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## **Collaborative maintenance of archaeological heritage in the digital era**

### *La manutenzione collaborativa del patrimonio archeologico nell'era digitale*

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#### ABSTRACT AND KEYWORDS

##### **Collaborative maintenance of archaeological heritage in the digital era**

In the field of collaborative maintenance of archaeological heritage supported by digital tools, this article proposes an innovative approach to its management and monitoring. Starting with the development of a scientific framework that addresses the constraints, gaps and scenarios, the authors conducted a bibliometric analysis and systematic review of the scientific literature and regulations, and a compilation of best practices. To develop the most effective approaches in the collaborative management of archaeological sites, the paper outlines the requirements under which maintenance communities to improve the effectiveness and efficiency of preventive and predictive maintenance. These conditions open up strategic scenarios for the stewardship of Italian archaeological sites by operating from a dual perspective. On one hand, it enhances high-visited sites, where participation improves the quality of monitoring data on maintenance status. On the other, it boots low-visited sites, where user involvement raises awareness among visitors regarding shared care initiatives.

**Keywords:** maintenance, archaeological heritage, digital tools, management, monitoring

##### **La manutenzione collaborativa del patrimonio archeologico nell'era digitale**

Nel campo della manutenzione collaborativa del patrimonio archeologico supportata da strumenti digitali, questo articolo propone un approccio innovativo di gestione e monitoraggio. Partendo dallo sviluppo di un quadro scientifico che affronta vincoli, *gap* e scenari, sono state effettuate un'analisi bibliometrica e sistemica della letteratura scientifica e della normativa, e una schedatura delle migliori pratiche. Al fine di sviluppare approcci più efficaci alla gestione collaborativa dei siti archeologici, il documento restituisce i requisiti che devono essere soddisfatti dalle comunità manutentive per migliorare l'efficacia e l'efficienza della manutenzione preventiva e predittiva. Tali condizioni aprono scenari strategici per la custodia dei siti archeologici italiani agendo in una duplice prospettiva. Da un lato, valorizzare i siti ad alta fruizione in cui la partecipazione incrementa la qualità di monitoraggio del dato sullo stato manutentivo. Dall'altro, migliorare i siti a bassa fruizione in cui il coinvolgimento dell'utenza incide sulla sensibilizzazione dei fruitori verso azioni cura condivisa.

**Parole chiave:** manutenzione, patrimoni archeologici, strumenti digitali, gestione, monitoraggio

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## 1. Introduction

The management and maintenance of archaeological heritage represent one of the main challenges in today's debate on cultural sustainability (Hauashdh et al., 2022). In Italy, where the archaeological heritage is vast and diverse, traditional approaches to maintenance are proving increasingly inadequate, especially given limited financial resources (Fan et al., 2023). Data from the National Institute of Statistics show that Italy's archaeological heritage (298 archaeological sites, areas, and parks) is part of a broader cultural system, including 4,416 public and private museums, archaeological sites, and monuments (Minicifre, MIC, 2025). This framework highlights the scale of Italy's cultural heritage and the need to analyse its geographical distribution and level of use, as archaeological heritage, though limited (approximately 7%), is particularly vulnerable and dependent on its transmission as a shared value. Furthermore, it is worth noting that archaeological sites often constitute an integrated system together with the museum facilities where the artefacts are housed, raising issues regarding both assets exposed to the elements and the buildings themselves.

Without maintenance interventions, archaeological sites are exposed to progressive technological and environmental decay. This can lead to serious and irreversible loss of original, irreplaceable material (Talamo, 2013). Conversely, planning and design of maintenance activities can help prolong the lifetime of archaeological elements, protective structures, and the equipment that enables their use. The paradigm of archaeological heritage maintenance has gradually evolved toward inclusive approaches, recognizing local communities and users as active participants in care, monitoring, and promotion processes (Cecchi & Gasparoli, 2010; Gasparoli, 2011). This transformation is part of a broader rethinking of cultural heritage governance. In this perspective, stewardship extends beyond institutions to involve a wide range of stakeholders, including residents, visitors, and civil society organisations. Collaborative maintenance thus emerges as a promising approach to improving the management of archaeological sites, integrating expert knowledge with user-based knowledge (Cattaneo, 2012).

At the same time, the development of digital technologies has opened up new opportunities for the monitoring and management of cultural heritage. The use of digital platforms, sensors, and data-driven systems enables the real-time collection of information useful for predictive analysis and the optimization of maintenance strategies (Pinto et al., 2022). Despite their potential, these tools are fragmented implemented, focusing primarily on the technological dimension with expert knowledge, without effective integration with participatory user involvement. The complexity of maintaining archaeological heritage stems from the multidimensional nature of the factors involved, including technological, managerial, economic, and social aspects (Fiore, 2008). At the same time, this multidimensionality requires a planning approach aiming at reducing the need for repairs after a breakdown, which negatively affect the maintenance of archaeological heritage and limit public access when they affect visitor facilities.

