to define matching entities, similarity measures, geometric constraints, and assumptions that narrow down the space of possible solutions.

Figure 41 Points detected on the image [124]

The process of defining these matching entities from the image is called feature extraction and is a well-established area of research in Computer Vision, with numerous algorithms developed for detecting keypoints within an image. These keypoints must be resilient to changes in illumination and scale across different frames to ensure reliable correspondences. This is essential for generating a dense point cloud.

Figure 42 Top row: Orientation of cameras calculated. Bottom row: Dense point cloud generated [124]

Generating a dense point cloud

Dense point cloud generation is a crucial step in the photogrammetry process, where a dense set of points is created by projecting common points from overlapping photos into 3D space. This step involves identifying and matching key features across the images and then using those correspondences to accurately map the scene's geometry. The resulting point cloud is highly detailed, representing the surface of the captured object or area with millions of points, each carrying spatial information. This dense point cloud serves as the foundation for creating precise 3D models and other secondary products, offering a comprehensive representation of the subject in digital form.

Creating secondary products

Secondary product generation is the stage where various outputs are created from the dense point cloud. These products include textured meshes, which provide detailed surface representations with realistic textures, and ortho-images, which are geometrically corrected photos that maintain accurate scale and proportions. This step transforms the raw data from the point cloud into usable formats for further analysis, visualization, and documentation. These secondary products are essential for applications in fields like architecture, archaeology, and conservation, as they allow for detailed examination and preservation of heritage structures or other captured subjects.

Analyzing and presenting the results

The analysis and/or presentation of results is the final step, where the generated products, such as 3D models or ortho-images, are further examined using third-party software. This stage allows for in-depth analysis, enabling professionals to assess the data for various applications, such as structural analysis, restoration planning, or historical studies. Additionally, the results can be presented in a variety of formats, including interactive 3D visualizations, reports, or virtual reality environments, making the data accessible to researchers, stakeholders, or the general public for educational or practical purposes.

Detailed Workflow

A more detailed workflow for SfM photogrammetric processing including intermediate products and metadata is described in [124]. Metadata plays a crucial role at every stage, some of it will be automatically produced by the software used (such as processing and accuracy reports, when available), while other components must be manually created by the project team.

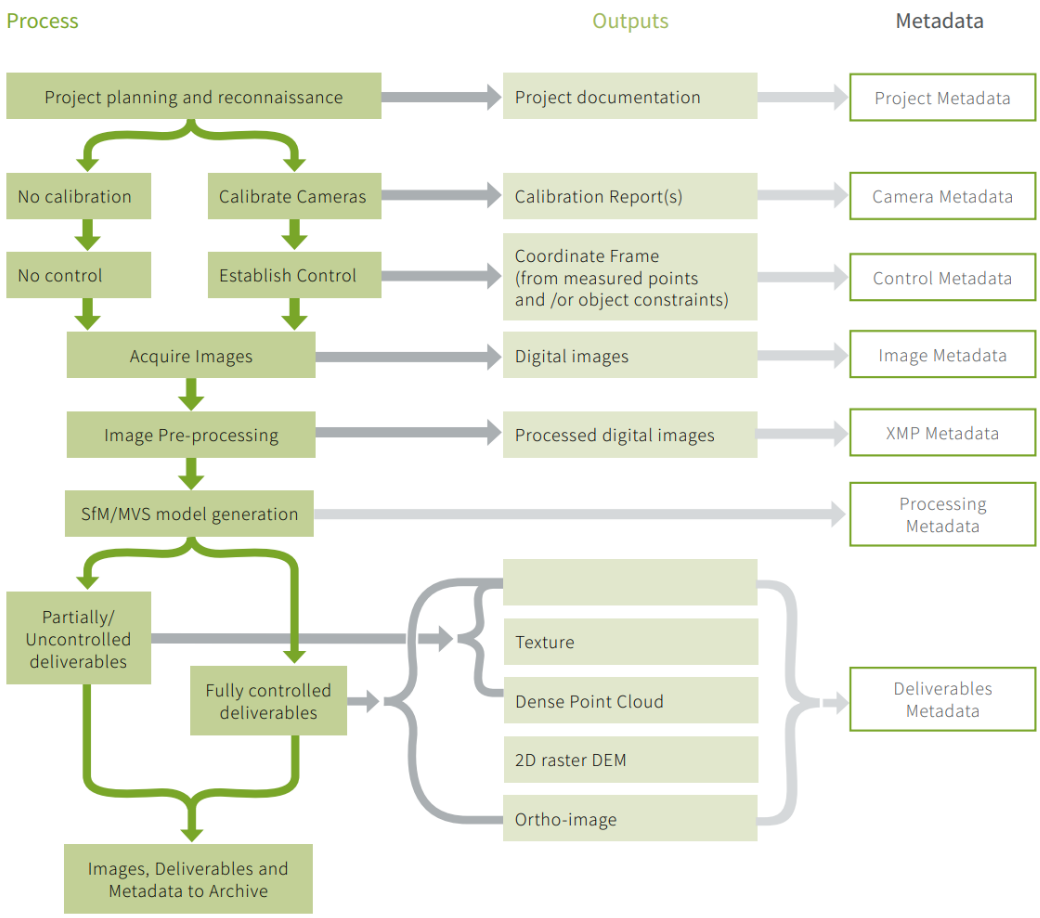


Figure 43 Photogrammetry Workflow **[124]**

Laser Scanning

3D laser scanning has emerged as a valuable tool for documenting heritage structures. It uses laser beams to produce highly detailed and accurate visual representations of heritage sites. The technology captures millions of data points by measuring the distance between the scanner and the surfaces of the structure. These data points are then compiled to create a detailed 3D point cloud, resulting in a digital replica of the heritage structure. This technology allows architects, conservators, and researchers to examine the structure from all angles, capturing intricate details and detecting even the smallest changes over time.

Types of scanners

In heritage documentation, two primary types of 3D laser scanners are commonly used: time-of-flight scanners and phase-shift scanners. Time-of-flight scanners (Figure 11) work by measuring the time it takes for a laser pulse to travel to and from the object, generating a highly accurate point cloud representation. On the other hand, phase-shift scanners (Figure 12) project a laser pattern onto the object and analyze the phase shift to calculate distances, offering enhanced detail for capturing intricate features. The choice between these scanners depends on various factors, including the size and complexity of the structure, the required level of detail, portability and accessibility needs, and budget considerations.

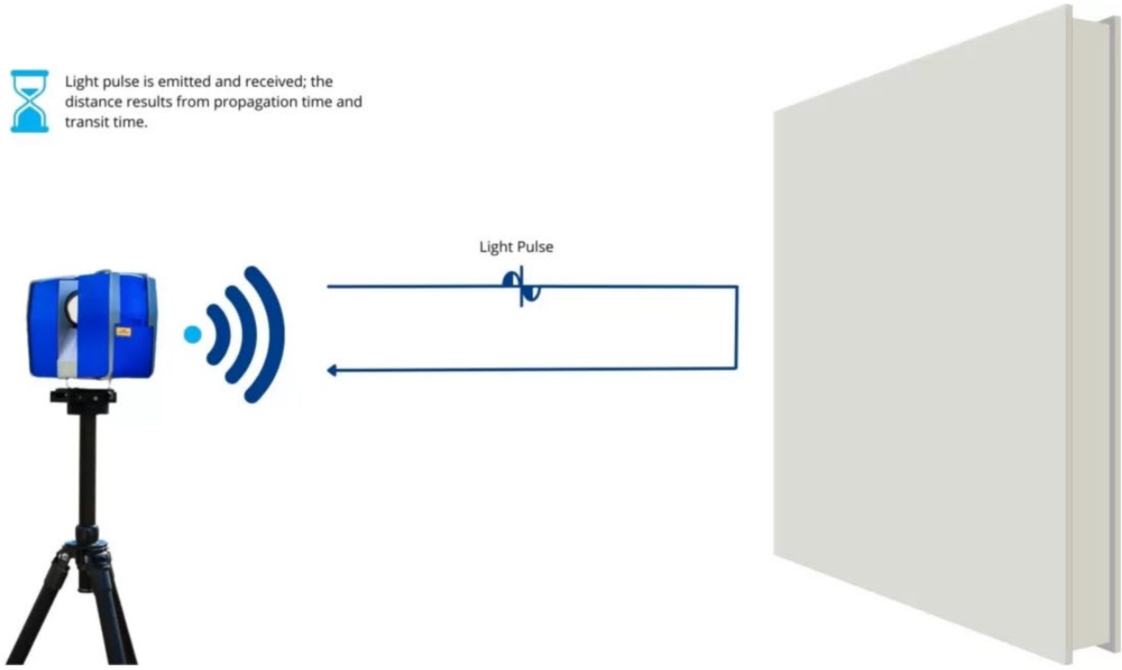


Figure 44 Time-of-flight laser scanner [125]

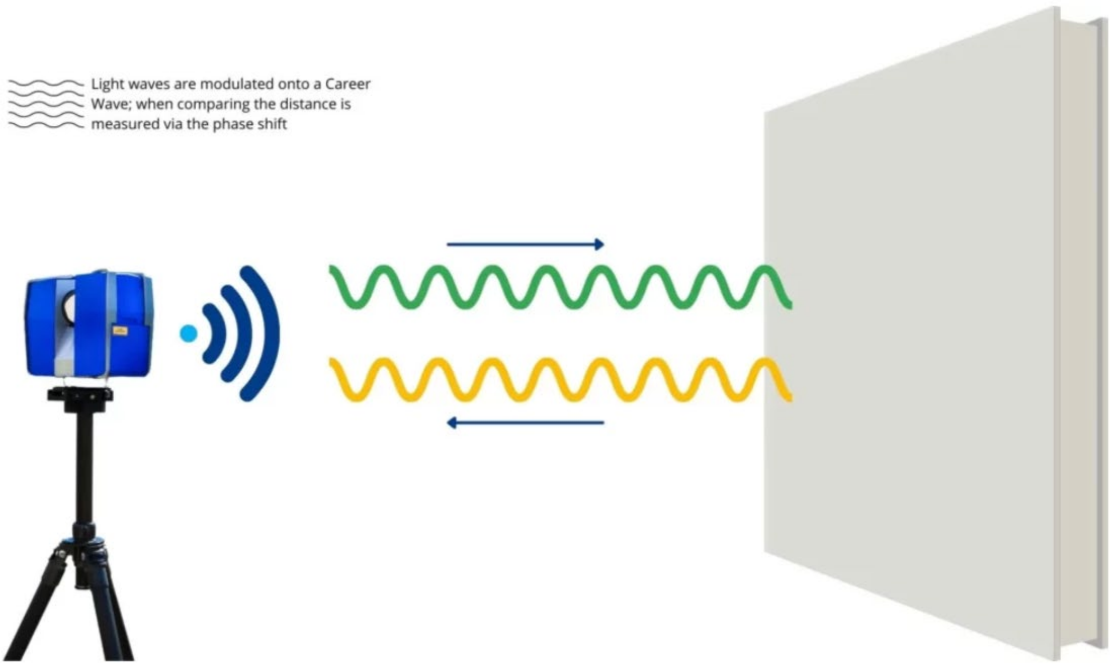


Figure 45 Phase shift scanner [125]

Process

A typical process workflow of 3D Laser Scanning for CH can be split in the following steps:

- Begin with planning and preparation: This involves obtaining necessary permits, choosing the appropriate scanner, and determining scan locations to ensure comprehensive coverage of the heritage structure.

- Proceed to on-site data capture: The scanner releases laser pulses, capturing millions of data points to create a detailed point cloud representation of the structure.
- Move on to data processing and registration: The captured data is refined to remove noise and imperfections, while individual scans are combined to form a complete 3D model.
- Generate the 3D model: The processed point cloud data is transformed into different 3D model formats for further analysis, visualization, and manipulation.
- Conclude with data archiving and dissemination: The finalized 3D data is securely archived for future reference and made accessible to researchers, educators, and the public.

Figure 46 Example of a point cloud captured by iPad Pro [126]

Comparison

When comparing laser scanning and photogrammetry in the context of cultural heritage preservation, each method offers unique advantages depending on the project's requirements. Photogrammetry is widely appreciated for its ability to capture highly detailed textures and vibrant colors, making it ideal for projects that prioritize visual accuracy, such as documenting the surface details of sculptures or murals. This technique is particularly useful for creating realistic, textured models that can be used in virtual museum exhibits or video game recreations of historical sites, where aesthetics and texture detail are paramount.

On the other hand, 3D laser scanning has gained significant traction in cultural heritage documentation due to its speed, precision, and versatility. It excels at capturing accurate geometric data, making it highly useful for creating precise 3D models of complex heritage structures or objects. For instance, laser scanning can rapidly capture intricate architectural features of historic buildings or monuments, providing highly accurate measurements that are critical for restoration or conservation efforts. In areas like archaeology, where time is often limited, laser scanning allows for the quick capture of entire excavation sites with millimeter accuracy.

In cultural heritage, if precision and the need to integrate 3D models into CAD applications for structural analysis or restoration planning are the priorities, 3D laser scanning is typically the preferred method. It provides accurate geometry and faster capture of large or intricate objects, essential for preserving fragile or deteriorating heritage structures.

However, when budget and time are not limiting factors, combining both 3D laser scanning and photogrammetry offers the best results. This hybrid approach ensures highly accurate geometric data from laser scanning while enhancing the digital model with rich, detailed textures from photogrammetry. In this way, cultural heritage professionals can achieve both precise representations for restoration and conservation, and visually engaging models for public display and virtual exploration. This combination is particularly beneficial for creating comprehensive, immersive digital replicas of historical sites or artifacts.

Solutions in Operations / Previous Projects

Alhambra

The following section outlines a set of tools and technologies planned for development to ensure a sustainable and educational tourist experience at the Alhambra site.

Capitalizable Asset Name	
Description	Among the main tools that can be used to ensure a sustainable and educational tourist experience at the Alhambra are: - **Augmented Reality (AR)** which allows visitors to enjoy visual recreations and virtual tours without damaging historical areas. - **Virtual Reality (VR),** like augmented reality, allows for the creation of interactive digital models of buildings, monuments, and other heritage objects. Using VR devices, these models can be explored, offering an immersive experience in the historical environment. Additionally, these highly precise 3D digital models of buildings, monuments, and other heritage objects that are still preserved can be used to document their current condition and to plan restoration or conservation work. - **Environmental sensors** that monitor real-time air quality and the level of structural deterioration caused by tourist activity, issuing alerts if critical levels are reached. - **An Artificial Intelligence (AI) system** to manage the flow of visitors, optimizing routes to avoid crowding and protect sensitive areas of the monument. - Other possible technologies applicable to the Alhambra and Generalife Monumental Complex could include: o **Light and humidity sensors** that monitor light and humidity inside the rooms, helping to maintain optimal

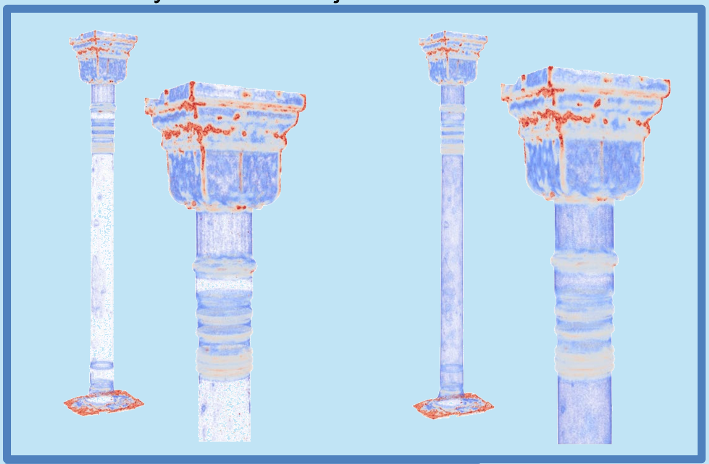
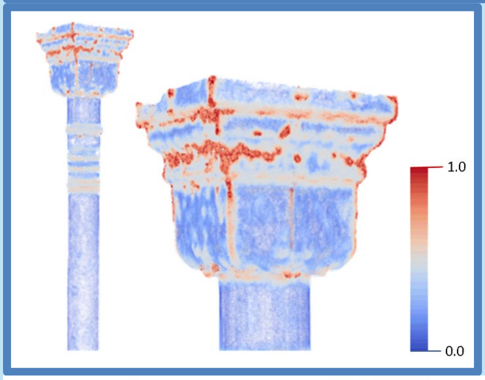
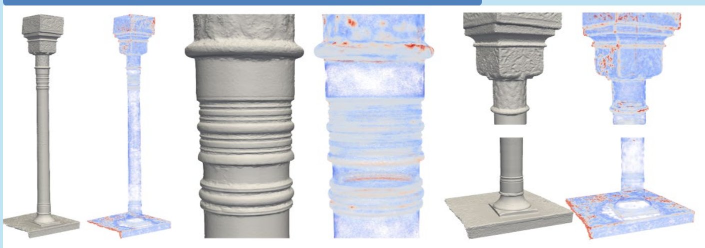
	conditions for the preservation of paintings and structures. ○ **Temperature and weather condition sensors** that aid in the design of routes within the monumental complex. ○ **Geolocation technology and GPS-guided tours**: Visitors can use a mobile application with geolocation that provides personalized routes, avoiding crowded areas in real-time and enhancing the experience by offering detailed information about each point. This reduces the overload of certain tourist spots by distributing visitors more evenly. Additionally, it could allow the design of routes based on ambient temperature, providing a better tourist experience. ○ **Solar energy**. The installation of solar panels to meet the energy needs of tourist facilities, such as information areas, rest zones, or route lighting, would reduce the carbon footprint and support sustainable tourism by using clean energy.
Problem	The main problem that this tool address is the preservation of historical heritage in the face of the large number of tourists who visit the Alhambra daily. The intensive use of certain areas threatens to deteriorate both the infrastructure and the visitor experience. Additionally, there is a need to improve accessibility and the dissemination of historical information in a non-invasive way. Beyond the previously mentioned issues, such as structural deterioration due to the high influx of visitors, it is also crucial to monitor the environmental impact (air pollution and erosion) caused by tourism. The lack of an integrated system to manage these aspects makes the long-term conservation of the heritage site more challenging.
Target Stakeholders	Insert the target stakeholders of the asset. It could be people, companies, public bodies, organizations adopting the asset. The main stakeholders in this tool are: - **Heritage managers** (in this specific case, the Alhambra's Board of Trustees – PAG). - **Heritage conservators**: experts responsible for protecting and restoring heritage. - **Technology companies** specializing in AR, AI, and sensors. - **Public institutions**, responsible for heritage and environmental conservation (ensuring sustainability in urban and heritage areas), as well as those related to tourism. - **Educational institutions**: universities and research centers interested in the study of technologies applied to tourism and heritage preservation/conservation. - **Visitors**.
Alternative solution	If any, are there alternative solutions to the problem that you are aware of The Alhambra's Board of Trustees (PAG) has implemented a reservation system for entry, but it is insufficient for managing real-time visitor flow. Mobile applications also exist, but they do not seem to integrate advanced AR tools or optimize tourist movement using AI. Another alternative could be the installation of interactive information panels powered by solar energy, providing real-time information without the need for a mobile device. However, these panels do not offer the same

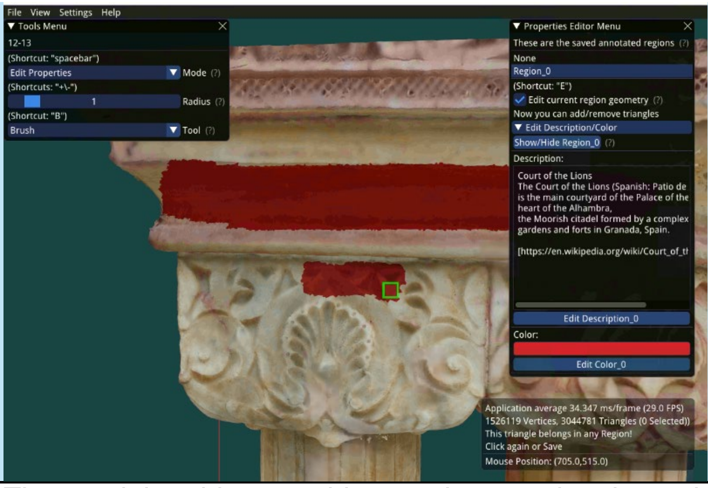
	educational depth or monitoring capabilities as an integrated solution with AR, AI, and sensors.
Owner	The system would be managed by the Alhambra's Board of Trustees (PA in collaboration with technology companies specialized in AR and AI.
Relevant URL	There is no direct link. The PAG website: https://www.alhambra - patronato.es/
Relevant Documentation	N/A
Current operational status/readiness/maturity level	Currently, this tool is in the conceptualization phase. Individual elements exist (AR applications and visitor management), but the integration of bot technologies into a single system is the long-term goal.
Delivery Date	N/A
Asset type	A software system and tool, combining AR and AI technologies.
IPR	Intellectual property rights are under development. The system is expecte to be implemented as proprietary software managed by the PAG, though collaboration with technology companies may be considered.
Partner Name:	UGR y PAG
Contact Person:	JUAN LOPEZ GALAN
Email:	<juans.lopez@juntadeandalucia.es>
Phone Number:	+34 958027991
Current/previous use of the Asset Currently, visitor entry and management systems are used in the Alhambra, but no solution has been implemented that combines AR with AI to optimize both the user experience and the preservation of the site.	
Country:	Spain
Region:	Andalucía

City/Town:	Granada
Description:	N/A
Replicability / Transferability of the Asset This type of technology can be replicated in other heritage sites facing similar conservation challenges a high tourist influx. The replicability of this system in other locations would depend on adapting to local conditions, such as climate (for sensor use) and existing technological infrastructure. It would be particularly interesting in those heritage sites where there is also a delicate balance between conservati and mass tourism. Regarding the other heritage sites included in the project, a similar solution could be replicated in: ● Epicurius Apollo & Nearby Villages, Western Greece. Replicable Technology: Environmental Sensors and Augmented Reality. ● Aquinum Archaeological Site, Aquino. Replicable technology: GPS self-guided tours and humidity sensors. ● Palazzo de Roli, Genoa. Tecnología replicable: Realidad Aumentada y Geolocalización. ● Rectors' Palace, Dubrovnik. Replicable technology: Light and humidity sensors and AI for tourist flow management. ● Old City, Limassol. Replicable technology: Solar energy and interactive panels. ● Canigou Grand Site, Occitanie. Replicable technology: Environmental sensors and solar energy.	
Preconditions	The installation of this tool would require suitable technological infrastructure, including precise GPS signage, servers for data management, and trained personnel in the use of AR and AI technologies. Additionally, it is crucial to have a team of heritage conservation experts collaborating with technology developers to ensure that the implemented tools respect the specific conservation needs of the site.
Preparatory actions	● **Technological feasibility studies** Ensure that the site has the appropriate infrastructure to support sensors and AI-based systems. ● **Staff training**: Train workers in the use and maintenance of the sensors and the management system. ● **Environmental studies** Conduct preliminary analyses of the environment to customize the sensors to the specific climate conditions and tourism levels of the site.
Costs/support	● **AR devices** glasses or compatible mobile devices. ● **Sensor infrastructure** to monitor air quality, humidity levels, and other environmental factors. ● **AI system** for optimizing tourist flow, which will require ongoing support and periodic updates. ● **Maintenance**: a dedicated team is needed to maintain and repair the sensors and the technological platform.

