Digital Twins for Cultural Heritage: A Systematic Analysis of the State of the Art

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Digital twin technology offers a transformative approach to preserve, manage, and enhance tangible cultural heritage through dynamic and immersive digital representations. Despite growing attention, research in this area remains fragmented and lacks systematic synthesis. This study presents a comprehensive systematic literature review analyzing the state-of-the-art in digital twin applications for tangible cultural heritage. A total of 108 studies published between 2002 and August 2025 were synthesized and categorized across three analytical dimensions: user-centric applications, enabling technologies, and maturity levels. The results indicate that most current implementations remain in early maturity stages primarily static digital replicas with limited adaptivity or intelligence. This trend reflects an ongoing transition toward dynamic, interoperable, and data-driven cultural heritage twins. User-centric applications increasingly leverage immersive technologies such as virtual and augmented reality to enhance accessibility and engagement, while enabling technologies like 3D modeling, real-time data integration, and AI-based analytics are still underutilized for intelligent operations. The findings highlight the need for innovation and standardization to advance maturity and scalability. Federated digital twins emerge as a promising pathway for collaborative, secure, and sustainable preservation and access to cultural heritage.

CCS Concepts: • **Computing methodologies → Modeling and simulation**; • **Applied computing → Arts and humanities**; • **Human-centered computing → Virtual reality**;

Additional Key Words and Phrases: Digital twins, cultural heritage, enabling technologies, virtual museums, digital heritage modeling, digital twin maturity model

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1 Introduction

Digital Twin (***DT***), defined as the interactive connection between a virtual model and its real-world counterpart, operates through an immersive virtual environment that dynamically mirrors the physical world by continuously updating itself based on real-time data [68]. A *DT* serves as a comprehensive representation of an object or system throughout its lifecycle [67], and is increasingly applied across industries for simulation, monitoring, and optimization [137].

A *DT* typically comprises four essential components: (1) the physical entity to be digitalized, (2) its virtual model that mirrors real-world attributes and behaviors, (3) the connection and synchronization mechanisms enabling continuous bidirectional data exchange, and (4) the stakeholders who interact with and benefit from the system [129]. For example, sensors and **Internet of Things** (**IoT**) devices collect real-time data from the physical object and transmit it to the digital model for synchronization, while simulations and insights generated in the virtual space inform decision-making and optimization for the physical entity.

In recent years, *DT* have gained traction in the context of ***Tangible Cultural Heritage (TCH)*** as powerful tools for preservation, restoration, and visitor engagement [87]. Cultural heritage can be categorized as *intangible* and *tangible*. ***Intangible Cultural Heritage (ICH)*** refers to practices, languages, knowledge systems, and oral traditions passed through generations [172], while *Tangible Cultural Heritage* encompasses monuments, artifacts, artworks, and culturally significant sites that reflect a community's history and identity [13].

The potential of *DT* for cultural heritage aligns with theories of presence and immersion, which suggest that individuals engage with virtual environments in ways similar to their interactions with physical spaces, often experiencing comparable emotional and cognitive responses [132]. These immersive properties make *DT* particularly valuable for cultural heritage, where authenticity and user experience are paramount.

Real-world implementations further illustrate the transformative potential of *DT* in cultural heritage. For example, UNESCO has promoted DT-based projects to digitally safeguard sites such as the ruins of Palmyra in Syria [37] and the Old Bridge of Mostar in Bosnia-Herzegovina [143], enabling virtual reconstructions after conflict-related destruction. Similarly, the Notre-Dame Cathedral restoration project in France has leveraged DTs created through laser scanning and photogrammetry to guide reconstruction efforts after the 2019 fire [55]. In the museum sector, initiatives such as the **Virtual Museums of the European Union** (**ViMM**) [147] and the Smithsonian's 3D Digitization Program [63] demonstrate how DTs enable immersive public access, interactive exhibitions, and long-term conservation planning. These cases highlight the practical relevance of DTs and reinforce the necessity of a systematic review to understand their broader role in TCH.

This article presents a ***Systematic Literature Review*** (***SLR***) to assess the current state of *DT* applications in *TCH*, focusing on three dimensions: (i) user-centric applications, (ii) enabling technologies, and (iii) maturity levels. This structured approach enables us to (1) evaluate how *DT* enhance user engagement and accessibility, (2) analyze enabling technologies such as 3D modeling, XR, IoT, and AI-driven analytics, and (3) assess the maturity of *DT* implementations, from static digital replicas to adaptive, intelligent systems.

The *objectives* of this review are threefold: (i) to provide a structured overview of *DT* concepts and their evolution in the TCH domain; (ii) to identify current applications of *DT* in cultural heritage, including monitoring, preservation, restoration, and immersive engagement; and (iii) to introduce a tri-dimensional analytical framework that considers user-centric perspectives, enabling technologies, and maturity levels. These objectives define the scope of the review and guide the subsequent analysis.

1.1 Motivation and Paper Contributions

The rapid evolution of *DT* technology presents significant opportunities for transforming the *TCH* domain by enabling dynamic, interactive, and immersive experiences. However, despite increasing interest, research on *DT* applications in *TCH* remains fragmented and limited in scope. Most studies address isolated aspects such as 3D reconstruction or visualization, while overlooking comprehensive frameworks that account for user experience, enabling technologies, and maturity levels. This fragmentation hinders the systematic adoption of *DT* in cultural heritage practice.

In addition, the literature reveals persistent challenges that justify the need for a systematic review. These include: (i) **technical challenges**, such as real-time synchronization, interoperability of heterogeneous platforms, and scalability; (ii) **legal and ethical challenges**, including intellectual property rights, privacy, and data ownership; (iii) **interoperability challenges**, stemming from the lack of standardized frameworks and protocols for data exchange across institutions; (iv) **organizational challenges**, such as limited institutional capacity and resistance to digital transformation; and (v) **data standardization challenges**, particularly harmonizing formats for 3D models, metadata, and archival datasets. Addressing these challenges requires a holistic analysis that integrates user perspectives, technological enablers, and maturity levels an approach that is currently missing in prior reviews.

The contribution of this article can be summarized as follows:

(1) Bridge theory and practice: Provide a comprehensive synthesis of how DTs are currently being applied in *TCH*, moving beyond theoretical definitions to real-world applications in preservation, restoration, monitoring, and immersive engagement.
(2) User-centric applications: Examine the extent to which DTs consider diverse stakeholders such as visitors, researchers, and educators focusing on accessibility, inclusivity, and engagement.
(3) Enabling technologies: Identify and analyze the technological foundations that support DT development for *TCH*, including 3D modeling (e.g., photogrammetry, laser scanning), immersive platforms (e.g., *Unity Reflect*, *Unreal Engine*), and data-driven approaches (AI, IoT, and XR).
(4) Maturity assessment: Propose a structured tri-dimensional framework for assessing DT maturity, ranging from static digital replicas to intelligent, adaptive systems an aspect largely overlooked in previous reviews.
(5) Implementation challenges: Systematically categorize the key barriers (technical, legal, interoperability, organizational, and data standardization), offering a roadmap for future research and practical deployment in cultural heritage.

1.2 Paper Structure

The article is structured as follows. Section 2 presents the background and related work on *DT* usage in the context of *TCH*, including a comparison with existing *SLRs* to highlight gaps in the literature and the novelty of this study. Section 3 describes the research methodology adopted to conduct the *SLR* following the guidelines in Ref. [72]. Through a four-step screening procedure, including snowballing, *108* relevant papers were selected from an initial set of *1,271* studies to address the research questions listed in Table 2.

Sections 4, 5, and 6 present the analysis of the results for each research question. Section 4 investigates the application of *DT* in *TCH*, integrating technical and user perspectives and discussing implications for preservation, education, and stakeholder engagement. Section 5 examines enabling technologies for *DTs* in *TCH*, focusing on data acquisition technologies, DT platforms, and intelligent systems, while Section 6 analyses the maturity levels of *DT* implementations in *TCH* domains.

Section 7 discusses *DT* applications from a user perspective, enabling technologies, maturity levels, and associated challenges, highlighting opportunities to address technological and methodological gaps. Section 8 outlines open challenges and future research directions, and Section 9 concludes the article.

2 Background and Related Work

The concept of the *DT* had evolved significantly since its introduction in 2002, when Michael Grieves first proposed it in the context of product lifecycle management [47]. Early *DT* implementations relied on static virtual representations with limited data integration. Advances in IoT, cloud computing, and artificial intelligence later transformed *DTs* into dynamic, real-time systems capable of continuous data exchange, simulation, and prediction [89].

By the 2010s, *DT* technology was widely adopted in sectors such as aerospace, manufacturing, healthcare, energy, and smart cities to support predictive maintenance, operational optimization, and urban planning [46, 83, 113]. More recently (2020–2025), the integration of *DTs* with AI, machine learning, **extended reality** (**XR**), and federated learning has enabled intelligent, immersive, and multi-stakeholder applications, including cultural heritage preservation [5, 38, 65]. In this domain, *DTs* facilitate interactive digital replicas of museums and historic sites, enhancing accessibility and engagement while safeguarding physical assets, and demonstrating the broader potential of *DT* technology to improve efficiency, resilience, and sustainability across domains [48].

2.1 Digital Twin for Cultural Heritage

DT have become transformative technology in *TCH*, enabling the preservation, management, and enhancement of historical sites and artifacts [29]. By creating virtual replicas of physical assets, *DTs* enable real-time monitoring, predictive maintenance, and interactive experiences for both heritage professionals and the public. Their adoption in museums and archaeological sites facilitates data-driven conservation, visitor behavior simulation, and improved accessibility through virtual tours [135]. These applications integrate emerging technologies such as IoT, AI, and XR to deliver adaptive, immersive, and collaborative solutions that address dynamic environmental and operational challenges [61, 94]. Recent developments emphasize scalable and template-based DT solutions, ensuring authenticity, sustainability, and lifecycle-oriented heritage management [25, 99].

While *DTs* share common features across domains such as data synchronization, predictive modeling, and simulation *DTs* for *TCH* require domain-specific adaptations [142]. In contrast to industrial DTs, which prioritize scalability and operational optimization, heritage-focused DTs emphasize immersive visualization, historical data integration, authenticity preservation, and user-centric interaction to support cultural storytelling and public engagement [21, 32, 103].

2.2 Related Work on Digital Twin for Cultural Heritage

Over the past two decades, there has been significant growth in the body of literature addressing the application of *DTs* to the realm of *TCH*. The utilization of *DT* in the management and preservation of *TCH* assets necessitates the adoption of a collaborative and integrated approach [148]. Currently, a systematic review of the literature has noted a substantial increase in the utilization of *DTs* within the *TCH* domain. The following *secondary studies* provide evidence of this trend.

