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The Pompeii sustainable management model

Monitoring and maintenance of cultural heritage using a processual approach

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1. Introduction

Preserving Pompeii has proved to be a major challenge for those responsible for managing, safeguarding, and enhancing the UNESCO world heritage site. Covering an area of 66 hectares, of which just over two-thirds have been excavated, Pompeii represents a vast and fragile archaeological heritage containing structures, frescoes, objects, mosaics, and infrastructure as a result of the eruption of Vesuvius in AD 79. Over the centuries, Pompeii has served as an international platform for experimenting with novel approaches towards archaeological investigation, restoration, and conservation. However, the effectiveness of these efforts has been influenced not only by technical solutions but also by the management models adopted by the administration. An emblematic example of this was the Great Pompeii Project (GPP) that ran from 2012 to 2022. The success of this project can be attributed to the organisational structure and integrated management model that was implemented, encompassing protection, research, conservation, access, and public understanding of the site [1, 2, 3].

A "Sustainable Management Model" is a comprehensive, process-based solution for implementing effective management in a complex site such as Pompeii. Sustainability involves a range of disciplines and requires a holistic approach in order to address multi-dimensional values [4]. The challenge for Pompeii is to safeguard and further improve on the high-quality standards achieved by the GPP in terms of conservation, renovation, access, and education through an ordinary and sustainable management process.

Figure 1. A view of the Archaeological Park of Pompeii.

The proposed model aims to integrate these aspects with economic sustainability and increased self-financing capabilities. It is inspired by the paradigm of "circular archaeology" that rejects a priori hierarchies between various aspects of cultural heritage management such as conservation, research, public outreach and economic development, underlining their mutual interdependencies [36].

As outlined in the UNESCO publication on managing cultural heritage [5], sustainable development entails the responsible application of limited resources that strikes a balance between fundamental human needs and those resources available to future generations. With regard to cultural heritage, sustainable development can be understood in two ways:

1. Intrinsic: as a concern with the conservation of heritage, considered as an end in itself;

2. Instrumental: as the possible contribution that heritage and its preservation can make to the environmental, social, and economic context.

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The first point is based on the assumption that cultural heritage and the ability to understand history through its material remains play a fundamental role in enhancing local communities and their well-being. The second point is a reminder that the heritage sector has its share in the responsibility for sustainability on a global scale, given the growing pressure from human activities, limited financial and environmental resources, and climate change.
The EU Framework for Action on Cultural Heritage recognises sustainability as a fundamental component of its five pillars [6, 7]. The recognition of cultural heritage as positively affecting social, capital, and economic growth, as well as environmental sustainability is well-established. The five pillars of this Framework for Action are:

1. Cultural heritage for an inclusive Europe: participation and access for all.

2. Cultural heritage for a sustainable Europe: smart solutions for a cohesive and sustainable future.

3. Cultural heritage for a resilient Europe: safeguarding endangered heritage.

4. Cultural heritage for an innovative Europe: mobilising knowledge and research.

5. Cultural heritage for stronger global partnerships: reinforcing international cooperation.

Managing cultural sites can be significantly challenging when hazardous conditions are present [8]. Arguably, this holds true, at least to some extent, for the environment of Pompeii. Recent meteorological phenomena have highlighted the fragility of the territory in which the site is located. Evidently, it is still not fully prepared for the risks that affect the site [9]. Any meaningful management approach must consider the hazards and risks that can threaten the preservation of the site from the viewpoint of sustainability. Implementing strategic programs that anticipate potential damage and catastrophes means deploying resources to safeguard and protect cultural heritage proactively and effectively.
Recent publications [9] dealing with the impact of climate change on cultural heritage emphasise the importance of variations in temperature, precipitation and wind. The available studies indicate significant impacts on archaeological sites, including:

- An increase in precipitation and humidity, coupled with higher temperatures, may result in material damage, e.g. through corrosion, biological deterioration, distortion, and cracking, as well as the formation of salt crystals causing efflorescence and subflorescence;

- The intensification of wind, particularly when associated with sand, salt, and atmospheric contaminants, can lead to surface erosion, increased water infiltration, structural damage, and even the collapse of structures;
- An increase in temperature risks increasing freeze-thaw cycles and greater temperature fluctuations throughout the day. These are likely to impact the frequency of phenomena linked to thermoclastism, potentially causing increased physical weathering damage to stone and ceramic materials;

- An increase in temperature and humidity could intensify biological degradation due to the creation of favourable conditions for mould growth and insect activity.

