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A DIGITAL TWIN THEORETICAL MODEL FOR HERITAGE SITE MANAGEMENT

Masud Hatami* and Turgay K. Koramaz

Urban and Regional Planning at Istanbul Technical University, Turkey.

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Abstract: As cities face population growth and infrastructure challenges, adapting to modern technologies is crucial. Particularly, the renewal of technology-supported infrastructures within smart cities leads to significant changes in urban areas. The management system of cultural heritage sites, like other urban areas, undergoes various transformations under the influence of digital transformation. Digital Twin technology offers significant opportunities for the creation and detailed analysis of large-scale knowledge bases for conservation policies in cultural heritage areas. This article searches for the theoretical basis of a prospective Digital Twin technology in cultural heritage sites, focusing on the development of a fundamental model for creating digital replicas of the physical assets. The aim is to provide a framework for leveraging Digital Twin technology in the management systems of cultural heritage sites. In this context, an alternative model is proposed by recommending the establishment of a digital information system, with the aim of enabling the continuous monitoring of indicators related to each proposed action in the management of cultural heritage sites. The parameters of the management system are identified as key factors of this method, with sustainable preventive conservation and the realization of potential predictions being defined as the main characteristics targeted by this method.

Keywords: Digital Twin, Smart Cities, Cultural Heritage, Sustainable Management

* Correspondence to: Masud Hatami. E-mail: masud.hatami@itu.com.tr

INTRODUCTION

The Digital Twin (DT) is defined as the virtual model of the real-world behavior and outcomes of a physical product or service (Qi *et al*., 2021). It is known not as a specific technology, but as a concept involving the integration of all processes, elements, and multiple technologies (Liu *et al*., 2021). Recently, the concept of the DT has started to be applied in the context of cities, particularly in smart city environments and applications (Ketzler *et al*., 2020; Camero *et al*., 2019).

Cities leverage digital technologies and integrated systems such as the Internet of Things (IoT), Artificial Intelligence, and data analysis solutions to achieve sustainability goals (Kaur *et al*., 2016). In Goal 11 of the United Nations Sustainable Development Goal, Sustainable Cities and Communities, the United Nations emphasizes making cities inclusive, safe, resilient and sustainable. This goal aims to "strengthen efforts to protect and safeguard the world's cultural and natural heritage." In recent years, steps have been taken to enhance the preservation of cultural heritage more effectively by digital technologies (Jouan & Pierre, 2020). The application of digital technologies in the field of cultural heritage conservation has yielded efficient results in recent years (Gabellone, 2022).

With the widespread use of information technologies, cultural heritage conservation has increasingly evolved into digital intelligence, becoming the focal point of preservation efforts (Xin *et al*., 2023). DT studies are effectively utilized in planning and conducting restoration and conservation works, just as in the industry. Instead of relying on current conservation planning predictions, cloud-based DT can be used to simulate different restoration and conservation scenarios, allowing conservation experts to choose the best approach for a specific object or area (Bruno *et al*., 2022; Ni *et al*., 2022; Chen and Cristiano, 2020).

The "Recommendation of 10/11/21 on a common European data space for cultural heritage" highlights the importance of digital technologies in enabling cultural heritage institutions to digitize their assets and reach wider audiences, thereby enhancing access to and discovery of cultural assets. It also emphasizes the importance of reusing these assets for innovative and creative services, including digital twins and monitoring technologies providing resilience to climate change and preventive conservation. Areas such as data management, decision-making, intelligence, visualization, and networking are among the critical issues requiring urgent solutions. To address these challenges, the DT for Cultural Heritage offers a significant approach. The integration of cultural heritage with digital technologies is built on continuous accumulation to provide technical support (Hermon *et al*., 2024). It is crucial to establish a foundational system for historical urban areas to perceive and highlight the impact and importance of DT studies in cultural heritage sites.

This paper aims to establish the theoretical foundation of DT technology, a critical component of digital management systems used effectively in cultural heritage sites, and focuses on the design of a model for developing digital replicas of physical assets. In addition, this study focusses to monitor the tracking, inquiry, and mapping of indicators related to each proposed action in the management of cultural heritage sites. In this context, an alternative model is presented by proposing the establishment of a digital urban information system.

Digital Twin and smart cities

The concept of DT was first applied in the aerospace industry. In the 1960s, NASA introduced the idea of a "digital twin" as a "living model" of the Apollo space mission, using simulators and a physical model of the spacecraft to evaluate the effects of an oxygen tank failure (Glaessgen *et al*., 2012). Kritzinger *et al*. (2018) categorized categorized DT based on the level of complete and reciprocal data integration between virtual and physical counterparts. DT create dynamic digital simulations by combining artificial intelligence, machine learning, and data analytics. These models learn and update from various sources, predicting the current and future states of their physical counterparts (Lu *et al*., 2020). While effectively used in the industry, this technology has also recently been employed in other sectors such as aviation, automation, maritime, healthcare, and energy (Enders *et al*., 2019). The broader adoption of DT technology is attributed to the advancement of virtual simulation technologies alongside advanced digital technologies like data collection and virtual production (Zheng *et al*., 2019).

By emphasizing digital technologies in urban environments, it is planned to strengthen monitoring and management systems. Innovative digital technologies also enhance the development of critical urban functions and infrastructures such as energy, water, and transportation (Gabrys., 2014; Lea *et al*., 2015; Olivares *et al*., 2013). DTs are precise virtual representations of physical assets that use interconnected digital information from sources like geographic information sensors, satellites, drones, and other sources to reflect reality. DT consist of three core functions: prediction (examining a system's behavior before its actual operation), monitoring (real-time status monitoring and control of the system), and diagnosis (analyzing errors after the system's operation). Moreover, DT leverage multiple technologies to understand (past), predict (future), and observe (real-time) their physical counterparts (Correia *et al*., 2023).

A city's DT is a system of interconnected DT representing specific aspects of the urban environment's operation and development (Ivanov *et al*., 2020). DT support fine-tuning and synchronization with the real state of urban infrastructure through real-time data from various sources (Ruohomäki *et al*., 2018). The continuous flow of data generated from different sources within the smart city's digital infrastructure is key to the effective operation of the city's DT (Jafari *et al*., 2023). This evolving technology allows for the monitoring, analysis, and development of physical prototypes in three stages: initially, various sensors and devices collect data to visualize the state. Then, smart software evaluates the collected data and proposes multiple solutions for each potential issue. Finally, intelligent algorithms select and implement the most suitable solution (Ćosović & Maksimović, 2022). This application is known as a complex system and time-consuming procedure involving the collaboration of many technologies and tools (**Table 1**).

In the literature, DT studies for cities are addressed across five different themes: data management, visualization, situational awareness, planning and forecasting, integration, and collaboration. Through these themes, the potentials and use cases provided and perceived by DT become comprehensible (Shahat *et al*., 2021).

Digital Twin and cultural heritage

DT technology used in cultural heritage sites often plays a critical role in creating data-driven, effective and long-term strategies for conservation planning and policies. DT studies offer various effective solutions to various challenges encountered within the framework of management systems prepared for the protection of cultural heritage sites. DT technology also has positive effects on the objectives of management plans for cultural heritage sites (such as transportation systems, cooperation and participation, environment, tourism, conservation interventions, infrastructure and risk).

Recent advancements in technology have led to a more streamlined development process for creating DT for cultural heritage. While earlier 3D scanners and photogrammetry required experts to manually integrate thousands of different images, current close-range imaging applications can produce the appearance of relatively flat surfaces quickly and automatically (Karami *et al*., 2022), and can increase functional skills and immersive sense better with artificial intelligence applications. These areas are:

- Smart: How artificial intelligence is embedded in nearly all technologies and creates entirely new categories.
- Digital: Merging digital and physical worlds to create immersive environments.
- Mesh: Leveraging the expanding connections among people, businesses, devices, content, and services.

According to Gartner (2019), the most important digital technological trend of 2019 was identified as "Digital Twin". By 2024, among the top 10 technological trends, "*Preserve the Future: Sustainable Technology*" was recognized as the third most significant strategic technology trend (Gartner., 2024). The importance of DT in historical urban areas can be evaluated from many perspectives. DT, as digital representations of physical entities, offer innovative solutions for the preservation, management, and development of these areas. In Shahat's (2021) study on "*Digital Twin Potentials of Cities*," the core

Table1. Technologies effectively utilized in DT.

