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## CULTURAL HERITAGE CONSERVATION IN THE DIGITAL ERA: A REVIEW OF DIGITAL TWIN AND 3D PRINTING APPLICATIONS

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**Abstract:** Digital Twin and 3D Printing technologies are advanced methods that integrate digital modeling, simulation, and automated fabrication and revolutionize various sectors. These technologies offer precise, efficient, and sustainable solutions, holding significant potential for enhancing preservation practices. Digital Twin technology enables the creation of detailed digital models, supporting real-time monitoring, predictive maintenance, and informed restoration planning. Meanwhile, 3D Printing allows the accurate reproduction of intricate architectural elements and artifacts, effectively bridging the gap between digital documentation and physical restoration. This review explores key research areas, including the replication of non-structural artifacts, structural rehabilitation, and material durability assessments. In total, 31 studies that included practical applications relevant to this study's scope were reviewed. Despite their numerous benefits, challenges such as high costs, specialized technical skills, and ethical considerations in heritage preservation remain. The study also anticipates future advancements, such as integrating smart materials, augmented reality, and robotics for autonomous restoration. This study provides insights into how Digital Twin and 3D Printing technologies can promote more effective, sustainable conservation practices in the digital age by evaluating current applications and challenges.

**Keywords:** Cultural heritage, Digital twin, Historical buildings, 3D printing, Restoration, Sustainability

### **Dijital Çağda Kültürel Mirasın Korunması: Dijital İkiz ve 3D Baskı Uygulamaları Üzerine Bir Derleme**

**Öz:** Dijital İkiz ve 3D Baskı teknolojileri, dijital modelleme, simülasyon ve otomatik fabrikasyonu entegre eden ve çeşitli sektörlerde devrim yaratan gelişmiş yöntemlerdir. Bu teknolojiler hassas, verimli ve sürdürülebilir çözümler sunmakta ve kültürel mirasın korunması uygulamalarını geliştirmek için önemli bir potansiyel barındırmaktadır. Dijital İkiz teknolojisi, gerçek zamanlı izleme, öngörücü bakım ve bilinçli restorasyon planlamasını destekleyen ayrıntılı dijital modellerin oluşturulmasını sağlar. Üç Boyutlu Baskı ise karmaşık mimari unsurların ve eserlerin doğru bir şekilde yeniden üretilmesini sağlayarak dijital dokümantasyon ve fiziksel restorasyon arasındaki boşluğu etkili bir şekilde doldurmaktadır. Bu derleme, yapısal olmayan eserlerin kopyalanması, yapısal rehabilitasyon ve malzeme dayanıklılık değerlendirmeleri de dahil olmak üzere önemli araştırma alanlarını incelemektedir. Toplama, pratik uygulamaları içeren ve bu derlemenin kapsamıyla ilgili olan 31 çalışma derlendi. Sayısız faydalara rağmen, yüksek maliyet, uzmanlık gerektiren teknik beceriler ve mirasın korunmasında etik hususlar gibi güçlükler bulunmaktadır. Çalışma aynı zamanda otonom restorasyon için akıllı malzemeler, artırılmış gerçeklik ve robotik entegrasyonu gibi gelecekteki gelişmeleri de öngörmektedir. Bu çalışma, mevcut uygulamaları ve zorlukları değerlendirerek Dijital İkiz ve 3D Baskı teknolojilerinin dijital çağda daha etkili, sürdürülebilir koruma uygulamalarını nasıl teşvik edebileceğine dair içgörüler sunmaktadır.

**Anahtar kelimeler:** Kültürel miras, Dijital ikiz, Tarihi yapılar, 3D baskı, Restorasyon, Sürdürülebilirlik

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## 1. INTRODUCTION

Historical buildings face increasing challenges such as material deterioration, structural instability, environmental effects, and the scarcity of skilled craftsmen. Traditional conservation methods often struggle to address these complex issues efficiently and sustainably. There is a growing need to adopt digital technologies that enable comprehensive documentation, precise diagnostics, and innovative restoration approaches to preserve cultural heritage effectively.

The construction industry has experienced significant digital transformations, reshaping traditional practices and enhancing efficiency. The integration of Industry 4.0 technologies such as Artificial Intelligence (AI), Digital Twin (DT), Building Information Modeling (BIM), Internet of Things (IoT), Virtual Reality (VR), Augmented Reality (AR), Robotics, and Additive Manufacturing (AM), also known as 3D Printing (3DP), has modernized an industry historically criticized for its limited innovation (Sherratt et al., 2020; You and Feng, 2020).

Adapting the construction sector to the digital era plays a crucial role in restoring and strengthening historical buildings, which present unique challenges due to their structural complexities and cultural significance. Among these technologies, DT and 3DP technologies offer significant potential in historic building restoration and rehabilitation (Dore and Murphy, 2017; Kantaros et al., 2023; Bourgeois et al., 2024). However, the pace and success of this adaptation depend on assessing the current level of implementation and envisioning future possibilities.

DTs provide high-fidelity virtual replicas that support real-time monitoring, predictive maintenance, and intervention planning for cultural-heritage assets, while also enabling wider public access through VR/AR and creating exact records for future reproduction (Yastikli, 2007; Bekele et al., 2018; Mahmoodian et al., 2022). Complementing these capabilities, 3DP rapidly fabricates intricate or missing elements, offering faster, less invasive, and more cost-effective restoration than conventional methods and thereby closing the gap between digital documentation and physical repair (Attaran, 2017; Sakin and Kiroglu, 2017; Xu et al., 2017; Tarhan et al., 2024).

Digital tools promise a safer transfer of historic buildings into the future. Yet most construction resources still target new concrete structures-a material responsible for roughly 8 % of global CO<sub>2</sub> emissions (Huang et al., 2018). Consequently, DT (Marienkov et al., 2024) and 3DP technologies (Tarhan and Şahin, 2021; Liu et al., 2024; Tarhan and Tarhan, 2025) are predominantly utilized in concrete structures. However, with growing awareness in recent years, DT technology has begun to be employed in the repair and rehabilitation of historical buildings (La Russa and Santagati, 2020; Rocca et al., 2023; Chaves et al., 2024). In the field of 3DP, although there is increasing interest in earth-based mixtures (Perrot et al., 2018; Tarhan and Perrot, 2023; Tarhan et al., 2024), research on lime-based mixtures - particularly important for repair activities of historical structures - has only recently commenced (Tarhan et al., 2024). Moreover, studies combining these two technologies are emerging to enhance the restoration and conservation of cultural heritage (Segreto et al., 2017; Codarin and Daubmann, 2021; Bourgeois et al., 2024).

This study aims to create a vision of the potential contributions of digitalization, the challenges encountered, and future expectations (digital rehabilitation) by focusing on the applications of DT and 3DP technologies in preserving cultural heritage. A structured literature review was conducted using the Scopus database to identify relevant peer-reviewed studies on using DT and 3DP technologies in conserving historical buildings. Boolean search queries were formulated to target works focusing on heritage structures and related restoration or rehabilitation processes (Table 1). For 3DP-related research, publications from 2010 to 2025 were considered, while for DT, the period was limited to 2019–2025, reflecting its more recent development. Only English-language documents were included. Studies unrelated to heritage applications, new-build contexts, or lacking practical implementation were excluded. Search results were initially screened based on title, abstract, and keywords, followed by full-text reading to confirm relevance

to the current review's scope. The final selection includes the peer-reviewed works synthesized in section 3 and section 4 of this article. The article's structure is as follows: first, the applications of DT and 3DP technologies in cultural heritage conservation are discussed; next, the challenges and opportunities presented by these technologies are evaluated; finally, potential future developments are envisioned.

**Table 1:** Search strategies used to identify relevant literature for this review.

Field	Boolean operators and keywords	Period	Records retrieved
3DP	(“historical building” OR “historical masonry” OR “cultural heritage”) AND (restoration OR rehabilitation OR conservation OR preservation OR retrofit OR strengthening OR reinforcement) AND (“3D printing” OR “additive manufacturing” OR “digital fabrication”)	2010-2025	140
DT	(“historical building” OR “historical masonry” OR “cultural heritage”) AND (restoration OR rehabilitation OR conservation OR preservation OR retrofit OR strengthening OR reinforcement) AND (“digital twin”)	2019-2025	154

## 2. DIGITAL TWIN IN HERITAGE CONSERVATION

DT technology represents a sophisticated process of creating and managing comprehensive digital representations of physical entities or systems. It establishes a dynamic link between the physical and digital realms through real-time data collection, advanced simulation techniques, and AI algorithms (Khajavi et al., 2019). As a key component of Industry 4.0, DTs are gaining increasing prominence, particularly in the fields of construction and architectural heritage preservation (Dore and Murphy, 2017).

The functionality of DT technology relies on integrating diverse data sources, including sensors, IoT devices, BIM systems, and laser scanning technologies. Data collected from these sources is processed and analyzed on cloud-based platforms, facilitating the creation of real-time digital representations of physical structures (Boje et al., 2020). DTs play key roles throughout a structure's lifecycle. During design, they simulate scenarios to optimize solutions. In construction, they monitor progress and identify issues. During operation, they support maintenance planning, maximize energy efficiency, and enhance user experiences (Sacks et al., 2020).

Notable applications include using laser scanning and photogrammetry to create accurate 3D models of existing building conditions, aiding in structural analysis, virtual restoration simulations, and risk prediction (Chiabrandi et al., 2017; Bekele et al., 2018). For example, Dang et al. (2023), in their study on heritage sites in China, revealed the widespread use of DT technology, particularly in sites listed before 1990. This growing trend highlights the critical role of DTs in heritage conservation processes. Applications range from precise documentation and virtual restoration planning to structural analysis, public participation, and sustainable conservation efforts.

