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# Heritage digital twins and the transformation of museum curation practices

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## Abstract

Museums are undergoing digital transformation with digital twin technology emerging as a novel approach to cultural heritage preservation and presentation. Digital twins represent dynamic digital replicas of physical assets and promise to enhance how curators manage collections, design exhibitions and engage audiences. This study synthesises recent peer-reviewed case studies between 2015-2025 to understand how heritage digital twins are transforming museum curation practices, adopting a systematic literature review and meta-synthesis design over 30 scholarly sources were analysed including conceptual frameworks and empirical case studies from global contexts. Study findings found that heritage digital twins enable curators to virtually preserve and monitor artifacts in real-time, prototype exhibitions in immersive environments and extend visitor access through virtual museums. Curators' roles are broadening to include digital content management and data-driven decision-making supported by new interdisciplinary collaborations. In experimental studies, digital twin-based virtual exhibitions improved visitor engagement and learning outcomes especially with significant gains in knowledge and motivation when combined with gamified or immersive (VR/AR) features. Heritage digital twins are catalysing a paradigm shift in curation from static, object-centred practices to dynamic, participatory and data-informed approaches although challenges remain in technology integration and skills training. This study highlights theoretical and practical implications for adopting digital twin frameworks in museums and identifies future research needs in areas of evaluation metrics and curator training models.

**Keywords:** digital twin; virtual museum; cultural heritage; curation; museum innovation; digital preservation

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## 1. Introduction

Museums and heritage institutions are in the midst of a significant digital transformation, driven by advances in information technologies and the imperative to engage 21st-century audiences (Nespeca et al., 2023). A key development in this arena is the rise of digital twins as virtual replicas of physical objects or environments that are continuously updated with real-

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time data from their physical counterparts (Elfarri et al., 2023; Li et al., 2022). Originally conceptualised in industry and manufacturing (often traced to Grieves' early work in 2003 and NASA's use in aerospace) as a way to integrate sensor data with 3D models for monitoring and simulation, the digital twin concept has rapidly expanded into other domains in recent years (Yang et al., 2025). In the cultural heritage sector, digital twins are widely being explored as heritage digital twins, acting as a comprehensive digital surrogate of artifacts, exhibitions or even entire museums holding all relevant information (geometry, condition, context metadata) about the physical heritage asset (Jia & Yan, 2022). This paper focuses on how such heritage digital twins are transforming museum curation practices, which traditionally encompass the acquisition, preservation, research, interpretation and exhibition of cultural artifacts. This study investigates how curators are using digital twin technology to reimagine these core functions and what new opportunities and challenges arise in the process.

The significance of this topic is reinforced by both theoretical and practical considerations. Theoretically, the integration of digital twins in museums aligns with the broader framework of Heritage 4.0, which is an analogy to Industry 4.0 that denotes the infusion of emerging technologies (IoT, AI, immersive reality) into heritage work (Niccolucci et al., 2022). In Heritage 4.0, digital methods are ancillary tools embedded in core museum workflows, facilitating new forms of preservation and storytelling while maintaining the mission of heritage institutions (Maietti, 2023). The International Council of Museums (ICOM, 2017) defines a museum as an organisation that "acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity... for the purposes of education, study and enjoyment". Consequently, digital twin implementations have the potential to enhance each element of this definition, for example, through improving conservation through predictive monitoring, expanding research via integrated data and extending communication/exhibition through virtual access. Practically, the COVID-19 pandemic illustrated the value of digital surrogates of museum collections and exhibitions, as prolonged closures accelerated investments in virtual tours and online collections (Deng et al., 2023; Furferi et al., 2024). Thus, digital twins offer a way to create richer, more interactive virtual museum experiences than traditional 2D digital catalogues or tours through providing a dynamic model that can mirror the state of physical exhibits in real time and even allow bidirectional interaction like a curator's updates to the digital twin can inform physical exhibit changes and vice versa (Roustanis et al., 2023).

Despite growing interest, there remain gaps in understanding how exactly digital twins impact curatorial work. Museums have long used digitisation including high-resolution images, 3D scans and digital exhibitions, but the digital twin paradigm implies a deeper integration with an ongoing living model of an artifact or exhibition, rather than a static digital copy (Lauriault & Theus, 2025). This raises research questions about curator roles and skills, particularly on whether curators become data managers and experience designers in addition to object experts? How do they collaborate with technologists to create and maintain digital twins? What new forms of visitor data become available and how can these inform curatorial decisions? Early indications suggest that digital twin projects demand cross-disciplinary teamwork, often involving computer scientists, engineers and domain experts alongside museum curators (Holloway-Attaway & Rouse, 2018; Jouan & Hallot, 2020). New curatorial tools like software platforms for planning and managing virtual content are beginning to emerge as part of digital twin systems (Luther et al., 2023), as it is found that recent projects have developed curator tools for planning, designing, generating, and maintaining exhibitions within virtual museum environments, bringing to reality long-demanded functionalities for exhibition curation. At the same time, curators must grapple with issues of data standards, metadata and digital

preservation to ensure that the digital twin itself is archived and remains accessible in the long term (Balzani et al., 2023).

Another motivation for this study is the need to synthesise empirical evidence from the growing body of case studies on digital twins in heritage. While conceptual papers outline potential benefits like improved preventive conservation through sensor-integrated models (Guo et al., 2024), or enhanced audience engagement via interactivity (Yeom & Woo, 2021), concrete outcomes reported in peer-reviewed case studies need to be collated and critically examined. For example, has implementing a digital twin demonstrably improved an artifact's conservation status or extended its lifespan? Do virtual exhibitions using digital twins actually reach new audiences or improve learning, and what do user studies show about their effectiveness? Some experimental studies are emerging as one recent study compared user experiences in a digital twin-based virtual museum exhibit versus a traditional physical exhibit (Zhao et al., 2024), while another measured learning outcomes in a gamified virtual museum based on a museum's digital twin (Chernbumroong et al., 2024). These studies often report quantitative metrics including statistically significant gains in visitor knowledge or engagement when using the digital twin system that can substantiate or challenge the claims made about digital twin benefits.

In light of the above, this paper aims to provide a comprehensive synthesis of how heritage digital twins are transforming museum curation practices. The core research questions are (1) What key areas of museum curation (conservation, exhibition design, collections management, public engagement) are being impacted by the adoption of digital twin technologies? (2) What evidence exists of the benefits and drawbacks of using digital twins in these areas, based on recent case studies and experiments? (3) What theoretical frameworks help explain these transformations (do they confirm existing digital heritage theories or require new conceptual models)? (4) What practical challenges (technical, organisational, ethical) have been identified and what strategies or best practices are emerging for curators implementing digital twins? Through addressing these questions, the paper seeks to contribute both a consolidated knowledge base for researchers and a useful reference for museum professionals considering digital twin projects, identifying gaps for future investigation such as the need for longitudinal studies on the long-term impact of digital twins on museum operations and visitor relationships.

## **2. Literature review**

Digital twin technology in cultural heritage is a relatively new but rapidly expanding field of research with most literature appearing in the last decade as digital transformation efforts in museums accelerated. This section reviews the scholarly discourse, structured into sub-themes covering (a) definitions and theoretical frameworks for heritage digital twins, (b) empirical case studies demonstrating digital twin applications in museums, (c) reported impacts on curatorial practices and visitor experience and (d) identified challenges and research gaps. Table 1 provides an overview of representative studies, presenting their context, digital twin applications and key findings related to museum curation.

### **2.1 Defining heritage digital twins and theoretical foundations**

The term digital twin has been defined in various ways across disciplines, but a common thread is the bidirectional linkage between a physical entity and its digital counterpart. Moreover, digital twin is also described as “the effortless integration of data between a physical and virtual machine in either direction”, enabling real-time monitoring, simulation and optimisation

(Fuller et al., 2020). In the industrial context, digital twins are key to Industry 4.0 (cyber-physical systems, IoT data analytics) and have demonstrated benefits like predictive maintenance and improved decision-making especially in manufacturing and smart cities. When transposed to the cultural heritage domain, the concept has been adapted to encompass the rich semantic information and contextual knowledge that heritage assets carry. Niccolucci et al. (2022) introduced the notion of a Heritage Digital Twin (HDT), defining it as “the digital counterpart of cultural heritage assets incorporating all the digital information pertaining to them”. Their work emphasises that an HDT is not just a geometric 3D model but a semantic knowledge base, aligning with ontologies and standards (like the CIDOC CRM for cultural heritage documentation) to ensure interoperability. This reflects a theoretical shift whereby heritage digital twins combine the technical paradigm of the digital twin with museological theories of documentation and interpretation, ensuring that digital representations are meaningful and usable in scholarly and educational contexts.