Technology	Explanation
Geographic Information and Application Technologies	In cities, research and mapping technologies are divided into two main components: investigating the city's topography, environment, and spatial structure; and mapping this information into an integrated system based on Geographic Information Systems (Yao *et al*., 2019).
Virtual Reality Modeling Technologies	DT technology transforms the physical city into a mirrored city, making it dismantlable, replicable, transferable, modifiable and re-operable. Furthermore, it involves the process of converting physical elements into digital representations that can be processed, analyzed, and managed by computers (Olfat *et al*., 2019).
5G Integrated Technologies for IoT and Physical Objects	IoT technology is recognized as the foundation for the collection of dynamic data involving acquisition control and sensing processes, as well as for the transmission of feedback (Grimaldi *et al*., 2019).
Blockchain and Information Management Technologies	Blockchain is a cryptographically linked and continually expanding list of records. Each block contains the cryptographic hash of the previous block, a timestamp, and transaction data (Mistry *et al*., 2020).
Data Communication Technologies	Various connection protocols are available for data flow between physical space and DT, as well as for communication within cyberspace among different software systems (Kavitha *et al*., 2020).

Table2. Outputs of DT technology

Topic	Application	The Importance of DT in Smart Cities	The Importance of DT in Cultural Heritage Areas
Data Management	• Data Processing • Collaboration • Integration • Open Source Software	• Enhanced Visibility • Optimization of Operation and Reduction of Energy Consumption • Increased User Interaction • Real-time Remote Monitoring and Control • Improved Efficiency and Safety • Better Documentation and Communication • More Efficient and Informed Decision Support System • Scenario and Risk Assessment	• Faster Production Time and Product Redesign • Reduction of Costs and Waste • Prediction of Issues and System Planning • Optimization of Solutions and Improvement of Maintenance • More Customized Products and Services • Accessibility • Safer Than Physical Counterparts • Training and More Effective Teamwork • Better Documentation and Communication
Visualization	• Real-Time 3D Experience • Multidimensional and Temporal Scales • Unified Platform • Behavior Modeling		
Situational Awareness	• Monitoring • Mapping • Analysis		
Planning and Forecasting	• Policy Evaluation • Simulation		
Integration and Collaboration	• Information Sharing • Collaborative Analysis • Joint Operations • Open Platforms		

characteristics of the final dataset obtained from various sources were examined under five main headings, and the applied features were explained. The **Table 2**, illustrates these features and underscores the importance of DT in both smart cities and cultural heritage areas.

The International Council on Monuments and Sites (ICOMOS) has identified eight distinct threats to cultural heritage sites. These threats include rapid demographic changes, climate change, natural disasters, and issues related to excessive tourism. Due to the complex and multilayered nature of these threats, the protection and effective management of cultural heritage necessitate the acquisition of accurate and diverse information. DT projects have increasingly been employed to create this database. DT offer planners and designers' various scenarios that not only address contemporary needs but also aid in preserving cultural heritage from a spatial planning perspective (Maksimović & Cosović, 2022).

In conclusion, DT are indispensable tools for decision-makers because they integrate heterogeneous data and information to provide interactive three-dimensional models of urban assets supported by real-time information. This capability facilitates more informed and effective decision-making in areas such as urban planning, infrastructure management, and emergency response. Additionally, these technological advancements enhance transparency by increasing citizen engagement in urban development processes in a more active and informed manner. Digital twin technology is utilized not only in cultural heritage sites of various scales but also in structures from different historical periods. In this context, **Table 3** shows some examples applied within the framework of DT technology.

The important benefits of the DT study for cultural heritage sites as follows:
In the context of the DT study, various benefits are derived based on the 9th (Industry, Innovation, and Infrastructure) and 11th (Sustainable Cities and Communities) Sustainable Development Goals set by the United Nations. The benefits based on the 9th Sustainable Development Goal include: the creation of decision support systems, optimization and control of processes, increased opportunities for preventive intervention, and the enhancement of quality of life in the area by reducing the impact of adverse environmental factors on heritage sites. Additionally, based on the 11th Sustainable Development Goal: ensuring smart city infrastructure within cultural heritage sites, safeguarding various dimensions of heritage sites through integrated and effective planning with innovative methods, continuous monitoring, flexibility, forecasting, and prediction criteria, identification of effective and cost-efficient smart solutions, preparation of data-driven simulations through big data formation, achieving high levels of participation in preservation and revitalization projects through digital methods, and coordinating interdisciplinary activities aimed at the preservation of cultural heritage sites are identified as prominent benefits (Yao *et al*., 2019; Olfat *et al*., 2019) . Also, DT studies facilitate the adaptation of smart infrastructure successfully implemented in smart cities to cultural heritage sites, thereby enabling the achievement of targeted outcomes through the use of digital

Table 3. Examples of DT applications.

DT in Smart Cities		DT in Historical Urban Areas	
Cities	Highlights	Cities	Highlights
Helsinki, 2019	The project aims to create high-quality DT city models for Kalasatama and share them as open data, serving as a platform for the entire lifecycle of the built environment (Airaksinen *et al*., 2019).	Bradford, 2022	The study covering the city center serves purposes such as planning, monitoring air pollution and traffic, and providing historical tours that showcase the city's past appearance (Digital Strategy for Bradford., 2022).
Rotterdam, 2020	It is effectively used in advanced urban planning, efficient infrastructure management, and enhanced environmental monitoring (Wu *et al*., 2021).	Florence, 2022	The Snap4City platform uses its data repository to integrate data into the city's 3D virtual entity, enabling various interventions in the digital environment, including infrastructure and energy management (Adreani *et al*., 2024).
Newcastle, 2022	The DT project enables real-time testing of the city's infrastructure in response to emergencies (Newcastle Digital Twin., 2019).	Bologna, 2023	The DT model for Bologna, prepared by REbuild Italia in 2023, not only reproduces the urban fabric but also provides an infrastructure for decision-makers (Bologna Digital Twin., 2023).
Singapore, 2023	World's first city-scale digital twin, Virtual Singapore, improves energy consumption, traffic flow, and facilitates urban development planning. Covering everything from bus stops to buildings, it is a data-rich and living digital twin (Dassault., 2019).	Historic Center of Vienna, 2020	Vienna's historic center features a DT used for urban planning and preservation. It helps evaluate the impact of new construction projects on the historical environment and aids in preserving the city's architectural heritage (Lehner *et al*., 2020).
Boston, 2018	The project assesses climate change impacts on urban infrastructure, optimizes maintenance, visualizes development projects, and promotes energy efficiency and sustainability (Tuchen *et al*., 2022).	Venice, 2023	Digital tools in Venice monitor water levels, preserve architecture, and aid in tourism and disaster management. The Urban DT enhances safety and efficiency by modeling and analyzing city systems (Rocca *et al*., 2023).

technologies in these areas (Bruno *et al*., 2022; Ni *et al*., 2022). DT leverage digital technologies and integrated systems such as the IoT, artificial intelligence (AI), and data analytics solutions to achieve sustainability goals[5]. Leveraging this technological advancement, the emphasis on digital technologies in cities is recognized as providing significant benefits in strengthening continuous monitoring and management systems (Jouan & Pierre, 2020; Xin *et al*., 2023). On the other hand, DT technology enables the integration of linked digital information from geographic information sensors, satellites, drones and other sources, along with the creation of a virtual replica of cultural heritage sites. This integration allows for effective analysis in heritage sites. The technology supports the management and preservation of heritage areas by creating digital models of physical heritage sites. Particularly, by integrating with geographical information systems and other data sources, detailed examinations of heritage sites can be conducted, making planning processes more efficient (Jafari *et al*., 2023). Finaly, DT technology is not limited to the protection of cultural heritage sites, but offers a variety of services in economic, social, cultural and other dimensions. This technology offers economic benefits by increasing tourism activities, expanding educational and research opportunities, and improving the management of heritage areas through digital reconstruction. Furthermore, it brings social and cultural gains by enhancing public access to cultural heritage, strengthening the sustainability of heritage, and adopting modern management practices required by the digital age (Xin *et al*., 2023).

