Application of the digital twin concept in cultural heritage

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Abstract
Cultural heritage has benefited for years from the availability of technology in the domain of digitalization; hence digital heritage emerged. Researchers in the cultural heritage domain have used tools and digital techniques as way to preserve historical and religious buildings so that they are everlasting in time. These are mostly viewed as autonomous attempts, rarely organized. One of the digital tools that arose from the field of product life cycle management is the digital twin, which is defined as digital representation of physical product. There is an ongoing debate whether cultural heritage can be fully viewed in terms of digital twin and if the application of the digital twin concept can be sustainable in the management of the cultural heritage environment. This paper aims to address the role of the digital twin within the cultural heritage domain and if it can be used to recreate certain phenomena or environmental situation resulting in reducing deterioration over time. This is important since heritage sites and historical buildings must be preserved for future generations.

Keywords
Cultural heritage, digital twin, IoT, preservation, data collection

1. Introduction

Heritage preservation is well-known as an activity that takes time and effort. A lot of work is done on a daily basis to protect built heritage from deteriorating and to keep it as authentic as possible. Over the previous decade, built heritage documentation, study, and preservation have gotten more technologically advanced, resulting in a greater diversity and complexity of information sources. Data acquisition (Drones, Electronic Distance Measurement (EDM), 3D scanning, Global Positioning System (GPS), Aerial Terrestrial Photogrammetry, etc.), data structuration (Computer Aided Design (CAD), Building Information Modeling (BIM), Geographic Information System (GIS), etc.), and data dissemination (CAD, BIM, GIS, etc.) technologies have aided in the creation of digital representations of built heritage, allowing for more effective planning, predictive maintenance, and strategic management. In other words, heritage digitization techniques have given not only a visual representation of heritage, but also a technological

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solution for effective conservation management [1, 2].

The rise of the Internet of Things (IoT) has enabled the introduction of new supporting tools for building operation and maintenance. Digital twins are made possible by the emergence of IoT sensors. Even though the phrase "digital twin" has no uniform definition (it is defined in a variety of ways by industry and academia), it can be characterized as a virtual representation of what has been generated [3, 4]. Digital twins are already being used in a variety of applications such as: manufacturing and process technologies, healthcare, meteorology, transportation, energy sector, education, etc [5]. The digital twin concept, as an emerging technology, will usher in a revolution in a multitude of fields, including the construction sector. A digital replica of the construction linked to knowledge databases and sensors delivering near-real time operational data from the real environment allows for the automatic detection of potential hazards and the execution of recommended feasible solutions under expert supervision [2].

This paper presents an attempt to examine the role of digital twins in the cultural heritage domain. The emphasis is on using digital twins to recreate specific phenomena or environmental situations in order to reduce deterioration over time. This is of immense importance because heritage sites and historical buildings must be preserved for future generations.

The remainder of this paper is organised as follows. The second section presents the digital twin concept and its enabling technologies. The usage of digital twins in the cultural heritage domain is presented in section 3, while benefits and problems of its implementation are discussed in the fourth section. The last section draws conclusions.

2. Digital Twin

A digital twin is a connected, virtual counterpart of a physical product, asset, or system that has both the elements and dynamics of the way the complex system runs and evolves over time. Hence, the digital twin architecture consists of three main components: the physical entity, the virtual model, and their connection [6]. Digital twins are used to track, analyze, and enhance physical prototypes and their roles can be broken down into three stages:

- See: a variety of sensors and devices gather data in order to visualize the situation.
- Think: intelligent software evaluates the collected data and, if a problem exists, identifies multiple possible remedies for each one.
- Do: smart algorithms select and implement the most appropriate solution.

Figure 1 shows how to build a digital twin using a range of enabling technologies.

Digital twin implementation is a complicated system and time-consuming procedure that involves numerous technologies and tools working together. The technologies that make it possible to build a digital twin model can be divided into the following categories [6, 8]:

- Technologies for physical objects - Physical objects are essential components of the digital twin because they produce a large quantity of heterogeneous datasets from the real world. Sensing and measurement technologies (e.g. IoT sensing technologies, particle-sensing technologies, reverse engineering, laser measurement, image recognition measurement, etc.), are used to sense real-world data.