Our sustainable management model distinguishes between the effects caused by rapid weather changers and those following very extreme events, both of which are related to effects of climate change. While fast weather changes have a tendency to lead to a slow but constant decay, extreme weather events tend to produce sudden and serious damage. The effects of rapid weather changes can to some extent be controlled by proactive maintenance,

while the effects of extreme events can be mitigated. Earthquakes, floods, oil spills, conflict and the outbreak of disease cannot be entirely prevented but mitigation measures can effectively reduce the risks accompanying these events [10].

The objective of this paper is describe the challenges and the strategies that the Archaeological Park of Pompeii has developed after the GPP, especially an innovative monitoring and maintenance program that was structured according to international standards [11, 12] as part of a broader approach aiming at promoting sustainable development within archaeological sites and their heritage communities.

2. Site context

The Archaeological Park of Pompeii is a local organisation belonging to the Ministry of Culture of Italy. In addition to the site of Pompeii, the Archaeological Park comprises other museums and cultural heritage sites. These include the Antiquarium of Boscoreale, the Castle of Lettere, the Archaeological Park of Longola in Poggiomarino, the archaeological museum at Quisisana in Castellammare di Stabia, the archaeological sites of Oplontis in Torre Annunziata, the villas of Stabiae in Castellamare di Stabia, Villa Regina in Boscoreale, and the Former Royal Bourbon Powder Factory in Scafati.

In January 2014, the 'Special Superintendency for the Archaeological Heritage of Naples and Pompeii' was divided into two institutions as per the Decree-Law no. 91 of August 8th, 2013 [13], with amendments of Law no. 112 of 7th October 2013 [14]. One institution was responsible for Naples, the Campi Flegrei area, and Caserta, while the other, the 'Special Superintendency for the Archaeological Heritage of Pompeii, Herculaneum and Stabiae' was responsible for the sites of Pompeii, Herculaneum, Stabiae, Oplontis, and Boscoreale. In 2016, this institution was renamed as 'Superintendency of Pompeii', and with the adoption of Ministerial Decree on 12th January 2017 (OJ 10/03/2017) [15], it was rebranded as the 'Archaeological Park of Pompeii' as to align with international standards for cultural institutions and sites. That same year, Herculaneum was separated from Pompeii to become the 'Archaeological Park of Herculaneum'.

The Park's sites lie at the foot of Vesuvius and in proximity to the Campi Flegrei area, one of the most hazardous volcanic sites in the world. Although the hazard linked to Vesuvius appears as the major threat to the area around Pompeii, the Campi Flegrei caldera, a complex and resurgent volcano, has experienced intense volcanism with eruptions concentrated in temporal clusters known as epochs and should therefore not be underestimated [16]. Both Vesuvius and Campi Flegrei are linked to a single deep magma system, which also feeds magma to Ischia. In addition, the ancient city of Pompeii is situated within a widely recognised seismotectonic context [17] that characterises Southern Italy with high to medium seismic activity. Pompeii's local seismic vulnerability has been evaluated [18] through an investigation of the repercussions resulting from the powerful earthquake in AD 62/63. Hydrogeological hazards are equally significant, as they affect the stability of existing walls and the preservation of the site as a whole.

The site of Pompeii and the complex problems that characterise its conservation and management have long attracted the attention of the international community. Negative media coverage culminated in November 2010 following the collapse of the Schola Armaturarum, which was attributed to a lack of maintenance and the effects of hydrogeological instability - a factor that is being amplified by the effects of climate change.

The Great Pompeii Project was conceived as a response to the preservation problems that the collapse had dramatically highlighted, thanks to the joint action of the then Ministry of Cultural Heritage Activities and Tourism and the Presidency of the Council of Ministers, with the aim of preventing the degradation and improving the conditions of the extant remains. In January 2012, the Ministry launched a special programme for the restoration of

the archaeological site of Pompeii. On that occasion, the Great Pompeii Project was presented as a "major community project" and subsequently approved by the European Commission, that authorised funding totalling 105 million Euros, of which 78 million came from the European Regional Development Fund (ERDF), as part of the interregional operational programme "Cultural, natural actuators and tourism", and 37 million from national funds.

The overall programme, composed of 76 projects and five sections, was funded in two phases: the first being an instalment of 39.7 million Euros (based on the POIn Cultural Attractors 2007-2013 programming cycle), the second amounting to 65.3 million Euros (valid for the next financial planning cycle, Axis I of the NOP Culture and Development 2014-2020).
Table 1 provides an overview of the five sections.