Maintenance effectiveness is a combination of technical, administrative, and managerial operations carried out throughout the asset's lifecycle to keep it in appropriate condition (Lee & Scott, 2008; Ciampa & Ferreira, 2024).

These activities, when applied to archaeological heritage, are carried out with a focus on preventive and/or predictive maintenance. From a methodological standpoint, this implies interpreting the maintenance of archaeological heritage as a key element of the sustainability of the entire management process, ensuring that it is not relegated to a final phase (Talamo & Bonanomi, 2019).

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Within this multifaceted framework, it is necessary to identify a system of appropriate actions that can ensure an effective and efficient approach to the transmission of the archaeological heritage to future generations.

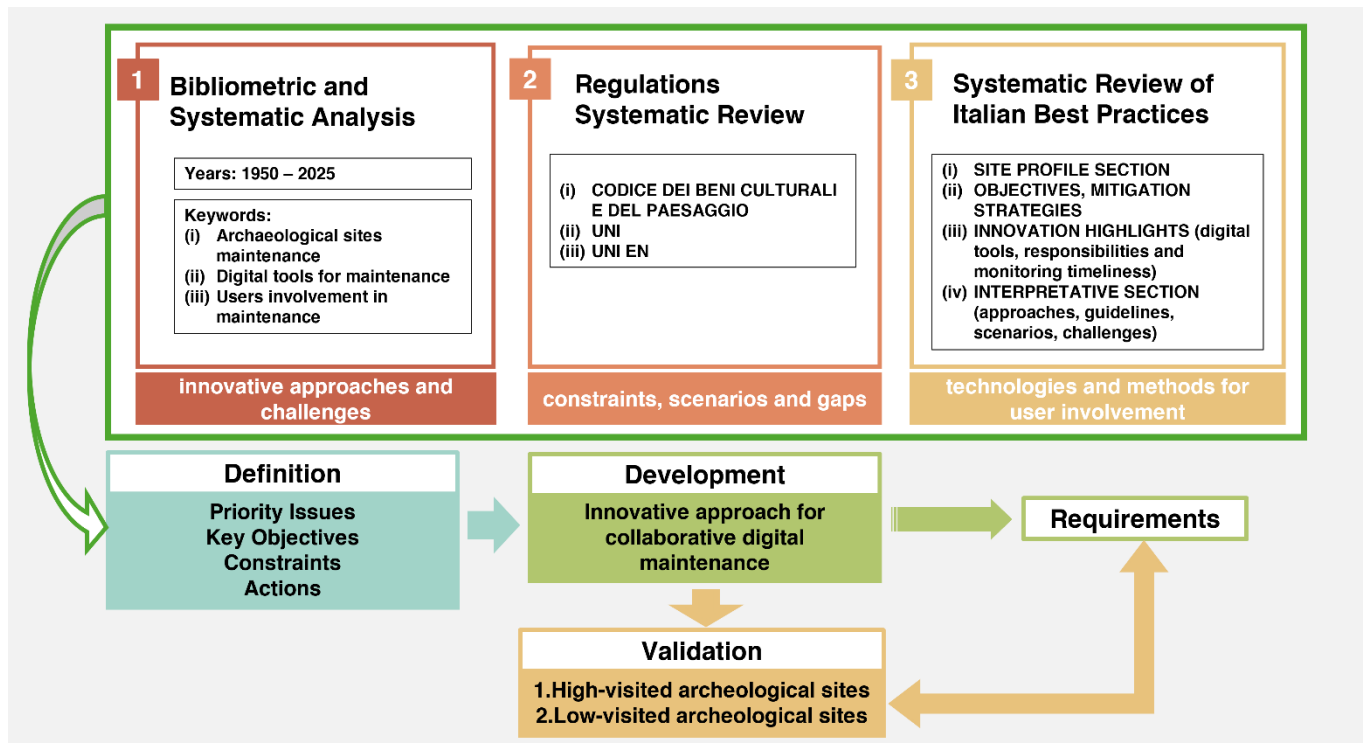
Therefore, the complexity of archaeological heritage maintenance lies in ensuring the long-term effectiveness of these efforts. This depends on the continuous updating of the information framework through monitoring activities. This lets to improve management practices and adapt maintenance activities to emerging needs. In light of these challenges, this paper proposes an innovative approach to the collaborative maintenance of archaeological heritage supported by digital tools, mitigating the gap between technological innovation and social participation. The research is based on the development of an integrated scientific framework that allows for a systematic examination of the main priority issues, key objectives, constraints and actions related to the topic.

In particular, the study is structured around three complementary analyses of the state of the art, with reference to the scientific literature, the current regulatory framework, and Italian best practices. This approach makes it possible to identify the main requirements through which maintenance communities – composed of residents and visitors – can effectively contribute to preventive and predictive maintenance processes.