The scientific literature has focused on two main areas: indoor environment control (La Russa and Santagati, 2020; Munoz-Pandiella et al., 2022; J. Zhang et al., 2023; Baeriswyl et al., 2023; Cascone et al., 2024) and structural assessment (Falcone et al., 2021; Funari et al., 2021; Moyano et al., 2022; Garcia-Leon et al., 2023; Rocca et al., 2023; Chaves et al., 2024). Indoor-focused studies aim to preserve original materials, enhance user comfort, and improve energy efficiency by monitoring real-time parameters like temperature, humidity, and air quality. Structural assessment studies focus on modeling the structural behavior of historic buildings, detecting and monitoring damage, providing decision support for restoration projects, and evaluating resilience against natural disasters.

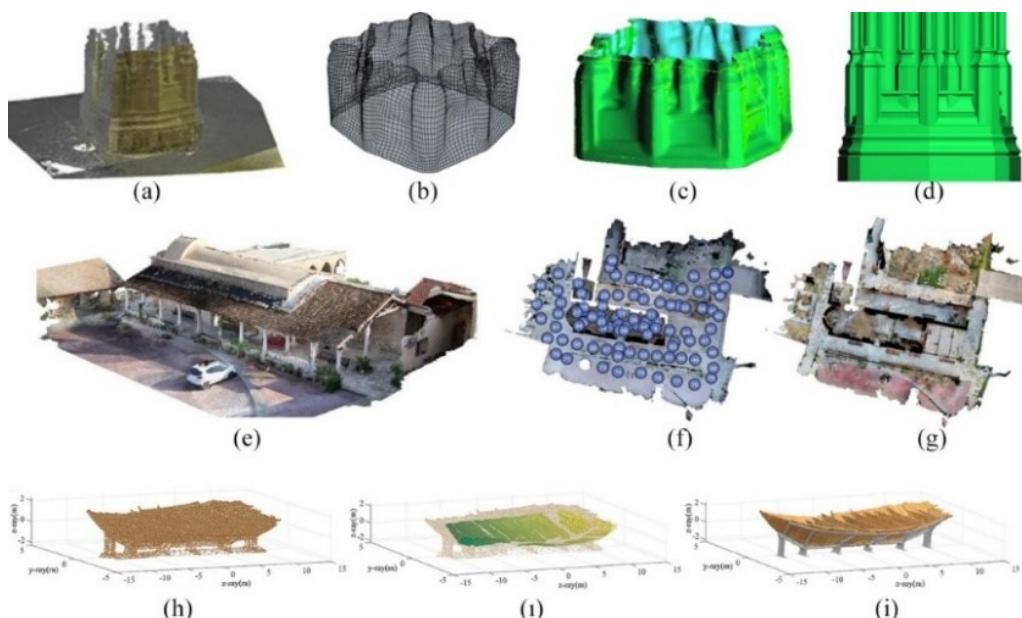
La Russa and Santagati (2020) developed a DT for Villa Zingali Tetto, a historic building in Catania constructed in 1930, to support the preservation of its museum collections (Figure 1(a-b)). Using laser scanners, photogrammetry, and archival research, they created a Historic Building Information Model through the PointCloud-to-BIM methodology, integrating data from 233 Terrestrial Laser Scanning scans. The model facilitated microclimate analysis, energy simulations, and the creation of a synthetic dataset for machine learning. A decision support system, based on multivariate linear regression, optimizes natural ventilation, visitor management, and HVAC usage by incorporating real-time temperature and humidity data, ensuring ideal conditions for the collections. Baeriswyl et al. (2023) utilized DT technology to convert an abandoned prison in Melipilla, Chile, into a modern library. The DT enabled real-time monitoring and optimization of building performance using data from IoT sensors, continuously tracking parameters such as temperature, humidity, and energy consumption. This data was integrated into a virtual model, simulating changes to the building and optimizing environmental conditions like ventilation through automation systems. The approach enhanced energy efficiency, preserved the historic structure's authenticity, and adapted the building for modern use while maintaining user comfort and sustainability with minimal intervention. Cascone et al. (2024) analyzed a DT application for the restoration and modernization of the historic "Ex Cinema Santa Barbara" in Paternò, Italy. Using BIM and Generative Design methodologies, a detailed BIM model was developed with Autodesk Revit, and generative algorithms were created via Dynamo. The project integrated IoT sensors and automation systems, forming a DT for real-time monitoring. Key outcomes included maintaining indoor temperatures at 20–24°C for 95% of operational hours, relative humidity at 30–50% for 92% of the time, and reducing artificial lighting needs by 40% during daylight hours. J. Zhang et al. (2023) introduced an integrated approach combining a novel Multiple Output Gated Recurrent Unit (GRU) deep learning model with Computational Fluid Dynamics (CFD) simulations to preserve indoor air quality in a historic building, FWD HOUSE 1881 (formerly the Hong Kong Marine Police Headquarters, Figure 1(c-f)). The system predicts temperature, humidity, and gas concentrations ( $\text{CO}_2$ ,  $\text{SO}_2$ ,  $\text{NO}_2$ ) up to 10 minutes ahead. CFD filled sensor gaps, and the GRU model reduced training time by 33% while improving accuracy by 11.3%. HVAC inlet velocities were optimized, enhancing air quality by up to 20%, with a DT-based platform automating real-time adjustments. Munoz-Pandiella et al. (2022) applied DT technology to medieval monuments in Cyprus, Italy, and Spain, emphasizing collaboration between art historians and technical experts. The study generated highly detailed DTs using terrestrial laser scanning, drone-based photogrammetry, and Hypercolorimetric Multispectral Imaging. Data processing included color correction, noise removal, and photogrammetric reconstruction with Reality Capture and Agisoft Metashape. Radiance and Lumen software were used for lighting simulations, recreating historical and artificial lighting conditions. This approach enabled the visualization of different historical periods, offering insights into the monuments' evolution and original appearances.



**Figure 1:**

*Villa Zingali Tetto (La Russa and Santagati 2020) a. Architectural details, b. HBIM perspective view; FWD HOUSE 1881 (J. Zhang et al. 2023) c. Automated control sequence depicted in the DT platform, d. Mesh configuration utilized in the analysis, and e, f. CFD simulation outcomes*

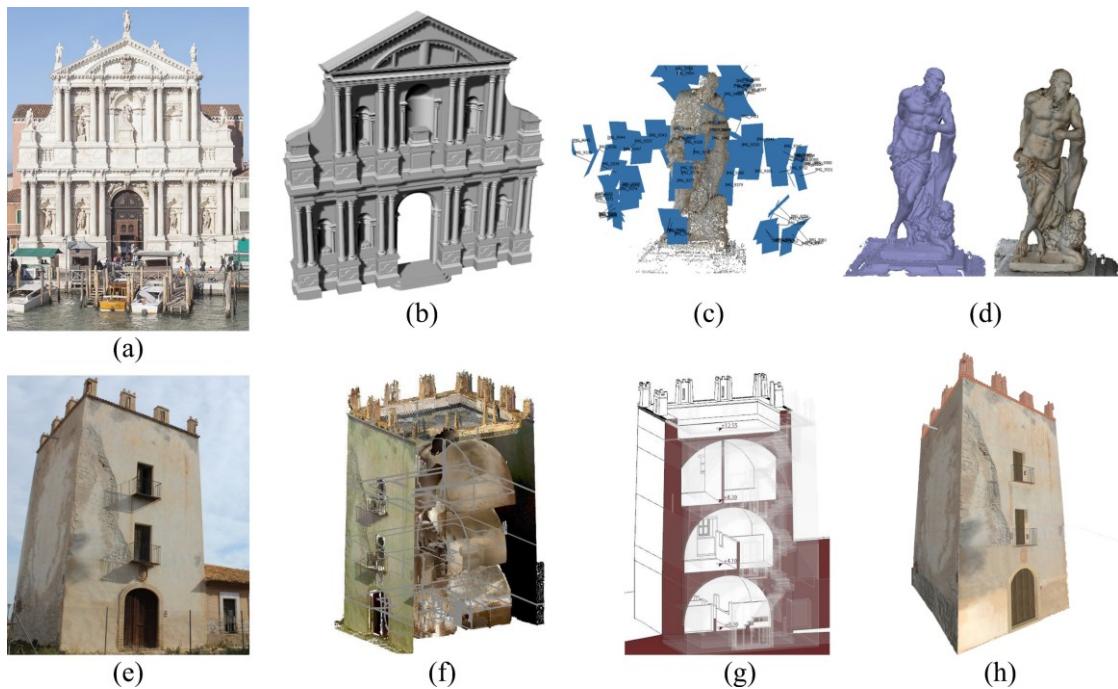
Moyano et al. (2022) presented a comprehensive methodology integrating HBIM and DT technologies for architectural heritage restoration. The study employed advanced data acquisition techniques, including laser scanning and photogrammetry. These were combined with digital modeling methods like semantic classification and adaptive meshing. The approach was demonstrated through a case study on reconstructing a column base at the Santiago Church in Jerez de la Frontera, Spain (Figure 2(a-d)). Revit and ArchiCAD were used to model complex geometries and historic details. Their integration supported precise restoration, structural analysis, and lifecycle management, highlighting the value of HBIM and DT in data-driven heritage conservation. Themistocleous et al. (2022) evaluated photogrammetry, depth camera mapping, and laser scanning for creating DT models, using the Monastery of Saint Nicholas of the Cats as a case study (Figure 2(e-g)). Photogrammetry achieved high accuracy (1.2 cm RMS error) but demanded significant time and planning. Depth camera mapping, while faster and offering interactive virtual experiences, showed reduced accuracy (4.8 cm RMS error). Laser scanning provided the highest precision (6 mm) but required extensive time and effort. The study concluded that photogrammetry is optimal for precise documentation, while depth cameras are suited for quick and accessible virtual applications. Ma et al. (2024) applied DT models to wooden heritage conservation, emphasizing multidimensional modeling for preventive care. Using digital image correlation, FE model updating, and moisture diffusion models, the DT enabled real-time monitoring and risk prediction for the Quanzhou ships (Figure 2(h-i)). The system integrated geometry, physics, and behavioral data, facilitating timely interventions. Results demonstrated the platform's effectiveness in monitoring and preserving wooden heritage, advancing preventive conservation practices.



