AlBalkhy, W., Lafhaj, Z., NG, M, S., Hackl, J. (2025). The Role of Digital Twin Systems and Lean Construction in the Preservation of Cultural Heritage. In O. Seppänen, L. Koskela, & K. Murata (Eds.), *Proceedings of the 33rd Annual Conference of the International Group for Lean Construction* (IGLC33) (pp. 905-916). doi.org/10.24928/2025/0171

THE ROLE OF DIGITAL TWIN SYSTEMS AND LEAN CONSTRUCTION IN THE PRESERVATION OF CULTURAL HERITAGE

Wassim AlBalkhy[1], Zoubeir Lafhaj[2], Ming Shan NG[3], Jurgen Hackl[4]

ABSTRACT

This study employs a Systematic Literature Review (SLR) approach to explore the diverse applications of Digital Twin Systems (DTs) in the preservation, restoration, renovation, and conservation of cultural heritage. Reviewing 81 studies, it was found that there is a significant emphasis on preserving tangible cultural heritage primarily in Europe and Asia, with lesser focus on intangible heritage and other global regions. The study highlights how DTs serve as pivotal technologies that bridge the physical and digital realms, enhancing data-centric decision-making and operational efficiencies in cultural heritage management. Additionally, the incorporation of lean construction principles is analyzed, demonstrating that integrating these principles with DTs can further enhance preservation efforts by optimizing resource use, reducing waste, and improving overall process efficiency in heritage conservation. This dual approach underscores the transformative potential of DTs when aligned with lean construction methodologies, offering a path toward sustainable and effective preservation practices.

KEYWORDS

Digital Twins; Cultural Heritage; Construction; Renovation; Preservation; Historical Artefacts, Monuments, and Sites; Lean Construction; Lean Construction 4.0.

INTRODUCTION

Cultural heritage is a valuable legacy inherited from previous generations, encompassing tangible elements such as buildings, artifacts, and monuments; and intangible expressions, including traditions, rituals, and craftsmanship. Preserving this heritage is vital not only for cultural identity and continuity but also for its economic and social contributions (Mekonnen et al., 2022). In the European Union alone, the cultural heritage sector sustains over 300,000 direct jobs and supports millions more through tourism, conservation, and related services (European Commission, 2023).

According to the the United Nations Educational, Scientific and Cultural Organization (UNESCO Institute for Statistics, 2009), cultural heritage spans both tangible and intangible assets, each holding historical, artistic, scientific, and social significance. The preservation of these diverse forms presents complex challenges requiring sustainable, respectful, and informed interventions. In response to these challenges, recent advancements in digital technologies are transforming how heritage is documented, maintained, and presented. Among these, Digital

[1] Researcher, Centrale Lille, CNRS, UMR 9013-LaMcube, Lille, France, wassim.albalkhy@gmail.com, https://orcid.org/0000-0002-4772-8133
[2] Full Professor, Centrale Lille, CNRS, UMR 9013-LaMcube, Lille, France, zoubeir.lafhaj@centralelille.fr, https://orcid.org/0000-0003-1985-9176
[3] Professor, Kyoto Institute of Technology, Japan, ng@kit.ac.jp, https://orcid.org/0000-0003-2610-3561
[4] Assistant Professor, Princeton University, USA, hackl@princeton.edu

Twin Systems (DTs) have emerged as powerful tools that connect physical heritage assets to real-time digital representations. These systems enable enhanced visualization, predictive maintenance, structural monitoring, and public engagement through data-driven simulations and extended reality applications (Agrawal et al., 2022; Luther et al., 2023; Mendoza et al., 2023).

While most research on DTs has focused on their technical capabilities, questions are now emerging around how these systems can be applied responsibly, inclusively, and effectively in culturally sensitive environments. This is where lean construction principles provide complementary value. Lean offers a philosophy centered on maximizing stakeholder value, minimizing waste, and fostering continuous improvement, collaboration, and respect for people, which are essential to ensuring that the use of advanced technologies remains human-centric and aligned with the purpose of preservation (Albalkhy, 2023; González et al., 2020).

This study therefore focuses primarily on examining the role of DTs in cultural heritage preservation but to ensure that this technological approach is situated within a framework that respects and enhances cultural value, the study also incorporates a thematic analysis of how lean construction principles, although not always present in existing DTs literature, can support, enhance, and ethically frame DTs applications.

Rather than reviewing both concepts as separate lines of research, this study aims to contextualize lean as a guiding framework that ensures DTs contribute to stakeholder value, avoid unnecessary or intrusive interventions, and promote a culture of collaboration among all parties involved in heritage conservation.

DIGITAL TWIN SYSTEMS

DTs have been defined by countless researchers and companies. The most common understanding of these systems is based on having a system of two main components: the physical and the digital twins with a bidirectional flow of data between them. The data collected from the physical twin flows to be processed in the mirrored digital twin to be analysed to support the decision-making processes (Agrawal et al., 2022).