Warmest Project

The tool was developed in the context of Warmest, a H-2020 Marie Curie Research and Innovation Staff Mobility Project. Its primary objective is to enhance maintenance procedures at cultural and natural heritage sites by introducing new technologies for data collection and innovative tools for data analysis.

Capitalizable Asset Name	
Description	Tool that enables the editing and annotation of 3D models of objects, accompanied by AI algorithms developed that allow the detection of saliency features and their color marking, as well as the detection of deficiencies in 3D models of symmetrical objects.   

	
Problem	The need that this tool addresses is related to the maintenance of cultural herita sites. The proposed methodology includes the 3D modeling of cultural heritage sites utilizing Structure from Motion (SfM) photogrammetry or LiDaR. The resulti point clou ds can be annotated with reference to potential defects (cracks, decolorification, etc) so as to trigger potential restoration actions. AI algorithms also allow detection of saliency areas that could trigger potential defects. The application of this metho dological approach with an appropriate periodicity can help detect deterioration of cultural heritage sites in the middle and long term du to external factors (climate change, meteorological phenomena, human presenc etc).
Target Stakeholde rs	Management bodies of cultural heritage sites, archaeological ephorates, museums, owners / managers of cultural heritage / historical buildings, historical centers of cities, cultural heritage monument owners
Alternative solution	Inspection of the monument
Owner	Industrial Systems Institute, ATHENA Research Center
Relevant URL	http://art3mis.athenarc.gr/
Relevant Documenta tion	Short Manual https://drive.google.com/file/d/1tIqKxujhbg4vntc05AC1R_aaKmENa8op/view?u sp=sharing Warmest Deliverable of Prototype D.5.1 https://drive.google.com/file/ d/1pcY66TfWzqGu2oY7MuUyYjMgC2sTGJTz/view usp=sharing
Current operational status/read iness/matu rity level	The tool is available for use in its web version. Adjustments are also possible depending on the application.

Delivery Date	Web version ready to use
Asset type	Tool
IPR	Tool developed in house by ATHENA Research Center
Partner Name:	Industrial Systems Institute, ATHENA Research Center
Contact Person:	Athanasios Kalogeras
Email:	kalogeras@isi.gr
Phone Number:	+306976112697
Current/previous use of the Asset	
Country:	Spain and Italy (pilot tested)
Region:	Andalucia and Tuscany (pilot tested)
City/Town:	Granada and Florence (pilot tested)
Description :	Use in 3D models of columns in Patio de Leones, Alhambra, Granada, Spain an Santa Croce Cluster, Florence, Italy
Replicability / Transferability of the Asset	
Preconditions	Use of the tool requires the 3D model in high resolution of the Cultural Heritage site / object. For larger models, there may be a need to not use the web version of the tool, bu rather the tool needs to be installed locally. This might create requiremets for the ICT equipment needed.
Preparatory actions	3D modelling of the site under investigation Purchase of needed equipment

Costs/support	No costs are associated There is need for training on the tool usage

Sensees Platform

The Sensees Platform is sensor platform that monitors various air quality and environmental parameters, such as noise and electromagnetic field levels, in an urban environment, while delivering real-time data insights.

Sensees Platform	
Description	Sensees Environment is a commercial smart sensor platform monitoring multiple air quality and other environmental parameters like noise or electromagnetic field levels in a city setting, all the while providing real time data insights. DURA uses the platform as the part of pilot project of measuring air quality in educational institutions in the city of Dubrovnik. As part of the Dubrovnik Smart City project, in 2019 the Dubrovnik Development Agency DURA completed the installation of the sensors as the part of the Pilot project of measuring air quality in educational institutions in the area of the city of Dubrovnik (three Dubrovnik primary schools and five Dubrovnik kindergartens).
Problem	The Sensees Environment platform aims to address several key urban and environmental problems: 1. Air Quality Monitoring Problem: Poor air quality in cities is a leading cause of respiratory diseases, health issues, and reduced quality of life. Major pollutants such as CO2, PM2.5, and NO2 often go unnoticed until they become a severe issue. 2. Noise Pollution Problem: Excessive noise in urban environments can lead to health issues l stress, hearing loss, and sleep disruption. Noise pollution often goes unmonitored in many cities.
Target Stakeholders	Given its focus on real-time monitoring of environmental conditions, appeals to a diverse set of stakeholders. These stakeholders are directly involved in urban planning, public health, environmental monitoring, and technology implementation. Here's a breakdown of the key target stakeholders: 1. City and Municipal Governments They need accurate, real - time data to monitor pollution levels, enforce environmental regulations, and plan interventions that improve urban living conditions. 2. Environmental Protection Agencies (EPAs) These agencies rely on robust environmental data to enforce pollution control laws, monitor air quality, and assess the impact of industrial and urban activities. 3. Urban Planners and Smart City Initiatives Urban planners need data to design cities that reduce pollution, manage noise levels, and ensure the well-being of residents. 4. Public Health Authorities Air pollution and noise are linked to a wide range of health problems, including respiratory illnesses, cardiovascular diseases, and mental health issues. 5. Academic and Research Institutions These institutions can use real-time data for research on air quality, noise pollution, and EMF impacts. 6. Citizens and Communities

	With rising awareness about environmental hazards, citi zens increasingly want access to real-time data to monitor air quality, noise levels, and electromagnetic fields in their neighborhoods. Empowering citizens to track environmental conditions, participate in public discussions, and advocate for cleaner, quieter, and safer living environments.
Alternative solution	
Owner	Smart Sense d.o.o.
Relevant URL	https://www.smart -sense.hr/en/products/outdoor/
Relevant Documentation	
Current operational status/readiness /maturity level	Operational
Delivery Date	Provide the (anticipated) date of delivery to the consortium of HERIT ADAP
Asset type	Tool
IPR	It is a commercial product.
Partner Name:	DURA
Contact Person:	Stjepan Cavar
Email:	scavar@dura.hr
Phone Number:	+ 385 20 640 556
Current/previous use of the Asset	
Country:	Croatia

Region:	Jadranska Hrvatska
City/Town:	Dubrovnik
Description:	DURA uses the platform as the part of pilot project of measuring air quality in educational institutions in the city of Dubrovnik. As part of the Dubrovnik Smart City project in 2019 the Dubrovnik Development Agency DURA completed the installation of the sensors as the part of the Pilot project of measuring air quality in educational institutions in the area of the city of Dubrovnik (three Dubrovnik primary schools and five Dubrovnik kindergartens). The installed air quality measurement system enables: - reading levels of CO2, temperature and humidity in the rooms where the sensors are installed - connecting sensors to the IoT (Internet of Things) infrastructure - use of application solution for data monitoring and analysis Air quality sensors use the existing NBIoT network (the same network is used by parking sensors installed in the city) to send measured data to a central database.
Replicability / Transferability of the Asset	
Preconditions	Are there preconditions (in terms of infrastructure, equipment, etc.) that hav to be met for the asset to be replicable in another area?
Preparatory actions	Are there preparatory actions (studies, training) that need to be made for th asset to be replicable in another area?
Costs/support	**It is a commercial platform.**

Occitanie Tourisme Observation

The Occitanie Tourisme Observation (OTO) platform of the CRTL Occitanie is focused on exploring tourism data in the Occitanie region. It serves as the web interface for accessing the Occitanie Tourist Information Hub (HIT), a technological platform designed for data aggregation and enrichment to support the CRTL Occitanie's data management strategy.

OTO – Occitanie Tourisme Observation (Occitanie Tourism Observation) / HIT (Hub d'Information Touristique)	
Description	The Occitanie Tourisme Observation (OTO) platform of the CRTL Occitanie is dedicated to exploring tourism data in the Occitanie region. It is the web interface for accessing the Occitanie Tourist Information Hub (HIT). As a reminder, the HIT is a technological platform for data aggregation and enrichment intended to support the data management strategy of the CRTL Occitanie.

	OTO brings together all the dashboards, tools and services developed and distributed by the CRTL Occitanie. The OTO platform is the general public and professional tool for sharing and consulting online data from the HIT Occitanie and associated services. It is administered by the CRTL Occitanie, its owner. The OTO platform mainly includes: - Data sets related to tourism activity and mobility across the Occitanie region. The data used is provided or captured from various certified sources and mainly from the institutional tourism ecosystem and CRTL Occitanie partners - Data sets related to the tourism economy across the Occitanie region and from the tourism economic ecosystem and CRTL Occitanie service providers - Access to an Occitanie territorial reference system: catalog of administrative zoning, isochrones and isodistances as well as various routes (pedestrian, bicycle, etc.); This repository is a major source of data cross-referencing with all the data available in the HIT Occitanie - A set of interfaces allowing the exploration of the datasets made available - Modules for consulting and/or downloading datasets according to the user's authorizations - Services for generating status reports on the HIT Occitanie data according to the user's authorizations - Documentation spaces - Messaging services allowing communication with the 3D Pole, administrator of the OTO platform
Problem	Even though it is based on a very open approach (particularly in terms of GIS tools), HIT today is mainly supplied by regional or bordering data.
Target Stakeholders	Destination management organizations (at political and technica levels), tourism businesses, students, researchers
Alternative solution	-
Owner	CRTLO
Relevant URL	https://outils.crtloccitanie.org/ Administered platform, requires a username and password
Relevant Documentation	CGU See below
Current operational status/readiness/maturity level	Operational tool on a regional scale, constantly evolving in term of available sources and functionalities

Delivery Date	Available
Asset type	It is the web interface for accessing the Occitanie Tourist Information Hub (HIT). OTO brings together all the dashboards, tools and services developed and distributed by the CRTL Occitanie.
IPR	The OTO platform is the general public and professional tool for sharing and consulting online data from the HIT Occitanie and associated services. It is administered by the CRTL Occitanie, its owner.
Partner Name:	CRTLO
Contact Person:	Dominique Thillet
Email:	Dominique.thillet@crtoccitanie.fr
Phone Number:	+33 6 88 05 41 28
Current/previous use of the Asset	
Country:	France
Region:	Occitanie
City/Town:	Whole region
Description:	Can be used for the analysis of the site selected in the Occitanie region
Replicability / Transferability of the Asset	
Preconditions	Would require adaptations to be used in other territories: identification of sources, consideration of the context
Preparatory actions	Technical studies et sources identification
Costs/support	Possible technical adaptation and source integration costs

Flux Vision Tourisme

Flux Vision Tourisme enables the measurement of population flows using real-time mobile data. Orange Business provides Flux Vision to analyze data on attendance, origin, and socio-demographic profiles. It helps measure attractiveness and enhance visitor insights through location data, offering reliable and accurate indicators to assess daily attendance and mobility. The statistics are anonymous and adhere to CNIL and GDPR guidelines.

Flux Vision Tourisme (Orange business)	
Description	Flux Vision Tourisme allows you to measure population flows using up-to-date mobile data Orange Business offers Flux Vision to analyze your attendance, origin and socio-demographic profile data. Flux Vision allows you to measure attractiveness and improve visitor knowledge using location data. These reliable and accurate indicators allow you to analyze the attendance and mobility of your areas every day. The statistics are anonymous and comply with CNIL and GDPR recommendations.
Problem	The cost can be significant, and the solution is not effective in al territories.
Target Stakeholders	Destination management organizations (at political and technica levels), tourism businesses, students, researchers
Alternative solution	No alternative solutions as comprehensive on French territory
Owner	Orange Business
Relevant URL	https://www.orange-business.com/fr/solutions/data-intelligence-iot/flux-vision
Relevant Documentation	https://www.orange-business.com/fr/solutions/data-intelligence-iot/flux-vision
Current operational status/readiness/maturity level	Operational in most territorial configurations except in areas tha are too small or not covered by enough telephone antennas
Delivery Date	Available in the Occitanie experimental territory
Asset type	Solution

IPR	Proprietary solution
Partner Name:	CRTLO
Contact Person:	Dominique THILLET
Email:	(Contact person's email)
Phone Number:	(Contact person's phone number)
Current/previous use of the Asset	
Country:	France
Region:	Occitanie
City/Town:	Massif du Canigou
Description:	Allows you to monitor daily tourist attendance by origin (in overnight stays and daily presence)
Replicability / Transferability of the Asset	
Preconditions	To be discussed with Orange Business if necessary
Preparatory actions	Identification of the relevant study scope
Costs/support	Costs

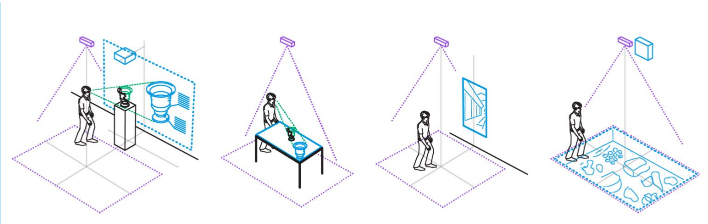
Murmuration

Murmuration delivers essential indicators for incorporating environmental considerations into decision-making processes across all sectors, including governments, businesses, and the general public. These indicators, derived from Earth observation data, offer global coverage and provide insights into past trends, present conditions, and future projections.

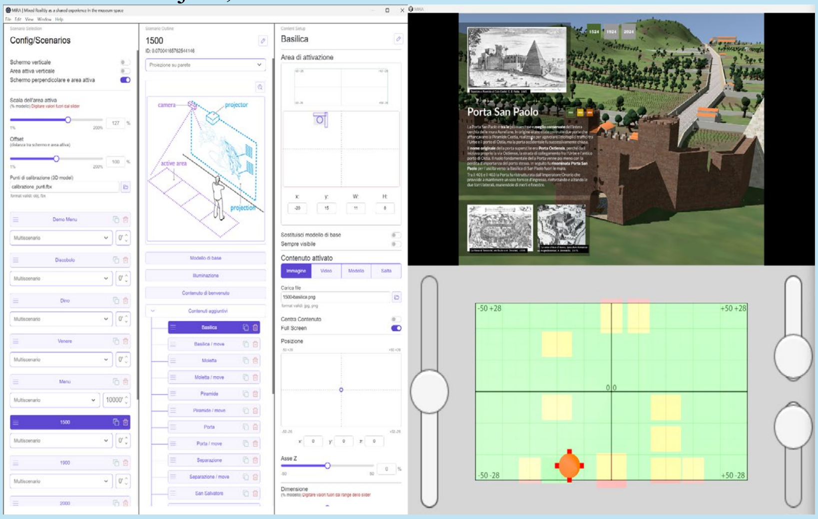
MURMURATION (SATELLITE DATA)	
Description	**Murmuration's solution** Murmuration provides the necessary **indicators** for integrating environmental issues into all decision-making processes and for all stakeholders, including governments, businesses, and the general public. Murmuration indicators are based on Earth observation data, offering global coverage and providing insights into the past, observations of the present, and a vision of the future.
Problem	Integration costs and data not always easy to analyze
Target Stakeholders	for all stakeholders, including governments, businesses, and the general public
Alternative solution	Not to my knowledge
Owner	Murmuration
Relevant URL	https://murmuration - sas.com/
Relevant Documentation	https://murmuration - sas.com/about/
Current operational status/readiness/maturity level	Operational but not for all indicators and all territories
Delivery Date	to be defined
Asset type	Decision- making dashboards that help understand the impact of human activity on the environment and the impact of climate change on human activities.
IPR	depends on the achievements
Partner Name:	CRTLO

Contact Person:	Dominique Thillet
Email:	Dominique.thillet@crtoccitanie.fr
Phone Number:	+33 6 88 05 41 28
Current/previous use of the Asset	
Country:	Worldwide
Region:	Some part of Occitanie
City/Town:	-
Description:	Dashboards dedicated to the analysis of the effects of climate change on territories
Replicability / Transferability of the Asset	
Preconditions	Discussion with Murmuration
Preparatory actions	studies
Costs/support	There may be costs to configure the tool according to the needs of the project

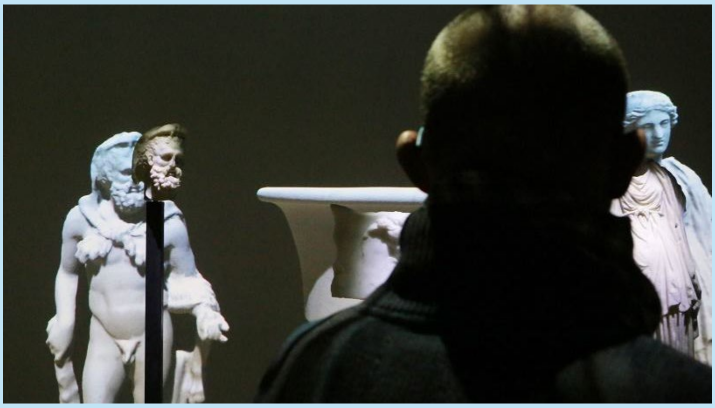
Capitalizable Asset Name	
Description	MIRA– Mixed Reality Ambiances The asset enables a kind of Mixed Reality (or virtual/augmented reality) experience without any device in physical contact with the museum visitor (unlike VR headsets or tablets), thus allowing quick and hygienic interaction with immersive digital contents. The system operates through mainstream hardware components: a PC, a depth sensor and a projector or TV display, which can be positioned in various ways.