**Figure 2:**

*A column base of Santiago Church (Moyano et al. 2022), a. Outcome of terrestrial laser scanning, b. 3D model created by simplifying the Quadmesh in Rhino V7, c. Comparative analysis between the construction model and the point cloud data of the pillar base, d. The idealized model of the column base is derived through segmentation. Monastery of Saint Nicholas of the Cats (Themistocleous et al. 2022), e. Photogrammetric model, f., g. Compilation of 98 individual depth camera acquisitions culminating in the final survey. The Quanzhou ships Ma et al. (2024), h. Point cloud data, which is captured via three-dimensional laser scanning i. Comprehensive 3D reconstruction combined with point cloud updating, i. Geometry modeling results.*

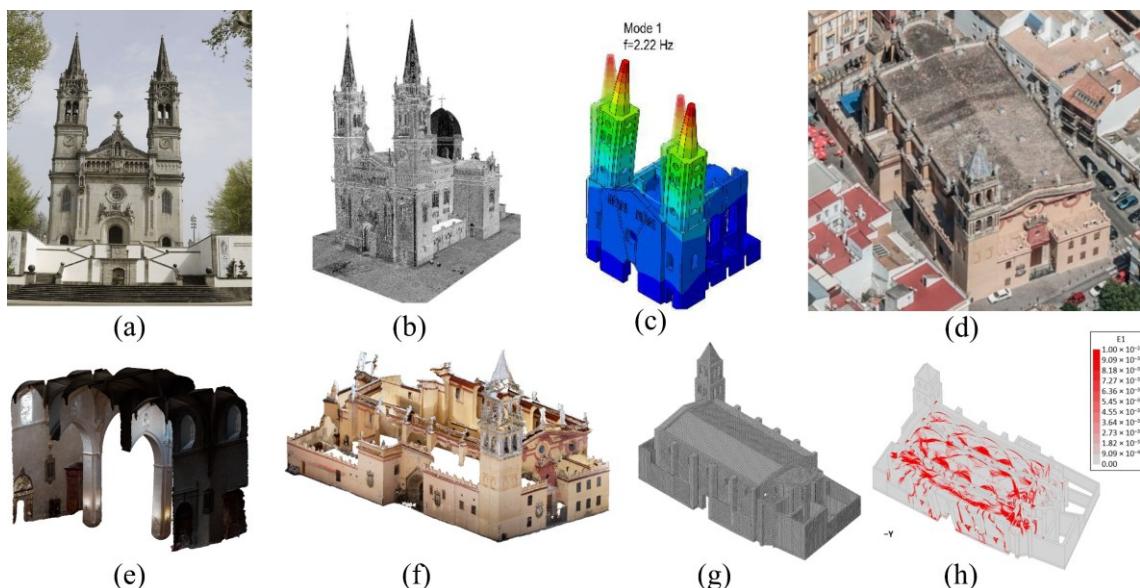
Rocca et al. (2023) developed a DT methodology for conserving the façade of the Church of Santa Maria di Nazareth in Venice. Using terrestrial laser scanning and drone photogrammetry, they created a detailed 3D model enriched with historical data, forming a "Historical Digital Twin" (Figure 3(a, b)). This model supported long-term, non-invasive monitoring of degradation and enabled FEM simulations to identify stress concentrations and assess the adequacy of stainless-steel reinforcements installed in earlier restorations (Figure 3(c, d)). The study demonstrated the DT's effectiveness in predictive maintenance and informed decision-making for sustainable heritage conservation. Falcone et al. (2021) developed a DT methodology for conserving the Quadriportico of the Cathedral of San Matteo in Salerno. Using wireless sensors and photogrammetry, they created a dynamic digital model to monitor environmental and structural conditions in real time. High-resolution 3D data, integrated with meteorological inputs, enabled tracking material degradation and structural changes. The DT employed graph databases for managing diverse data streams, supporting automated analysis, predictive modeling, and informed decision-making. This study demonstrated DT's capacity to enhance long-term heritage conservation by enabling continuous monitoring, preventive maintenance, and accessible, data-driven insights. García-León et al. (2023) applied HBIM for the restoration of Rame Tower in Spain (Figure 3(e)). By integrating TLS for the exterior and photogrammetry for the interior, they created a detailed 3D point cloud model, which informed a DT replicating the tower's structural and material features (Figure 3(f-h)). Enriched with historical data, the DT supported restoration planning, long-term monitoring, and maintenance strategies. The study demonstrated how HBIM and DTs enhance restoration accuracy, address structural complexities, and facilitate data-driven lifecycle management for heritage preservation.



**Figure 3:**

*Church of Santa Maria di Nazareth's Façade (Rocca et al. 2023) a. View, b. DT representation, c., d. 3D modeling steps of the San Girolamo statue on the façade. Rame Tower (García-León et al. 2023) e. The current state of South and West facades, f. Point cloud alignment and quota management in BIM software, g. East-West axonometric split of the model, h. 3D HBIM view of Rame Tower.*

Funari et al. (2021) applied DT technology to the conservation of historic masonry through a parametric Scan-to-FEM workflow (Figure 4(a–c)). In a case study on the Church of St. Torcato in Portugal, 3D laser scans and geometric data were processed in Rhino3D and Grasshopper, then imported into Abaqus for FE analysis. A component library was created, and the model was calibrated via inverse dynamic analysis using long-term vibration data recorded before and after interventions such as foundation consolidation. The calibrated model successfully replicated structural behavior, identified vulnerable areas, and predicted damage patterns—matching observed cracks from previous settlements—thus demonstrating its predictive potential for heritage structures. Chaves et al. (2024) presented a methodology for utilizing DTs in the preventive conservation of historic buildings, demonstrated through a case study of the Church of Santa Ana in Seville, Spain (Figure 4(d–h)). The study integrates historical data, advanced surveying techniques, and vulnerability assessments, creating high-resolution 3D models of the church's interior and exterior spaces using photogrammetry. Material characterization involves visual inspections and non-destructive testing, such as sonic tests, while dynamic identification tests reveal the building's structural behavior. Two numerical models were developed. The first is a high-fidelity model calibrated with operational modal analysis data for condition monitoring. The second, simplified model assesses seismic vulnerability, showing greater vulnerability in the transverse direction (0.12g) than in the longitudinal direction (0.3g). The HBIM consolidates all data, including damage mapping, test results, and 360° views, providing a comprehensive tool for ongoing monitoring and conservation planning. This research highlights the role of DTs in identifying structural vulnerabilities and enabling data-driven preservation strategies.



**Figure 4:**

St. Torcato Church (Funari et al. 2021) **a.** Front view, **b.** Point cloud views, **c.** First mode shape. Church of Santa Ana (Chaves et al. 2024) **d.** Aerial view, **e.** Photogrammetric model of the transverse arch, **f.** Exterior photogrammetric model, **g.** High-fidelity FEM model, **h.** Principal tensile strains for maximum displacements.

### 3. 3D PRINTING IN HERITAGE CONSERVATION

In heritage conservation, 3DP has proven invaluable for accurately reproducing missing or damaged architectural elements, especially unique components that traditional methods cannot replicate (Xu et al., 2017; Bourgeois et al., 2024). It bridges traditional craftsmanship with modern innovation, offering solutions for reconstructing both digital and physical models of historical

structures (Xu et al., 2017; Camacho et al., 2018; L. Zhang et al., 2023). The scientific literature on 3DP technologies in cultural heritage conservation underscores several key research areas. Among these are the reproduction of non-structural artifacts (Echavarria et al., 2016; Segreto et al., 2017; Di Paola et al., 2017; Fragkos et al., 2018; Luca et al., 2019; Tucci et al., 2019; Comes et al., 2021; Parfenov et al., 2022; Liu et al., 2022; Kantaros, et al., 2023; Bourgeois et al., 2024), large-scale structural restoration (Xu et al., 2017; Codarin, 2020; Codarin and Daubmann, 2021; Altadonna et al., 2023) and the evaluation of material durability for these applications (Mansi et al., 2023; Fico et al., 2023; Higueras et al., 2024).

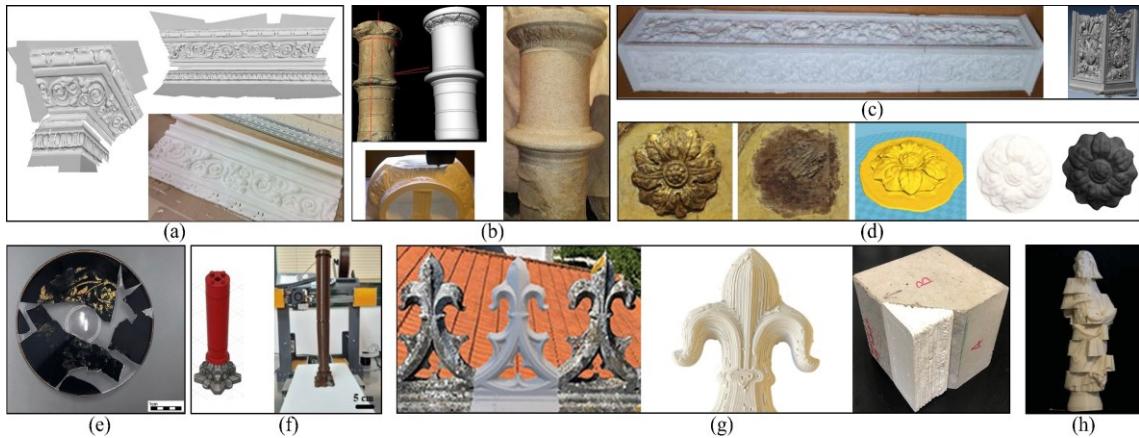
Echavarria et al. (2016) explored the restoration of ornamental moldings in historical buildings using 3D scanning and AM. A Breuckmann smart scan device and Geomagic Studio were used to capture and reconstruct intricate geometries, including missing sections (Figure 5(a)). Two workflows were tested: 3D-printed molds for plaster casting and Fused Deposition Modeling (FDM) printing. Although direct 3DP enabled faster and more customizable solutions, concerns over material durability favored plaster casting for authenticity. The study highlights the importance of balancing innovation with material compatibility in heritage conservation.