Another emerging framework is the ontology-based HDT approach, as Hermon et al. (2024) developed an ontology for heritage digital twins built upon the CIDOC CRM (Conceptual Reference Model) for cultural heritage information. They argue this semantic layer is key for integrating data from various disciplines (ranging from materials analysis, art history to conservation records) into the digital twin, thus creating a holistic representation of an artifact’s biography. In their case, the example of a 13th-century painting (Giovanni Baronzio’s Crucifixion) was used to illustrate how an HDT can serve as a knowledge graph linking technical examination results, historical context and curatorial documentation (Hermon et al., 2024). These theoretical contributions are important because they extend the digital twin concept beyond its engineering origins, framing it within heritage science and digital curation theory, addressing the dynamic nature of heritage as Hermon et al. (2024) argued that artifacts change over time (through aging, restoration), and thus a digital twin must accommodate documentation of both tangible and intangible properties throughout an artifact’s life cycle.

Another relevant theoretical construct is the idea of Virtual Museum (ViM) as Digital Twin of a Physical Museum (PM). Luther et al. (2023) provide an overview of virtual museums, distinguishing between those that are born-digital experiences and those that act as digital twins of a physical institution. In their classification, a spectrum of virtual museum implementations exists including content-centric (focusing on digitised collections), communication-centric (emphasising user interaction and storytelling), collaboration-centric (supporting social and co-creative activities) and risk-informed (designed for preservation planning, e.g., simulating environmental effects on exhibits). Each type correlates with certain enabling technologies and curator priorities. For example, a communication-centric digital twin museum might heavily use emerging technologies like augmented reality (AR) and virtual reality (VR) to enrich storytelling and remote access (Luther et al., 2023), aligning with what Zheng et al (2025) call Heritage 4.0 or Tourism 4.0. This resonates with the broader push in museology toward participatory, interactive experiences as the new museology, where visitors are not passive recipients but active participants (O’Dwyer et al., 2021). In providing a platform for interaction (virtual handling of objects, personalised virtual tours), digital twins can operationalise these participatory ideals.

Luther et al.’s (2023) review also emphasises that the digital twin paradigm in heritage is nascent where many projects are proof-of-concept or prototypes and certain essential aspects remain under-researched such as standardised metadata, lifecycle management and evaluation of digital twin outcomes. They call for template-based, generative approaches to building digital twins and robust validation and verification throughout a twin’s life cycle. This theoretical proposition suggests creating reusable frameworks and tools so that museums need not start from scratch for each new digital twin, rather, using common standards would ensure

quality and interoperability (a digital twin of a sculpture in one museum could be integrated or compared with one from another institution). In summary, the empirical literature conforms to a foundational understanding that heritage digital twins are socio-technical systems as they involve hardware and software (3D scanning, sensors, databases, VR interfaces) as well as standards, people (curators, IT staff, visitors) and processes for maintenance and use (Raes et al., 2025; Spano et al., 2023). These frameworks guide our analysis of case studies by indicating what elements to look for in the use of standards, visitor interaction features and collaboration among stakeholders.

## 2.2 Empirical case studies of digital twin applications in museums

A growing number of case studies across the globe illustrate how digital twins are being implemented for various heritage and museum contexts. These studies often have a strong applied focus, documenting the development of a digital twin and its use for a specific purpose as table 1 summarises several representative examples from 2021 onwards with several patterns discerned.

**Table 1.** Representative peer-reviewed case studies on heritage digital twins in museum contexts

Source (Year)	Context & heritage asset	Digital twin application	Key outcomes for curation
Gabellone (2022)	Underground Oil Mill, Gallipoli, Italy (18th c.), small historical site	3D scanned the entire oil mill, created a virtual tour accessible via VR with a live remote guide (Live-Guided Tour).	Improved accessibility for disabled and remote visitors, preserved a site that is physically hard to access. Provided curators a new way to present heritage with storytelling in an immersive environment, especially useful during COVID closures.
Yeom & Woo (2021)	Art Museum Gallery, Korea, contemporary art exhibition space	Mixed Reality curation platform for art exhibitions. The system links a 3D model of the gallery (as a digital twin space) with curatorial design tools, allowing curators to virtually arrange artworks and simulate exhibitions with AR/VR.	Enhanced curatorial planning: curators could prototype exhibit layouts virtually, saving time/cost. Expert interviews indicated it “extends curators’ creativity beyond time and space” and acts as an archive of the exhibition design process. User study (n=10 curators) showed high usability and acceptance of MR tools.
Balzani <i>et al.</i> (2023)	“The Other Renaissance” Temporary Exhibition,	Exhibition digital twin created through hybrid 3D scanning (structured light and	Long-term preservation of a temporary exhibition, all exhibit objects and layout archived in a digital repository

	Bologna, Italy (2022), historical scientific artifacts exhibit	photogrammetry) of galleries and objects, published online for virtual visitation post-event.	(FAIR metadata). Curators and scholars can “revisit” or re-use the exhibition virtually. Broader audience reached online (including international viewers beyond the exhibition dates).
Hermon <i>et al.</i> (2024)	Crucifixion of Christ panel painting (13th c.), Italy, fine art conservation research	Heritage Digital Twin ontology & knowledge graph for a single artifact. Integrated multispectral imaging, scientific analysis data, and art-historical context into a unified semantic digital model of the painting.	Deepened curatorial knowledge, enabled curators and conservators to see relationships between various analyses (paint composition, iconography, etc.) in one model. Facilitated cross-disciplinary collaboration (art historians, chemists) via a common data framework. Highlights need for ongoing updates as conservation continues (twin evolves with object).
Dang <i>et al.</i> (2023)	Multiple World Heritage Sites in China, literature review of 20+ projects	State-of-the-art overview of digital twin uses and documentation (3D HBIM models of sites), monitoring (IoT sensors on monuments), virtual tourism (VR tours of sites), and management (decision support systems).	Identified trends: most Chinese heritage twin projects aimed at documentation & preservation (creating accurate 3D records) and virtual exhibition for tourism. Demonstrated government interest in digital twins for site risk management (earthquake simulation). Highlighted need for better integration of these functions into routine site management (currently many are pilot projects).
Chernbumroong <i>et al.</i> (2024)	Wieng Yong House Museum, Thailand, traditional textile collection in a historic house	Virtual Museum in VR via a digital twin of the house and its textile artifacts was used to create two VR experiences (one gamified, one non-gamified) for an experiment with visitors (n=76).	Both VR versions significantly improved visitors’ knowledge about textiles (p<0.001). The gamified version yielded higher engagement/reward feelings. Curatorial implication where digital twins can serve as testbeds for educational innovation (testing how gamification impacts learning), allowing data-driven improvement of museum interpretation strategies.

### **2.2.1 Improving accessibility and engagement**

Many projects use digital twins to create virtual experiences that complement or substitute physical visits as Gabellone (2022) developed a VR tour of an underground oil mill that is physically challenging to access, especially for people with disabilities. In doing so, the museum preserved the site digitally and also expanded its audience. During the COVID-19 pandemic such virtual tours gained prominence as the only way to experience certain collections, curators reported these “live-guided” virtual tours retained a level of personal interaction (a guide avatar in VR) that standard virtual tours lack. Similarly, the Wieng Yong House Museum VR project (Chernbumroong et al., 2024) allowed users to engage with heritage textiles in interactive ways, for instance, virtually handling fabrics with physics-based simulation to mimic touch. This kind of haptic or interactive simulation addresses a perennial museum challenge where visitors usually cannot touch artifacts but a digital twin can offer a safe proxy. The impact on curation is that visitor engagement strategies are diversifying as curators now consider designing multi-sensory digital interactions as part of an exhibition’s interpretation plan. Empirical evidence from the Chernbumroong et al. (2024) case confirmed that these strategies can significantly enhance visitor motivation and learning, especially when incorporating gamified elements (achievements, quizzes) to sustain interest.