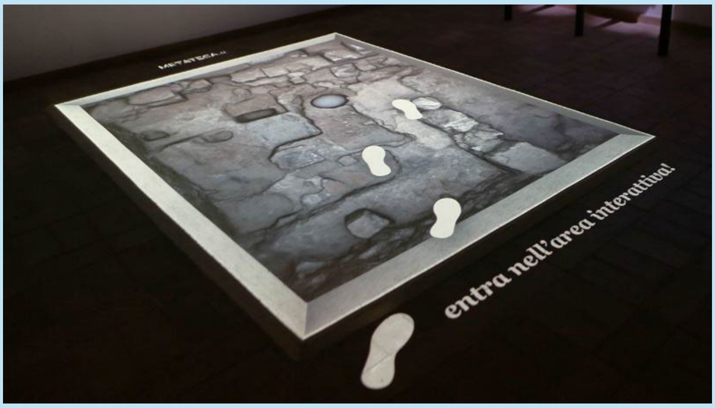


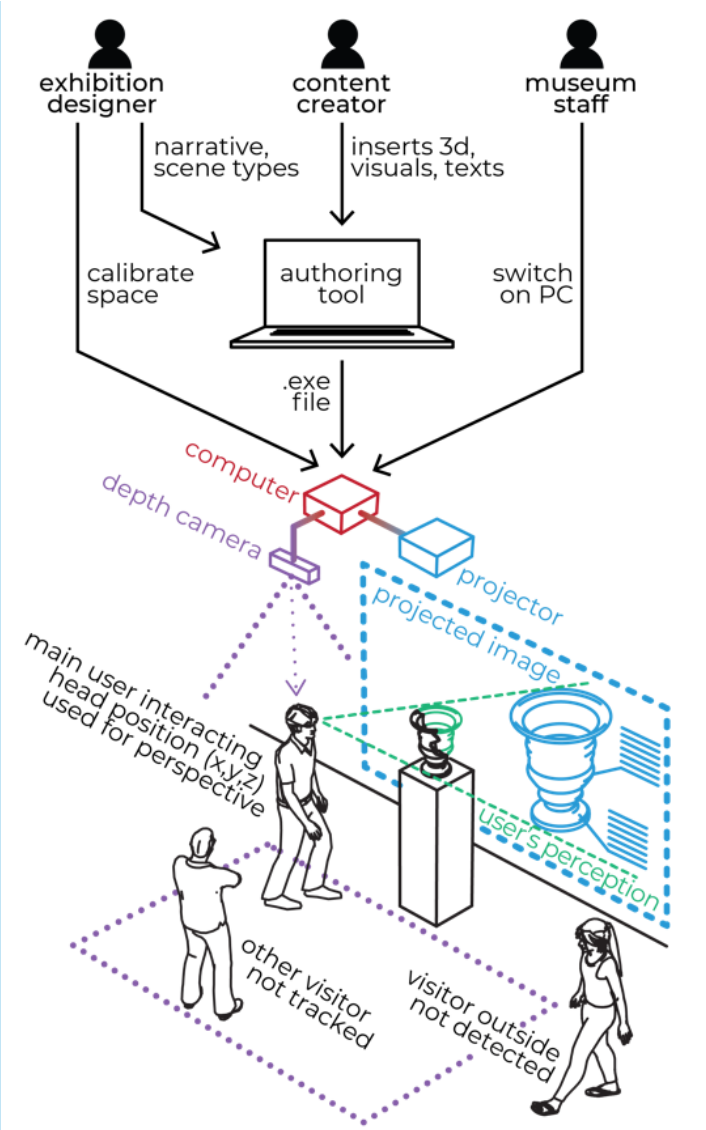
The asset itself is composed of two software tools: an Authoring Tool which is used for the configuration of interactive multimedia contents without coding, and a Museum Runtime software, which is visualizing the interactive contents, as well as calibrating the spatial relation between virtual contents, real-world object, the screen and users in the active area.



Content wise, the system allows the Mixed Reality integration of exhibited artifacts, as well as VR scenes such as virtual windows or glass floor effects, with the possibility of moving around for a 3D effect, jumping between points of interest, or visualizing extra info layers.



	  entra nell'area interattiva!  celexon



System scheme and basic spatial setup

Problem	The asset tackles the problem of effective and intuitive multimedia communication in museum spaces. Immersive eXtended Reality (XR– VR, AR, MR) experiences today require devices in close contact with the users (HMDs, tablets), which makes them hard to manage in busy museums. MIRA mitigates this with a non - touch immersive 3D visualization and gestural control. On the other hand, interactive installations usually require significant software development effort. MIRA mitigates this by offering an authoring tool ready for the no-code configuration of a wide range of experiences.
Target Stakeholders	Exhibition spaces (museums, indoor archeological sites, etc) are the main stakeholders for raising the attractiveness of their offer. Other institutions or public spaces: possibility of installing “preview” experiences popularizing (minor) tourist attractions. Installable indoor (e.g. stations) or outdoor (better for evening/dark).

	The final beneficiaries are tourists as well as locals who may discover minor attractions.
Alternative solution	There are no significant competitors offering the same experience, although similar information and multimedia content can be offered on other devices, e.g. personal smartphone, tablet / touchscreen kiosks, etc.
Owner	Sapienza University of Rome / Interdepartmental Centre "Sapienza Design Research (SDR)
Relevant URL	https://miracms.wordpress.com/
Relevant Documentation	Scientific articles discussing the system: - Saviano, M., Malakuczi, V., Imbesi, L. (2023). *Visor-less XR in museums. A Content Management System for Immersive Installations*. In 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), Shanghai, China, 2023, pp. 551-556, doi: 10.1109/VRW58643.2023.00122. - Saviano, M., Malakuczi, V., Imbesi, L. (2024). Toward Accessible Mixed Reality in the Museum: Usability Principles for Disadvantaged Visitors and a Feasibility Evaluation for a New MR System." *The International Journal of Design in Society* 18 (1): 65-81. ISSN 2325-1360, doi:10.18848/2325-1328/CGP/v18i01/65-81. - Botte, B., Marinensi, G., Malakuczi, V., Vitaletti, W. (2024). Innovative Technologies in Museums: A Review of Gamified Augmented Reality Experiences. In: INTED2024 Proceedings. 18th International Technology, Education and Development Conference. Valencia, Spain. 4-6 March, 2024. ISBN: 978-84-09-59215-9, ISSN: 2340-1079, doi: 10.21125/inted.2024 Further documentation available on request.
Current operational status/readiness /maturity level	The current maturity of the MIRA system is about TRL-6 (System prototype demonstration in operational environment), as through the last financing (DTC Lazio) the software components have been set up and demonstrated with cultural contents at a museum, tested with users. For implementation, some guidance is still necessary from the developers (Sapienza).
Delivery Date	31.12.2024
Asset type	Software tools: - Authoring Tool (browser based) for the configuration of cultural contents. - Museum Runtime software (Unity based) and space calibration tool for the museum space. (the hardware requirements are described in the last section)
IPR	The MIRA system's software tools were developed in-house. It is not yet ready to be open sourced, but available for use by the Herit Adapt partnership.
Partner Name:	PP4- SDR (Sapienza University of Rome)

Contact Person:	Viktor Malakuczi Ioannis Chatzigiannakis
Email:	viktor.malakuczi@uniroma1.it ichatz@diag.uniroma1.it
Phone Number:	+39 3270497381 +39 345 9248431
Current/previous use of the Asset	
Country:	Italy
Region:	Lazio
City/Town:	Rome
Description:	The asset has been installed and tested for a limited time at "Museo della V Ostiense – Porta San Paolo", as a final result of the project "MiRA: Mixed Reality Ambiances. A CMS for museums". This pilot test has provided an immersive 3D reconstruction of the Museum's neighborhood, showing its evolution across 3 historic eras. For each era, a selection of points of intere can be visited through a virtual flight and relevant information is visualised a an augmented reality info layer. Moreover, the installation presented a few additional (unrelated) contents to demonstrate the MIRA system's further functionalities, such as the mixed reality integration of a physically present sculpture, the explanation of a dinosaur's composition and environment, an the explanation of a painting.
Replicability / Transferability of the Asset	
Preconditions	The system has the following spatial and hardware requirements: Space: the system can be installed with horizontal or vertical visualization, in multip dimensions. Projection is possible on pavement, table or wall/screen. Monitors/TVs might be also used. The depth sensor should be positioned at a height of about 3 meters, facing users. Typically, the users interact with the system by moving in an area ranging from 2x2 to 4x4 meters, to be left without obstacles. Ideally the environment should dark or shaded for realistic image, particular in case of projections. Outdoor installation is possible for evening use, e.g. projecting on a light gray asphalt sidewalk. Hardware: - the system operates ideally on a gaming PC (Intel i5+, RTX4070+). - Depth sensor: Time-of-Flight (ToF) technology, possibly Azure Kinect compatible (Orbecc Femto Bolt on the current market).

	- Display: projector or TV/monitor. Luminosity and dimensions according to needs. Minimum resolution FullHD, recommended is 4K. If the walls are not uniform white, projection screen might be necessary.
Preparatory actions	While the interfaces are quite user friendly, some training would be necessary. The resources needed are highly dependent on the kind of 3D models and the complexity of cultural information to be communicated.
Costs/support	Implementing the system at other project partners would benefit from supervision of the original developers of the system (Sapienza), in order to produce content and interactions that are effective on this particular kind of installation.

HERIT ADAPT pilots

The project envisages the following pilots in the partner territories.

Western Greece

General Information

1. **Pilot Site Name**
   Temple of Apollo Epicurius

2. **Pilot Site Location**
   Bassae, Phigaleia, Region of Western Greece, Greece

3. **Partner involved in Pilot Experimentation**
   ATHENA/ISI
   Dr. Athanasios Kalogeras
   kalogeras@isi.gr

   Region of Western Grece
   Mr Lavrentios Vasiliadis
   l.vasileiadis@pde.gov.gr

4. **Pilot site Ownership Information**
   Ministry of Culture – Ephorate of Antiquities of Ilia

5. **Pilot site description (indicative length: 100 words)**
   The Temple of Apollo Epicurius, a UNESCO World Heritage site, is an ancient Greek temple located in Bassae, Peloponnese, Greece. Renowned for the unique combination of a variety of novel ideas both in its external appearance and in its internal arrangements, is dated to 420-400 BC and is believed to be the work of Iktinos, the architect of the Parthenon. Its remote mountainous settings and exceptional preservation make it a significant cultural heritage monument. A shelter, which will be removed at the end of the works, was erected in 1987 to protect the temple against the region's extreme weather conditions.

6. **Pilot site typology**
   - UNESCO sites with landmark or dispersed monuments

Pilot Experimentation

1. Objective of experimentation

- Creation of 3D models incorporating accurate geometry and texture details
- The resulting model of the temple could be used for a variety of cases, including educational and touristic purposes, and most importantly for restoration and conservation in a scientific, sustainable and climate-change resilient manner.
- Use of ART3MIS tool capitalized by former Warmest project for potential annotation of defects on the resulting model
- Pilot development of AI algorithms that could help in the context of helping match broken parts of the temple material and help the restoration work

2. Pilot Experimentation Design

- Obtain necessary license from the Ephorate of Antiquities of Ilia for data collection, drone operation, and on-site access
- Conduct preliminary surveys to understand lighting patterns and their impact on data collection as well the impact of the shelter to the GNSS signal.
- Design precise drone flight paths to ensure comprehensive coverage of the temple's structure. Plan for overlapping images to facilitate seamless stitching in the photogrammetry software.
- Use high-resolution handheld camera for intricate details such as carvings, inscriptions, and small architectural features.
- Utilize RTK (Real-Time Kinematic) base stations for enhanced georeferencing accuracy.
- Cross-reference drone and handheld camera datasets to ensure comprehensive coverage and prevent data gaps.

3. Activities and tools

Activities

1. Pre-Experimentation Planning:
    - Conduct a detailed analysis of the site, including terrain mapping and identifying potential logistical challenges (e.g., terrain difficulty, weather).

2. Data Collection:
    - Drone-Based Imaging: Capture high-resolution aerial images from multiple angles and elevations.

- Ground-Level Imaging: Utilize DSLR cameras and 360-degree cameras for capturing close-up textures and interior features. Focus on specific areas of interest, like structural damage, carvings, or erosion patterns.

3. Data Processing:
   - Image Preprocessing: Calibrate images for color consistency and correct for lens distortions before photogrammetry processing.
   - 3D Reconstruction: Use photogrammetry software to create a detailed 3D model, ensuring high resolution for both texture and geometry.
4. Model Refinement:
   - Conduct quality control checks to refine the model, eliminating noise and ensuring fidelity.
5. Archival and Sharing:
   - Archive all collected data and models in a digital repository for future research and public access.

Tools

1. Hardware:
   - Drones: Equipped with high-resolution cameras, RTK GPS, and LiDAR sensors for aerial and terrain mapping.
   1. Handheld Cameras: High-resolution DSLRs for detailed close-ups and portable 360-degree cameras for immersive capture.
   2. Stabilization Equipment: Tripods, gimbals, and stabilizers for sharp and consistent image capture.
   3. RTK Base station for delivering centimeter accuracy.
2. Software:
   - Photogrammetry Software: Agisoft Metashape, RealityCapture, or Pix4D for 3D model reconstruction.
   - Image Processing Tools for preprocessing captured images.
   - 3D Model Editing: Blender, MeshLab, or Rhino for model refinement and texturing.
   - ART3MIS tool to be capitalized from former Warmest project
   - Special AI algorithms pilot developed and tested

.

4. Expected pilot outcome

1. High-Resolution 3D Model for Scientific and Preservation Purposes:
   - A detailed, high-fidelity 3D model capturing the exact geometry and texture of the Temple of Apollo Epicurius.
   - The model will incorporate fine details such as carvings, cracks, and other structural vulnerabilities to assist in restoration planning, conservation strategies, and scientific analysis.
   - Scaffolding and other temporary external structures will be excluded
2. Low-Resolution 3D Model for Dissemination and Educational Outreach:
   - A simplified version of the 3D model optimized for dissemination to the general public.

- This model will be used for virtual tours, educational platforms, and integration into multimedia presentations, ensuring accessibility across devices and audiences.

3. Raw Image Data Archive:
    - A comprehensive dataset of high-resolution raw images collected during the pilot experimentation.
    - This dataset will include aerial images and close-up details for archival purposes.
    - The raw data will serve as a resource for future research and potential reprocessing with evolving technologies.

4. Reignition of widespread interest for the temple. Through touristic infrastructure and planning/monitoring of flows.

5. Resources

Resources can be counted as the expertise of those involved in tasks such as: flying the drones optimally to procure images, expertise of those utilizing the image processing programs, and those who will tie together all these components to create a useful 3D representation of the temple.

6. Data Collection

Data collection is a critical step in the photogrammetry process, as the quality and completeness of the captured images directly influence the accuracy and fidelity of the final 3D model. Precise and comprehensive data acquisition ensures that every architectural detail of the ancient temple is represented, minimizing gaps or distortions in the final reconstruction.
The process begins with the drone capturing aerial images of the temple's exterior. These images are taken from multiple angles and elevations to ensure adequate overlap, which is crucial for the photogrammetry software to stitch the data into a coherent 3D model. The accuracy of the drone's flight plan is ensured by the use of a Real-Time Kinematic (RTK) base station, which provides high-precision georeferencing, enhancing the spatial accuracy of the images and the final model. Careful planning of the drone's flight path allows it to photograph all accessible areas, focusing on both horizontal and vertical perspectives. Adjustments are made to compensate for the transparent shelter, such as using polarizing filters or carefully timing the capture to minimize glare and reflections. The drone is particularly effective for covering wide areas and reaching sections of the temple that are elevated or otherwise difficult to approach manually. For areas that the drone cannot effectively document, handheld cameras are used to capture high-resolution images. These cameras allow close-up photography of intricate details, such as carvings, inscriptions, or small structural features. Photographers carefully document these areas from multiple angles, ensuring significant overlap with the drone-captured images. Lighting conditions are managed meticulously, using additional light sources, if necessary, to ensure the fine textures and features are well-documented. Stability is prioritized during this process, with the use of tripods or gimbals to maintain sharpness and avoid motion blur.
Once all images have been collected, the dataset from both the drone and handheld cameras is cross-referenced to ensure there are no gaps. This integrated dataset serves as the foundation for constructing the 3D model, emphasizing the importance of thorough and precise data collection as the cornerstone of the project's success.

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It has to be also mentioned that TWG of the project will be utilized in the context of collection of data and information related to the association of the project with the wider neighboring area to exploit synergies.

7. Pilot Experimentation Sustainability

SDG 11: Sustainable Cities and Communities.Target 11.4: Strengthen efforts to protect and safeguard the world's cultural and natural heritage. The project contributes to the conservation and safeguarding of the Temple of Apollo Epicurius by employing advanced technologies for preservation, ensuring its longevity and accessibility for future generations.

SDG 13: Climate Action.Target 13.1: Strengthen resilience and adaptive capacity to climate-related hazards. By addressing the impacts of extreme weather conditions on the temple's limestone structure, the project promotes innovative and climate-resilient preservation techniques.

SDG 9: Industry, Innovation, and Infrastructure.Target 9.5: Enhance scientific research and upgrade the technological capabilities of sectors. The implementation of photogrammetry, drone operations, and high-resolution imaging advances scientific research and technological capabilities in cultural heritage preservation.

SDG 8: Decent Work and Economic Growth. Target 8.9: Promote sustainable tourism that creates jobs and promotes local culture and products. The pilot supports sustainable tourism development while regulating visitor flows and enhancing the temple's visibility as a cultural and historical landmark.

SDG 4: Quality Education. Target 4.7: Ensure learners acquire knowledge and skills to promote sustainable development. The creation of a detailed 3D model serves as an educational resource, spreading awareness of the temple's historical and architectural significance among students, researchers, and the general public.

SDG 17: Partnerships for the Goals. Target 17.17: Encourage and promote effective public, public-private, and civil society partnerships. Collaboration among local authorities, cultural heritage organizations, and technology providers ensures the successful implementation and sustainability of the project.

8. Pilot Experimentation Evaluation

1. Coverage of the Temple During Data Acquisition
   - KPI: Percentage of the temple's structure successfully documented during data collection.
   - Methodology: Compare captured images to the predefined site coverage plan to identify any gaps or omissions.
2. Review from Stakeholders
   - KPI: Level of expert satisfaction with the high-resolution 3D model's utility for restoration and conservation.
   - Methodology: Gather qualitative and quantitative feedback through post-experimentation surveys or discussions with archaeologists and conservationists.

Cyprus

General Information

1. **Pilot Site Name**

   Temple of Appolon Hylates

2. **Pilot Site Location**

   Limassol, Cyprus

3. **Partner involved in Pilot Experimentation**

   Provide Partner Name, and Responsible Person Contact Details: Christina Kanellaki, c.kanellaki@limassoltourism.com

4. **Pilot site Ownership Information**

   Provide data on who is/are the owner(s) of the site, type of institution: **Department of Antiquities**
   Contact details of relevant persons: **Katerina Papanikolaou,**
   katerina581939@gmail.com
   antiquitiesdept@da.culture.gov.cy

5. **Pilot site description**
   Apollon Hylates, a sanctuary, was an important religious centre. Originally, the site consisted of a temple, a circular monument, and a formalized Archaic Altar and Precinct. During the Roman period the site was extended with the addition of the south and north buildings, which may have been used for the display of votives or the accommodation of visitors. Most of the monuments belong to the site's 1st century AD restorations and consist of Apollo's temple (which has been partly restored), pilgrim halls, the 'palaistra' (where athletes exercised and played games), a bath complex, and a holy precinct.

6. **Pilot site typology**

   - Cultural Heritage monuments

Pilot Experimentation

1. **Objective of experimentation**

   The main objective of the experimentation in the pilot site of Limassol is to minimize the environmental impacts and enhance visitors experience to increase the number of tourists in a less known Cultural and Natural heritage Site.

2. Pilot Experimentation Design

- Obtain necessary license from the Cyprus Department of Antiquities and Sovereign Base Areas Administration for data collection, drone operation, and on-site access
- Conduct preliminary surveys to understand lighting patterns and their impact on data collection.
- Design precise drone flight paths to ensure comprehensive coverage of the temple's structure. Plan for overlapping images to facilitate seamless stitching in the photogrammetry software.
- Utilize terrestrial laser scanner to achieve sub centimetre accuracy and to capture intricate details such as carvings and small architectural features.

3. Activities and tools

Activities

1. Pre-Experimentation Planning:
   - Conduct a detailed analysis of the site, including terrain mapping and identifying potential logistical challenges (e.g., terrain difficulty, weather).
2. Data Collection:
   - Drone-Based Imaging: Capture high-resolution aerial images from multiple angles and elevations.
   - Ground-Level Imaging: Utilize terrestrial laser scanner 360-degree camera images to capture close-up textures.
3. Data Processing:
   - Image Preprocessing: Calibrate images for color consistency and correct for lens distortions before photogrammetry processing.
   - 3D Reconstruction: Use photogrammetry software to create a detailed 3D model, ensuring high resolution for both texture and geometry.
4. Model Refinement:
   - Conduct quality control checks to refine the model, eliminating noise and ensuring fidelity.
5. Archival and Sharing:
   - Archive all collected data and models in a digital repository for future research and public access.