Table 1. Summary of plans, actions and related cost of the GPP

SECTIONS	*ACTIONS*	*COST*	
		Amount by sector	*Total*
Documentation	Analysis of surveys and diagnostic campaigns	8.200.000	8.200.000
Restoration	Works with advanced planning Works to be designed	47.000.000 38.000.000	85.000.000
Outreach and communication	Adaptation of services to the public Promotion and communication	5.000.000 2.000.000	7.000.000
Safety	Remote surveillance Plant safety	700.000 1.300.000	2.000.000
Capacity building	Technological adaptation Capacity building	1.000.000 1.800.000	2.800.000
	TOTAL	**105.000.000 €**	**105.000.000 €**

The critical situation was mainly the result of the scale of the site, the damage sustained in the earthquake in 1980, and the lack of maintenance over many years [19].
The Documentation section included the development of the so-called Information System (SiPompei), i.e. a digital platform that describes and catalogues the entire ancient city of Pompeii. The principle aim of the SiPompei is to support the maintenance management through a georeferenced relational database to monitor the at-risk conditions [3]. However, as a result of the lack of user-friendly features, the SiPompei was hardly used by the staff of the Archaeological Park after its launch. This meant that is was also not updated.
More recently, the open access digital archive OpenPompeii [21] has been launched to offer easy and user-friendly access to research data, imagery and the digital archives of the Park. OpenPompeii is linked to the SiPompei platform, to the Archaeological Information System of the Vesuvian Area (SIAV), and to digitalised photographic and historical archives (Tolomeo). SIAV was developed (2001-2007) before the GPP with the aim of collecting data from the Vesuvian area and making them accessible online [22].
With regard to safety and security, a further project named Smart@POMPEI was developed to manage and control the safety of both visitors and archaeological monuments thanks to an agreement signed in May 2015 by the Ministry of Cultural Heritage and Activities and Tourism (MiBACT) and the National Research Council (CNR). Smart@POMPEI led to the development of a platform capable of integrating video surveillance, access control, anti-intrusion systems, and environmental monitoring by means of sensors, drones, etc. [23].
Figure 2 describes the map of the Informative Systems of Pompeii.

Figure 2. Information Systems for the management of the Archaeological Park of Pompeii.

3. The Sustainable Management Model of Pompeii

In the field of cultural heritage, preservation is increasingly perceived as a major challenge. Nowadays there are numerous approaches to conservation, restoration and renovation. However, it is necessary to bear in mind that there are substantial differences between these concepts [24]:

- Conservation means consolidating and preserving structures. Preservation lies at the heart of the concept of conservation. Together with consolidation and safeguarding measures, conservation aims to protect the fabric of a monument and to prevent further loss;
- Restoration means restoring a building or painting to its original condition. Restoration aims to accentuate aspects of a monument that are hidden (for whatever reason), disfigured or impaired. It is concerned with the overall appearance of the monument as historical and artistic evidence. Following on from the consolidation and conservation of the original fabric, restoration adds new elements without impairing the original ones;
- Renovation means to renew. Renovation aims to achieve aesthetic unity in a monument in the sense of "making new again".

Conservation, restoration, and renovation constitute a graduated system of preservation measures which are interconnected. According to the circumstances, they may be carried out one after the other or simultaneously.

Of the various activities designed to ensure the preservation of archaeological remains, such as repairing, consolidating, rebuilding and modernising, maintenance plays a key role.

Indeed, article 4 of the Venice Charter [25] places maintenance first in the context of conserving sites and monuments.

In the aftermath of the GPP, which represented an exceptional intervention realised thanks to special funding, we increasingly need to shift our attention toward maintenance activities carried out on a daily basis with the ordinary funds.

However, a successful management model should take into account all possible risks: In addition to common risks, it is therefore also necessary to consider those situations that can turn into catastrophes. For this purpose, management models should be based on an approach that prevents and mitigates risks and, if necessary, can be integrated with a disaster risk management plan [10].

As has become clear, an integrated management approach for cultural heritage sites is of paramount importance. Its contents can be analysed on three levels: as a philosophy, as a process, and as a result [5].

The philosophy refers to the transformation envisaged for the organisation, the culture and attitudes of the actors, and the way in which different disciplines and sectors interact to achieve the goals.

By envisaging the management and maintenance approach as a process, we can appreciate the open nature of forms of collaboration that foster innovation and unorthodox thinking, creating a safe and encouraging environment.

The results of this approach consist in improvements and innovative solutions at a scientific, technical and administrative level that can also be applied to other sites. They therefore represent an added value beyond the limits of the organisation.