Focusing on the Italian context makes it possible to highlight the specific challenges associated with managing archaeological heritage sites characterized by varying levels of visitor traffic. On the one hand, high-visited sites offer greater opportunities for data collection and continuous monitoring, but they are also vulnerable to deterioration due to heavy use. On the other hand, low-visited sites – often marginal or less accessible – face challenges related to resource scarcity, also opening up opportunities for implementing shared stewardship practices and collective care. Finally, this paper advances the state of the art by proposing a replicable and transferable approach to collaborative maintenance based on digital tools, improving management efficiency while enhancing the social value of heritage. In this context, the research aligns with recent European guidelines promoting integrated, inclusive, and digitally supported management models.

## **2. Method and materials**

The research adopts a multi-method approach aimed at developing an integrated scientific framework for the collaborative maintenance of archaeological heritage supported by digital tools. The complexity of the topic required the integration of different levels of analysis to capture its theoretical, regulatory, and operational dimensions. To this end, the methodological design was structured into three complementary components: a bibliometric and systematic analysis of the literature and regulations, and a scientific cataloguing of Italian best practices on the topic. By synthesizing the results, the study identified priority issues, key objectives, constraints and actions, which served as the basis for developing requirements for effective participatory digital maintenance. These requirements were then validated in two Italian cases – one in North and one in South – characterized by different level of visitation (Figure 1).

**Figure 1. Research methodological outline**

Source: Authors' elaboration

### 2.1. Bibliometric and systematic analysis of the literature

The first methodological component, conducting a bibliometric analysis, aimed at identifying priority issues and the key objectives of the collaborative maintenance of archaeological parks supported by digital tools. The analysis was based on data extracted from scientific databases, focusing on the main themes and their link due to their relevance in the international scientific landscape. The research was limited to documents published between 1950 and 2025 on topics related to the maintenance of archaeological sites, digital tools for maintenance, participatory maintenance, and strategies for the care of archaeological parks. From a corpus of 675 articles, the interconnections between the main concepts facilitated the identification of dominant themes of the scientific debate and gaps in the literature. The analysis revealed a set of shared approaches, traceable to the main international trajectories of innovation in the maintenance of built heritage. A central role was moving beyond the view of maintenance as a marginal activity, in favour of a structured approach capable of integrating training, planning, and an understanding of the economic and cultural value of maintenance policies. Starting with the Faro Convention and subsequent European strategies, the cultural heritage is gradually evolving into a shared resource and a means of encouraging public participation. It acknowledges the important and active role that communities play in the care and transmission of local values (Council of Europe, 2005). Since archaeological heritage is the tangible result of a community's cultural evolution over time, it represents ancient roots to share in the responsibility of promoting its care and transmission to future generations. Viewing archaeological heritage as a layered resource of collective interest means engaging with a complex field - a repository of the history and community identity. In line with this vision, the European Commission launched the Europe 2020 strategy, developed in response to the major global economic and financial recession that unfolded between 2007 and 2013. The aim was to promote

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participation and innovation in heritage, recognizing it as a sustainable European resource (Council of Europe, 1992-2020).

The main challenges at the international level concern strategies for implementing these innovative measures for the maintenance of archaeological sites, generating positive impacts at various scales while fostering shared values of strategic interest. Since 2014, the Council of Europe has recognized that participatory governance of cultural heritage can contribute to democratic, sustainable, and cohesive inclusivity in addressing current and future challenges (Council of Europe, 1975). The European Commission views user involvement in heritage care as a further synergy for establishing sustainable frameworks for both conservation and use.

These challenges are further shaped by the emergence of digital technologies, which enable more proactive and data-driven maintenance approaches, overcoming the limitations of traditional preventive strategies. However, despite numerous European initiatives supporting heritage digitization, specific guidelines for applying digital tools to the collaborative maintenance of archaeological sites remain limited.

## *2.2. Systematic review of maintenance regulations*

The second methodological component involved a systematic analysis of the regulatory framework governing the maintenance of archaeological heritage. The analysis was conducted by categorizing technical regulations and tracing the points of intersection between their respective historical developments.

Focusing on the main provisions of the Italian regulatory framework regarding archaeological parks - particularly the Code of Cultural Heritage and Landscape and the Guidelines for the Establishment and Enhancement of Archaeological Park - the analysis highlights the need to integrate protection, enhancement, maintenance planning, and the participation of stakeholders emerges (Congress on the European Architectural Heritage, 1975; Ministero della Cultura, 2004).

The systematic analysis of regulations and standards was particularly appropriate given the evolving nature of these instruments, especially in fields marked by rapid technological developments and continuous regulatory updates. This approach enabled the identification of key shared and non-negotiable constraints associated with collaborative maintenance using digital tools.