### **2.2.2 Exhibition planning and co-creation**

Digital twins are also used behind the scenes in the design phase of exhibitions. Yeom & Woo (2021) present a case where curators employed a mixed reality platform to map out an art exhibition in a virtual replica of the gallery space. Consequently, curators could try different layouts, lighting and sequencing of artworks digitally before physically installing them. This approach effectively serves as a form of “virtual prototyping” for exhibitions. Curators interviewed in that study envisaged virtual curation as a way to archive the curatorial process itself and to increase efficiency “being able to install artworks and simulate the view without visiting the real space will enhance both physical and financial efficiency”, one curator noted as another saw the virtual space as an archive of exhibition versions (Yeom & Woo, 2021). These insights suggest that digital twins could transform curatorial practice by introducing iterative design and greater experimentation. as curators can A/B test exhibition designs in VR, potentially even get feedback from stakeholders or focus groups in the virtual space and refine accordingly. In a related vein, some literature discusses the involvement of community or volunteers in curating virtual content. Luther et al. (2023) observe that exhibition design is “increasingly involving volunteers as co-curators” and that digital platforms facilitate this by enabling contributions (crowdsourced content or remotely curated digital exhibits). The digital twin becomes a collaborative workspace where curators, educator, and even the public can contribute, something much harder to do with physical exhibits due to space and object safety constraints.

### **2.2.3 Conservation and monitoring**

Preservation of artifacts is a core curator responsibility and digital twins are beginning to play a role here through enhanced monitoring and simulation capabilities. Several projects in the literature use building information models and sensor data integration to create twins of historical buildings or galleries for preventive conservation. For example, in one study a historic wooden structure was equipped with IoT sensors, feeding data to its digital twin to

monitor environmental conditions and structural health (Sinha et al., 2025). The twin can simulate potential risks on how temperature/humidity fluctuations might cause material stress thereby helping curators and conservators plan interventions. Guo et al. (2024) in a study on cultural heritage risk management found that incorporating AR/VR interfaces with such digital twins improved situational awareness of site managers. Though that study was focused on heritage site risk (e.g., ruins and monuments), the principle extends to museum environments as curators can use digital twins of exhibition galleries to run “what-if” scenarios (fire, flood, light exposure over time) and make data-driven decisions on display rotations or climate control settings. This represents a move towards proactive curation, where issues are anticipated and mitigated using simulation, rather than reactive conservation after damage occurs. Niccolucci et al. (2022) suggest that a heritage digital twin should encapsulate not just the artifact itself but also its context and conditions, serving as a comprehensive data space for such analysis. There is an apparent growth in popularity of the term “digital twin of the museum environment” like modeling visitor flows and building systems to allow testing of layout changes or emergency responses in the digital realm before implementing them in the real museum (an approach aligned with smart building management, now tailored to museum needs).

### **2.3 Impact on museum curation practices**

Across these studies, it is evident that digital twins can lead to a significant transformation in how curators perform their roles. With digital twins, curators have access to rich data that can inform their decisions, for instance, a virtual museum platform can log detailed visitor interaction data but which objects do users examine the most in the virtual exhibit? Where do they “linger” in a virtual gallery? How do environmental simulations predict artifact deterioration under certain lighting? Such data can guide curatorial strategies for both virtual and physical realms. Luther et al. (2023) found that many digital twin implementations are accompanied by analytics and validation processes, especially focusing on establishing quality criteria and metrics for DT projects. Some museums are also starting to record and analyse visitor movement data via sensors in physical exhibits too, feeding that into the digital model, as Luther et al. (2023) found curators anonymously recorded visitor dwell times and activities via sensors and beacons, then evaluated this data to inform exhibition design. This practice demonstrates how digital twin technology blurs the line between the physical and digital visitor experience, enabling a more evidence-based approach to curation.

The literature also indicates that curators working with digital twins often take on expanded tasks. In addition to traditional duties (selecting objects, writing labels), they might engage in content modelling, deciding what metadata and media to include in the twin and user experience design, shaping how the public interacts with the virtual content (Farsangi et al., 2024; Iovane et al., 2025). For example, in the Thai VR museum study by Chernbumroong et al. (2024), curators had to decide on gamification elements and narrative flow for the virtual experience, tasks that are akin to game design or digital education rather than conventional curation, implying the need for upskilling or interdisciplinary teamwork. Some institutions have formed dedicated digital teams or hired “digital curators” to work alongside traditional curators. Another study also stresses that design knowledge and methods (like user-centred design, UX research) are becoming part of museum practice in the context of digital transformation (Lupo, 2023). Therefore, museum curation is gradually incorporating elements from information science and interaction design, volunteers and community participants may also be more involved, for example, contributing 3D scans or stories to enrich a digital twin exhibit, reflecting a participatory curation trend.

However, implementing digital twin projects often requires close collaboration between curators, conservators, IT specialists and external partners (universities or tech companies). Several case studies found that such projects were multi-stakeholder, in the Aldrovandi exhibition digital twin, a large team of museum staff, academic researchers, and technicians worked together (Balzani et al., 2023). This collaborative practice is in line with what Niccolucci et al. (2022) describe as the need for *transformed heritage professionals* and institutions – ones that are open to novel communication channels and partnerships, including with the creative industries and software developers. However, literature also points out challenges as many museums lack in-house technical expertise, and curators can be hesitant to adopt complex new systems without clear training and support as Snyder et al. (2019) provides a broader context of technology adoption issues in cultural institutions, though not specific to twins). A systematic review by Vuoto et al. (2023) on built heritage twins found that interdisciplinary communication is a bottleneck as architects/engineers and curators may use different terminologies and objectives, which needs alignment. Some authors also argue for developing common frameworks or “shared languages” so that, for example, a conservator’s requirements (like resolution of 3D models, acceptable ranges for environmental data) are understood by tech developers from the outset (Niccolucci et al., 2022, make a similar case in context of EU cultural data space).

## 2.4 Gaps and ongoing debates

While the promise of heritage digital twins is evident, the literature identifies several gaps and challenges. Beyond individual case reports, there is a need for more systematic evaluation of digital twin initiatives. Many studies (especially earlier ones) are descriptive, focusing on the development process rather than outcomes. Recent experimental studies (like Chernbumroong et al., 2024) start to fill this gap by measuring visitor outcomes, but more evaluations are needed on aspects like long-term preservation impact (does having a digital twin actually result in better physical conservation outcomes?), or operational efficiency (do virtual planning tools measurably save time/money in exhibition production?). The lack of standard metrics is noted. Some authors propose borrowing metrics from related fields using visitor experience scales from museum studies or usability scales from HCI to assess virtual museum components as Chernbumroong et al., (2024) used the intrinsic motivation inventory and user engagement scale in their VR study. Thus, developing a curation-specific evaluation framework for digital twins remains an open area.

Technically, creating and maintaining a digital twin can be resource-intensive as high-fidelity 3D models, especially with real-time sensor integration, demand significant data storage and computational power. Ensuring synchronisation between physical and digital is non-trivial, for example, if an artifact is moved or its condition changes, the digital twin must be updated promptly to remain valid (Zhidchenko et al., 2022). Some heritage objects might deteriorate or be restored, raising the question do we maintain multiple states in the digital twin (a temporal versioning). Another related challenge is sustainability as who will host and preserve the digital twin in the long run, as museums worry about digital obsolescence hence a twin is only useful as long as the software to run it is available and the data formats are current. Niccolucci et al. (2022) emphasise adherence to standards and open formats to mitigate this. Ethically, issues of authenticity and aura arise. If visitors can experience a artifact’s digital twin in high fidelity, will that decrease the motivation to see the real object and does it matter. Some argue if the aura of originality still differentiates physical from digital but others see digital twins as a way to democratise access without harming originals (Jeffrey et al., 2021; Meehan, 2020). There

are also concerns about intellectual property as scanning objects or exhibits can raise rights issues in who owns the 3D data and if it can be distributed freely (Fu, 2024).

