

Article

Digital Transformation in African Heritage Preservation: A Digital Twin Framework for a Sustainable Bab Al-Mansour in Meknes City, Morocco

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Highlights

What are the main findings?

- The study develops a Digital Twin Heritage Building (DT_{HB}) framework based on digital transformation, integrating HBIM, IoT sensors, and predictive analytics to address structural and environmental challenges.
- The DT_{HB} framework enables real-time monitoring, scenario simulations, and predictive maintenance, offering a replicable model for African heritage sites.

What is the implication of the main finding?

- The research demonstrates how digital transformation addresses Africa's unique heritage preservation challenges through scalable and sustainable solutions.
- By preserving cultural landmarks like Bab Al-Mansour, the study enhances sustainable development, cultural identity, and tourism across the African continent.



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Abstract: The advent of digital transformation has redefined the preservation of cultural heritage and historic sites through the integration of Digital Twin technology. Initially developed for industrial applications, Digital Twins are now increasingly employed in heritage conservation as dynamic, digital replicas of physical assets and environments. These systems enable detailed, interactive approaches to documentation, management, and preservation. This paper presents a detailed framework for implementing Digital Twin technology in the management of heritage buildings. By utilizing advanced methods for data collection, processing, and analysis, the framework creates a robust data hub for Digital Twin Heritage Buildings (DT_{HB}). This architecture enhances real-time monitoring, improves accuracy, reduces operational costs, and enables predictive maintenance while minimizing invasive inspections. Focusing on Bab Al-Mansour Gate in Meknes, Morocco, a significant cultural landmark, this research outlines the workflow for developing a Bab Al-Mansour DT_{HB} platform. The platform monitors structural health and detects damage over time, offering a dynamic tool for conservation planning. By integrating innovative technologies with data-driven solutions, this study provides a replicable model for preserving heritage sites, addressing critical gaps in real-time monitoring, resource optimization, and environmental risk mitigation.

Keywords: heritage building; digital twin; HBIM; data-driven; predictive maintenance; real-time monitoring; Bab Al-Mansour gate

1. Introduction

Heritage buildings are invaluable cultural assets that embody the historical, architectural, and social narratives of past civilizations [1]. These structures serve as legacies from the past, shaping the inspiration and identity we pass on to future generations [2]. However, due to their susceptibility to environmental conditions, structural degradation, and other risk factors, preserving these cultural treasures is both essential and challenging [1,3]. Traditional methods of preserving heritage buildings often fall short of addressing the complexities and dynamic challenges these structures face today [4,5]. Environmental degradation, climate change, urbanization, and natural disasters pose significant threats to their integrity [6]. In Africa, the need for effective heritage preservation is particularly acute due to a combination of financial, environmental, and infrastructural limitations that distinguish its conservation challenges from those in other regions [7]. African heritage sites often endure extreme weather, including arid conditions, which accelerates material degradation, while limited conservation funding and technological access make it difficult to implement consistent preservation practices. North Africa, in particular, offers a rich heritage and ancient landmarks, with iconic examples such as Bab Al-Mansour in Morocco and significant architectural heritage in Egypt, like its historic mosques and ancient urban structures. These sites exemplify North Africa's architectural sophistication, blending indigenous, Islamic, and Andalusian influences. Renowned for its detailed zellige tilework and meticulously carved arches, Bab Al-Mansour highlights North Africa's legacy as a hub of artistic and engineering excellence. This unique heritage underscores the region's contribution to global cultural identity while positioning it as a promising focus for integrating technological advancements such as Industry 4.0 and emerging Industry 5.0 principles [8]. Bab Al-Mansour's significance extends beyond Morocco's borders, positioning it as a symbol of African cultural heritage. This unique convergence of cultural richness and conservation challenges makes Bab Al-Mansour an ideal case study for developing and testing innovative, sustainable digital conservation methods applicable to Africa's broader heritage landscape.

While Digital Twin (DT) technology has been widely applied in industrial and urban domains, its integration into heritage conservation remains underexplored [9–11]. Existing studies focus on isolated applications of technologies such as Heritage Building Information Modelling (HBIM) [10]. However, there is a lack of robust frameworks that integrate these tools with real-time monitoring, predictive analytics, and sustainable preservation principles, especially in the African context [12–14]. This study bridges this gap by introducing a Digital Twin Heritage Building (DT_{HB}) framework, offering a unified solution that enhances monitoring, analysis, and conservation efforts for African heritage sites. The framework integrates HBIM, IoT sensors, and predictive analytics to address both architectural and environmental challenges. At its core, the data hub DT_{HB} functions as the central repository for real-time data integration and analysis. The Bab Al-Mansour DT_{HB} platform represents a site-specific application of the DT_{HB} framework, utilizing the data hub DT_{HB} for real-time monitoring, predictive analytics, and visualization. This study aims to address the following research questions:

1. How can a scalable DT_{HB} framework be developed to integrate real-time monitoring, predictive modeling, and data management for heritage preservation?

2. What are the technical and methodological challenges in applying the DT_{HB} framework to heritage buildings with complex architectural and historical characteristics, such as Bab Al-Mansour?
3. How can the data hub DT_{HB} support dynamic, site-specific implementations, such as the Bab Al-Mansour DT_{HB} platform, while maintaining generalizability to other heritage sites?

The novelty of this research lies in its emphasis on integrating advanced technologies, such as HBIM, IoT sensors, and predictive analytics, into a unified platform that supports preventive conservation and scenario simulation. Unlike prior works that primarily document or reconstruct heritage sites [15–18], this framework emphasizes real-time monitoring, scenario simulation, and preventive conservation. Furthermore, the study introduces a data hub DT_{HB} that consolidates diverse data streams into a dynamic, interactive model, enabling predictive maintenance and informed conservation measures. The integration of Industry 4.0 principles ensures the use of cutting-edge automation and analytics, while the Industry 5.0 emphasis on sustainability and heritage preservation aligns with African cultural and environmental goals. This study highlights the critical intersection between heritage conservation and sustainable development, particularly within the African context, where cultural landmarks face increased threats from environmental pressures and urban encroachment. Africa's heritage sites hold immense cultural and historical value, fostering identity, tourism, and economic growth, making their preservation essential. By adopting a sustainable approach, this research contributes to the long-term resilience of these landmarks. While Bab Al-Mansour demonstrates the framework's application, the DT_{HB} model offers a replicable and scalable solution for conservation practices across the continent, addressing the dual challenges of architectural preservation and resource management.

A DT_{HB} is a digital replica of a physical heritage structure, encompassing its geometry, historical data, and current state [19]. By integrating HBIM with GIS, reality capture technologies, VR/AR, IoT, AI, and data analytics, a DT_{HB} provides a multidimensional, interactive model for real-time monitoring, analysis, and management [20,21]. This innovative approach enhances environmental management, supports preservation efforts, and provides accurate databases for future renovations and emergency interventions [18]. Ensuring consistency with the HBIM framework is essential for heritage buildings [22,23]. DT_{HB} functions by constructing digital replicas while embodying their cultural, social, historical, and esthetic values [13,24]. These values serve as critical references for guiding preservation efforts [25–27]. The incorporation of these multifaceted heritage values into DT_{HB} models poses challenges due to their tangible and intangible aspects [28,29]. The initial stage involves understanding the building's cultural significance, including its historical context, traditional uses, and community role [30]. Subsequent stages include documenting the building's historical events, architectural styles, and construction methods, as well as evaluating the unique architectural and artistic qualities that contribute to its identity [31].

Bab Al-Mansour, renowned for its intricate architectural details and historical significance, requires meticulous preservation efforts. Digital Twin technology offers an accurate digital replica of the gate, capturing its current state in high detail, ensuring that its architectural integrity and historical narratives are maintained for future generations. This research proposes the creation of a Bab Al-Mansour DT_{HB} platform to monitor and preserve the structure by identifying defects and areas of damage over time. By leveraging advanced monitoring and predictive analytics, this study aims to safeguard Bab Al-Mansour's physical structure while providing a replicable framework for African heritage conservation. The platform documents the challenges encountered, solutions adopted, and processes followed, ensuring the preservation of this iconic Moroccan monument. Although only traditional plans, sections, and elevations were initially required, adopting a scan-to-HBIM approach

yielded superior results [32]. HBIM models offer detailed representations of a building's physical and functional characteristics, forming a foundation for developing a Digital Twin that integrates real-time data from sensors, simulations, and predictive analytics. The study emphasizes the transformative potential of DTHBs in preventive conservation by predicting potential threats and recommending targeted interventions. By focusing on Bab Al-Mansour, this research underscores the broader applicability of the DT_{HB} framework, advocating for its adoption across culturally significant African landmarks.