In their review of 228 studies of DTs in the built environment, AlBalkhy et al (2024) analysed 34 definitions of DTs and proposed the following definition: "A digital twin is a living virtual replica of a physical twin such as a product, asset, component, process, or system. Supported by technologies such as Artificial Intelligence (AI), Machine Learning (ML), sensors, and IoT, a flow of data between the digital and physical twins is made to ensure that digital twins are continuously updated and adapted to the changes in the physical twins. Which allows sharing insights, supporting decision-making, and enabling simulation, prediction, monitoring, control, and performance optimization of the physical twin throughout its lifecycle. Digital twins can range from simple prototypes to sophisticated models with self-learning and adapting capabilities, depending on their level of complexity". The study also proposed a structure for DTs as shown in Figure 1. The structure shows four main layers for these systems:

- The Physical Layer involves physical components such as buildings, cities, products, processes, or systems equipped with tools for data acquisition, including sensors, 3D scanners, and historical, social, and public data sources. Data is transferred to the Digital Layer through communication protocols or manually entered.
- The Digital Layer incorporates data integration, modelling tools, and analytics systems to create virtual models from the gathered data, supporting visualization, tracking, prediction, and control.
- The Application Layer enables users to leverage the system for various purposes, such as sustainability management and facility management, with interfaces for improved performance visualisation.

- The users' layer involves diverse stakeholders benefiting, affecting, and using the DTs (e.g. clients, operators, managers, engineers, suppliers…etc.).
- The layers are interconnected: The Physical layer provides real-time data to the Digital layer, enhancing visualization for the Application layer. This aids user decision-making, leading to optimization in the Application layer, and real-time control of physical components by the Digital layer.

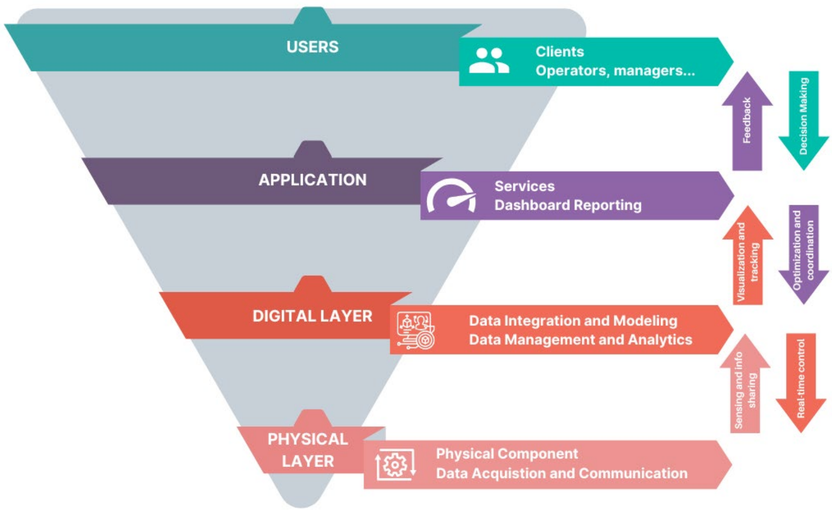

Figure 1: The structure of Digital Twin Systems (AlBalkhy et al., 2024).

RESEARCH METHODOLOGY

The primary objective of this SLR was to investigate the diverse applications of DTs for cultural heritage preservation. The SLR adheres to the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) guidelines, which ensure unbiased source selection, transparency, and repeatability. The review process involved three main phases: identification, screening, and eligibility (Albalkhy & Sweis, 2021; Schuldt et al., 2021).

The primary aim of the study is to explore how DTs are being used to address challenges in cultural heritage preservation. While lean construction principles are not the direct subject of the literature search, they are introduced during the discussion phase as a framework to evaluate and reflect on the findings. Lean is used to frame how DTs can be implemented in ways that maximize stakeholder value, eliminate waste, and foster collaboration, without introducing additional social or operational burdens. This approach reflects the belief that technology alone is not sufficient, and its value lies in how it is used. Thus, lean thinking helps assess whether DTs are serving preservation goals effectively, respectfully, and efficiently.

As shown in Figure 2, during the identification phase, sources were searched using a combination of keywords including "digital twin", "digital twins", "virtual twin", "virtual twins", "digital twinning", "virtual twinning", and terms related to heritage preservation such as "historical buildings", "Cultural Heritage", "Conservation", "Preservation", and "Cultural Preservation". This initial search yielded 217 sources.