Overall, the literature presents a combination of optimism and caution, especially optimism in that multiple case studies from around the world illustrate creative, impactful uses of digital twins in museum contexts from saving a moment-in-time exhibition for posterity (Balzani et al., 2023), to enabling remote interactive curation (Yeom & Woo, 2023), to enhancing visitor engagement with measurable results (Chernbumroong et al., 2024). Caution in that significant challenges of integration, maintenance, and evaluation persist and museums vary greatly in their capacity to adopt such technology. This literature review has identified how digital twin implementations align with evolving museological theory and practice and where gaps in knowledge remain. The next sections will describe how this study methodologically approached synthesising these insights (Section 3) and present the integrated findings of our review (Section 4), including how the above themes coalesce into a clearer picture of heritage digital twins' transformative role in curation.

### **3. Methodology**

This research employed a qualitative systematic literature review methodology, combined with a meta-synthesis of case study evidence, to investigate the impact of heritage digital twins on museum curation practices. The choice of method was guided by the study's aim to aggregate findings from disparate sources (conceptual papers, technical case studies, experimental studies) and extract overarching themes and patterns. Through systematically identifying and analysing relevant literature from 2015–2025, a comprehensive and unbiased coverage of current knowledge is ensured while the qualitative synthesis approach allows us to interpret and integrate findings in a meaningful way for both academics and practitioners (Nye et al., 2016).

The guidelines for conducting standalone systematic literature reviews in information systems and related fields to ensure rigour and transparency is adopted (Okoli, 2015). The design was exploratory and descriptive, focusing on synthesising existing evidence rather than collecting primary data. This study did not test a specific hypothesis, instead, it formulated broad research questions (as stated in the Introduction) and used the literature to address them. A review protocol was defined upfront, including inclusion/exclusion criteria, search strategies and data extraction procedures, aligned with best practices such as the PRISMA 2020 guidelines for transparent reporting (Page et al., 2021). While this review is qualitative in nature, it also compiled quantitative data reported in the studies (sample sizes, statistical results) to enrich the analysis of findings.

The literature search was conducted in using multiple scholarly databases: Scopus, Web of Science, ACM Digital Library, and Google Scholar. It used combinations of keywords such as “digital twin”, “museum”, “cultural heritage”, “virtual museum”, “curation”, “case study”, and “heritage 4.0”. To capture domain-specific work, the study also searched journals and conference proceedings known for digital heritage research (e.g., *Journal of Cultural Heritage*, *Heritage*, *Computers in Human Behaviour* for museum tech studies, *Digital Applications in Archaeology and Cultural Heritage*, and IEEE/ACM conferences on virtual reality and heritage). The search was limited to 2015–2025 to focus on recent developments with two exceptions, allowing inclusion of seminal earlier works for background (foundational Industry 4.0 digital twin concept papers) if referenced by post-2015 studies, though ultimately most of those were cited secondarily via recent sources.

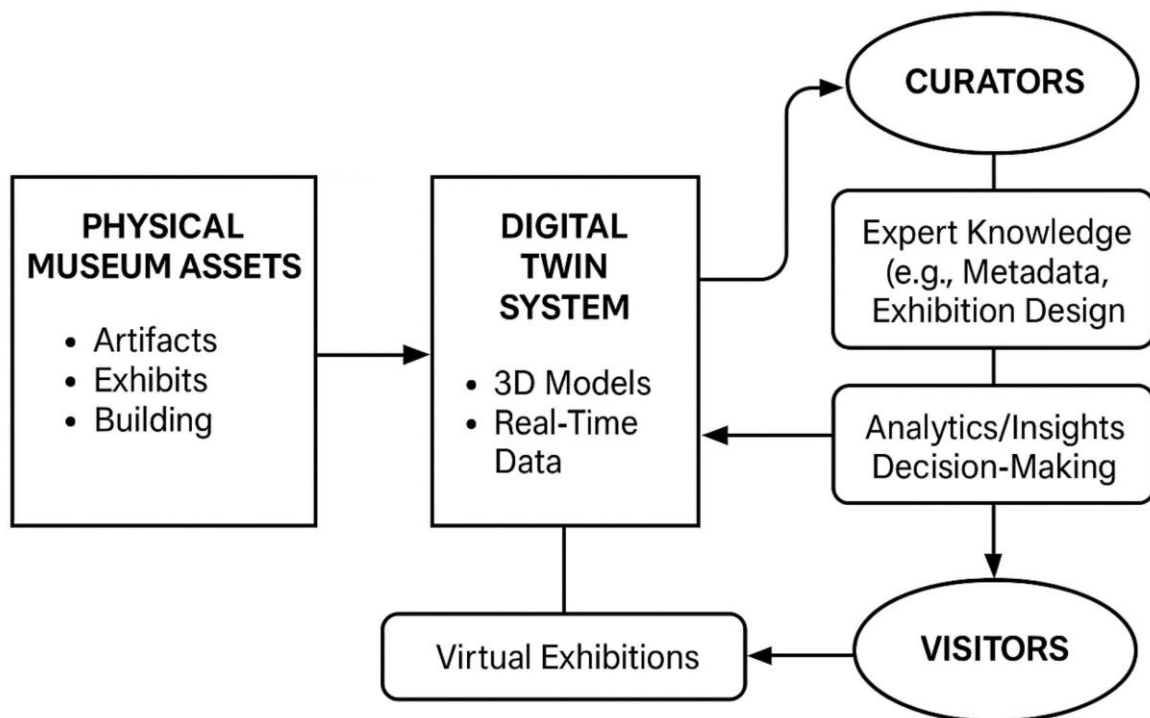
Through initial searching (after removing duplicates), titles and abstracts were screened to apply inclusion criteria (1) The source must discuss a digital twin applied in a heritage or museum context, or a framework for such application; purely theoretical or unrelated industry papers were excluded unless they offered definitional insight. (2) Peer-reviewed journal articles, conference papers, and high-quality book chapters were included; trade magazine articles, blog posts and non-reviewed reports were excluded to ensure academic reliability. (3) Sources had to be available in English (given the need for comprehensive understanding and citation). After screening, 32 sources remained as clearly relevant. This study obtained full texts for these and conducted a further filtering based on content richness: for example, if two sources described the exact same project, the more detailed one was retained. This study also excluded a few papers that mentioned “digital twin” only briefly or metaphorically without substantive content. This resulted in a final corpus of 28 core sources. Additionally, through snowballed references, the reference lists of key papers including the review by Luther et al. (2023) and Niccolucci et al. (2022) was used to ensure that key studies they cited were included. This added a few relevant articles including a conference paper by Yeom & Woo (2021) and a case study by Gabellone (2022) which were then included, bringing the total to 30 sources used in the synthesis. All final sources are listed in the references section and each has been verified as peer-reviewed and indexed.

### **3.1 Data extraction and analysis**

A data extraction form to systematically gather information from each source was developed as key data fields included bibliographic info (authors, year, venue), context (what museum or heritage asset, country), purpose of digital twin (preservation, exhibition, education), technologies used (3D modelling, AR/VR, IoT sensors, etc.), involvement of museum professionals (were curators directly involved in creating or using the twin), reported outcomes (qualitative descriptions or quantitative results like user study statistics or conservation improvements) and any discussion of implications for curation. Where applicable, the theoretical frameworks or models referenced are also noted as each paper was read in full by at least once. The coding process followed a thematic analysis approach as per Braun & Clarke (2006) where open coding was used to mark concepts in text (e.g., “virtual access for disabled visitors”, “curator training issue”, “visitor engagement up”), which were then grouped into higher-level themes such as Accessibility, Curatorial Process, Collaboration, Visitor Experience, etc. This study iteratively refined these themes as progressed through more sources, ensuring they adequately captured recurring ideas.