The integration of 3D technologies in cultural heritage conservation has proven effective, particularly in restoring and reproducing sculptures. Di Paola et al. (2017) demonstrated this by applying 3D scanning and printing to restore the colossal Zeus enthroned statue from Soluntum, housed in the Archaeological Museum “A. Salinas” in Palermo. Using an Artec Spider scanner, they captured throne leg geometries with 0.1 mm accuracy (Figure 5(b)). Processed via Artec Studio and Leios, missing parts were reconstructed with Polylactic Acid (PLA) using FDM (0.25 mm resolution, 90 mm/s). The integration followed conservation principles of recognizability, compatibility, and reversibility, demonstrating the practical value of 3DP in sustainable, cost-effective restoration. Segreto et al. (2017) explored reverse engineering (RE) and 3DP for replicating cultural artifacts, focusing on a 6th-century marble column from the Basilica of San Giovanni Maggiore in Naples (Figure 5(c)). The column was scanned using a Romer Arm laser system and a Digital Close Range Photogrammetry (DCRP) setup. While the laser system provided highly detailed point clouds, it required 8 hours to scan a 77 cm section. DCRP captured the entire 5 m column in 70 minutes with reduced precision. Models were processed with Polyworks V12 and Agisoft PhotoScan software, and the 5 m column was 3D printed at 20% scale using FDM with PLA on a Delta Wasp 40x70 printer in 33 hours. The study highlights trade-offs between accuracy, speed, and cost in RE-based heritage preservation. Tucci et al. (2019) used photogrammetry and 3DP to replicate two deteriorated marble statues from the Baptistry of San Giovanni in Corte, Italy (Figure 5(h)). High-resolution 3D models were generated via Structure from Motion, processing 350-400 photos per statue using Agisoft Metashape. This combination of digital acquisition and AM provided a highly accurate base for replication. A Klonerh 3D printer (700mm x 700mm x 1800mm) with FDM technology produced full-scale replicas, employing acrylonitrile styrene acrylate filament for outdoor durability. The statues were printed in segments (up to 48 h each), assembled, and finished through sandblasting and color tuning. Accuracy tests confirmed the method’s precision, highlighting its value for heritage replication and accessibility. The study showed that digital modeling and 3DP effectively produce precise replicas, offering innovative solutions for cultural heritage conservation and accessibility. Kantaros et al. (2023) applied 3DP to improve museum accessibility by producing scaled replicas of statues like “Apollo of Piraeus” and “Artemis Kindyas” at the Piraeus Archaeological Museum using Fused Filament Fabrication (FFF) technology with a sustainable material blend of 70% recycled PLA and 30% virgin PLA. Recycled material was processed with 3DEvo systems, and optimized printing parameters were implemented through G-code, ensuring precision. The replicas enhanced tactile engagement for visually impaired visitors while promoting circular economy practices in cultural heritage.

Focusing on the reconstruction of missing parts in artifacts, several studies have showcased innovative approaches using 3D technologies. Fragkos et al. (2018) presented an innovative

approach to reconstructing missing fragments of an archaeological find using 3D technologies. A NextEngine 3D laser scanner captured high-resolution data from a ceramic pottery artifact, processed with ScanStudio, Geomagic Studio, and Solidworks for refinement. The missing piece was recreated with Acrylonitrile Butadiene Styrene filament on a BCN3D Sigma printer, using water-soluble polyvinyl alcohol supports to minimize contact with fragile surfaces. The reconstructed fragment was accurately integrated into the pottery, showcasing the method's precision and potential in digital archaeology. Luca et al. (2019) addressed the restoration of missing ornaments on a 17th-century gilded wooden door in a Turin church using handheld structured handheld volumetric scanners and 3DP (Figure 5(d)). Among tested methods (TLS, F6 SMART and F6 SR), the F6 SR scanner and CloudCompare software produced the highest-quality mesh. Elements were printed in black PLA using a Delta WASP 4070 printer, following reversibility and recognizability principles of modern restoration. The study demonstrated the efficiency of handheld structured light scanners in capturing intricate architectural details and integrating 3D-printed components into historical restorations. Comes et al. (2021) utilized 3D technologies to reconstruct missing Dacian ornamental discs from the Piatra Roșie hillfort, Romania, using Viuscan laser scanning (0.1 mm resolution) and Blender for digital modeling. The 420 mm diameter discs were replicated in PLA, with intricate details restored from photographic references. Post-processing with acetone and black spray paint enhanced authenticity. This interdisciplinary method highlighted the role of 3DP in transforming inaccessible heritage into tangible, preservable, and exhibit-ready cultural assets, enriching both museum experiences and scientific research. Liu et al. (2022) developed a "transparent reversible prosthesis" for a gold-decorated Black Ding bowl from the Chifeng Museum, combining digital modeling, virtual reconstruction, and 3DP (Figure 5(e)). Using a portable laser scanner, they created precise 3D models of 14 fragments, enabling the design of a non-invasive prosthesis made from VeroUltraClear™ resin, chosen for its mechanical strength and compatibility with conservation principles. Printed on a Stratasys J850™ with 14  $\mu\text{m}$  resolution, the prosthesis securely held fragments without adhesives, adhering to reversibility standards. Accelerated UV aging tests confirmed stable mechanical integrity despite yellowing. This case study showcased how advanced 3D technologies offer both physical restoration and digital preservation of complex archaeological artifacts while maintaining ethical standards of cultural heritage conservation. Parfenov et al. (2022) restored two damaged cultural heritage artifacts using advanced laser-based AM methods: the "Eva at the Fountain" zinc sculpture via laser stereolithography and a heavily damaged cast-iron star using Direct Metal Laser Sintering (DMLS) and Laser Cladding (LC). DMLS ensured  $\pm 0.7$  mm accuracy, while LC reinforced sections with Inconel 625 powder. Although FDM offered a low-cost option, its material limitations reinforced the need to match AM techniques with specific restoration goals. This research underscored the precision and versatility of DMLS and LC for preserving intricate, historically significant artifacts, advocating for a balanced approach to sustainability and accuracy in cultural heritage conservation. Rizzo et al. (2023) restored missing columns of a 17th-century wooden ciborium (Figure 5(f)) using a hybrid workflow. Photogrammetry and manual 2D drawings were converted into refined 3D models via Rhinoceros and Fusion 360. PETG filament, which is chosen for its superior durability and chemical resistance, was printed using FFF (0.2 mm layer height, 20% infill) on a 3DPRN LAB printer. Traditional finishes—Bologna plaster, rabbit glue, and gold leaf—ensured aesthetic consistency. This approach enabled fast, cost-effective, and accurate reproduction of complex geometries while preserving the artifact's integrity. Bourgeois et al. (2024) applied 3D technologies to heritage restoration, focusing on the Fleur-de-Lis ornament at Batalha Monastery (Figure 5(g)). Using photogrammetry (Sony A6100, Recap Pro, Leica Cyclone 3DR) and 3DP (Delta Wasp 40,100), they optimized print quality through tailored extruder sizes. Mortars with white Portland cement, kaolinitic clay, fine sand, and nano clay additives improved printability and layer stability. Reducing binder content and increasing aggregate dosage enhanced geometric

precision. The study emphasized both the potential and ethical responsibilities of 3D technology-based heritage restoration.

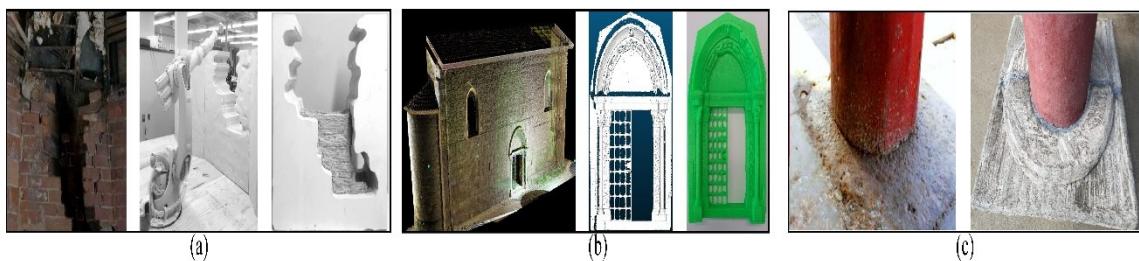


**Figure 5:**

**a.** Resulting 3D models of linear and corner molding patterns, fabrication of cornice sections via AM (Echavarria et al. 2016), **b.** Virtual reconstruction of missing parts, printing phase, and integration of the printed sections (Di Paola et al. 2017), **c.** Downscaled column replica fabricated through AM and refined polygon mesh (Segreto et al. 2017), **d.** Decorative rosette: absence, modeling, and printing of missing objects (Luca et al. 2019), **e.** Conservation-restoration result of the gold-foil decorated Black Ding bowl (Liu et al. 2022), **f.** Wooden ciborium column model with PLA-printed prototypes (Rizzo et al. 2023), **g.** Modeling a missing part printed part, and Incorporation of the printed element in the fragmented cube Bourgeois et al. (2024), **h.** Replica of St. John the Baptist statue composed of multiple 3D-printed blocks prior to assembly (Tucci et al. 2019).