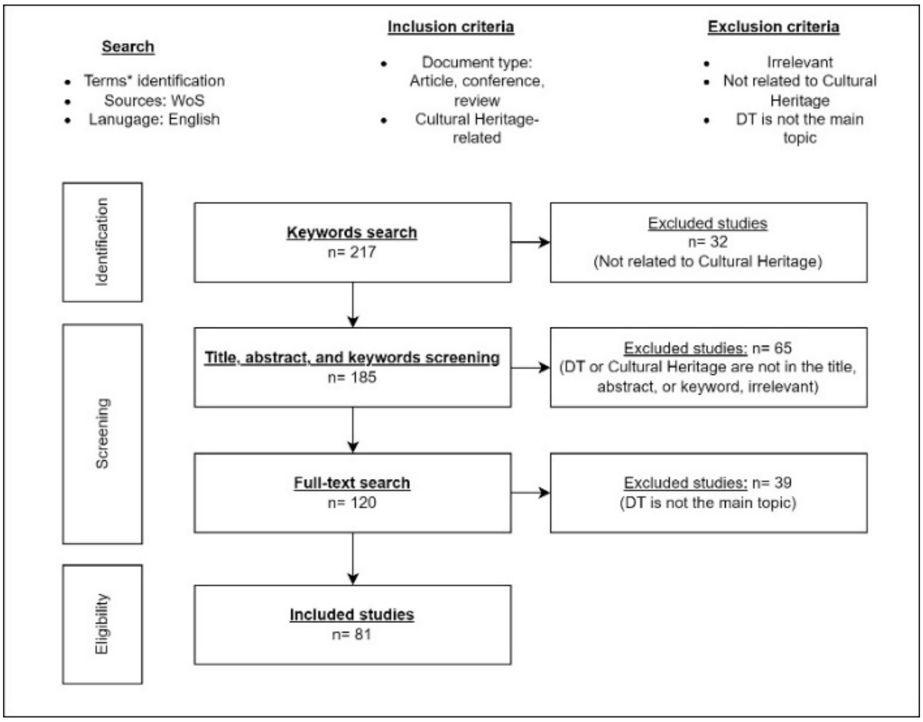

Figure 2: The SLR approach

In the screening phase, sources not directly related to DTs or cultural heritage were excluded based on abstracts, ensuring that only the most relevant studies were carried forward for in-depth review. The full texts of the remaining studies were then scrutinized for detailed analysis.

The eligibility phase involved a more refined exclusion of sources that, although initially appearing relevant, did not focus sufficiently on the utilization of DTs in the context outlined by the research questions. This refinement resulted in a final selection of 81 studies that were included in the analysis.

Following the review, the results were interpreted through a lean construction lens, drawing on established principles such as value delivery, waste elimination, continuous improvement, stakeholder collaboration, and respect for people. This interpretive layer was not based on a second literature review, but rather served to evaluate the implications of DT practices from a lean-informed perspective. The goal was to consider whether DTs are being used in ways that promote sustainability, engagement, and ethical preservation, rather than merely applying technology for its own sake.

RESULTS

LITERATURE CHARACTERIZATION

The analysis of the studies showed a noticeable increase in interest in the studied topic. This is evident by the annual increase in publications. Regarding the keywords, the analysis showed different purposes for DTs such as documentation, management, conservation, preservation, structural health monitoring, and maintenance. Concerning the location of the chosen heritage, the analysis showed that Italy had the highest share of studies (around one-third of the studies were conducted on heritages located in Italy). Additionally, the analysis showed that the highest interest in the topic was in Europe as different case studies were found in Spain, Portugal, France, Norway, Belgium, Sweden, Malta, Netherlands, Cyprus, and the Czech Republic. The interest was then in Asia with a majority of studies in China (7 studies), then Hong Kong, Uzbekistan, Korea, and Jordan.

TARGETED HERITAGES, USED TOOLS, AND DIGITAL TWIN SYSTEMS PURPOSES

The 81 studies focused on different types of elements and structures. More specifically, some studies investigated the use of DTs for specific paintings (e.g. Mona Lisa) (Amelio & Zarri, 2019; Lorenzo et al., 2020), sculptures (Attademo, 2023; Sebar et al., 2023), movable artifacts (P. Wang et al., 2023), or museums' collections (Scalas et al., 2020). Other studies focused on the twinning of complete buildings or structures. These studies covered various types of heritages including modern buildings (e.g. Sydney Opera House) (Massafra et al., 2022; Tahmasebinia et al., 2019), stone masonry structures (Angjeliu et al., 2020; Funari et al., 2021), wooden structures (P. Wang et al., 2023; Youn et al., 2021), museums (Xu et al., 2021), concrete structures (Tahmasebinia et al., 2019), religious heritage buildings (Angjeliu et al., 2020; Attademo, 2023; Takhirov et al., 2023), historic political locations (e.g. First Italian Parliament) (Bevilacqua et al., 2022), and commercial heritage buildings (Zhang et al., 2023). Other cases focused on historic city centers and cultural landscapes (Lopez-Gonzalez & Garcia-Valldecabres, 2023), historic transportation projects (Brumana et al., 2023; Kong & Hucks, 2023), archaeological ruins (Stanga et al., 2023), and intangible cultural heritage (e.g. Miao Silver Craftsmanship in China) (M. Wang & Lau, 2023).

Regarding the used technologies, the analysis shows that Building Information Modeling (BIM) and Historic Building Information Modeling (HBIM) (Cardinali et al., 2023; Lopez-Gonzalez & Garcia-Valldecabres, 2023; Massafra et al., 2022; Stanga et al., 2023; Vila-Cha et al., 2023; Youn et al., 2021) and laser scanning and photogrammetry (Angjeliu et al., 2020; Brumana et al., 2023; Marquez de la Plata et al., 2023; Stanga et al., 2023) are among the most used tools in building these systems. In addition to sensors and the Internet of Things (IoT) (Ni et al., 2022; Vila-Cha et al., 2023; Zhang et al., 2023), Artificial Intelligence (AI) and machine learning (Amelio & Zarri, 2019; Angjeliu et al., 2020; Jia & Yan, 2022; Zhao et al., 2022), Finite Element Models (FEM) (Angjeliu et al., 2020; Funari et al., 2021; Jouan & Hallot, 2020), Geographic information systems (GIS) (Jia & Yan, 2022; Jouan & Hallot, 2020; Lopez-Gonzalez & Garcia-Valldecabres, 2023), unmanned Extended reality (XR), Augmented Reality (AR), and Virtual Reality (VR) (Bevilacqua et al., 2022; Marquez de la Plata et al., 2023; Stanga et al., 2023).