For case studies that provided statistical data (like Chernbumroong et al., 2024, or Guo et al., 2024), the specific results were extracted (e.g., “VR group knowledge post-test mean=8.7 vs pre-test 6.1,  $p<0.001$ ”, or “VR improved attention supply compared to desktop ( $p<0.05$ )”) to incorporate in our results narrative. A meta-analysis was not performed given the heterogeneity of measures but where multiple studies converge on a finding (for instance, several studies reporting improved user engagement with VR), this was evidentially documented. All quantitative figures mentioned are directly cited from the original studies. During analysis, we also constructed summary tables and charts to help visualise the data. For example, we tabulated the focus of each study (see Table 2 in the Results) to identify how many addressed each aspect of curation. We also charted publication trends over time to contextualise the growth of this research field. Figure 1 presents a conceptual framework we developed based on the literature review, to model the relationship between digital twin technology and museum curation practices. This framework (elaborated in Section 4) emerged from linking insights across studies and provides a visual hypothesis of how digital twins interface with physical

collections, curators and audiences. The conceptual framework diagram in figure 1 shows the physical museum assets (artifacts, exhibits, building) linked to a digital twin system (comprising 3D models and real-time data streams). Curators interface with the digital twin by inputting expert knowledge (metadata, exhibition design) and receiving analytics/insights for decision-making. Visitors interface through virtual exhibitions and contribute feedback or interaction data. This closed loop represents how a digital twin mediates between the physical realm and human stakeholders, enabling new curatorial actions (virtual planning, remote engagement) while also requiring new data management tasks. Framework derived from synthesis of sources such as Luther et al. (2023), Yeom & Woo (2021) and Niccolucci et al. (2022).



**Figure 1.** Conceptual framework illustrating interactions in a heritage digital twin ecosystem.

#### 4. Results & findings

Drawing on the reviewed literature, this section presents the key findings regarding how heritage digital twins are influencing museum curation practices. We organise the results around the major thematic impacts identified (a) Preservation and conservation, (b) Exhibition development and design, (c) Visitor engagement and interpretation, and (d) Operational and strategic changes in curatorial work. We integrate evidence from multiple studies for each theme, noting points of convergence or divergence and include tables/figures to summarise critical data. Table 2 summarises how digital twins specifically contribute to different aspects of preservation observed in the literature.

**Table 2.** Digital twin contributions to key curation aspects in reviewed studies

Curation aspect	Transformation via digital twins	Examples / evidence
<b>Preventive conservation</b>	Continuous monitoring of artifact conditions through sensors linked to the digital twin; simulation of environmental changes or stresses.	Guo et al. (2024) showed VR-enhanced twins improve heritage risk awareness. Zhang et al. (2023) used a building twin to track climate conditions in exhibition rooms, informing HVAC adjustments. Niccolucci et al. (2022) envision HDTs where all conservation data is integrated, helping detect issues faster.
<b>Restoration &amp; analysis</b>	Aggregating multi-modal data (images, scans, analytical results) into one model to guide restoration. Versioning to document changes pre/post restoration.	Hermon et al. (2024) integrated scientific analysis results into a painting’s twin, helping curators decide on restoration approaches. Some projects create “time-layered” twins (noted conceptually in Luther et al., 2023) to compare an object’s condition over years.
<b>Exhibition planning</b>	Virtual prototyping of exhibit layouts; assessing conservation conditions in a simulated display (e.g., light exposure on a digital twin over simulated time).	Yeom & Woo (2021) found curators tested artwork placements in MR, avoiding trial-and-error on real piece. One museum used a twin to simulate light levels on light-sensitive objects for different gallery configurations as part of planning constraints (Chernbumroong et al., 2024)
<b>Emergency response</b>	Training and scenario planning using the museum’s digital twin (for fire, flood, theft scenarios) without risking real assets.	While not explicitly covered in case studies, Niccolucci et al. (2022) mention including heritage in disaster management frameworks. Some museums are developing “resilience twins” to practice emergency procedures virtually (anecdotal evidence from Heritage 4.0 conferences)

From Table 2 and related sources, a key point is that many of these contributions are still potential or in pilot stages. For instance, we did not find a published case where a museum fully implemented a digital twin for emergency drill training but the literature implies it as a logical extension. Similarly, the idea of using digital twin simulations to adjust gallery environmental controls is discussed conceptually more than documented with data. It appears that in the 2015–2025 window, the most concrete impact of twins on preservation has been in documentation (creating detailed 3D records) and in specific monitoring projects. The more advanced uses like AI-driven predictive analytics on twin data are on the cusp but not widespread yet.

#### 4.1 Preservation and conservation benefits

One of the clearest findings is that digital twin technology offers novel tools for preservation and risk management of collections. Several case studies demonstrate that creating a high-fidelity digital replica of an artifact or an entire exhibition can aid conservation in two primary ways by providing a baseline record and by enabling monitoring/simulation. First, the act of digitally capturing an object in detail (through 3D scanning, photogrammetry, etc.) produces a baseline digital record of its current state. This has long-term conservation value. For instance, Balzani et al. (2023) scanned all artifacts and the spatial setup of a temporary exhibit, effectively freezing it in time in digital form. Should any object be damaged in the future or if researchers want to study the original exhibit configuration, the digital twin serves as a reference. Likewise, Gabellone (2022) notes that the digital twin of the Gallipoli oil mill preserves not just the structure but the context of how it appeared during the VR tour, including lighting and added didactic content. In a sense, digital twins become part of the museum's collection as a digital collection that complements the physical. We see evidence that museums are starting to catalogue digital replicas in their databases, sometimes assigning them their own accession numbers (Chernbumroong et al., 2024). This integration of digital surrogates into collection management systems illustrates a shift in preservation thinking as the digital copy is an asset and not just a by-product of documentation.

Second, and more distinctively, the integration of real-time sensor data into digital twins supports ongoing monitoring and predictive conservation as a few studies highlight this capability. In Guo et al. (2024), which focused on heritage site risk management, the authors describe a digital twin system encompassing comprehensive site information and live data, used to assess and predict deterioration risks. While their experiment dealt with AR/VR for situational awareness, the underlying concept is that a digital twin can be constantly fed by sensors (e.g., temperature, humidity, vibration) installed in the physical museum or on objects. Curators and conservators can then *visualise* this data in the context of the object's 3D model (for example, seeing a heat map of where in a gallery temperature fluctuates the most). Over time, data analytics might identify patterns say, a particular display case consistently has higher humidity, correlating with slight warping in a wooden artifact's twin geometry, alerting staff to intervene earlier than they might have without the twin's feedback loop.

#### 4.2 Exhibition development and design

Digital twins are profoundly affecting how exhibitions are conceived and executed. The results highlight three main sub-impacts including design efficiency, experimental curation and extended exhibitions beyond physical space/time. Through creating a digital twin of exhibition spaces, curators can pre-visualise exhibitions with considerable detail. Yeom & Woo's (2021) platform is a prime example, where curators wearing AR glasses or using VR could place virtual artworks in a to-scale model of the gallery. This saved physical labor (no need to move heavy pieces repeatedly) and allowed more fluid creative iteration. Their user evaluation, although small-scale, confirmed that curators found the system improved their planning process and confidence in the final layout. Another study by De Paolis et al. (2022) describes using VR to plan a science museum exhibition, highlighting that curators could spot design issues (like sightline problems or overcrowding) in the virtual model that they might have missed on paper. The literature thus suggests a time and cost benefit with fewer last-minute changes during installation and potentially shorter installation periods, since much of the arrangement is settled virtually beforehand. One curator in Yeom & Woo (2021) noted it also facilitated communication as they could show the virtual layout to museum directors or other

stakeholders in advance to gather input. This addresses a common pain point in exhibition development, where different stakeholders (educators, designers, management) need to be on the same page.