2. Materials and Methods

2.1. Bab Al-Mansour: An African Heritage Case Study

Bab al-Mansour, also known as Bab Mansour el-Aleuj (Figure 1), is one of Morocco's most significant historical landmarks. Situated in Meknes city, the gate exemplifies the fusion of Moroccan and broader African design principles, serving as a distinguished symbol of the region's architectural sophistication and cultural legacy [33–36].

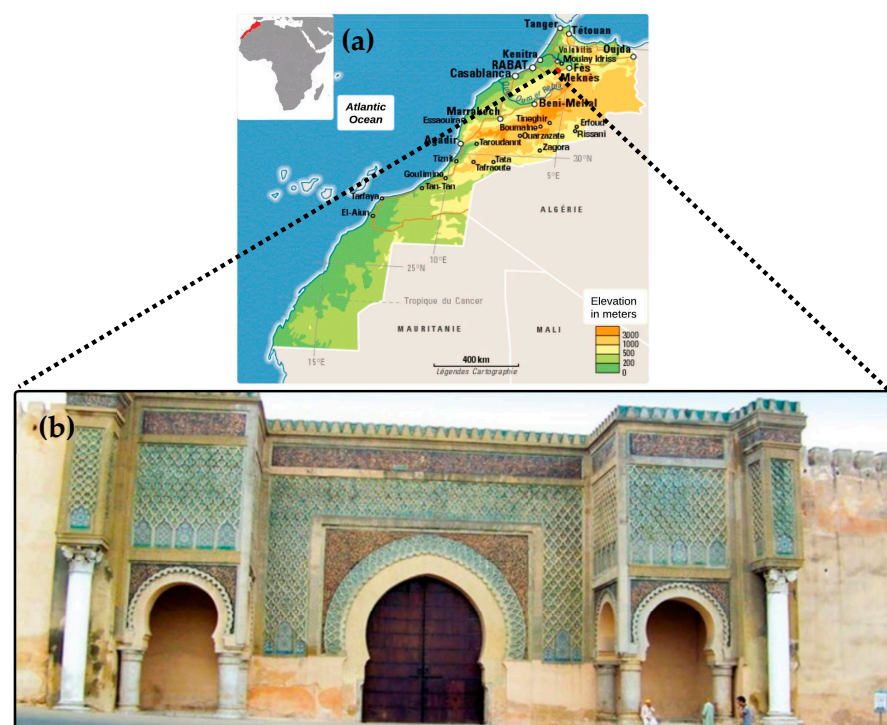


Figure 1. Bab Al-Mansour: (a) regional location and (b) monument detail.

These architectural elements are vividly illustrated in Figure 2. Figure 2a displays the main arch adorned with intricate zellige tilework, characterized by geometric patterns and Arabic calligraphy that are emblematic of North African and Islamic craftsmanship. Figure 2b illustrates the lower arches framed by grand marble columns, showcasing the Roman influence that intermingles with Moroccan design. Figure 2c–e highlight further ornamental details, such as the intricate capitals of the columns and the elaborate mosaic tilework covering the facade, capturing the artisans' mastery in blending diverse cultural motifs into a cohesive esthetic.

Despite their cultural and architectural value, landmarks like Bab Al-Mansour face challenges unique to African heritage sites. Limited conservation resources, environmental threats, and a lack of preservation infrastructure necessitate adaptive and innovative approaches to ensure their longevity. These conditions emphasize the resilience of African heritage and the need for targeted preservation efforts.

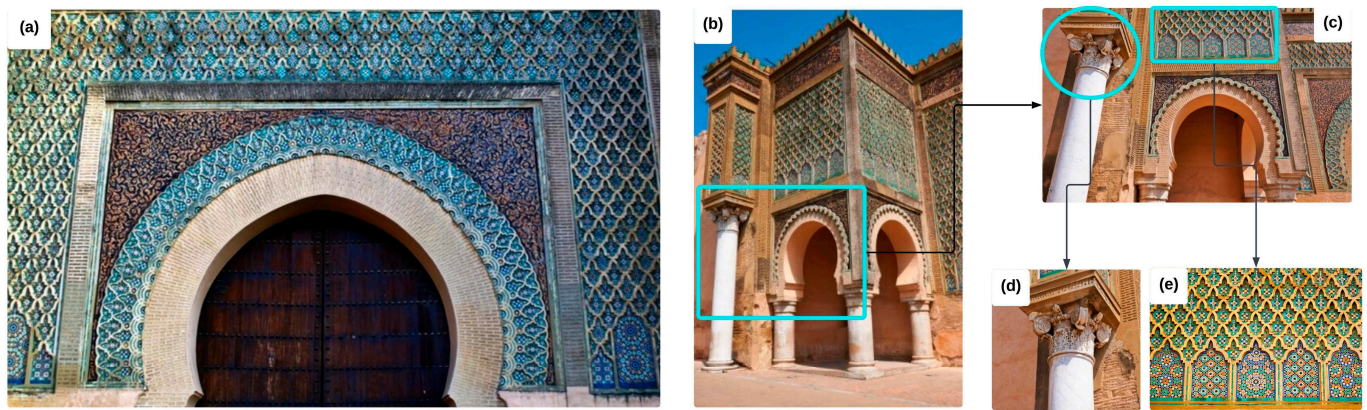


Figure 2. Architectural details of Bab Al-Mansour gate: (a) main arch, (b) lower arches, (c) decorative tilework, (d) column Capital, and (e) mosaic patterns.

2.2. Surveying and Mapping Technologies for Bab Mansour

Accurate graphical and spatial data are essential for generating the Digital Twin of Bab Mansour. For large-scale surveying and mapping, Remote Sensing (RS) extends the observational range of ground-based methods, capturing high-resolution satellite and aerial images of the monument and its surrounding landscape [36]. These images can be integrated into GIS to create a comprehensive digital map of the site. Figure 3 presents various levels of detail (LoD) for the 3D representation of Bab Mansour and its surrounding urban context. In Figure 3a, LoD 0 depicts Bab Mansour in brown, offering a simple footprint of the buildings in the area. Figure 3b enhances this view with an RBV satellite image in the background, providing geographical context. Figure 3c,d transition to LoD1, utilizing SRTM data as a Digital Elevation Model (DEM) for a 2.5D visualization, which captures both horizontal and vertical details of the terrain and built environment. These progressive LoDs allow for a comprehensive understanding of Bab Mansour's spatial positioning and elevation, which is essential for urban planning and heritage conservation efforts. To address the identified research gaps, this study emphasizes the unique benefits of applying the DT framework to Bab Mansour. Unlike previous studies that primarily focus on enhancing visitor engagement or addressing GIS-related urban planning challenges [37], this research demonstrates how DT technology advances the preservation of heritage structures through innovative surveying and mapping techniques. By integrating tools such as RS, GIS, and advanced visualization methods, this study captures the intricate architectural details of Bab Mansour while also offering a replicable framework for managing complex heritage sites. Moreover, parallels are drawn with established methodologies, such as those in Digital Twin as a Service (DTaaS) in Industry 4.0 [38], to highlight how the Bab Mansour Digital Twin contributes to broader heritage preservation techniques by providing actionable insights, real-time monitoring, and scalable solutions.

For more detailed and precise mapping of Bab Mansour's intricate architectural features, LiDAR (Light Detection and Ranging) and PhoDAR (Photogrammetric Detection and Ranging) are key technologies [39]. LiDAR, with its laser sensing capabilities, captures point cloud data that include attributes like echo count and intensity, providing accurate spatial information for large areas, including Bab Mansour's intricate facade and structural elements. UAVs, helicopters, or drones equipped with LiDAR systems, along with ground-based terrestrial laser scanning (TLS), can rapidly capture highly detailed information about the gate's tilework, arches, and carvings [40,41]. PhoDAR technology, using Structure from Motion (SfM) methodology, generates 3D models by stitching together multiple images captured from different angles, often using UAVs or handheld cameras [42,43]. This method is particularly effective for reconstructing the intricate exterior patterns and textures of Bab

Mansour, as demonstrated in its successful application to complex structures such as the Imperial Palaces and the Dazu Rock Carvings. For ultra-high-resolution imaging, nap-of-the-object photogrammetry can be applied to Bab Mansour's delicate elements, capturing detailed close-ups of its finest architectural features through drone-based photography.