By responding to the specific challenges of our time (including climate change, sustainable development, and alignment and revival of cultural and collective values), the Sustainable Management Model for Pompeii features significant innovations compared to past strategies:

- It is a "model" rather than a "project" because it aims to implement a sustainable management program that does not conclude with the depletion of the initial funding. Instead, it seeks to develop economic sustainability over time to ultimately merge into the routine management of the Park.

- At the same time, it exceeds the scope of a "great project" by working at a "micro" level:

the model prioritises a set of integrated actions, procedures, and interventions that may appear limited in themselves in themselves but that actually are part of a long-term perspective and a strategy to accommodate new requirements and changes, such as climate change, economic development, etc.

- It has been developed from the ground up and encompasses the territory around Pompeii with its archaeological sites. Its explicit aim is to promote growth, including economic development, across a significant area that extends beyond the boundaries of the ancient urban centre of Pompeii.

The overall management strategy of Pompeii is based on four main objectives that correspond to four different areas of risk and opportunities for growth and improvement (figure 3):

1. Heritage protection and maintenance.
2. Sustainable visitor services, education and communication.
3. Inclusion of local communities and a contribution to cultural and economic development in the area.
4. Strengthening innovation and leadership skills at all levels within the organisation.

In our model, protection and maintenance assume a central role. In particular, maintenance is essential when it comes to creating a balance between maximising performance and minimising costs. This involves technical, managerial, and administrative activities aimed at preserving the cultural heritage and benefitting heritage communities and audiences, both now and in the future.

Today, a major concern regarding complex archaeological sites is the risk of falling below essential conservation levels, as highlighted by the experience leading to the GPP. Furthermore, natural risks (seismic, volcanic, etc.) and the impact of climate change need to be taken into account.

In order to improve safety and risk management, we can work on various levels. The areas that are accessible for visitors can be diversified and enlarged so as to reduce risks stemming from overcrowded zones and so-called anthropic pressure. This involves both creating new facilities and tours in Pompeii (e.g., tour around the city walls, permanent exhibition of the cast of victims of the eruption and organic materials in the Great Palestra, creation of a space for temporary exhibitions and accessible storerooms in the area of San Paolino, etc.)

Figure 3. Elements of the Sustainable Management Model of the Archaeological Park of Pompeii.

and developing the other archaeological sites around Pompeii. A further possibility consists in illuminating parts of the site that can be visited in the evening and at night time. Not only will this contribute to offering a more intimate and less crowded experience to visitors, but it will also extend the length of the average stay in the area. Opening storerooms and excavation sites to visitor groups is another possibility to create an in-depth experience, slow tourism and thus reduce anthropic risk factors. Ticketing policies, reward systems and free transport from Pompeii to other sites are yet another way of diversifying and amplifying the visitors' experience.

However, any model that deals with the material dimension of conservation cannot succeed without systematic monitoring. Only in-depth, up-dated knowledge of the site in its entirety allows for thorough planning of proactive maintenance and for effective damage control. Therefore, the Archaeological Park of Pompeii has launched a new monitoring system. While in the past, monitoring was carried out by archaeologists and architects of the Park on a random, non-periodic basis, today's digital technologies help us create the conditions in order to monitor the site systematically and update the site and up-date our knowledge periodically. Moreover, storing and processing large amounts of data makes it possible to compare data sets from different moments and time horizons. To this end, AI can be deployed to detect transformation processes that can subsequently be analysed by the Park's technical staff.

The Sustainable Management Model of Pompeii can be summarised in the following figure, which highlights the importance of multi- and transdisciplinary approaches which require a common language to manage and integrate different skills and competences within a common vision.