Tools

1. Hardware:
   - Drones: Equipped with high-resolution cameras and GPS for aerial and terrain mapping.
   - Cameras: 360-degree camera attached to the terrestrial laser scanner producing high-quality photospheres with 5-bracket HDR imaging.
   - Advanced precision imaging terrestrial laser scanner capable of achieving and accuracy below 5mm.
2. Software:

- Photogrammetry Software: Agisoft Metashape or RealityCapture for 3D model reconstruction.
- Image Processing Tools for preprocessing captured images.
- 3D Model Editing: Blender, MeshLab, or ZBrush for model refinement and texturing.

4. Expected pilot outcome

1. High-Resolution 3D Model for Scientific and Preservation Purposes:
    - A detailed, high-fidelity 3D model capturing the exact geometry and texture of the Temple of Apollo Hylates.
    - The model will incorporate fine details such as carvings, cracks, and other structural vulnerabilities to assist in restoration planning, conservation strategies, and scientific analysis.
2. Low-Resolution 3D Model for Dissemination and Educational Outreach:
    - A simplified version of the 3D model optimized for dissemination to the general public.
    - This model will be used for virtual tours, educational platforms, and integration into multimedia presentations, ensuring accessibility across devices and audiences.
3. Raw Image Data Archive:
    - A comprehensive dataset of high-resolution raw images collected during the pilot experimentation.
    - This dataset will include aerial images and close-up details for archival purposes.
    - The raw data will serve as a resource for future research and potential reprocessing with evolving technologies.

5. Resources

LTC contracted external expertise for the creation of 3D Modelling of the temple. They have the knowledge and equipment to create the 3D representation of the Temple. A laptop also must be purchased with appropriate specification to be used in events for the presentation of 3D modelling of the pilot area.

6. Data Collection

Data collection is an important step in the process of documenting the Temple of Apollon Hylates. The precision and completeness of the gathered data can significantly affect the accuracy and fidelity of the resulting 3D model. This stage ensures the capture of all geometric and visual elements of the structure, leaving minimal room for gaps or distortions during the next phases of reconstruction. By integrating laser scanning and drone photogrammetry a comprehensive and multidimensional approach to the documentation process is achieved.
The process begins with the use of terrestrial laser scanning to capture the temple’s accessible sections with an extremely high level of precision. The laser scanner is strategically placed around the structure to achieve full coverage while minimizing occlusions from architectural features or nearby objects. By emitting laser beams and measuring their return times, the

scanner records millions of data points, creating a detailed point cloud that represents the geometry of the temple. All scans are aligned using the scanner's native software and alignment is optimized until the required accuracy is achieved. At the end of this stage the final alignment report is evaluated to verifying that all the alignment deviances are less than 3mm. This step provides a foundational dataset with sub-centimetre accuracy for the lower and mid-level sections of the structure.
To document the higher and less accessible parts of the temple, drone photogrammetry is used. A pre-planned flight path ensures that the drone captures images from multiple perspectives and elevations while also focusing on both horizontal and vertical orientations to achieve the optimal coverage. Adequate image overlap, usually 60-80%, is maintained to ensure seamless stitching during the photogrammetric processing. Each image is geotagged using the drone's onboard GPS system.
For areas requiring detailed surface information, an increased number of high-resolution images is captured using the drone's onboard camera. These images focus on intricate features such as carvings or small architectural elements that demand high fidelity in the final model.
After the data collection is complete, the datasets from the laser scanner and drone camera are cross-referenced to verify completeness. Any identified gaps are addressed with additional scans or images. The resulting integrated dataset serves as a robust foundation for generating an accurate and visually rich 3D model of the temple. The thorough and precise data collection process is vital for ensuring the success of the documentation project, as it captures not only the structure but also its contextual relationship with the surrounding environment, leveraging synergies with the wider area to enhance the final output.

7. Pilot Experimentation Sustainability

1. **SDG 4 - Quality Education:** The creation of 3D model serves as an educational tool for students and general public.
2. **SDG 9 - Industry, Innovation, and Infrastructure**: The implementation of photogrammetry, drone operations, and high-resolution imaging advances scientific research and technological capabilities in cultural heritage preservation.
3. **SDG 11 - Sustainable Cities and Communities**: The project contributes to the conservation and safeguarding of the Temple of Apollo Epicurius by employing advanced technologies for preservation, ensuring its longevity and accessibility for future generations.
4. **SDG 13 - Climate Action:** Continuous cooperation with the Territorial Working Groups and stakeholders to discuss solutions to prevent deterioration of the temple from extreme weather conditions and promote innovative and climate-resilient preservation techniques.
5. **SDG 17- Partnerships for the Goals**: Continuous collaboration among key stakeholders to ensure the successful implementation and sustainability of projects' activities.

8. Pilot Experimentation Evaluation

(What are the KPIs envisaged for the success of the experimentation? What is the methodology for their collection?)

1. Coverage of the Temple During Data Acquisition
   - KPI: Percentage of the temple's structure successfully documented during data collection.

- Methodology: Compare captured images to the predefined site coverage plan to identify any gaps or omissions.

2. Review of Stakeholders

- KPI: Level of expert satisfaction with the high-resolution 3D model's utility for restoration and conservation.

Methodology: Gather qualitative and quantitative feedback through post-experimentation surveys or discussions with archaeologists and conservationists.

Croatia

General Information

1. **Pilot Site Name**
Rector's Palace, Dubrovnik

2. **Pilot Site Location**

Dubrovnik,
Jadranska Hrvatska, Dubrovačko-neretvanska županija,
Croatia

3. **Partner involved in Pilot Experimentation**
Dubrovnik development agency, DURA
Stjepan Ćavar, scavar@dura.hr, + 385 20 640 556

4. **Pilot site Ownership Information**
Dubrovački muzeja
Marija Šiša Vivek, marija.sisavivek@dumus.hr
Dino Lokas, dino.lokas@dumus.hr

5. **Pilot site description (indicative length: 100 words)**
Rector's Palace in Dubrovnik was built as the seat of government and residence of the rector, the highest political function in the Republic of Dubrovnik. The first mention of the building dates back to the 13th century . The palace houses the halls of the Great and Small Councils, state offices, courtroom, prison, armory, and powder magazine. Today, the Rector's Palace is a historical museum within the Dubrovnik Museums. It is furnished with period furniture from the 19th century, collected from old Dubrovnik palaces and summer residences.

6. **Pilot site typology**
- UNESCO sites with landmark or dispersed monuments

Pilot Experimentation

1. **Objective of experimentation**
   - Creation of accurate, high-resolution 3D models of a section of the Rector's Palace. These models will provide a precise digital record that can be used for conservation, restoration, and educational purposes.
   - Enhanced Environmental Monitoring: Focus on analyzing historical temperature and humidity data from the Palace, developing a predictive application to forecast critical environmental conditions.

2. **Pilot Experimentation Design**
   -Limited time windows for conducting drone flights due to visitor activity in the monument area. Restricted access to certain areas of the Rector's Palace may require coordination with local authorities or site managers.
   - Weather conditions (rain, wind, and lighting) could impact drone operations and sensor accuracy.
   - Historical environmental data may be incomplete or inconsistent, requiring additional processing or estimation.
   - Required for drone operations within the historical core of Dubrovnik. An external partner will handle this process. Permits must comply with local aviation and cultural heritage preservation regulations.

3. **Activities and tools**

   - Data Acquisition:
     Photogrammetry: Capture high-resolution images using drones and ground-based cameras.
     Perform systematic imaging to ensure overlapping coverage (60-70%) of the target area.
     LiDAR Scanning: Conduct ground-based or drone-mounted LiDAR scans for accurate 3D data, particularly for intricate architectural details.
     Environmental Sensing: Use of IoT-enabled sensors already placed in the monument to monitor temperature, humidity, and other environmental factors in and around the Rector's Palace. Collect historical environmental data for analysis.

   - Data Processing and Model Construction:
     Use photogrammetry software to reconstruct high-resolution 3D models from images. Process LiDAR data using tools to refine and merge with photogrammetry outputs. Analyze historical and real-time environmental data to identify patterns and potential risks.

   - Development of Predictive Tools:
     AI Algorithms: Use machine learning models to predict critical environmental conditions based on historical and sensor data.
     Train algorithms on datasets to anticipate fluctuations in temperature, humidity, or other harmful conditions.

   - Visualization Dashboards:
     Develop interactive dashboards for museum staff to monitor and forecast environmental conditions. Include alerts and recommendations for proactive preservation measures.

4. Expected pilot outcome

1. High-Resolution 3D Models
Outcome: Creation of accurate and detailed 3D models of the selected section of the Rector's Palace. Models will serve as a digital archive, facilitating conservation planning, restoration work, and virtual educational applications.
2. Functional Environmental Monitoring System
Outcome: Identification of potential environmental risks and thresholds harmful to the building's materials and artifacts.
3. Predictive Application for Environmental Management
Outcome: Development of a software prototype capable of forecasting environmental conditions and recommending preventive actions. Integration of AI algorithms for time-series forecasting and anomaly detection to predict critical conditions. User-friendly dashboard for real-time monitoring and alerts.

5. Resources

External expertise will be engaged to execute the required tasks through an open procurement procedure, ensuring transparency and the selection of the most qualified professionals or organizations for the project's needs. This approach guarantees that the chosen experts have the necessary skills and experience to deliver high-quality results while adhering to project goals and timelines.

6. Data Collection

The environmental data collected from the existing sensors will be provided to our team by the staff of the Rector's Palace, as per the agreement already in place. This arrangement ensures seamless access to historical and real-time data, facilitating efficient analysis and integration into the project.

7. Pilot Experimentation Sustainability

The sustainability of the pilot experimentation is ensured through careful planning, resource optimization, and the integration of long-term benefits into its outcomes.

The pilot experimentation for the Rector's Palace aligns with several United Nations Sustainable Development Goals (SDGs), supporting both heritage preservation and sustainable development through technological innovation.

Below are the relevant SDGs:

1. **SDG 9: Industry, Innovation, and Infrastructure Target 9.1:** Develop quality, reliable, sustainable, and resilient infrastructure.

The use of advanced technologies like drones, LiDAR, and IoT sensors in cultural heritage preservation aligns with the goal of developing innovative infrastructure that is both sustainable and resilient.

Target 9.5: Enhance scientific research, upgrade the technological capabilities of industrial sectors.

The integration of AI for predictive environmental monitoring and 3D modeling supports the enhancement of scientific research and the technological capacity in the field of cultural heritage preservation.

2. **SDG 11: Sustainable Cities and Communities Target 11.4:** Strengthen efforts to protect and safeguard the world's cultural and natural heritage.

The project directly contributes to the conservation and safeguarding of the Rector's Palace, a cultural heritage site, by utilizing cutting-edge technology to preserve its structure and environmental conditions.

Target 11.7: Provide universal access to safe, inclusive, and accessible green and public spaces.

The use of predictive environmental tools to safeguard the building from environmental damage ensures the continued accessibility of the Rector's Palace for the public and future generations.

3. **SDG 13: Climate Action Target 13.2:** Integrate climate change measures into national policies, strategies, and planning.

The environmental monitoring component of the project helps in assessing how climate factors (e.g., temperature and humidity fluctuations) impact the palace, enabling climate-responsive management and conservation strategies.

4. **SDG 4: Quality Education Target 4.7:** Ensure that all learners acquire the knowledge and skills needed to promote sustainable development.

By creating digital 3D models and immersive tools for education, the project contributes to providing innovative learning tools that teach heritage conservation and the application of technology in cultural preservation.

5. **SDG 12: Responsible Consumption and Production Target 12.6:** Encourage companies, especially large and transnational companies, to adopt sustainable practices.

The project promotes sustainable practices in heritage conservation by using non-invasive technologies like drones and IoT sensors that reduce the need for physical interventions, thus minimizing waste and damage to the palace.

6. **SDG 17: Partnerships for the Goals Target 17.6:** Enhance the global partnership for sustainable development.

The pilot involves partnerships with external expertise, local institutions, and conservation experts to ensure the success of the project, demonstrating the value of collaborative efforts in achieving sustainability goals.

8. Pilot Experimentation Evaluation

The success of the pilot experimentation for the Rector's Palace will be evaluated using the following KPIs, which align with both the technical and operational goals of the project. The methodology for their collection is outlined to ensure accurate measurement and analysis.

1. Accuracy of 3D Models

KPI: Percentage of the Rector's Palace section accurately represented in the 3D model.

Methodology: The 3D model will be compared with high-resolution photographs, architectural blueprints, and onsite measurements.

Stakeholder Review: Feedback from conservation experts to ensure the model meets the required standards for use in preservation planning.

2. Reliability of Environmental Data

KPI: Consistency and reliability of environmental data collected by sensors (temperature, humidity, air quality).

Methodology: Cross-referencing real-time data with historical records or external reference data to check for anomalies. Periodic checks to ensure sensors are calibrated and working correctly. Analysis of missing or corrupted data points over time, aiming for 95% data availability.

3. Predictive Accuracy of Environmental Monitoring Application

KPI: Accuracy of the AI-driven predictions for environmental changes, particularly in temperature and humidity.

Methodology: Forecast vs. Actual: Compare predicted values with actual environmental conditions over time to assess predictive model performance. Validation of AI models with actual data during different seasons to ensure robustness. The goal is to maintain a prediction accuracy of at least 85%.

Methodology for KPI Collection

- Data Logging & Software Tools: Environmental data collected by IoT sensors will be logged and stored in a cloud-based system for analysis.
- AI model predictions will be logged and compared with actual environmental data.
- Independent Reviews**:** Conservation experts will be consulted to review the 3D models and environmental data for accuracy and completeness, ensuring high standards for cultural heritage preservation.

Montenegro

General Information

1. **Pilot Site Name**

   Medieval Fortress Žabljak Crnojevića, Montenegro

2. **Pilot Site Location**

   Old Royal Capital Cetinje

3. **Partner involved in Pilot Experimentation**

   Old Royal Capital Cetinje

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Local Tourism Organization of Old Royal Capital Cetinje
Nikola Jablan: nikola.jablan@cetinje.travel

4. Pilot site Ownership Information

Current ownership of the Fortress is Primary school “Boro Vukmirović” Rijeka Crnojevića, but it’s undergoing a procedure for transferring the legal documents regarding ownership of the monument from the school to the Cetinje Municipality (Old Royal Capital Cetinje). The process, once finished will allow Cetinje the rightful ownership status as well as possibility to continuously oversee the progress of the Fortress and its’ surroundings.

5. Pilot site description

Žabljak Crnojevića is an abandoned medieval fortress in Montenegro. It is located on the confluence of the Morača river in Lake Skadar. The level of Lake Skadar fluctuates throughout the year, so that during high water levels, Lake Skadar and Malo Blato are one body of water, while in the summer they are two separate lakes, with water from Malo Blato flowing into Lake Skadar.
The first known written testimony of the fortress originate from mid-14th century. The fortress served as the capital of Zeta under the Crnojević dynasty from 1466 till 1478, being the seat of Stefan and Ivan Crnojević. However, Ivan Crnojević was forced to move the capital in 1478 when the Ottomans seized the town during the siege of Shkodra, holding it until the decision of the Berlin Congress in 1878 when it fell under Montenegrin administration once again after 400 years of Turkish rule. The town has tall walls with towers, as well as one gate. Within the walls can be found: Ivan Crnojević’s court, Church of Saint George (was turned into a mosque during Ottoman rule), housing and military facilities, a warehouse for clothes and a water tank, most of which are preserved.
Due to its strategic position, Žabljak had an important place in controlling a large part of Lake Skadar and the Zeta valley during the Crnojević era, and until its conquest by the Turks in 1478, it was the capital city of the Crnojević dynasty.
With the arrival of the Turks in the Balkans in the 15th century, Žabljak was a military counterweight to Shkodra on the Bojana River. Under the onslaught of the Ottomans, Ivan Crnojević first retreated in 1478 to the Rijeka town of Obod (near today's Rijeka Crnojevića) and from there to Cetinje plain, where he founded a monastery. After its roots and centuries-long existence in Duklja and Zeta, the seat of the Montenegrin state thus retreated from the Mediterranean belt to the mountainous continental hinterland.
Three hundred years later, the roles are changing, the South Slavic peoples strive for liberation - the power of the Ottoman Empire is declining. The area around Rijeka Crnojevića has already been occupied by the warlike Montenegrin tribe of Ceklin. The famous siege of Žabljak in

1835, during the reign of Petar II Petrović Njegoš, is when twelve brave young Montenegrins sneaked up at night and climbed the walls to surprise the larger Turkish garrison inside.
From the Berlin Congress held in 1878, Žabljak finally belongs to Montenegro.
After that, the fortress was used as a military arsenal until World War I, and then as a gendarmerie station for whose needs a barracks was built on the site of a destroyed mosque. The fortress also housed a police station, and was later adapted for the needs of a school.
Since 1961, this historic city has been entered into the Register of Immovable Cultural Monuments of Montenegro and thus placed under the protection of the Law.
As a historical complex of exceptional importance, it has been included in the first category of monumental values.
Despite its great historical significance, Žabljak Crnojevića does not receive the care of society that it really deserves, and the city-fortress is in very poor condition. The fortress is difficult to access by land for most of the year, given that during periods of high water levels, the lake floods the access road, so communication with the surrounding settlements is only possible by boat.
The hill-fortress of Žabljak Crnojevića can be reached from Podgorica via the main road Podgorica - Bar. At the foot of the Žabljak Crnojevića hill, the asphalt road ends and there is a spacious area where you can park your vehicle. To the right of the parking lot is a watercourse formed by numerous springs below the Ponari settlement, and to the left is a macadam road to nearby houses, which in the dry season - when the lake water level drops - allows you to walk across meadows to the Kom Monastery (about 4 km away).

Fortress: 1.400 m2
Environment: 15.159 m2

6. Pilot site typology

- Natural Heritage or/and Cultural Heritage monuments

  ASSOCIATED PARTNER: “ADMINISTRATION FOR PROTECTION OF CULTURAL PROPERTY MONTENEGRO”
  The “Administration For Protection Of Cultural Property Montenegro” is an associated partner on Herit Adapt project.
  The Administration for the Protection of Cultural Property of Montenegro is an entity that carries out tasks related to: research, study, documentation and recording of cultural property; collection, professional processing and preservation of documentation on cultural property; establishment of prior protection of objects, buildings, sites and areas and other material assets that are reasonably believed to have cultural value; determination of the cultural value of cultural property; determination of the status of cultural property and establishment of permanent protection of cultural property; continuous monitoring of the condition of cultural property and revaluation of their cultural value; determination of the reasons and adoption of decisions on the termination of the status of cultural property; formation of cultural property files; establishment and maintenance of registers of cultural property in analogue and electronic form; establishment and maintenance of an information system of cultural property and its connection with other appropriate information systems; cooperation with owners and holders of cultural property and non-governmental organizations dealing with the protection of cultural property; appointment of a temporary guardian for a cultural property; giving an opinion on the temporary removal of cultural property; care for imported cultural property; return of cultural objects that have been

illegally removed from the territory of the Member States of the European Union, the territory of other countries and from Montenegro; ensuring the timely return of temporarily removed cultural property and determining the condition in which it was returned; determining the purpose and manner of using cultural property for the purpose of sustainable development and granting approval for the use of cultural property for commercial purposes; recording objects, objects, sites, areas and other material assets that enjoy prior protection; issuing permits for archaeological and conservation research; suspending research and revoking research permits; determining the value and status of chance finds; preparing and adopting studies on the protection of cultural property for the purposes of drafting state and local planning documents; cooperating with those responsible for preparatory work and those processing planning documents; considering and giving opinions on planning documents; granting consent for geological research in the vicinity of cultural property; issuing conservation conditions and granting consent for conservation projects; temporarily or permanently suspending the implementation of conservation measures or the performance of works on cultural property; accepting completed works on cultural property after the conservation measures have been implemented; suspending works on cultural property that are performed without or in addition to the approved conservation project; providing professional assistance to owners and holders of cultural property; carrying out inspection supervision in relation to the condition of cultural property; respecting the established regime and implementing protection measures on cultural property, as well as exercising the rights and obligations of owners and holders of cultural property; as well as other tasks assigned to its jurisdiction.