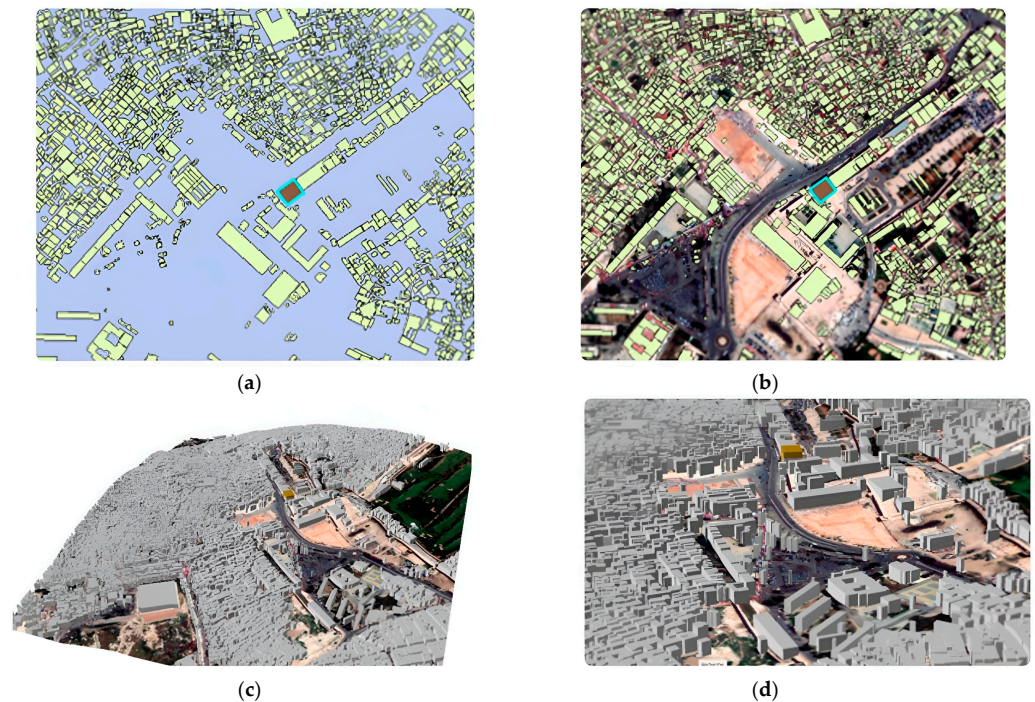


Figure 3. Visualization of Bab Al-Mansour in blue square from LoD 0 to LoD 1 with 2.5D DEM integration: (a) LoD 0 with context, (b) LoD 0 with RBV imagery, (c) LoD 1 with 2.5D SRTM DEM, (d) Enhanced LoD 1 with zoomed-in 2.5D visualization.

By integrating spatial data from GPS and RS into LiDAR and PhoDAR, the surface and texture information of Bab Mansour can be plotted with great precision, ensuring an accurate digital model of the monument. LiDAR can compensate for any limitations in texture capture by PhoDAR, ensuring both surface accuracy and high-quality color rendering [44,45]. This combined approach of macro and meso-scale surveying technologies offers a robust solution for creating an accurate and detailed Digital Twin of Bab Mansour. Terrestrial LiDAR would be the most used tool for detecting and positioning the gate's architectural elements with precision [46,47]. To effectively monitor and preserve Bab al-Mansour, it is essential to strategically place sensors and Internet of Cultural Things (IoCT) devices in key areas to collect real-time data on the structure's condition. The main archway, being the most significant load-bearing structure, should be equipped with strain gauges and displacement sensors on the keystone and lower sections to monitor stress, strain, and displacement. Additionally, vibration sensors should be attached to the inner surface of the arch to detect any vibrations caused by traffic, nearby construction, or seismic activity. Acoustic emission sensors near the keystone area can capture the sound of cracking or other structural failures within the arch.

High-resolution laser scanning is conducted to capture precise geometric data of Bab Mansour (Figure 4a,b). This process generates a detailed point cloud that serves as the foundation for the DT_{HB} platform. Point cloud processing is a crucial step in the creation of detailed 3D models for HBIM [46–48]. This process involves converting raw data captured through laser scanning into a structured format that can be used to generate accurate digital representations of heritage buildings [49–51]. The field of heritage building has inspired, over the last few years, a greater interest more and more on behalf of the scientific

community that deals with surveying [2]. The idea that knowledge of a site does not apply only to its history but must necessarily include its characteristics of position, shape and geometry, is gathering pace [52]. Constructive techniques, make analysis of geometrical details easier, which is difficult to achieve with traditional techniques [20]. The biggest problems in the use of survey techniques are the graphic outputs for restorers and architects; in fact, they often do not know the real potential of these techniques, methodologies, and functionalities and they expect traditional outputs such as the floor plans, sections, and front elevation of a cultural asset [52]. In the following example, a case study focused on finding a workflow to support a study, restoration, and conservation project of cultural heritage, automatically (or with a limited manual operation) extracting graphic outputs from laser scanner surveys performed in the ancient Medina of Meknes.

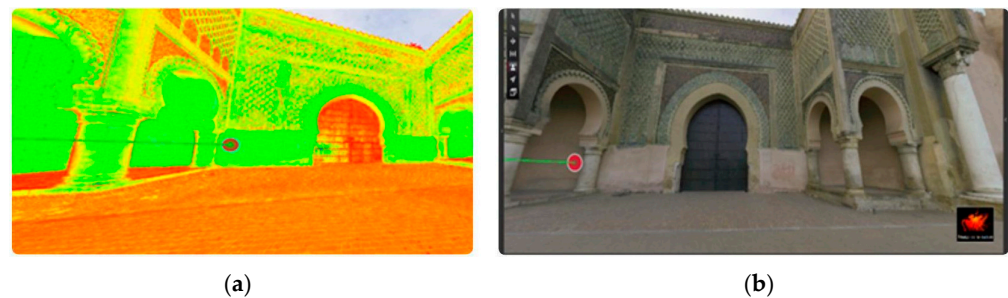


Figure 4. (a) Cloud point data cleaned, registered, resampled, color mapped, and texture draped by the image in (b) acquired by optical sensor.

The architecture of the Data Hub for DT_{HB} integrates diverse data sources and advanced analytics tools to support heritage conservation efforts. Figure 5 illustrates the workflow, highlighting how data from various sources is processed and stored in optimized systems, enabling predictive analytics and real-time insights essential for managing and preserving heritage sites effectively.

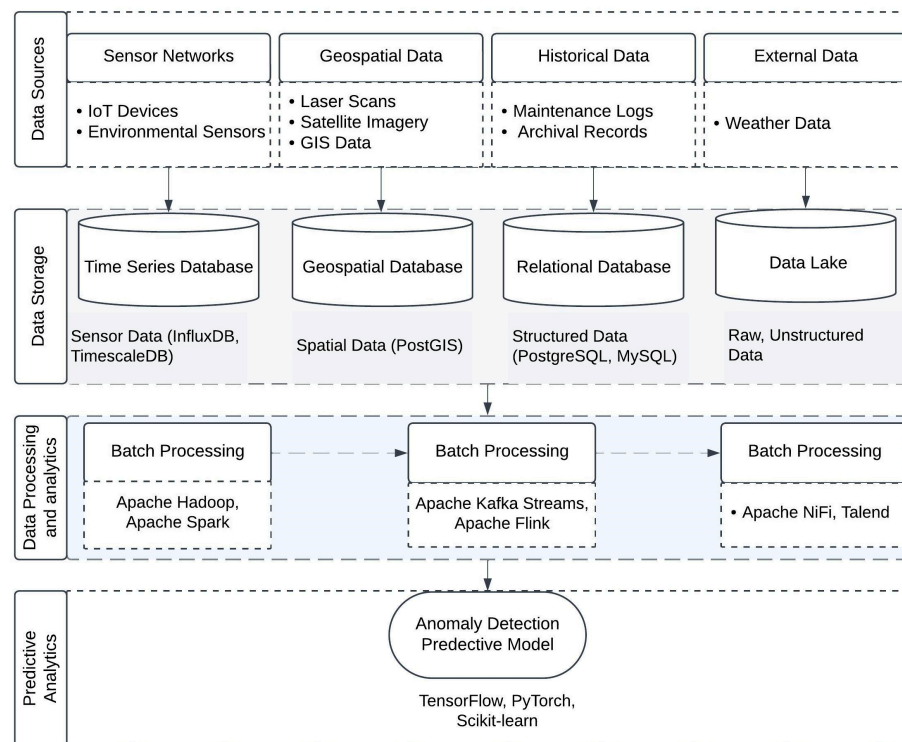


Figure 5. Data Hub Architecture for DT_{HB} : sources, storage, and analytics.