Concerning the purpose of DTs, Agrawal et al. (2022) proposed that Gartner's taxonomy of analytical capabilities for digitalization frameworks (Gartner, 2013) is a valuable tool for evaluating how DTs can assist the decision-making process. Their developed model, depicted in Figure 3, outlines how DTs can impact decision-making through four distinct modes:

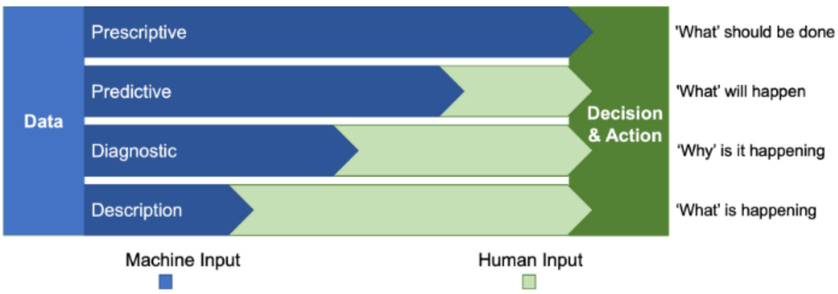

Figure 3: Levels of analytical capabilities of Digital Twin systems (Agrawal et al., 2022).

- Descriptive: DTs provide real-time insights into the current state of the physical environment, enabling informed decision-making based on actual data. This was more apparent in this review when DTs were used to improve the documentation of cultural heritage by creating digital records for information management (Biagini et al., 2022).

- Diagnostic: DTs help identify the root causes of observed phenomena, facilitating corrective actions and improving operational efficiency. This was when DTs were used to assess structural conditions, damages, and energy efficiency and the causes of deviations from the regular performance (Cardinali et al., 2023; Massafra et al., 2022).
- Predictive: DTs utilize historical data and predictive algorithms to forecast future events and potential impacts, allowing proactive planning and risk mitigation. This was shown when DTs were used to predict future behaviour and preventive preservation and maintenance of cultural heritage assets using simulations (Jouan & Hallot, 2020; Lorenzo et al., 2020).
- Prescriptive: DTs can autonomously make decisions based on predefined objectives, automating processes and optimizing performance. This was seen when the outputs of DTs were based on intervention plans to support conservation, restoration, and renovation works (Gros et al., 2023). It is worth mentioning that most of the studies focused on using DTs for descriptive or predictive purposes. Fewer studies were used to support prescriptive purposes.

Digital Twin Systems Applications for Cultural Heritage Preservation

The analysis of the 81 studies revealed that DTs can be used for various applications to preserve cultural heritage. These applications can be classified into five main groups as follows:

Documentation

DTs are revolutionizing the preservation of cultural heritage assets by providing a dynamic and interactive approach to capturing, storing, and analyzing data. They enable the creation of highly detailed 3D models that capture the essence of artifacts, buildings, and landscapes, encompassing their geometry, material properties, and essential information. These very detailed representations support accurate restoration efforts, ensuring the faithful reconstruction of delicate features and dimensions.

Additionally, DTs serve as a means of digital preservation and archiving, safeguarding cultural heritage against the destructive forces of time and technological advancements. As a result, ensuring the accessibility and longevity of the cultural legacy for future generations (Biagini et al., 2022; Moyano et al., 2021, 2022; Niccolucci et al., 2022; Spano et al., 2023; Stanga et al., 2023).

Structural Monitoring, Risk Management, and Preventive Maintenance

One of the key applications of DTs lies in the structural monitoring of cultural assets. By analyzing real-time data from sensors embedded in the structure, DTs can detect subtle changes in vibration, temperature, and other parameters, alerting conservators to potential structural issues before they cause damage (Angjeliu et al., 2020; Shabani et al., 2022; Vila-Cha et al., 2023). This proactive approach ensures the timely intervention and prevention of structural failures. DTs also play a crucial role in assessing the condition of masonry facades and roofs. By creating detailed 3D models of these elements, digital twins enable conservators to identify areas of deterioration, such as cracks, erosion, or loose masonry (Funari et al., 2021; Jouan & Hallot, 2020; Shabani et al., 2022; Takhirov et al., 2023). This information is invaluable for planning and scheduling maintenance and restoration work, ensuring the continued stability and integrity of these critical components. Moreover, DTs can contribute to assessing potential risks such as water damages and fire hazards and understanding the extent of damages caused by earthquakes, wars, or other disasters (Gros et al., 2023; Jouan & Hallot, 2020; Li et al., 2023). Accordingly, supporting maintenance, restoration, and renovation works to be scheduled as early as possible.

Heritage Visualization and Public Engagement

One of the most exciting applications of DTs in heritage visualization is the creation of virtual tours. These tours allow visitors to explore historic sites from the comfort of their own homes or in person, using AR or VR headsets. Visitors can virtually walk through ancient ruins, step into grand palaces, or even stand in the middle of bustling marketplaces, all while gaining insights into the history and culture of these places (Bevilacqua et al., 2022; Lopez-Gonzalez & Garcia-Valldecabres, 2023; Lucchi, 2023; Luther et al., 2023; Marquez de la Plata et al., 2023; Stanga et al., 2023).

DTs also play a crucial role in education and public engagement. By integrating 3D reconstruction and virtual reality, DTs enable the creation of interactive exhibits and educational programs that bring heritage sites and their stories to life. Visitors can learn about the history of a site, its significance, and the people who lived there (Bevilacqua et al., 2022; Scalas et al., 2020; Stanga et al., 2023).