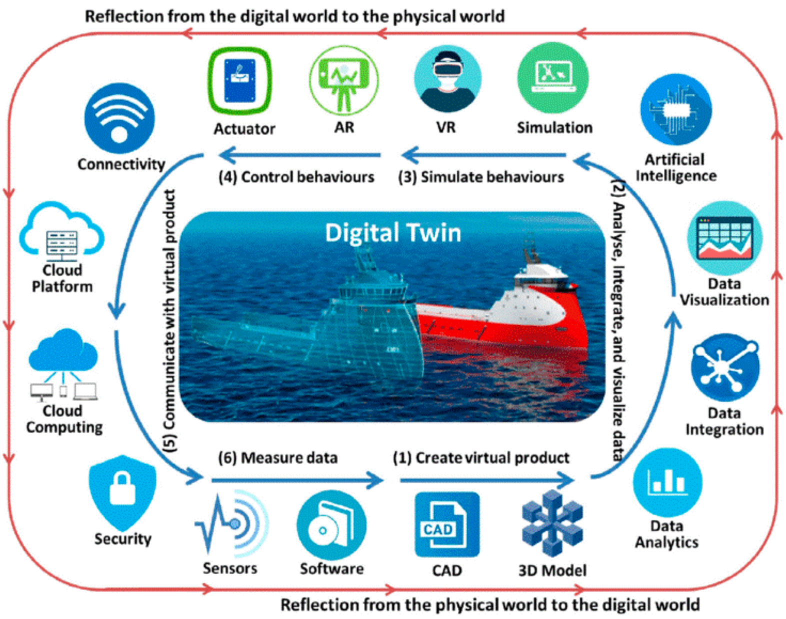

Figure 1: The digital twin's enabling technologies (image obtained from [7])

- Technologies for data construction and management - A huge quantity of multi-source, diverse datasets are created from physical objects. The next steps include data collection, transmission, storage, processing, fusion, and visualization. For data identification and near-real time perception, IoT technologies, cameras, sensors, bar codes, quick response (QR) codes, and radio frequency identification (RFID) devices are commonly used. A vast amount of data can be correctly structured and utilized thanks to the development of big data storage frameworks like distributed file storage (DFS), HBase, MySQL, NoSQL database, and NewSQL database. Big data analytics are used to undertake data processing, with the goal of extracting and generating valuable and meaningful data from a considerable number of diverse sets of data that can be incomplete, unstructured, noisy, fuzzy, and random. Big data analytics can be broken down into three categories: analytic visualizations, data mining algorithms, and predictive analytic capabilities. Data visualization is a technique for presenting data analysis results in a simple, intuitive, and interactive way and it changes in response to the applications it is utilized for. Data visualization methods can be classified into geometry-based technologies, pixel-oriented technologies, icon-based technologies, layer-based technologies, image-based technologies, etc, according to the concept of their visualization.
- Technologies for virtual modeling - Modeling is the process of converting a physical item into digital representations that computers can process, analyze, and manage. Modeling is likely the most important aspect of a digital twin. A complete digital twin model includes its geometry (shape, size, position, and assembly relationship), physical characteristics (tolerances, material properties, and assembly information), behavior (how the virtual

model reacts to external stimuli), and its rules (associations and constraints that can be used to analyze, judge, evaluate, optimize, and predict object performance). To assess the accuracy of the virtual model, it is essential to use verification, validation, and accreditation (VVA) technology.
- Services technologies – Digital twin services technologies are designed to achieve various goals in various applications. A service description is a precise declaration of a specific need. A primary purpose of a digital twin is to have near-real time visualization of digital twin services, which necessitates computer graphics processing technologies (e.g. computer graphics, 3D rendering, image processing, graphics engine, virtual-reality synchronization technologies, etc.).
- Connection and data transmission technologies - For the digital twin to provide near-real time control and virtual-real state mapping, high-fidelity connection mechanisms are required. There are numerous connection protocols for data flow between the physical space and the digital twin, as well as within the cyber space among various software. Wire transmission and wireless transmission are the two current data transmission methods. The adoption of 5G contributes to meeting high accuracy and low latency demands.
- Environment coupling technologies - The virtual environment model, like the digital twin virtual model, includes geometry, physics, and behavioral data. Environment visualization is just as important as virtual model visualization. A multi-channel immersive stereoscopic display approach using wearable devices (e.g. head-mounted displays, tactile gloves) in combination with virtual reality (VR) and mixed reality (MR) would be appropriate for environment visualization. In other words, human-computer interaction technologies (e.g., VR, augmented reality (AR), MR) as well as human–robot interaction and collaboration should be incorporated.