ASSOCIATED PARTNER: “MINISTRY OF CULTURE AND MEDIA MONTENEGRO”

Ministry of Culture and Media Montenegro is an associated partner on Herit Adapt project. The Ministry of Culture and Media carries out administrative tasks related to: the development of cultural and artistic creativity; protection, preservation, valorization and presentation of cultural heritage; development of creative industries; realization of public interest in culture; preparation of draft laws, other regulations and general acts in the field of culture, giving opinions on draft laws and other regulations regulating issues related to culture.

ASSOCIATED PARTNER: “LOCAL TOURISM ORGANIZATION OF OLD ROYAL CAPITAL CETINJE”

Local Tourism Organization Of Old Royal Capital Cetinje is an associated partner on Herit Adapt project.
It was established in 2005 and its rights and obligations are determined by the Law on Tourist Organizations and the Statute of the Tourist Organization of the Royal Capital of Cetinje.
The activities of the Tourist Organization of the Royal Capital of Cetinje are created with a goal of shaping the tourist offer of Cetinje, which is considered the cultural and historical capital of Montenegro. The goals relate to the improvement and promotion of the original values of the area of the Royal Capital of Cetinje towards the development of tourism, cooperation with legal and natural persons engaged in tourism and hospitality, museums, churches, the city administration, the national tourist organization, the civil sector and other entities that are directly or indirectly involved in tourism and hospitality.
The Local Tourist Organization of the Royal Capital of Cetinje also organizes cultural, sports and other events that contribute to the enrichment of the tourist offer in the urban

and rural areas. Also, the aforementioned organization encourages and organizes activities related to environmental protection, provides accommodation and designs activities during the stay of study groups and journalists in the territory of the Royal Capital of Cetinje, provides information to tourists, registers and monitors tourist traffic and conducts other activities related to assessing the quality of the tourist product in the area of the Royal Capital of Cetinje.

Pilot Experimentation

1. Objective of experimentation

The objective of the Pilot site experimentation is Fortress Žabljak Crnojevića, which has a very important typology and is directly threatened by climate change, according to various seasons. The aim is to develop a 3D model of the fortress using the specialized LIDAR Drone for the better preservation of the monument and its valorization for touristic purposes.

2. Pilot Experimentation Design

(Specify any design aspects related to the pilot experimentation: obstacles, need for permits, need for purchase of equipment, needs for installation, timeline)

There are no obstacles for the development of the 3D model of the fortress. The equipment needed for this type of activity is a LIDAR drone that will make a precise 3D model of the fortress for better monitoring and preservation.

3. Activities and tools

(Specify the main activities envisaged, the main technologies engaged, and tools involved, e.g. installation of sensing infrastructure, photogrammetry for 3D model construction, AI algorithms, XR, nature based solutions etc)

LIDAR drone as explained in the previous chapter.

4. Expected pilot outcome

(What is the expected outcome of the pilot experimentation? Also include timeline for the expected outcomes, if possible/applicable)

1. Virtual Recreation of the Communication System (December 2024 - December 2025)

- Develop an immersive virtual recreation of the fortress using advanced digital tools (e.g., LIDAR drone).
- Ensure the digital representation is historically accurate and accessible for exhibitions and remote visitors.

2. Dissemination and Exhibition of the Virtual Recreation (January - September 2026)

- Exhibit the virtual recreation in:

    - Museums (Old Royal Capital Cetinje).
- Engage both local and international audiences, including those unable to visit the physical sites.

Impact and Goals

- Enhance knowledge and appreciation of the Žabljak Crnojevića Fortress.
- Redirect tourist flows to lesser-known areas while raising awareness of their cultural importance.
- Integrate digital technology to preserve and showcase cultural heritage for future generations.

5. Resources

(Specify if all needed resources for the pilot experimentation are available: staff, equipment, facilities, external expertise, etc. Specify additional support that might be necessary)

- Equipment necessary for the representation of the fortress (specialized LIDAR drone)
- Hiring an external company for the piloting of the drone and development of the 3D model

6. Data Collection

(Specify data that is needed for the experimentation and their potential sources / methodology of data collection, and timeline for data collection activities (start, end))

Required Data

1. **Historical and Cultural Data**
    - Detailed information on the historical use, architecture, and location of the fortress.
    - Archival data on the fortress.
2. **Tourist Behavior and Traffic Data**
    - Current visitor flow patterns to the fortress and nearby areas.
    - Interest levels in cultural heritage and eco-tourism activities.
3. **Digital Infrastructure Data**
    - Information on the existing digital tools and technologies available for virtual recreation.
    - Technical specifications of the fortress for accurate 3D modeling.

Potential Data Sources

1. **Archives and Libraries**
    - Administration for Protection of Cultural Property of Montenegro, Ministry of Culture and Media, State Archive.
2. **On-Site Surveys**
    - Visitor surveys to assess interest in the pilot activities.

Methodology for Data Collection

1. **Fieldwork**
   - On-site measurements, visibility analysis, and condition assessments.
2. **Technology-Driven Data Collection**
   - Use drones and LIDAR technology for accurate mapping and modeling.

7. Pilot Experimentation Sustainability

(Specify relevant SDGs that the pilot experimentation relates to)

The pilot experimentation aligns with the following Sustainable Development Goals (SDGs):

SDG 4: Quality Education

- The pilot promotes educational opportunities by enhancing understanding of the Nasrid Kingdom's history, architecture, and cultural practices.
- Virtual recreations and museum exhibits provide inclusive learning platforms, accessible to all, including students and researchers.

SDG 7: Affordable and Clean Energy

- Encourages the adoption of renewable energy and energy-efficient technologies in tourism infrastructure, such as solar-powered facilities at pilot sites.
- Reduces the carbon footprint of tourism activities through eco-friendly practices.

SDG 10: Reduced Inequalities

- Improves accessibility to cultural heritage for individuals with disabilities through virtual reality and inclusive tourism offerings.
- Promotes the economic inclusion of local communities by generating job opportunities and supporting local businesses in lesser-known areas.

8. Pilot Experimentation Evaluation

(What are the KPIs envisaged for the success of the experimentation? What is the methodology for their collection?)

Key Performance Indicators (KPIs) for Pilot Success

1. Cultural and Heritage Impact

- **KPI 1**: Number of visitors to lesser-known sites linked to Žabljak Crnojevića.
- **KPI 2**: Percentage increase in awareness of Žabljak Crnojevića.

2. Tourism Diversification

- **KPI 3**: Decrease in visitor concentration at the Old Royal Capital Cetinje.

3. Environmental Sustainability

- **KPI 4**: Biodiversity impact assessment in affected rural and cultural zones.

4. Economic and Social Benefits

- **KPI 5**: Increase in revenue for local businesses in lesser-known areas.
- **KPI 6**: Level of community participation (e.g., number of locals involved in pilot activities).

Methodology for KPI Collection

1. **Visitor Surveys**
   - Conduct surveys at key sites before and after the pilot to measure awareness, satisfaction, and cultural interest.
2. **Financial and Economic Data Collection**
   - Conduct interviews with business owners to assess economic impact.

3. **Community Feedback**
   - Organize focus groups and interviews with community members to gauge participation and satisfaction.
   - Survey evaluation of user perceptions of the virtual reality tool of the fortress.
4. **Periodic Reporting**
   - Collect and report data at regular intervals throughout the pilot (e.g., quarterly) to monitor progress.

Spain

General Information

1. **Pilot Site Name**

   Monumental Complex of Alhambra and Generalife

2. **Pilot Site Location**

   Granada, Andalusia, Spain

3. **Partner involved in Pilot Experimentation**
   Board of Alhambra and Generalife
   Director: Rodrigo Ruíz Jiménez p.direccion.pag@juntadeandalucia.es
   Conservation director: Antonio Peral antoniog.peral@juntadeandalucia.es
   Secretariat: Lorena Fernández lorena.fernandez.payan@juntadeandalucia.es
   Research director: Juan López juans.lopez@juntadeandalucia.es

4. **Pilot site Ownership Information**

   At present the Monument is managed through an independent body with its own juridical status, the Board of Trustees of the Alhambra and the Generalife. Its governing board is made up of representatives of central, regional and local government and of the University.
   It has an executive Director General and an advisory Technical Committee.

   The “Board of Trustees of Alhambra y Generalife” is the Autonomous Organism with juridical own personality specialized in the Conservation of the Patrimony of the Alhambra and Generalife, Granada (Spain). It depends on the Regional Andalusian Government and in its organs of Direction includes representatives of the central government, autonomous, local and University of Granada.

Its mission is the integrated management of cultural heritage which constitutes the monumental site of the Alhambra and Generalife: real estate, furniture, museums, archives, library, archaeological areas, biodiversity, intangible heritage by embracing the principles of the World Heritage Convention (inscribed on the list in 1984) and its main aims being the protection, conservation and restoration, research, public visitation and distribution of the assets it manages.

5. Pilot site description

The Alhambra and Generalife is a group of monuments in Granada in southern Spain and is a very complex and diverse piece of the Spanish heritage. It was originally built as a separate palace-city on a hill in Granada and was the seat of power for the Nasrid Dynasty and its court. It was also the capital of a state, the Kingdom of Granada, whose territories stretched over the south-east of the Iberian Peninsula and formed the last remnants of Al Andalus.
The Alhambra is a palace and fortress complex located in Granada, Spain. It is one of the most famous monuments of Islamic architecture and one of the best-preserved palaces of the historic Islamic world, in addition to containing notable examples of Spanish Renaissance architecture. The complex was begun in 1238 by Muhammad I Ibn al-Ahmar, the first Nasrid emir and founder of the Emirate of Granada, the last Muslim state of Al-Andalus. It was built on the Sabika hill, an outcrop of the Sierra Nevada which had been the site of earlier fortresses and of the 11th-century palace of Samuel ibn Naghrillah. Later Nasrid rulers continuously modified the site. The most significant construction campaigns, which gave the royal palaces much of their defining character, took place in the 14th century during the reigns of Yusuf I and Muhammad V. After the conclusion of the Christian Reconquista in 1492, the site became the Royal Court of Ferdinand and Isabella (where Christopher Columbus received royal endorsement for his expedition), and the palaces were partially altered. In 1526, Charles V commissioned a new Renaissance-style palace in direct juxtaposition with the Nasrid palaces, but it was left uncompleted in the early 17th century. The site fell into disrepair over the following centuries, with its buildings occupied by squatters. The troops of Napoleon destroyed parts of it in 1812. After this, the Alhambra became an attraction for British, American, and other European Romantic travellers. The most influential of them was Washington Irving, whose Tales of the Alhambra (1832) brought international attention to the site. The Alhambra was one of the first Islamic monuments to become the object of modern scientific study and has been the subject of numerous restorations since the 19th century. It is now one of Spain's major tourist attractions and a UNESCO World Heritage Site.
During the Nasrid era, the Alhambra was a self-contained city separate from the rest of Granada below. It contained most of the amenities of a Muslim city such as a Friday Mosque, hammams (public baths), roads, houses, artisan workshops, a tannery, and a sophisticated water supply system. As a royal city and citadel, it contained at least six major palaces, most of them located along the northern edge where they commanded views over the Albaicín quarter. The most famous and best-preserved are the Mexuar, the Comares Palace, the Palace of the Lions, and the Partal Palace, which form the main attraction to visitors today. The other palaces are known from historical sources and from modern excavations. At the Alhambra's western tip is the Alcazaba fortress. Multiple smaller towers and fortified gates are also located along the Alhambra's walls. Outside the Alhambra walls and located nearby to the east is the Generalife, a former Nasrid country estate and summer palace accompanied by historic orchards and modern landscaped gardens.
The architecture of the Nasrid palaces reflects the tradition of Moorish architecture developed over previous centuries. It is characterized by the use of the courtyard as a central space and basic unit around which other halls and rooms were organized. Courtyards typically had water

features at their centre, such as a reflective pool or a fountain. Decoration was focused on the inside of the building and was executed primarily with tile mosaics on lower walls and carved stucco on the upper walls. Geometric patterns, vegetal motifs, and Arabic inscriptions were the main types of decorative motifs. Additionally, "stalactite"-like sculpting, known as muqarnas, was used for three-dimensional features like vaulted ceilings.

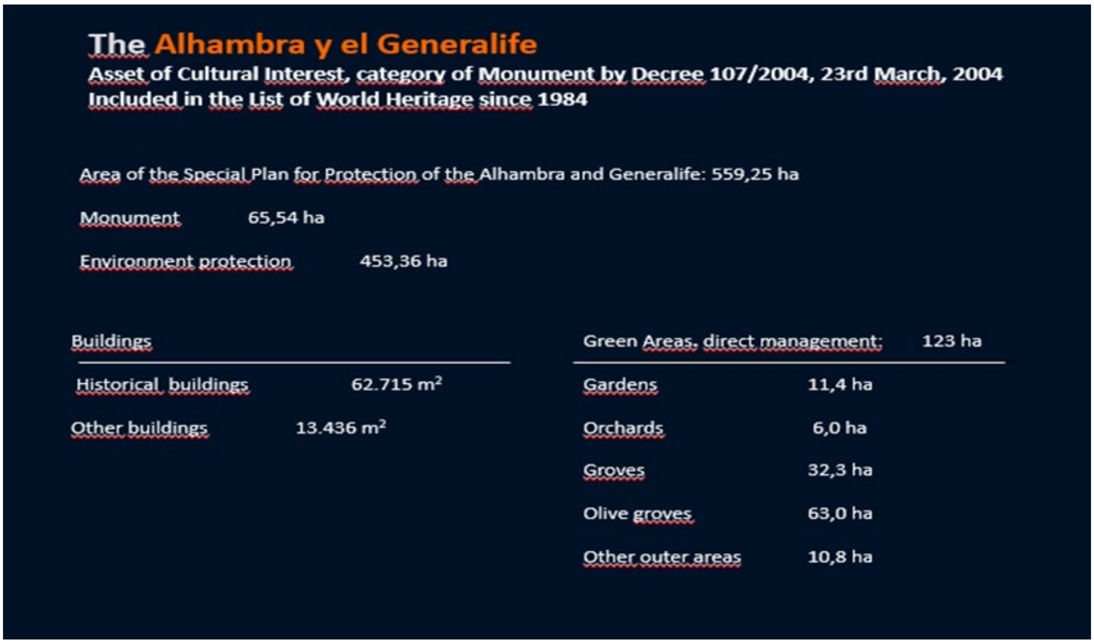
The Alhambra covers a large tract of land of more than five hundred (500) hectares, of which sixty-five (65) belong to the monument itself and four hundred fifty (450) to the protection belt around it:

Area of the Special Plan for Protection of the Alhambra and Generalife: 559,25 ha
Monument: 65,54 ha
Environment protection: 453,36 ha

Buildings
Historical buildings: 62.715 m^2
Other buildings: 13.436 m^2

Green Areas, direct management: 123 ha
Gardens: 11,4 ha
Orchards: 6,0 ha
Groves: 32,3 ha
Olive groves: 63,0 ha

Other outer areas: 10,8 ha



6. **Pilot site typology**
   (Select appropriate)
   - UNESCO sites with landmark or dispersed monuments

- Natural Heritage or/and Cultural Heritage monuments

Monumental Complex of Alhambra and Generalife included in the List of World Heritage since 1984

ASSOCIATED PARTNER: “CONSORTIUM FOR THE DEVELOPEMENT OF SIERRA ELVIRA MEADOWS”

The “Consorcio para el Desarrollo de la Vega Sierra Elvira” (a Consortium for the development of Sierra Elvira Meadows) is associated partner in Herit Adapt. It was constituted in 1995 under the principles of territorial solidarity and to strengthen the identity of the region, with the firm intention to develop and promote all kinds of actions that lead to social and economic improvement for the area.

It is a local public entity currently made up of 36 municipalities of the region of La Vega Sierra Elvira and Maria Madrid Foundation (nonprofit institution that promotes training and support to needed families), who came to settle a territorial unit with homogeneous characteristics, located in the metropolitan area of the province of Granada (Andalusia-Spain).

Its main objectives to pursue are: encouragement of inter-municipal cooperation, promotion of activities to reverse the socio-economic diversification of the consortium municipalities, enhancement of instruments that promote quality of life and environmental surroundings, to disseminate and promote the cultural values of the region, encourage participation / young people in the activities of the region, the implementation of services, advisory and study in general.

ROLE OF THE CONSORTIUM FOR THE DEVELOPEMENT OF SIERRA ELVIRA MEADOWS IN THE PILOT EXPERIMENTATION

Particularly interesting in the area is the study of the towers of the Kingdom of Granada, a system of watch towers that that could be used to communicate news from one to the other by means of signals, like a "telegraph" line, to the Alhambra in Granada . Although the construction of the towers was carried out at different times, we must highlight their perfect distribution, the result of a geographical study and a perfect knowledge of the terrain.

Despite the internal wars and differences within the kingdom, or precisely because of them, this system would be the quickest way to keep the whole territory informed, from the border castles to the lands located in the interior of the province of Granada[1].

Please check Pilot Experimentation Design below for specifications on the objectives and scope of the pilot proposal.

Pilot Experimentation

1. Objective of experimentation

The aim of the pilot test is the promotion and development of lesser-known and less visited tourist sites in Granada. Specifically, the aim is to take advantage of the tourist attraction of the Alhambra and the Generalife to redirect some of the flows of travelers to other lesser known areas of the province, whose history and culture are closely related to the history and culture of the monumental complex of the Alhambra and the Generalife, through the development of activities that arouse interest in these other areas of lesser tourist development, but which have a rich cultural heritage.

2. Pilot Experimentation Design

The pilot test will focus on the activity promoted by the *Cultural and Tourist Association La Pileta*, which aims to reproduce the way the Nasrid people used to communicate between the different watchtowers and watchtowers by means of mirrors reflecting sunlight during the day or torches at night.

The watchtowers are distributed over a group of hills, which together give the impression of forming several lines that can be identified from north to south and seem to follow the courses of rivers or take advantage of natural passages. In addition to the watchtowers that corresponded to the frontier of the Nasrid kingdom proper, there are also transversal lines in the interior, running east to west, in the form of concentric belts around the capital of the kingdom. Together they formed a system that could be used to communicate, by means of signals, the news produced from one to the other, like a 'telegraph' line, to the Alhambra of Granada itself (Arguelles Márquez, 1995)[2]. This line of towers was very important for keeping the city of Granada informed.

The pilot test will consist of setting up this communication system between 45 watchtowers, located in different municipalities in the province of Granada, using mirrors during the day and torches at night, with the end point of this communication system being the Torre de la Vela, a watchtower located in the palatine city of the Alhambra, as shown in the table below.

AREA	WATCH TOWER (LOCATION)
COLOMERA (1)	1.- La Atalaya (Colomera)
MOCLÍN (2 a 7)	2.- Torre de La Porqueriza (Moclín) 3.- Torre de Mingoandrés (Moclín) 4.- Torre de La Solana (Moclín) 5.- Alto de la Torrecilla (Moclín) 6.- Torre de la Gallina. (Íllora) 7.- Torre de La Mesa o de La Cuesta. (Íllora)
INTERMEDIATE (8 y 9)	8.- Torre del Morrón. (Íllora) 9.- Torre de Jorbas. (Íllora)
MONTEFRÍO (10 a 16)	10.- La Torrecilla (en el límite Montefrío-Íllora) 11.- Torre Quebrada (Montefrío) 12.- Torre del Cortijuelo (Montefrío) 13.- Torre de los Anillos (Montefrío) 14.- Torre de Los Guzmanes (Montefrío) 15.- Torre del Hachuelo (Montefrío) 16.- Torre del Sol (Montefrío)
ÍLLORA (17 a 20)	17.- Torre del Charcón (Íllora) 18.- Tajo del Sol (Íllora) 19.- El Fuerte (Íllora) 20.- Torre de Pedrizaguilla (Íllora)
TOCÓN-RÍO GENIL (21 a23)	21.- Torre de Clementino (Tocón/Íllora) 22.- Torre de La Encantada. (Brácana-Íllora) 23.- Cerro Vacas (Íllora)
ZAGRA-LOJA (24 a 29)	24.- Torre Pesquera (Zagra) 25.- Torre Martilla (Zagra) 26.- Torre Agicampe (Loja)

	27.- Torre de la Torrecilla (Loja) 28.- Torre del Cortijo del Aire (Loja) 29.- Torre de la Silla del Moro (Loja)
EL SALAR-ALHAMA DE GRANADA (30 a 33)	30.- Torreón de Los Tajos (Salar) 31.- Torre de La Gallina (Salar) 32.- Torre de La Solana (Alhama de Granada) 33.- Torre de Buenavista (Alhama de Granada)
ALHAMA-ZAFARRAYA (34 a 36)	34.- Torre Donna 35.- La Torrecilla (Alhama de Granada) 36.- Torre Jota
LA VEGA -IN THE AREA AROUND GRANADA- (37 a 44)	37.- Torre Atalaya (Cogollos Vega) 38.- Torre del Chaparral de Cartuja (Güevéjar) 39.- Torre de la Atalaya (Albolote) 40.- Peñón de Zujaira (Pinos Puente) 41.-Torre de Romilla (Romilla/Chauchina) 42.- Atalaya de Boldonar (Cerro Alonso/Cijuela) 43.- Atalaya de la Malahá 44.- Atalaya de Agrón.
LA ALHAMBRA (45)	**45.- TORRE DE LA VELA**

Of the 45 watchtowers included in the table and participating in the pilot experience, 24 belong to a municipality of the *Consorcio para el desarrollo Vega-Sierra Elvira*, HERIT ADAPT's associated partner, and the last of them, the Torre de la Vela, is in the pilot centre, the monumental complex of the Alhambra and the Generalife.