To ensure seamless integration between physical and virtual representations, Figure 6 outlines the transformation process from the physical historical building (P) to the virtual historical model (V) through various integration and processing steps. These include data cleaning, registration, segmentation, resampling, storage, and visualization, all supported by sensors, IoT devices, and point cloud data. This process facilitates dynamic interactions and provides a detailed and accessible digital replica of the heritage site.

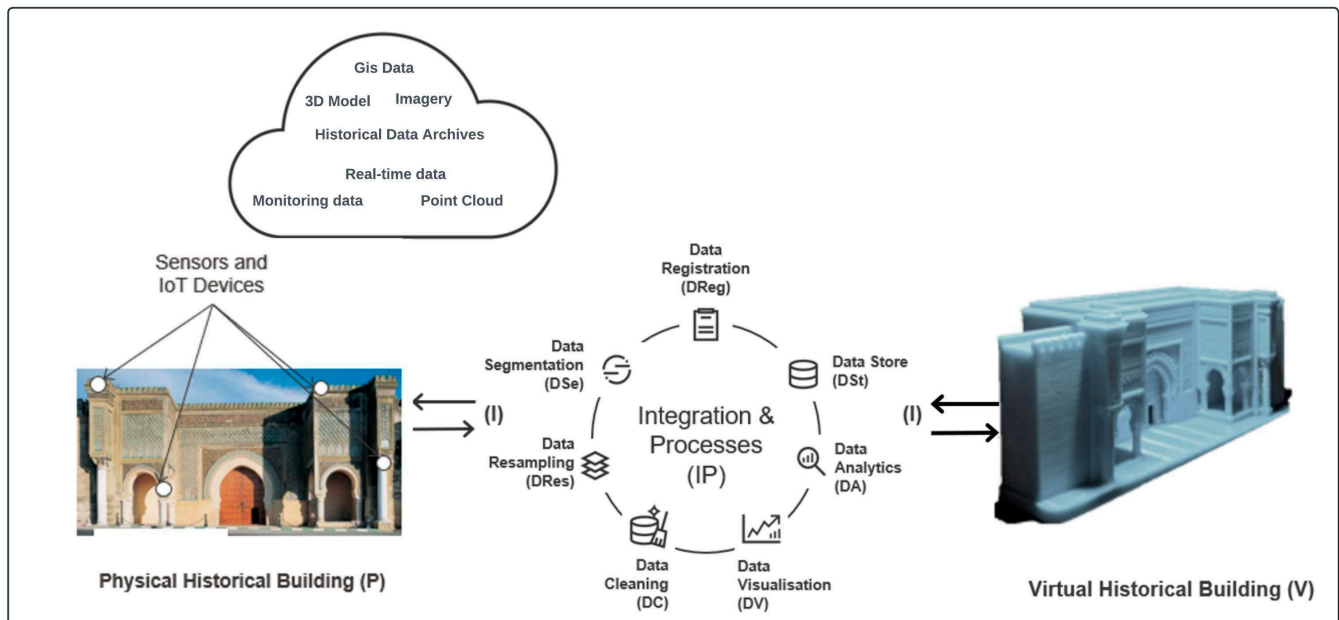


Figure 6. Key elements of a DT_{HB} framework: physical entities (PE), virtual entities (VE), connected data (I) and governing integration and processes (IP).

2.3. Methodology

2.3.1. General Workflow for DT_{HB} Development

The methodology outlined in this study is structured to address the research questions by demonstrating the development of the DT_{HB} framework, overcoming technical challenges, and validating the framework through a case study application to Bab Al-Mansour. While Bab Al-Mansour serves as a representative case study to illustrate the application of the DT_{HB} framework, the methodology is designed to be adaptable and scalable for heritage sites across Africa. The framework provides a modular approach that accommodates the unique architectural, environmental, and cultural characteristics of various heritage buildings, ensuring its broad applicability. This approach integrates advanced technologies, including HBIM, IoT sensors, real-time monitoring, and predictive analytics, to address the complexities of heritage preservation.

- Integrating immersive technologies into DT_{HB}

Immersive technologies, including VR, AR, and MR are integrated to engage users in innovative ways. VR enables users to virtually explore the detailed 3D model of the historical building, offering an immersive experience of the gate's intricate architectural features from any location globally [52–54]. AR overlays digital information onto the physical site, allowing visitors to visualize historical reconstructions, restoration data, and interactive storytelling [52,53]. MR bridges the physical and digital realms, enabling users to interact with holographic projections of restoration processes or historical events directly on-site [55–57]. By incorporating these immersive tools, the Digital Twin becomes a platform for experiential learning and public engagement, complementing its technical preservation functions.

- Integrating GIS data into DT_{HB}

The integration of GIS data into the DT_{HB} platform enhances spatial analysis and management capabilities for Bab Mansour. The GIS database acts as a repository for spatial data, including 3D models, structural details, and environmental information, which are continuously fed into the data hub for DT_{HB}. Real-time data from IoT sensors monitoring structural health and environmental conditions flow back into the GIS database, ensuring updated spatial layers and accurate visualization of the gate's current condition. Predictive simulations using GIS data help assess future risks, such as structural deterioration or environmental impacts, with results visualized directly on GIS maps. This integration allows for dynamic updates and supports informed conservation decisions. Additionally, the GIS database includes historical data, such as prior restoration efforts, enabling the Digital Twin to analyze trends and optimize future preservation efforts.

- Integrating HBIM model to DT_{HB}

HBIM serves as a critical tool for documenting and managing heritage buildings with precision [58–61]. This methodology involves developing a digital representation of Bab Mansour that incorporates historical, architectural, and structural details derived from laser scanning and photogrammetry. The HBIM model facilitates conservation planning, preventive maintenance, and restoration simulations [62–67]. As historical structures often feature irregular geometries, the HBIM process requires careful architectural surveys and extensive scan points, ensuring accuracy despite increased time and cost [68–70]. As illustrated in Figure 7, the procedure follows a four-step investigation method, enhancing the DTHB framework by combining geometrical precision with material and historical attributes in detailed parametric models.

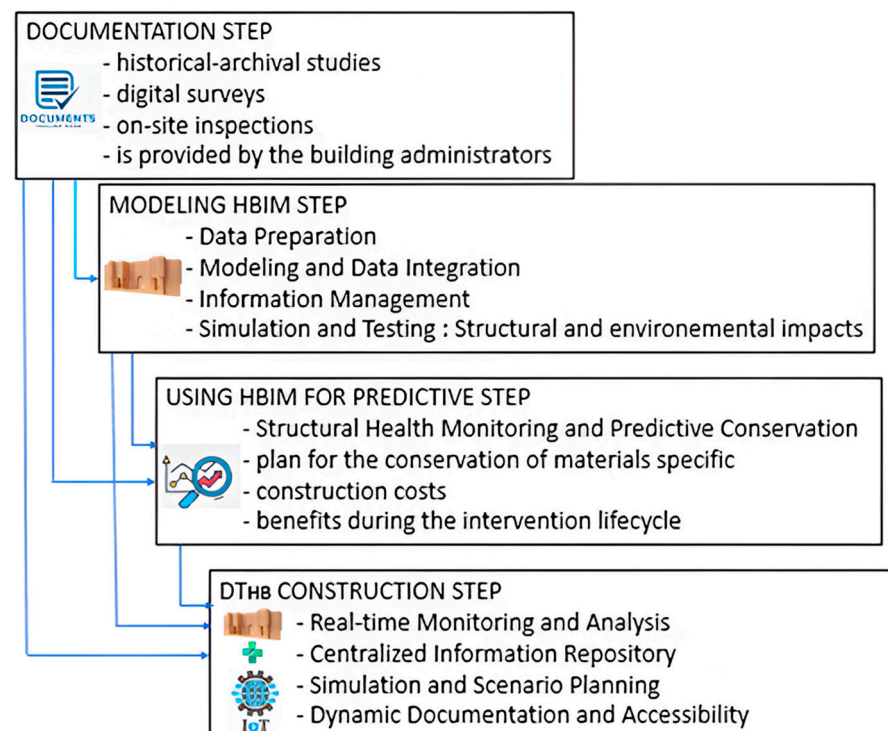


Figure 7. From the HBIM-based to DT_{HB} workflow.

