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Adaptive Immersive Experiences: Comparative Study on Villa Regina

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Abstract **– The application of immersive technologies for enhancing and managing cultural resources has become a vital frontier in the digitization of archaeological artifacts. This contribution introduces an application designed for Villa Regina in Boscoreale (Pompeii Archaeological Park), which encompasses the development of two digital environments: a 360° virtual tour for dissemination purposes and a VR environment derived from a parametric BIM model intended for maintenance and data visualization from sensors (Digital Twin). The objective of this study is to analyze and evaluate the two solutions for various user profiles, assessing their functional, communicative, and operational efficacy on several levels. The comparative assessment, conducted through simulations and qualitative feedback, highlights the strengths, shortcomings, and integrative potential of the two systems. Implementing a rule-based recommendation system is suggested to enhance the personalization of the experience. The concept proposes a cohesive and flexible perspective on digital technologies for heritage, adept at integrating public communication and technical administration within a dynamic information ecosystem.**

I. INTRODUCTION

Digital technology advancements in recent decades have had a significant impact on the cultural heritage sector, drastically altering how both tangible and intangible property are maintained, shared, and documented. Immersive technologies, including virtual reality (VR), augmented reality (AR), and 360° virtual tours, are providing novel opportunities for accessibility, enabling the public to explore previously unreachable locations, and for conservation, supplying sophisticated tools for monitoring and managing the physical degradation of heritage sites[1]. In the realm of archaeological heritage, these technologies provide an essential resource. In addition to enhancing communication and historical storytelling through three-dimensional reconstructions and interactive tours, they facilitate the management of challenges related to the fragility and complexity of sites[2]. The integration of parametric models, IoT sensors, and simulated environments has given rise to the concept of the Digital Twin (DT), a precise digital replica of a physical entity, continuously updated in real time, that is proficient in facilitating activities such as structural monitoring, predictive maintenance, and conservation planning[3], [4]. Given the context, for these solutions to have a genuine and practical impact, it is crucial to create experiences that cater to users' diverse levels of knowledge and individual needs[5]. The general public—tourists, students, and inquisitive visitors—seeks an intuitive, engaging, and instructive experience focused on discovery and learning. Conversely, there are specialized professionals – such as restorers, archaeologists, and conservation technicians – who require exact, analytical instruments designed for technical and operational assistance[6]. In light of the scenario mentioned above, it is necessary to create a multi-tiered user framework that provides parallel yet potentially interrelated pathways tailored according to the user profile. This method enables the adjustment of content and interactions' complexity without replicating the fundamental technological framework[7], [8], [9]. The implementation of adaptable digital environments, scalable interfaces, and intelligent systems may serve as a sustainable solution, effectively addressing the diverse needs of the industry in a differentiated yet integrated manner[10]. This study aligns with the theoretical and operational framework, offering a comparative analysis of two digital environments developed for a real archaeological site: a 360° panoramic virtual tour aimed at dissemination and education and a VR environment derived from a parametric BIM model designed for predictive maintenance via integration with sensor data. The objective of this study is to assess the efficacy of two solutions for two distinct user profiles, analyzing the benefits, constraints, and potential of a multi-tiered strategy for digitizing cultural assets.

II. RELATED WORK

In recent years, the use of technologies such as virtual tours and VR in the field of cultural heritage has expanded considerably, not only in Italy but internationally. This trend is fueled by the growing need to make historical, artistic and archaeological heritage more accessible, interactive and engaging, even remotely. Advances in digitization have been made possible thanks to the evolution of surveying techniques, such as photogrammetry and laser scanning, and the development of advanced software for data processing and visualization [11]. Today, many archaeological sites are being digitized to offer immersive and informative experiences. Among the most relevant cases are the Neolithic site of Choirokoitia in Cyprus [12] and the Oppidum of Ulaca in Spain [13], where interactive virtual tours based on 360° panoramic photographs were created, with the addition of information hotspots. Similarly, in the cryptoporticus of the archaeological site of Egnatia [14] VR was used to support technical knowledge of the site, while for the Temple of Abu Simbel in Egypt [15], a 3D model and a virtual tour were created to increase awareness, tourism and conservation. In the case of the Versilia Plain [16], VR has been integrated with Web Mapping tools to create tourist itineraries that combine physical and virtual experiences, improving fruition and learning. A similar approach has also been adopted in Romania to enhance historic wooden churches, through digital surveys and the creation of virtual environments accessible via apps or online platforms. AR is also used for dissemination purposes. For example, at the rock site of Cova dels Cavalls, in Spain [17] AR allows you to view virtual reconstructions of the original paintings, improving the experience of guided tours. An even more innovative form is underwater AR (UWAR), used in the Underwater Archaeological Park of Baia, Italy, which allows divers to explore archaeological remains with informative digital overlays. These examples demonstrate how immersive technologies are not only tools for dissemination, but real resources for the conservation, enhancement and sustainable management of cultural and archaeological heritage.