The analysis yielded a set of approaches that define maintenance as a combination of technical, administrative, and managerial operations carried out throughout the asset's lifecycle, aimed at maintaining it to proper condition. The analysed UNI and UNI EN standards highlighted the centrality of scheduled maintenance, maintainability, information systems for maintenance management, and the need to integrate performance evaluation within a circular and sustainable vision (Pacífico et al., 2023). The UNI EN 13306:2010-12 standard defines maintenance as the combination of all technical, administrative, and managerial operations performed throughout the life cycle of an entity, aimed at maintaining it. In the archaeological context, these activities aim to preserve performance levels rather than introduce new ones. Within the construction process framework defined by UNI 10838:1999 - an organized sequence from needs identification to design and implementation - maintenance is positioned within the management phase. This approach is also extended to archaeological heritage, incorporating performance and value assessment within a circular and sustainable framework.

According to UNI 11257:2007, this concept forms the basis of planned maintenance, which is implemented through a pre-established plan involving forecasts, control procedures and analysis of historical data.

Similarly, the UNI 9910:1991 standard introduces the requirement of maintainability

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by drawing on the concept of management focused on “maintenance intelligence”. The primary information systems for maintenance are often selected based on their ability to enable the collection, processing, and management of data related to the archaeological site. The UNI 10951:2001 standard defines Maintenance Management Information Systems (SIGeM) as decision-making tools based on integrated databases and designed to support the planning and control of maintenance activities.

The analysis highlighted a series of challenges linked, on the one hand, to the regulatory and organizational fragmentation that still hinders unified maintenance management. On the other, the mandatory digitization of processes introduced by public procurement regulations. A priority issue concerns the role of the Maintenance Plan, which, despite being a potentially strategic tool, often remains limited to draft, without any real impact on management practices.

Finally, the analysis identifies persistent regulatory gaps, particularly the lack of specific provisions for user participation in maintenance processes and the absence of a comprehensive framework for integrating digital tools into collaborative maintenance models.

### *2.3. Scientific cataloguing of Italian best practices*

The third methodological component involved the selection, cataloguing, and scientific analysis of best practices related to the maintenance of archaeological sites. The selection process was based on an integrated view of the archaeological site, as a complex system whose maintenance requires a synergistic combination of technical, administrative, and managerial actions. The practices were selected based on their alignment with national and international maintenance standards, as well as on their ability to integrate stakeholder participation and the use of digital tools (Azzalin, 2020).

Seven successful models were identified, considered relevant for their ability to simultaneously integrate corrective, preventive, and predictive maintenance strategies. For each practice, a scientific profile was developed, divided into four sections: (i) a site profile section; (ii) a descriptive section covering objectives, and mitigation strategies; (iii) a section dedicated to the innovation highlights, with reference to digital tools, planned actions, responsibilities, and monitoring timeliness; (iv) an interpretive section addressing the approaches, guidelines, scenarios, and challenges that emerged.

The case studies analysed at the national level were Aquileia (Lei et al., 2018), the Colosseum Archaeological Park (Jasiulewicz-Kaczmarek et al., 2020), Pompeii, and Herculaneum (Fan & Chung, 2022) in Italy. The variety of cases made it possible to compare models characterized by different levels of complexity, different technological solutions, and different governance structures.

The analysis of the data sheets provided information regarding: the technical and structural characteristics of the structures; the technologies used for performance monitoring and the analysis of the evolving behaviour of visitor facilities; the economic and functional models adopted for planning maintenance activities; and the forms of engagement involving staff, users, and stakeholders. Overall, the cases demonstrated the potential of integrating digital systems with increasingly structured forms of user and community engagement.

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### 3. Results and discussion

#### 3.1 Priority issues, key objectives, constraints, and actions

The integration of these three methodological enabled the development of a comprehensive framework linking theoretical, regulatory, and empirical dimensions. This framework made it possible to identify the main enabling requirements for the construction of maintenance communities, understood as networks of individuals – including residents, visitors, technicians, managers, and institutions - involved in the processes of care, monitoring, and transmission of the archaeological heritage. From this perspective, digital tools can be relational devices that enable an approach capable of facilitating communication, coordination, and shared accountability. The framework lets distinguish the operational conditions of high-visited sites, where participation can enhance the quality and timeliness of monitoring, from those of low-visited sites, where user involvement plays a strategic role in raising awareness, widespread oversight, and shared care.

The analysis identifies seven priority issues. The first concerns the need of a multidimensional approach to maintenance, balancing technological, managerial, economic, and social factors, recognizing the maintenance as a continuous process rather than episodic one. The second concerns the fragmentation of responsibilities and the lack of integrated strategies, addressing the complexity of archaeological sites to their area and the inadequacy of conservation measures. The third refers to the need for a transition between different maintenance models, as the shift from reactive or corrective maintenance to a preventive and predictive approach. It appears essential to ensure the conservation of the original material, while containing costs and increasing the effectiveness of interventions. The fourth concerns the role of technology and innovation, linked to the need to employ digital tools that allow for more effective monitoring before irreversible damage occurs. The fifth relates to inadequate training and the resulting operational inefficiency. The sixth concerns the economic sustainability of more efficient management, aimed at reducing waste and emergency investments. Finally, the seventh point concerns a necessary cultural shift, whereby maintenance must be recognized as a structural component of the conservation and management of archaeological parks. This vision moves beyond a reactive approach and promoting systematic and planned actions.