Sustainability and Climate Change Impact Mitigation

By simulating renovation projects, DTs allow for the visualization of construction methods, energy efficiency analysis, and the impact of green retrofitting. They also play a crucial role in mitigating the impact of climate change on cultural heritage. By deploying digital twins and AI/ML algorithms, conservators can detect and assess the degradation of heritage assets caused by extreme weather events and environmental factors. Which enables early intervention and targeted restoration efforts, ensuring the long-term resilience of heritage assets in the face of a changing climate (Massafra et al., 2022; Zhang et al., 2023).

Artifacts and Museum Collections Preservation

DTs offer a range of applications in the preservation and documentation of artifacts and museum collections. One example of these applications involved advanced AI and Knowledge Representation to digitize iconic items like the Mona Lisa by Leonardo Da Vinci, capturing both physical and conveyed messages (Amelio & Zarri, 2019). Another application focused on medieval sculptural heritage, creating a digital twin library of fragments for academics and VR experiences for the public (Attademo, 2023). Additionally, DTs were used to support documentation, material characterization, preservation, deterioration prediction, and conservation treatments of artifacts, museum collections, and sculptures (Attademo, 2023; Sebar et al., 2023). For non-tangible heritage, DTs based on non-fungible tokens (NFTs) were used to preserve Miao silver craftsmanship, extending its lifespan and commercial value (M. Wang & Lau, 2023). Moreover, DTs were used to create interactive lighting systems for museums, allowing for real-time monitoring and optimization of lighting based on visitor patterns (Xu et al., 2021).

DISCUSSION OF THE RESULTS FROM LEAN PERSPECTIVES

Although this study did not conduct a separate review of lean construction literature, the results of the DTs analysis could be interpreted through the lens of lean principles to reflect critically on the value-driven, sustainable, and collaborative application of technology in heritage contexts. This lean-informed interpretation responds to the need to ensure that technological solutions; especially those as complex and resource-intensive as DTs, are not implemented solely for innovation's sake, but rather in ways that genuinely serve the preservation of cultural heritage and the people connected to it.

The convergence of lean construction and Construction 4.0 technologies represents a transformative approach to modern construction practices, enhancing efficiency and value delivery. Lean principles, which focus on maximizing value and minimizing waste, significantly bolster the implementation of Construction 4.0 by ensuring that innovations are applied with a clear focus on value. Conversely, Construction 4.0 technologies, characterized by digitization and automation, enhance the delivery of lean principles by improving process efficiency and resource utilization (Albalkhy, 2023; Albalkhy et al., 2024; Fang & Gao, 2024; Forcael, 2024; González et al., 2020). This symbiotic relationship fosters an environment where both methodologies support and amplify the benefits of the other.

In the realm of cultural heritage, the application of DTs for documentation and digital archiving clearly aligns with lean principles focused on minimizing unnecessary effort and maximizing stakeholder value. Digital modeling and non-intrusive data capture reduce physical interaction with fragile or irreplaceable assets. From a lean perspective, this helps avoid potential damage and inefficient workflows by enabling teams to plan interventions with greater precision, avoiding redundant site visits, delays, and miscommunications.

Similarly, the use of DTs for structural monitoring, preventive maintenance, and risk management reflects the lean aim of creating reliable, stable workflows. By incorporating sensor data and predictive analytics, heritage professionals can anticipate and respond to deterioration or damage before it escalates. This supports a culture of continuous improvement, where preservation strategies evolve with real-time feedback and performance data rather than relying on reactive or ad-hoc interventions.

DTs also have significant value in enhancing public engagement and educational outreach. Through immersive visualization technologies such as virtual reality and augmented reality, users can explore and learn from heritage assets without placing physical strain on the actual sites or collections. This represents a clear application of lean's stakeholder-focused approach. Providing wider access to cultural knowledge while preserving physical integrity addresses the dual goal of inclusivity and protection—maximizing societal benefit while minimizing resource use and risk.

In the context of climate change and long-term sustainability, DTs enable simulations of environmental stress, energy use, and retrofitting scenarios. These capabilities reinforce lean's emphasis on waste reduction and sustainable planning. Decisions about restoration materials, interventions, or energy strategies can be tested virtually, allowing for proactive, informed planning that reduces trial-and-error waste and aligns with long-term preservation goals.

Moreover, DTs used for artifact preservation and museum collection management illustrate lean's concern with respecting people and knowledge systems. By digitizing and curating artifacts virtually, museums can reduce the need for physical handling while enabling scholars, educators, and the public to engage with cultural assets in rich and interactive ways. This approach not only safeguards the objects themselves but also ensures broader, more equitable access to heritage experiences.

Taken together, these findings suggest that lean thinking offers a valuable ethical and strategic framework for the deployment of DTs in cultural heritage preservation. It highlights who benefits—namely, heritage professionals, policymakers, communities, and knowledge holders—and how. Lean provides a way to assess whether DTs truly serve their intended purpose, avoid unnecessary complexity or exclusion, and contribute to a sustainable, respectful, and collaborative preservation environment.

Rather than presenting lean construction as a co-equal subject of inquiry, this discussion illustrates how lean can be used to assess and guide DT applications. It reinforces the idea that technological solutions, while powerful, must be critically examined in light of their implementation, impact, and alignment with broader goals of heritage conservation. Lean principles help avoid the risk of deploying technology in ways that disempower people or overlook cultural contexts. Instead, they provide a path for integrating innovation within a value-driven, people-centered heritage framework.