2.3.2. Sensor Deployment and Real-Time Data Integration

The goal of DT_{HB} is to replicate the real-time behavior of Bab Mansour throughout its lifecycle. A static model, built on graphical, spatial, and attribute datasets, can be enhanced with dynamic features obtained from sensor-based monitoring, enabling real-time

updates and automatic calibration through IoT technology. The DT_{HB} platform consolidates multiple data streams, including meteorological conditions, environmental factors, local biodiversity, and visitor statistics, integrating them with heritage management and security systems for comprehensive monitoring and preservation. The suggested sensors emplacement at Bab Al-Mansour is based on structural and environmental analyses. Table 1 summarizes the types of sensors recommended for integration into the Digital Twin framework, their proposed locations, and the parameters they are designed to monitor. These recommendations aim to facilitate real-time data integration and proactive monitoring. The DT_{HB} platform interfaces with a centralized management system known as data hub DT_{HB}, which classifies and archives mural damage, monitors environmental conditions and structural stability, and assesses visitor impact.

Table 1. Suggested sensor types, their purposes, proposed placements, and monitored parameters for DT_{HB}.

Sensor Type	Purpose	Proposed Placement	Parameters Monitored
Strain Gauges	Monitor stress and deformation in key structural areas	Load-bearing arches and pillars	Stress and strain values
Vibration Sensors	Detect vibrations caused by external forces	Structural columns and foundation	Frequency, amplitude, and duration
Acoustic Emission Sensors	Identify early-stage micro-cracks	High-stress zones, such as the main arch keystone	Micro-crack patterns
Environmental Sensors	Measure humidity, temperature, and air quality	External walls	Humidity, temperature, air pollutants (e.g., PM2.5, PM10)
Displacement Sensors	Monitor movement or deformation over time	Corners of arches, base of walls	Horizontal/vertical displacement

2.3.3. Predictive Modeling and Data Analysis

Predictive modeling and data analysis are integral components of the proposed DT_{HB} framework, enabling proactive and data-driven decision-making for heritage conservation. Physics-informed models, such as Finite Element Analysis, are proposed to simulate the structural response of heritage buildings under varying environmental and stress conditions, identifying high-stress zones and potential vulnerabilities. Machine learning techniques, including random forest, neural networks, and support vector machines, are recommended to process historical and real-time data from sensors [21]. These models can predict structural degradation, assess environmental impacts, and classify risk levels to support targeted interventions [40,51]. Furthermore, linear regression models are suggested to analyze correlations between environmental factors, such as pollutant levels, and material degradation [66]. Table 2 provides a summary of the proposed predictive models, their purposes, applications, and expected outcomes, demonstrating how they contribute to the analytical capabilities of the DT_{HB} framework.

Table 2. Proposed models for predictive modeling and data analysis.

Model Type	Purpose	Proposed Application	Expected Outcome
Finite Element Analysis	Simulate structural stress and deformation	Analyze load-bearing elements under environmental conditions	Identification of high-stress zones and structural vulnerabilities
Random Forest	Predict structural degradation based on sensor data	Process historical and real-time data from strain and vibration sensors	Early detection of degradation patterns
Neural Networks	Forecast environmental impacts on structural integrity	Integrate structural and environmental data for long-term predictions	Enhanced planning for restoration and maintenance
Support Vector Machines	Classify structural conditions into risk levels	Categorize monitored data into stable, moderate, or critical conditions	Enable targeted interventions based on risk classification
Linear Regression	Analyze relationships between environmental factors	Correlate pollutant levels with material degradation	Quantify environmental impacts on structural integrity

2.3.4. Integrated HBIM Database Creation, Modeling, and Ontology Development for Bab Al-Mansour

The development of the HBIM database is a meticulous process that transforms raw survey data into a structured and semantically enriched model, capable of supporting advanced conservation and restoration activities [69–72]. The workflow for constructing such models begins with data collection, incorporating archival documents, material composition analyses, and condition assessments, alongside high-resolution spherical photographs and terrestrial laser scanning data (Figure 8). These inputs enable a robust understanding of a heritage structure’s materials, historical transformations, and current conditions [73–76].

Following data collection, the data processing phase aligns and scales cloud point data, supported by the analysis of historical modifications and construction techniques. This ensures the preparation of cohesive datasets that form the foundation for precise 3D modeling. The scan-to-HBIM and mesh-to-HBIM stages further refine these datasets, converting raw reality point clouds into detailed parametric components and comprehensive geometric models [77–80]. These workflows are critical for capturing intricate architectural elements like arches, columns, and decorative patterns, as illustrated in Figure 9, which outlines the overall modeling process from laser point cloud acquisition to the creation of enriched HBIM objects in IFC format.

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Semantic enrichment enhances these models by integrating metadata that links spatial elements with cultural and historical information, facilitating advanced querying and relational analysis [80,81]. This process is exemplified in the creation of an IFC model that is later converted to RDF format, enabling semantic relationships between architectural components, such as “isPartOf” and “hasCulturalValue” (Figure 8). This ontological

framework facilitates operational management and positions the Digital Twin as a crucial asset for sustainable heritage protection.

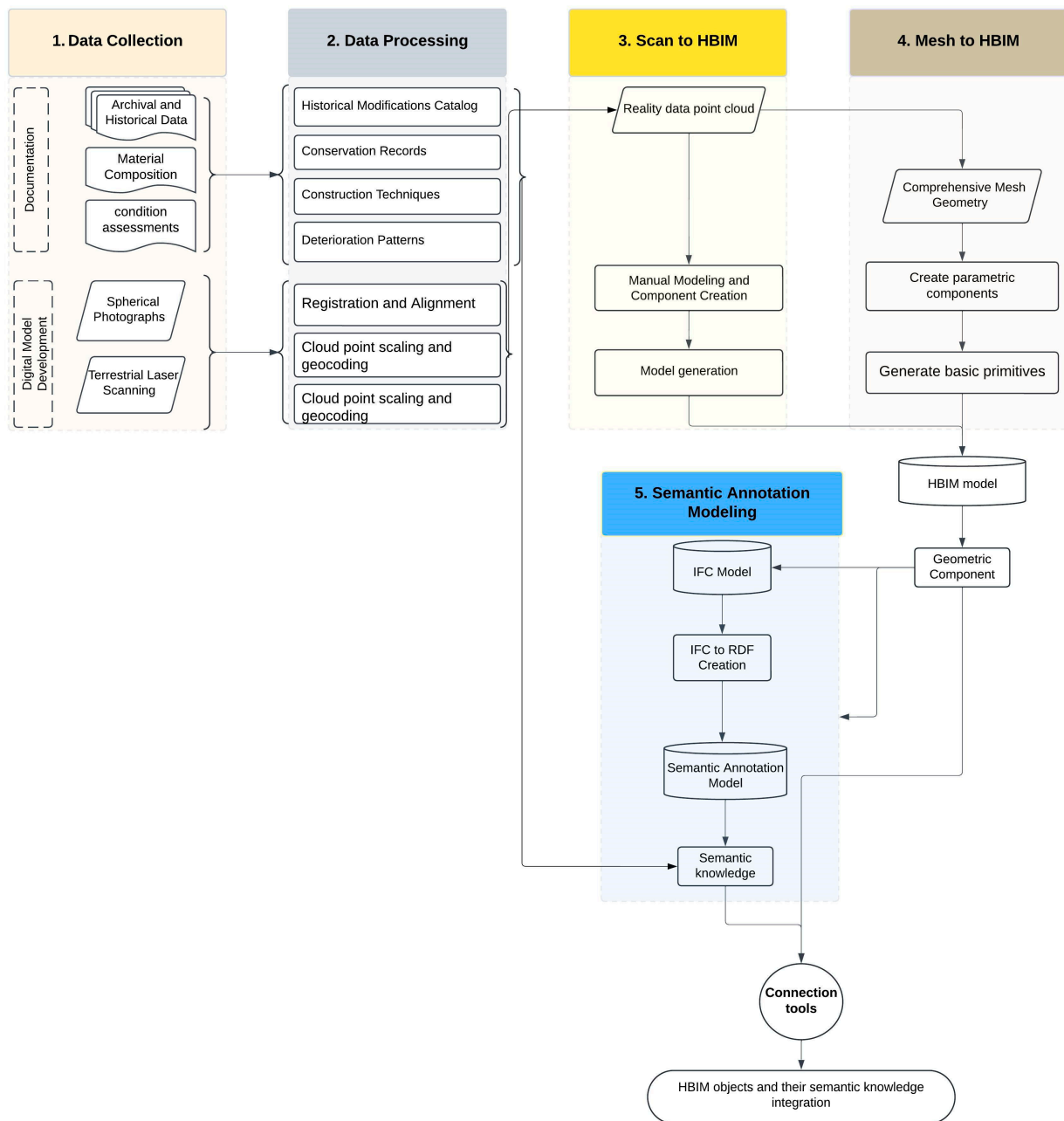


Figure 8. Process flow for HBIM from data collection to semantic annotation.