These issues have been linked to a corresponding set of core objectives. The first concerns the promotion of policies to overcome the maintenance as a marginal activity, improving performance and reducing the fragmented use of new technologies. The second concerns the integration of maintenance into heritage planning and enhancement processes, treating it as a shared resource to engage citizens and institutions in the preservation of the archaeological site. The third relates to the promotion of innovation in cultural heritage as a sustainable resource, with advanced technologies such as IoT, Digital Twin, and artificial intelligence to optimize maintenance interventions. The fourth focuses on strengthening democratic inclusivity of users in decision-making processes aimed at sustainable conservation. The fifth concerns the implementation of a holistic approach to maintenance, for integrating scientific knowledge, advanced techniques, and community participation. The sixth concerns the adoption of proactive maintenance models based on predictive data analysis and the use of digital technologies to make the maintenance more collaborative and sustainable. Finally, the seventh refers to the promotion of the digitization of maintenance processes through participatory virtual platforms. An equal number of constraints accompanies these objectives. The first concerns the absence of an effective obligation for the concrete implementation of the Maintenance Plan. This often results in a formal document lacking real impact and

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which currently excludes a significant portion of the existing heritage, being mandatory only for new construction or renovation projects pursuant to Legislative Decree 163/2006 and Presidential Decree 207/2010.

The second issue relates to the inconsistency and fragmentation in the adoption of Maintenance Management Information Systems (SIGeM), as required by the UNI 10951:2001 standard and Legislative Decree 50/2016, which made the digitization of maintenance activities mandatory in Europe, including Italy. The third concerns the use of uniform and shared tools to ensure consistency in maintenance, as required by UNI 11257:2007. Overall, the fragmentation of responsibilities between public and private entities and the absence of a standardized participatory approach hinder genuine collaborative implementation in archaeological parks. The fourth constraint concerns user participation and engagement. Although UNI EN 13306:2018 recognizes an active role for visitors, users, and technicians in the maintenance process, such participation remains limited, and the digital tools that could facilitate widespread monitoring and reporting of anomalies lack defined protocols for integrating this data into decision-making systems. The fifth constraint concerns the use of software for drafting not site-specific documents with lack of frequent updates and proper information management reduces the effectiveness of maintenance. The sixth issue concerns the distribution of responsibilities in defining roles: the UNI EN 15628:2014 and UNI 10992:2002 standards identify key roles such as technician, supervisor, and maintenance manager. While the client's involvement in monitoring activities is required, reducing control over quality and response times. Finally, the seventh point concerns the lack of clear financial criteria for the sustainability of maintenance, which is still perceived as a cost rather than an investment.

Lastly, a corresponding set of actions derived from the analysis has been associated with this framework. The first involves multi-level monitoring using digital technologies, such as drones, satellites, environmental sensors, and geotechnical instruments. It aimed at collecting real-time data and monitoring the condition of structures. The second consists of building predictive models for preventive maintenance, to analyse historical data and anticipate critical issues before they result in damage. The third involves the development of digital platforms for heritage management, through the creation of centralized databases and open-source platforms for integrating information, improving management, and optimizing interventions. The fourth focuses on promoting stakeholder participation and engagement through workshops and projects that allow visitors to observe care activities up close and understand the value of maintenance. The fifth relates to the integration of alert systems for timely response to interventions, through the implementation of automated algorithms capable of flagging structural or climatic anomalies and enabling rapid, targeted action. The sixth concerns virtual reconstructions and digital accessibility, through 3D models, augmented reality, and immersive experiences designed to make heritage accessible to a remote and broader audience. Finally, the seventh concerns cooperation among entities to define a network strategy, based on collaborations between local institutions, universities, and stakeholders. This can establish shared management and promote transnational networks for heritage promotion.

### *3.2 An innovative approach to collaborative digital preservation of archaeological heritage: new requirements for future scenarios*

An innovative approach to the maintenance of archaeological heritage emerges, based on the convergence of digitization, participation, and systemic management of the asset's life cycle. This approach goes beyond traditional methods by proposing

a vision in which maintenance is a continuous, predictive, and shared process capable of integrating technical, social, and economic dimensions.

The innovation lies in reinterpreting maintenance as a relational and informational ecosystem, in which digital tools play an enabling role in connecting data, actors, and decisions. In this framework, technologies support processes of co-production of knowledge and widespread empowerment. At the same time, the active involvement of communities enables the expansion of the information base through forms of widespread and participatory monitoring, strengthening the sense of belonging and awareness of the value of heritage.