In Ref. [58] the authors investigate the theoretical and practical links between *DT* application in ***Heritage Facilities Management*** (***HFM***) from a life cycle management perspective and to signpost the future development directions of *DT* in *HFM*. The review results show that *DT* has been mainly adopted to support decision-making on conservation approach and method selection, performance monitoring and prediction, maintenance strategies design and development, and energy evaluation and management. In their study, authors in Ref. [94], focused on digital transformation in leisure activities, especially all kinds of museums, exhibitions, and their *DTs*. Through a literature search and evaluation, they provide an analytic overview of the necessary concepts and methods involved in a collaborative effort to produce a cost-effective approach to a semi-automatically generated virtual museum. The findings and conclusions of this study concerning the life cycle of a *DT* essentially relate and are limited to the field of *Heritage 4.0* and virtual museums of all categories. Although these fields offer insights into key aspects of human society, they primarily emphasize the past rather than the future and are significantly less complex compared with the modern challenges and solutions found in *Industry 4.0* subdomains. Authors in Ref. [34] studied the digitization efforts in *TCH* has sparked global interest in their potential implications for preserving, presenting, and managing *TCH* assets in China. This study summarizes the dimensions and complexity of *DT* applications on cultural world heritage sites in China, which vary significantly. *DT* technology has been widely applied to monuments, cultural landscapes, groups of buildings, and sites. The most commonly used methods for collecting graphical and spatial data are 3D laser scanning and photogrammetry, with their earliest application dating back to the 1980s, coinciding with the inscription of cultural world heritage sites. This article investigates the relationship between *DT* technology and heritage conservation, categorizing *DT* techniques into six levels to address three main tasks: data acquisition, visualization, and application. It systematically examines Chinese heritage digitization practices, taking into account variations in complexity and purposes, and highlights typological and chronological characteristics as well as the involvement of stakeholders. The study aims [148] to define the role of *DT* in the conservation of **built cultural heritage** (**BCH**). It systematically reviews existing literature to clarify the concept, application areas, and enabling technologies of DT in this domain. The study seeks to identify current limitations, such as the lack of standardized frameworks and real-time data integration.

More recently, Mazzetto et al. [29], provided an interdisciplinary synthesis combining DT with BIM, IoT, machine learning, and AR/VR for heritage building conservation, identifying interoperability and DT–BIM integration as major research gaps. Another systematic review on the management of heritage facilities explores the integration of DT and HBIM for conservation and energy management, highlighting structured lifecycle modeling as a key enabler [59].

Meanwhile, our systematic literature review examines the three dimensions of *DT* in *TCH*: user-centric applications, enabling technologies, and maturity level. It provides an overview of how these elements interrelate, assesses the current state of *DT* in cultural heritage, and identifies factors affecting effectiveness and future development. Table 1 summarizes each *SLR* and indicates which dimensions they address, highlighting the novelty of our work. Overall, studies show progress from static 3D reconstructions to AI, IoT, and XR-integrated projects such as church artifact monitoring, Notre Dame restoration [55], and UNESCO reconstructions [143] but gaps remain in user-centered evaluation, accessibility, holistic AI, IoT integration, and structured DT maturity assessment. Our tri-dimensional framework addresses these gaps and guides future DT development in *TCH*.

3 Research Method

The SLR presented in this study follows the guidelines proposed by Kitchenham et al. [72], which structure the methodology into three standardised stages, including planning, conducting, and reporting. This section focuses on the planning and conducting stages, while the reporting stage is addressed in the subsequent sections, where the results are presented to address the **research questions** (***RQs***). Additional details on the overall SLR process are provided in our replication package [31].

Table 1. Comparative Analysis of Prior Surveys with Respect to the Three Dimensions Considered in This Study

Title	Dimension(s) Considered
Digital twin applications on cultural world heritage sites in China: A state-of-the-art overview [34]	None
Digital twin application in heritage facilities management: systematic literature review and future development direction [58]	None
Digital Twins and Enabling Technologies in Museums and Cultural Heritage: An Overview [94]	Enabling technologies
Shaping Digital Twin Concept for Built Cultural Heritage Conservation: A Systematic Literature Review [148]	Enabling technologies
Integrating emerging technologies with digital twins for heritage building conservation: an interdisciplinary approach with expert insights and bibliometric analysis [29]	Enabling technologies and maturity levels
Digital twin application in heritage facilities management: Systematic literature review and future development directions [59]	Enabling technologies

Table 2. Research Questions

ID	Research Question.
RQ1	How can digital twin technologies enhance the management and experience of tangible cultural heritage?
RQ1.1	How have DT Technologies been adopted in the context of tangible cultural heritage?
RQ1.2	How have digital twins been used to improve stakeholders' experiences?
RQ2	How is digital twin used in the context of cultural heritage?
RQ2.1	What platforms and tools are used for deploying digital twins of cultural heritage for public access?
RQ2.2	What methods are commonly used to capture data for creating *digital twins* of *tangible cultural heritage* sites and artifacts?
RQ2.3	How does *digital twin* intelligence leverage advanced operations for tangible cultural heritage?
RQ3	What is the current maturity level of *digital twins* in the context of *tangible cultural heritage*?
RQ3.1	What is a representative model to assess the maturity of *digital twin* implementations in *tangible cultural heritage*?
RQ3.2	How can the advancement of *digital twin* implementation be evaluated to assess its maturity in *tangible cultural heritage*?

3.1 Planning the Review

In a *SLR*, the formulation of *RQs* plays a crucial role in providing a well-defined and organised framework for the review process. Table 2 shows the three main research questions we aim at answering with respect to the defined three dimensions: ***user perspective***, ***enabling technologies***, and ***maturity level*** of the *DT* adoption in the context of *TCH*. Research question *RQ1* investigates the application of *DT*s technology in *TCH*, focusing on both technical and *user perspectives* to explore how *DT* contribute to preservation, education, and user engagement. *RQ2* addresses how *DT*s are used in *TCH*, examining the *enabling technologies*, platforms, and tools for their deployment. Finally, *RQ3* explores the *maturity level* of *DT* in *TCH* by evaluating the model and the current implementation stages and computational intelligence to assess their operational efficiency and effectiveness in preservation and management.

We limited our search to four databases: *Scopus*, *IEEE Xplore*, *ACM Digital Library*, and *Web of Science*. We also included *Google Scholar* to broaden coverage, restricting the analysis to the first 100 relevant results to balance comprehensiveness and feasibility [62]. Multiple search strings were tested and evaluated based on the relevance of retrieved papers by (i) verifying the inclusion of pilot studies [97, 119, 162] and (ii) independently screening the titles and abstracts of the first 10 results per database, followed by author discussion. Based on this process, we defined a general search string, which was adapted to each database's syntax.

(((“digital” AND (“twin” OR “replica” OR “copy”)) OR ((“virtual” AND (“copy” OR “representation” OR “twin*”)))) AND (“cultural heritage*” OR “museum*” OR “gallery*” OR “archeological site*”)*

The data extraction plan structured the SLR into a four-phase screening process, supported by *Zotero* and *Microsoft Excel*. Predefined inclusion and exclusion criteria were applied in each phase to identify relevant studies, with papers failing any mandatory exclusion criterion removed and inclusion criteria used as quality metrics. Primary screening, conducted by the first author, assessed accessibility, language, duplication, and publication year, with the search restricted to publications from 2002 onward to reflect the introduction of the digital twin concept by *Grieves* [47]. Secondary screening, performed by the first and second authors, evaluated titles, abstracts, introductions, and conclusions, with the third author supporting disagreement resolution. Tertiary screening involved full-text evaluation by the first author, with inclusion criteria scored on a three-point scale (0, 0.5, 1); papers scoring at least 2.5 in the secondary screening advanced to the tertiary screening, while only papers scoring above 1 were retained for full-text analysis. Finally, forward and backward snowballing was applied to identify additional relevant studies [159].

3.2 Conducting and Reporting the Review

Following the guidelines by Kitchenham et al. [72], the conduction phase focused on extracting and synthesising data from the selected studies to address the *RQs*. The search returned 1,271 records in total: 355 from ACM Digital Library, 191 from IEEE Xplore, 447 from Scopus, 178 from Web of Science, and 100 from Google Scholar. After primary screening, 296 papers were retained based on accessibility, language, duplication, and publication year. Secondary screening, which evaluated titles, abstracts, introductions, and conclusions, reduced the set to 134 studies, while tertiary screening based on full-text evaluation resulted in 99 studies. Forward and backward snowballing was then applied, leading to a final set of 108 included studies. For the data extraction phase, we established the 20 RQ-related parameters shown in Table 3, inferred from the literature on digital twins [32, 48], to capture the data required to address the *RQs* and their sub-questions. Data synthesis was performed by analysing and summarising the findings from the included primary studies. Qualitative data were synthesised using thematic analysis [139], while quantitative data were analysed through meta-analysis [28].

4 Digital Twin Technologies for Tangible Cultural Heritage Management (RQ1)

The main objective of this section is to comprehensively address the application of *DT* technology to tangible cultural heritage by integrating both technical and user perspectives. The investigation will contribute to understanding how *DT* can serve as tools for preservation, education, and enhanced user engagement while ensuring accessibility and stakeholder participation, thus addressing the objectives of RQ1.1 and RQ1.2. This aligns with the main research question RQ1: *“How can DT technologies enhance the management and experience of tangible cultural heritage?*

Table 3. Selected Parameters for the Study

ID	Name	ID	Name
RQ1.1.P1	Types of artworks [102]	RQ2.3.P1	Activity level [32, 115]
RQ1.1.P2	Purpose of the tangible cultural heritage digital twin [26, 97]	RQ2.3.P2	Functional layer of DT [32]
RQ1.1.P3	Digital twin techniques [148]	RQ3.1.P1	Model update frequency [23]
RQ1.2.P1	Immersive technologies [126]	RQ3.1.P2	Twin models [32]
RQ1.2.P2	Digital heritage user experience [76]	RQ3.1.P3	Model security [86]
RQ1.2.P3	End users of digital heritage [15]	RQ3.1.P4	Verification and Validation of DT Models [149]
RQ2.1.P1	3D modeling software [60]	RQ3.2.P1	Stage of DT implementation [32, 80]
RQ2.1.P2	Digital twin platforms [122]	RQ3.2.P2	Connectivity mode [32, 80]
RQ2.2.P1	Data-acquisition technology [15]	RQ3.2.P3	Computational Intelligence [23]
RQ2.2.P2	Types of data [15]		

4.1 Adoption of DT Technologies (RQ1.1)

This section aims to answer RQ1.1, *"How have DT Technologies been adopted in the context of tangible cultural heritage? "*. The objective of this research question is to explore the rationale behind the adoption of *DT* technologies for *TCH* and to investigate the types of cultural artifacts where *DT* are applied to enhance services. To address this research query, we've utilized specific elements. These include **types of artwork**, **DT techniques**, and **purpose of the *TCH DT***. These components are crucial in the adoption of *DTs* within the *TCH* realm. They collectively enable the generation of immersive and educational renditions aimed at conserving, safeguarding, and showcasing our diverse cultural legacy for posterity. In the realm of *TCH* studies, the digital preservation of artworks emerges as a pivotal undertaking. This domain focuses on implementing strategies geared towards safeguarding and proliferating our *TCH*, with the overarching goal of ensuring its accessibility and enduring significance for future generations [32].