By considering the importance of DT studies, this research will catalyst to the adaptation and preservation of heritage sites in the digital age. Adreani *et al*., (2023) identifies three key procedures in the DT processes of smart cities. The alignment of these procedures with the cultural heritage sites can be described through the following method:

- Data Acquisition: In this phase, an inventory of the physical assets of cultural heritage sites will be created, and data collection methods for each asset will be defined separately. The Data Center (DC) and the Digital Services Center (DS), as outlined in the methodology section, will form the core components of this phase. The Data Center (DC) will facilitate the collection of data from various sources into a single

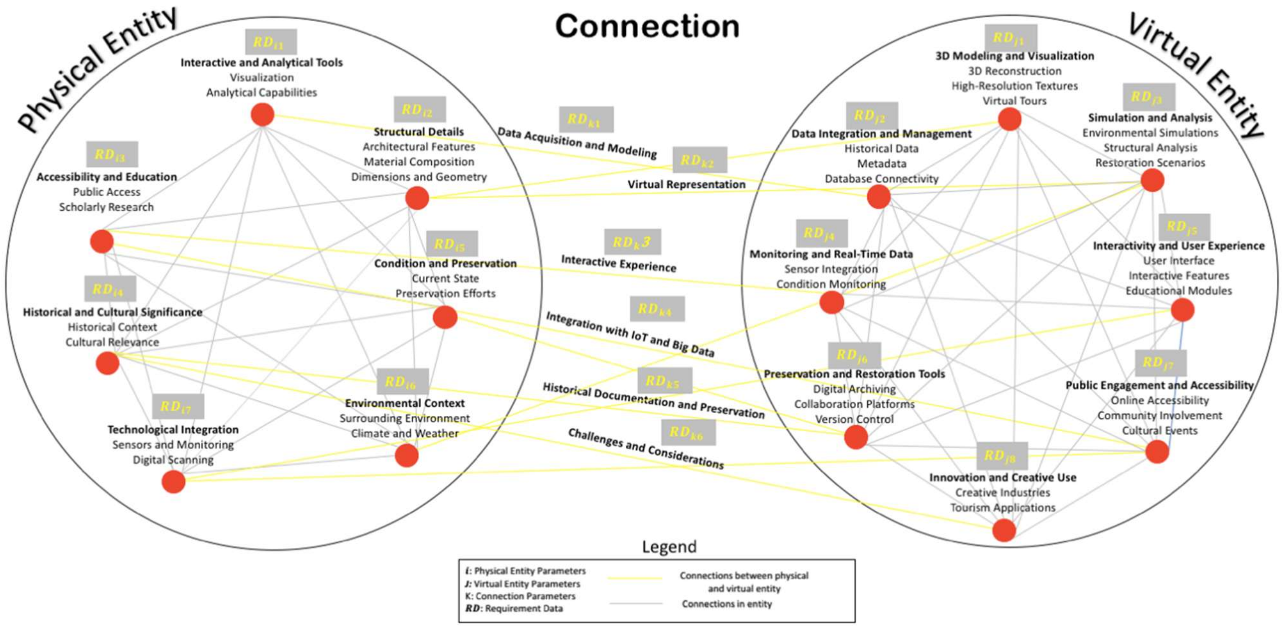

Fig. 1 DT model basic dimensions.

platform during the DT application process. The Digital Services Center (DS) will encompass functions such as environmental monitoring and control, structural monitoring and reinforcement, restoration, hazard simulation, and conservation planning.

- Production: In this phase, the data collected at the Data Center (DC) regarding the physical assets of cultural heritage sites will be processed and analyzed. The Data Operation Center (DO) is a user-focused service terminal that encompasses the necessary data, models, algorithms, and simulations required for the DT application process.
- Integration and Distribution: The analyses and activities derived from the Data Operation (DO) are aggregated within the Virtual Entities (VE) dimension, providing real-time capabilities for monitoring and managing the actual dimensions. In the final stage, potential scenarios emerging from the Virtual Entities Center are communicated to the Decision Making (DM) bodies, facilitating rapid intervention opportunities without delay.

METHODOLOGY

This paper develops a theoretical framework for DT technology in cultural heritage sites, focusing on creating digital replicas of physical assets. This framework not only enables the digital reconstruction of assets, but also explores how DT technology can be used effectively in cultural heritage sites by examining the theoretical underpinnings of this process in detail. This chapter aims to discuss the model and the technical process in detail. The core framework of the model is based on the objectives of the management system for heritage sites, the challenges encountered in achieving these objectives, and the digital technologies proposed to address these challenges (**Fig. 1**).

Ketzler (2020) defined three main layers in his Smart City Digital Twin: The first layer is the City Information Model, which includes heterogeneous data types such as buildings, maps and sensor data. The second layer covers basic functions and communication, and can realize analytics and software applications, enabled by an appropriate IoT/IoE platform that can manage big data. The last layer focuses on visualization and deployment through 3D engines and web applications. In Grieves (2017), DT models are considered as a three-dimensional model that includes a physical entity (Physical Entity), a virtual entity (Virtual Entity) and the connections between them.

Based on the basic structure of this theoretical model, Tao in China proposed a five-dimensional model including physical assets, virtual assets, services, twin data, and the links between them. In addition, Qi (2019) discusses the enabling technologies for DT studies in five different sections. These are Services, Connectors, Models, Physical and Data technologies. On the same basis, in 2024, Liu and Wang prepared a framework for the DT model of historical sites (Liu *et al.*, 2024). This framework is as follows:

$$\mathrm{DT}DT_{(HS)} = (PE_{(HS)}, VE_{(HS)}, DTS_{(HS)}, TDS_{(HS)}, CN_{(HS)})$$

Inspired by previous studies, the general management plan objectives for heritage sites form the core framework of this work. These objectives are listed as Management and Coordination, Conservation - Planning, Conservation - Restoration, Accessibility, Education, Awareness Raising and Participation, Visitor Management and Risk Management (Management Plan., 2018). Each objective is supported by specific strategies and actions, and various performance indicators have been developed to monitor and evaluate these actions. In the development of the model, it was firstly aimed to define the parameters (Physical Entity, Virtual Entity and Connections) covered by each action. Performance indicators play a key role in determining these parameters. The proposed model is intended to be flexible and updatable, and in this context, it is envisaged to keep the parameters dynamic in a way to be constantly compatible with technological innovations and current systems. Thus, the updating capacity of the model is increased with the integration of new technologies that may emerge in the future. The general framework for the first stage of the proposed DT theoretical model is detailed in **Eq. (1).**

$$\mathrm{DT}_{(\mathrm{CH})} = \sum_{i=1}^{n} \mathrm{PE}_{(\mathrm{CH})}\ [RD_i] + \sum_{j=1}^{m} \mathrm{VE}_{(\mathrm{CH})}\ [RD_j] + \sum_{k=1}^{p} \mathrm{CN}\ [RD_k] \quad (1)$$

PE: physical entity of cultural heritage areas
VE: virtual entity of cultural heritage areas
CN: connections among physical and virtual entity
RD: requirement data (variable parameters)
$\mathrm{RD_i}$: i are variable parameters of physical entities
$\mathrm{RD_j}$: j are variable parameters of virtual entities
$\mathrm{RD_k}$: k are variable parameters of connections (enabling and virtual technologies)

In the management plan, in addition to identifying the physical and virtual assets for the actions defined in line with each objective, it is of great importance to detail the factors and content of the "Connections" section, which is the most critical stage of the model. Links consist of enabling and virtual technologies, including all digital technologies used effectively for each action. In this context, the Connections phase is described in **Eq. (2)**, which is divided into four different categories. This stage plays a critical role in achieving the set objectives by enabling interactions between physical and virtual assets, data flows and integration of processes. The four factors proposed in the connection phase are the Data Center, Data Service, Data Operation, and Decision-Making process. Each factor establishes links between different components of the model, facilitating the collection, processing, and integration of data into the decision-making processes.

$$\mathrm{CN}_{(\mathrm{CH})} = \sum_{t=1}^{y} \mathrm{DC}_{(\mathrm{CH})}\ [RD_t] + \sum_{s=1}^{z} \mathrm{DS}_{(\mathrm{CH})}\ [RD_s] + \sum_{f=1}^{e} \mathrm{DO}_{(\mathrm{CH})}\ [RD_f] + \sum_{x=1}^{h} \mathrm{DM}_{(\mathrm{CH})}\ [RD_x] \quad (2)$$

DC: data center
DS: data services
DO: data operation
DM: decision making
$\mathrm{RD_t}$: t are variable parameters in data center
RD_s: s are variable parameters in data services
$\mathrm{RD_f}$: f are variable parameters in data operation
RD_x: x are various decision making bodies
y, z, e, h: are the number of variable parameters

After defining the main components of the developed DT model—physical assets, virtual assets, and the connections between these two components—the structure of the main model was determined as shown in **Eq. (3)**. Based on the defined equation, the aim is to define and apply variable parameters for each action in line with the objectives set in the management plan, following the same methodological process.

$$\mathrm{DT}_{(\mathrm{CH})} = \sum_{1}^{a}\left[\mathrm{PE}_{(\mathrm{CH})} RD_i (\mathrm{DC_t}, \mathrm{DS_s}, \mathrm{DO_f}, \mathrm{DM_x})\right] + \sum_{1}^{b}\left[\mathrm{VE}_{(\mathrm{CH})} RD_j (\mathrm{DC_t}, \mathrm{DS_s}, \mathrm{DO_f}, \mathrm{DM_x})\right] + \sum_{1}^{c}\left[\mathrm{CN}_{(CH)} RD_k \left(\mathrm{DC_t}, \mathrm{DS_s}, \mathrm{DO_f}, \mathrm{DM_x}\right)\right] \quad (3)$$

$\mathrm{DC_t}$: data center and requirement data variable parameters
$\mathrm{DS_s}$: data services and requirement data variable parameters
$\mathrm{DO_f}$: data operation and requirement data variable parameters
$\mathrm{DM_x}$: decision making and requirement data variable parameters
a: is the number of variable parameters in physical entities
b: is the number of variable parameters in virtual entities
c: is the number of variable parameters in decision making bodies

Based on the three key components mentioned in Adreani's study (data collection, generation, integration and distribution), referenced in the previous section, the equation in our proposed theoretical model is framed within the context of these three components. **Fig. 2** shows in detail how the parameters of the model are structured within the framework of these three phases.