III. MATERIALS AND METHODS

The project's methodological architecture is structured into three primary phases: data collecting, digital solution creation, and varied user application. Each step is interlinked inside a circular system that enables the adaptation and modulation of content and functionality based on the user profile and intended application.

The initial phase entails the collection and organization of data, categorized into three primary types: Historical and archive data, encompassing documentary sources, historical maps, archival surveys, excavation notes, and scientific publications. This content establishes the narrative and interpretive foundation for the digital experiences, offering crucial cultural and chronological context for understanding the site; Metric and photographic information obtained via 3D surveys (laser scanning, photogrammetry) and high-resolution photographic campaigns. These establish the physical and visual foundation for the development of digital environments, ensuring high spatial fidelity and the ability to produce precise models of the archaeological site; Real-time data from in-situ sensors (IoT) that monitor environmental and structural characteristics, including temperature, humidity, vibrations, and water presence. This data is crucial for the development of the DT, a dynamic digital representation of the site that is updated in real-time and capable of representing its conservation status. Each data type contributes uniquely to the development of the two digital environments designated for the second phase. Two separate immersive experiences were created and developed based on the obtained data, adhering to various logic and aims, although grounded in a shared information foundation. The initial component is a 360° panoramic Virtual Tour, primarily constructed from photographic and historical information. This environment is tailored for diffusion and aims to provide an accessible, intuitive, and narrative exploring experience. The content is structured in either sequential or free mode, incorporating contextual information points, voice aids, and graphic reconstructions. The language is streamlined, intended for a general audience, and focuses on active learning. The second environment is a three-dimensional information model, navigable in VR, constructed on a Building Information Modeling (BIM) foundation and supplemented with sensory data. The geometric model is augmented with technical specifications, maintenance parameters, environmental data, and records of interventions. The incorporation of dynamic sensor fluxes converts the model into an authentic DT, making it applicable for analysis, simulations, and the strategic planning of conservation measures. This environment is designed for proficient and technical users, featuring a more intricate and analytical framework. The concluding element of the process pertains to user engagement with the two developed digital environments, which are no longer viewed as inflexible solutions designated for a particular user type but rather as versatile instruments capable of accommodating material and capabilities customized to the user's profile and goals. The BIM-based VR Environment, while intended for expert users, has been built to incorporate historical, cultural, and narrative information for a broader audience. Through the use of immersive navigation, non-specialist users can access contextual explanations, thematic sections, reconstructive models, or chronological timelines, thereby converting the technical environment into a profoundly immersive cultural experience. The public accessibility of the technology environment addresses the necessity to harness its immersive potential for educational and tourism objectives. The analytical methodology extends beyond assessing technologies based solely on their initial intended application; it also examines their adaptability and cross-disciplinary potential across various environments. The comparison considers not only efficacy regarding a given target but also the capacity of both technologies to adapt in hybrid situations, addressing diverse objectives and user profiles.

IV. USER TARGETS AND GOALS

A key aspect of the project is identifying user profiles and delineating the functional objectives that each digital environment must fulfill. The adopted methodological approach is predicated on the notion that the appreciation of cultural heritage can and should be tailored to the user's competence level, while simultaneously remaining accessible and adaptable for various kinds of engagement. The aim is not merely to develop two separate digital tools but to evaluate methods of integration and cross-pollination across goals, functionalities, and content. The fundamental user comprises tourists, students, educators, and enthusiasts, possessing a generally low to moderate degree of technical proficiency yet demonstrating a pronounced interest in history, archaeology, and the cultural enrichment of the site. The primary aim for this user type is active learning, contextual comprehension of the material, and the opportunity to explore it in an accessible and engaging manner. The 360° Virtual Tour is well-suited to address these requirements, thanks to its intuitive framework, visual and textual storytelling, and compatibility with standard devices. The fundamental user can thereby engage in an immersive experience characterized by enhanced spatial complexity while preserving a directed and comprehensible experience. Proficient users encompass restorers, archaeologists, conservation technicians, and heritage managers. levels. In this instance, we aimed to explore a method of cross-utilization, anticipating that expert users could leverage the 360° Virtual Tour as a streamlined interface for accessing environmental data, which would be advantageous in scenarios such as swift inspections, remote site