Diverse **types of artworks**, such as *buildings*, *paintings*, *drawings*, *monuments*, and *sculptures*, are under consideration for digitalization. The complete list of possible values associated with the *types of artworks* parameter can be found in our replication package [31]. Findings from our study reveal that among the selected 108 studies, buildings emerge as the most digitized form of artwork, with 61 (≈ 57%) studies focusing on them. *Sculptures* closely follows with 33 (≈ 30%) studies, while *monuments* account for 11 (≈ 10%) studies, and *paintings* and *drawings* are represented by 2 (≈ 2%) and 1 (≈ 1%) studies, respectively. This prioritization is influenced by the widespread presence of *buildings* and *sculptures* in cultural institutions worldwide and their capacity to represent various societal aspects. *Monuments*, *paintings*, and *drawings* receive comparatively less focus, potentially due to their varied sizes and mediums [32]. This prioritization highlights the importance of preserving architectural and sculptural heritage, which embodies diverse cultural narratives. This choice reflects the commitment to digitizing these forms of art, ensuring that they remain accessible to future generations, and safeguarding their significance in *TCH* preservation [98].

The **purpose of *DT* for *TCH*** is to enable the *preservation*, *conservation*, and *restoration* of cultural artifacts through virtual replication of cultural artifacts and artworks. This technological advancement allows us to recreate and safeguard *TCH* in a digital format. In this context, our study examines the rationale behind *DT*, emphasizing their importance in *preservation*, *conservation*, and *restoration* efforts for *TCH* to play the crucial roles in safeguarding and maintaining the diversity of human history, art, and traditions [158]. An analysis of included study papers reveals that *preservation* is the primary purpose, with 63 (≈ 58%) studies dedicated to this aspect, followed by *conservation* 29 (≈ 27%) and *restoration* 15 (≈ 14%), while 1 (≈ 1%) study does not explicitly state its purpose of *DT* utilization. Our study highlights *preservation* as the primary driving force behind the creation of virtual replicas of museums and cultural artifacts. It emerges as the most prominent motivation, given its central focus on preventing deterioration and preserving the original condition of these invaluable treasures and environments. By meticulously documenting every detail in digital form, *preservation* ensures that the essence and integrity of these artifacts remain intact for future generations to experience and appreciate [35]. In contrast, *conservation* steps in to address existing damage, employing strategies to manage and mitigate further degradation [86]. When creating virtual replicas, *preservation* ensures meticulous documentation of the current state, capturing every detail with precision. Meanwhile, *conservation* efforts focus on digital *restoration*, meticulously repairing any flaws or imperfections present in the scanned artifacts. Restoration, a facet closely intertwined with *conservation*, involves digitally recreating missing elements to restore the artifact to its original splendor. Together, *preservation*, *conservation*, and *restoration* converge in the digital realm, where advanced technologies enable the faithful *preservation* and *restoration* of *TCH* for future generations to appreciate and cherish [153].

In the digitalization of *TCH*, a diverse array of **DT techniques** have emerged, offering innovative ways to capture and preserve the essence of historical sites, artifacts, and cultural treasures. These techniques can be broadly categorized into *data-driven models* that focus on learning from data, *physics-based models* that simulate physical principles, and *hybrid models* that combine both approaches for a more robust representation within the *DT* framework [98]. A recent study sheds light on the evolving landscape of *DT* techniques within the *TCH* sector, revealing a predominant utilization of data-driven approaches over the last two decades because *data-driven DTs* offer greater adaptability to changes in the cultural heritage environment. As new data becomes available, or heritage operations evolve, the *DT* can be updated and refined to reflect these changes, while *physics-based DTs* often require complex mathematical models and extensive computational resources to simulate physical phenomena accurately. This flexibility allows for ongoing optimization and improvement of user experiences and operational efficiency [30, 151]. This trend is confirmed by our study, revealing a notable prevalence of *data-driven DT techniques*, with 74 ($\approx$ 68%) out of 108 selected studies featuring their utilization. In contrast,*physics-based techniques* were employed in 5 ($\approx$ 5%) out of the included studies, and *hybrid DT techniques* were utilized in 20 ($\approx$ 19%) of the studies. Notably, 9 ($\approx$ 8%) studies within the pool did not explicitly specify the technique employed, indicating the evolving and sometimes complex nature of *DT* applications within the *TCH* sector. The decision between employing *data-driven* or *physics-based* approaches should be guided by the particular research goals, the accessibility of data, and the characteristics of the *TCH* elements being studied [121].

Answer to Research Question 1.1. The pattern, derived from the information presented in Table 4, underscored the prevalence of digitalization practices geared towards the preservation of *TCH*. This trend suggests a concerted effort within the *TCH* sector to leverage *DT* technologies to safeguard and immortalize *artworks* such as sculptures, buildings, monuments, paintings, and drawings. Among the observed patterns, a significant correlation was found between the digitalization of buildings and sculptures and the practices of preservation, conservation, and restoration, with the latter occurring in descending order. Conversely, paintings, drawings, and monuments demonstrated weaker associations with these preservation, conservation, and restoration methods. Moreover, the robust correlation between preservation objectives and the digitalization of artworks, particularly buildings, and sculptures, underscores the overarching theme of leveraging *DT* technologies for *TCH* conservation. Here, preservation encompasses not only physical artifact protection but also archival and digital conservation aspects. This integration of preservation and digitalization signifies a comprehensive approach to ensuring the endurance and accessibility of *TCH* assets.

Table 4. Co-Occurance of Studies on Types of Artworks (*RQ1.1.P1*) and Purpose of the CH DT(*RQ1.1.P2*)

	Preservation	**Conservation**	**Restoration**
Building	[4, 20, 21, 24, 39, 42, 51, 66, 69, 70, 74, 75, 77, 81, 92, 93, 96, 108, 111, 114, 116, 120, 125–127, 133, 134, 138, 141, 154, 161, 163, 164, 170, 171]	[1, 33, 52, 57, 64, 78–80, 90, 98, 146, 155, 162, 164, 167, 168, 173]	[12, 16, 22, 26, 54, 56, 88, 106, 117]
Sculpture	[3, 6, 14, 17, 19, 25, 30, 40, 49, 82, 84, 85, 97, 105, 109, 132, 145, 150, 156]	[41, 44, 71, 95, 112, 119, 136, 153]	[101, 131, 165]
Painting	[110]	[91]	N/A
Drawing	N/A	[45]	N/A
Monuments	[53, 118, 128, 140, 152, 166]	[9, 11]	[107, 123, 157]

Table 5. Co-Occurance of Purpose of the TCH Digital Twin (*RQ1.1.P2*) and Digital Twin Techniques (*RQ1.1.P3*)

	Preservation	**Conservation**	**Restoration**
Data-driven DT	[6, 14, 17, 19, 20, 25, 30, 39, 40, 42, 49, 50, 66, 70, 73–75, 82, 84, 85, 92, 93, 96, 105, 108–111, 114, 120, 125–128, 132, 133, 138, 141, 145, 150, 152, 154, 156, 164, 166]	[1, 9, 33, 41, 44, 45, 57, 71, 79, 90, 91, 95, 98, 112, 136, 144, 146, 167, 173]	[12, 16, 22, 54, 56, 101, 106, 107, 131, 157]
Physics-based DT	[21]	[80, 119]	[117]
Hybrid DT	[3, 24, 51, 53, 77, 97, 118, 134, 140, 161, 163, 170]	[52, 153, 155, 162, 168]	[88, 123]

The investigation conducted in this section delved into the exploration of parameters that exhibited more frequent occurrences and significant patterns within our research findings. The observed patterns were then organized into, revealing noteworthy insights. Among the patterns identified in Table 5, digitalization for preservation purposes and the application of data-driven *DT* techniques emerged as the most recurrent themes in the context of our study. The pattern, derived from the information presented in Table 5, underscored the prevalence of digitalization practices geared toward the preservation of *TCH*. Data-driven techniques often require less computational resources compared with physics-based models, making them more scalable for large-scale applications like visitor flow analysis in *TCH* sites [126, 132].

4.2 Immersive Technologies for Improving Stakeholders Experience (RQ1.2).

This subsection aims to answer RQ1.2, *"How digital twins have been used for improving stakeholders experience?"*. To assess the effectiveness of *DT* applications in overcoming physical limitations, expanding audience reach, and fostering deeper connections with *TCH* in alignment with the main research question objectives, we consider parameters such as immersive technologies, access devices, and end users. These elements facilitate immersive and interactive engagement with cultural artifacts and exhibits, significantly enhancing stakeholders' experiences within cultural heritage sites.

In the pursuit of improving stakeholders experiences, in the context of *DTs*, researchers, and practitioners have explored **immersive technologies** such as ***Virtual Reality*** (***VR***) and ***Augmented Reality*** (***AR***), *images*, and *videos* [126]. These *techniques* aim at captivating and engage users, offering deeper insights and fostering emotional connections. The toolbox of techniques ranges from the use of *images* to cutting-edge technologies like *VR* and *AR*. This study investigates the prevalence and effectiveness of these methods in enhancing user experiences. Among the 108 studies examined, three primary methods emerged: *images*, *VR* and *AR*, and *videos*. The most widely used type, with 59 (≈ 55%) out of included studies, were *images*. It serves as a visual aid, helping convey information, set the ambiance, and evoke emotions. On the other side, *VR* and *AR* are employed in 39 (≈ 36%) studies respectively. These technologies take stakeholders on immersive journeys, allowing them to explore virtual realms, interact with digital replicas, and experience historical or artistic contexts in novel ways. Recent frameworks, such as those proposed by Anwar et al. [5], emphasize the integration of XR and metaverse technologies to enhance emotional engagement, motivation, and learning outcomes in cultural heritage education. These models advocate for immersive storytelling, gamified environments, and social interaction features such as avatars and collaborative exploration that deepen user experience and accessibility. Moreover, standardized UX evaluation methodologies like ISO 9241-210 are increasingly applied to assess the effectiveness of immersive heritage platforms. While *videos* are a less common choice among the techniques explored in this study, their capacity to add motion, storytelling, and auditory elements to the user experience is not to be underestimated. The limited use of *videos* in 2 (≈ 2%) out of the total included studies suggests that there is potential for further exploration of this medium to enhance stakeholders' engagement. The remaining 8 (≈ 7%) studies did not explicitly specify the methods or techniques employed to enhance stakeholders' experiences, highlighting an area for further research and innovation. The research findings indicate that *images* have been the predominant and extensively utilized method to enhance the experiences of stakeholders in recent decades. This prevalence highlights the lasting significance of visual content in conveying information, establishing the atmosphere, and evoking emotional reactions from stakeholders. Furthermore, the relatively lower prevalence of *VR* and *AR* compared with *images*, in our study, suggests a burgeoning interest in harnessing these technologies to craft increasingly immersive and interactive user experiences.

The utilization of *DT* technology in the digitization of heritage materials emphasizes the critical importance of the **devices** employed to enhance the user experience [98]. The quality of digital interactions is substantially influenced by individual preferences and the devices utilized as users engage with these digitized assets [169]. This research explores the complexities of user experience within the digital realm, examining the impact of *computers*, *smartphones*, and *tablets*. A notable aspect of this investigation is the preference among users for *computers*, primarily driven by the ubiquitous utilization of web-based platforms. This trend is underscored by the inclusion of 62 (≈ 58%) studies out of a total of included studies, with 37 (≈ 34%) studies focusing on smartphone accessibility and 9 (≈ 8%) on tablet usage. In this study, we find that users exhibit a noticeable preference for *computers* as their primary means of accessing content. This preference is driven by several factors, one of which is the widespread use of web-based platforms that are often optimized for computer interfaces. Furthermore, the prioritization of experimental approaches within this domain signifies a collective effort to enhance user experiences. Researchers and practitioners are committed to gaining valuable insights into user preferences and behaviors, intending to achieve platform-independent outcomes. The dedication to enhancing user interactions with historical, cultural, and artistic artifacts serves as a testament to the importance of preserving and sharing our rich heritage in the digital age [49].