The Data Center, defined within the framework of the model under consideration, carries out the recording, classification and storage of data in a digital environment; it also ensures that preliminary analysis of each action is performed. The Data Service unit is responsible for integrating the data, performing final analyses and managing the creation of big data. The

Data Operation phase involves preparing interactive maps in collaboration with interdisciplinary experts, performing simulations in line with the analyses and transferring these data to virtual entities. Virtual Entity involves creating models and algorithms, comparing virtual and real assets and preparing data-driven protection plans. Finally, the Decision-Making phase aims to increase the possibility of rapid response, real-time monitoring, preventive protection, implement protection plans and adopt a digital management approach.

DT Theoretical Framework for the Istanbul Historic Peninsula

In Turkey's urban heritage areas, the effective use of digital technologies to develop a comprehensive method for digital preservation and usage based on DT has become essential. This study aims to create a technical framework for data collection and analysis using digital technologies within the scope of the IHP management plan objectives. As of 2024, among the 195 States Parties that have ratified the World Heritage Convention, Turkey has a total of 21 heritage sites, 19 of which are cultural and 2 of which are mixed. This

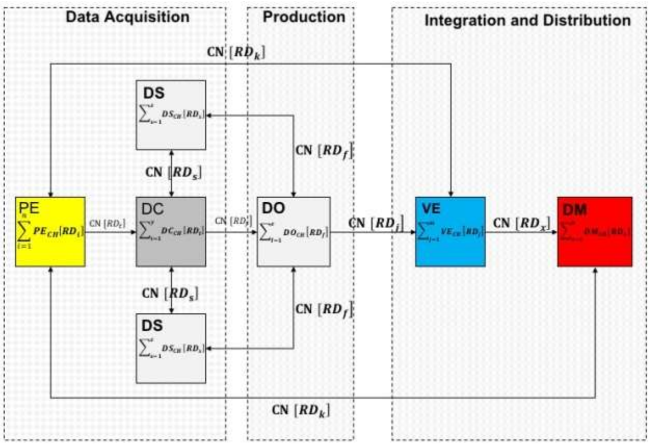

Fig. 2 DT model scheme for cultural heritage sites.

shows that Turkey has a very important position in the world heritage list. In addition, the historical peninsula of Istanbul, which was included in the list in 1985, is among the first sites from Turkey to be included in the list, emphasizing the importance of this area. Located at the intersection of Asia and Europe, Istanbul reflects a unique character with the collage of different layers and different urban textures that overlap as a result of the occupation of many different civilizations (Kubat & Ayşe Sema, 2018). The Historic Areas of Istanbul; Sultanahmet Archaeological Park, Suleymaniye Mosque and its Surroundings Conservation Area, Zeyrek Mosque (Pantocrator Monastery) and its Surroundings Conservation Area and Istanbul Land Walls, a core area of 765.5 hectares in total, were included in the World Heritage List in 1985 (**Fig. 3**). Management plans are plans that ensure the preservation of the outstanding universal value of an asset by considering sustainable and holistic approaches and that establish the link between conservation and evaluation and provide the opportunity to keep the asset alive (Gülersoy & Ayrancı, 2011). In 2005, the World Heritage Committee introduced the obligation to submit a management plan with the nomination dossiers of the sites to be included in the world heritage list in the Implementation Guide. Although the historical peninsula of Istanbul was included in the world heritage list in 1984, the management plan was prepared in 2011 and then updated in 2016 and 2018 within the scope of world heritage conventions and circulars (Management Plan., 2018). For the management plan prepared for the historical peninsula of Istanbul, 7 objectives, 30 strategies and 50 actions were identified. Monitoring and management of the actions are carried out through periodic reports.

In 2003, important issues related to the protection of digital heritage were discussed at the UNESCO session and this was emphasized as the beginning of a new era in the management system of cultural heritage sites. Since this turning point, the step-by-step development of the digital management approach in cultural heritage sites has become evident with the implementation of different projects. The most obvious example of this development is the effective use of Information and Communication Technologies (ICT) in various dimensions of cultural heritage management. In this context, Koramaz (2018) emphasized that ICTs play a critical role in increasing public sensitivity and historical orientation in cultural heritage management. In addition to being effective in different stages of the cultural heritage management process such as inventory, data collection, documentation, analytical assessments and communication, ICTs can promote economic and social convergence between different social classes in the use and access of technology. This new digital management approach has been increasingly adopted and implemented in recent years within the framework of DT technology.

DT technology, which has recently been used in the context of smart cities, has slowly started to take root in Turkey. For example, the Metro Istanbul DT Project and BİMTAS's use of drone imagery to transform the current situation into three-dimensional mesh models with up-to-date data are examples of these efforts. However, the fact that this technology has not yet been used effectively enough in cultural heritage sites is considered an important shortcoming. With the necessary steps taken to adapt this technology for the preservation of heritage sites in Turkey, it has become inevitable for our cultural heritage to align with the digital age.

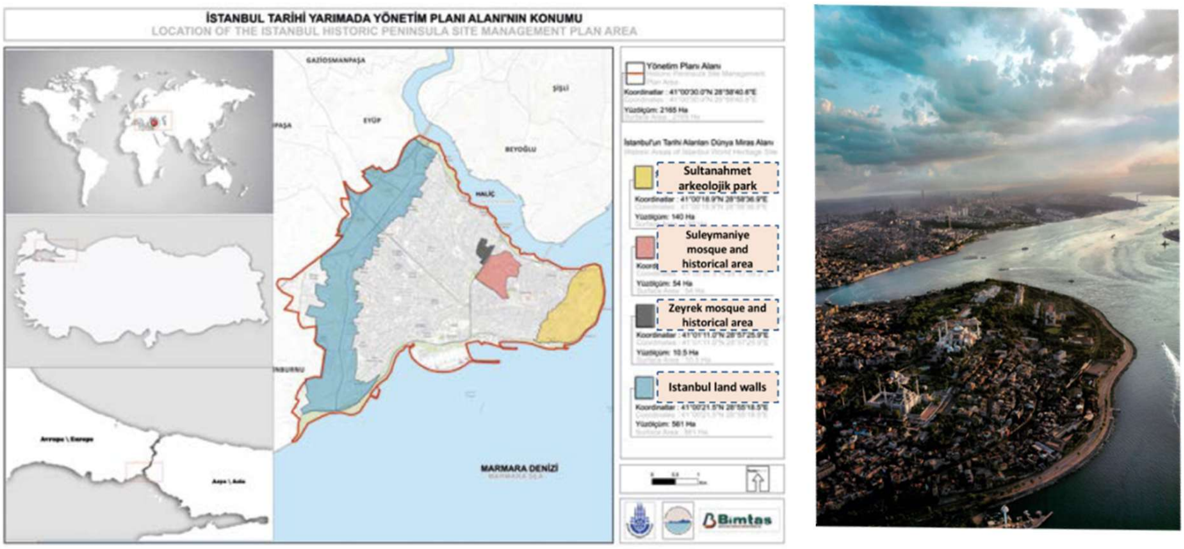

Fig. 3 The location of the historic peninsula.

The fundamental principle of this study is to facilitate the creation of a new digital management approach for heritage sites in Turkey by benefiting from innovative innovations and to operate in accordance with international digital working guidelines. In Florence (Adreani *et al*., 2024), in Broadford (Airaksinen *et al*., 2019), and in Dubrovnik (Pereira *et al*., 2018), efforts to gradually digitalize and utilize various aspects of DT technology in cultural heritage sites are ongoing. Similarly, in Turkey, it is inevitable to leverage these advancements and establish the foundations for digital management dimensions. Consequently, the integration of DT technology into a heritage site such as the Historic Peninsula of Istanbul is inevitable to support the digital transformation of the site and provide innovative solutions for its management and conservation. By creating a virtual replica of the Historic Peninsula, this technology can provide detailed modeling of the site and thus contribute to the development of management strategies.