In this sense, collaborative maintenance serves as a mechanism of combining operational efficiency with social value, contributing to the development of sustainable management models. The proposed approach follows an adaptive logic, capable of tailoring strategies to the characteristics of specific contexts. In high-visited sites, the proposed approach optimizes information flows and continuous monitoring; in low-visited sites, it implements widespread stewardship practices and community outreach. The effective implementation of the identified approach requires the fulfilment of a series of fundamental requirements that make this vision applicable and operational:

- *Integration of information systems* concerns the presence of interoperable digital platforms capable of collecting, managing, and updating data from various sources (sensors, surveys, user reports).
- *Development of a knowledge framework* concerns the availability of an up-to-date database regarding the site's condition, its components, and expected performance levels.
- *Adoption of predictive models* concerns the use of advanced analytical tools to anticipate critical issues and plan maintenance interventions.
- *Active stakeholder engagement* concerns the implementation of participatory processes that include local communities, users, technicians, and institutions in data collection and decision-making processes.
- *Definition of roles and responsibilities* concerns the structuring of an organizational system that identifies competencies and responsibilities among the various stakeholders involved.
- *Training and capacity building* concerns the development of technical and digital skills among operators and raising user awareness regarding maintenance processes.
- *Integration with the regulatory framework* concerns the aligning with current regulations and standards, while promoting the updating of regulatory tools toward collaborative models.
- *Economic sustainability of the model* concerns the definition of financial strategies that treat maintenance as an investment, integrating public and private resources with innovative models.
- *Scalability and adaptability* concern the model's ability to be applied in different contexts, tailoring tools and processes to the specific characteristics of each site.

This flexibility allows for its transferability and replicability in diverse contexts, establishing it as a scalable operational model at the European level.

### 3.3 A comparative analysis of high-visited and low-visited archaeological sites

Data from the Ministry of Culture for 2024 show that the Campania Region has a significant concentration of state-owned monuments and archaeological sites, with an uneven distribution across the provinces. As shown in Table 1, a particularly significant finding emerges from the comparative analysis between the provinces of

Salerno and Caserta. Despite a numerically similar number of archaeological sites, there is a marked discrepancy in visitor numbers. This divergence highlights how factors (accessibility, the sites' reputation, regional promotion strategies, and integration with the local tourism offering) have a decisive impact on the attractiveness of archaeological sites. In this context, the province of Caserta stands out as a prime example of a mismatch between the heritage and intensity of use, suggesting the presence of critical issues related to enhancement and management processes.

**Table 1. Archaeological sites and visitor distribution by province**

Province	No. State-owned Monuments and Archaeological Sites	Total Visitors	Level of use
Avellino	6	22.819	Medium
Benevento	1	32.572	Medium
Caserta	3	2.259	Low
Napoli	20	7.204.497	High
Salerno	3	144.831	Medium /High
<b>Total</b>	<b>30</b>	<b>7.406.978</b>	-

Source: ISTAT, 2025

In order to apply, and validate the identified requirements, two archaeological sites, with contrasting visitor intensity conditions, were selected within the Campania region. The validation phase (§ 3.3), exploratory in nature, is carried out on two selected archaeological sites, which are in municipal areas with similar population densities and are characterised by different intensivity of use. These results in contrasting deterioration processes: abandonment at the site with low visitor numbers and physical wear at the site with high visitor numbers.

In the province of Salerno, the Archaeological Park of Paestum and Velia (comprising the archaeological site of Paestum, the National Archaeological Museum, and the Archaeological Park of Elea-Velia) was chosen, which recorded a high number of visitors (450,677) in 2024. For the province of Caserta, the Archaeological Circuit of Santa Maria Capua Vetere was selected (comprising the Campanian Amphitheater, the Mithraeum, the Antiquarium, and the State Archaeological Museum of Ancient Capua), which recorded approximately 44,000 visitors in the same year, making it a low-visited site.

This comparison allows to analyse the applicability of collaborative maintenance requirements under different conditions, distinguishing between high-visited contexts (characterized by high visitor flows and greater availability of data for continuous monitoring) and low-visited contexts (marked by limited visitation and fewer resources). In this framework, the participation plays a strategic role in raising awareness and fostering a sense of shared stewardship. From this perspective, opportunities and potential emerge related to the integration of digital tools, management models, and user engagement.

#### *3.4 Validation of requirements at the archaeological sites of Santa Maria Capua Vetere and Paestum-Velia*

The two archaeological sites were analysed through a survey (Figure 2). It examined management practices, the use of digital tools, and ongoing management and enhancement projects, with the aim of highlighting the benefits that a collaborative maintenance approach.