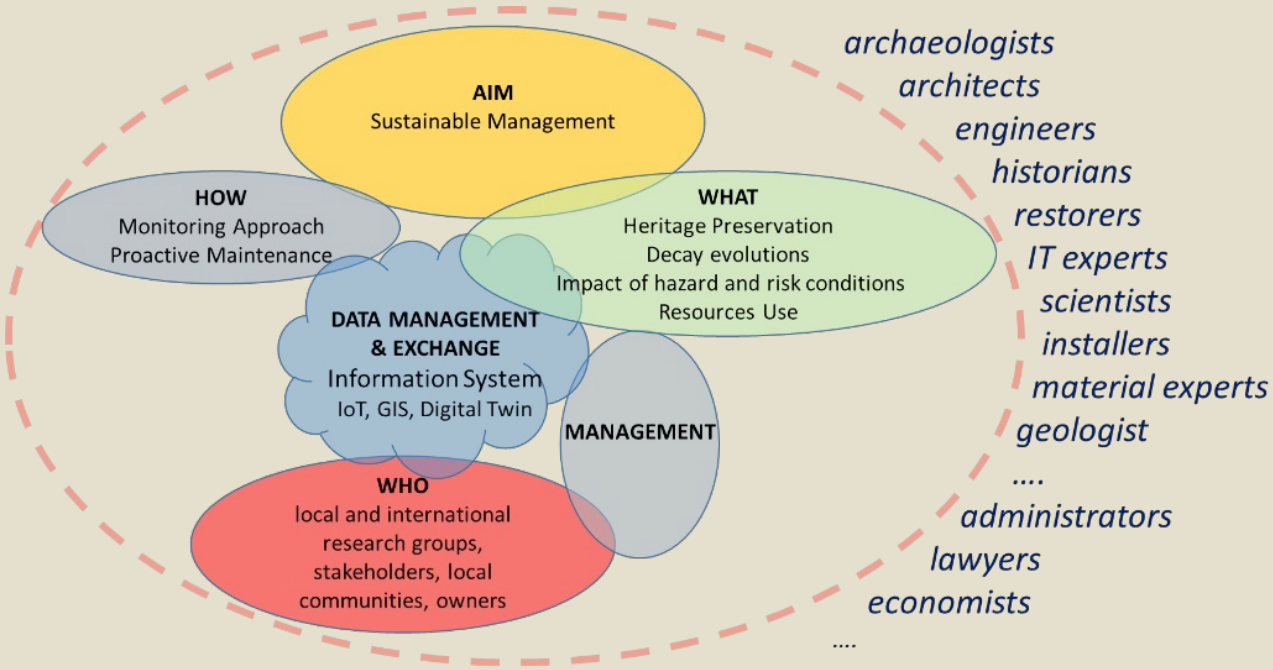

Figure 3. Elements of the Sustainable Management Model of the Archaeological Park of Pompeii.

4. The Maintenance Approach

The lack of the ordinary maintenance activities [24, 26, 27] increases the need for more expensive repairs and, in the case of a cultural heritage site, the risk of irreparable damage to its integrity and authenticity [28]. In order to prevent and mitigate damage, to monitor deterioration processes, and to maintain the standards achieved through the activities of the GPP, we have adopted a proactive approach. The main goal is to avoid, check and mitigate as far as possible damage caused by natural factors or specific actions for exceptional natural or manmade risks. In addition, maintenance can be carried out with minimum intervention according to the Venice Chart and Nara principles [25, 30].

A successful strategy will need to define performance targets as well as alarm levels. Furthermore, it needs to outline and forecast the decay processes that affect the site in order to predetermine ordinary maintenance within the general management plan. For this purpose, it is necessary to improve the accuracy through regular and ordinary maintenance based on all the available data in any given moment.

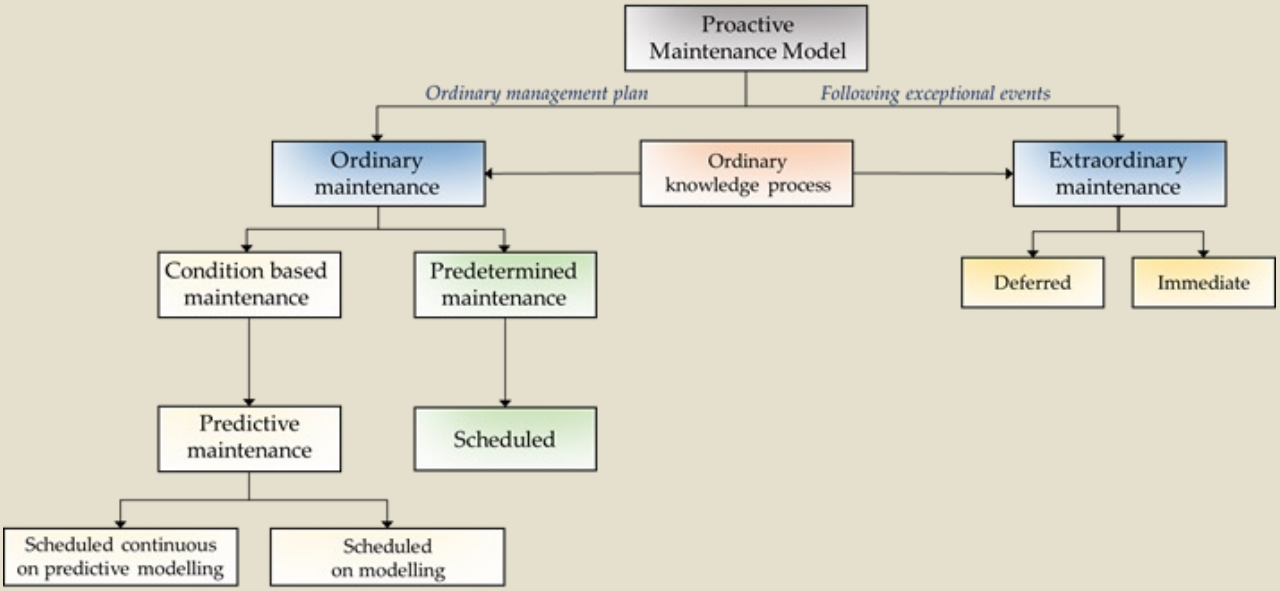

Figure 5. Flow-chart Proactive Maintenance Model.