This representation of the communication system between watchtowers can be recreated using virtual reality tools, so that it can be disseminated and exhibited in the museums of the different municipalities where the watchtowers are located, as well as in the museum of the Alhambra and/or in some other museum in the city of Granada, where the culture and traditional methods used by the Nasrid people to communicate between the different populations scattered throughout the province can be disseminated. In addition, tourists visiting the Alhambra or Granada will be made aware of the cultural and monumental heritage located in some of the towns which, in addition to the watchtowers, have well-preserved castles.

3. Activities and tools

See section 3, Pilot Experimentation Design

4. Expected pilot outcome

1. Staging of the Communication System (April - June 2024)

- Successfully demonstrate the historical communication system used in the Nasrid Kingdom, connecting 45 watchtowers with mirrors (day) and torches (night).
- Highlight the significance of the watchtower network in the context of the Nasrid Kingdom's cultural and historical heritage.

2. Virtual Recreation of the Communication System (September - December 2025)

- Develop an immersive virtual recreation of the communication system using advanced digital tools (e.g., VR, photogrammetry).
- Ensure the digital representation is historically accurate and accessible for exhibitions and remote visitors.

3. Dissemination and Exhibition of the Virtual Recreation (January - September 2026)

- Exhibit the virtual recreation in:
  - Museums (Alhambra Museum, museums in the city of Granada, and other municipalities involved in the pilot).
  - Educational and cultural platforms to raise awareness of Nasrid heritage.
- Engage both local and international audiences, including those unable to visit the physical sites.

Impact and Goals

- Enhance knowledge and appreciation of the Nasrid Kingdom's historical communication network.
- Redirect tourist flows to lesser-known areas while raising awareness of their cultural importance.
- Integrate digital technology to preserve and showcase cultural heritage for future generations.

5. Resources

- Equipment necessary for the representation of the communication system between the watchtowers (mirrors, torches, ...)
- Personnel for the staging
- Hiring an external company for the virtual recreation of the communication system between the watchtowers.

6. Data Collection

Required Data

1. **Historical and Cultural Data**
   - Detailed information on the historical use, architecture, and location of the watchtowers.
   - Archival data on the Nasrid Kingdom's communication systems.
2. **Geospatial and Environmental Data**
   - Geographic coordinates and elevation profiles of the 45 watchtowers.
   - Environmental conditions (lighting, terrain, vegetation) affecting visibility between towers.
3. **Tourist Behavior and Traffic Data**
   - Current visitor flow patterns to the Alhambra and nearby areas.

- Interest levels in cultural heritage and eco-tourism activities.

4. **Digital Infrastructure Data**
   - Information on the existing digital tools and technologies available for virtual recreation.
   - Technical specifications of watchtowers for accurate 3D modeling.

Potential Data Sources

1. **Archives and Libraries**
   - Historical documents and manuscripts from the Board of Trustees of the Alhambra and Generalife.
   - University of Granada and local cultural institutions.
2. **On-Site Surveys**
   - Field studies to measure visibility and connectivity between watchtowers.
   - Visitor surveys to assess interest in the pilot activities.
3. **Remote Sensing and GIS Tools**
   - Satellite imagery and topographic maps for geospatial data collection.
4. **Technical Reports**
   - Data from previous restoration or maintenance projects on the watchtowers.

Methodology for Data Collection

1. **Archival Research**
   - Collaboration with historians and archaeologists for historical accuracy.
2. **Fieldwork**
   - On-site measurements, visibility analysis, and condition assessments.
3. **Tourist Surveys**
   - Conduct surveys before and after pilot implementation to measure engagement.
4. **Technology-Driven Data Collection**
   - Use drones, GIS software, and photogrammetry for accurate mapping and modeling.

Timeline for Data Collection Activities (approach)

- **January 2024 - March 2024**: Archival research and initial field surveys.
- **April 2024 - June 2024**: On-site data collection and visibility testing during the staging.
- **July 2024 - December 2024**: Compilation of geospatial data and visitor behavior analysis.
- **January 2025 - June 2025**: Data processing for virtual recreation and pilot evaluation.

7. Pilot Experimentation Sustainability

The pilot experimentation aligns with the following Sustainable Development Goals (SDGs):

SDG 4: Quality Education

- The pilot promotes educational opportunities by enhancing understanding of the Nasrid Kingdom's history, architecture, and cultural practices.

- Virtual recreations and museum exhibits provide inclusive learning platforms, accessible to all, including students and researchers.

SDG 7: Affordable and Clean Energy

- Encourages the adoption of renewable energy and energy-efficient technologies in tourism infrastructure, such as solar-powered facilities at pilot sites.
- Reduces the carbon footprint of tourism activities through eco-friendly practices.

SDG 10: Reduced Inequalities

- Improves accessibility to cultural heritage for individuals with disabilities through virtual reality and inclusive tourism offerings.
- Promotes the economic inclusion of local communities by generating job opportunities and supporting local businesses in lesser-known areas.

8. Pilot Experimentation Evaluation

Key Performance Indicators (KPIs) for Pilot Success

1. Cultural and Heritage Impact

- **KPI 1**: Number of visitors to lesser-known sites linked to the Alhambra.
- **KPI 2**: Attendance at cultural workshops, events, and activities.
- **KPI 3**: Percentage increase in awareness of Nasrid Kingdom heritage (measured through visitor surveys).

2. Tourism Diversification

- **KPI 4**: Decrease in visitor concentration at the Alhambra during the pilot period.
- **KPI 5**: Number of guided tours and eco-tourism packages booked for lesser-known sites.
- **KPI 6**: Distribution of tourist traffic across pilot sites.

3. Environmental Sustainability

- **KPI 7**: Reduction in waste generated per tourist in pilot areas (tracked before and after the pilot).
- **KPI 8**: Water and energy consumption metrics in pilot areas.
- **KPI 9**: Biodiversity impact assessment in affected rural and cultural zones.

4. Economic and Social Benefits

- **KPI 10**: Increase in revenue for local businesses in lesser-known areas.
- **KPI 11**: Number of jobs created through pilot activities.
- **KPI 12**: Level of community participation (e.g., number of locals involved in pilot activities).

Methodology for KPI Collection

1. **Visitor Surveys**

- Conduct surveys at key sites before and after the pilot to measure awareness, satisfaction, and cultural interest.
- Use digital tools (e.g., apps or QR codes) to collect feedback.

2. **Traffic and Flow Analysis**
   - Install visitor counters at pilot sites to track tourist numbers to the experimental pilot.
   - Use GIS mapping tools to analyze movement patterns and tourism flows.
3. **Environmental Monitoring**
   - Use sensors to monitor waste levels, water, and energy consumption.
   - Partner with local environmental agencies to assess biodiversity changes.
4. **Financial and Economic Data Collection**
   - Gather financial data from local businesses, such as revenue and footfall.
   - Conduct interviews with business owners to assess economic impact.
5. **Community Feedback**
   - Organize focus groups and interviews with community members to gauge participation and satisfaction.
     - Survey evaluation of user perceptions of the virtual reality tool for the recreation of the communication system between the watchtowers.
6. **Periodic Reporting**
   - Collect and report data at regular intervals throughout the pilot (e.g., quarterly) to monitor progress.

[1] Argüelles Márquez, M. (1995). Sistema de vigilancia y control del Reino Nazarí en Granada. *Arqueología Y Territorio Medieval*, *2*, 83-97. https://doi.org/10.17561/aytm.v2i0.1607

[2] Argüelles Márquez, M. (1995). Sistema de vigilancia y control del Reino Nazarí en Granada. *Arqueología Y Territorio Medieval*, *2*, 83-97. https://doi.org/10.17561/aytm.v2i0.1607

Rome, Italy

General Information

1. **Pilot Site Name**

   Roman houses of Celio Hill

2. **Pilot Site Location**

   Rome, Lazio, Italy.

3. **Partner involved in Pilot Experimentation**

   CoopCulture, and Responsible Person Contact Details:
   Paula Autore, p.autore@coopculture.it

4. Pilot site Ownership Information

The archaeological complex of the Roman houses of Celio Hill is managed by CoopCulture, a cooperative operating in Italy's heritage and cultural activities sector. CoopCulture addresses the increasingly complex demands of this evolving field, focusing on the integration of cultural heritage with the surrounding territory, as well as the synergy between culture, tourism, and the local economy. With more than 30 years of experience, CoopCulture maintains a widespread presence, managing over 250 sites, including museums, archaeological areas, cultural venues, libraries, villages, and territories across the Italian peninsula.

Corso del Popolo, 40
IT-30172 Venice
Website: www.coopculture.it
Email: info@coopculture.it

5. Pilot site description

The Roman houses of the Celio represent one of the most fascinating places in underground Rome due to the presence of original decorations and the events that over the centuries have profoundly changed the structure. The extraordinary state of preservation of the frescoed rooms and the very high artistic value and religious interest make the Roman Houses of the Celio a fundamental step in the knowledge of ancient Rome.

The Case, or Domus, Romane del Celio, below the basilica of Saints John and Paul, between the Colosseum and the Circus Maximus, were opened to the public in 2002.

Also known as the 'house of the martyrs John and Paul', they contain over four centuries of history and bear witness to the passage and coexistence of paganism and Christianity.

To date, four main phases of use have been identified for the complex:

Phase 1 – The Domus:

At the beginning of the 2nd century, the area of the present Basilica was occupied by a two-storey luxury residential building. It overlooked an alley parallel to the Clivo di Scauro and featured a thermal bath on the ground floor with living quarters on the upper floor.

Phase 2 – The Insula:

At the beginning of the 3rd century, an insula, a multi-storey block of flats, was constructed opposite the domus. This building was divided into rental apartments, with commercial spaces on the ground floor and smaller flats on the upper levels, accommodating less affluent residents.

Phase 3 – The New Domus:

Between the late 3rd and early 4th centuries, the entire block was purchased by a single owner. While the upper floors likely remained divided into rental apartments, the ground floor was converted into an elegant residence for the family that owned the property.

Phase 4 – The Domus of the Martyrs:

In the second half of the 4th century, Christian tradition identifies this site as the dwelling place of Saints John and Paul. The construction of the Basilica above, initiated at the start of the 5th century by Senator Pammachio—who is probably the last known owner—led to the obliteration of the underlying Roman rooms.

6. **Pilot site typology**
   The Roman houses of Celio Hill is a Cultural Heritage Monument.

   - Natural Heritage or/and Cultural Heritage monuments

Pilot Experimentation

1. **Objective of experimentation**
   The objective of the experimentation at the Roman houses of Celio Hill is threefold. The first goal is to analyze the visitor experience at the site and develop a holistic approach to enhance its quality. This includes seamlessly integrating Extended Reality (XR) applications to highlight significant information, presenting it in an engaging and appealing manner, and assessing the impact of these technologies on the overall visitor experience.

   The second goal focuses on increasing visitor numbers to the Roman houses of Celio Hill by creating an attractive experience that combines traditional cultural heritage site visits with state-of-the-art XR technologies, thereby contributing to the site's sustainability.

   The final goal is to position the Roman houses of Celio Hill within a tourist route that attracts visitors, utilizing XR technologies and promotional events. This strategic location serves as a starting point for itineraries that redirect tourist flows toward lesser-known attractions in the area. The approach also aims to alleviate overcrowding around the Colosseum by providing alternative starting points for exploring the region.

Figure 1: Roman houses of Celio Hill

2. **Pilot Experimentation Design**

   The Pilot Experimentation Design can be divided into the following phases:

1. **Preparation:**
   a. Historical and Archaeological Content Documentation

      Study and document the historical and archaeological significance of the Roman Houses ensuring accurate and accessible information for future research and public knowledge. This includes detailed records of the site's architecture, artifacts, and cultural context.

   b. Roman houses of Celio Hill Visit Experience Analysis

Analyze the current visitor experience at the Roman Houses, identifying strengths and areas for improvement. This includes assessing visitor engagement, satisfaction, and educational impact. The goal is to enhance the overall experience and create a deeper connection with the site.

c. Urban Analysis of the Celio Hill Area

Conduct an in-depth urban analysis of the Celio Hill area to understand its relationship with nearby sites. This includes examining pedestrian flow, connectivity, and the integration of the Roman Houses within the broader urban landscape. Identifying opportunities for better accessibility and tourist routing.

d. Design of Tourist Itineraries

Create and design optimized tourist itineraries that incorporate the Roman houses of Celio Hill and surrounding sites. These itineraries aim to offer a comprehensive and engaging visit experience. Tailor routes to different types of visitors, such as cultural enthusiasts or family tourists.

e. Design of XR Interventions to Enhance Visit Experience

Develop XR interventions that enhance the visitor experience within the Roman Houses and connect it to the larger Celio Hill area and tourist itineraries. This could involve Augmented Reality (AR) or Virtual Reality (VR) installations, interactive displays, or immersive storytelling elements that engage visitors in the site's history.

f. Design Promotional Materials and Activities

Design marketing materials and promotional activities to attract visitors to the Roman Houses. This includes print materials, digital content, and special events. Engage potential visitors through campaigns that highlight the historical significance and unique offerings of the site.

2. **Evaluation:**

a. Evaluation of the Current Roman houses of Celio Hill Visit Experience

Assess the current visitor experience through surveys, and observation. Identify strengths, weaknesses, and areas for improvement. Focus on how visitors engage with the site's historical and cultural aspects. Measure visitors flow and numbers.

b. Deployment of XR Interventions and Promotional Materials/Activities

Deploy the XR applications inside the Roman houses of Celio Hill, train the staff in their functionality, and integrate them into the visit experience. Launch promotional campaigns and activities to increase site visibility.

c. Evaluation of the Enhanced Roman houses of Celio Hill Visit Experience and connection to the Celio Hill area.

Assess the impact of XR interventions and promotional efforts on visitor engagement and satisfaction. Collect feedback to determine how these changes have improved the visitor experience and promoted connection to the rest of the Celio Hill area. Measure improvements in visitors flow and number of visitors.

d. Comparison of Visit Experience Quality and Site Sustainability

Analyze how enhancements to the visit experience align with the site's sustainability goals. Compare visitor satisfaction before and after interventions. Evaluate the long-term sustainability of tourism practices introduced to the site.

3. **Activities and tools**

The overall strategy for promoting the Roman houses of Celio Hill involves the design, development, deployment, and evaluation of interactive, non-invasive XR interventions, providing a holistic, multi-level experience for visitors to engage with. Those interventions integrate technologies such as 2D Graphics, 3D Graphics (produced either manually or using 3D scanning), Interactive Maps, 2D/3D Sound, Projections & Projection Mapping, Virtual and Augmented Reality and Interactive Displays.

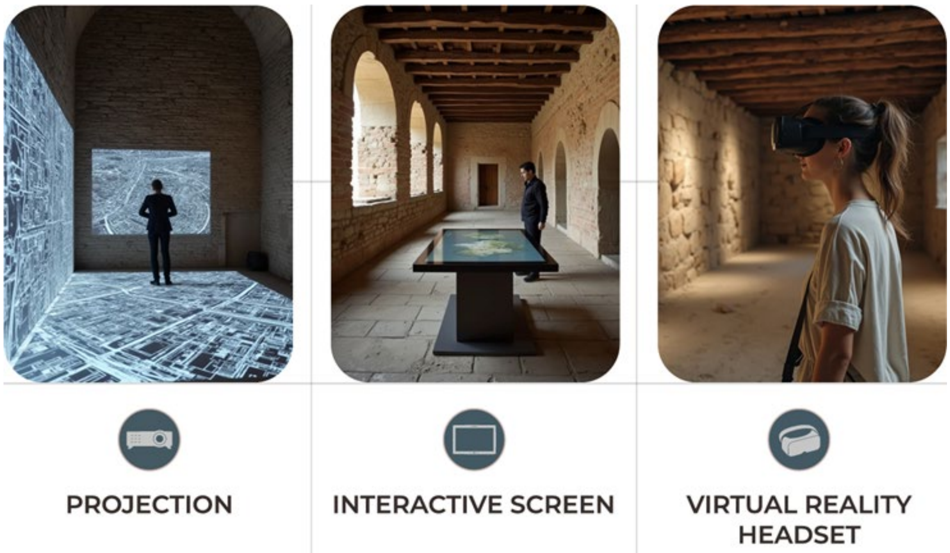


Figure 47 Celio Hill Map and nearby attractions**.**

Up until now, our plan has been to integrate 10 XR interventions into the current visitor experience of the Roman houses of Celio Hill. The first intervention (see figure 48-1) includes a floor projection in the introduction room of the site, providing important information about its structure and location within the broader area of Celio Hill. The second intervention (see Figure 48-2) is located into the same room and involves access to a virtual tour through an interactive display, allowing visitors to explore areas of the Roman houses of Celio Hill that are currently inaccessible to the public.

The third XR intervention is located in the Bottega room of the site, which served as a shop (see Figure 48-3), and allows visitors to experience the currently empty space as a vibrant, reconstructed Roman shop using either a VR headset or a tablet. Visitors can interact with digital content and learn about space's history and past functionality. Inside the same Bottega room is the fourth XR intervention, an interactive display that allows visitors to obtain information about the broader Celio Hill area and learn about outdoor points of interest and itineraries to motivate them to further explore the location (see Figure 48-4).

The fifth XR intervention refers to the Sala del Ceni room next to the Bottega. This intervention will allow visitors to experience a Roman dinner in an immersive manner by observing video projections of human figures, representing guests, and listening to Latin phrases discussing everyday life in ancient Rome (see Figure 48-5). The sixth XR intervention will be placed in the same room and is based on an interactive display placed in front of a locked room containing several artifacts inaccessible to the public (see Figure 48-6). Visitors will be able to select the artifacts on the display, and they will be highlighted by an automatic light projector placed inside the locked room. Simultaneously, the interactive display will provide information related to the selected artifact, offering a meaningful experience for the visitor that bridges both the real and virtual worlds while allowing access to fragile artefacts.