They present different governance models. The Archaeological Circuit of Santa

Maria Capua Vetere is managed by the Regional Directorate of Museums, a decentralized structure of the Ministry of Culture characterized by a centralized organization and limited managerial autonomy. This configuration marks the site’s operational capacity on the flexibility in activating innovative strategies and in planning maintenance activities, constrained by not tailored procedures.

**Figure 2. Survey of Paestum-Velia and S. M. Capua Vetere archaeological sites**



Source: Authors’ elaboration

The Archaeological Park of Paestum and Velia operates as an autonomous institution, endowed with administrative, financial, and decision-making independence, enabling a capacity for planning and managing interventions. This autonomy translates into the development of more maintenance models, based on the integration of digital technologies, continuous monitoring, and the predictive approach.

Consequently, different governance models directly influence maintenance management practices. In centrally managed contexts, maintenance tends to remain more reactive and less integrated with managerial autonomy towards systemic, planned, and innovation-oriented approaches. This difference highlights how organizational structure represents a key enabling factor in the implementation of collaborative maintenance models. It affects both the adoption of digital tools and the level of stakeholder involvement in heritage care processes.

In the case of the Paestum and Velia Archaeological Park, the presence of advanced projects such as HERA (Heritage Experience through Augmented Reality Applications) highlights the potential of integrating IoT, HBIM, and Digital Twin

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technologies for continuous monitoring and predictive maintenance. In this context, collaborative maintenance can help enhance these systems by incorporating input from users and stakeholders. This can expand the information base, improving the timeliness of reports, and strengthening the link between monitoring processes and site enhancement. HERA is an advanced system based on augmented reality technologies and three-dimensional modelling. The application enables immersive visualization of archaeological contexts through mobile devices, integrating digital content - such as 3D models, virtual reconstructions, and stratigraphic information - with the real environment. From a technical perspective, HERA relies on interoperable digital models, often derived from HBIM and GIS platforms, as well as on the georeferencing of content to ensure context-aware user experiences. The system is designed to collect user interaction data to analyse patterns of use and, potentially, to integrate information supporting site monitoring and management processes.

In this perspective, HERA operates as a platform for connecting experiential, informational, and managerial dimensions, providing a technological infrastructure potentially extendable to collaborative maintenance processes. This platform supports data collection and analysis through a process, supported by a rule chain system, structured in three phases: (i) the survey of the area using a laser scanner to obtain a three-dimensional model into which sensor data are integrated; (ii) the installation of advanced sensors designed to monitor environmental, and structural parameters (temperature, humidity, atmospheric pressure, volatile organic compounds; air quality, wind speed and direction; structural vibrations; temperature variations on masonry surfaces); (iii) the ThingsBoard platform, an open-source solution, which enables real-time data collection, analysis and visualisation.

The integration of data with the HBIM model, dynamically updates the digital model, whereby each physical sensor is associated with a corresponding “virtual” sensor of the monitored object.

In the case of the Archaeological Circuit of Santa Maria Capua Vetere, initiatives such as the VETEREA project demonstrate the use of digital tools for understanding, managing, and promoting cultural heritage.

VETERA is configured as a digital platform aimed at the collection, organization, and management of heritage-related information. The system is based on georeferenced databases and the integration of heterogeneous informational content, including historical data, technical-scientific documentation, and information related to the conservation state of artifacts. The system architecture enables data consultation and updating by operators, supporting decision-making processes and improving the traceability of information over time. VETEREA proposes a shift from traditional approaches towards a data-driven and digitally mediated model of heritage interpretation. By integrating AI and automatic learning paradigms, it becomes possible to process heterogeneous datasets and reconstruct the hidden archaeological layers in a virtual environment. This enables the creation of a Digital Twin that operates as an interface between the visible city and its invisible historical substratum. The project also emphasises the role of digital storytelling as a tool for enhancing both understanding and engagement.

Through narrative-based approaches, complex archaeological information can be translated into accessible and meaningful experiences for diverse audiences, including local communities and visitors. In perspective, this digital infrastructure can be extended to incorporate participatory functionalities, allowing the collection of user-generated reports and the activation of forms of distributed monitoring. HERA represents a fully integrated digital ecosystem supporting the entire lifecycle

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management of archaeological heritage, including documentation, monitoring, maintenance, and valorisation. Conversely, VETEREA operates primarily as a knowledge infrastructure, focused on the collection, organization, and accessibility of heterogeneous data, with emerging potential for participatory and distributed monitoring applications.

From this perspective, the requirements identified (see §3.1), once applied in various usage contexts, highlight the potential benefits of adopting a collaborative maintenance approach using digital tools (Table 2).

