DIGITAL TWIN ECOSYSTEM FOR HERITAGE MANAGEMENT - THE CASE OF COLONIA ULPIA TRAIANA AUGUSTA DACICA SARMIZEGETUSA

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Abstract: This paper explores the application of Digital Twin technologies in the sustainable management of cultural heritage. It includes a theoretical overview, international best practices, and a case study of Sarmizegetusa Romană, highlighting how digital tools can enhance conservation, visitor experience, and data-informed decision-making.
Keywords: Digital Twin, heritage management, sustainable tourism, immersive technologies, smart cultural destinations.

1. Introduction

In an era of fast technological change and mounting pressure on heritage sites, sustainable management has become a key concern. Threats like degradation, overtourism, poor maintenance, and limited digital access highlight the need for innovative solutions that protect cultural value while enriching visitor experiences.

In this context, the concept of Digital Twin has gained prominence as a transformative tool in heritage management. A Digital Twin refers to a highly detailed, dynamic digital replica of a physical asset or environment. Originally used in engineering and manufacturing industries, this concept has recently found promising applications in cultural heritage preservation, urban planning, and tourism development [1]. By integrating technologies such as 3D modeling, drone imaging, geographic information systems (GIS), and real-time data from environmental sensors, Digital Twins enable the creation of interactive models that mirror the current and potential future states of heritage sites.

The adoption of Digital Twins in the cultural heritage sector reflects a broader shift toward digitization, participatory governance, and the sustainable development of tourism. These technologies serve not only as tools for environmental monitoring, tracking humidity, structural shifts, and other risk factors but also as platforms that enable virtual reconstructions, facilitate remote access, and enhance visitor engagement through immersive experiences [2]. From UNESCO's cultural preservation initiatives to local tourism strategies, the integration of digital replicas into heritage site management is becoming a strategic priority.

This paper explores the role of Digital Twin technology in redefining the management of cultural heritage destinations, with a particular focus on the case of Colonia Ulpia Traiana Augusta Dacica Sarmizegetusa, a Roman archaeological site in modern-day Romania. Through a theoretical synthesis and comparative analysis of international best practices, this study argues that the implementation of a Digital Twin system can enhance both the conservation and touristic valorization of the site, aligning with global standards for innovation in cultural heritage management.

2. Background and Literature Overview

The integration of digital technologies in cultural heritage management has seen remarkable growth in recent decades. As heritage sites face increasing risks due to climate change, uncontrolled tourism, and lack of maintenance, researchers and practitioners have turned to advanced tools such as Digital Twins, 3D reconstruction, geographic information systems (GIS), and augmented reality (AR) to support preservation and improve accessibility.

The Digital Twin concept, originally coined by Michael Grieves in 2003 and later developed within the aerospace and manufacturing sectors, has been successfully adapted to the heritage domain [1]. A Digital Twin in cultural heritage consists of a virtual and real-time connected model of a physical site, enriched with data from various sensors, historical records, and geospatial technologies [3]. This digital counterpart serves multiple purposes: environmental monitoring, preventive maintenance, risk analysis, virtual visualization, and education.

In Pompeii, a digital reconstruction supports both research and virtual tourism. At Notre-Dame de Paris, pre-fire 3D scans proved essential for restoration efforts. Similarly, Stonehenge's high-resolution models enable advanced analysis and simulate environmental and tourism impacts [4][5]

From a theoretical perspective, several studies emphasize the strategic benefits of using Digital Twins in sustainable destination management. According to

Ioannides et al. [2], digital replicas serve as collaborative platforms that bring together archaeologists, local authorities, and the general public in co-creating narratives and interpretations of cultural sites. This democratization of access and knowledge supports transparency and long-term engagement. Similarly, Pescarin highlights the pedagogical potential of Digital Twins, especially when combined with AR or VR tools, to enhance visitor experiences and provide inclusive access for individuals with limited mobility [6].

In a complementary perspective, URBIM [7] highlights the potential of Digital Twin technology when integrated with Building Information Modeling (BIM), the Internet of Things (IoT), and augmented or virtual reality. Rather than functioning as static representations, Digital Twins become dynamic digital ecosystems that enable real-time monitoring, visitor flow simulation, environmental risk anticipation, and operational optimization. Furthermore, the incorporation of metaverse platforms opens new avenues for immersive tourism experiences, improving accessibility for individuals with reduced mobility and attracting broader audiences through virtual reconstructions. This holistic approach positions Digital Twin technology as a central pillar of smart tourism and aligns with the principles of Tourism 4.0, which emphasize sustainability, technological innovation, and community engagement.