CONCLUSIONS

This study examined the diverse applications of DTs in cultural heritage preservation through a systematic literature review. The review revealed that DTs offer valuable capabilities for documentation, structural monitoring, simulation, and visualization of heritage assets, contributing to more informed, proactive, and efficient preservation strategies. Their ability to create detailed virtual representations and enable real-time feedback supports the long-term resilience and accessibility of both tangible and intangible heritage.

While the literature primarily focused on technological applications, the study reflected critically on these results through the lens of lean construction principles, not as a co-investigated topic, but as a conceptual framework to guide the responsible use of DTs. Lean thinking helped interpret how DTs can contribute meaningfully to sustainable and inclusive heritage practices. Lean offers guidance to ensure that DT deployment enhances the cultural, ethical, and social dimensions of heritage work.

It is important to acknowledge that the reviewed studies overwhelmingly focused on tangible heritage and the descriptive and predictive capabilities of DTs. Applications addressing intangible cultural heritage and prescriptive decision-making remain limited. Moreover, few studies explicitly explore the integration of lean thinking with digital preservation tools. Future studies that can fill these gaps are recommended.

By presenting a lean-informed interpretation of DT applications, this study contributes to a growing conversation about the ethical and strategic deployment of technology in heritage contexts. It encourages researchers, conservationists, and policymakers to consider not only what DTs can do, but how they are used, for whom, and to what end. Future research may further explore this convergence through case studies or frameworks that operationalize lean principles within digital preservation workflows.

REFERENCES

Agrawal, A., Fischer, M., & Singh, V. (2022). Digital Twin: From Concept to Practice. *Journal of Management in Engineering*, *38*(3), 06022001. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001034

Albalkhy, W. (2023). *The Ontology of Lean Construction 4.0 in the Construction Industry*. https://theses.hal.science/tel-04474366

AlBalkhy, W., Karmaoui, D., Ducoulombier, L., Lafhaj, Z., & Linner, T. (2024). Digital twins in the built environment: Definition, applications, and challenges. *Automation in Construction*, *162*, 105368. https://doi.org/10.1016/j.autcon.2024.105368

Albalkhy, W., & Sweis, R. (2021). Barriers to adopting lean construction in the construction industry: a literature review. *International Journal of Lean Six Sigma*, *12*(2), 210–236. https://doi.org/10.1108/IJLSS-12-2018-0144

Albalkhy, W., Sweis, R., Jaï, H., & Lafhaj, Z. (2024). The integration between Lean Construction and the Internet of Things (IoT): a systematic literature review. *Smart and Sustainable Built Environment*, *ahead-of-p*(ahead-of-print). https://doi.org/10.1108/SASBE-02-2024-0042

Amelio, A., & Zarri, G. P. (2019). Conceptual Encoding and Advanced Management of Leonardo da Vinci's Mona Lisa: Preliminary Results. *Information*, *10*(10), 321. https://doi.org/10.3390/info10100321

Angjeliu, G., Coronelli, D., & Cardani, G. (2020). Development of the simulation model for Digital Twin applications in historical masonry buildings: The integration between numerical and experimental reality. *Computers & Structures*, *238*. https://doi.org/10.1016/j.compstruc.2020.106282

Attademo, G. (2023). Sculptural Fragments from The Church of San Gennaro Extra Moenia in Naples: Digital Twins for Heritage Knowledge, Analysis and Fruition. *SCIRES-IT-*

Scientific Research and Information Technology, *13*(1), 41–52. https://doi.org/10.2423/i22394303v13n1p41

Bevilacqua, M. G., Giordano, A., Russo, M., Spallone, R., & Soc, I. C. (2022). 3D Reconstruction, Digital Twinning, and Virtual Reality: Architectural Heritage Applications. In *IEEE Conference on Virtual Reality and 3D User Interfaces (IEEE VR)* (pp. 915–919). https://doi.org/10.1109/VRW55335.2022.00031

Biagini, C., Bongini, A., & Verdiani, G. (2022). From Geospatial Data to HBIM of Romanic Churches in Sardinia: Modelling, Check and Validation. In M. A. Rodenas-Lopez, J. Calvo-Lopez, & M. Salcedo-Galera (Eds.), *19th International Conference on Graphic Design in Architecture (EGA) - Motto - Beyond Drawings - The Use of Architectural Graphics* (pp. 368–378). Springer International Publishing Ag.

Brumana, R., Quilici, S., Oliva, L., Previtali, M., Gabriele, M., & Stanga, C. (2023). Multi-Sensor HR Mass Data Models toward Multi-Temporal-Layered Digital Twins: Maintenance, Design and XR Informed Tour of the Multi-Stratified Appian Way (PAAA). *Sensors*, *23*(20), 8556. https://doi.org/10.3390/s23208556

Cardinali, V., Ciuffreda, A. L., Coli, M., De Stefano, M., Meli, F., Tanganelli, M., & Trovatelli, F. (2023). An Oriented H-BIM Approach for the Seismic Assessment of Cultural Heritage Buildings: Palazzo Vecchio in Florence. *Buildings*, *13*(4), 913. https://doi.org/10.3390/buildings13040913

Fang, Y., & Gao, S. (2024). Construction 4.0 technology and lean construction ambidexterity capability in China's construction industry: a sociotechnical systems perspective. *Construction Innovation*, *ahead-of-print*. https://doi.org/10.1108/CI-12-2023-0302

Forcael, E. (2024). Lean Construction 4.0 and Society 5.0, How Close Are They? *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction (IGLC 32)*, 1280–1292. https://doi.org/10.24928/2024/0237

Funari, M. F., Hajjat, A. E., Masciotta, M. G., Oliveira, D. V, & Lourenco, P. B. (2021). A Parametric Scan-to-FEM Framework for the Digital Twin Generation of Historic Masonry Structures. *Sustainability*, *13*(19).