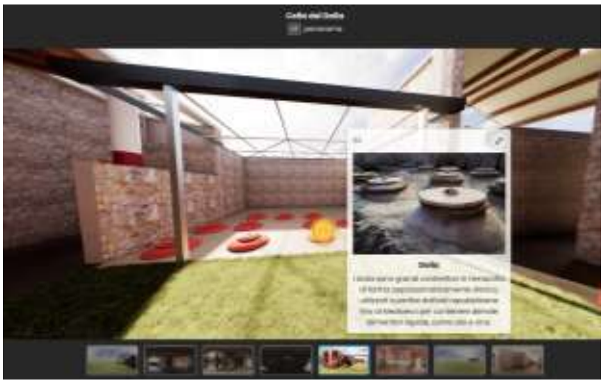

Fig. 1. Part of the virtual VR environment of Villa Regina

evaluations, or disseminating information to non-technical stakeholders. The panoramic tour serves as a streamlined variant of the effectiveness of the two digital solutions more broadly, analyzing them in terms of parameters such as usability, degree of immersion, and adaptability to different contexts of use. An additional purpose is to assess the scalability of the employed models, specifically the feasibility of replicating the methodology and technical solutions at other archaeological or cultural sites while preserving functional consistency and operational flexibility. The initiative aims to foster a cohesive perspective on the digital experience, where dissemination and conservation objectives are viewed as interrelated elements of a collective information ecosystem. This analysis also examines the concept of cross-cutting interfaces, probing the extent to which a unified digital environment can address diverse requirements through simplification, content curation, and dynamic adaptation mechanisms. This multifaceted and adaptable viewpoint enables us to envision a new era of digital instruments for cultural heritage, distinguished by substantial inclusivity, efficient technical governance, and enduring sustainability.

V. CASE STUDY

As already mentioned in the introduction, the goal of this work is, starting from the same case study, to create two different digital environments, a 360 virtual tour and a VR environment based on a BIM model, to compare them and study their advantages and differences depending on the type of use and the user. The case study in question is Villa Regina, an archaeological site, located in Boscoreale, Campania. It is, in particular, one of the many rustic villas in the Vesuvius area, it is well preserved and of great importance, therefore ideal for designing alternative and innovative digital paths, also aimed at promoting minor sites. In order to create a BIM-based virtual environment, the workflow to follow is long and complex, and the steps to follow are many. Meanwhile, in this case, it would be more appropriate to talk about HBIM, or Heritage or Historic Building Information Modeling, since Villa Regina is part of the Italian historical-artistic heritage. HBIM, in fact, was born precisely from the need to apply BIM also to historic buildings, which by their very nature, are often the result of stratifications of evolutionary phases, materials and architectural changes that have followed one another over the years. Therefore, the first step for a correct approach to HBIM is the search for all