Recent research consolidates this systemic vision, suggesting that Digital Twins in cultural heritage require a multilayered architecture. According to Vacca et al. [8], a typical implementation consists of a physical layer (sensors and hardware), a data processing layer, and a service layer that supports visualization and end-user interaction. This modular framework enhances scalability and ensures long-term interoperability, which are critical for sustainable and adaptive heritage site management.

Furthermore, Digital Twins support the principles of smart tourism, a concept that advocates for the use of technology to create efficient, personalized, and environmentally responsible visitor experiences [9]. By enabling predictive analytics and dynamic visitor flow management, these tools help avoid congestion, minimize physical degradation, and inform strategic planning for heritage conservation.

McKinsey & Company [10] defines Digital Twins as dynamic, continuously updated digital environments that reflect physical systems throughout their lifecycle. It identifies four categories, product, data, system, and infrastructure twins, with the latter especially relevant for heritage site management. These models, powered by real-time sensor data and AI analytics, support scenario analysis, resource planning, and sustainable maintenance. As "decision environments," Digital Twins optimize both cultural preservation and tourism infrastructure.

Building on these views, Florido-Benítez [11] analyzes Digital Twins within Smart Tourist Destinations (STDs) as transformative tools that go beyond optimization, reshaping sustainability, governance, and competitiveness in tourism. Integrated with AI, IoT, VR/AR, and blockchain, DTs enable real-time analytics, predictive responses, personalized services, and inclusive accessibility. Defined by real-time analysis, digital–physical convergence, and adaptive learning, they also serve as platforms for co-creation. Nonetheless, challenges such as cybersecurity, cost, and privacy require coordinated regulatory responses. In this context, DTs emerge as critical infrastructures for sustainable and inclusive tourism innovation.

In summary, the current literature reveals a strong convergence between technological innovation, participatory governance, and sustainable cultural tourism. While many of these applications remain concentrated in well-funded sites in Western Europe or North America, they offer transferable models that can be adapted to emerging destinations such as Sarmizegetusa Romană.

Building on the international experience, the following case study examines how the principles and technologies behind Digital Twins can be effectively implemented in Romania, using Sarmizegetusa Romană as a representative example of untapped heritage potential.

3. Methodological Proposal and Case Study

This section outlines a strategic methodological framework for implementing a Digital Twin system within a heritage tourism context, with a specific focus on the Roman archaeological site of Colonia Ulpia Traiana Augusta Dacica Sarmizegetusa. The proposal is informed by a comparative analysis of internationally recognized projects and builds upon the conceptual premises discussed earlier. While the approach remains theoretical, it is grounded in recent technological advancements and interdisciplinary practices in cultural heritage preservation and tourism innovation.

Located in the historical region of Țara Hațegului in Hunedoara County, Romania, Colonia Ulpia Traiana Augusta Dacica Sarmizegetusa, commonly referred to as Sarmizegetusa Romană, represents one of the most significant archaeological and cultural heritage sites in the country. Founded in the early 2nd century A.D. by Emperor Trajan following the Dacian Wars, the city was the first Roman colony in the newly established province of Dacia. It served as the administrative, military, economic, and religious capital of the province.

The urban area covered approximately 33 hectares within the city walls and over 80 hectares outside the fortifications, featuring a Roman forum, temples dedicated to classical deities, public baths, administrative buildings, an amphitheater, and a highly structured street network. Archaeological evidence

suggests the settlement once hosted a population exceeding 30,000 inhabitants [12]. Despite its outstanding historical value, the site today faces numerous challenges.

Among the most pressing issues are the physical degradation of structures due to exposure to weather, the absence of systematic conservation interventions**,** limited digital promotion, and an underdeveloped tourism infrastructure. In some areas, ancient ruins extend into private property, complicating site protection and restoration efforts. Moreover, compared to other prominent European heritage sites, Sarmizegetusa suffers from insufficient visibility in both domestic and international cultural circuits.

In light of these conditions, the introduction of a Digital Twin system is proposed as an innovative and viable approach to revitalize and sustainably manage the site. This system would consist of a high-precision, three-dimensional digital replica of the archaeological complex, developed using technologies such as laser scanning, drone-based aerial photography, GIS mapping**,** and environmental sensor networks. More than a static visual reconstruction, the Digital Twin would operate as an interactive, real-time management platform, supporting both conservation and tourism planning.