This study also explores the dynamic landscape of end-users within the digital heritage domain, with a focus on the application of *DTs*. It explores the various categories of **end-users**, ranging from the *public* to *researchers*, *students*, and *educators*. The digitalized *TCH*, enriched by *DT* technology, offers a valuable resource that caters to a diverse audience. This investigation highlights the significance of digitized *TCH* as a versatile and accessible resource. It provides engagement opportunities for the *public*, research possibilities for *scholars* and *researchers*, and educational experiences for

Table 6. Co-Occurance of Studies on Access Devices (*RQ1.2.P2*) and End Users of Digital Heritage (*RQ1.2.P3*)

	General public	Researchers	Students and educators
Computers	[3, 6, 12, 25, 26, 30, 39, 45, 49, 50, 54, 64, 66, 71, 74, 80, 93, 95, 98, 105, 107, 108, 117, 127, 132, 140, 141, 152, 156, 157, 162, 167, 169]	[1, 20, 21, 33, 40, 70, 75, 79, 81, 90, 92, 97, 106, 111, 114, 116, 119, 120, 134, 136, 138, 146, 153, 155, 163, 164]	[19, 41, 57, 112]
Smartphones	[9, 14, 16, 17, 24, 44, 51–53, 56, 69, 77, 78, 82, 84, 88, 101, 109, 110, 118, 125, 126, 128, 133, 145, 150, 161, 165, 166, 170]	[85, 144, 168, 171]	[22, 91]
Tablets	[11, 42, 73, 96, 123, 131]	[4, 154, 173]	N/A

students and *educators*. The analysis of the data reveals that there is a broad focus in the studies, with 69 (≈ 64%) primarily catering to the interests and needs of the *general public*. Additionally, 33 (≈ 30%) studies accommodate the requirements of *researchers*. However, the emphasis on *students and educators* is relatively limited, with only 6 (≈ 6%) study specifically addressing their unique needs out of the total included studies. As a result, it becomes evident that recent research on *DTs* within the *TCH* domain lacks sufficient emphasis on distinct user groups. While the majority of the studies are dedicated to catering to the general public and researchers, there is a notable gap in addressing the needs of students and educators. This area presents an opportunity for future research and development to enhance educational experiences and make the wealth of digitalized *TCH* more accessible and impactful for educational purposes.

Answer to Research Question 1.2. This part of the study proposed to enhance the experience of stakeholders in the digital heritage by identifying key parameters, including *immersive technologies*, *end-users of digital heritage*, and *access devices*. This aimed to explore user engagement dynamics and provide insights into the evolving landscape of digital interactions with cultural artifacts. From Table 6 is evident that the general public constitutes a major audience for digitized *TCH*, and using computers as their primary tools, individuals from the public domain engage with images, indicating a widespread embrace of digital platforms for cultural exploration. A noteworthy observation from our research is the enduring prevalence of images as the primary content accessed by users in the digital realm. Despite the advancements in virtual technologies, traditional forms of visual representation remain the dominant means through which the public accesses and appreciates digitized cultural artifacts. This underscores the enduring power of visual narratives in conveying the essence of *TCH*, even in a digital context.

Immersive technologies, facilitated through computer-based interactions, emerged as a significant channel for the public to explore digitized *TCH* [107]. The utilization of *VR* and *AR* in the context of immersive technology was particularly notable. Our findings indicate a close affinity for *VR* and *AR* technologies, highlighting their role in enhancing the immersive experience for the public, as depicted in Table 7. The integration of these technologies adds a layer of interactivity and realism, providing users with a more engaging and dynamic exploration of cultural artifacts.

5 Technology Usage of Digital Twin in Tangible Cultural Heritage (RQ2)

This section addresses three sub-research questions focused on data acquisition technologies, digital twin platforms, and digital twin intelligence. These elements collectively answer the main research question of RQ2: *"How is digital twin used in the context of tangible cultural heritage?"* The objective is to evaluate the current use of digital twin technologies and their enabling technologies in the preservation and management of tangible cultural heritage.

Table 7. Co-Occurance of Studies on Access devices (*RQ1.2.P2*) and Immersive Technologies (*RQ1.2.P1*)

	General public	Researchers	Students and educators
VR/AR	[6, 12, 16, 17, 24, 25, 30, 44, 51, 53, 54, 66, 69, 73, 77, 78, 84, 88, 93, 101, 107, 108, 117, 118, 125, 126, 141, 157, 161, 162, 165, 166, 170]	[1, 20, 90, 119, 153, 171]	N/A
Images	[3, 9, 11, 14, 26, 39, 42, 45, 50, 52, 56, 64, 71, 74, 80, 82, 95, 96, 98, 105, 109, 110, 123, 127, 128, 131, 133, 140, 145, 150, 156, 167]	[4, 40, 50, 70, 75, 81, 85, 106, 111, 114, 120, 134, 136, 138, 144, 146, 154, 155, 163, 164, 168, 173]	[19, 22, 57, 91, 112]
Videos	[49]	[33]	N/A

5.1 Tools and Platforms Used for the Deployment of Digital Twin (RQ2.1)

This subsection seeks to address RQ2.1, *"What platforms and tools are used for deploying digital twins of tangible cultural heritage for public access?"*. This sub-RQ aims to support the objectives of the main research question by investigating key tools and platforms to understand the current utilization of *DT* in *TCH*. To answer this research question, we have employed two crucial parameters: **3D modeling software** and ***DT* platforms**. The selection of these parameters is based on their fundamental roles in the creation and application of *DT* for *TCH*. **3D modeling software** is essential for generating accurate and detailed 3D models of *TCH* sites, which form the basis for virtual reconstructions. ***DT* platforms** are critical for developing immersive *DT* environments, as they enable dynamic simulations and real-time interactions, enhancing user engagement with historical reconstructions[122]. Recent studies, such as Anwar et al.[5], propose a structured architecture model for XR and metaverse applications in cultural heritage. This model guides the development of immersive educational environments by integrating real-time simulation, user interaction layers, and metadata-driven content delivery. Incorporating such frameworks into *DT* platforms can enhance scalability, interoperability, and user engagement. In the expansive domain of *DT* creation and advancement, a plethora of **3D modeling software** options are available, each offering unique features and capabilities. Prominent among these are *Autodesk*, *Blender*, *SketchUp*, *Reality Capture*, and *3DGIS tools* [60]. Delving into the specifics, our research reveals that *Blender* emerges as the front-runner among the utilized 3D modeling tools, being the choice in 21 ($\approx$ 19%) of the studies. Following closely is *Autodesk*, making its mark in 20 ($\approx$ 19%) studies, while *SketchUp* and *3DGIS* each contribute to 2 ($\approx$ 2%) studies. *Reality Capture*, on the other hand, features in 8($\approx$ 7%) of the total studies. This distribution sheds light on the current landscape, indicating that despite the array of available 3D modeling tools, the practical application in *DT* research remains somewhat limited. This subtle exploration leads to a significant inference that the predominant focus in *DT* research appears to be concentrated on the theoretical or conceptual level, with a notable gap in the practical application of 3D modeling tools to create *DTs*.

The intricate landscape of *DT* implementation, and the utilization of specialized **platforms** like *Unity Reflect*, *Unreal Engine* stand out to materialize *DTs*, transforming them into virtual replicas of physical objects [122]. However, our comprehensive study unveils a striking observation: only a modest fraction, 29 ($\approx$ 27%) studies out of the total included studies, incorporate these platforms in their *DT* endeavors. Delving into the specifics, *Unity Reflect* emerges as the predominant choice, featuring in 24 ($\approx$ 22%) of the 108 total included studies. Following in the hierarchy is Unreal Engine, making its mark in 4($\approx$ 4%) studies, while *3DGIS* covers a single ($\approx$ 1%) study. This distribution illuminates a prevailing scenario where the practical application of *DT* platforms remains somewhat limited, particularly within the *TCH* domain. This observation prompts a significant inference: the deployment of *DTs*, as facilitated by dedicated platforms, is still in the early stages of practical application. The limited representation of studies incorporating these platforms indicates a gap between the theoretical understanding of *DTs* and their tangible, hands-on use. Looking ahead, the future holds promising prospects for a more extensive exploration of *DT* platforms in the context of *TCH*. The study serves as a foundational step, shedding light on the current limitations and providing a springboard for future investigations. The envisioned exploration encompasses a more in-depth understanding of how platforms like *Unity Reflect* and *Unreal Engine* can be instrumental in the preservation, conservation, and restoration efforts within the *TCH* domain.

Answer to Research Question 2.1. In *DTs*, the initial steps involve choosing *3D modeling tools* and *DT platforms* to create virtual replicas of physical objects, especially in *TCH* contexts. These tools hold immense importance, particularly in the development of virtual heritage sites, where they serve as essential components. The diverse landscape of *DT* creation offers numerous options for 3D modeling software alongside implementing platforms, each offering distinct features and capabilities. However, the study underscores that the practical application of *DT* platforms remains somewhat limited, particularly within the *TCH* domain. This observation leads to a significant inference: the deployment of *DTs*, facilitated by dedicated platforms, is still in its early stages of practical application. The limited representation of studies integrating these platforms indicates a gap between the theoretical understanding of *DTs* and their tangible, hands-on implementation. Considering these findings, we recommend the adoption of advanced platforms such as Unity Reflect and Unreal Engine with advanced 3D modeling tools. Furthermore, if feasible, we suggest extending this recommendation to include cloud-based platforms such as *AWS* and *Azure DT*. The inclusion of cloud-based platforms offers several advantages in terms of scalability, flexibility, and accessibility. These platforms provide powerful computing resources that enable the processing of large datasets and real-time simulations, which are essential for managing complex *DT* environments.

5.2 Digital Twin Data Acquisition Techniques (RQ2.2)

This subsection is dedicated to exploring RQ2.2, *"What methods are commonly used to capture data for creating digital twins of tangible cultural heritage sites and artifacts? "* This sub-RQ focus is on examining the data acquisition techniques employed in the creation of *DT*, along with the types of data essential for accurately representing *TCH*.