Fig. 2. Entrance to the Virtual Tour of Villa Regina

the available paper and digital documentation, historical and recent, available at state archives, local authorities, libraries and any archive that may have information relating to the construction. In this case, the research conducted allowed us to trace the date of construction of the villa, the purpose for which it was built, but also to discover the construction materials and the functions that took place inside. It was discovered at this stage, that the villa dates back to the first century AD, was buried by the eruption in 79 AD and rediscovered in 1977. Compared to the luxurious Pompeian villas, Villa Regina was intended for wine and agricultural production, favored by the fertile soil of Vesuvius. To confirm this, during the excavations, the tools used for the production and storage of wine were found, such as the torcularium (crusher), and the underground dolia. The villa has a simple plan, articulated around a central courtyard, with rooms dedicated to agricultural activities and the daily life of workers. In fact, the main rooms are the torcularium, where the grapes were pressed, the cellarium, a warehouse with large underground dolias, used for the fermentation of wine and, finally, the essential residential rooms, intended for workers. Finally, from the historical research conducted, information was also obtained on the materials used for its construction, which were those typical of the local area, such as stone, tiles and tiles in brick, cocciopesto and wood. Materials that guaranteed strength and durability to the structure, fundamental characteristics for a building used for agricultural production. The next phase is the survey phase, an essential step at the base of modeling and consequently of the graphic rendering. In the case of Villa Regina, the survey was carried out both with a Laser Scanner and a drone. The 3D laser scanner that was used is the Leika BLK360, designed to quickly acquire spatial and visual data of indoor and outdoor environments, and for this reason widely used in the fields of architecture, engineering, cultural heritage conservation and 3D modeling. Once the scan is initiated, the BLK360 uses a time-of-flight laser to measure distances to surrounding surfaces, generating a highly detailed 3D point cloud that represents the three-dimensional geometry of the environment, with high accuracy. In parallel, the scanner also captures high-resolution panoramic images thanks to its built-in cameras. These photographs are then superimposed on the point cloud, returning an immersive and photorealistic representation of the space acquired. The drone survey, then, made it possible to obtain detailed and high-resolution data, in the form of orthophotos, i.e. aerial photos without perspective distortions, which allow to further detail the point cloud already obtained by the laser scanner survey. The data obtained from the survey are then imported into specialized BIM software, where they are modeled in a virtual environment. The software chosen for the modeling was Autodesk Revit, which made it possible to recreate the spaces of the villa in a fairly realistic way. During this phase, the historical elements of the Villa, such as frescoes, cornices and lintels, were also carefully documented to ensure a precise representation of the original building Villa Regina, an example of a historic structure with considerable archaeological value, which for this reason can take advantage of IoT and the use of sensors in general, to address the specific challenges of dated buildings, such as conservation, security and maintenance. First of all, before the installation of the sensors, an in-depth assessment was carried out both on the parameters to be monitored, and consequently on the type of sensors to be installed, and on the environmental and structural conditions of the building, in order to identify the areas that could best benefit from this technology. In the choice of sensors, then, the least invasive and therefore compatible with the historical architecture were chosen, in particular wireless or battery-powered sensors. Therefore, in light of the above, for the monitoring of the structure, it was decided to install a series of sensors including fixed thermal cameras, accelerometers, humidity sensors, but also temperature sensors and rain gauges, to determine, for example, the surface temperature of the walls, the presence or absence of humidity in the rooms, or even any vibrations of the subsoil. Since Villa Regina is a tourist site, it was decided to use two additional sensors: cameras to monitor access in real time and for greater control, and a sensor for counting people, therefore capable of defining the flow of visitors. Once the three-dimensional BIM model was obtained, the next step was first to export the model in a format compatible with VR engines, and then import it into the chosen graphics engine. In our case, the file was exported in .obj format, and then uploaded into Unity. Unity is a cross-platform graphics engine used to create interactive 2D, 3D and VR applications, and for this reason it turned out to be perfect for our goal: to recreate the VR environment of the Villa. The entire immersive experience was then designed within the engine, then navigation paths, interactions with objects and user interfaces were defined, differentiating each of these aspects by type of user. In the second case, the archaeological site of Villa Regina was made usable thanks to the creation of a Virtual Tour 360. Since this is composed of 360° spherical panoramic photos, its realization compared to the first environment made in VR was faster and more intuitive. The first phase of historical and digital documentation was common to both environments. To get the tour, however, the Ricoh Theta was used, which is a compact camera designed specifically for 360° spherical panoramic photography. With the special app, the camera was managed and controlled remotely, this allowed you to take one or more 360° spherical photos at strategic points of the place to be documented, but without appearing in the shot. Once the various shots were completed, they were linked within the 3D Vista Pro software. In particular, the connection between the photos takes place by inserting hotspots, i.e. invisible or visible buttons that allow you to switch from one view to another. In this phase, therefore, the photos have been sequenced, but above all icons and information sheets have been added on the various environments or on particular elements present within them.