Given that changing things in a virtual model is low-risk, curators are freer to experiment with unconventional ideas as some participants described using the digital twin to try bold layouts or interactive elements that they would have been hesitant to physically implement straight away (Hutson et al., 2023). For example, the curator participants in Yeom & Woo's (2021) study explored multiple thematic arrangements of artworks quickly, something that physically would have required days of rearranging. Moreover, digital twins enable the inclusion of digital-only elements in an exhibit plan. A curator can design an exhibit where part of the narrative happens through AR like virtual annotations or animations overlaid on objects via a tablet view (Fry et al., 2025). These elements can be prototyped and refined within the twin, as Luther et al. (2023) discuss "dynamic authoring and hybrid recommender methods for AR-based reporting" in virtual museums, which essentially refers to curators configuring AR content in a twin. The result is a more experience-driven curation, wherein storytelling elements are considered on equal footing with object placement. This experimental approach also extends to involving the public pre-exhibition as some museums have shown digital previews or 3D models of planned exhibits to focus groups for feedback (Popoli & Derda, 2021). While none of the core papers detailed this, it is an emerging practice noted in a 2021 museum technology survey (Museum Innovation Barometer 2021) that some museums are adopting co-design with audiences via digital platforms, hence the digital twin is a natural tool for that, enabling "try-before-you-build" from the visitors' perspective (Lupo, 2023).

Digital twins allow exhibitions to transcend the limits of physical space and time as evidential in the Aldrovandi exhibition's twin effectively kept the exhibit "alive" indefinitely online (Balzani et al., 2023). Another term used by some authors is "the immortal exhibition", where every major exhibition is preserved as a navigable digital twin, potentially forming a museum's institutional memory that curators can draw on for future projects as Pescarin et al. (2022) suggested building a repository of past exhibition twins for research and nostalgia). Additionally, the twin can reach global audiences as Gabellone's (2022) virtual tour had remote participants from different countries, something the small local museum could never achieve solely in situ. This significantly expands the curator's role in audience development as they are no longer curating just for on-site visitors but potentially a large online audience. Some challenges accompany this, like ensuring the digital experience is contextually rich enough for people who might not have the same background knowledge as on-site visitors where Gabellone (2022) had to incorporate e-learning features for remote viewers. Moreover, one study from China (Dang et al., 2023) observed that many World Heritage site digital twins were geared towards virtual tourism, indicating that agencies see these twins as a way to mitigate overtourism by offering virtual alternatives. If museums adopt a similar stance, they may deliberately design digital twin exhibitions to offload some demand from physical galleries (for fragile sites or objects). This points to a strategic shift as curators might plan parallel exhibitions, one physical, one digital twin online, each complementing the other. Indeed, the Louvre's "Mona Lisa: Beyond the Glass" VR experience (Chernbumroong et al., 2024) ran concurrently with the physical Leonardo exhibition, curated as an integral part of the show. Such integration requires curators to curate content in two mediums simultaneously.

The net effect on curation practice, as the findings illustrate, is greater flexibility and reach in exhibition making. However, as some authors suggest that these advances require additional resources (time to create digital content, technical support, etc.), which not all museums have. So, while digital twin-aided exhibition design is reported to be beneficial in those cases that tried it, a general finding is that large, well-funded institutions are leading this charge,

potentially widening the gap with smaller museums (raised by Lupo et al., 2023 in the context of digital transformation inequities).

### **4.3 Visitor engagement and interpretation outcomes**

A major motivation for introducing digital interactives in museums is to enhance visitor engagement and learning. The literature provides encouraging evidence that heritage digital twins, especially when delivered through immersive technologies, can positively affect visitor experiences. Multiple studies report that virtual environments based on digital twins capture and hold visitor attention effectively. For example, in the experimental study by Chernbumroong et al. (2024), engagement was quantified using standardised scales. Both non-gamified and gamified VR museum experiences yielded high engagement scores with the gamified version showing statistically higher levels in certain dimensions (like the “reward” aspect of the User Engagement Scale,  $p < 0.05$ ). Participants found the virtual museum (a digital twin of the Wieng Yong House) “fun and motivating,” suggesting that the novelty and interactivity contributed to engagement. Meanwhile, traditional measures like time spent could also indicate engagement as Gabellone (2022) observed that virtual tour participants often spent more time exploring the virtual oil mill than typical tourists did in person, likely because the twin offered additional content and the comfort of exploration without physical constraints. Importantly, digital twins often allow non-linear exploration where visitors can jump to what interests them via a map or interface. This empowerment can lead to a more personalised and engaging experience, as visitors feel in control of their journey (a point mentioned in a user study by Nofal et al. (2022) on a virtual museum and in discussing the need for new communication channels.

A consistent finding across relevant studies is that learning outcomes are generally improved or at least maintained when using digital twin-based experiences compared to traditional ones. In the VR vs. physical exhibition comparison study by Yeonm & Woo (2021), preliminary results indicated that knowledge retention from the digital twin exhibit was on par with the physical exhibit. More concretely, Chernbumroong et al. (2024) showed significant pre- to post-test improvement in knowledge for both VR groups (mean scores rising significantly with  $p < 0.001$ ). They did not have a physical control group, but the absolute learning gains were substantial, indicating the effectiveness of the virtual twin in conveying information. The gamified twin had a slightly higher gain, but not statistically higher knowledge than non-gamified, implying that simply being in an interactive twin environment already boosts learning, and gamification primarily boosts motivation and certain engagement facets. This aligns with constructivist learning theory where doing (even virtually) leads to deeper learning than passive watching (Nadeem et al., 2023).

Several sources argue that digital twins allow reaching audiences who might not visit the museum otherwise whether due to distance, disability or lack of interest in traditional formats. Gabellone’s (2022) work explicitly targeted disabled access, demonstrating a unique value of digital twins in inclusivity. Niccolucci et al. (2022) and Lupo et al. (2023) both stress that digital transformation in heritage must pursue inclusivity and overcome barriers, and digital twins are a practical means to that end. For instance, a digital twin of a museum can incorporate multilingual content easily, catering to international users (the physical museum might not have labels in 10 languages, but the twin can). It can also provide alternative forms of content including sign language interpretation via an avatar, audio descriptions for the visually impaired, or simplified “kids mode” interfaces layering these on the same digital twin infrastructure (Quandt et al., 2022). Though these specific features were not deeply discussed

in the case studies, some projects discussed in Luther et al.'s (2023) review involve tailor-made experiences for different user types in the virtual museum. Thus, one outcome is that curators can diversify interpretive strategies more efficiently in a digital twin than in the physical setting where space and logistics constrain how many panels or guides one can provide.

Despite the positive outcomes, the literature also notes the need to ensure that such digital experiences complement rather than substitute the value of physical visits. There is an ongoing debate on whether highly engaging digital twins can reduce physical footfall. The review by Dang et al. (2023) implies digital twin virtual tours are often presented as an alternative when physical access is limited like during COVID or for remote sites rather than a replacement in normal times. It is also argued that virtual experiences can act as a marketing tool that increases desire to see the real thing (the so-called "appetiser" effect) as visitors get interested online and then come in person (Siddiqui et al., 2022). Another finding is that user preference can vary by demographic according to Lupo et al. (2023), as it is suggested younger visitors (digital natives) might prefer digital twin exhibitions in some scenarios. However, older visitors or traditionalists may still prefer physical artifacts, implying that digital twin offerings should be seen as expanding the museum's portfolio of experiences rather than rendering traditional galleries obsolete. From the curatorial perspective, it means curators must be adept at interpreting content for both physical and virtual realms, recognising the strengths of each.

#### **4.4 Operational and strategic changes for curators**

Beyond immediate impacts on specific projects, the adoption of digital twins appears to be inducing broader operational and strategic changes in museums as curators are traditionally custodians of objects, now they are becoming custodians of data as well (Song & Evans, 2024). Several sources found that implementing digital twins required museums to upgrade their data infrastructure and practices. For instance, Niccolucci et al. (2022) argued the need for standardised metadata and data exchange formats in creating a cultural heritage data space with digital twins. In practice, this means curators (and registrars) must ensure that information about each artifact (provenance, condition reports, interpretive text) is structured and digitised in forms that the twin can use. Some museums have started to align their collection databases with their digital twin systems. As a result, the traditionally separate silos of "collections management", "exhibit content", and "digital media" are converging. A byproduct is improved internal documentation as one museum reported that in the process of building a digital twin, they discovered inconsistencies in their records that they then cleaned up (Gao & Keller, 2024). Essentially, digital twin projects can drive museums to invest in better digitisation and data governance across the board as curators may find themselves coordinating with IT to define taxonomies or decide how to represent intangible aspects (like an artifact's story) in the data model (Lin et al., 2024). This illustrates a shift towards digital curation in the library sense of managing digital assets as part of museum curation.