The maintenance model has been engineered according to the International Organisation of Standardisation (ISO) [29], which, in the case of an archaeological site, can be outlined in the following flow-chart.

Proactive maintenance strategies aim to anticipate and address potential risk conditions by controlling the circumstances that can lead to damage. With regard to archaeological remains, the implementation of such strategies is advantageous as it allows early identification of at-risk areas that can affect the safety of the site. The applied approach consists of ordinary maintenance activities to avoid or reduce the impact of damage due to natural decay and/ of predicting the occurrence of damage or critical conditions.

Our goal is to schedule maintenance activities based on objective criteria and suitable time windows according to accepted risk levels. Ordinary maintenance also involves condition-based activities, which depend on the ongoing monitoring of data. In practice, the monitoring approach compares the evolution of physical parameters with a set of criteria, thresholds, and alarm scales. If the observed conditions are acceptable, no specific maintenance will be carried out. However, if the conditions do not meet acceptable standards, maintenance will be necessary within a reasonable timespan.

This type of maintenance could be defined as non-proactive condition-based maintenance, as it does not involve making predictions related to a specific case. Proactive condition-based maintenance, on the other hand, uses data collected throughout the system's lifespan to generate or update a forecast about its future condition.

Following extreme or exceptional events, a specific maintenance plan may be required. However, within the scope of a sustainable management approach, emergency scenarios, while not really controllable, become less difficult to address as resources and capacities are continuously deployed and enhanced and can be oriented toward unforeseen goals rapidly.

5. The Monitoring Strategy

Any maintenance approach requires detailed and updated knowledge of the dynamic evolution of hazards and potential damage to the cultural heritage. In fact, without such knowledge, preservation is doomed to fall short of the complexity of a site like Pompeii. In order to be effective, monitoring has to be systematic (covering the entire site) and repeatable (periodic monitoring guarantees updated data sets). In this sense, archaeological sites can learn from other fields where similar approaches have already been developed [31, 32, 33]. Furthermore, in the long run, only sustainable monitoring approaches that are independent from special funding can be successful [34, 35].

In the case of Pompeii, considering the complexity and vulnerability of the site, the many and varied assets, the countless hazards and risks, a suitable multi-level and multi-scale monitoring approach has been developed. In particular, the monitoring system is based on different methodologies and techniques, each with a specific data/time resolution (multi-scale). Equally, the accuracy of assessments is organised in three different levels (multi-level):

1. Local Assessment (LA)
2. General Assessment (GA)
3. Detailed Assessment (DA)

LA provides an extensive understanding of the condition of the site by means of expeditious onsite surveys carried out annually by multidisciplinary teams (archaeologists, restorers, architects, engineers).

GA creates general overviews through monthly drone flights. The data is analysed with the help of artificial intelligence (AI) applications.

GA can be considered as a method to quickly manage emergency situations. LA and GA can be used to both identify and resolve critical issues through ordinary maintenance and to recognise the circumstances that require the in-depth assessment of DA.

DA is carried out promptly in response to the results of the LA and/or GA and provides in-depth assessments. Critical at-risk issues can be resolved also with the support of monitoring devices.

The monitoring approach implemented in Pompeii (Figure 6) uses WebGIS, IoT and Digital Twins to describe the condition of the site with the aim of developing predictive models to support proactive maintenance policies.