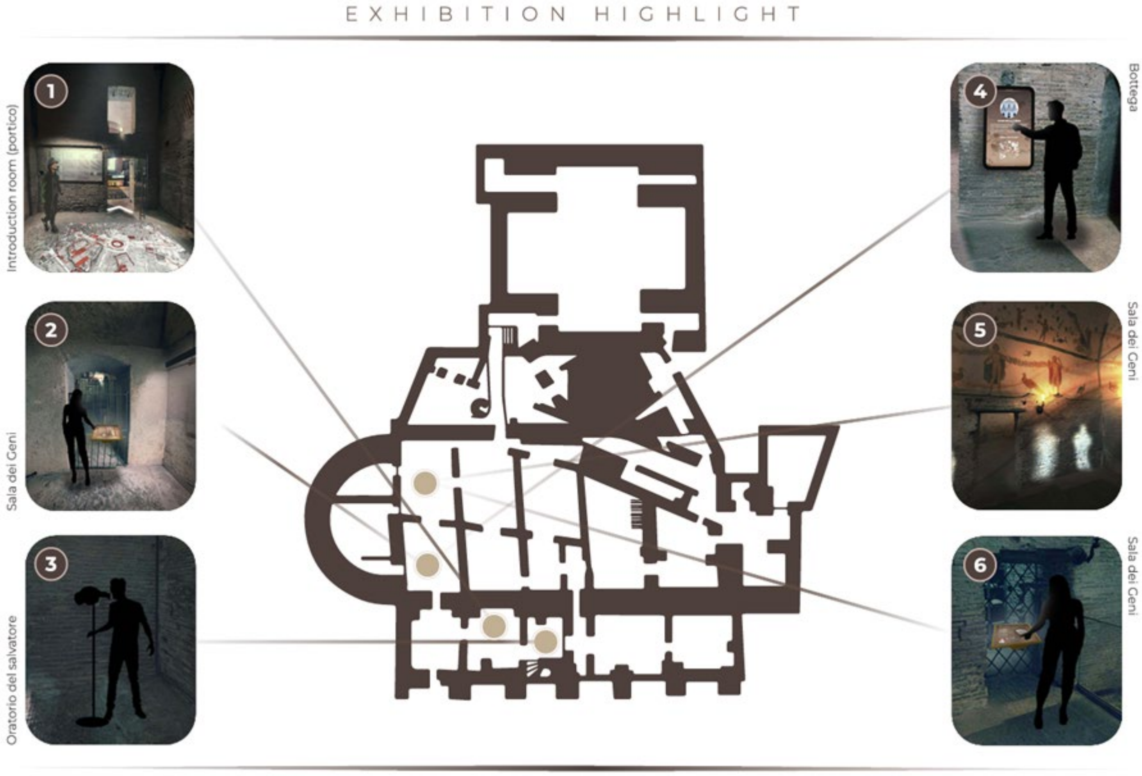


Figure 48 XR interventions 1-6.

Continuing, the next XR intervention will take place at the Sala Accesso al Confession (see Figure 49-7). This intervention follows the same principles as the one in the Sala del Ceni room, with its content focusing on the martyrdom of the saints that occurred in that exact room. Next, the eighth XR intervention will be placed in the Cella Vinaria room, where an interactive display will inform visitors about food and wine preservation techniques employed by ancient Romans (see Figure 49-8).

Finally, both the ninth (see Figure 49-9) and tenth (see Figure 49-10) XR interventions will provide visitors with access to locations of the Roman houses of Celio Hill that are currently inaccessible to the public, through virtual tours operated using interactive displays.

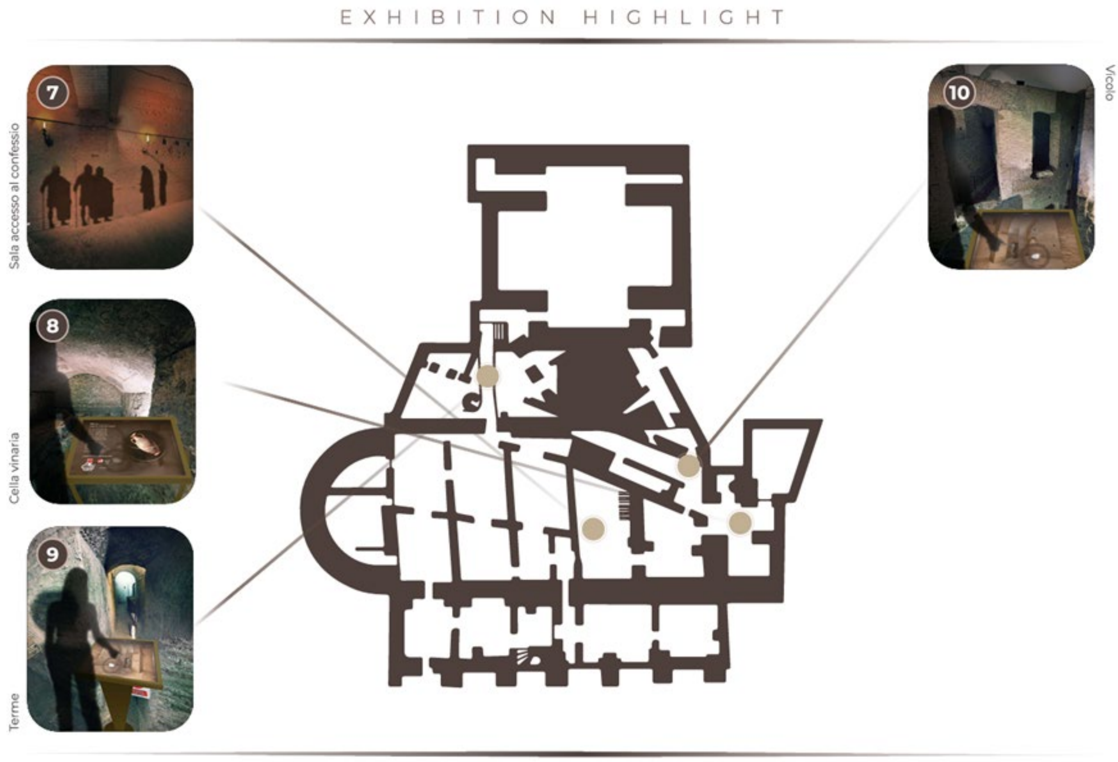


Figure 49 XR interventions 7-10.

As mentioned above, during the fourth XR intervention, visitors will receive information about both the Roman houses of Celio Hill and the surrounding area. This intervention will provide visitors with tourist itineraries to follow, motivating them to visit the rest of the Celio Hill. Visitors will be able to save these itineraries as interactive maps using a provided QR code for later use.

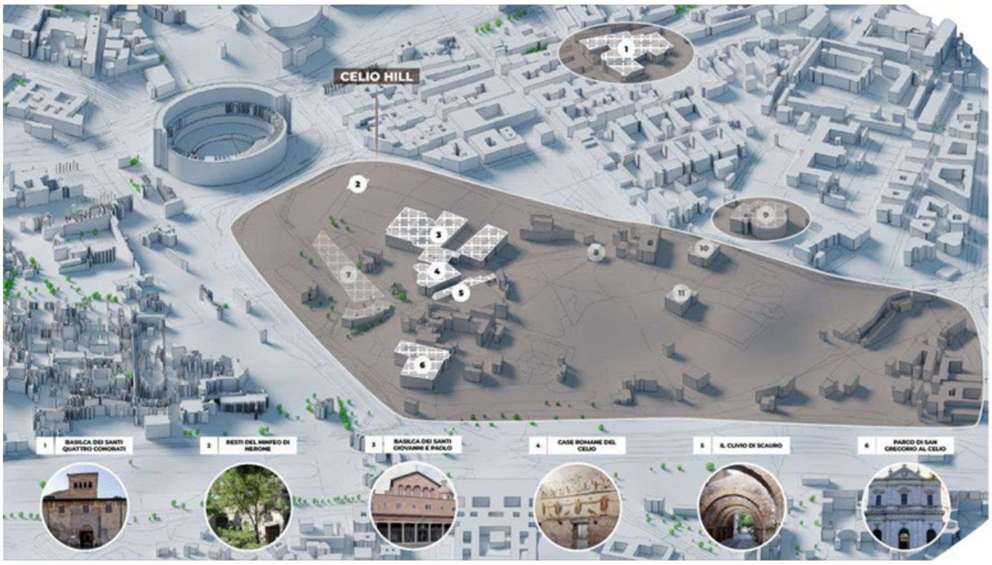


Figure 50 Tourist itinerary example.

The intervention at the pilot site will also offer tourists activities that motivate them to visit interesting parts of Celio Hill. One example of such an activity is to provide them with a different stamp at each site they visit, allowing them to complete a postcard after visiting all the required sites.

Figure 51 Tourist activity example.

Finally, the intervention at the Roman houses of Celio Hill will be concluded with the creation of promotional materials based on the XR interventions, designed to further assist with visitor engagement.

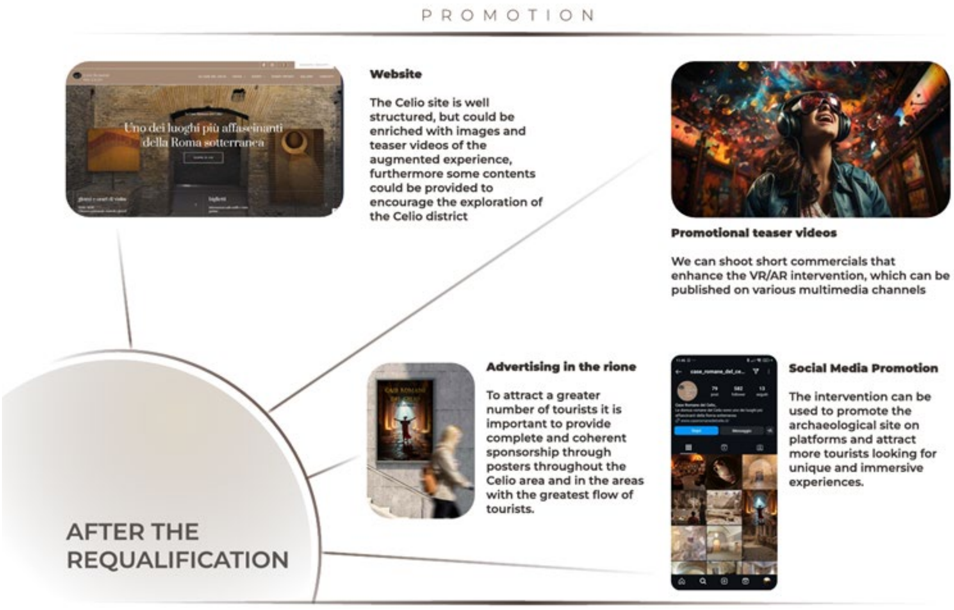


Figure 52 Tourist activity example.

4. Expected pilot outcome

The first expected pilot outcome is the enhancement of the visitor experience at the Roman houses of Celio Hill. This will be achieved by increasing visitor engagement and satisfaction through the integration of XR technologies, which will create immersive and educational content. Additionally, the proposed XR interventions will improve accessibility for diverse audiences by offering virtual tours of fragile or inaccessible areas while providing invaluable educational information to visitors.

The integration of XR interventions into updated tourist itineraries, activities, and promotional materials is expected to boost visitor numbers to the site. It will also raise awareness about the Roman Houses and the broader Celio Hill area among both tourists and locals.

The increase in visitor flow will contribute to higher site revenue and the creation of job opportunities in areas such as site management, guiding, and technology implementation. These developments will enhance local community engagement and foster educational awareness of the site's historical and cultural significance.

Another anticipated redistributing tourist traffic to the Roman houses of Celio Hill. This redistribution will not only improve the visitor experience across the entire area but will also direct meaningful traffic to the Roman houses of Celio Hill by incorporating the Celio Hill area into tourist itineraries.

All the aforementioned outcomes will contribute to the sustainability of the site, further supporting funding for excavation and conservation efforts. Finally, the integration of the Roman houses of Celio Hill with surrounding areas will aid in establishing the Roman Houses as a central hub, serving as the starting point for exploring the broader Celio Hill area.

5. Resources

First and foremost, the resources required for the pilot execution include a well-organized project management team, which has already been formed by the project participants. This team comprises experienced product designers, XR consultants and developers, and cultural heritage management experts.

The design of the intervention for the Roman houses of Celio Hill also necessitates close collaboration with its managers and employees. The project management team has already presented the intervention design (including XR applications, urban analysis – tourist itineraries, and promotional materials examples) to the managing organization, CoopCulture, and refined it based on feedback from its involved members. Also, the management team will consult employees providing guided tours at the sites on the content of the XR interventions, tourist itineraries, and promotional material to be developed.

Upon finalizing the XR interventions, tourist itineraries, and promotional materials, the project management team will train the guides and staff of the Roman houses of Celio Hill on using the applications and assisting visitors to experience them as seamlessly as possible.

Regarding equipment, the intervention at the Roman houses of Celio Hill requires purchasing items to support the XR experience, such as VR headsets, projectors, PCs, controllers, and related hardware. The designed interventions are intended to be as minimally invasive to the current site structure as possible. Any necessary modifications for placing the equipment will be managed by the project management team.

Finally, the execution of the pilot requires the support of the managing organization, CoopCulture, for data collection from visitors. This will be managed through a contract with the organization, specifically for this purpose, and will be overseen by the project management team.

6. Data Collection

Data collection for designing and developing the overall intervention at the Roman houses of Celio Hill includes gathering historical data related to the site's history and evolution. Additionally, the creation of tourist itineraries requires the collection of geospatial data, allowing the project management team to analyze related sites in the broader Celio Hill area and design meaningful itineraries. Finally, tourist behavior and traffic data will be extracted from the site's existing visitor management services to assess the current situation and evaluate any changes after the implementation of the interventions.

Visit experience related data collection will primarily focus on questionnaires, observations, and short interviews with visitors to the Roman houses of Celio Hill. Specifically, the first phase of the pilot will concentrate on evaluating the current quality of the visitor experience at the site. Contracted individuals will observe and document visitor behavior and collect feedback through questionnaires and short interviews regarding their visit experience. This will include information on how visitors learned about the site, their motivations for visiting it and the broader area of the Celio Hill, their expectations, and the extent to which those expectations were met after the visit.

After the interventions integration contracted individuals will follow the same process attempting to capture the updated visit experience to the site along with motivation to visit the rest of the Celio Hill area. This pilot stage will allow for assessing the impact of the XR interventions on the overall visit experience quality improvement and the sustainability of the site. It will reveal usability issues and dictate possible improvements.

For both stages of the pilot execution mentioned above, the project management team will create templates for questionnaires, short interviews, and behavior observation forms. These standardized templates will assist in the proper visualization and comparison of the evaluation results.

Finally, log data will be incorporated into the data collection to further support the evaluation results. The project management team will first compare visitor flow before and after the integration of the intervention to the site to identify any potential benefits. This can be easily carried out using the already deployed ticket services of the site. Additionally, log data will be recorded locally during the use of each XR intervention (e.g., usage times, time spent, number of user interactions, etc.) to assess their impact on visitor engagement.

The aforementioned approach will allow for an in-depth analysis of the impact of the intervention on the Roman houses of Celio Hill and its surrounding area.

An indicative timeline for the design and development of the intervention along with the pilot execution plan can be found below:

- Current Visit Experience Analysis, Content Collection/Documentation, and Urban Analysis (July 2024 – October 2024).
- Design of Intervention (XR Applications, Tourist Itineraries, & Promotional Actions) (November 2024 – December 2024).
- Development of Intervention (January 2025 – May 2025).
- Data Collection – Assessment of Current Visit Experience Quality (February 2025 – May 2025).
- Deployment of Intervention and Staff Training (June 2025).
- Data Collection – Assessment of Updated Visit Experience Quality (July 2025 – October 2025).
- Analysis and presentation of Pilot Results (December 2025).

7. Pilot Experimentation Sustainability

Sustainable Development Goals (SDGs) of the pilot execution are presented in Table 1 below:

SDG 4: Quality Education	The XR interventions at the Roman houses of Celio Hill offer immersive educational content, enhancing visitor engagement and awareness of the site's historical and cultural significance. By integrating XR technology, visitors can explore the Roman Houses interactively, fostering learning.
SDG 8: Decent Work and Economic Growth	The pilot boosts local economic growth by increasing visitor engagement and site revenue. It also creates jobs in guiding, site management, and technology, contributing to the economic vitality of the surrounding community.
SDG 9: Industry, Innovation, and Infrastructure	By integrating XR technologies, the pilot introduces technological innovation to cultural heritage management, enhancing infrastructure and fostering innovation in tourism.
SDG 11: Sustainable Cities and Communities	The pilot supports sustainable tourism by redistributing visitor traffic highlighting lesser known areas, alleviating overcrowding at nearby attractions like the Colosseum, and involving local guides. This helps develop more sustainable urban tourism in the Celio Hill area.
SDG 12: Responsible Consumption and Production	Using energy-efficient XR devices and promoting virtual engagement reduces the environmental impact and helps preserve the site's cultural integrity. It encourages responsible consumption by limiting physical interventions.
SDG 13: Climate Action	Energy-efficient XR technologies and remote access solutions mitigate the environmental footprint of tourism, particularly to fragile areas, contributing to climate change mitigation.
SDG 17: Partnerships for the Goals	The pilot relies on collaboration with local stakeholders, including CoopCulture and technology providers, to integrate XR technology and promote sustainable tourism, fostering multi-stakeholder partnerships to achieve sustainability goals.

Table 1: SDGs of the pilot.

8. Pilot Experimentation Evaluation

The success of the pilot experimentation evaluation will be measured by tracking the following KPIs.

1. Visitor Experience Enhancement
    a. **KPI 1:** Percentage of visitors interacting with XR interventions (e.g., time spent using XR content, number of interactions).
    b. **KPI 2:** Increased average rating from post-visit surveys regarding the quality of the visit experience compared to the one before the intervention.
    c. **KPI 3:** Percentage of visitors using virtual tours of fragile or inaccessible areas.
2. Increase in Visitor Numbers and Awareness
    a. **KPI 4:** Percentage increase in visitor numbers compared to the pre-pilot period.
    b. **KPI 5:** Percentage of visitors who learned about the existence and historical significance of the Roman Houses and the broader Celio Hill area through promotional materials.
    c. **KPI 6:** Percentage increase of visitors expressing a greater understanding of the site's historical and cultural importance compared to ones visiting the site before the intervention.

3. Economic Growth and Job Creation
    a. **KPI 7:** Percentage increase in site revenue due to the pilot, particularly from increased visitor numbers.
    b. **KPI 8:** Percentage increase in guided tours bookings after the integration of the interventions.
4. Site Sustainability and Long-Term Impact
    a. **KPI 9:** Increase in funds raised for excavation and conservation efforts due to higher visitor numbers and site revenue.
    b. **KPI 10:** Percentage of visitors motivated to visit Celio Hill after visiting the Roman Houses.
    c. **KPI 11:** Number of tourists visiting the Roman Houses of Celio Hill as a starting point for exploring the broader Celio Hill area.

[1] https://www.mdpi.com/2076-2607/11/7/1770

Genoa, Italy

General Information

1. **Pilot Site Name**

   Unesco site of Genoa: "Le Strade Nuove e il sistema dei Palazzi del Rolli" ("The New Roads and the System of Rolli Palaces" and their buffer zone.

2. **Pilot Site Location**

   Genoa, Liguria Region, Italy

3. **Partner involved in Pilot Experimentation**

   Municipality of Genoa Tourism Department, Communication and Events department, Culture and Museums department, Economic Development Department and Unesco Office of the Municipality.

4. **Pilot site Ownership Information**

   Municipality of Genoa (Local Authority), Private owners, other public and private institutions (chamber of Commerce, private banks)

5. **Pilot site description (indicative length: 100 words)**
   In 2006, UNESCO recognized the splendid Renaissance and Baroque palaces of the aristocracy of Genoa as a World Heritage Site, with the official name "Le Strade Nuove e il sistema dei Palazzi del Rolli" ("The New Roads and the System of the Palazzi del Rolli").

The UNESCO site includes 42 palaces, among the more than 100 ones still existing throughout the historic center of the city that constitute the so called **buffer zone** of Unesco site. In many cases, the palaces are privately owned, the headquarters of companies and offices, or still inhabited by noble families. But some Palazzi dei Rolli can be visited all year round.
Recently the buffer zone of Unesco site in Genoa has entered in the overall cultural promotion strategy of the Administration.
https://www.rolliestradenuove.it/

6. **Pilot site typology**

- UNESCO sites with landmark or dispersed Palaces and monuments

Pilot Experimentation

1. **Objective of experimentation**

Thanks to the recognition as a Unesco Site, Rolli Palaces has been the most important asset for culture and tourism promotion of Genoa; tourism grew every year transforming Genoa to a cultural and touristic city. Visitors discovered a vibrant city and its historical center, showcasing architecture, art, and culture that span centuries.
During the years it has also created the "Rolli Days" initiative; a 2 day initiative where most of Rolli Palaces (normally closed to people as private) are open for citizens and visitors. This initiative carried to the city and to the Unesco Site of Genoa a great visibility all over the world that brought more tourism. During the pandemic, the initiative has been transformed in Rolli Days Digital, thanks to video animated by Cultural Heritage experts in order to give the opportunity to visit Rolli Palaces without moving. The digital experience is still working as a different way to visit Rolli Palaces.
https://landing.visitgenoa.it/rollidays-online/

At the same time the administration started to work toward sustainable tourism thanks to European projects and other initiatives in order to prevent extreme situations that a lot of cities in Italy and Europe are facing now, with a focus on the **widening and diversification of the tourism offer** of the city.