**Table 2. Collaborative maintenance potential benefits in archaeological sites**

<b>Requirements</b>	<b>Benefits at high-visited sites (Paestum-Velia)</b>	<b>Benefits at low-visited sites (S.M. Capua Vetere)</b>
Integration of information systems	Integration of user-generated data into existing digital systems, improving the continuity and timeliness of monitoring	Establishment of basic information flows through widespread notifications and accessible digital tools
Development of a knowledge framework	Continuous database updates based on continuous monitoring data from non-expert users	Gradual development of a body of knowledge based on data collected collaboratively
Adoption of predictive models	Improved accuracy of predictive models thanks to an increase in available data	Future training of predictive models through the generation of initial datasets
Active stakeholder engagement	Active user participation in monitoring and reporting processes	Engaging local communities in the stewardship and shared care of the site
Definition of roles and responsibilities	Support for existing organizational systems through the integration of new stakeholders	Strengthening coordination between local stakeholders and institutions
Training and capacity building	Building skills among managers and raising awareness among users	Launching awareness-raising initiatives and basic training programs
Integration with the regulatory framework	Support for the operational implementation of integrated management models	Experimenting with participatory practices
Economic sustainability of the model	Optimization of resources through widespread monitoring and a reduction in emergency response efforts	Cost reduction and mobilization of local resources through participatory approaches
Scalability and adaptability	Model replicability	Adaptation to local conditions and available resources

Source: Authors' elaboration

In contexts characterized by high levels of visitor flows, the use of digital tools that enable community participation represents both the volume and continuity of data collection, as mechanism to improve the accuracy and timeliness of monitoring processes. By integrating user-generated inputs within information systems, such tools contribute to strengthening real-time decision-making, optimizing maintenance planning, and increasing the overall efficiency of site management.

The use of digital tools designed for community engagement serves to improve data collection as a way to involve local communities, helping to strengthen a sense of belonging and foster shared care practices.

The integration of digital tools and active participation improves the effectiveness of identified requirements, enhancing existing systems in high-use contexts and

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establishing new monitoring and management mechanisms in low-use contexts. From this perspective, collaborative maintenance emerges as an approach for strengthening existing processes while increasing the social value and sustainability of archaeological heritage management.

#### **4. Conclusion**

The paper explored the topic of collaborative maintenance of archaeological heritage supported by digital tools, developing an integrated scientific framework capable of linking theoretical, regulatory, and empirical dimensions.

This approach enabled to identify the priority issues, key objectives, constraints, and actions that characterize the evolution of management models for archaeological sites. As well as it highlights the strategic role of maintenance communities and digital technologies in the processes of caring for archaeological heritage. The analysis showed that maintenance must be a continuous, systemic, and integrated process for connecting technical, organizational, social, and economic aspects. In this context, the main innovation of the research lies in defining an approach that combines digitization and participation, reinterpreting technological tools as relational and enabling devices for the construction of collaborative management models. The proposal of a set of operational requirements also represents an original contribution, replicable and adaptable in different contexts. Validation has shown that the proposed approach can serve both to enhance monitoring and management systems in high-visited contexts to foster participatory processes and the development of a knowledge framework in low-visited contexts. In both cases, the integration of digital tools and user engagement serves as a strategic lever for improving maintenance effectiveness and strengthening the social value of heritage.

Therefore, the comparison between Paestum-Velia and Santa Maria Capua Vetere demonstrates the applicability and adaptability of the proposed requirements across different operational scenarios. However, the sample size does not allow statistical generalisation of the findings. Future research should extend the validation to a broader, more geographically diverse set of archaeological sites. This should include sites with different governance structures, heritage typologies and levels of available digital tools, testing the robustness and transferability of the developed approach. In conclusion, this research contributes to advancing the debate on the sustainable management of archaeological heritage by proposing an integrated and scalable approach capable of combining technological innovation with social participation. This approach offers a potential response to contemporary conservation challenges, providing new perspectives for the development of more resilient, inclusive, and long-term maintenance systems.

#### **Author Contributions**

Conceptualization F.C.; Methodology F.C. and M.R.P.; Validation F.C. and C.D.G.; Formal Analysis F.C.; Investigation F.C.; Resources F.C. and M.R.P.; Data Curation F.C. and C.D.G.; Writing - Original draft preparation F.C.; Review & Editing M.R.P, F.C. and C.D.G.; Visualization C.D.G.

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### Conflicts of Interest

The authors declare no conflict of interest.

### Originality

The authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere, in English or any other language. The manuscript has been read and approved by all named authors and there are no other persons who satisfied the criteria for authorship but are not listed. The authors also declare to have obtained the permission to reproduce in this manuscript any text, illustrations, charts, tables, photographs, or other material from previously published sources (journals, books, websites, etc).

### Use of generative AI and AI-assisted technologies

The authors declare that he did not use AI and AI-assisted technologies in the writing of the manuscript; this declaration only refers to the writing process, and not to the use of AI tools to analyse and draw insights from data as part of the research process. The author also did not use AI or AI-assisted tools to create or alter images and this may include enhancing, obscuring, moving, removing, or introducing a specific feature within an image or figure, or eliminating any information present in the original.

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