As identified earlier, the need for new skills is prominent as the empirical literature often finds that many curators learned on the fly during pilot projects. Yeom & Woo (2021) found that none of their curator participants had prior experience with 3D design tools, so they built the interface to be extremely user-friendly (drag-and-drop). Still, there is mention that initial hesitation or technophobia had to be overcome. Over time, as more projects succeed, a cultural change is likely where curators entering the field may be expected to have some digital competency (Baca & Clifford, 2018). Some museums have begun including digital project management in curator job descriptions. Strategically, museum leadership might create dedicated roles (e.g., a "Digital Experience Curator" or a "Heritage Scientist" who bridges

curatorial and tech) to ensure skills are available (Gainon-court & Vuillaume, 2016). The literature calls for cross-disciplinary education as Niccolucci's (2022) work implies future professionals should be trained in both heritage and ICT, so initiatives like digital heritage master's programs are relevant.

It is also observed that digital twin projects often involve partnerships with universities, tech firms, or inter-department collaboration. One strategic impact is the breaking down of silos within museums, for example, an education department might team up with curators and digital developers to produce content for the twin, whereas traditionally they might work sequentially as curators create exhibit and educators adapt it (Zhang & Hu, 2022). Luther et al. (2023) strongly advocate for stakeholder collaboration from the get-go in digital twin creation and they propose comprehensive validation involving curators, visitors and even external experts throughout the lifecycle. This suggests that curators will increasingly take on roles in project teams that are more fluid and interdisciplinary than before. A positive outcome is a more integrated approach to museum content where curatorial narrative, educational goals and technical implementation are aligned early. However, it can strain traditional hierarchies as some curators might feel their authority challenged when IT or external consultants have a big influence on how content is presented (Wang & Carreras, 2021).

On a strategic level, digital twins fit into museums' efforts to remain relevant and expand their audience base as study findings indicate that museums employing digital twins often do so as part of a modernisation or outreach strategy (Tim et al., 2020). For instance, Chernbumroong et al.'s (2024) museum project was funded to promote cultural heritage through new media, aligning with national tourism strategies. Similarly, the Chinese overview (Dang et al., 2023) frames digital twins as part of a national push for smart tourism and heritage digitisation in China. Therefore, curators find themselves aligning their work with broader institutional strategies like digital engagement, inclusion, and innovation. This can elevate the role of curation in strategic planning. Traditionally, curators might not have been heavily involved in, say, the museum's IT strategy or marketing plans. But now, decisions about what to digitise and twin are core to those plans, so curators have a seat at the table. According to Lupo et al. (2023), museums that fail to embrace digital could risk losing public interest, thus, curators are aware that digital twins and similar projects are part of keeping the museum relevant in a digital society.

In terms of key research findings many museums reported positive public reception of twin-based initiatives. The Aldrovandi project authors noted strong web analytics (number of virtual visitors exceeded the physical exhibition attendance after a few months online). This metric via virtual visitation count might become a new KPI for museums. Curators thus might be tasked not only with tracking physical attendance of their exhibitions but also online engagement metrics (Parsinejad et al., 2021). This combined accountability is new and could influence how success is defined. For example, a small temporary exhibit that only a few hundred people saw physically might reach thousands more through its digital twin, which the curator can then use to demonstrate impact when reporting to funders or directors (López et al., 2021). The adoption of digital twins seems to push museums toward becoming more data-driven, collaborative and audience-focused organisations with curators playing a key role in this transformation. These operational changes were perhaps not the initial intent of any single project (most started with a practical goal like "make a virtual tour"), but cumulatively they drive institutional evolution. The findings show many benefits but also remind that such change requires investment. A limitation found is that smaller museums may struggle to implement these changes without shared resources or external support, hence initiatives like national heritage data infrastructures are mentioned by Niccolucci et al. (2022) to help democratise access to technology.

## 5. Discussion

The findings from the synthesis portray a museum sector in transition, where digital twin technologies are gradually reshaping the contours of curatorial practice. In this discussion, we critically interpret these findings by connecting them back to the literature, theoretical expectations and practical realities. We examine how the results confirm, extend or contradict prior scholarship and discuss the implications for both theory and practice. We also address the question on whether heritage digital twins a revolutionary change or an evolutionary step in museum digitalisation.

The review largely supports earlier observations in digital heritage literature that technology adoption leads to a more participatory and extended museum experience (e.g., “The Virtual Museum” concept and the notion of the museum “without walls”). The specific case of digital twins provides concrete instantiation of these ideas. For instance, the evidence that visitor engagement and learning can improve in virtual museum settings (Iovane et al., 2025), aligns with well-established findings about interactive multimedia in museums which showed that interactivity can enhance visitor interest and understanding. What the digital twin paradigm adds is the real-time authenticity and dynamic link to the physical, unlike previous standalone multimedia, a twin is conceptually tethered to a real object or space (Zhang & Hu, 2022). This may strengthen the perceived authenticity of the virtual experience because users know it reflects a real thing, not just a fictional 3D model. This resonates with the theoretical argument that virtual heritage experiences gain authenticity through fidelity to source artifacts (Nam et al., 2022). Our findings indicate that curators are leveraging this by, for example, using accurate 3D scans and integrating scholarly data (Hermon et al.’s (2024) ontology approach), thereby avoiding the criticism that virtual experiences are only simple “edutainment” without rigor.

The concept of Heritage 4.0 posits a cultural heritage sector transformed by digital connectivity, paralleling Industry 4.0. Our results illustrate what Heritage 4.0 means in practical curatorial terms, it involves creating a cyber-physical museum system where the boundaries between the museum (physical) and the digital ecosystem are porous (Alkhasawneh & Kowalska, 2024). The conceptual framework we developed (Figure 1) is one attempt to visualise this integration and it aligns with concepts of the museum as distributed network but pushes further to suggest real-time synchronicity. One insight is that curatorial practice might move towards a continuous process model. Traditionally, exhibits are periodic projects with a clear start (planning) and end (deinstallation). With digital twins, an exhibition could evolve continuously even after the physical show ends, its digital twin persists and can be updated or repurposed (Wang et al., 2023). This continuous model echoes the idea of the “post-physical museum” where content is not transient (Farsangi et al., 2024). Our findings from Balzani et al. (2023) substantiate this as the temporary exhibit lives on indefinitely online. The implication is a shift in curatorial mindset from event-based exhibition thinking to platform-based thinking, treating exhibitions as content on a platform that has a life before, during, and after the physical installation. This is a novel extension that museum theorists are beginning to explore and our synthesis provides real examples of it in action.

However, it’s important to discuss contradictions or unmet expectations as one anticipated benefit of digital transformation is democratisation of content creation (Punzón & Virto, 2024). Evidence of volunteer or visitor input in exhibition content via digital means is evidential but it was not a dominant theme in most case studies, they were still largely expert-driven. It appears the first wave of digital twin projects are focusing on delivering content to audiences rather than co-creating content with audiences (Luther et al., 2023). This could be seen as a conservative approach as using cutting-edge tech but maintaining traditional authorship structures. However, as tools become more user-friendly, one can foresee more crowd-sourced

contributions (e.g., visitors uploading their own 3D scans or narratives into a museum's twin). The Luther et al. (2023) review hints at emerging co-curation practice, but on the ground, it might be a few years away from truly participatory digital twins as this is apparent gap between the ideal of participatory theory and current practice.