Gartner. (2013). *Extend Your Portfolio of Analytics Capabilities*. https://www.gartner.com/en/documents/2594822

González, V. A., Hamzeh, F., & Alarcón, L. F. (2020). *Lean Construction 4.0* (Vol. 5, Issue 3). Routledge.

Gros, A., Guillem, A., De Luca, L., Baillieul, E., Duvocelle, B., Malavergne, O., Leroux, L., & Zimmer, T. (2023). Faceting the post-disaster built heritage reconstruction process within the digital twin framework for Notre-Dame de Paris. *Scientific Reports*, *13*(1), 5981.

Jia, H. M., & Yan, J. (2022). Construction of Heritage Digital Resource Platform Based on Digital Twin Technology. *Mathematical Problems in Engineering*, *2022*. https://doi.org/10.1155/2022/4361135

Jouan, P., & Hallot, P. (2020). Digital Twin: Research Framework to Support Preventive Conservation Policies. *ISPRS International Journal of Geo-Information*, *9*(4).

Kong, X., & Hucks, R. G. (2023). Preserving our heritage: A photogrammetry-based digital twin framework for monitoring deteriorations of historic structures. *Automation in Construction*, *152*, 104928. https://doi.org/10.1016/j.autcon.2023.104928

Li, Y., Du, Y., Yang, M., Liang, J., Bai, H., Li, R., & Law, A. (2023). A review of the tools and techniques used in the digital preservation of architectural heritage within disaster cycles. *Heritage Science*, *11*(1), 199.

Lopez-Gonzalez, C., & Garcia-Valldecabres, J. (2023). The Integration of HBIM-SIG in the Development of a Virtual Itinerary in a Historical Centre. *Sustainability*, *15*(18), 13931. https://doi.org/10.3390/su151813931

Lorenzo, R., Fabrice, B., Paolo, D. V, Jean-Christophe, D., Giacomo, G., Franck, H., Delphine, J., Paola, M., Marco, T., Elisabeth, R., Luca, U., Joseph, G., & IOP. (2020). Learning from Objects: the use of advanced numerical methods to exploit a complete set of information from experimental data, for the Mona Lisa's Digital-Twin. In *International Conference Florence Heri-Tech: The Future of Heritage Science and Technologies* (Vol. 949).

Lucchi, E. (2023). Digital twins for the automation of the heritage construction sector. *Automation in Construction*, *156*, 105073. https://doi.org/10.1016/j.autcon.2023.105073

Luther, W., Baloian, N., Biella, D., & Sacher, D. (2023). Digital Twins and Enabling Technologies in Museums and Cultural Heritage: An Overview. *Sensors*, *23*(3), 1583. https://doi.org/10.3390/s23031583

Marquez de la Plata, A. R., Cruz Franco, P. A., & Ramos Sanchez, J. A. (2023). Application of New Technologies for the Graphic and Constructive Analysis and Dissemination of the Archaeological Heritage of Merida, Spain. In H. Varum & T. C. Ferreira (Eds.), *10th Conference on ReUSO - Documentation, Restoration and Reuse of Heritage* (Vol. 26, pp. 71–89). Springer International Publishing Ag.

Massafra, A., Predari, G., & Gulli, R. (2022). Towards digital twin driven cultural heritage management: a HBIM-based workflow for energy improvement of modern buildings. In R. Shults & A. Dlesk (Eds.), *ISPRS WG V/7 Conference on Measurement, Visualisation and Processing in BIM for Design and Construction Management II* (Vols. 46–5, pp. 149–157). Copernicus Gesellschaft Mbh.

Mekonnen, H., Bires, Z., & Berhanu, K. (2022). Practices and challenges of cultural heritage conservation in historical and religious heritage sites: evidence from North Shoa Zone, Amhara Region, Ethiopia. *Heritage Science*, *10*(1), 1–22. https://heritagesciencejournal.springeropen.com/articles/10.1186/s40494-022-00802-6

Mendoza, M. A. D., De La Hoz Franco, E., & Gómez, J. E. G. (2023). Technologies for the Preservation of Cultural Heritage—A Systematic Review of the Literature. *Sustainability*, *15*(2), 1059. https://doi.org/10.3390/su15021059

Moyano, J., Carreno, E., Nieto-Julian, J. E., Gil-Arizon, I., & Bruno, S. (2022). Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project. *Automation in Construction*, *143*, 104551. https://doi.org/10.1016/j.autcon.2022.104551

Moyano, J., Leon, J., Nieto-Julian, J. E., & Bruno, S. (2021). Semantic interpretation of architectural and archaeological geometries: Point cloud segmentation for HBIM parameterisation. *Automation in Construction*, *130*, 103856. https://doi.org/10.1016/j.autcon.2021.103856