Challenges in the management system of the historic peninsula and potential impacts of DT technology

The management system of the Historical Peninsula, despite being an area where Istanbul's cultural and historical heritage is most concentrated and a focal point for tourists, faces various challenges. As identified in the 2018 management plan, insufficient inter-institutional relationships and connections have adverse effects on the implementation of conservation plans. Additionally, other challenges include the low level of public participation in conservation plans, the lack of a strong culture of conservation and planning, and the insufficient provision of information and technical support in conservation processes. Furthermore, the inadequate and ineffective use of digital technologies in the area is particularly noteworthy. These issues not only diminish the quality of life for local residents but also negatively impact the preservation of the region's historical and cultural fabric. In this context, it is imperative to prioritize a digital management approach and effectively utilize innovative systems and technologies in the area.

Koramaz and Belli (2020) examined the impact of smart technologies on the Historic Peninsula of Istanbul. In this context, it was determined that some important technologically supported works have been realized in the Historic Peninsula. Among these studies, the realization of applications such as digital archiving and record creation processes, 3D Surface Models project using LIDAR technology, Web Based 3D Guide Application, various application projects for service purposes have played an important role in the formation of positive effects in the area. Although some technological studies have gained momentum recently, especially within the municipality and the site presidency, the fact that these studies are not integrated and not carried out in a planned manner in the site management system still does not have the necessary impact on conservation processes.

One of the effective technologies for ensuring that the management system of the Historical Peninsula is carried out within a planned process, minimizing the challenges faced in the area, and enabling the integrated implementation of all conservation plans is known as DT technology. This technology not only addresses existing issues but also allows for the identification of potential future problems in advance, facilitating the development of a proactive management strategy. Therefore, DT initiatives are expected to play a significant role in the sustainable management of the Historical Peninsula.

This technology has the potential to offer significant opportunities for optimizing management processes and detecting potential issues in advance within a complex and sensitive area like the Historical Peninsula. However, the implementation of DT technology in this context may encounter specific challenges. First, the data collection process necessary for the effective use of this technology may be limited due to the need to preserve the historical fabric and the area's geographical conditions. Additionally, integrating existing infrastructure with digital technologies could be time-consuming and costly. Second, the successful application of such technology requires collaboration with international experts and the sharing of knowledge. Finally, the sustainable updating and management of the DT model present another significant challenge.

To demonstrate the working methodology of the DT model developed for Istanbul's Historical Peninsula, Strategy 13 and Action 49, which fall under Visitor Management—one of the seven goals outlined in the management plan—have been selected for focus at this stage. Within the framework of Action 49, the parameters of Physical Assets, Virtual Assets, and Connections will be defined across the phases of Data Collection, Production, Integration, and Distribution. To determine these parameters, the goals and performance indicators associated with Action 49 in the management plan will first be thoroughly analyzed.

Scenario of the historic peninsula dt theoretical model: visitor management

According to data presented by the Istanbul Provincial Directorate of Culture and Tourism, Istanbul welcomed more than 17 million tourists in 2023 (**Fig. 4**). However, more than half of these tourists visited Istanbul's historical peninsula and cultural heritage sites. This has resulted in intensive tourism as well as negative environmental impacts. At the same time, the lack of sufficient digitalization and innovation in terms of visitor management has led to various problems. Therefore, DT technology can play an important role in providing innovative solutions for heritage sites by creating a DT Working Model for managing visitor management objectives based on digital data.

In order to test the DT model developed for the Historic Peninsula of Istanbul, the sixth objective of the management plan, visitor management, was addressed at this stage. The aim is to use the DT technology within the framework of the model to address the 13th strategy of the visitor management objective (to enrich and increase the quality of area experience of visitors). The general scope of this strategy is to enrich the site experience by presenting visitors with various scenarios. Action 49 (to define tour itineraries specific to the world heritage area and to include them in promotion documents) in the 13th Strategy is the area where we aim to implement the model.

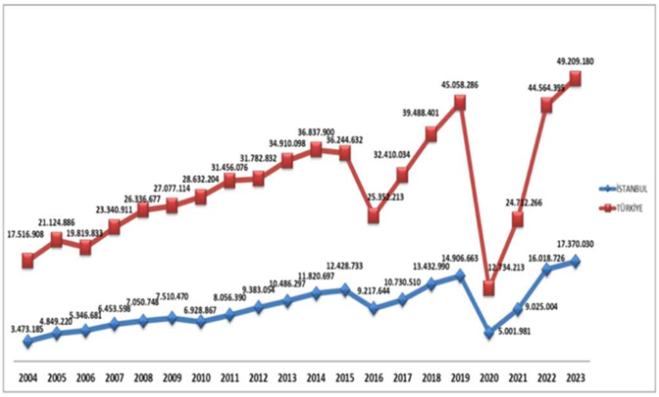

Fig. 4 Monthly number of foreign visitors between 2022-2024. (Istanbul Provincial Directorate of Culture and Tourism, 2024).

Visitor management ------▶ **Strategy 13** ------▶ **Action 49**

The general architecture of the DT model developed for the visitor management of the Historic Peninsula of Istanbul and how it works and how it is integrated with the various stages is explained in **Fig. 5**. As stated in the architecture of the proposed DT model, in order to build the model, it is first necessary to carefully define the parameters within its scope. The process of defining the parameters is based on the previously discussed equations for the model and the variables included in these equations. These equations enable the detailed modeling and integration of various physical systems in the virtual world.

The accuracy of the model depends on how accurately these equations and parameters are defined. Accordingly, the targets set for Action 49 on Visitor Management within the scope of the Historic Peninsula Management Plan will be used as the basis for determining the parameters in the equation.

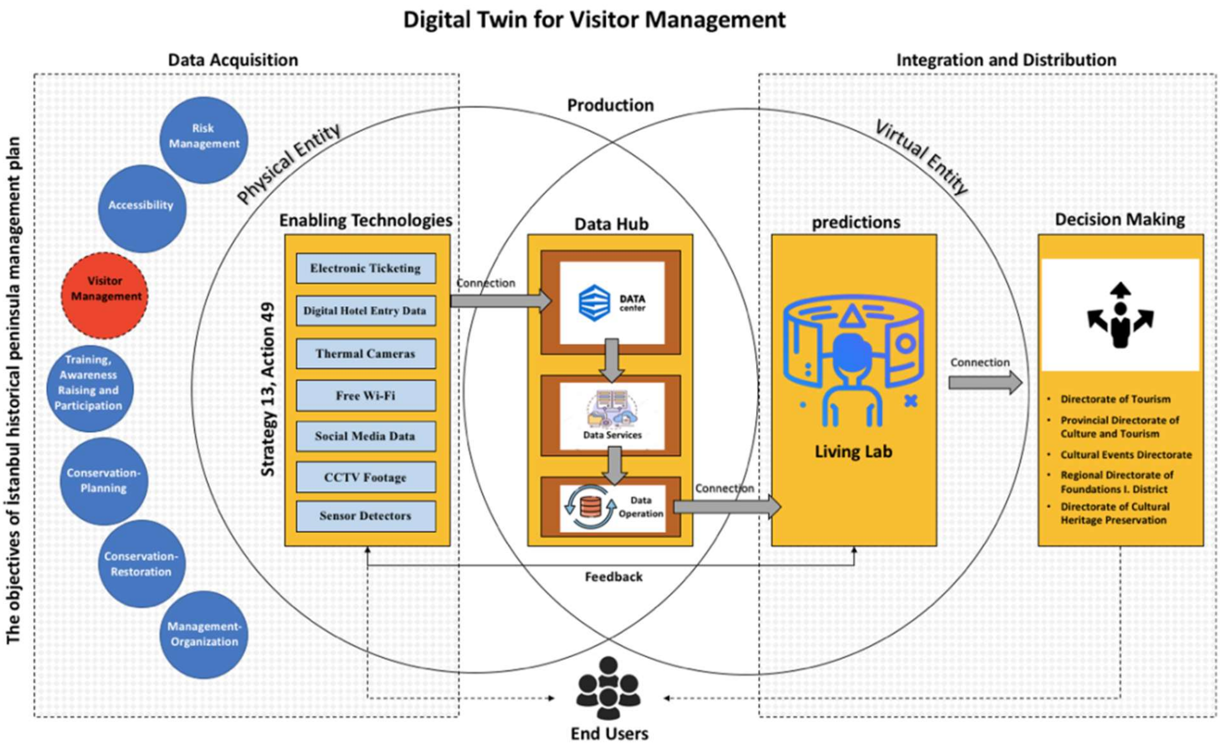

Fig. 5 Overview of the DT architecture for visitor management.

Four objectives were identified in Action 49. These are:

- Identification of alternative routes beyond the most visited locations in the area,
- Development of thematic routes throughout the management plan area and integration with the world heritage site,
- Development of various tour programs based on tourist profiles and lengths of stay,
- Inclusion of the developed tour programs in promotional document.