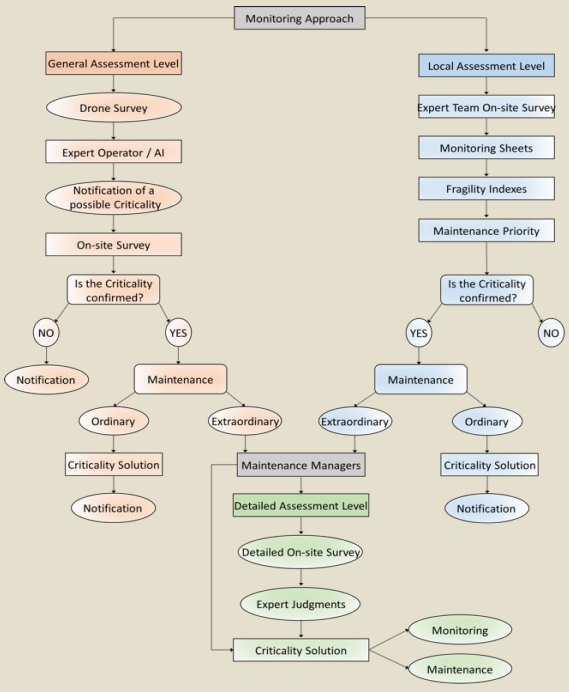

Figure 6. Flow-chart Monitoring approach.

The GA level involves the analysis of high-resolution images, obtained by a drone survey (figure 7 a), with the aim of evaluating the evolution of the site, by comparing images taken at different times of throughout the year. The images are georeferenced using a specific procedure (figure 7 b) and catalogued in the GIS database of the Park.

The LA level involves compiling standardised monitoring forms to identify and describe the most characteristic and frequent forms of decay for each type of element found in Pompeii, such as: wall structures; decorations; architraves; horizontal elements.

Figure 8 shows the screenshots of the web app that has been developed to support the periodical surveys.

In the case of exceptional conditions of decay or following exceptional events, the monitoring approach can help evaluate the need for a DA level. The DA level is conducted by teams of experts in the field of archaeology, architecture, engineering, restoration, etc. and includes the use of sensors to improve our understanding of the local conditions. Figure 9 shows an example of a test site in the Archaeological Park of Pompeii.

Figure 7. Survey plan for the acquisition of orthophotos of the Park via drone.

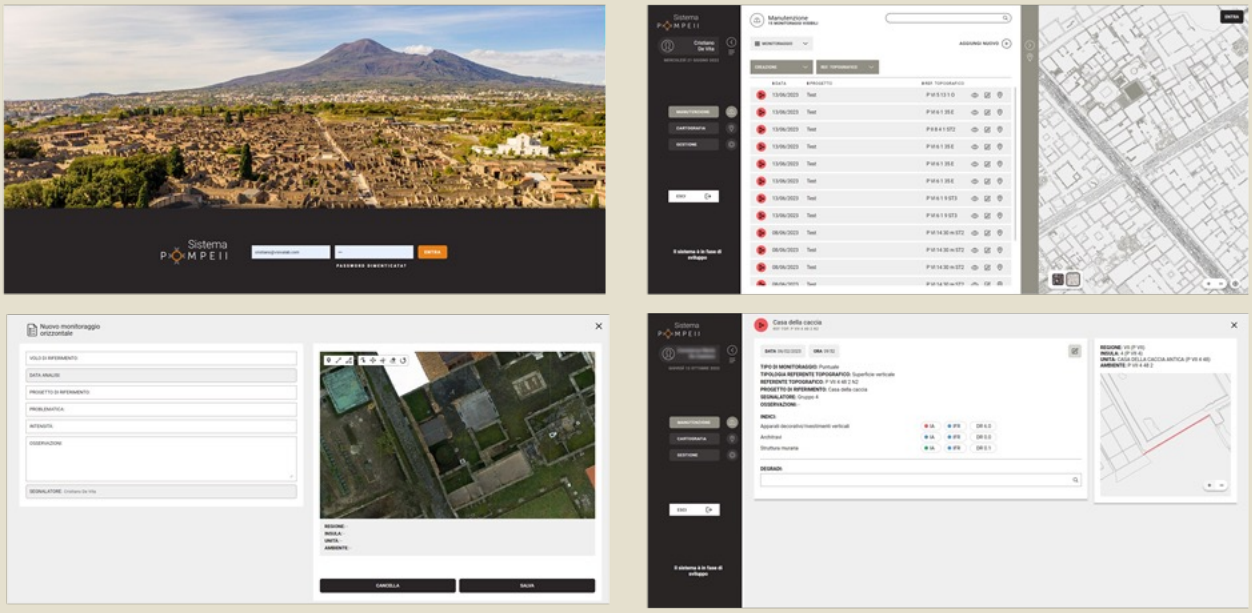

Figure 8. Web-based software for Local Assessment Level.