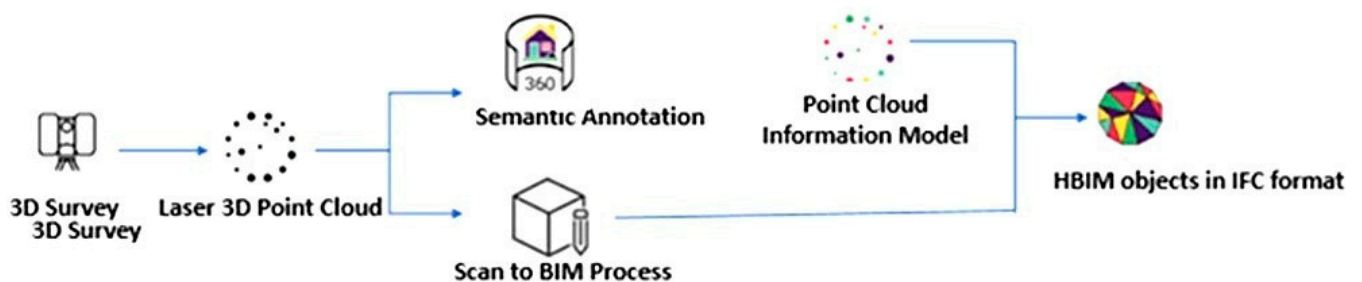


Figure 9. Workflow for HBIM model construction.

The final stage involves preparing the HBIM model for web-based applications, ensuring accessibility and visualization capabilities. Using specialized tools like the Feature Manipulation Engine [82,83], the IFC data are converted into CityGML format, achieving LoD3 appropriate for documenting complex external attributes of historical sites like Bab Al-Mansour (Figure 10a). The integration of geometric and semantic data preserves critical architectural elements while enhancing the model's interdisciplinary utility [84,85]. This approach is further validated using tools like QGIS and is prepared for web streaming through platforms such as Cesium Ion, as demonstrated in Figure 10b, which highlights the detailed geometry and property analysis facilitated by FME Inspector.

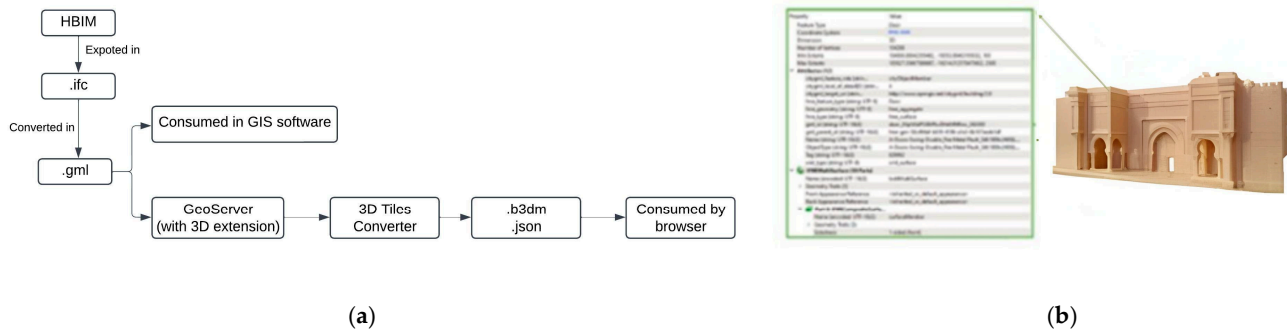


Figure 10. (a) Web integration of HBIM using CityGML and (b) detailed geometry and property analysis via Feature Manipulation Engine inspector.

2.3.5. Key Performance Indicators' (KPIs) Calculation in the DT_{HB} for Bab Al-Mansour Preservation

For the preservation of Bab Al-Mansour, the Key Performance Indicators (KPIs) can be calculated in the DTHB to assess the effectiveness of conservation efforts and the overall condition of the heritage building. KPIs represent a novel and essential contribution of this study, providing a quantitative framework to evaluate and optimize heritage preservation efforts. These metrics facilitate real-time monitoring of Bab Al-Mansour's condition and enable data-driven decision-making, bridging traditional conservation techniques with advanced digital methodologies. Similarly to how KPIs are used for traffic simulations in smart cities, these metrics should capture both objective (quantifiable) and subjective (qualitative) aspects of preservation [86]. These KPIs are:

- **Structural Integrity Score**—an objective measure of the overall structural health of Bab Al-Mansour, derived from sensor data monitoring cracks, deformation, and stress in the building materials. The SIS ensures the early detection of structural vulnerabilities, allowing heritage managers to prioritize critical areas for intervention and mitigate potential risks effectively. This score is calculated using real-time data collected from IoT sensors installed throughout the structure, which aggregate readings from different areas to provide a comprehensive assessment of the building's stability. The formula for the Structural Integrity Score (SIS) is the sum of stability metrics from all sensors divided by the total number of sensor data points, offering a clear and quantifiable understanding of the monument's structural condition. Consequently, the SIS is represented in Equation (1) as follows:

$$SIS = \frac{\sum_s \sum_{i,j,k} SM_{s(i,j,k)}}{\sum_s \sum_{i,j,k} SDP_{s(i,j,k)}} \quad (1)$$

where

$SM_{s(i,j,k)}$ represents the stability metrics recorded by sensor s at location (i,j,k) ;

$SDP_{s(i,j,k)}$ refers to the individual data points collected by sensor s at the same geographical coordinates.

- Environmental Degradation Impact (EDI)—evaluates the effect of environmental factors such as humidity, pollution, and temperature on the building's materials and overall condition [87]. This metric quantifies the cumulative effects of external environmental factors, guiding proactive conservation strategies to prevent material degradation [88]. The EDI is calculated by combining real-time data from environmental sensors with historical weather records to assess how these external conditions influence Bab Al-Mansour's surfaces and structural elements. The formula used is the sum of the impact of humidity, pollution, and temperature divided by the number of degraded sections identified by the sensors. A higher Degradation Impact score indicates accelerated deterioration of the materials, signaling the need for more frequent maintenance and intervention efforts to preserve the building's integrity. EDI is demonstrated in Equation (2) as follows:

$$EDI = \frac{\sum_s \sum_{i,j,k} DM_{s(i,j,k)}}{\sum_s \sum_{i,j,k} EDP_{s(i,j,k)}} \quad (2)$$

where

$DM_{s(i,j,k)}$ represents the environmental degradation metrics (such as pollution levels, humidity, or temperature) recorded by sensor s at the geographical coordinates (i,j,k) ;

$EDP_{s(i,j,k)}$ refers to the individual environmental data points collected by sensor s at the same geographical coordinates.

- The Conservation Cost Efficiency (CCE)—an objective metric that compares the financial costs of various conservation interventions to their effectiveness in enhancing the building's preservation, providing an extensive financial evaluation that enables to identify the most cost-effective interventions for maintaining the structure's integrity and exterior appearance [89–91]. It is calculated by aggregating data from the financial records of past preservation projects and correlating these costs with measurable improvements in the structure's integrity or esthetic restoration. The formula is defined as the improvement in the structural or esthetic score divided by the cost of the intervention. Higher values of this KPI indicate more cost-efficient interventions, signifying that the conservation efforts have yielded significant preservation benefits relative to their financial investment. The CCE Equation (3) is defined as follows:

$$CCE = \frac{\sum_s \sum_{i,j,k} IP_{s(i,j,k)}}{\sum_s \sum_{i,j,k} CC_{s(i,j,k)}} \quad (3)$$

where

IP represents the improvement in structural or esthetic preservation recorded by sensor s at the geographical coordinates (i,j,k) ;

$CC_{s(i,j,k)}$ refers to the cost incurred for the conservation intervention at the location covered by sensor s at the same geographical coordinates.