This section highlights the techniques for **data acquisition** from physical artifacts and transforms them into virtual representations [153]. Our study explores the efficacy of well-known data acquisition techniques such as *photogrammetry*, *3D laser scanning*, and *sensor-based* techniques. Our analysis reveals that *Photogrammetry* predominates, with 44 (≈ 41%) out of the total included studies. *3D laser scanning* follows closely, with 34 (≈ 31%) studies employing it. In contrast, data collection based on *sensors* is slow, with only 30 (≈ 28%) studies using this approach. These statistics underscore the pivotal role of *3D laser scanning*, renowned for its precision and efficiency in capturing 3D data. Additionally, *photogrammetry* shines as a widely adopted technique in the field. However, *sensor-based* data collection is less emphasized, as indicated by our study's findings. The statistical distribution of these data acquisition techniques within the selected studies sheds light on their relative significance. *3D laser scanning* and *photogrammetry* are the primary choices for acquiring data from physical artifacts and converting them into digital forms. Their efficiency and precision make them invaluable for capturing the intricacies of *TCH* items. However, the relatively limited use of *sensor-based* data collection methods indicates potential for further development and application in this domain . *Sensor-based* techniques offer unique advantages, including non-contact scanning and real-time data acquisition, which can be leveraged for specific applications within the *TCH* digitalization landscape [21].

In the field of developing *DTs* for *TCH* digitalization, the acquisition of diverse **data types** is essential for accurate representation. These types encompass *visual data*, *technical data*, and

Table 8. Co-Occurance of Studies on Data-Acquisition Technology (*RQ2.2.P1*) and Type of Data (*RQ2.2.P2*)

	Photogrammetry	**3D laser Scanner**	**Sensor**
Visual data	[6, 24, 25, 30, 44, 45, 49, 51, 52, 64, 66, 69, 71, 73, 78, 81, 88, 98, 105, 109, 117, 118, 131–133, 138, 140, 150, 157, 161, 166, 170]	[11, 12, 16, 17, 26, 33, 50, 74, 77, 82, 90, 93, 96, 101, 107, 110, 114, 125–127, 141, 152, 156, 163, 165, 167]	[3, 9, 53, 162]
Metadata	[14, 91, 111, 173]	[1, 80, 92, 119]	[4, 19, 21, 41, 56, 57, 79, 85, 112, 120, 144, 146, 153, 155]
Technical data	[40, 42, 84, 95, 97, 108, 145]	[22, 39, 54, 75, 116, 123, 168, 169]	[20, 70, 106, 134, 136, 154, 164, 171]

metadata [10]. Analysis of the included studies reveals that a substantial majority, 62 (≈ 58%) out of 108, primarily rely on *visual data*. The preference for *visual data* is often attributed to its simplicity in comparison to other data types. While *visual data* is undeniably valuable, fostering advanced and thorough research necessitates prioritizing the utilization of *metadata* and *technical data* types [79]. Our findings indicate that the selected studies related to *DTs* in the *TCH* context do not adequately emphasize the inclusion of *metadata* and *technical data* types, with only 23(≈ 21%) studies utilizing *technical data* and *metadata*, which is also 23(≈ 21%). The study's findings reveal a gap in the emphasis placed on *technical data* and *metadata* within the selected studies. *Technical data* encompasses information related to the artifact's materials, dimensions, and structural properties [116]. *Metadata* includes contextual information, such as historical significance, origin, and provenance [146]. These data types provide essential insights that deepen our understanding of the artifact and its place in history. To foster advanced and thorough research in the field of *DTs* for *TCH*, it is advisable to prioritize the utilization of technical data and *metadata* [92].

Answer to Research Question 2.2. This section explores the methods used for digitalizing *TCH*, with a focus on techniques for capturing data from physical artifacts and converting them into virtual representations. The study investigates the effectiveness of three primary **data acquisition techniques**: *photogrammetry*, *3D laser scanning*, and *sensor-based* approaches [21]. Our focus extended to the key patterns associated with data acquisition techniques and the specific *types of data* collected within the realm of digitalized *TCH*. This perspective aimed to recognize the details of the methodologies employed in capturing and representing cultural artifacts digitally. From this approach, a compelling pattern emerged, highlighting a significant co-occurrence between the utilization of 3D laser scanners and the capture of visual **data type**. This convergence suggests a strategic synergy between the precision offered by 3D laser scanners and the richness of visual data, fostering a comprehensive and detailed representation of cultural artifacts. The prevalence of this co-occurrence underscores the significance of visual fidelity in the digitalization process, emphasizing the importance of capturing subtle details and textures to create a faithful *DT*, as illustrated in Table 8. A parallel pattern that emerged in our research involved the frequent co-occurrence of photogrammetry as a data acquisition technique, coupled with the capture of visual data. Photogrammetry, relying on the principles of extracting information from photographs, emerged as a viable and complementary approach to 3D laser scanning. Combining photogrammetry with visual data further enriches the digitalization process, providing an alternative method that aligns with the imperative of visual accuracy. Within the identified patterns, our research revealed a dominance of visual data as the primary type collected through photogrammetry and 3D laser scanning techniques. However, there were fewer instances of simultaneous utilization of sensor-based data acquisition techniques alongside metadata and technical data types. This underscores the evolving sophistication of *DT* studies at a nascent phase. To conclude, our suggestion supports the adoption of sensors for data acquisition and the integration of metadata into the digitalization process.

5.3 Digital Twin Intelligence (RQ2.3)

This subsection explores digital twin operations RQ2.3,*"How does digital twin intelligence leverage advanced operations for tangible cultural heritage?"*. This sub-research question aims to emphasize the operation of digital twins on TCH, supporting the main research question's objectives regarding the current utilization of digital twin technology. We employed the following parameters to address this question. These include the **activity level of *DT*** assesses the efficiency, reliability, and resilience of current *DT* operations in TCH. The ***DT* functional layer** evaluates the representation, analysis, interaction, and optimization of physical assets within the current *DT* of *TCH*. The selection of these two parameters is driven by their complementary roles in understanding both the operational effectiveness and the functional capabilities of digital twins in the context of cultural heritage. The *activity level* provides insight into how well the *DT* performs in real-world scenarios, while the *functional layer* focuses on how physical assets are digitally represented and managed, ensuring that both technical and practical aspects are fully addressed.

Within the *TCH* sector, *DT* operations are categorized into two main types based on their **activity level**. *Active DTs* not only replicate the physical system but also engage with it in real-time, facilitating control, simulation, and optimization. On the other hand, *passive DT* are representations of physical assets, systems, or processes that primarily concentrate on monitoring [32]. This classification hinges on the degree of activity inherent in the *DT*, serving as a surrogate measure for its maturity level and richness in functionality [132]. Our comprehensive analysis highlights this distinction, showing that a significant proportion of the studies included, specifically 55 ($\approx$ 51%) studies, are categorized as *passive DTs*. The remaining 53 ($\approx$ 49%) studies, constituting the minority, align with the *active DT* type. The distinction between *active* and *passive DTs* serves as a crucial lens through which to assess the maturity and functionality of these digital replicas within the context of *TCH*. The classification is rooted in the activity concept, encapsulating the level of engagement and dynamic interaction facilitated by the *DT* [115].

In the field of *DT* applications, our focus goes beyond simple implementation to explore the **functionality layers**. These layers encompass three essential components: the *presentation layer*, which functions as the interface that enables user interaction with the digital twin and its data, including visualization, user interfaces, and reporting capabilities. The *prediction layer* utilizes machine learning methodologies to anticipate future states, behaviors, or outcomes of the physical system, and the *prescription layer* of a *DT* suggests actions or interventions aimed at enhancing the performance, efficiency, or resilience of the physical system [21, 32]. In our comprehensive study, notably, a substantial emphasis emerges on the *presentation layer*, encapsulating a remarkable 57 ($\approx$ 53%) of the studies analyzed. This layer, positioned at the forefront, primarily concerns itself with the visual representation and portrayal of *DT* data and insights. Following in the hierarchy is the prediction layer, encompassing 42 ($\approx$ 39%) studies, and trailing behind is the prescription layer, with a mere 9 ($\approx$ 8%) studies contributing to this segment. In synthesizing these findings, it becomes apparent that the functional layers of the *DT*, as revealed by our study, are skewed towards the foundational *presentation layer*. While this layer is indispensable for effective communication and understanding, a more comprehensive exploration of the *prediction* and *prescription layers* is warranted to unlock the full potential of *DTs*. The dominance of the *presentation layer* suggests that the current maturity level of *DTs*, especially within the *TCH* domain, may be at an early stage akin to infancy in its development [21].

Table 9. Co-Occurance of Studies on Activity Level (*RQ2.3.P1*) and Functional Layer of Digital Twin (*RQ2.3.P2*)

	Presentation layer	Prediction layer	Prescription layer
Active DT	[25, 49, 51, 54, 69, 108, 118, 140, 152, 166, 167]	[4, 9, 14, 19, 20, 22, 40, 41, 52, 53, 57, 70, 75, 79–81, 84, 85, 90, 96, 106, 107, 112, 114, 116, 117, 119, 120, 134, 136, 138, 144–146, 153–155, 163, 164, 168, 171, 173]	[1, 3, 21, 39, 56, 97, 128, 162, 169]
Passive DT	[6, 11, 12, 16, 17, 24, 26, 30, 33, 42, 44, 45, 50, 64, 66, 71, 73, 74, 77, 78, 82, 88, 91–93, 95, 98, 101, 105, 109–111, 123, 125, 126, 130–133, 141, 150, 156, 157, 161, 165, 170]	N/A	N/A

Answer to Research Question 2.3. In the pursuit of comprehensively understanding the landscape of *DT* application in the *TCH* domain, our exploration has centered around key facets pivotal for assessing the current intelligence status of *DTs*.

After thoroughly analyzing the research, our objective was to identify the pivotal parameters shaping the present scenario in both theory and practice concerning the operation of *DTs* in *TCH*. The findings highlight a notable prevalence of the passive *DT* and the presentation functional layer, as illustrated in Table 9. This observation signifies a discernible pattern that characterizes the contemporary landscape of *DT* applications in *TCH*.

Table 9 visually encapsulates current trends in *DT* implementation. In particular, the dominance of the passive *DT* and the emphasis on the presentation functional layer align with a focus on descriptive modeling over the comprehensive exploration of the predictive and prescriptive layers. While revealing the current state, these patterns also spark further inquiries. Slight bonding in the co-occurrence of parameters related to prediction and prescription layers suggests potential growth in *DT* research within *TCH*. The infancy stage indicates ample room for exploration, particularly in embracing dynamic functionalities and advanced modeling techniques. In essence, our study's findings underscore a pivotal moment in the evolution of *DT* applications in *TCH*, signaling the potential for maturation and diversification.

6 The Maturity Level of Digital Twin in Tangible Cultural Heritage (RQ3)

This section aims to address two sub-research questions, focusing on the representative model and the implementation level to assess maturity,*"What is the current maturity level of digital twins in the context of tangible cultural heritage?"*. The objective of this research question is to determine the current maturity level of digital twin technology in the tangible cultural heritage domain. To address these objectives, we utilized the following parameters in the sub-research questions **model update frequency**, **twin models**, **model security**, and **verification and validation of DT models** , **implementation stage**, **connectivity mode**, and **computational intelligence** to evaluate the effectiveness of operational efficiency, real-time monitoring and control, and predictive maintenance within *TCH* domains.

6.1 Models to Assess the Maturity Level of Digital Twin (RQ3.1)

This section is designed to address RQ3.1 *What is a representative model to assess the maturity of digital twin implementations in tangible cultural heritage?* This sub-research question aims to support the main research question's objective by investigating representative models to determine the current maturity level of digital twin technology. In response to this objective, we've employed the following parameters: **model update frequency**, **twin models**, **model security**, and **verification and validation of DT models** because these parameters play essential roles in *DT* development by ensuring that the twin accurately reflects the physical system, operates securely and possesses the computational capabilities.