Xu et al. (2017) employed 3D laser scanning and AM to restore a damaged ornamental plinth from a historical building (Figure 6(c)). High-resolution scanning captured intricate surface details, with the data refined in Geomagic Studio to create an accurate digital model. A cement-mortar-based 3DP process was used for physical reproduction, chosen for its stone-like properties to maintain the plinth's structural and aesthetic integrity. A modified algorithm optimized slicing and nozzle path planning, enhancing accuracy and strength. Compressive strength tests confirmed suitability for restoration, yielding 19.8 MPa vertically and 15.6 MPa laterally. This combination of 3D scanning, advanced modeling with Geomagic Studio, and cement-mortar-based 3DP demonstrates a robust method for restoring historical architectural elements, supporting the growing role of DT technologies and 3DP in sustainable and precise cultural heritage preservation. Codarin (2020) explored AM technologies for cultural heritage restoration, focusing on the Woodward Avenue Presbyterian Church in Detroit (Figure 6(a)). The study combined 3D scanning, LIDAR, and drone photogrammetry to create digital models of damaged areas, which guided a 6-axis robotic arm equipped with a clay extrusion nozzle. Clay was selected for its workability and ability to produce high-quality finishes. Robot movements were simulated virtually to ensure precision and prevent errors, enabling efficient restoration of complex geometries while reducing material waste and preserving architectural integrity. Building on this, Codarin and Daubmann (2021) applied robotic fabrication to reconstruct a missing wall volume. Using a 6-axis Kuka robot with a custom clay extruder, the team 3D-printed the wall gap at a 1:1 scale with raw clay. The workflow integrated 3D scanning, digital modeling, and robotic path simulation through Grasshopper and Kuka Prc plug-ins. Careful management of clay viscosity and layer drying prevented structural collapse during the four-session extrusion process. While showcasing the feasibility of cost-effective robotic fabrication for conservation, the study identified areas for improvement, including advanced end-effectors, real-time sensing, and

greater system flexibility. They concluded that robotic fabrication could become a viable conservation method with future refinements, requiring interdisciplinary teams skilled in design, digital modeling, and fabrication techniques. Altadonna et al. (2023) compared CNC milling and Material Extrusion 3DP (MEX) for architectural heritage restoration, using the Gothic church of Santa Maria Alemanna in Messina, Italy, as a case study. Detailed 3D models were created using laser scanning with a Leica HDS 4050, followed by CNC milling with polystyrene and MEX with PLA to produce replicas of an architectural portion of the facade (Figure 6(b)). A Life Cycle Assessment (LCA) adhering to ISO standards revealed that MEX reduced carbon emissions by 27% and minimized waste (7g vs. 160g for CNC) but showed higher freshwater ecotoxicity and land-use impacts due to PLA's agricultural origins. The study underscored MEX's environmental advantages while emphasizing the importance of considering material properties, production time, and project requirements in method selection, highlighting 3DP's growing role in sustainable cultural heritage restoration.



**Figure 6:**

- a.** Damaged wall addressed for restoration (Codarin 2020). Experimental setup and creation of wall gap geometry using robotic AM (Codarin and Daubmann 2021). **b.** Laser scanner-generated point cloud of Santa Maria Alemanna Church (Altadonna et al. 2023). **c.** Fully damaged plinth and subsequent installation of the 3D-printed replacement plinth (Xu et al. 2017).

In addition to restoration techniques and structural applications, the evaluation of material durability is crucial for ensuring the longevity and effectiveness of 3D-printed components in cultural heritage conservation. Higueras et al. (2024) evaluated the long-term behavior of thirteen FDM filaments for small heritage objects under 300 hours of accelerated aging under controlled environmental conditions (temperature, humidity, and irradiance). Key properties such as color, glossiness, pH, and volatile organic compound emissions were assessed, revealing epoxy and polypropylene as the most stable materials, with Flex material showing significant changes in chroma and hue. The results suggested that material selection for object restoration must prioritize stability in aging conditions to ensure the preservation of cultural artifacts over time. Mansi et al. (2023) investigated 3D-printed nanocomposite materials for restoring exterior artworks, using PLA filament enhanced with 3% SiC, SiO<sub>2</sub>, and TiO<sub>2</sub> nanoparticles via twin-screw extrusion. The nanoparticles, synthesized by CO<sub>2</sub> laser pyrolysis, measured 25 nm (SiC), 10 nm (SiO<sub>2</sub>), and 13 nm (TiO<sub>2</sub>). Mechanical tests revealed that SiC and SiO<sub>2</sub> improved stiffness and strain, while TiO<sub>2</sub> reduced these properties. Water absorption tests showed that PLA-SiO<sub>2</sub> composites had 50% greater hydrophobicity than pure PLA, making them the most suitable for cultural heritage restoration due to their enhanced mechanical properties and water resistance. Further optimization is recommended for broader applications. Fico et al. (2023) compared FFF and CNC milling for restoring missing columns of a 17th-century wooden tabernacle, using PETG for 3DP and European pine for CNC. CAD models were created with Rhinoceros and Fusion 360, converted to STL files via Cura software. Material analysis, including FTIR, XRD, DSC, and mechanical testing, revealed that PETG exhibited superior durability and water repellency after artificial aging. While CNC milling was faster, FFF proved more cost-effective, produced less waste, and offered greater material stability, making it the preferred method. This work demonstrated the

potential of 3DP, particularly FFF, in cultural heritage conservation as a sustainable approach to replicating complex architectural elements while maintaining key material properties.

#### 4. CHALLENGES, OPPORTUNITIES AND FUTURE EXPECTATIONS

The integration of DT and 3DP technologies in the rehabilitation of historical buildings offers transformative potential for cultural heritage conservation. While these innovations present significant opportunities, they also bring challenges that must be addressed to maximize their impact.

A significant opportunity lies in DT technology's ability to support real-time monitoring, structural analysis, and virtual restoration planning in heritage conservation (Bruno et al., 2018). By generating accurate 3D models, experts can simulate intervention scenarios, assess structural conditions, and optimize maintenance strategies without physically interfering with the structure (Dore and Murphy, 2017; Bruno et al., 2018). Integration with VR and AR tools enhances public engagement through immersive educational experiences (Barazzetti and Banfi, 2017). Additionally, DTs contribute to sustainable restoration by reducing invasiveness and enabling timely, data-informed decisions (Barsanti et al., 2024).

3DP technology enables the precise reproduction of intricate architectural components that are difficult or impossible to replicate using traditional methods (Ngo et al., 2018; Tarhan and Şahin, 2019). Utilizing materials compatible with original structures supports heritage sites' aesthetic and historical integrity while significantly reducing restoration time and labor requirements (Wu et al., 2016). Recent advancements—such as large-scale printers capable of extruding concrete-like materials and the development of optimized printable mixes—have enhanced design flexibility, reduced waste, and improved cost-efficiency in conservation applications (Gao et al., 2015; Puzatova et al., 2022; Zuo et al., 2024).

These technologies' true potential emerges when integrated into a structured workflow. Initially, drones equipped with laser scanners and AI-based image analysis accurately map structural damage, generating detailed 3D data. These data are then processed through BIM and advanced reconstruction algorithms to create a precise DT, enabling comprehensive virtual assessment and proactive repair planning. The damaged regions identified by the DT are digitally modeled, and fabrication instructions, including printable geometries and precise robotic tool paths, are generated and validated. Guided by these DT-derived instructions, robotic arms fabricate and install custom-made replacement components or infill masonry, ensuring high precision and minimal material waste. Throughout this process, the DT continuously monitors restoration activities in real-time, allowing adaptive adjustments that maintain structural integrity and visual consistency. This seamless digital-to-physical loop—from damage detection and virtual diagnosis to automated manufacturing and ongoing monitoring—minimizes human error, significantly reduces restoration time, and guarantees structurally and aesthetically compatible repairs, ultimately enhancing the quality, sustainability, and efficiency of heritage conservation practices.

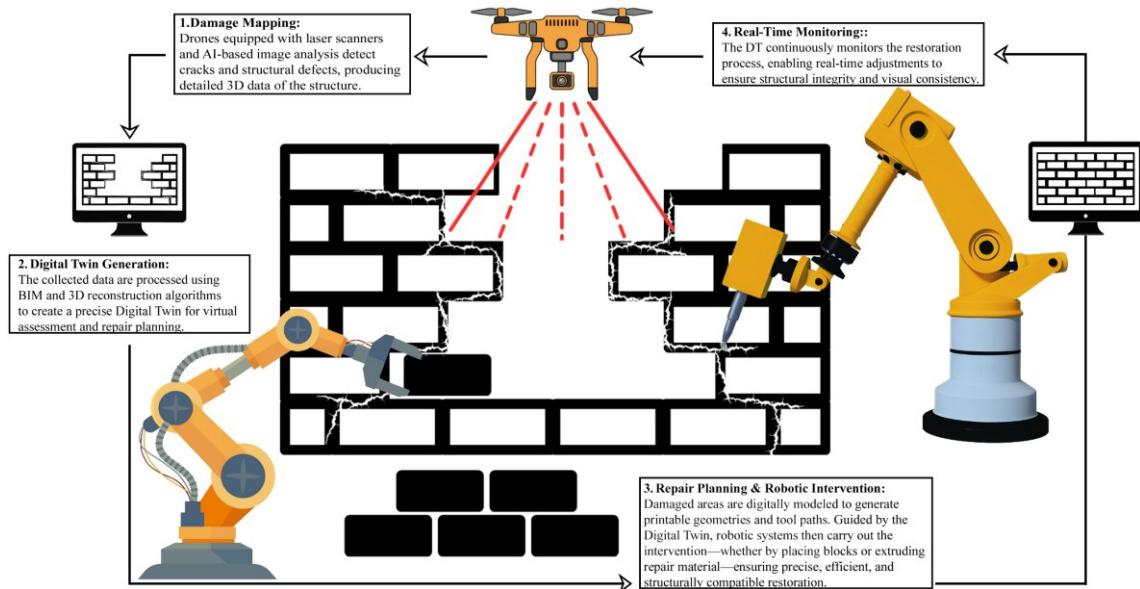
An envisioned advancement proposed in this study is the use of autonomous drones and robotic systems for restoration. This idea finds early echoes in works like Codarin and Daubmann (2021), representing an initial phase of such applications. In this concept, drones with imaging and scanning capabilities could map areas of damage on historical structures, producing detailed DTs to guide restoration planning, as illustrated in Figure 7. Using these digital models, robotic arms could then be deployed to precisely place repair materials, such as blocks or bricks, while a secondary arm would inject mortar or binding agents to connect these components and repair cracks. Further refinement in this vision could include a steel rail system, enabling robotic arms to autonomously navigate the site and conduct targeted repairs on damaged sections. This approach could enhance efficiency and safety by minimizing manual labor in hazardous areas and facilitating highly accurate, structurally aligned repairs. It may be particularly beneficial for hard-

to-reach locations where traditional scaffolding is impractical. In this workflow, once the restoration is completed, embedded sensors (e.g., crack, acceleration, temperature, and humidity sensors) continuously feed real-time data into the Digital Twin, allowing the model to remain current.