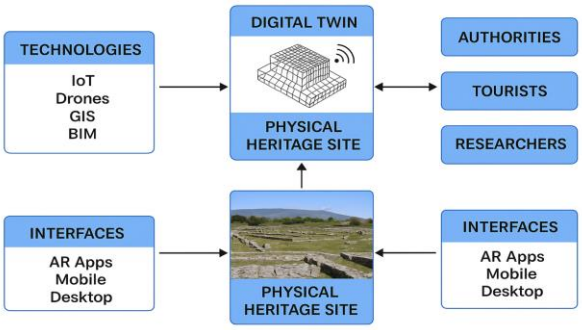

Fig. 1. Digital twin ecosystem for heritage management.

For instance, real-time monitoring of environmental parameters, such as humidity, soil vibration, and temperature fluctuations would allow early detection of degradation processes and enable prompt conservation responses. The platform would also facilitate the virtual reconstruction of the Roman city's architecture and urban landscape, offering a comprehensive view of its former grandeur and spatial logic.

A key advantage of the Digital Twin is its potential to digitally enhance the visitor experience. Tourists could engage with the site through interactive virtual tours, accessible remotely via dedicated web platforms or on-site via augmented reality (AR) applications on smartphones or tablets. This immersive approach would allow users to visualize reconstructed Roman buildings over existing ruins, supported by contextual information, historical narratives, and 3D animations. Such tools can significantly increase the site's appeal, particularly for younger audiences and individuals with limited mobility.

In the long term, the Digital Twin system would also support strategic planning for sustainable tourism. By analyzing tourist flows and predicting usage patterns, local authorities could develop alternative routes, identify vulnerable zones, and implement visitor regulation policies that mitigate pressure on fragile areas. Moreover, community involvement could be fostered through participatory mapping, digital heritage workshops, and inclusive promotional campaigns, integrating local residents into the cultural and economic revitalization process.

This proposal aligns with international best practices in digital heritage management. At Pompeii, geospatial technologies and photogrammetry have enabled detailed digital reconstructions for research and virtual tourism [13]. Similarly, high-precision laser scans facilitated the Digital Twin guiding Notre-Dame's restoration after the 2019 fire [14]. At Stonehenge, 3D modeling supports both conservation and public engagement through interactive visualization [15].

Although Sarmizegetusa Romană shares the historical and symbolic depth of these sites, it lacks the digital infrastructure and integrated management necessary for comparable valorization. A Digital Twin system would strengthen its conservation efforts and establish a scalable model for digitally driven heritage management in Eastern Europe.

4. Conclusions

The integration of Digital Twin technologies in heritage site management marks a shift toward sustainable, participatory, and digitally informed practices. As shown in projects like Pompeii, Notre-Dame de Paris, and Stonehenge, digital replicas support not only conservation and monitoring, but also education, crisis response, and visitor engagement. These examples highlight how digitization can transform static heritage into dynamic, accessible experiences, advancing preservation and responsible tourism.

The case of Sarmizegetusa Romană reflects many of the challenges shared by heritage sites in Eastern Europe: fragmented ownership, insufficient funding, and limited integration into digital and tourism networks. However, it also presents an exceptional opportunity. With its rich Roman legacy, urban complexity, and symbolic resonance in Romanian cultural identity, Sarmizegetusa offers a fertile ground for implementing a Digital Twin strategy that is both innovative and replicable.

By adopting this model, local authorities and cultural institutions could overcome current limitations and align with European best practices in heritage management. A Digital Twin system would allow for real-time environmental monitoring, predictive maintenance, interactive visitor experiences, and data-

driven decision-making, enhancing both protection and promotion. Moreover, it would enable the inclusion of local communities in heritage valorization processes, fostering a sense of ownership and economic participation.

This study argues that adopting Digital Twin technologies in heritage tourism signifies more than a technological upgrade—it marks a paradigm shift in preserving, interpreting, and experiencing cultural heritage. For underrepresented sites like Sarmizegetusa Romană, a Digital Twin system could offer a scalable model for sustainable heritage valorization in Romania and beyond. Integrating digital infrastructure with strategic planning and stakeholder collaboration can stimulate academic research, enhance cultural education, and foster innovation in tourism.

Although this proposal is conceptual and grounded in secondary sources and international case studies, it establishes a foundation for future empirical validation. Pilot projects, stakeholder engagement, and field research will be crucial to test feasibility, estimate costs, and assess visitor responses. Adapting Western frameworks to the Eastern European context will also require overcoming structural challenges, including limited funding, infrastructure gaps, and bureaucratic inertia.

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