In the evaluation of *DT* maturity within the *TCH* domain, one critical parameter is **model update frequency** [23]. The intervals at which these updates occur, ranging from *real-time* to *hourly*, *daily*, and *weekly*, significantly influence the maturity level of *DTs*.The decreasing time intervals from *weekly* to *real-time* updates signify the advancement of the *DT* model. Our study's findings reveal a landscape where 35 (≈ 32%) out of the total included studies for weekly updates, 25 (≈ 23%) studies lean towards daily updates, 16(≈ 15%) studies prefer hourly updates, and 17 (≈ 16%) studies embrace real-time updates. Regrettably, 15 (≈ 14%) studies remain silent on their frequency of updates, lacking clarity on the communication of updates between the physical and digital realms. This discovery emphasizes a compelling need for substantial efforts to push the application of *DTs* in *TCH*, considering the prevalence of studies primarily relying on weekly updates, indicative of a *pre-DT* implementation stage. The absence of a clear update frequency in 15 studies further underscores the infancy of *DT* applications in this domain. The transition from weekly to real-time updates is not merely a technological advancement but a paradigm shift that allows for a more dynamic and responsive interaction between physical and digital representations. Encouraging a proactive approach to updating practices will boost *DT* applications to higher maturity levels, enhancing their effectiveness in the preservation and exploration of *TCH*.

In the landscape of *DT* implementation, two significant types of **twin models** are evident: *design-time* and *runtime DTs* [72]. Both are integral to the evaluation of *DT* maturity, especially in *TCH* research and applications. *Runtime DTs* offer real-time insights, playing a crucial role in the continuous management and conservation of cultural artifacts. On the other hand, *design-time DTs*, more commonly employed, contribute to the planning and design phases of projects. Our research shows that *design-time DTs* and *runtime DTs* are equally represented in the included studies: each category appears in 54 studies (≈ 50%). This parity indicates that the research community is split between projects focused on planning/design (documentation, 3D reconstruction and analysis) and projects that target operational, sensor-driven behaviors. While design-time DTs remain critical for documentation, planning and virtual reconstructions, the equal representation of runtime DTs signals a clear emergence of sensor-enabled, real-time monitoring and analytic deployments in TCH. Nevertheless, many runtime implementations still rely on limited update frequencies or uni-directional synchronization; advancing runtime capabilities requires improvements in interoperability, scalable data pipelines and automated feedback loops.

In the development and application of *DT* models, safeguarding data emerges as a paramount concern when evaluating the maturity level of *DTs*. These combined measures are crucial for upholding the **security**, privacy, and ethical handling of data within the expansive framework of *DTs* [86]. Within the scope of our study, a noteworthy finding comes to light, revealing that among the 108 included studies, 57 (≈ 53%) were categorized as *non-protected*, while 51 (≈ 47%) fell under the classification of *protected*. This revelation underscores a significant gap in the implementation of security measures within the realm of *DTs*, particularly in *TCH* research. The prevalence of *non-protected* instances implies that security considerations are still in their nascent stages, and the absence of robust protective measures poses challenges to realizing the full potential of *DTs*. Without adequate security protocols in place to shield the communication channels between virtual and physical systems, the effectiveness and reliability of *DTs* are compromised. Addressing this security gap requires a concerted effort to integrate advanced security measures into the *DT* framework [2]. This includes implementing encryption techniques to secure data transmission, establishing stringent access controls to regulate system entry, adopting anonymization practices to protect user identities, and adhering to ethical considerations in data handling. Moreover, cultivating a culture of awareness regarding data security and privacy is crucial for all stakeholders involved in *DT* applications within *TCH* research. In the domain of *DT* applications, the cornerstone of effectiveness lies in the verification and validation of *DT* models, a crucial consideration, particularly within the context of *TCH* research. To navigate and comprehend the multifaceted landscape of *DTs*, we have undertaken a classification of **verification and validation**, dividing it into three distinct dimensions: *model checking*, which entails validating the accuracy, completeness, and consistency of the *DT* model against real-world data and specifications [160]. *Simulation* is utilized to replicate the behavior, performance, and responses of the physical system under various conditions or scenarios. *Testing* involves subjecting the *DT* to real-world conditions or scenarios to assess its performance, reliability, and validity [149]. Our study unravels a subtle distribution within these classifications, shedding light on the prevailing trends in verification and validation techniques. *Model checking* emerges as a focal point in our analysis, capturing the attention of 46 (≈ 43%) out of the total studies included in our investigation. The prominence of *model checking* signifies a widespread acknowledgment of the importance of rigorously validating the fidelity and accuracy of *DT* representations within the *TCH* research domain. *Simulations*, featuring in 28 (≈ 26%) out of the total studies. *Simulations*, in this context, involve the emulation of real-world scenarios to observe and analyze the *DT's* responses and behaviors. This dimension adds a layer of dynamism to the understanding of *DT* functionalities, providing insights into how these virtual replicas respond to diverse conditions. In tandem, *testing*, as another facet of model validation, is observed in 14 (≈ 13%) studies within our analysis. In the context of *DTs*, *testing* involves subjecting the virtual replicas to various scenarios to assess their performance, robustness, and reliability. This dimension is crucial for ensuring that *DTs* not only mirror reality but also withstand the complexities of different environmental conditions. However, 20 (≈ 18%) studies, out of the total studies, did not explicitly articulate the model validation techniques. This observation implies a lack of clarity regarding the chosen model validation techniques and suggests that the field is still evolving, with researchers potentially grappling with the intricacies of identifying and articulating the precise purposes of verification and validation in the context of *DTs*.

Answer to Research Question 3.1. In *DT* implementations, evaluating the maturity level is a critical aspect, particularly concerning *TCH* perspectives. Our study focuses on assessing the maturity of *DT* representative models, considering key parameters such as model *update frequency*, *twining model*,*model security*, and *verification and validation of digital twin models*. In the examination of maturity level, we delved into identifying salient parameters consistently emerging in our study, directly linked to the maturation of the *DT* model. As depicted in Table 10, a robust correlation was observed between the frequency of weekly model updates and the *DT* during the design phase. This correlation extended to daily updates, exhibiting a frequent association with runtime *DTs*. It is noteworthy that the transition from a weekly update frequency to real-time updates signifies the strength of the model. However, our overall study emphasizes a strong co-occurrence between a weekly update frequency and, a design-time *DT*. This observation directly indicates that the current state of the *DT* representative model is at an early, or infant, stage of maturity.

In the extended investigation of our study, a robust association was found, between weekly updates and non-protected data models. The protected data model shows the correlation with real-time, hourly, and daily updates as encapsulated in Table 11. This observation underscores the progression of the *DT* maturity level.

Table 12 illustrates the relationship between *model update frequencies* and *the verification and validation (V&V)* methods employed in *(DT)* implementations. As *DTs* progress from foundational

Table 10. Co-Occurance of Studies on Model Update Frequency (*RQ3.1.P1*) and Twin Models (*RQ3.1.P2*)

	Weekly update	Daily update	Hourly update	Real-time
Design time DT	[6, 11, 16, 24, 26, 42, 44, 49, 64, 77, 78, 82, 88, 91, 93, 95, 96, 98, 101, 105, 111, 118, 123, 125, 127, 132, 133, 140, 156, 157, 161, 166, 170]	[69, 126]	N/A	N/A
Runtime DT	[40, 54]	[9, 17, 19, 21, 22, 25, 33, 41, 51, 52, 66, 70, 75, 90, 107, 114, 152–154, 163, 164, 171, 173]	[1, 4, 39, 53, 56, 79–81, 84, 97, 106, 112, 117, 119, 120, 155, 162, 169]	[3, 14, 20, 57, 85, 116, 128, 134, 136, 138, 144–146, 167, 168]

Table 11. Co-Occurance of Studies on Model Update Frequency (*RQ3.1.P1*) and Model Security (*RQ3.1.P3*)

	Weekly update	Daily update	Hourly update	Real-time
Protected	[40]	[9, 17, 19, 21, 25, 41, 52, 66, 70, 75, 90, 114, 152–154, 163, 164, 171, 173]	[1, 4, 53, 56, 80, 81, 84, 97, 106, 112, 117, 119, 120, 155, 162, 169]	[3, 14, 20, 57, 85, 128, 134, 136, 138, 144–146, 167, 168]
Non-protected	[6, 11, 16, 24, 26, 40, 42, 44, 49, 54, 64, 77, 78, 82, 88, 91, 93, 95, 96, 98, 101, 105, 111, 118, 123, 125, 127, 132, 133, 140, 157, 161, 166, 170]	[22, 33, 51, 69, 107, 126]	[39, 79, 116]	

Table 12. Co-Occurance of Studies on Model Update Frequency (*RQ3.1.P1*) and Verification and Validation of DT Models (*RQ3.1.P4*)

	Weekly update	Daily update	Hourly update	Real-time
Simulation	[6, 24, 40, 64, 77, 82, 88, 93, 118, 123, 125, 133, 157, 161, 166, 170]	[69, 153, 171]	[1, 4, 53, 112, 117]	[57, 146]
Model-checking	[11, 49, 54, 91, 96, 105, 127, 132]	[9, 22, 41, 51, 52, 66, 70, 75, 90, 107, 114, 152, 154, 163, 173]	[39, 79, 81, 97, 106, 119, 120, 155, 162, 169]	[16, 20, 85, 128, 138, 167, 168]
Testing	[16]	[17, 21, 25, 164]	[56, 80, 84]	[3, 14, 134, 136, 144, 145]

to advanced stages, there is a notable shift in update frequency and V&V techniques. In the foundational phase, *DTs* often rely on weekly updates and primarily utilize simulation and model-checking methods for validation. This approach provides a basic level of synchronization between the physical and digital counterparts. As systems mature, the update frequency increases to daily or hourly intervals, incorporating testing methods to enhance accuracy and reliability. *DTs* achieve real-time updates in the most advanced stages, employing comprehensive testing methodologies to ensure immediate and precise reflection of the physical system's state [160]. This progression underscores the evolution of the maturity of *DT*, highlighting the importance of frequent data updates and robust V&V processes to maintain the integrity and performance of the system.