Although each type of digital twin has unique properties, all digital twins share the following characteristics [9]:

- High-fidelity - the digital twin should be an accurate representations of the physical entity, including its geometry, characteristics, behaviors, and rules.
- Dynamic – Keeping the physical and virtual worlds connected and communicating means that the digital twin model changes whenever the physical system evolves.
- Self-adaption and self-optimization – the digital twin can learn from numerous sources and update itself in near-real time to display its status, working state, or position.
- Identifiable - each physical asset must have its own digital counterpart so the digital twin can be uniquely identified from its physical twin or vice versa.
- Multi-scale and Multi-physical - A digital twin is a virtual replica of its physical counterpart, and it must incorporate the physical counterpart's qualities at many scales or levels. Because the model is based on the physical properties of the physical twin, the digital twin is also multi-physical.
- Multidisciplinary – Industry 4.0's backbone is the digital twin, which brings together a variety of disciplines like information and communication technologies (ICTs), computer science, electrical, mechanical, and industrial engineering, automation, and more.
- Hierarchical – The hierarchical character of the digital twin stems from the fact that each component and part of the final product has its own digital twin model.

The formation of a virtual representation of a physical object and interchange of quantitative and qualitative data, historical data, environmental data, and near-real time data enable the digital twin to accomplish the following activities [9]:

- A detailed examination of the physical twin.
- New or current product/process design and validation
- Simulation of the physical twin's health condition.
- Increasing the physical twin's safety and reliability.
- Part, product, process, or production line optimization.
- Following the progress of the physical twin throughout its life-cycle.
- Prediction of the physical twin's performance.
- Controlling the physical twin in near-real time.

3. Digital Twin Technology in Cultural Heritage

Considering that the wealth of humankind embedded in cultural heritage domain is large, we are in constant need of promoting cultural heritage [10, 11, 12] as well as performing data analytics [13, 14, 15] for preservation and reconstruction purposes. Availability of technology and recognition of the importance of such works has created new research interest in which researchers are making substantial progress. Although technology is assisting in the preservation of immovable and movable cultural heritage it is nevertheless a race against time in which the tempo of acquiring documentation and performing analysis of monuments, historical buildings or archaeological sites could often mean maintaining the unaltered originals of our past. This section will provide recent trends and discuss digital twin importance in cultural heritage preservation.

Digital twin is a promising technology used in cultural heritage preservation that allows for a complex interaction between actual physical objects (be it monuments, historical buildings, or archaeological sites) and their virtual representations. Preventive approaches when it comes to preservation of cultural heritage are preferred to corrective ones. Heritage Building Information Modelling (HBIM) models are one of the researched instances of using collaborative data management together with preservation projects. The research framework presented in [16] consists of integrating HBIM models in the digital twin environment with focus on supporting preservation of cultural heritage. The encompassing method recognizes the importance of HBIM model integration beyond the project stage, automatization of data analytics and simulation processes in the digital twin and consequently increased understanding of the effects preservation would have on cultural heritage sites and their patrons. The authors provide a complete value-based risk management plan process consisting of analysis, diagnosis, therapy, and control part presented in Charter—Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage [17].

Historical buildings are subject to environmental factors that could interfere with their preservation. In the past, there have been numerous cases of different kinds of proposals and analysis aiming at assessing micro-climatic performances of historical buildings and monuments [18, 19, 20]. In addition, there are strategies for energy efficiency improvements of historic buildings in Europe in accordance with UN initiatives for sustainable development. The authors in [21] address preservation of modern heritage (prior to 1970s) in Italy arguing that the built heritage of this time lacks a framework sensible in energy and seismic efficiency. Their case study encompassed all the buildings belonging to Alma Mater Studiorum University of Bologna with particular focus on the Institute of Mathematics of Bologna being built prior to the existence of energy efficiency regulations and seismic building codes. HBIM and Building Energy Model (BEM) model were developed in accordance with an open international standard – digital description of built environment. The authors concluded that the research they conducted presents the first step in advancing towards a digital twin of the building that could be used to improve energy efficiency via calibration, evaluation, and predictive techniques for energy consumption reduction.