To measure the progress of the specified targets for this action, performance indicators such as the number of alternative routes, the number of thematic routes, and the number of trained tour guides specific to the World Heritage Site have been identified. These targets and performance indicators will be taken into account to define the parameters within the proposed model. In this way, the accuracy and effectiveness of the model will be enhanced, allowing for a more efficient monitoring and management of the process of achieving the targets.

Under the proposed model, the parameters defined for Action 49 are as follows

$$\mathrm{DT_{(CH)}} = \sum_{i=1}^{n} \mathrm{PE_{(CH)}}\ [RD_i] + \sum_{j=1}^{m} \mathrm{VE_{(CH)}}\ [RD_j] + \sum_{k=1}^{p} \mathrm{CN}\ [RD_k]$$

Where:

RD_i: i1. Museums, i2. Exhibitions, i3. Mosques, i4. Palaces

RD_j: j1. Development of predictive models and algorithms, j2. Comparison of predicted routes, j3. Application of predictive model studies

RD_k: k1. Electronic ticketing, k2. Digital hotel entry data, k3. Thermal cameras, k4. Free Wi-Fi, k5. Social media data, k6. CCTV footage, k7. Sensor Detectors, k8. Drone surveillance system

$$\mathrm{CN_{(CH)}} = \sum_{t=1}^{y} \mathrm{DC_{(CH)}}\ [RD_t] + \sum_{s=1}^{z} \mathrm{DS_{(CH)}}\ [RD_s] + \sum_{f=1}^{e} \mathrm{DO_{(CH)}}\ [RD_f] + \sum_{x=1}^{h} \mathrm{DM_{(CH)}}\ [RD_x]$$

Where: $\mathrm{DC_{(CH)}}\ [RD_t]$: t1. Determination of Museum Entry Data, t2. Identification of Occupancy and Vacancy Routes, t3. Measurement of Visitor Behavior, t4. Preliminary Analyses

$\mathrm{DS_{(CH)}}\ [RD_s]$: s1. Formation of Big Data, s2. Integration of Data, s3. Final Analysis

$\mathrm{DO_{(CH)}}\ [RD_f]$: f1. Visualization of Data, f2. Execution of Predictive Simulations, f3. Transfer of Simulations to Virtual Environment

$\mathrm{DM_{(CH)}}\ [RD_x]$: x1. Directorate of Tourism, x2. Cultural Events Directorate, x3. Provincial Directorate of Culture and Tourism, x4. Regional Directorate of Foundations I. District, x5. Directorate of Cultural Heritage Preservation

The explanations regarding the stages and applications of the equation used in the proposed DT model are depicted in **Fig. 6**. This figure details the role of the equation within the model process and illustrates how it is integrated at each stage.

After the first and second equations define the parameters considered within the scope of Action 49's DT model, these parameters will be brought together in the third equation to complete the DT model. In this process, each parameter is categorized into different categories: physical entities, virtual entities and connections. The third equation shows how these categories interact with each other and form the overall structure of the model. Thus, the DT model will be presented as a concrete solution for the visitor management objectives of IHP.

In line with Action 49 of Strategy 13, it is aimed to determine tour routes in world heritage sites and include them in promotional documents. The purpose of including this action within the scope of the DT is to control the negative environmental impacts on heritage sites by monitoring the flow of visitors, determining the routes and distributing the density within the framework of the DT project. The hypothesis of this action is to suggest that negative impacts on cultural heritage sites can be controlled through early intervention by digitally classifying the occupancy-vacancy rates and determining the routes of visitor flow. It is also aimed to direct visitors to different museums, prevent negative impacts by controlling occupancy rates, adopt a preventive conservation approach, maximize security issues and implement the concept of sustainable tourism in line with SDG targets. **Figure 6** shows in detail how the first set of parameters (t1, s1, f1, j1, x1) defined under Action 49 are processed within the framework of the DT model. Each of these parameters represents a specific data flow and interaction within the model. The figure discusses how these parameters are integrated into the DT model, how the relationships between them are established and how they ultimately contribute to the integrity of the model (**Fig. 7**).

Once all the variables related to the action determined within the framework of the model have been defined, the process of collecting and processing the data related to these variables will be initiated. In this process, data acquisition methods for each variable will be carefully considered and measurement methods will be shaped accordingly. In the data collection phase, a comprehensive data set will be created by considering the current status of physical assets, digital representations of virtual assets and the links between these two types of assets. In this way, all the metrics required for the successful implementation of the action will be clearly identified and integrated into the DT model.

$$\mathbf{DT_{(CH)}} = \underbrace{\textstyle\sum_1^a[\mathbf{PE_{(CH)}}\boldsymbol{RD_i}(\mathrm{DC_t, DS_s, DO_f, DM_x})]}_{1} + \underbrace{\textstyle\sum_1^b[\mathbf{VE_{(CH)}}\boldsymbol{RD_j}(\mathrm{DC_t, DS_s, DO_f, DM_x})]}_{2} + \underbrace{\textstyle\sum_1^c[\mathbf{CN_{(\mathit{CH})}}\boldsymbol{RD_k}(\mathrm{DC_t, DS_s, DO_f, DM_x})]}_{3}$$

$$\textstyle\sum_{i=1}^{4}[\mathbf{PE_{(CH)}RD_{i1,i2,i3,i4}}(\mathbf{DC_{t1,t2,t3,t4}}, \mathbf{DS_{s1,s2,s3}}, \mathbf{DO_{f1,f2,f3}}, \mathbf{DM_{x1,x2,x3,x4,x5}})] \quad (1)$$

$$\textstyle\sum_{j=1}^{3}[\mathbf{PE_{(CH)}RD_{j1,j2,j3}}(\mathbf{DC_{t1,t2,t3,t4}}, \mathbf{DS_{s1,s2,s3}}, \mathbf{DO_{f1,f2,f3}}, \mathbf{DM_{x1,x2,x3,x4,x5}})] \quad (2)$$

$$\textstyle\sum_{k=1}^{8}[\mathbf{PE_{(CH)}RD_{k1,k2,k3,k4,k5,k6,k7,k8}}(\mathbf{DC_{t1,t2,t3,t4}}, \mathbf{DS_{s1,s2,s3}}, \mathbf{DO_{f1,f2,f3}}, \mathbf{DM_{x1,x2,x3,x4,x5}})] \quad (3)$$

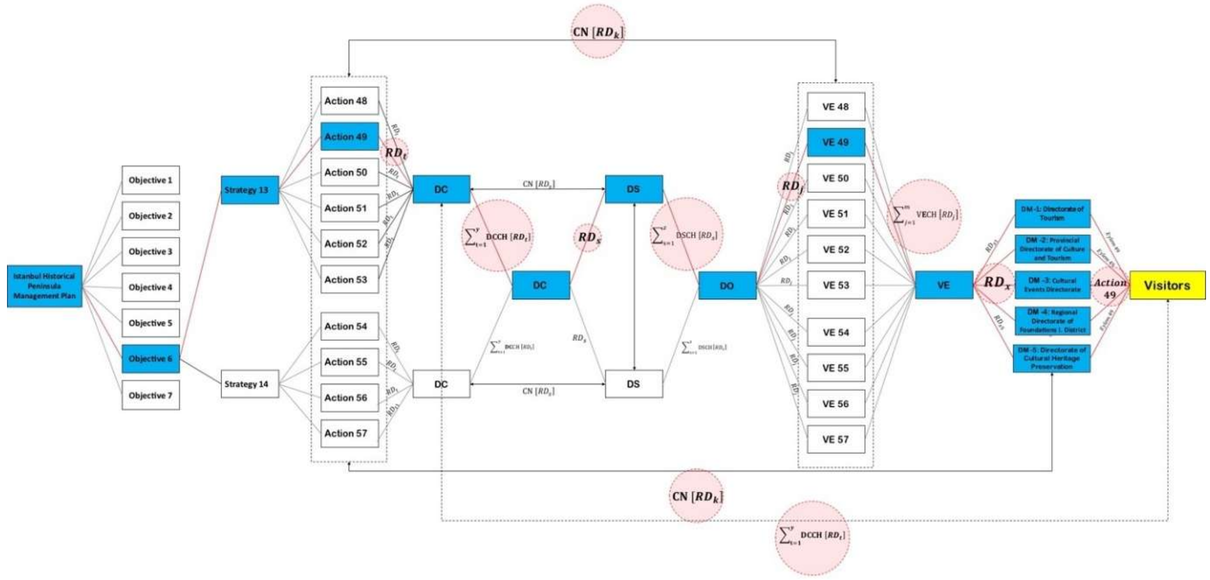

Fig. 6 Visitor management framework for the DT approach in the Istanbul Historical Peninsula management plan.