6.2 Implementation of Digital Twin (RQ3.2)

This section aims to address RQ3.2 *: How can the advancement of digital twin implementation be evaluated to assess its maturity in cultural heritage?* . This sub-research question aims to assess the implementation stage of digital twin technology, supporting the main research question in evaluating its current maturity level in the TCH domain. To address this objective, we've employed the following parameters:**implementation stage**, **connectivity mode**, and **computational**

intelligence because these parameters are crucial in DT development, as they ensure effective communication between the physical and virtual twins, accurately represent the physical system, and integrate the necessary computational capabilities for analysis and simulation. Within the literature, there have been multiple endeavors to establish a framework for gauging the maturity or sophistication levels of *DTs* [104]. The initial definition takes a sector-wide perspective, primarily focused on the industry. This categorization delineates the following levels: level 1 or *pre-DT* (virtual system model with an emphasis on technology/technical-risk mitigation); level 2 or *DT* (virtual system model if the physical twin exists); level 3 or *adaptive DT* (virtual system model of the physical twin with adaptive UI); level 4 *intelligent DT* (virtual system model of the physical twin with adaptive UI and reinforcement learning) [80, 142]. From this definitional framework, our exploration delves into the **implementation stage**. This investigation aims to measure the maturity level of *DT* applications, specifically in the context of *TCH*. Our study presents an in-depth picture, revealing that within the spectrum of digital twins, *DT*, and adaptive *DT*, *DT* holds the most influence, dominating the landscape with 59 (≈ 55%) out of the 108 included studies. This is followed by the *pre-DT* category, accounting for 40 (≈ 37%) studies, while *adaptive digital twin* claim a smaller share, represented in only 9(≈ 8%) studies. Notably, the intelligent DT category remains unexplored, as no studies have delved into its maturity level, presenting an area ripe for further investigation. This signals an infancy stage, calling for concerted efforts to propel *DT* applications to higher levels of sophistication. The unexplored realm of intelligent *DTs* provides an avenue for future research, presenting an exciting opportunity to advance the capabilities of *DTs* within the rich tapestry of *TCH*.

DTs tailored for *TCH*, the profound impact of **connectivity modes** on the orchestration of data flow between the physical entity and its virtual counterpart is paramount. This section provides an in-depth exploration of *bidirectional*, *unidirectional*, and *automatic* connectivity within the unique context of *DTs* designed for *TCH* preservation and exploration [169]. The selection of a specific connectivity mode emerges as a pivotal factor, serving as a critical determinant in the comprehensive assessment of the *DT* maturity level [142]. From this perspective, our comprehensive studies embark on an exploration of the existing connectivity landscape, which includes 108 meticulously selected studies. The findings shed light on the prevalent connectivity status within this domain. Notably, 51 (≈ 47%) out of the total studies predominantly employ *unidirectional* connectivity characterized by the singular flow of data in either direction, from the physical entity to the *DT* or vice versa. This *unidirectional* approach is instrumental in scenarios where a one-way exchange of data suffices for the objectives of monitoring or control. Conversely, *bidirectional* connectivity, denoting a dynamic and reciprocal exchange of data between the physical entity and its digital representation in both directions, is evident in 47 (≈ 44%) studies. This mode facilitates real-time interactions, feedback loops, and a synchronized exchange of information, enriching the *DT* capabilities. Moreover, the examination reveals that *automatic* connectivity, where the *DT* autonomously initiates, establishes, and maintains connections with the physical entity without requiring manual intervention, is featured in 5 (≈ 5%) studies. This autonomy streamlines processes, enhancing operational efficiency and reducing the need for constant human oversight. However, it's noteworthy that in 5(≈ 5%) studies, connectivity between the physical and virtual entities is not explicitly demonstrated.

In digital twin advancement, **computational intelligence** plays a significant role in evaluating the maturity of *DTs*. Computational capabilities combine *statistical modeling* to comprehend the behavior of the system using historical data, *predictive modeling* to anticipate future behavior and outcomes, and *adaptive behavior* to adapt and learn autonomously from the environment [124]. The results of our study highlight the significant emphasis placed on predictive modeling, which was utilized in 47 (≈ 44%) out of 108 surveyed studies. Statistical modeling is used in 36 (≈ 33%) studies, while adaptive behavior is found in only 10 (≈ 9%) studies. In particular, 15 (≈ 14%) studies do not

Table 13. Co-Occurance of Studies on Stage of Digital Twin Implementation (*RQ3.2.P1*) and Connectivity Mode (*RQ3.2.P2*)

	Pre-digital twin	**Digital twin**	**Adaptive digital twin**	**Intelligent digital twin**
Unidirectional	[6, 11, 24, 33, 42, 44, 45, 49, 50, 64, 73, 74, 77, 78, 82, 88, 92, 93, 95, 98, 101, 105, 109, 111, 123, 125–127, 133, 140, 141, 150, 156, 161, 166, 170]	[16, 22, 26, 30, 40, 54, 91, 96, 108, 110, 118, 132, 157, 163]	N/A	N/A
Bidirectional	N/A	[9, 14, 17, 19, 20, 25, 39, 41, 51–53, 56, 57, 66, 69, 70, 75, 79, 81, 84, 85, 90, 106, 107, 112, 114, 116, 117, 120, 128, 134, 136, 138, 144–146, 152–155, 164, 167, 168, 173]	[1, 56, 80, 119, 128]	N/A
Automatic	N/A	[97]	[3, 21, 162, 169]	N/A

explicitly outline the modeling techniques used within computational intelligence. These discoveries have significant implications, indicating a dominant tendency in *DT* implementation that places a strong emphasis on statistical modeling. This observation initiates a thorough evaluation of the current maturity level of *DTs* at the initial stage, particularly within the *TCH* domain.

Answer to Research Question 3.2. Assessing the maturity level of *DTs* in the *TCH* domain involves a multifaceted examination, encompassing *implementation stages* ,*computational intelligence* and *connectivity modes*. This task is to identify the current implementation stage, evaluate the connectivity mode and computational capacity, which are integral elements in assessing the sophistication and effectiveness of *DT* applications. In measuring the implementation stage, well-established categories are employed, delineating the journey from *pre-DT* to *intelligent DT*. Each stage aligns with specific connectivity modes such as unidirectional, bidirectional, and automatic, showcasing the evolution in information flow as the implementation stage progresses. The correlation between *implementation stages,connectivity modes*, and *computational intelligence* illustrates that as the implementation stage advances from *pre-DT* to *intelligent DT*, the strength of connectivity also advances from unidirectional to automatic information flow,while computational intelligence advances from statistical modeling to adaptive behavior. The prevailing connectivity paradigm in *TCH* leans heavily towards unidirectional modes, predominantly featuring *DT* stages. This underscores the foundational maturity level, prompting a call for exploration into advanced connectivity modes like bidirectional and automatic communication, as well as predictive modeling and adaptive behavior. We delved into prominent patterns, evident in the co-occurrence displayed in the provided Tables 13 and 14, consecutively.

7 Discussion

This article provided an in-depth exploration of the rapidly evolving applications of *DT* technology in *TCH*, emphasizing its transformative potential from a user perspective, the enabling technologies driving its adoption, and an evaluation of its current maturity level [32, 47].

Figure 1 presents a tri-dimensional, taxonomy-informed conceptual framework for *DT* applications in *TCH*, addressing RQ1–RQ3 along three dimensions: user-centric applications, enabling technologies, and maturity and operations. Relationship strengths (strong, moderate, and weak) ,determined based on the frequency and consistency of evidence reported in the reviewed literature.. User-centric applications cover artwork types, purposes (preservation, conservation, and restoration), and *DT* techniques, showing preservation relies on photogrammetry and laser

Table 14. Co-Occurance of Studies on Stage of Digital Twin Implementation (*RQ3.2.P1*) and Computational Intelligence (*RQ3.2.P3*)

	Pre-digital twin	**Digital twin**	**Adaptive digital twin**	**Intelligent digital twin**
Statistical modeling	[8, 11, 24, 33, 42, 50, 77, 88, 92, 93, 95, 98, 105, 109, 123, 125–127, 131, 133, 140, 161, 166, 170]	[16, 17, 25, 26, 30, 51, 70, 91, 110, 118, 132, 157]	N/A	N/A
Predictive modeling	[49]	[9, 14, 19, 20, 22, 39–41, 52–54, 57, 66, 75, 79, 81, 84, 85, 90, 96, 97, 107, 112, 114, 116, 120, 134, 136, 138, 144, 146, 153–155, 155, 163, 164, 167, 168, 173]	[80, 119]	N/A
Adaptive behaviors	N/A	[117, 145, 152]	[1, 3, 21, 56, 128, 162, 169]	N/A

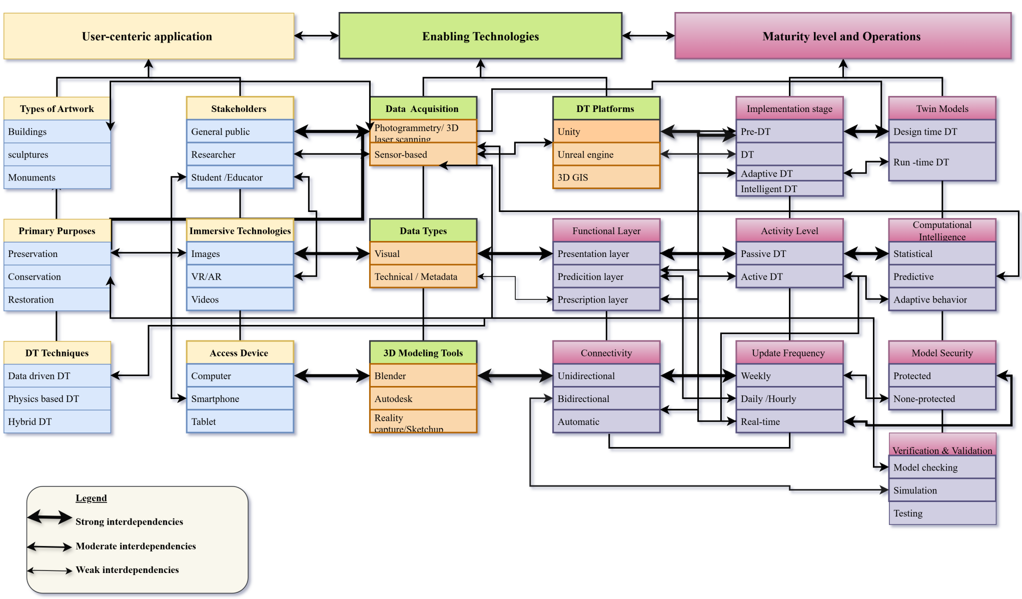

Fig. 1. Taxonomy-informed conceptual framework for *DT* applications in tangible cultural heritage, structured along three complementary dimensions: user-centric applications, enabling technologies, and maturity levels, along with their interdependencies. Arrow thickness indicates relationship strength: thick lines = strong, medium lines = moderate, thin lines = weak.

scanning, conservation uses sensor-based monitoring, and public-oriented applications favor image-based visualization while immersive VR/AR is limited. Enabling technologies include data acquisition, 3D modeling, and visualization platforms, with design-time models relying on photogrammetry/laser scanning, runtime monitoring on sensors, and platforms like Unity Reflect enabling immersive experiences. Maturity and operations capture lifecycle stages, twin models, functional layers, connectivity, update frequency, security, V&V, and computational intelligence, revealing early-stage dominance with presentation layers, unidirectional connectivity, limited predictive capabilities, and intelligence evolving from statistical models to adaptive behaviors in advanced *DTs*.