The pilot experimentation fits totally in the wider Municipal strategy as one of its goals is the diversification of the touristic offer related to Cultural Heritage of the city.
As said, the Rolli Palaces of Unesco are still one of the most important attractions of the city, and the number of tourists is growing. These numbers are getting every year closer to the carrying capacity limit and this can carry different problems to the usability of the Palaces, their conservation and protection.
In this sector (Genoa cultural heritage promotion) the Administration has been working in the very last years on the promotion of the **buffer zone of Unesco Site in Genoa.** As defined by Unesco a buffer zone is "an area ensuring an additional level of protection to a World Heritage Site". For the UNESCO site ***"Genoa, Le Strade Nuove and the system of the*** *Palazzi dei Rolli"*, the nomination dossier set the buffer zone as the perimeter of the historical city centre identified by the Municipal Urban Plan in force. This area of the city centre is full of beautiful Palaces, monuments and cultural attractions. The promotion of

Palaces, Villas and Monuments of this area can be part of the possible solutions to reduce overcrowding in some Palaces.

The experimentation aims at the promotion of historic and cultural places and/or palaces outside the Unesco Site of Genoa, so in its buffer zone.
This promotion will be declined in different activities as:

- the creation and promotion of new cultural and natural touristic experiences in the Unesco site buffer zone,
- creation of thematic guided tours with a specific insight on sustainability, climate change and the need of protection of cultural heritage,
- promotion of guided tours and experiences out of rush touristic hours
- creation of digital and physical tools for the promotion and communication (touristic guides) of the buffer zone of Unesco site in Genoa,
- a renewed way to communicate and promote Genoa Cultural Heritage, Rolli Palaces of the Unesco site and its buffer zone in a more updated way including themes related to resilience and the responsibility of the preservation of Cultural Heritage for future generations.

2. Pilot Experimentation Design

The experimentation design will be carried on by the Municipality, with the different Departments (Culture, Communication, Tourism) involved in the project. The University of Genoa (Environment Engineering Faculty), coordinator of the TWG will provide scientific support to the experimentation, will create tools to measure the effects of the experimentation and will analyse the effects and result of the experimentation.
The experimentation will be implemented between the summer and starting of autumn 2025.

3. Activities and tools

Regeneration and promotion of places (that can be Palaces and/or City Museums) included in the buffer zone of Unesco site, at walking distance from the hotspots of Unesco site in Genoa (in order to foster sustainable mobility).
Creation of digital material (photos/videos) to update with buffer zone cultural heritage, the actual material of Rolli Palaces and create a more updated (including climate change theme) touristic guides and digital guides.
The material can also be used for the monitoring of the conservation state of some Palaces and Monuments.

4. Expected pilot outcome

The expected outcomes will be a wider and update promotion of the buffer zone of Unesco site of Genoa and its Palaces and Monuments in order on one side to spread the visitors of Unesco well known Palaces of Genoa, but above all to promote less know places,Palaces,Museums or Monuments that are hidden beauties of the city and an important part of the cultural heritage of the city.
An increase of the visits to less knows Palaces, Museums and Monuments with a stable number of visits to the Unesco “hotspots palaces”.

A more satisfaction for the tourist that is visiting the more known places of Unesco site (as they should be less crowded) and a more satisfaction for those tourists that want to experience and visit something different, knew and less crowded.
A renewed interest of citizens to less known Palaces, Museums and Monuments of their Historic Centre.

The satisfaction can be calculated with questionnaire and the number of visits by the Tourism Department.

5. Resources

The resources will be used to:

- regenerate and promote less known Palaces, Museums Monuments,
- realize and acquire promotional material (photos, video etc)
- perform communication campaigns (digital and physical)
- achieve promotion with cultural initiatives and events

6. Data Collection

For data collection the IAT (touristic information point) will be involved to know the numbers of visitors using the new diversificated offer. A short questionnaire will be elaborated on the experimentation to give to tourists to ask their opinion on the opportunity. Data will be collected on promotion materials.

The University of Genoa, (Environment engineering Faculty), will work on the results of the questionnaires.

7. Pilot Experimentation Sustainability

The regeneration and promotion of places in the buffer zone, can be renewed in the future with new funds (National, European etc) and at the same time if the results are positive and there will be an increase in visitors in less known places, the future promotion and regeneration can be self done.

8. Pilot Experimentation Evaluation

The evaluation will be carried on by the University of Genoa (Environment engineering Faculty) with the data collected during and after the experimentation and will be provided to Municipality Departments.

France

General Information

1. **Pilot Site Name**

CANIGO GRAND SITE / VILLEFRANCHE DE CONFLENT

2. **Pilot Site Location**

VILLEFRANCHE DE CONFLENT, PYRÉNÉES ORIENTALES, OCCITANIE, FRANCE

3. **Partner involved in Pilot Experimentation**

CRTL OCCITANIE (Angelika SAUERMOST : angelika.sauermost@crtoccitanie.fr, Dominique THILLET : dominique.thillet@crtoccitanie.fr)

4. **Pilot site Ownership Information**

(Provide data on who is/are the owner(s) of the site, type of institution, Contact details of relevant persons)
SYNDICAT MIXTE CANIGOU GRAND SITE & TOWN OF VILLEFRANCHE DE CONFLENT (Florian Chardon : florian.chardon@canigo-grandsite.fr)

5. **Pilot site description** (indicative length: 100 words) **: 96 words**

The fortified city of Villefranche de Conflent has been founded in 1092 to control the access to 3 valleys. The city has been attached to France in 1659 (Treaty of the Pyrenees). The ramparts of Villefranche de Conflent were built in the Middle Ages and transformed by Vauban under the reign of Louis XIV. They have been on UNESCO's World Heritage List since 2008, together with 12 other fortified Vauban sites. Today the city is part of the Canigo Grand Site, thanks to which it is connected to an important sustainability, tourism and local development project.

6. **Pilot site typology**

(Select appropriate)

- UNESCO sites with landmark or dispersed monuments
- ~~Natural Heritage or/and Cultural Heritage monuments~~

Pilot Experimentation

1. **Objective of experimentation**

(Detail what is the objective of the experimentation of each pilot site)

   1. Measure and establish a clear understanding of visitor numbers in Villefranche de Conflent, linked to the wider pilot area of Canigo Grand Site, using existing or developing tools and drawing on studies conducted or planned by the Syndicat Mixte

Canigou Grand Site, the Pyrénées-Orientales Tourist Board (ADT), CRTL Occitanie, and other key stakeholders.

2. Identify potential risks and assess vulnerabilities related to climate change within the experimental area, leveraging current and emerging initiatives and tools, with a particular emphasis on water resource challenges.
3. Coordinate similar projects and valuable or emerging initiatives to amplify and/or accelerate results at the pilot site, with the goal of later sharing insights with other regional sites.
4. Engage the TWG Territorial Working Group throughout all phases of the experimentation, ensuring effective communication and information sharing. Focus on the need to inform, raise awareness, and widely share the progress, outcomes, and best practices from the experiment.

2. **Pilot Experimentation Design**

(Specify any design aspects related to the pilot experimentation: obstacles, need for permits, need for purchase of equipment, needs for installation, timeline)

Timeline : 2025 (start as soon as possible)
No special designs necessary

3. **Activities and tools**

(Specify the main activities envisaged, the main technologies engaged, and tools involved, e.g. installation of sensing infrastructure, photogrammetry for 3D model construction, AI algorithms, XR, nature based solutions etc)

Flux Vision Orange; Satellite data, OTO internal CRTL Occitanie tourism observation and planification tool helping monitoring and decision making
Testing "Adaptour" a new national tool that is able to help identifying risks and vulnerability concerning the territory and tourism businesses.

4. **Expected pilot outcome**

(What is the expected outcome of the pilot experimentation? Also include timeline for the expected outcomes, if possible/applicable)

- Know the risks the territory is facing
- Know the degree of vulnerability of the territory
- Contribute to the wider tourism observation tools on the territory and connect it to the regional tool
- Raise awareness on climate change and especially on lack of water
- Connect the problematics of climate change to the follow ups on the territory
- Empower localy and the regional team in order to spread out the lessons learnt and transfer the results

5. **Resources**

(Specify if all needed resources for the pilot experimentation are available: staff, equipment, facilities, external expertise, etc. Specify additional support that might be necessary)
Staff :

- CRTL : 3 persons at different times

- Syndicat mixte Canigo Grand Site : 1 person

External expertise :

- Adaptour expert
- Expert capable of linking the data monitoring part to the risks and vulnerability part to the stakeholders

6. **Data Collection**
(Specify data that is needed for the experimentation and their potential sources / methodology of data collection, and timeline for data collection activities (start, end))
Data sets :

- Flux vision (private)
- Satellite data (open data with private tool / dashboard)
- OTO (CRTL tool)
- Others (to be specified)

7. **Pilot Experimentation Sustainability**
(Specify relevant SDGs that the pilot experimentation relates to)

6 - Clean water and sanitation

12 - Responsible consumption and production

13 - Climate action

17 - Partnerships fot the goals

8. **Pilot Experimentation Evaluation**
(What are the KPIs envisaged for the success of the experimentation? What is the methodology for their collection?)

- Number of tourists monitored on site
- Number of stakeholders implied
- Number of climate risks identified on site
- Number of people informed throug the infodays
- Quality of the projects connected to the experimentation
- (Can be completed)

Mapping of pilots to previous projects

The effective integration of technological solutions into tourism management and monitoring relies heavily on understanding the alignment of current pilot initiatives with successful past projects. This chapter explores the intersection between pilots under the HERIT-ADAPT project and pre-existing frameworks, systems, and technologies that have demonstrated value in fostering sustainability and resilience. By examining the technological state-of-play in relevant domains—such as sensory infrastructures, IoT, AI, and Big Data analytics—this analysis contextualizes how these advancements have been utilized to monitor tourism flows and mitigate risks to natural and cultural heritage. The mapping exercise will not only highlight lessons learned from prior implementations but will also assess the capacity of each pilot to adopt and scale these innovations effectively, ensuring alignment with HERIT-ADAPT's overarching objectives.

Pilot Site Name	Partner	Previous Solution	Linked R&D Project	Description
Temple of Apollo Epicurius	RWG and ATHENA	ART3MIS tool	H-2020 MCR Warmest	Tool that enables the editing and annotation of 3D models of objects, accompanied by AI algorithms developed that allow the detection of saliency features and their color marking, as well as the detection of deficiencies in 3D models of symmetrical objects.
Temple of Appolon Hylates	LTC			
Medieval Fortress Žabljak Crnojevića	PCT/ORCC			
Rector's Palace, Dubrovnik	DURA	Sensees Platfrom	Dubrovnik Smart City project	Platform that monitors air quality and noise pollution
Monumental Complex of	UGR	3dguides		Innovative platform, through which

Alhambra and Generalife				anyone can build his own multilingual guides enhanced with 3D and Augmented Reality
Roman houses of Celio Hill	SDR	Audioguide		The pilot site is a conventional museum (indoor archaeological site) with no technologies installed in the exhibition space. To improve visitor experience, an optional audioguide is available, which can be used through a smartphone rented at the entrance (or downloaded and activated with a unique code on a personal smartphone). The site manager CoopCulture has an in-house, customisable audioguide application, adapted to various other sites.
The System of l Rolli Palaces and their buffer zone	COGME	**Alter Eco Project** (protection of Mediteranean cities charachteristics from overtourism)		Tourism offer diversification in space and time

		Tourism Friendly cities project (Find a balance between tourism as economic asset and the protection of local communities from overtourism) **Androni project** (national law funds for Unesco sites; regeneration, and involvement of local community in the promotion of the the "entrance halls" of historic palaces of the city centre) **Rollindagando** project (Municipal funds: update of cultural mapping of Genoa heritage with an analysis of the conservation state of the cultural heritage) **Doge** (national project; communication activities to promote the historic palaces system of welcoming in Genoa) Carruggi (national PNRR)	GIS research	Regenerationa and promotion of Palaces, Museums and Monuments of Unesco buffer zone.
CANIGO GRAND SITE / VILLEFRANCHE DE CONFLENT	CRTLO	• Occitanie Tourisme Observation (OTO) • Flux Vision Tourisme platform,		**OTO** is the web interface for accessing the Occitanie Tourist Information Hub (HIT) **Flux Vision Tourisme** allows you to measure population flows using up-to-date mobile data

Sustainability and Resilience in HERIT ADAPT

We continue in this section with a brief comparative presentation of the Sustainable Development Goals (SDGs), as defined by the United Nations. Table 1 showcases the various SDGs covered by the pilot use cases of the project. It also highlights the significance of advanced technology integration in addressing multiple sustainability challenges within heritage preservation projects. By contributing to various SDGs, the project not only enhances visitor experiences but also promotes sustainable tourism practices and preservation of Europe's heritage for future generations.

Table 3: List of Sustainable Development Goals (SDGs) covered by each pilot site in HERIT ADAPT

	SDG4	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG17
W. Greece	x			x	x		x		x	x
Limassol	x				x		x		x	x
Dubrovnik	x				x		x		x	x
Cetinje	x		x			x				
Granada	x		x			x				
Rome	x			x	x		x	x	x	x
Genoa	x			x			x	x		x
Occitanie		x						x	x	X

Overall, the use cases selected for the pilots of HERIT ADAPT, together with the integration of technologies like XR, drones, IoT sensors, and LiDAR into the project, presents an opportunity to contribute to various aspects of sustainability, seen through the lens of tourism and heritage preservation. From the use cases chosen by the consortium partners and presented in previous sections of this document, the technology applications in heritage preservation envisioned in the project contribute to the following SDGs:

- *Education* (**SDG 4**) by providing immersive and inclusive learning experiences.
- *Access to clean water and sanitation* (**SDG 6**) by facilitating monitoring and management of water quality and consumption patterns at a local level.
- *Affordable and clean energy* (**SDG 7**) through energy-efficient devices and remote access solutions.
- *Decent work and economic growth* (**SDG 8**) via creating jobs and promoting local culture and products, while promoting sustainable tourism.
- *Industry, innovation, and infrastructure* (**SDG 9**) with technological innovations and sustainable infrastructure development.
- *Reduced inequalities* (**SDG 10**) by improving accessibility and economic opportunities for local communities.
- *Sustainable cities and communities* (**SDG 11**) through promoting sustainable tourism and urban planning.
- *Responsible consumption and production* (**SDG 12**) by reducing the environmental footprint of tourism and preserving cultural sites.

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- *Climate action* (**SDG 13**) through mitigating the environmental impact of tourism on fragile areas.
- *Partnerships for the goals* (**SDG 17**) through collaborations between stakeholders, local communities, and technology providers.

Overall, the pilot use cases in HERIT ADAPT demonstrate that advanced technologies can lead to several benefits in preserving cultural heritage, while simultaneously addressing a number of sustainability challenges. The potential outcomes include enhanced visitor experiences, economic growth, technological innovation, sustainable tourism practices, and climate change mitigation. With respect to examples of specific targets in the aforementioned SDGs, illustrating the contribution of the project, the following give some indications:

- *Target 4.7 - Ensure that all learners acquire the knowledge and skills needed to promote sustainable development*: By creating digital 3D models and immersive tools for education, the project contributes to providing innovative learning tools that teach heritage conservation and the application of technology in cultural preservation.
- *Target 9.1 - Develop quality, reliable, sustainable, and resilient infrastructure*: The use of advanced technologies like drones, LiDAR, and IoT sensors in cultural heritage preservation aligns with the goal of developing innovative infrastructure that is both sustainable and resilient.
- *Target 9.5 - Enhance scientific research, upgrade the technological capabilities of industrial sectors*: The integration of AI for predictive environmental monitoring and 3D modeling supports the enhancement of scientific research and the technological capacity in the field of cultural heritage preservation.
- *Target 11.4 - Strengthen efforts to protect and safeguard the world's cultural and natural heritage*: The project directly contributes to the conservation and safeguarding of the Rector's Palace, a cultural heritage site, by utilizing cutting-edge technology to preserve its structure and environmental conditions.
- *Target 11.7 - Provide universal access to safe, inclusive, and accessible green and public spaces*: The use of predictive environmental tools to safeguard the building from environmental damage ensures the continued accessibility for current and future generations.
- *Target 12.6 - Encourage companies, especially large and transnational companies, to adopt sustainable practices*: The project promotes sustainable practices in heritage conservation by using non-invasive technologies like drones and IoT sensors that reduce the need for physical interventions, thus minimizing waste and damage to heritage sites.
- *Target 13.2 - Integrate climate change measures into national policies, strategies, and planning*: The environmental monitoring component of the project helps in assessing how climate factors impact heritage sites, enabling climate-responsive management and conservation strategies.
- *Target 17.6 - Enhance the global partnership for sustainable development*: Several pilots in the project involve partnerships with external experts, local institutions and other stakeholders to ensure the success of the project, demonstrating the value of collaborative efforts in achieving sustainability goals.

With respect to the implications of HERIT ADAPT for other related initiatives and projects in sustainable tourism, it can inspire other pilot sites around Europe to adopt similar approaches to cultural heritage preservation and sustainable development. By integrating advanced technologies into their initiatives, they can not only contribute to various SDGs but also establish a solid foundation for future collaborations among stakeholders.

In terms of sustainable tourism practices, HERIT ADAPT aims to display the potential of advanced technology applications in promoting such practices. They redistribute visitor traffic, involve local guides and businesses, and preserve cultural sites through energy-efficient solutions, remote access, and reduced physical interventions.

Regarding resilience in heritage preservation, as the impact of climate change poses a significant threat to heritage sites across Europe, investigating how technology applications can contribute to enhancing their resilience can provide valuable insights for future preservation efforts and potential funding opportunities.

The HERIT ADAPT envisaged pilot experimentation involves testing a number of technological solutions in the context of monitoring and collecting information from pilot sites. This can be thought of as contributing significantly to a pre-disaster phase identifying heritage site vulnerabilities and needs for restoration and maintenance. Risks can be attributed to climate crisis and natural hazards, as well as tourist flows and overtourism. The identification of risks, heritage site vulnerabilities, and ways to enhance their restoration and resilience can be thought of as parts of the envisaged HERIT ADAPT Sustainable Tourism Model.

Furthermore, enhancing the sustainability and resilience of heritage sites can be thought of as enhancing the resilience of their relevant destinations. As destination resilience represents an ability to prepare for, withstand, and recover from adverse events, both cultural and natural heritage can be regarded as dynamic resources enhancing destination resilience. According to the RESILIAGE project (https://resiliage.eu/) concepts, key drivers of heritage-based resilience include adaptive governance, involving diverse stakeholders in risk management; health and wellbeing, addressing both physical and psychological aspects; active memory, leveraging collective historical knowledge; social interaction and inclusiveness, ensuring all community members are involved; and socio-economic resilience, exploring how heritage can contribute to economic recovery and diversification. The HERIT ADAPT methodological approach with its recognition of heritage sites as important assets of tourism destinations, Territorial Working Groups engaging the entire Quadruple Helix in partner territories, co-created Sustainable Tourism Model, use of innovative technologies, pilot testing, co-creation of Sustainable and Resilience Tourism Strategies, and Transferability Plan, drives towards the same direction of enhanced territorial resilience.

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Conclusion

The HERIT ADAPT project places great emphasis to its pilot experimentation in the Euro MED Area. As outlined in the sections above the pilot testing can be classified as following:

- 3D Modeling of Cultural Heritage sites aiming at enhancing their restoration and maintenance: applicable to the pilot sites of Western Greece, Limassol, Dubrovnik, and Cetinje
- Enhancing visitor experience either utilizing 3D virtual models of cultural heritage sites as above, or by using VR / XR technologies : applicable in Granada and Rome
- Enhancing environmental monitoring and management : applicable to Dubrovnik
- Tourism offer diversification and management of tourism flows : applicable to all pilot sites and especially Granada, Genoa and Occitanie
- Identification of risks and vulnerabilities : primarily applicable to Occitanie

All pilot sites envisaged in the different partner countries refer either to Unesco heritage sites (as is the case in Western Greece, Dubrovnik, Granada, Genoa and Occitanie), or other natural or cultural heritage sites (as is the case in Limassol, Cetinje, and Rome). The project recognizes the fact that Heritage sites represent significant assets for tourist destinations that enhance their sustainability and resilience, addressing all three pillars of sustainability, and being dynamic resources for destination and community resilience.

The use of technological solutions that enable better monitoring of heritage sites, the collection of data regarding their status, environmental conditions, tourism flows, risks and vulnerabilities, are significant contributions towards enhancing overall Sustainability and Resilience of territories. To this end, the present report provides important input towards the HERIT ADAPT Sustainable Tourism Model. It also drafts requirements for the pilot experimentation phase, including prerequisites and needs for necessary developments and enhancements of existing tools.

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