Ni, Z. J., Liu, Y., Karlsson, M., & Gong, S. F. (2022). Enabling Preventive Conservation of Historic Buildings Through Cloud-Based Digital Twins: A Case Study in the City Theatre, Norrkoping. *IEEE Access*, *10*, 90924–90939. https://doi.org/10.1109/ACCESS.2022.3202181

Niccolucci, F., Felicetti, A., & Hermon, S. (2022). Populating the Data Space for Cultural Heritage with Heritage Digital Twins. *DATA*, *7*(8), 105. https://doi.org/10.3390/data7080105

Scalas, A., Mortara, M., & Spagnuolo, M. (2020). A pipeline for the preparation of artefacts that provides annotations persistence. *Journal of Cultural Heritage*, *41*, 113–124. https://doi.org/10.1016/j.culher.2019.06.006

Schuldt, S. J., Jagoda, J. A., Hoisington, A. J., & Delorit, J. D. (2021). A systematic review and analysis of the viability of 3D-printed construction in remote environments. *Automation in Construction*, *125*(February). https://doi.org/10.1016/j.autcon.2021.103642

Sebar, L. E., Lombardo, L., Buscaglia, P., Cavaleri, T., Lo Giudice, A., Re, A., Borla, M., Aicardi, S., & Grassini, S. (2023). 3D Multispectral Imaging for Cultural Heritage Preservation: The Case Study of a Wooden Sculpture of the Museo Egizio di Torino.

Heritage, *6*(3), 2783–2795. https://doi.org/10.3390/heritage6030148

Shabani, A., Feyzabadi, M., & Kioumarsi, M. (2022). Model updating of a masonry tower based on operational modal analysis: The role of soil-structure interaction. *Case Studies in Construction Materials*, *16*, e00957. https://doi.org/10.1016/j.cscm.2022.e00957

Spano, A., Patrucco, G., Sammartano, G., Perri, S., Avena, M., Fillia, E., & Milan, S. (2023). Digital Twinning for 20th Century Concrete Heritage: HBIM Cognitive Model for Torino Esposizioni Halls. *SENSORS*, *23*(10), 4791. https://doi.org/10.3390/s23104791

Stanga, C., Banfi, F., & Roascio, S. (2023). Enhancing Building Archaeology: Drawing, UAV Photogrammetry and Scan-to-BIM-to-VR Process of Ancient Roman Ruins. *Drones*, *7*(8), 521. https://doi.org/10.3390/drones7080521

Tahmasebinia, F., Fogerty, D., Wu, L. O., Li, Z. C., Sepasgozar, S. M. E., Zhang, K., Sepasgozar, S., & Marroquin, F. A. (2019). Numerical Analysis of the Creep and Shrinkage Experienced in the Sydney Opera House and the Rise of Digital Twin as Future Monitoring Technology. *Buildings*, *9*(6). https://doi.org/10.3390/buildings9060137

Takhirov, S., Rakhmonov, B., Nafasov, R., Samandarov, A., & Sultanova, S. (2023). Laser Scanning and Ambient Vibration Study of Juma Mosque in Khiva (Uzbekistan) with Subsequent Finite Element Modeling of Its Minaret. *Remote Sensing*, *15*(6), 1632. https://doi.org/10.3390/rs15061632

UNESCO Institute for Statistics. (2009). *2009 UNESCO Framework for Cultural Statistics| Cultural Heritage*. https://uis.unesco.org/en/glossary-term/cultural-heritage

Vila-Cha, E., Barontini, A., & Lourenco, P. B. (2023). Implementation of a Condition Monitoring Strategy for the Monastery of Salzedas, Portugal: Challenges and Optimisation. *Buildings*, *13*(3), 719. https://doi.org/10.3390/buildings13030719

Wang, M., & Lau, N. (2023). NFT Digital Twins: A Digitalization Strategy to Preserve and Sustain Miao Silver Craftsmanship in the Metaverse Era. *Heritage*, *6*(2), 1921–1941. https://doi.org/10.3390/heritage6020103

Wang, P., Ma, X., Fei, L., Zhang, H., Zhao, D., & Zhao, J. (2023). When the digital twin meets the preventive conservation of movable wooden artifacts. *Heritage Science*, *11*(1), 54.

Xu, L. J., Yan, S. Z., Chen, Z., & Chen, X. (2021). Design of the Museum Interactive Lighting System Based on the Digital Twin Technology. *Scientific Programming*, *2021*. https://doi.org/10.1155/2021/4824417

Youn, H. C., Yoon, J. S., & Ryoo, S. L. (2021). HBIM for the Characteristics of Korean Traditional Wooden Architecture: Bracket Set Modelling Based on 3D Scanning. *Buildings*, *11*(11). https://doi.org/10.3390/buildings11110506

Zhang, J., Chan, C. C. C., Kwok, H. H. L., & Cheng, J. C. P. (2023). Multi-indicator adaptive HVAC control system for low-energy indoor air quality management of heritage building preservation. *Building and Environment*, *246*, 110910. https://doi.org/10.1016/j.buildenv.2023.110910

Zhao, J., Guo, L., & Li, Y. (2022). Application of Digital Twin Combined with Artificial Intelligence and 5G Technology in the Art Design of Digital Museums. *Wireless Communications & Mobile Computing*, *2022*, 8214514. https://doi.org/10.1155/2022/8214514