These technologies also enhance public engagement and education by providing virtual access to cultural heritage sites. VR and AR applications derived from DTs allow for immersive experiences, making heritage accessible to broader audiences regardless of geographic limitations. Furthermore, 3DP contributes to sustainability by reducing material waste and enabling the use of recycled materials, while DTs optimize energy efficiency in heritage buildings, minimizing their ecological impact.

Despite these opportunities, significant challenges remain. High initial equipment, software, and training costs can hinder adoption, particularly for smaller institutions. Widespread implementation is further constrained by data security concerns and resistance to adopting new approaches within the construction sector (Barsanti et al., 2024). Technical expertise is another significant hurdle. The effective use of DT and 3DP technologies demands interdisciplinary collaboration among conservationists, engineers, computer scientists, and materials specialists. In addition to initial costs and training demands, heritage professionals must also consider the long-term durability of 3DP materials and the scalability of DT systems. These practical constraints can affect adoption decisions, particularly for small institutions with limited budgets, where phased implementation or collaborative resource-sharing models may offer feasible alternatives. Bridging the gap between traditional conservation methods and modern digital practices requires not only technical proficiency but also a cultural shift within the conservation community. Resistance to adopting new technologies and a lack of standardized training programs can impede this integration.

Data management and security are critical concerns as DTs generate vast amounts of data. Robust storage solutions and standardized protocols are essential to ensure data integrity and prevent unauthorized access. Ensuring material compatibility and long-term performance remains a key challenge in 3DP-based restoration, particularly in improving structural integrity and addressing technical limitations of existing systems (El-Sayegh et al., 2020; Khan et al., 2021). Selecting appropriate materials that match the physical and chemical properties of the original structures is essential to prevent adverse reactions or accelerated degradation. Ongoing research into suitable materials, such as lime-based mixtures for repair activities (Tarhan et al., 2024), is necessary to ensure that 3D-printed components contribute positively to the conservation of historic buildings.



**Figure 7:**

*The future of masonry building rehabilitation is envisioned by integrating advanced robotic systems, drone-based monitoring, and 3D mortar printing for automated damage identification and repair of historic masonry buildings.*

Technological limitations, such as insufficient resolution for scanning and printing complex geometries or large-scale structures, further constrain these innovations. Ethical concerns surrounding the authenticity and cultural significance of digital replicas must also be addressed to balance technological progress with respect for traditional craftsmanship and heritage values. Without proper oversight, digital replicas could weaken the unique value of original artifacts, allow unauthorized or commercial use, or leave local communities out of decisions about their heritage. To prevent these risks, it is vital to use secure and traceable databases to avoid unauthorized copying or misuse of digital models, and to include clear information with each model that explains its purpose, origin, and permitted uses. Incorporating these ethical safeguards into international guidelines and standards will help ensure that digital technologies respect and protect cultural values. In addition, addressing issues such as cost, data management, and material compatibility remains essential for the responsible and effective adoption of DT and 3DP technologies in heritage conservation.

Looking toward the future, several trends and advancements promise to enhance historical building rehabilitation: (i) The development of smart materials and 4D Printing that can adapt to environmental conditions or self-heal over time could revolutionize restoration practices, offering sustainable and long-lasting solutions. (ii) Incorporating machine learning algorithms can optimize repair strategies, predict future deterioration, and enhance the overall management of conservation projects. (iii) Augmented and Virtual Reality technologies can provide immersive experiences for education and public engagement, making cultural heritage more accessible and fostering greater appreciation. (iv) Utilizing environmentally friendly and locally sourced materials in 3DP supports sustainable practices and reduces the carbon footprint of restoration activities. (v) Advanced robotic systems, such as robotic arms mounted on movable scaffolding, can perform precise restoration tasks, especially in inaccessible areas, improving efficiency and safety.

## 5. CONCLUSIONS

This review has explored the application of Digital Twin (DT) and 3D Printing (3DP) technologies in the rehabilitation of historical buildings. Studies and case examples have demonstrated how these technologies can revolutionize restoration efforts. DT facilitates the creation of precise digital replicas, enabling detailed analysis, real-time monitoring, and predictive maintenance to support proactive preservation strategies. Examples include the use of drones equipped with advanced scanning devices to perform DT modeling, efficiently identifying areas of damage or deterioration. Similarly, 3DP offers innovative solutions for replicating intricate architectural elements, preserving heritage sites' aesthetic and historical integrity through complex geometries that are challenging to achieve with traditional methods.

As a next step, this study envisages an end-to-end workflow in which drones capture damage data for DT updates and rail-mounted robotic arms carry out 'scan-to-print' masonry infill; once the intervention is complete, embedded sensors continuously feed real-time structural data into the DT, allowing for ongoing monitoring, early anomaly detection, and adaptive maintenance in inaccessible areas.

However, material choice must match the physico-chemical behavior of the host fabric. Accelerated-ageing tests indicate that epoxy- and polypropylene-based prints remain dimensionally stable, while standard PLA and PETG absorb moisture and warp (Higuera et al., 2024). Recycled PLA filaments help reduce waste but share the same moisture sensitivity unless modified. SiO<sub>2</sub>-reinforced PLA raises hydrophobicity by roughly 50 % (Mansi et al., 2023), improving suitability for outdoor sculpture repairs, yet differential thermal expansion with stone or timber substrates still requires assessment. Direct metal-laser-sintered Inconel 625 parts deliver high strength (Parfenov et al., 2022) but may suffer galvanic corrosion and stiffness mismatch. Finally, printable lime-based mortars - now being tested in early trials (e.g., Tarhan et al., 2024) - offer improved chemical compatibility with historic masonry. However, further mix optimisation is required to confirm long-term durability and full suitability for restoration work. Hybrid solutions - such as PETG prints later finished with gold leaf and plaster (Rizzo et al., 2023) - should likewise be pre-tested for thermal expansion, moisture transfer, and reversible adhesion before on-site installation.

While these technologies offer significant benefits, several challenges hinder their widespread adoption. High initial costs for equipment and software, the need for specialized technical expertise, and concerns regarding the long-term durability of 3D-printed materials are notable obstacles. Ethical considerations related to authenticity and the importance of documentation and reversibility in restoration processes also require careful attention. Addressing these challenges necessitates interdisciplinary collaboration, ongoing research into material science, and adherence to conservation principles.

Looking ahead, future research should focus on five main areas: (i) Materials science - develop printable lime- and mineral-based mortars and assess their long-term durability and compatibility; (ii) Computational methods - combine real-time data with DT models, advanced numerical simulations, and AI tools for predicting structural issues and optimising 3D-printed repairs; (iii) Robotic fabrication - create autonomous systems for heritage-compatible 3DP with minimal site disruption; (iv) Visualisation and analytics - use edge-AI and XR technologies for on-site monitoring and decision support; (v) Social engagement and ethics - promote public involvement through open-access models and establish guidelines on authenticity and reversibility.

## CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## AUTHOR CONTRIBUTIONS

In this paper, İsmail Hakkı Tarhan contributed to conceptualization, methodology, software and computational analysis, investigation, data curation, visualization, writing – original draft and review&editing. Yeşim Tarhan contributed to conceptualization, material investigation and evaluation, investigation, resources, formal analysis, and writing – review & editing.

## REFERENCES

1. Altadonna, A., Cucinotta, F., Raffaele, M., Salmeri, F., and Sfravara, F. (2023). Environmental Impact Assessment of Different Manufacturing Technologies Oriented to Architectonic Recovery and Conservation of Cultural Heritage. *Sustainability (Switzerland)*, 15(18). [doi:10.3390/su151813487](https://doi.org/10.3390/su151813487)
2. Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, 60(5), 677–688. [doi:10.1016/j.bushor.2017.05.011](https://doi.org/10.1016/j.bushor.2017.05.011)
3. Baeriswyl, M. V. C., Palacios, G. T., Lannefranque, J. A., Tagliabue, L., and Rinaldi, S. (2023). Regeneration of a former prison in melipilla, Chile: use of digital technology in a heritage restoration project. *Proceedings of the European Conference on Computing in Construction*, 4. [doi:10.35490/EC3.2023.318](https://doi.org/10.35490/EC3.2023.318)
4. Barazzetti, L., and Banfi, F. (2017). Historic BIM for Mobile VR/AR Applications. In *Mixed Reality and Gamification for Cultural Heritage* (pp. 271–290). Springer, Cham. [doi:10.1007/978-3-319-49607-8\\_10](https://doi.org/10.1007/978-3-319-49607-8_10)
5. Barsanti, G., Mousavi, Y., Gharineiat, Z., Agha Karimi, A., McDougall, K., Rossi, A., and Gonizzi Barsanti, S. (2024). Digital Twin Technology in Built Environment: A Review of Applications, Capabilities and Challenges. *Smart Cities 2024*, 7(5), 2594–2615. [doi:10.3390/SMARTCITIES7050101](https://doi.org/10.3390/SMARTCITIES7050101)
6. Bekele, M. K., Pierdicca, R., Frontoni, E., Malinverni, E. S., and Gain, J. (2018). A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage. *Journal on Computing and Cultural Heritage (JOCCH)*, 11(2). [doi:10.1145/3145534](https://doi.org/10.1145/3145534)
7. Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114, 103179. [doi:10.1016/J.AUTCON.2020.103179](https://doi.org/10.1016/J.AUTCON.2020.103179)
8. Bourgeois, I., Ascensão, G., Ferreira, V., and Rodrigues, H. (2024). Methodology for the Application of 3D Technologies for the Conservation and Recovery of Built Heritage Elements. *International Journal of Architectural Heritage*. [doi:10.1080/15583058.2024.2341327](https://doi.org/10.1080/15583058.2024.2341327)
9. Bruno, S., De Fino, M., and Fatiguso, F. (2018). Historic Building Information Modelling: performance assessment for diagnosis-aided information modeling and management. *Automation in Construction*, 86, 256–276. [doi:10.1016/J.AUTCON.2017.11.009](https://doi.org/10.1016/J.AUTCON.2017.11.009)
10. Camacho, D. D., Clayton, P., O'Brien, W. J., Seepersad, C., Juenger, M., Ferron, R., and Salamone, S. (2018). Applications of additive manufacturing in the construction industry – A forward-looking review. *Automation in Construction*, 89, 110–119. [doi:10.1016/J.AUTCON.2017.12.031](https://doi.org/10.1016/J.AUTCON.2017.12.031)
11. Cascone, S., Parisi, G., and Caponetto, R. (2024). BIM-Based Strategies for the Revitalization and Automated Management of Buildings: A Case Study. *Sustainability 2024*, 16(16), 6720. [doi:10.3390/SU16166720](https://doi.org/10.3390/SU16166720)