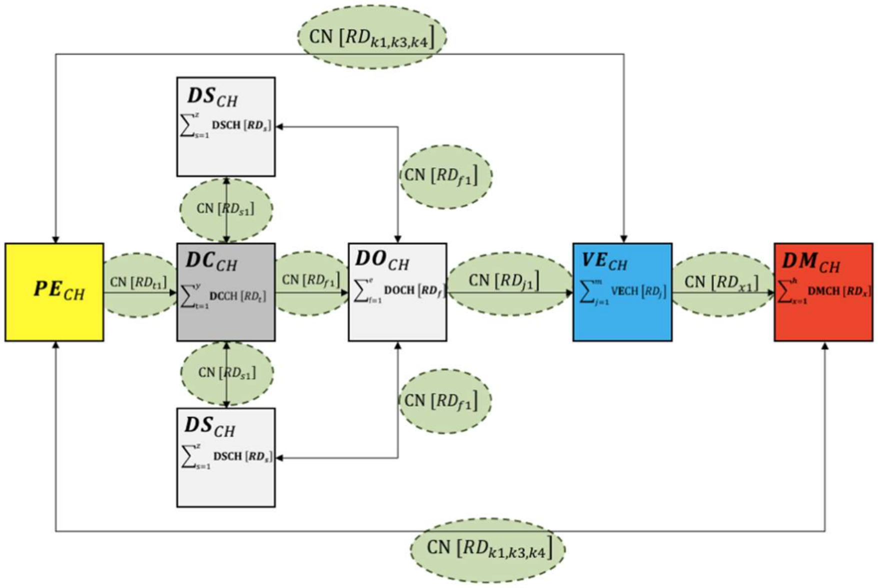

Fig. 7 Parameters of visitor management objectives within the scope of the DT model

Table 4 presents the results obtained in the DT model for Action 49 and future projections based on these results. This table is used to assess the current performance of the model as well as to anticipate possible future scenarios. The data provided by the model provides both an analysis of the current situation and important information to inform future planning processes (**Table 4**).

CONCLUSION

As the use of digital technologies and platforms in cultural heritage sites increases, real-time data collection can yield valuable insights for various purposes, such as monitoring and controlling assets, optimizing processes, and generating economic value. The lack of effective use of digital technologies in the preservation of Istanbul's Historic Peninsula has created a significant gap, recognized as a major deficiency in site management. The role of digital technologies is crucial in addressing the challenges outlined in the management plan. Therefore, the implementation of innovative technologies and smart systems in the Historic Peninsula is essential. These technologies will provide significant advantages in the preservation and management of the site and help address existing shortcomings.

The aim of this study is to integrate smart systems and contemporary technologies within the framework of DT technology into a theoretical model designed for the management of cultural heritage sites, specifically focusing on the Historic Peninsula of Istanbul, which forms the basis of the original research. In this context, a foundational model has been developed for creating the DT of cultural assets in the Historic Peninsula. Through the DT approach, this study addresses three key areas identified in the literature for cultural heritage sites: Data Acquisition, Production, and Integration and Distribution. To address these areas, a new six-dimensional model has been established for the Historic Peninsula. These dimensions include Physical Entity, Data Center, Data Services (Data Acquisition phase), Data Operation (Production phase), Virtual Entity, and Decision-Making (Integration and Distribution phase).

The model developed in this study is structured based on the seven main objectives outlined in the management plan for Istanbul's Historic Peninsula. Parameters for the model have been defined with consideration to the strategies and actions aligned with each objective. Acknowledging the potential for these parameters to evolve over time, the model is designed to be flexible and capable of incorporating new parameters in the future. The core element of the model is the establishment of robust connections between physical and virtual entities. This phase not only involves enabling technologies but also includes the analysis of data collected through these technologies and the generation of future predictions based on these analyses. The proposed model aims to provide detailed insights that deeply connect cultural assets between the physical and virtual worlds, facilitating the management of various dimensions of heritage sites in a digital environment for the future. This approach not only supports the development of preventive conservation strategies through real-time monitoring but also enables future predictions and analyses through interdisciplinary collaboration.

Table 4. Visitor management outcomes assessed under the DT framework.

Visitor Management		
Objective: Ensuring sustainable tourism within the Istanbul Historical Peninsula heritage site through the formation of big data via smart systems and innovative innovations, thereby achieving effective protection within international frameworks		
Strategy 13: To enrich and increase the quality of area experience of visitors. Action 49: Determination of tour routes and inclusion in promotional documents within world heritage sites		
Enabling Technologies	Results	Future Predictions
• Electronic Ticketing • Digital Hotel Entry Data • Thermal Cameras • Free Wi-Fi • Social Media Data • CCTV Footage • Sensor Detectors • Drone Imaging System	•Guiding tourism flow •Ensuring early intervention •Providing real-time live monitoring •Planning a multidimensional management system in a digital environment •Facilitating service ease •Enhancing security in the area •Providing information to tourists in a digital environment	• Socio-economic criteria • Visitor flow • Number of visitors • Negative environmental impacts • Marketing strategies
Virtual Entity		
• Development of Predictive Models and Algorithms: Creating predictive models and algorithms within the scope of the objectives. • Comparison of Predicted Routes: Comparing predicted routes with actual conditions in both virtual and real environments. • Application of Predictive Model Studies: Transferring the developed predictive model studies for implementation by the decision-making body.		
Data Center		
• Determination of Museum Entry Data: Identifying the number of entries, entry times, gender, and age of visitors through the ELK ticketing system. • Identification of Occupancy and Vacancy Routes: Using drone imagery to determine routes with varying levels of occupancy and vacancy. • Measurement of Visitor Behavior: Assessing visitor behavior through free Wi-Fi data. • Preliminary Analyses: Conducting preliminary analyses by designated experts within the scope of the objectives.		
Data Services		
• Formation of Big Data: Creating big data through the collected information. • Integration of Data: Ensuring the integration of the identified data in a digital environment. • Final Analysis: Conducting final analyses on the collected data by experts.		
Data Operation		
• Visualization of Data: Displaying data on interactive maps in a digital environment through the collaboration of interdisciplinary experts. • Execution of Predictive Simulations: Performing predictive simulations within the scope of the objectives. • Transfer of Simulations to Virtual Environment: Converting the prepared simulations into a virtual environment.		
Decision Making		
• Communication of Predicted Routes: Providing the relevant body with the predicted routes for visitor use. • Real-Time Monitoring: Enabling the relevant body to monitor the area due to the capability for real-time tracking. • Preventive Protection Interventions: Facilitating preventive protection interventions by the relevant body in emergency situations as needed.		

REFERENCES

Adreani, L., Bellini, P., Colombo, C., Fanfani, M., Nesi, P., Pantaleo, G., & Pisanu, R. (2024). Implementing integrated digital twin modelling and representation into the Snap4City platform for smart city solutions. Multimedia Tools and Applications, 83(12), 37121-37146.

Adreani, L., Bellini, P., Fanfani, M., Nesi, P., & Pantaleo, G. (2023, June). Design and develop of a smart city digital twin with 3d representation and user interface for what-if analysis. In International Conference on Computational Science and Its Applications (pp. 531-548). Cham: Springer Nature Switzerland.

Airaksinen, E., M. Bergström, H. Heinonen, K. Kaisla, K. Lahti, and J. Suomisto. (2019). "The kalasatama digital twins project: The final report of the KIRA-digi pilot project".

Belli, B., & Koramaz, T. K. (2020). Transformation of Urban Space by Smart Technologies: Evidence and Traces from Istanbul Historical Peninsula. In Reconstructing Urban Ambiance in Smart Public Places (pp. 82-113).

Bologna Digital Twin Enhancing the public value of data, (2023).

Bruno, S., Scioti, A., Pierucci, A., Rubino, R., Di Noia, T., & Fatiguso, F. (2022). VERBUM--VIRTUAL ENHANCED REALITY FOR BUILDING MODELLING (VIRTUAL TECHNICAL TOUR IN DIGITAL TWINS FOR BUILDING CONSERVATION). Journal of Information Technology in Construction, 27.

Camero, Andrés, and Enrique Alba. "Smart City and information technology: A review." cities 93 (2019): 84-94.

Chen, Y., & Bellavitis, C. (2020). Blockchain disruption and decentralized finance: The rise of decentralized business models. Journal of Business Venturing Insights, 13, e00151.

Correia, L. F. R., dos Santos Bartholo, R., Brufato, A. W., & Thomé Sanchez, E. C. (2023). Toward a Digital Twin for Cultural Heritage. In Advances in Tourism, Technology and Systems: Selected Papers from ICOTTS 2022, Volume 1 (pp. 419-430). Singapore: Springer Nature Singapore.