The authors in [22] employ an integrated informative system together with digital twin technology aiming at maintenance and preservation of cultural heritage assets. They specifically focus on natural and human induced disasters and their effects on tangible cultural heritage, namely art objects (Mater Matuta and the Resting Satyr), housed in an archaeological museum in South Italy. The methodology proposed is in line with principles of safeguarding and conservation of historical buildings and it is interdisciplinary in nature. Their general framework consists of firstly surveying the art object in three aspects (historical, artistic, and architectural) providing the history of the art objects, properties of the materials used, and the present state of conservation; secondly acquiring two and three dimensional data of the whole art object and its relevant elements providing a high-precision laser-scanned 3D model and high-quality orthomosaics; and lastly providing a diagnosis of the art object state based on information gathered or performing additional surveying and data acquiring needed from other disciplines. The authors' advantages of modeling art objects as a composition of three elements (container, content, and sensors) are twofold: first, the model is easily connected to a monitoring system, hence management and cataloging of the information can be supervised and improved, and second, the structural performance of the art object can be assessed either by observing all elements together or each component element separately. The authors conclude that use of a digital twin with an integrated informative system is plausible although more research is needed for the development of generalized practical applications. Nevertheless, they suggest that a fully operational digital twin is needed for protection and preservation of cultural heritage.

The authors in [23] employ digital twin technology aiming at inspecting structural systems of historic buildings, namely Milan's Cathedral, as well as providing predictive analysis predictive analysis of the maintenance of the cathedral in terms of damage restoration processes. In addition, based on previous failures in parts of the structure, deeper insight into future structural behavior could be obtained. The authors developed a simulation model for digital twin application based on nonlinear finite element modelling. Geometric inputs assembled in hierarchical way (complete model, structural elements, and components) were used to create a complete model of the building structure. The authors use concepts from real geometry and structural geometry to understand the correspondence of geometry to structural components and identify positions for new sensor locations as well as continually update the existing model without compromising structural behavior. The results of the presently developed digital twin model show there is a possibility of using it for various preservation tasks while future development could include using virtual sensors for positions not reachable physically or taking into account effects of environment on the damages.

The authors in [24] propose the use of a digital twin for preservation of historical buildings recognizing that improving energy efficiency, while using machine learning models for energy consumption prediction on historical data, can yield sustainable building maintenance. In addition, proposed are various prediction tasks to be performed in a cloud-based digitalization framework, such as facade decay, visitor movement as well as anomaly detection. The proposed framework architecture consists of two main parts that are organized in several layers. The local part uses a perception layer for data collection and the collected information is communicated via edge devices and a transmission layer to the cloud part of the framework. In addition, storage, analysis, and application layer of the cloud part are responsible for storing data, evaluating data, and creating AI models as well as providing maintenance and energy consumption prediction by means of user applications. The authors have created digital twin room using Platform as a Service (PaaS) Azure digital twin in the chosen historical building, deployed sensors for data collection and are proposing to extract useful information from the data to continue researching energy efficiency optimization and smart maintenance.

The authors in [25] present ROCK (Regeneration and Optimization of Cultural heritage in creative and Knowledge cities), a platform supporting the use of digital tools in the cultural heritage domain intended to encompass various digital platforms and strengthen the connection between the physical and virtual domains. Its goals are not only applicable in cultural heritage preservation but also in collecting, managing and sharing of information that could use the combined efforts of all stakeholders, such as academic researchers, professionals, and in particular citizens in creating future collaborative platforms for tangible and intangible cultural heritage resources. The authors conclude that historic centers of several European cities were regenerated by means of citizen participation, hence digital twins were used for learning and contribution in the transformation of physical spaces and understanding the impacts of such transformations.

The authors in [26, 27] presented a live-guided VR tour of an underground oil-mill in the town of Gallipoli, Italy for a content that is not accessible for people with disabilities and inspired by the pandemic situation in 2019 that limited public access to enclosed places. The author developed a virtual visit using a web application with a remotely present real guide in a platform for multiple simultaneous users. The complex interior of the underground mill was virtualized using digital photogrammetry and a 3D model was created. The authors' future aim is to create an advanced model for cultural heritage management and to develop a digital twin for optimization, increase in efficiency and predictive data analytics.