12. Chaves, E., Aguilar, J., Barontini, A., Mendes, N., and Compán, V. (2024). Digital Tools for the Preventive Conservation of Built Heritage: The Church of Santa Ana in Seville. *Heritage 2024*, 7(7), 3470–3494. [doi:10.3390/HERITAGE070164](https://doi.org/10.3390/HERITAGE070164)
13. Chiabrando, F., Lo Turco, M., and Santagati, C. (2017). Digital invasions: from point clouds to historical building object modeling (h-bom) of a unesco whl site. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2-W3(2W3)*, 171–178. [doi:10.5194/ISPRS-ARCHIVES-XLII-2-W3-171-2017](https://doi.org/10.5194/ISPRS-ARCHIVES-XLII-2-W3-171-2017)
14. Codarin, S. (2020). Additive Manufacturing Technologies in Restoration: An Innovative Workflow for Interventions on Cultural Heritage. *Cubic Journal*, (3), 32-55. [doi:10.31182/cubic.2020.3.023](https://doi.org/10.31182/cubic.2020.3.023)
15. Codarin, S., and Daubmann, K. (2021). Robotic Fabrication in Conservation: Digital Workflows and Skills Evaluation. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 12642 LNCS, 241–253. [doi:10.1007/978-3-030-73043-7\\_20](https://doi.org/10.1007/978-3-030-73043-7_20)
16. Comes, R., Grec, C., Neamțu, C., Găzdac, C., and Mateescu-suciul, I. (2021). Intangible heritage?...not anymore, from photo to 3d printed cultural heritage assets replicas. The two missing iron discs from the dacian hillfort of piatra roșie (romania). *Journal of ancient history and archaeology*, 8(1). [doi:10.14795/j.v8i1.622](https://doi.org/10.14795/j.v8i1.622)
17. Dang, X., Liu, W., Hong, Q., Wang, Y., and Chen, X. (2023). Digital twin applications on cultural world heritage sites in China: A state-of-the-art overview. *Journal of Cultural Heritage*, 64, 228–243. [doi:10.1016/J.CULHER.2023.10.005](https://doi.org/10.1016/J.CULHER.2023.10.005)
18. Di Paola, F., Milazzo, G., and Spatafora, F. (2017). Computer aided restoration tools to assist the conservation of an ancient sculpture, The colossal statue of zeus enthroned. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(2W5), 177–184. [doi:10.5194/isprs-archives-XLII-2-W5-177-2017](https://doi.org/10.5194/isprs-archives-XLII-2-W5-177-2017)
19. Dore, C., and Murphy, M. (2017). Current state of the art historic building information modelling. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 185–192. [doi:10.5194/isprs-archives-XLII-2-W5-185-2017](https://doi.org/10.5194/isprs-archives-XLII-2-W5-185-2017)
20. Echavarria, K. R., Song, R., Few, D., and E Sáy, A. M. (2016). Restoration of Architectural Ornament for Historic Buildings. *GraDiFab 2016 - Eurographics Workshop on Graphics for Digital Fabrication*, 39–48. [doi:10.2312/gdf.20161077](https://doi.org/10.2312/gdf.20161077)
21. El-Sayegh, S., Romdhane, L., and Manjikian, S. (2020). A critical review of 3D printing in construction: benefits, challenges, and risks. *Archives of Civil and Mechanical Engineering*, 20(2), 1–25. [doi:10.1007/S43452-020-00038-W](https://doi.org/10.1007/S43452-020-00038-W)
22. Falcone, M., Origlia, A., Campi, M., and DI Martino, S. (2021). From architectural survey to continuous monitoring: graph-based data management for cultural heritage conservation with digital twins. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLIII-B4-2021(B4-2021)*, 47–53. [doi:10.5194/ISPRS-ARCHIVES-XLIII-B4-2021-47-2021](https://doi.org/10.5194/ISPRS-ARCHIVES-XLIII-B4-2021-47-2021)
23. Fico, D., Rizzo, D., Montagna, F., and Esposito Corcione, C. (2023). Fused Filament Fabrication and Computer Numerical Control Milling in Cultural Heritage Conservation. *Materials*, 16(8). [doi:10.3390/ma16083038](https://doi.org/10.3390/ma16083038)
24. Fragkos, S., Tzimtzimis, E., Tzetzis, D., Dodun, O., and Kyrtatsis, P. (2018). 3D laser scanning and digital restoration of an archaeological find. *MATEC Web of Conferences*, 178. [doi:10.1051/matecconf/201817803013](https://doi.org/10.1051/matecconf/201817803013)
25. Funari, M. F., Hajjat, A. E., Masciotta, M. G., Oliveira, D. V., and Lourenço, P. B. (2021). A Parametric Scan-to-FEM Framework for the Digital Twin Generation of Historic Masonry Structures. *Sustainability 2021*, 13(19), 11088. [doi:10.3390/SU131911088](https://doi.org/10.3390/SU131911088)

26. Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C. L., Shin, Y. C., Zhang, S., and Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*, 69, 65–89. [doi:10.1016/J.CAD.2015.04.001](https://doi.org/10.1016/J.CAD.2015.04.001)
27. Garcia-Leon, J., Murrieri, P., and Collado-Espejo, P. E. (2023). Hbim as a tool for the analysis and conservation of architectural heritage. Case study: the rame tower's digital twin. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-2-2023(M-2-2023), 637–644. [doi:10.5194/ISPRS-ARCHIVES-XLVIII-M-2-2023-637-2023](https://doi.org/10.5194/ISPRS-ARCHIVES-XLVIII-M-2-2023-637-2023)
28. Higueras, M., Carrasco-Huertas, A., Calero-Castillo, A. I., Moreno Alcaide, M., and Collado Montero, F. J. (2024). Study of liquid photopolymer 3D printing resins exposed to accelerated aging for cultural heritage purposes. *Rapid Prototyping Journal*, 30(7), 1476–1485. [doi:10.1108/RPJ-01-2024-0015](https://doi.org/10.1108/RPJ-01-2024-0015)
29. Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., and Zhang, X. (2018). Carbon emission of global construction sector. *Renewable and Sustainable Energy Reviews*, 81, 1906–1916. [doi:10.1016/J.RSER.2017.06.001](https://doi.org/10.1016/J.RSER.2017.06.001)
30. Kantaros, A., Ganetsos, T., and Petrescu, F. I. T. (2023). Three-Dimensional Printing and 3D Scanning: Emerging Technologies Exhibiting High Potential in the Field of Cultural Heritage. *Applied Sciences* 2023, 13(8), 4777. [doi:10.3390/APP13084777](https://doi.org/10.3390/APP13084777)
31. Kantaros, A., Soulis, E., and Alyssandratos, E. (2023). Digitization of Ancient Artefacts and Fabrication of Sustainable 3D-Printed Replicas for Intended Use by Visitors with Disabilities: The Case of Piraeus Archaeological Museum. *Sustainability (Switzerland)*, 15(17). [doi:10.3390/su151712689](https://doi.org/10.3390/su151712689)
32. Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., and Holmstrom, J. (2019). Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7, 147406–147419. [doi:10.1109/ACCESS.2019.2946515](https://doi.org/10.1109/ACCESS.2019.2946515)
33. Khan, S. A., Koç, M., and Al-Ghamdi, S. G. (2021). Sustainability assessment, potentials and challenges of 3D printed concrete structures: A systematic review for built environmental applications. *Journal of Cleaner Production*, 303, 127027. [doi:10.1016/J.JCLEPRO.2021.127027](https://doi.org/10.1016/J.JCLEPRO.2021.127027)
34. La Russa, F. M., and Santagati, C. (2020). Historical sentient – building information model: a digital twin for the management of museum collections in historical architectures. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B4-2020(B4), 755–762. [doi:10.5194/ISPRS-ARCHIVES-XLIII-B4-2020-755-2020](https://doi.org/10.5194/ISPRS-ARCHIVES-XLIII-B4-2020-755-2020)
35. Liu, B., Guo, Y., Wang, Y., Liu, Q., Hu, Y., Wang, L., and Qian, K. (2024). Study on the compression performance of 3D printing concrete permanent formwork composite columns. *Journal of Building Engineering*, 98, 111245. [doi:10.1016/j.jobe.2024.111245](https://doi.org/10.1016/j.jobe.2024.111245)
36. Liu, S., Tu, Y., Wang, X., Qin, B., Xie, Z., Zhang, Y., Zhang, H., and Hu, D. (2022). Transparent reversible prosthesis, a new way to complete the conservation–restoration of a Black Ding bowl with application of 3D technologies. *Heritage Science*, 10(1). [doi:10.1186/s40494-022-00646-0](https://doi.org/10.1186/s40494-022-00646-0)
37. Luca, D. De, Giudice, M. Del, Grasso, N., Matrone, F., Osello, A., and Piras, M. (2019). Handheld volumetric scanner for 3D printed integrations of historical elements: comparison and results. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(2/W15), 381–388. [doi:10.5194/isprs-archives-XLII-2-W15-381-2019](https://doi.org/10.5194/isprs-archives-XLII-2-W15-381-2019)
38. Ma, X., Zhao, J., Wang, P., Du, J., Liu, J., and Zhao, D. (2024). Digital twin of wooden heritage through multidimensional model construction and integration. *Structural Health Monitoring*, 14759217241262969. [doi:10.1177/14759217241262969](https://doi.org/10.1177/14759217241262969)