Ćosović, M., & Maksimović, M. (2022, September). Application of the digital twin concept in cultural heritage. In Proceedings of VIPERC2022: 1st International virtual conference on visual pattern extraction and recognition for cultural heritage understanding (Vol. 12).

Dassault Systèmes. (2019). 3DEXPERIENCity- Virtual Singapore: Singapore's Innovative City Project. Accessed October 31, (2019). https://www.ge.com/digital/sites/default/files/download_assets/GE-Digital-Power-Plant-Brochure.pdf.

Digital Strategy for Bradford District. (2022). City of Bradford & Metropolitan District Digital Strategy, 2022 – 2027.

Enders, M. R., & Hoßbach, N. (2019). Dimensions of digital twin applications-a literature review.

Gabellone, F. (2022). Digital Twin: a new perspective for cultural heritage management and fruition. Acta Imeko, 11(1), 7-pp.

Gabrys, J. (2014). Programming environments: Environmentality and citizen sensing in the smart city. Environment and planning D: Society and space, 32(1), 30-48.

Gartner, Top 10 strategic technology trends. (2019). [https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2019]

Gartner, Top 10 strategic technology trends. (2024). [https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2024]

Glaessgen, E., & Stargel, D. (2012, April). The digital twin paradigm for future NASA and US Air Force vehicles. In 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA (p. 1818).

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. Transdisciplinary perspectives on complex systems: New findings and approaches, 85-113.

Grimaldi, D., & Fernandez, V. (2019). Performance of an internet of things project in the public sector: The case of Nice smart city. The Journal of High Technology Management Research, 30(1), 27-39.

Gülersoy, N. Z, and Ayranci. I. (2011). "koruma alanlarinda yönetim plani." İTÜ Çevre ve Şehircilik Uygulama Araştırma Merkezi İSTANBUL, 2011.

Hermon, Sorin, Franco Niccolucci, Nikolas Bakirtzis, and Svetlana Gasanova. "A Heritage Digital Twin ontology-based description of Giovanni Baronzio's "Crucifixion of Christ" analytical investigation." Journal of Cultural Heritage 66 (2024): 48-58.

Ivanov, S., Nikolskaya, K., Radchenko, G., Sokolinsky, L., & Zymbler, M. (2020, November). Digital twin of city: Concept overview. In 2020 Global Smart Industry Conference (GloSIC) (pp. 178-186). IEEE.

Jafari, M., Kavousi-Fard, A., Chen, T., & Karimi, M. (2023). A review on digital twin technology in smart grid, transportation system and smart city: Challenges and future. IEEE Access, 11, 17471-17484.

Jouan, P., & Hallot, P. (2020). Digital twin: Research framework to support preventive conservation policies. ISPRS International Journal of Geo-Information, 9(4), 228.

Karami, A., Menna, F., & Remondino, F. (2022). Combining photogrammetry and photometric stereo to achieve precise and complete 3D reconstruction. Sensors, 22(21), 8172.

Kaur, M. J., & Maheshwari, P. (2016, March). Building smart cities applications using IoT and cloud-based architectures. In 2016 international conference on industrial informatics and computer systems (CIICS) (pp. 1-5). IEEE.

Kavitha, B. C., Vallikannu, R., & Sankaran, K. S. (2020). Delay-aware concurrent data management method for IoT collaborative mobile edge computing environment. Microprocessors and Microsystems, 74, 103021.

Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., & Logg, A. (2020). Digital twins for cities: A state of the art review. Built Environment, 46(4), 547-573.

Koramaz, T. K. (2018). Information and communication technologies in cultural heritage management. In Cultural Heritage (pp. 155-166). Routledge.

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. Ifac-PapersOnline, 51(11), 1016-1022.

Kubat, A. S. (2018). İstanbul Tarihi Yarımada: Morfogenetik Yapısı ve Değişim Süreci. Türkiye Kentsel Morfoloji Ağı, 17-33.

Lea, R., Blackstock, M., Giang, N., & Vogt, D. (2015, September). Smart cities: Engaging users and developers to foster innovation ecosystems. In Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers (pp. 1535-1542).

Lehner, H., & Dorffner, L. (2020). Digital geoTwin Vienna: Towards a digital twin city as geodata hub.

Liu, M., Fang, S., Dong, H., & Xu, C. (2021). Review of digital twin about concepts, technologies, and industrial applications. Journal of manufacturing systems, 58, 346-361.

Liu, Zherong, and Jiang Wang. "Protection and Utilization of Historical Sites Using Digital Twins." Buildings 14, no. 4 (2024): 1019.

Lu, Q., Parlikad, A. K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., ... & Schooling, J. (2020). Developing a digital twin at building and city levels: Case study of West Cambridge campus. Journal of Management in Engineering, 36(3), 05020004.

Maksimović, M., & Ćosović, M. (2022, March). Towards the implementation of iot system for preservation: the church of holy archangels michael and gabriel case study. In 2022 21st International Symposium INFOTEH-JAHORINA (INFOTEH) (pp. 1-6). IEEE.

Management Plan. (2018). Istanbul Historic Peninsula Management Plan was approved by the Coordination and Supervision Board of the Presidency of the Site with the decision dated 08/05/2018 and numbered 01.

Mistry, I., Tanwar, S., Tyagi, S., & Kumar, N. (2020). Blockchain for 5G-enabled IoT for industrial automation: A systematic review, solutions, and challenges. Mechanical systems and signal processing, 135, 106382.

Newcastle University. (2019). Newcastle's "digital twin" to help city plan for disasters. Published 2019. Accessed November 4, 2019. https://www.ncl.ac.uk/press/articles/ archive/2019/01/digitaltwin/.

Ni, Z., Liu, Y., Karlsson, M., & Gong, S. (2022). Enabling preventive conservation of historic buildings through cloud-based digital twins: A case study in the city theatre, norrköping. IEEE Access, 10, 90924-90939.

Olfat, H., Atazadeh, B., Shojaei, D., & Rajabifard, A. (2019). The feasibility of a BIM-driven approach to support building subdivision workflows—case study of Victoria, Australia. ISPRS International Journal of Geo-Information, 8(11), 499.

Olivares, T., Royo, F., & Ortiz, A. M. (2013, November). An experimental testbed for smart cities applications. In Proceedings of the 11th ACM international symposium on Mobility management and wireless access (pp. 115-118).

Pereira, P., & Martins, J. (2018, September). Sustainable Heritage Management Towards Mass Tourism Impact: the HERIT-DATA project. In 2018 International Conference on Intelligent Systems (IS) (pp. 801-806). IEEE.

Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., ... & Nee, A. Y. (2021). Enabling technologies and tools for digital twin. Journal of Manufacturing Systems, 58, 3-21.

Rocca, I., Forti, I., D'Acunto, G., & Saetta, A. (2023). Survey, Diagnostics, Monitoring Methodology and Digital Twin for the Conservation of the Facade of the Church of Santa Maria DI Nazareth in Venice. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 48, 1331-1336.

Ruohomäki, T., Airaksinen, E., Huuska, P., Kesäniemi, O., Martikka, M., & Suomisto, J. (2018, September). Smart city platform enabling digital twin. In 2018 International Conference on Intelligent Systems (IS) (pp. 155-161). IEEE.

Shahat, E., Hyun, C. T., & Yeom, C. (2021). City digital twin potentials: A review and research agenda. Sustainability, 13(6), 3386.

Tao, Fei, Weiran Liu, Jianhua Liu, Xiaojun Liu, Qiang Liu, Ting Qu, Tianliang Hu et al. "Digital twin and its potential application exploration." Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS 24, no. 1 (2018): 1-18.

Tuchen, S., LaFrance-Linden, D., Hanley, B., Lu, J., McGovern, S., & Litvack-Winkler, M. (2022, September). Urban Air Mobility (UAM) and Total Mobility Innovation Framework and Analysis Case Study: Boston Area Digital Twin and Economic Analysis. In

2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC) (pp. 1-14). IEEE.

Wu, Y., Zhang, K., & Zhang, Y. (2021). Digital twin networks: A survey. IEEE Internet of Things Journal, 8(18), 13789-13804.

Xin, L., Hongyu, G., Kyeong, S. E., Qitao, W., Guojun, Y., & Bangkun, D. (2023, May). Towards cultural heritage digital twin: concept, characteristics, framework and applications. In 2023 9th International Conference on Virtual Reality (ICVR) (pp. 549-557). IEEE.

Yao, H., Qin, R., & Chen, X. (2019). Unmanned aerial vehicle for remote sensing applications—A review. Remote Sensing, 11(12), 1443.

Zheng, Y., Yang, S., & Cheng, H. (2019). An application framework of digital twin and its case study. Journal of ambient intelligence and humanized computing, 10, 1141-1153.