The authors in [28] present methodology for AR visualization and interpretation of two buildings: the Ballroom, and the St. Francis of Assisi Church, in Belo Horizonte, Brazil. The general framework employed for preservation of cultural heritage consists of data collection (historical and spatial), data processing for dense surface model creation and use of HBIM for digital twin modeling. The authors' contribution is implementation of the heritage buildings in virtual world via AR application on a tablet or smart phone in addition to real life experience. They propose that future work will include knowledge-based information that could be used within previously developed HBIM for heritage preservation purposes.

4. The Advantages and Challenges of Digital Twin Technology

Any system or process can benefit from digital twin technology because it reduces errors, uncertainties, inefficiency, and costs. A digital twin is said to have the following advantages [5, 9]:

- Faster production time and product re-designing - Digital twins can be employed at many stages of the product design process, shortening design and analysis cycles and making prototyping and re-designing faster and more efficient.
- Decreasing costs and waste - A digital twin is created primarily with virtual resources, hence the overall prototyping' cost decreases over time. A digital twin enables cost-free testing of products under a number of test situations in a virtual environment, including damaging scenarios. This minimizes development costs and time to market, increases the life of equipment and assets while also saving on material waste.
- Predicting problems/system planning - A digital twin allows for the discovery and prediction of problems and failures at various phases of the product life-cycle. This is especially useful for products with several parts, complicated structures, and multiple materials, because as a product's complexity grows, it becomes more difficult to predict component failures using traditional methods. In the digital world, fault correction is considerably easier, cheaper, and faster than in the physical world. A digital twin enables the identification and virtually elimination of all future output hazards before the product enters into production, hence ensuring that the physical twin will function as planned.
- Optimizing solutions and improved maintenance - A digital twin can predict defects and damage at various phases of the product life-cycle, allowing for more exact predictive maintenance scheduling. Faults in the system can be detected much earlier thanks to near-real time smart analysis of big data collected by multiple sensors monitoring the physical assets. With near-real time sensor data and predictive advice via machine learning and artificial intelligence, production efficiency improves, and maintenance expenses decrease. The continuous feedback loop between a digital twin and its physical equivalent can be used to constantly validate and improve the system's process.
- More customized products and services - A digital twin allows for more rapid adaptation to changing market trends and stakeholder preferences.
- Accessibility - Getting a near-real time, in-depth perspective of a huge physical system is typically challenging, if not impossible. Virtual replicas maintain constant remote control over their physical counterparts, collecting data from a variety of sources via sensors. By examining the obtained data, potential problems can be predicted and addressed in a timely manner. Hence, the benefit of a digital twin is that it may be accessed from anywhere, allowing users to remotely monitor and adjust system performance.
- Safer than physical counterpart - Digital twin's capacity to remotely access its physical counterpart and its predictive nature, can help to lessen the likelihood of accidents and dangerous breakdowns. This will ensure that risky, boring, and unclean jobs are assigned to robots, who will be controlled remotely by operators. In this way, operators can focus on actions that are more creative and innovative.

- Training and more effective teamwork - A digital twin can be utilized to create more effective and illustrative safety training programs than standard methods. Operators can be taught using a digital twin before working on a high-risk site or with hazardous machinery to lessen the risks. Process automation and access to system information 24x7 allows technicians to better utilize their time in enhancing synergies and inter-team communication, resulting in increased productivity and operational efficiency.
- Better documentation and communication - Digital twin construction requires data synchronization across several software programs, databases, hard copies, and other sources. Therefore, it can be used as a tool for communicating and documenting the physical twin's behavior and mechanics. Near-real time information combined with automated reporting contributes to keep stakeholders informed, thus improving transparency.