User-Centric Applications of DT: *DT* technology in *TCH* has fundamentally transformed how users interact with and experience cultural assets. From the user's perspective, *DTs* serve as powerful tools for public engagement, educational outreach, and research facilitation. Immersive technologies such as VR and AR enrich user interactions, offering immersive explorations of heritage artifacts and sites [92, 98]. However, recent studies reveal that static 3D models remain predominant, while fully interactive DT-driven VR/AR experiences are rare, highlighting a significant gap between research and practice [136, 161]. This gap highlights the opportunity to expand immersive platforms to make *TCH* experiences more dynamic, inclusive, and engaging, particularly for younger audiences and students. In practice, the Louvre Abu Dhabi's XR project and the Virtual Rome initiative demonstrate how DT-driven VR/AR can scale heritage education and tourism, but these remain isolated cases rather than systemic adoption [36, 43]. Additionally, *DTs* offer researchers a risk-free method to analyze artifacts, while educators and students gain unprecedented access to interactive learning resources [49]. Nevertheless, the limited focus on these user groups in current research underscores the need to broaden educational and accessibility-driven applications of DTs, ensuring inclusivity and engagement for diverse audiences.

Enabling Technologies: The development and deployment of *DTs* for *TCH* rely on advanced enabling technologies, including data acquisition methods, modeling tools, and platforms. While 3D laser scanning and photogrammetry dominate for their precision and efficiency, sensor-based methods remain underutilized. Integration of real-time environmental monitoring through sensor data could greatly enhance *DTs*, enabling dynamic updates and proactive conservation strategies [107]. Current *DT* implementations heavily emphasize the presentation layer (visualization), but predictive and prescriptive layers remain underdeveloped. Progress in these areas is vital for unlocking the full potential of *DTs* as dynamic, intelligent systems capable of real-time monitoring, simulation, and intervention. Recent findings confirm that most TCH-related *DTs* are still "unidirectional," synchronizing data from physical to digital, but lacking feedback loops to inform real-world interventions [7]. Advancing connectivity and cyber-physical intelligence could enable *DTs* to transition from passive representations to adaptive, interactive systems that respond dynamically to environmental and operational changes [124]. Moreover, the limited application of runtime *DTs* within the domain reflects the nascent maturity of the field. While design-time *DT* play an essential role in planning and strategizing cultural preservation, runtime *DTs* hold immense potential for real-time intervention and dynamic operational control. For instance, the Notre-Dame *DT* project integrates sensor-driven runtime monitoring for structural risk prediction, demonstrating the practical feasibility of real-time updates for heritage resilience.

Evaluating DT Maturity Levels: The maturity of *DT* applications in tangible cultural heritage is still in its infancy. Most implementations align with foundational *DT* or pre-*DT* stages , characterized by static digital models and limited real-time interaction. Adaptive and intelligent DTs, which incorporate real-time updates, predictive modeling, and autonomous behaviors, remain largely unexplored. Weekly or daily model updates, rather than real-time synchronization, dominate heritage DT implementations, confirming the observations of Refs. [84, 138, 163] that maturity in this field lags far behind industrial DT practice. Significant gaps in data security, simulation capabilities, and real-time interactivity hinder the evolution of *DTs*. Addressing these challenges through investments in advanced technologies, robust frameworks, and interdisciplinary collaboration is crucial for enhancing *DT* maturity. Such advancements would enable *DTs* to transition from basic visualization tools to comprehensive systems capable of supporting predictive and prescriptive functionalities for conservation and management. To support this transition, leveraging advanced platforms such as Unity Reflect, Unreal Engine, or cloud-based solutions like AWS IoT TwinMaker can provide scalable infrastructure for managing complex data and real-time synchronization in heritage DT projects [80, 142]. Furthermore, fostering collaborative ecosystems that involve stakeholders from technology, heritage conservation, and academia will accelerate the adoption and sophistication of *DTs*.

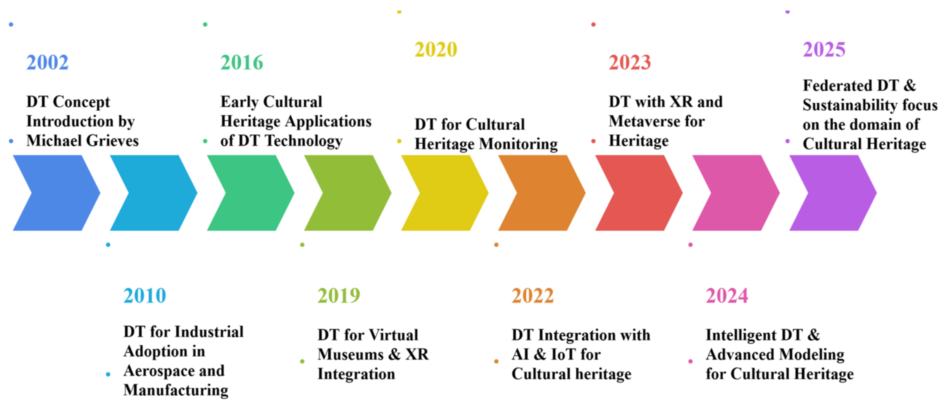

Fig. 2. Timeline of *DT* evolution in cultural heritage (2002–2025), highlighting milestones from conceptual origin to intelligent and federated *DT* frameworks. Adapted from [3, 5, 27, 47, 55, 58, 73, 74, 100, 137].

7.1 Historical Context and Evolution DT

Originally developed for industrial and engineering applications, *DT* technology has progressively emerged as a key enabler for the monitoring, conservation, preservation, dissemination, and management of *TCH* assets [32, 132]. By enabling dynamic digital replicas of artifacts, monuments, and heritage sites, *DTs* support real-time monitoring, simulation, and interaction, offering innovative approaches to mitigate degradation, environmental risks, and long-term deterioration [97].

The shift from traditional documentation methods (e.g., drawings, casts, and photographs) toward digitally integrated workflows reflects a broader transition to data-driven heritage preservation, powered by IoT, AI, machine learning, 3D scanning, and XR technologies [29]. In parallel, standardized UX evaluation frameworks (e.g., ISO 9241-210) have gained relevance in assessing immersive heritage platforms, ensuring accessibility, usability, and effectiveness across diverse user groups [5]. Recent real-world applications, including the Notre-Dame restoration, IoT-based monitoring of church artworks, and XR-supported museum education, confirm the growing maturity of these integrated approaches [7, 55].

Figure 2 presents a chronological overview of the evolution of *DT* technology from its conceptual origin in 2002 to advanced applications in cultural heritage by 2025. The timeline highlights major milestones, including the initial development of *DT* concepts for industrial systems (2002–2010), early adoption in cultural heritage contexts (2016), integration with virtual museums and XR platforms (2019), and the incorporation of AI and IoT for heritage monitoring (2022). Recent developments emphasize immersive XR and metaverse-based experiences (2023), intelligent *DTs* and advanced modeling (2024), and federated *DT* frameworks with sustainability considerations (2025). This evolution reflects the transition from static digital representations to adaptive, intelligent, and collaborative *DT* systems for cultural heritage.

8 Open Challenges and Future Directions

This section highlights the open research challenges identified through the analysis of *DT* technology in *TCH* and outlines future research directions to address these gaps. These challenges span technological, methodological, legal, and practical aspects.

8.1 Open Challenges from the Analysis

Enhanced Data Interoperability: A critical challenge is the lack of interoperability among heterogeneous data sources, including 3D scans, IoT sensors, environmental data, and historical records [152]. Most *DT* implementations operate in silos, limiting data sharing, increasing costs, and hindering cross-institutional collaboration. Developing open standards, metadata schemas, and interoperable protocols is essential to enable seamless data exchange and multi-stakeholder collaboration [21, 145].

Comprehensive Data Integration: Current *DTs* emphasize geometric and structural data, often neglecting contextual information such as cultural significance, oral histories, and intangible heritage [18, 146]. This reduces authenticity and educational value. Integrating rich metadata, historical narratives, and environmental data can support more meaningful representations and informed conservation decisions [39, 97].

Advanced Modeling Techniques: Most *DT* models remain visualization-oriented, with limited predictive or prescriptive capabilities [169]. Hybrid approaches combining data-driven techniques with physics-based models can better capture material decay, structural behavior, and risk evolution. Recent AI-driven monitoring and DT-supported restoration projects demonstrate the potential of predictive modeling for proactive conservation [39].

Immersive, Scalable, and Inclusive Applications: Although VR and AR are increasingly explored, many applications remain static and device-dependent [126]. Scalable DTs that support immersive interaction across mobile, web, and XR platforms are needed to enhance education, tourism, and public engagement while ensuring accessibility and inclusivity [44, 107].

Security and Ethical Governance: As *DTs* manage sensitive heritage data, cybersecurity and ethical concerns become critical [71, 152]. Blockchain and encryption can protect data integrity and access, but governance frameworks are also required to address digital ownership, copyright, and data sovereignty across institutional and national boundaries [167].

8.2 Future Directions

Building on these challenges, future research must adopt more practical, interdisciplinary, and forward-looking approaches to *DTs* in cultural heritage.

First, **integration of AI, IoT, and cloud computing** should move beyond visualization to enable predictive analytics, adaptive conservation, and real-time decision support. Case studies such as Notre Dame's DT-enabled restoration and IoT-based church monitoring demonstrate that these approaches are already feasible but require broader validation and standardization.

Second, the adoption of **Federated Digital Twins (FDTs)** offers a promising direction. Unlike centralized DTs, FDTs enable secure, decentralized collaboration across multiple institutions. They address interoperability and privacy challenges by allowing distributed data processing while ensuring local data sovereignty. *FDT* frameworks could standardize formats, governance protocols, and data sharing agreements between heritage institutions, making *DT* solutions more scalable and sustainable.

Third, **maturity assessment frameworks** are urgently needed. Current *DT* implementations lack structured evaluation, hindering progress from static models toward intelligent, adaptive systems. Future research should establish benchmarks that assess update frequency, interactivity, bidirectional connectivity, and integration of contextual metadata.

Finally, **inclusive and accessible *DT* design** should prioritize lightweight, mobile-first, and web-based solutions for diverse users, including tourists, educators, and scholars, lowering technological barriers for equitable access. XR-based virtual tourism frameworks [5] further enable remote, immersive exploration of heritage sites, reducing physical degradation while enhancing learning and engagement. Overall, advancing interoperable, intelligent, and federated *DT* ecosystems ensures heritage preservation is technologically advanced, ethically grounded, accessible, and sustainable, supporting education, public engagement, and research in the digital era.

9 Conclusion

This study presents a comprehensive review of *DT* applications in *TCH*, structured around user-centric applications, enabling technologies, and maturity levels. Findings reveal that most DTs remain in early-stage development, relying on static models and unidirectional data flows. Interactive features, real-time updates, and adaptive intelligence are underutilized. The lack of standardized maturity frameworks and limited integration of metadata and sensor-based data hinder progress. To address these gaps, we propose adopting **Federated Digital Twins** (**FDTs**), cloud-based platforms, and inclusive design strategies that support diverse users and devices. Embedding structured evaluation models and nurturing interdisciplinary collaboration will allow *DTs* to evolve into intelligent, scalable, and ethically grounded systems. These advances will improve the preservation, education and public participation of cultural heritage in the digital era. In particular, our tri-dimensional framework provides a roadmap that can guide museums, heritage authorities, and real-world practices in designing scalable and interoperable DT solutions while ensuring their evolution toward inclusive, sustainable, and high-impact applications. Beyond the academic contribution, this study offers an instrument to position cultural heritage's current practices with respect to the state-of-the-art, and actionable recommendations for researchers, policymakers, and practitioners.

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