- Emergency Preparedness and Response Time (EPRT)—an objective KPI that measures the efficiency of implementing interventions in response to environmental threats or structural failures identified by the Digital Twin system, optimizing disaster response strategies by analyzing past interventions to ensure timely actions that mitigate structural and cultural damage. This metric is calculated using data from past emergency interventions to determine the average time required to address critical issues, such as closing off affected areas or conducting immediate repairs. The formula is the total

time taken to address an emergency divided by the number of emergency events detected. Lower response times indicate a more effective and well-prepared emergency management system, ensuring timely actions to mitigate potential damage and preserve the heritage site's integrity. The EPRT is defined in Equation (4) as follows:

$$EPRT = \frac{\sum_s \sum_{i,j,k} RT_{s(i,j,k)}}{\sum_s \sum_{i,j,k} NEE_{s(i,j,k)}} \quad (4)$$

where

$RT_{s(i,j,k)}$ represents the time taken to respond to an emergency event, as recorded by sensor s at the geographical coordinates (i,j,k) ;

$NEE_{s(i,j,k)}$ refers to the number of emergency events detected at the location covered by sensors at the same geographical coordinates

- Restoration Longevity (RL)—a metric that tracks the intervals between major conservation or restoration efforts on specific areas of the monument, assessing the durability and effectiveness of preservation techniques to ensure long-term conservation while minimizing the frequency of interventions. It is calculated by dividing the time since the last restoration by the total number of significant restorations conducted in that area. Longer intervals between restoration activities indicate that the applied techniques are more durable and effective, ensuring that the heritage structure remains stable and intact for extended periods without the need for frequent interventions.

$$RL = \frac{\sum_s \sum_{i,j,k} TSLR_{s(i,j,k)}}{\sum_s \sum_{i,j,k} NR_{s(i,j,k)}} \quad (5)$$

where

$TSLR_{s(i,j,k)}$ represents the time elapsed since the last restoration was carried out, as measured by sensor s at the geographical coordinates (i,j,k) ;

$NR_{s(i,j,k)}$ refers to the number of significant restoration efforts completed at the location covered by sensor s at the same geographical coordinates.

2.3.6. Using HBIM for Predictive Step with Integrated KPIs

The HBIM predictive phase leverages the HBIM model to enable proactive management and conservation of heritage buildings by integrating structural health monitoring, real-time condition tracking, and predictive conservation [90,91]. KPIs, such as Structural Stability Score, Material Conservation Index, Cost Efficiency, and Environmental Impact Assessment, provide quantitative metrics to evaluate conservation strategies and monitor the building's condition over time [92–94]. Reverse engineering techniques are employed to reconstruct missing or damaged sections of the building, filling gaps in the digital representation while tracking the restoration success rate to ensure reconstruction accuracy [95]. This phase serves as the foundation for subsequent applications, including structural analysis, restoration planning, and integration into a broader DT_{HB} platform. The resulting HBIM model, enriched with KPI metrics, offers an interactive understanding of the asset's structural and architectural characteristics [92,93]. KPIs also facilitate data-driven decision-making by providing real-time feedback on parameters such as maintenance frequency and cost-benefit ratio [96]. The conservation plan for Bab Al-Mansour includes strategies for the preservation of materials specific to its structure, such as unique types of stone, wood, and mortar, ensuring their longevity and historical accuracy. The Material Degradation Index is evaluated to monitor ongoing deterioration. Construction costs are calculated using HBIM data, providing precise financial planning and resource allocation, while intervention benefits are forecasted through enhanced structural stability,

optimized maintenance schedules, and improved preservation of historical details, all measured through KPIs like Cost Efficiency and Preservation Benefit Score. The KPIs outlined in this study provide a robust framework for quantifying heritage preservation efforts, bridging the gap between digital and physical conservation methodologies. Given their depth and potential applicability to diverse heritage sites, these KPIs represent a significant contribution to the field and can form the foundation for standalone research focused on their broader application and refinement. The integration of KPIs throughout this predictive approach ensures long-term efficiency, cost-effectiveness, and sustainability, supporting well-informed and robust conservation strategies to safeguard the integrity and authenticity of heritage buildings like Bab Al-Mansour.

2.3.7. Construction Step and Probabilistic Formulation of the DT_{HB}

The DT_{HB} framework represents a groundbreaking approach to the preservation and management of heritage buildings. By leveraging advanced Digital Twin technology, this framework creates a detailed virtual replica of a heritage structure, enabling real-time monitoring and analysis of environmental conditions, structural health, and occupancy [97]. The DT_{HB} framework integrates sensors, cloud computing, and predictive analytics to provide a comprehensive and dynamic model that not only mirrors the physical state of the historical building but also simulates future scenarios [98]. This innovative approach allows for proactive preservation efforts, informed decision-making, and enhanced visualization through 3D models, AR, and VR applications. By ensuring continuous data flow and employing sophisticated analysis tools, the DT_{HB} framework aims to safeguard the integrity and longevity of heritage buildings, ultimately contributing to the sustainable preservation of cultural heritage. The establishment of the DT_{HB} involves several key steps, beginning with data integration and IoT implementation within the HBIM model to embed historical records, documents, and annotations, while linking oral histories and narratives to specific parts of the structure. Sensor deployment is essential, enabling the continuous monitoring of environmental conditions, such as temperature and humidity, along with structural health indicators, including stress levels and vibrations. These sensors ensure that real-time data feeds into the DT_{HB}, allowing for ongoing monitoring and maintenance of the building's condition. Additionally, extracting geometric primitives is crucial for creating an accurate and robust architectural model, which serves as a solid foundation for the preservation, management, and analysis of heritage buildings, ensuring the maintenance of their historical and structural integrity [99].

An essential aspect of this framework is the calculation of KPIs to assess preservation effectiveness. Metrics such as Structural Integrity Score, Environmental Impact Assessment, and Restoration Longevity are derived from sensor data to quantitatively evaluate the building's condition. For example, the Structural Integrity Score utilizes data from crack and deformation sensors, while the Environmental Impact Assessment gauges how external factors like humidity and temperature influence materials over time. These KPIs facilitate data-driven decision-making, ultimately enhancing the durability and long-term preservation of heritage structures.

All collected information is centralized in an Information Repository, providing a cohesive digital platform where historical records, structural health data, and maintenance logs are stored and easily accessed [95,96]. This repository, enriched with KPI metrics, serves as the backbone for simulation and scenario planning, enabling heritage managers to create and test various intervention strategies and conservation techniques under different environmental conditions [97]. The system also includes dynamic documentation and accessibility, to update, review, and share information in real time, ensuring that all conservation efforts are based on the most current and accurate data [97]. Through this

integrated approach, the DT_{HB} construction step, with the incorporation of KPI calculations, lays the foundation for a robust and sustainable preservation strategy. It supports effective decision-making and long-term conservation planning by providing a quantitative basis for evaluating the impact of different preservation strategies and ensuring the optimal allocation of resources based on measurable outcomes.

The DT_{HB} framework is a dynamic, integrated system that represents real-world building digitally and enables real-time monitoring, analysis, and decision-making for its preservation. The DT_{HB} framework is defined by the integration and interaction of its fundamental components. These include physical entities (PE_t), which represent the real-world aspects at time t of Bab Al-Mansour physical state at time t such as structural elements, materials, and environmental conditions; virtual entities (VE_t), which form the DT_{HB} counterpart at time t , incorporating HBIM, 3D GIS, and IoT data integration for a comprehensive representation; and bidirectional communication (BC_t), ensuring real-time synchronization and data exchange between the physical and virtual entities. Additionally, the framework relies on Key Performance Indicators ($KPIs_t$) at time t to provide quantitative measures of structural health, environmental impact, and the efficiency of restoration efforts. Finally, External Interventions (EI_t) represents a comprehensive model that integrates conservation efforts, restoration activities at time t . This framework encompasses computational models, simulations, and decision-support algorithms at time t that facilitate data-driven monitoring, predictive analysis, and strategic decision-making, collectively creating a robust and dynamic system for heritage preservation. The framework can be mathematically formulated as follows:

$$P[PE_t, VE_t, Os_t, EI_t, KPIs_t, BC_t] = P(PE_t/VE_t, EI_t, Os_t, BC_t) \times P(Os_t/VE_t, BC_t) \times P(VE_t/EI_t, BC_t) \times P(EI_t/BC_t) \times P(BC_t) \times P(KPIs_t/PE_t, VE_t, Os_t, EI_t, BC_t) \quad (6)$$

This equation describes the joint probability distribution of all variables at time t , capturing the interactions among the physical state, sensor observations, Digital Twin updates via bidirectional communication, and external interventions.