In the context of digital twin benefits in cultural heritage, the following can be emphasized. The benefits of applying the digital twin concept in the cultural heritage domain are mainly for preservation purposes of cultural heritage buildings. Recently, there have been initiatives regarding energy efficiency of historical buildings within the sustainable development framework of modern cities. Predominantly, cultural heritage can benefit from digital twin technology in the maintenance domain together with predictive tasks of determining the influence of environmental conditions as well as natural events such as earthquakes on heritage sustainability. A digital twin improves the relationship between the digital model and the physical domain of heritage assets by merging digital replicas with near-real time operational data from on-site sensors using IoT infrastructure. The major benefit of a digital twin is its ability to automate some processes related to early detection of threat, risk assessments, solution identification, and impact assessment. Thus, in the cultural heritage domain, deploying digital twins allows decision-makers to remotely monitor and observe structure performance in near-real time and focus attention on the most critical parts of the system. This saves the time it takes to gather the information decision-makers need, improving the ability to predict when maintenance is needed and responding quickly to damaged systems. As a result, the rate of degradation and the negative consequences of failures are reduced, the resulting loss of relevance is avoided or at least lowered, and the need for intervention and the expense of conservation work are decreased. Digital twin technology in cultural heritage also allows for availability, accessibility and transparency in documentation and communication via intelligent and semantically enhanced 3D representation.

Although the initial costs of creating a digital twin of cultural heritage wealth is beyond comprehension small steps need to be undertaken in that direction. By allowing virtualization of maintenance tasks future costs can be marginally minimized and solutions to problems optimized.

On the other hand, there are issues involved with the creation of digital twins. These challenges vary in terms of size, application domain, and complexity of a digital twin, but there are a few that are constant [29, 30, 31, 9]:

- IT infrastructure – The proper operation of a digital twin depends on a well-designed and scalable IT infrastructure that allows for near-real time two-way communication and data exchange between the physical item and its digital twin. For near-real time processing of available data and efficient management of the indispensable sensors connected to digital twin, up-to-date hardware and software components, as well as fast, reliable, and available connectivity in various locations, are required.

- Useful data – A digital twin works with large amounts of data from various sources that have multiple dimensions and scales. Product data, environmental data, network, hardware and software related data, historical data, real-world data, virtual-world data, management data, customer data are all examples of data sources. Data collection and management are essential components of digital twin adoption. The effective utilization of digital twins necessitates the extraction of useful data from a large amount of heterogeneous data and the discovery of previously unknown patterns.
- Privacy and security - When designing a digital twin, privacy and security are critical factors to consider in order to be secured from hacking and viruses, thus preventing the destruction of critical information relating to the physical environment.
- Trust - The adoption of digital twins will necessitate the development of trust. Security and privacy, as well as an understanding of the benefits of digital twins and their ability to work as intended, are all necessary for establishing trust in the concept of digital twins.
- Expectations – Organizations will embrace digital twin technologies if they have adequate IT infrastructure and a better understanding of data required for analytics.
- Standards and regulations - Modeling is crucial for a digital twin to be used in practice. Because there is no standard for how each model should be created, a consistent methodology is required from the early design phase through the simulation of a digital twin. In addition to standardized modeling, standardizing interfaces, protocols, and data are critical for effective third-party communication, product and human safety, data security, and integrity, among other things.
- Design modelling - For future efficient usage of the digital twin concept, guaranteeing that domain use information is transmitted to each of the development and functional stages of a digital twin's modeling is crucial.

In the domain of cultural heritage, the major challenges are presented as follows. One of the major issues is obtaining adequate communication and computing technologies that can facilitate, for example, preservation tasks. In particular, the process of data collection and data storage over a long period of time can be challenging as performance of these tasks is in direct correlation with the success of cultural heritage digital twin performance. In order to develop predictive tasks computing power is needed, especially if near-real time predictive tasks are required. Another challenge is regarding unification of protocols and standards used in the wide range of technologies and tools that are used and developed by different entities. Data and models used in cultural heritage should be standardized by using common standards, formats and protocols.

5. Conclusion

The expansion of digitalization has resulted in grouping together already existing technologies such as 3D modeling, prototyping, and simulation of the system and labeling it digital twin technology. Researchers in the pre-digital-twin cultural heritage domain have used tools and digital techniques as a way to preserve historical and religious buildings but it was not the most cost-effective and efficient process since it lacked integration. Digital twin technology emerges as inevitable progress of the virtual and physical worlds coupling and providing integrated solutions to monitoring, diagnostic, predictive and optimizing tasks. Even though digital twin technology is used successfully in many different fields, the cultural heritage domain has yet to experience its full impact. To provide sustainable management of a cultural heritage environment most stakeholders involved need information to support the decision making process. This is done through integration of HBIM model and management process data implementing forecasting performance management in cultural heritage. Still, there is a global under-investment in digital twin technology in cultural heritage and the question of whether the digital twin concept can be sustainable in the management of cultural heritage environment.

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