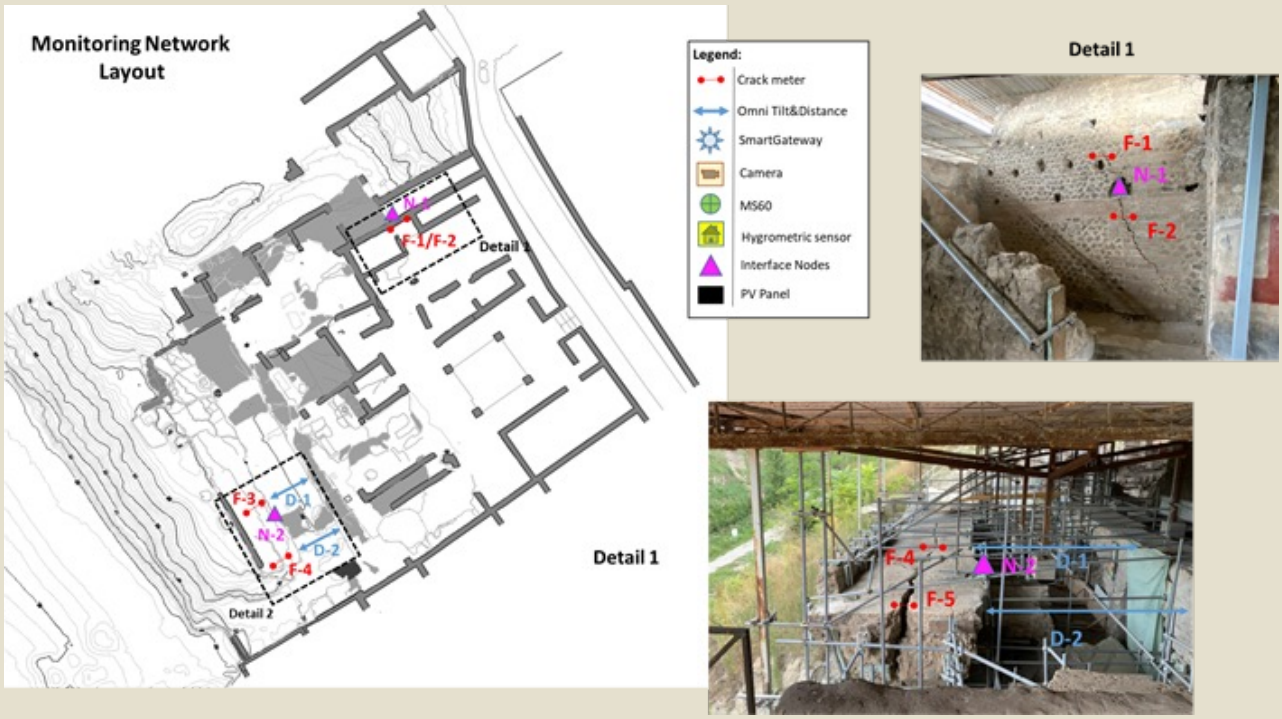

Figure 9. Example of monitoring networks into the Archaeological Park of Pompeii.

6. Conclusions

The conservation of Pompeii represents a major challenge for the management of the site. Based on the experience of the Great Pompeii Project, a new model has been developed over the last three years. It is based on the idea that a significant improvement can be achieved if the scale is amplified from a project-based to a model-based approach. While a project has a beginning and an end, a model is open to further enhancement and development. Moreover, it can be integrated into the ordinary activities of the Park, while a project remains necessarily limited and therefore exceptional. The maintenance programme is linked, and responds to, the data obtained from periodic and systematic monitoring of the entire site, supported by a web app and the use of AI.

Overall, the model aims to achieve a sustainable transition from a state of exceptionality to one of normality. It consists of integrated approaches and strategies that consider the condition of the site as well as the risks and hazards to which it could be subjected. Moreover it aims to use human and economic resources responsibly, implementing innovative technologies to preserve the site, and improving the accessibility and public outreach of the site.

The Archaeological Park of Pompeii is currently implementing a series of initiatives that will make it possible to achieve a number of goals, also in regard to the sustainable development of less well-known sites in the area. Thus, local communities can be involved more actively and their economies can benefit from increased visitor numbers. At the same time, the impact of overtourism and anthropic pressure on hot spots within the cultural heritage landscape can be mitigated.

The model we propose here aims to preserve and protect the heritage by employing proactive maintenance approaches based on systematic, periodically updated data. Sustainability is considered a central goal that can be achieved partly through the use of digital technologies, AI and processual thinking.

Author Contributions

Management Model Conception, G.Z., L.P., V.C.; Development Support, L.P., V.C.; Supervision G.Z.; Scientific Analysis to Support Monitoring L.P., C.L., C.M.D.G.; Technical Management and Implementation V.C., A.S., A.Z.; all authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

All the data and the model are the property of the Archaeological Park of Pompeii (PAP).

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