VI. COMPARATIVE VALIDATION

The comparative assessment of the two intended digital environments is crucial for comprehending the efficacy of the implemented solutions for user profiles and anticipated objectives. The selected methodology was qualitative-exploratory, emulating a testing environment with representative users and developing usage scenarios to elucidate the strengths, shortcomings, and evolutionary potential of the two settings. The assessment procedure consisted of three primary phases: observation of user behavior during contact, gathering input through qualitative questionnaires and semi-structured interviews, and cross-analysis of the findings. Participants were categorized into). Every user engaged with both the 360° Virtual Tour and the VR+BIM Environment, receiving directives on tasks to do and content to locate. Basic users predominantly assessed the 360° Virtual Tour as an accessible, intuitive, and engaging tool, particularly valuing the clarity of the content and the ease of navigation. The experience was practical for learning due to the inclusion of concise texts, audiovisual aids, and clear information points. Nevertheless, participants articulated a sense of 'physical' detachment from the location, perceiving the encounter as less immersive than anticipated. In contrast, the VR environment, including the BIM model, which was initially regarded as intricate and less accessible, elicited a significant emotional response once the immersive experience commenced. The DT functionality, providing access to real-time data on environmental conditions, was identified as a crucial component for more dynamic and informed management of the archaeological asset. There was a desire for enhanced interface customization and improved visual differentiation between information levels to prevent cognitive overload. The 360° Virtual Tour was unexpectedly assessed favorably by expert users as an efficient reference tool, beneficial for preliminary inspections, briefings with other operators, or communication with non-technical individuals. The integration of IoT data into the tour was deemed highly helpful, particularly for remote control operations and information dissemination throughout the decision-making process. The simulation results indicate that the two digital environments are effective not just in achieving their primary aims of dissemination and management but also have considerable cross-cutting potential. The Virtual Tour, enhanced with dynamic data, can be built as a streamlined version of the DT, beneficial in flexible operating contexts. The VR+BIM environment, when equipped with modular access levels, can be transformed into an immersive, exploratory space accessible to non-experts, thereby enhancing instructional efficacy and emotional engagement with the site.

The evaluation experience underscored:

- the necessity of tailoring information and interfaces;
- the strategic synergy between the two settings;
- the imperative to develop hybrid and scalable tools that can adapt to many circumstances while maintaining consistency.

The results, derived from a qualitative simulation, offer valuable insights for developing future models of multi-level digital usage and suggest a paradigm in which the interaction between technology and users is dynamic, evolutionary, and adaptable.

VII. CONCLUSIONS

The study demonstrated that the integration of various immersive technologies—namely, panoramic virtual tours and VR settings derived from parametric models—can serve as an effective and adaptable framework for enhancing and managing archaeological assets. The implementation of a multi-tiered methodological framework, which differentiates yet does not strictly segregate user profiles, facilitated the assessment of interoperability and transversality between the two environments, transcending the conventional dichotomy between dissemination tools and technical analysis tools. The comparative assessment, executed via simulations and qualitative analyses, validated the efficacy of the two environments within their respective contexts while primarily emphasizing the potential for cross-utilization: expert users regarded the virtual tour as a streamlined and functional interface for consultation and communication; conversely, novice users exhibited interest and engagement in the immersive exploration of the VR environment, contingent upon the content being delivered in an accessible format. The results indicate the necessity of developing digital systems that can dynamically adjust to users via customizable interfaces, guided pathways, and modular information tiers. In this regard, a notably intriguing prospect is the incorporation of a rule-based recommender system. This system can autonomously suggest content or features based on usage profiles, prior interaction pathways, stated interests, or professional duties, thereby enhancing the experience and enabling targeted access to the most relevant information. The availability of real-time data from IoT sensors enhances the model's potential, converting the digital environment into a dynamic information ecosystem that aligns with the DT paradigm. Prospects can be divided into two primary avenues: firstly, expanding the model to additional cultural sites, emphasizing scalability and economic sustainability; secondly, implementing quantitative evaluation systems (such as eye-tracking, interaction logs, and UX metrics) to enhance the project's experimental dimension. Integration with intelligent tools, such as recommendation systems and artificial intelligence modules, could improve the experience by making it more flexible and personalized in terms of dissemination and technology. The conducted research illustrates that integrating information models, immersive environments, dynamic data, and adaptive logic can establish a robust foundation for creating advanced digital tools that facilitate the dual objectives of cultural heritage: conveying the past and safeguarding the future..

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