39. Mahmoodian, M., Shahrvir, F., Setunge, S., and Mazaheri, S. (2022). Development of Digital Twin for Intelligent Maintenance of Civil Infrastructure. *Sustainability*, 14(14), 8664. [doi:10.3390/su14148664](https://doi.org/10.3390/su14148664)
40. Mansi, E., Terranova, G., Linardi, D., Marfia, S., Monaldo, E., Ricci, M., Imbimbo, M., Pelliccio, A., Brunetin, A., and D'Amato, R. (2023). Development of 3D printed nanomaterials for restoration of exterior artworks. *Journal of Physics: Conference Series*, 2579(1). [doi:10.1088/1742-6596/2579/1/012004](https://doi.org/10.1088/1742-6596/2579/1/012004)
41. Marienkov, M., Kaliukh, I., and Trofymchuk, O. (2024). The digital twin use for modeling the multi-storey building response to seismic impacts. *Structural Concrete*, 25(3), 2079–2096. [doi:10.1002/suco.202300695](https://doi.org/10.1002/suco.202300695)
42. Moyano, J., Carreño, E., Nieto-Julian, J. E., Gil-Arizón, I., and Bruno, S. (2022). Systematic approach to generate Historical Building Information Modelling (HBIM) in architectural restoration project. *Automation in Construction*, 143, 104551. [doi:10.1016/j.autcon.2022.104551](https://doi.org/10.1016/j.autcon.2022.104551)
43. Munoz-Pandiella, I., Bosch, C., Guardia, M., Cayuela, B., Pogliani, P., Bordi, G., Paschali, M., Andujar, C., and Charalambous, P. (2022). Digital Twins for Medieval Monuments: Requirements from Art Historians and Technical Challenges for Analysis and Restoration. *2022 International Conference on Interactive Media, Smart Systems and Emerging Technologies, IMET 2022 - Proceedings*. [doi:10.1109/IMET54801.2022.9929510](https://doi.org/10.1109/IMET54801.2022.9929510)
44. Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., and Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, 143, 172–196. [doi:10.1016/J.COMPOSITESB.2018.02.012](https://doi.org/10.1016/J.COMPOSITESB.2018.02.012)
45. Parfenov, V., Igoshin, S., Masaylo, D., Orlov, A., and Kuliashou, D. (2022). Use of 3D Laser Scanning and Additive Technologies for Reconstruction of Damaged and Destroyed Cultural Heritage Objects. *Quantum Beam Science*, 6(1). [doi:10.3390/qubs6010011](https://doi.org/10.3390/qubs6010011)
46. Perrot, A., Rangeard, D., and Courteille, E. (2018). 3D printing of earth-based materials: Processing aspects. *Construction and Building Materials*, 172, 670–676. [doi:10.1016/j.conbuildmat.2018.04.017](https://doi.org/10.1016/j.conbuildmat.2018.04.017)
47. Puzatova, A., Shakor, P., Laghi, V., and Dmitrieva, M. (2022). Large-Scale 3D Printing for Construction Application by Means of Robotic Arm and Gantry 3D Printer: A Review. *Buildings 2022*, 12(11), 2023. [doi:10.3390/BUILDINGS12112023](https://doi.org/10.3390/BUILDINGS12112023)
48. Rizzo, D., Fico, D., Montagna, F., Casciaro, R., and Esposito Corcione, C. (2023). From Virtual Reconstruction to Additive Manufacturing: Application of Advanced Technologies for the Integration of a 17th-Century Wooden Ciborium. *Materials*, 16(4). [doi:10.3390/ma16041424](https://doi.org/10.3390/ma16041424)
49. Rocca, I., Forti, I., D'Acunto, G., and Saetta, A. (2023). Survey, diagnostics, monitoring methodology and digital twin for the conservation of the facade of the church of santa maria di nazareth in venice. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-M-2-2023(M-2-2023), 1331–1336. [doi:10.5194/ISPRS-ARCHIVES-XLVIII-M-2-2023-1331-2023](https://doi.org/10.5194/ISPRS-ARCHIVES-XLVIII-M-2-2023-1331-2023)
50. Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., and Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, 1(6), e14. [doi:10.1017/DCE.2020.16](https://doi.org/10.1017/DCE.2020.16)
51. Sakin, M., and Kiroglu, Y. C. (2017). 3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM. *Energy Procedia*, 134, 702–711. [doi:10.1016/J.EGYPRO.2017.09.562](https://doi.org/10.1016/J.EGYPRO.2017.09.562)
52. Segreto, T., Bottillo, A., Teti, R., Galantucci, L. M., Lavecchia, F., and Galantucci, M. B. (2017). Non-contact Reverse Engineering Modeling for Additive Manufacturing of Down Scaled Cultural Artefacts. *Procedia CIRP*, 62, 481–486. [doi:10.1016/j.procir.2017.03.042](https://doi.org/10.1016/j.procir.2017.03.042)

53. Sherratt, F., Dowsett, R., and Sherratt, S. (2020). Construction 4.0 and its potential impact on people working in the construction industry. *Proceedings of the Institution of Civil Engineers-Management, Procurement and Law*, 173(4), 145–152. [doi:10.1680/JMAPL.19.00053](https://doi.org/10.1680/JMAPL.19.00053)
54. Tarhan, Y., and Perrot, A. (2023). Reinforcement of 3D printable earth-based mortar with natural textile material. *Materials Today: Proceedings*. [doi:10.1016/J.MATPR.2023.08.056](https://doi.org/10.1016/J.MATPR.2023.08.056)
55. Tarhan, Y., and Şahin, R. (2019). Developments of 3D concrete printing process. *International Civil Engineering and Architecture Conference*. <https://www.researchgate.net/publication/333673859>
56. Tarhan, Y., and Şahin, R. (2021). Fresh and Rheological Performances of Air-Entrained 3D Printable Mortars. *Materials 2021*, 14(9), 2409. [doi:10.3390/MA14092409](https://doi.org/10.3390/MA14092409)
57. Tarhan, Y., Tarhan, İ. H., Jacquet, Y., and Perrot, A. (2024). Mechanical behaviour of 3D printed and textile-reinforced eco-friendly composites. *Journal of Sustainable Cement-Based Materials*, 1–19. [doi:10.1080/21650373.2024.2396420](https://doi.org/10.1080/21650373.2024.2396420)
58. Tarhan, İ. H., and Tarhan, Y. (2025). Nonlinear in-plane response of 3D-printed concrete walls with varied infill patterns: Experimental mix design and numerical structural assessment, *Challenge Journal of Structural Mechanics*, 11(3), 160-173. [doi:10.20528/cjsmec.2025.03.005](https://doi.org/10.20528/cjsmec.2025.03.005)
59. Themistocleous, K., Evagorou, E., Mettas, C., and Hadjimitsis, D. G. (2022). The use of digital twin models to document cultural heritage monuments. In *Earth Resources and Environmental Remote Sensing/GIS Applications XIII*, Vol. 12268, pp. 55-64). SPIE. [doi:10.1117/12.2636332](https://doi.org/10.1117/12.2636332)
60. Tucci, G., Bonora, V., Tesi, V., and Pagnini, B. (2019, December). Additive manufacturing of marble statues: 3D replicas for the preservation of the originals. *IMEKO TC-4 International Conference on Metrology for Archaeology and Cultural Heritage*, 288-293.
61. Wu, P., Wang, J., and Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. *Automation in Construction*, 68, 21–31. [doi:10.1016/J.AUTCON.2016.04.005](https://doi.org/10.1016/J.AUTCON.2016.04.005)
62. Xu, J., Ding, L., and Love, P. E. D. (2017). Digital reproduction of historical building ornamental components: From 3D scanning to 3D printing. *Automation in Construction*, 76, 85–96. [doi:10.1016/J.AUTCON.2017.01.010](https://doi.org/10.1016/J.AUTCON.2017.01.010)
63. Yastikli, N. (2007). Documentation of cultural heritage using digital photogrammetry and laser scanning. *Journal of Cultural Heritage*, 8(4), 423–427. [doi:10.1016/j.culher.2007.06.003](https://doi.org/10.1016/j.culher.2007.06.003)
64. You, Z., and Feng, L. (2020). Integration of Industry 4.0 Related Technologies in Construction Industry: A Framework of Cyber-Physical System. *IEEE Access*, 8, 122908–122922. [doi:10.1109/ACCESS.2020.3007206](https://doi.org/10.1109/ACCESS.2020.3007206)
65. Zhang, J., Poon, K. H., Kwok, H. H. L., Hou, F., and Cheng, J. C. P. (2023). Predictive control of HVAC by multiple output GRU - CFD integration approach to manage multiple IAQ for commercial heritage building preservation. *Building and Environment*, 245, 110802. [doi:10.1016/j.buildenv.2023.110802](https://doi.org/10.1016/j.buildenv.2023.110802)
66. Zuo, Z., De Corte, W., Huang, Y., Chen, X., Zhang, Y., Li, J., Zhang, L., Xiao, J., Yuan, Y., Zhang, K., Zhang, L., and Mechtherine, V. (2024). Strategies towards large-scale 3D printing without size constraints. *Virtual and Physical Prototyping*, 19(1). [doi:10.1080/17452759.2024.2346821](https://doi.org/10.1080/17452759.2024.2346821)