Another tension is between the physical and digital in terms of value. A critical voice in museum studies might question whether a digital twin can ever replicate the aura of the original artifact (Lauriault & Theus, 2025). The findings show digital twins complement the physical rather than replace its unique value. For example, while VR increased knowledge and was engaging, Chernbumroong et al. (2024) did not claim that it superseded the authenticity of seeing real textiles. Alternatively, some participants in such studies often express a desire to see the real thing after experiencing the virtual (anecdotal feedback sometimes noted by museum staff, even if not formalised in our sources). This suggests that digital twins might amplify interest in originals, thus contradicting any fear that virtual will cannibalise physical visitation. It's consistent with the "appetiser" hypothesis mentioned earlier and counters a strand of thought that digital experiences could render actual visits obsolete (Baker et al., 2023). The situation can be likened to how the proliferation of art images online did not diminish museum attendance, arguably it increased it by building global interest.

From a practice standpoint, our results imply several actionable insights as museums implementing digital twins should invest in staff training and cross-department collaboration early on. A lesson learned from case studies is that involving curators, educators and IT from the planning stage (as Luther et al. (2023) advise leads to more successful outcomes. Also, results underline the importance of evaluating digital initiatives. Only a few projects (like the VR experiments) rigorously evaluated outcomes, but those that did were able to demonstrate value in concrete terms (knowledge gains, engagement metrics). This is crucial for justifying funding and scaling up these innovations. Therefore, museum managers should incorporate evaluation frameworks (surveys, observation, analytics) whenever a new digital twin project is launched, to build evidence of impact.

Moreover, the findings prompt a reconsideration of the curator's role identity, as we might be witnessing the emergence of what could be called the "digital curator", not in the sense of a social media manager but a hybrid professional who curates experiences that are simultaneously physical and digital. This role requires literacy in technology, an understanding of user experience and traditional subject expertise as it crosses the line between curator, designer and technologist. The literature has started to discuss such hybrid roles and our synthesis provides concrete tasks these hybrids do, as evidential in curators in Yeom & Woo's (2021) study effectively did UI layout by placing artworks in MR which is a task akin to level design in gaming. This suggests museum studies programs and professional development need to adapt, training future curators in at least basic aspects of 3D modelling, interaction design and data analysis.

The results also suggest the validity of diffusion of innovations theory in this context as digital twins can be seen as an innovation that diffuses through the museum sector (Gao & Keller, 2024). Early adopters, often larger museums or those with research ties have shown success, which acts as proof-of-concept, as a cascade can be anticipated when medium and smaller museums pick up on the techniques, especially as tools become more accessible (for example, cheaper 3D scanners or open-source virtual museum platforms). One challenge is resource disparity as some findings like those of Dang et al. (2023), allude to heavy resource investment. If digital twins are to proliferate, cost-effective solutions and perhaps shared infrastructure (national heritage twin platforms) might be needed. Strategically, this could mirror the way

collection digitisation was once expensive and limited to big institutions but is now common with cheaper cameras and shared repositories.

It is also important to recognise that not every digital twin project has been an unqualified success, while the identified sources report generally positive outcomes, publication bias might hide projects that struggled. A critical perspective would be to ask if the digital twins are solving actual curatorial problems or are they tech-driven projects looking for a purpose. The best cases reviewed clearly addressed specific needs like access for disabled visitors or preserving a temporary exhibit, but there could be cases (not in our set, but conceivable) where a museum invests in a flashy digital twin that neither staff nor visitors really use after the novelty wears off. Sustaining engagement is an issue as the Aldrovandi exhibit's twin had initial success online, but will it continue to attract viewers years later. Without ongoing curation (updating content, promoting it), digital twins could become digital tombs. This highlights the necessity for ongoing maintenance and essentially curating the digital twin itself over time, which can be resource-intensive. Museums must plan for that in their strategy, or risk digital twins becoming stale. This is a new kind of maintenance unlike a physical exhibit that is disassembled after 3 months, a digital twin potentially lives indefinitely, demanding server upkeep, software updates and periodic content refresh. Recognising this long-term commitment is key and our findings suggest that awareness is starting as Niccolucci's (2002) emphasis on lifecycle management and quality assurance in twins illustrate that.

Overall, our discussion affirms that heritage digital twins are a transformative innovation in museum curation, aligning with and extending current scholarly thought. They push museums toward more interactive, data-informed and continuous modes of operation. The findings reinforce optimistic views about technology's role in enhancing museum relevance and accessibility, while also injecting caution that these projects require clear purpose, interdisciplinary effort, and sustained resources. The next and final section will succinctly conclude the paper by summarising contributions, acknowledging the study's limitations, and suggesting future research pathways building on these insights.

## **6. Conclusion**

This paper set out to investigate how the advent of heritage digital twins is transforming museum curation practices. Through a systematic synthesis of over 30 peer-reviewed sources from 2015–2025, we have shown that digital twin technologies are a new technical tool and more importantly act as a catalyst for deeper changes in the museum sector. The identified evidence show that heritage digital twins have demonstrable benefits for preservation (creating detailed digital records and enabling preventive monitoring), for exhibition design (allowing virtual prototyping and iteration) and for visitor engagement (enhancing interactivity, reach, and learning outcomes). For example, multiple case studies reported improved visitor knowledge retention and motivation when using digital twin-based VR exhibits with statistical significance in controlled experiments. These findings give museum professionals concrete data and examples to inform their own digital initiatives. This study also linked practical outcomes to emerging theoretical frameworks like Heritage 4.0 and participatory museology as the analysis suggests that digital twins operationalise many aspects of these theories, they embed advanced technology into everyday curatorial work, foster stakeholder collaboration and open new channels for audience participation. We proposed a conceptual model (Figure 1) depicting the museum as an interactive cyber-physical system, which scholars can further refine or test. The review also highlighted an ongoing evolution of the curator's role towards a more digital, data-driven, and continuous engagement with content. We discussed how curators

are becoming experience designers and data managers, working in tandem with technologists, and how these calls for new skills and training pathways in the profession. This study thus contributes to museum studies literature by articulating what the oft-mentioned “digital curator” actually does in practice, grounded in case evidence.

## **6.1 Limitations**

We acknowledge that our review is limited by the quality of the available literature. To maximise quality, we prioritised peer-reviewed journal articles, which generally have more rigorous methodology descriptions, over short conference papers. There is a potential publication bias in that successful or positive case studies are more likely to be published as failed projects or negative results might be under-reported. We attempted to identify any critiques or cautionary notes within the literature and included perspectives from conceptual works that discuss pitfalls. Furthermore, by including a diverse range of publication venues (technical, museological, educational technology), we mitigated disciplinary bias and captured different viewpoints. The analysis was primarily qualitative, so researcher bias in theme interpretation is possible; to counter this, the team engaged in reflexive discussion, and any differing interpretations of a study were resolved by re-examining the source text together, for example, whether a given outcome was truly due to the digital twin or other factors.

In summary, the methodology ensured a systematic gathering and synthesis of current knowledge on heritage digital twins in museums. The approach is justified academically as it follows established SLR procedures and it is suitable for the research problem which spans technological and museological domains. By grounding our method in literature review best practices and carefully documenting each step (search, selection, coding, synthesis), we aim to provide a transparent and reproducible study. The next section presents the results and findings derived through this process. Despite these contributions, we acknowledge limitations. The literature available is still relatively nascent, as many digital twin projects are pilot efforts and long-term impacts are not yet fully observable. Our reliance on published studies means unsuccessful projects or internal museum experiments might be under-represented, potentially skewing the review towards positive outcomes. Additionally, while we sought global sources, there is a slight bias towards examples from Europe and Asia where such projects are documented; other regions’ perspectives (Africa, Latin America) on digital twins in heritage remain to be explored in future research.

## **6.2 Implications for future studies**

Looking ahead, we identify several promising directions for further inquiry as longitudinal studies would be valuable, for instance, tracking a museum’s use of digital twins over a decade to see how it affects visitor patterns, revenue, or collection care outcomes. Comparative studies could also be insightful, comparing museums that implement digital twins with those that don’t, to quantify differences in engagement or efficiency. From a technical angle, research on standardising heritage digital twin frameworks, perhaps developing open-source platforms would help lower barriers for smaller institutions. There is also room to explore deeper into user experience research especially on what design features in a museum’s digital twin make it most effective for learning or enjoyment? Finally, the ethical and policy implications deserve attention including questions of digital authenticity, rights management of 3D data and the digital divide ensuring that increasing digital offerings do not exclude those with limited online access.

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