- Estimation of $P(PE_t/VE_t, EI_t, Os_t, BC_t)$

Machine learning models estimate the physical state (PE_t) of a heritage building by identifying relationships between sensor observations (Os_t), external interventions (EI_t), and the Digital Twin state (VE_t). Furthermore, bidirectional communication (BC_t) facilitates real-time synchronization and feedback between the physical and digital states, significantly enhancing the accuracy of these predictions. Let SPA represent the simulation and predictive analytics used within the framework to encompass forecasting of structural degradation, environmental impacts, and restoration requirements of PE at time t (Figure 11). The predicted physical state is represented mathematically in Equation (7) as

$$\widehat{PE}_t = f_{ML}(VE_t, EI_t, Os_t, BC_t; \theta) \quad (7)$$

where f_{ML} is the machine learning model (e.g., neural network, gradient boosting) with parameters θ learned from training data. Here, $\widehat{PE}_t$ represents the predicted physical state, dynamically updated through BC_t as it integrates real-time feedback and sensor data. The probability distribution of the physical state can be approximated as

$$P(PE_t/VE_t, EI_t, Os_t, BC_t) \approx \mathcal{N}(\widehat{PE}_t, \sigma^2) \quad (8)$$

where $\mathcal{N}(\widehat{PE}_t, \sigma^2)$ is a Gaussian distribution centered at the ML prediction $\widehat{PE}_t$ with variance σ^2 . This approach ensures that BC_t facilitates the seamless exchange of data between the physical and digital systems, enhancing the reliability of state estimation in the Digital Twin framework.

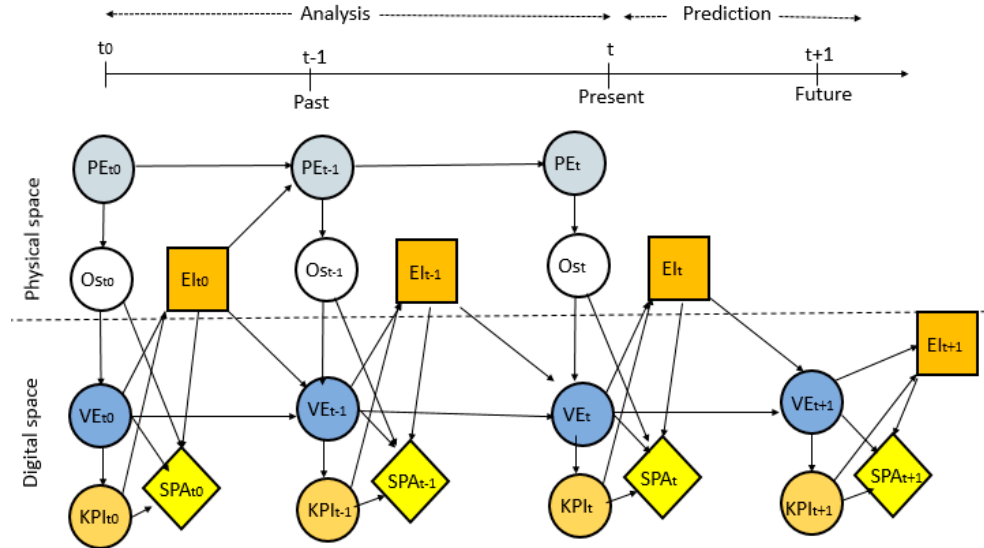


Figure 11. Probabilistic graphical model for coupled evolution of physical and digital spaces in a heritage building Digital Twin framework.

- Updating the Digital Twin $P(VE_t / EI_t, BC_t)$

The Digital Twin evolves over time, influenced by external interventions (EI_t) such as restoration activities or conservation efforts, with updates dynamically refined through bidirectional communication (BC_t). Machine learning predicts the updated Digital Twin state as

$$\widehat{VE}_t = h_{ML}(VE_{t-1}, EI_t, BC_t; \phi) \quad (9)$$

h_{ML} represents the machine learning model that incorporates past Digital Twin states at time $t - 1$ (VE_{t-1}) and external interventions (EI_t), with ϕ as the model parameters (Figure 10). Bidirectional communication ensures that real-time feedback between the physical and digital systems aligns the state of the Digital Twin with changes in the physical structure. The probability distribution for the updated Digital Twin state is approximated as

$$P(VE_t / EI_t, BC_t) \approx \mathcal{N}(\widehat{VE}_t, \sigma^2) \quad (10)$$

$\mathcal{N}(\widehat{VE}_t, \sigma^2)$ is a Gaussian distribution centered at the predicted Digital Twin state with variance σ^2 .

- Mathematical Formulation of the DT_{HB} Framework

The integration of machine learning into the Digital Twin framework is mathematically represented through the joint probability distribution of its components at time t . The joint distribution of the physical state (PE_t), observations (OSt), Digital Twin state (VE_t), external interventions (EI_t), and Key Performance Indicators ($KPIs_t$) is expressed as $P[PE_t, VE_t, OSt, EI_t, KPIs_t, BC_t]$. Machine learning models approximate this distribution by learning the underlying relationships among these variables:

$$P[PE_t, VE_t, OSt, EI_t, KPIs_t, BC_t] \approx \prod_{i=1}^n f_{ML,i}(\hat{X}, \phi_i) \quad (11)$$

Here, $f_{ML,i}$ denotes the ML model for each component of the distribution, $\hat{X}$ represents the predicted input variables (e.g., PE_t , VE_t , Os_t , El_t , $KPIs_t$), and ϕ_i are the parameters learned for the i th model. This formulation allows the framework to combine real-time data, probabilistic relationships, and predictive insights to dynamically update the digital twin, enabling accurate monitoring, forecasting, and decision-making for heritage building management.

2.3.8. The Proposed Framework Architecture

The data hub DT_{HB} is an integrated framework designed to connect multiple processes, data streams, and IoT layers to enhance the preservation, monitoring, and management of heritage buildings. This architecture begins with the Process of HBIM context database establishment, which is foundational to the DT_{HB} . The process includes capturing data from the physical historical heritage context using reality capture techniques such as photogrammetry and laser scanning to create detailed point cloud models. These models are then transformed through HBIM object modeling into a structured HBIM database with semantic attributes for each building element. This initial phase establishes a rich, interactive model of the heritage building, allowing it to serve as the basis for further data integration and monitoring [21,97]. The central data hub DT_{HB} serves as both a centralized data integration platform and an interoperability hub within the architecture, synchronizing information from various sources, including GIS data, historical archives, sensors, Internet of Cultural Things (IoCT) devices, and 3D imagery [100]. Acting as an interoperability hub, the data hub DT_{HB} enables different devices, data sources, and systems, each potentially using distinct protocols and formats, to communicate and function cohesively. This capability is essential in the context of heritage buildings where diverse data sources, such as environmental sensors, structural health monitors, and visitor tracking systems, must be integrated to provide a comprehensive, unified view of the monument's condition [101].

Real-time monitoring is enabled by continuous data collection from these devices, allowing for immediate tracking of environmental and structural conditions. The interoperability of the hub ensures that data from these varied sources can be seamlessly processed and analyzed in real time, regardless of the originating device or protocol. This hub also supports predictive analytics and simulation data, which provide insights into potential deterioration or damage, facilitating proactive preservation decisions. The interoperability function of the data hub DT_{HB} allows for scalable integration, making it easier to incorporate additional sensors or data sources as the needs of the heritage building evolve.

Various interactive processes such as real-time monitoring and predictive analytics surround the data hub DT_{HB} . These processes allow for the synchronization of perceived data (real-world conditions) with driven data (simulations and analysis), ensuring that conservation efforts are dynamically aligned with the monument's current state. Preventive maintenance plans are developed based on predictive insights, allowing heritage managers to address issues before they become critical.

The framework provides service data for conservation and protection of the heritage building and data-driven decision-making for optimized heritage management. These functionalities are supported by bidirectional communication, where environmental control instructions are generated based on perceived data, leading to actions like adjusting humidity or temperature for preservation. Additionally, the interaction arrows illustrate the seamless integration and flow of information within the data hub DT_{HB} , facilitating advanced functions such as conservation impact assessment, microbial risk monitoring, and enhancement of the visitor experience.

This structured, interconnected framework allows the data hub DT_{HB} to create an interactive and dynamic representation of the heritage building, with real-time monitoring and predictive conservation measures that help in making informed, long-term management decisions. By acting as an interoperability hub, the data hub DT_{HB} ensures that all data sources communicate effectively, enabling a cohesive system that optimizes heritage preservation. The platform organizes data into categories such as structural elements, materials, historical records, and environmental metrics, allowing for efficient metadata tagging, retrieval, and analysis. Through continuous synchronization and interaction across all levels, the data hub DT_{HB} optimizes heritage preservation by providing a comprehensive and responsive Digital Twin architecture (Figure 12).

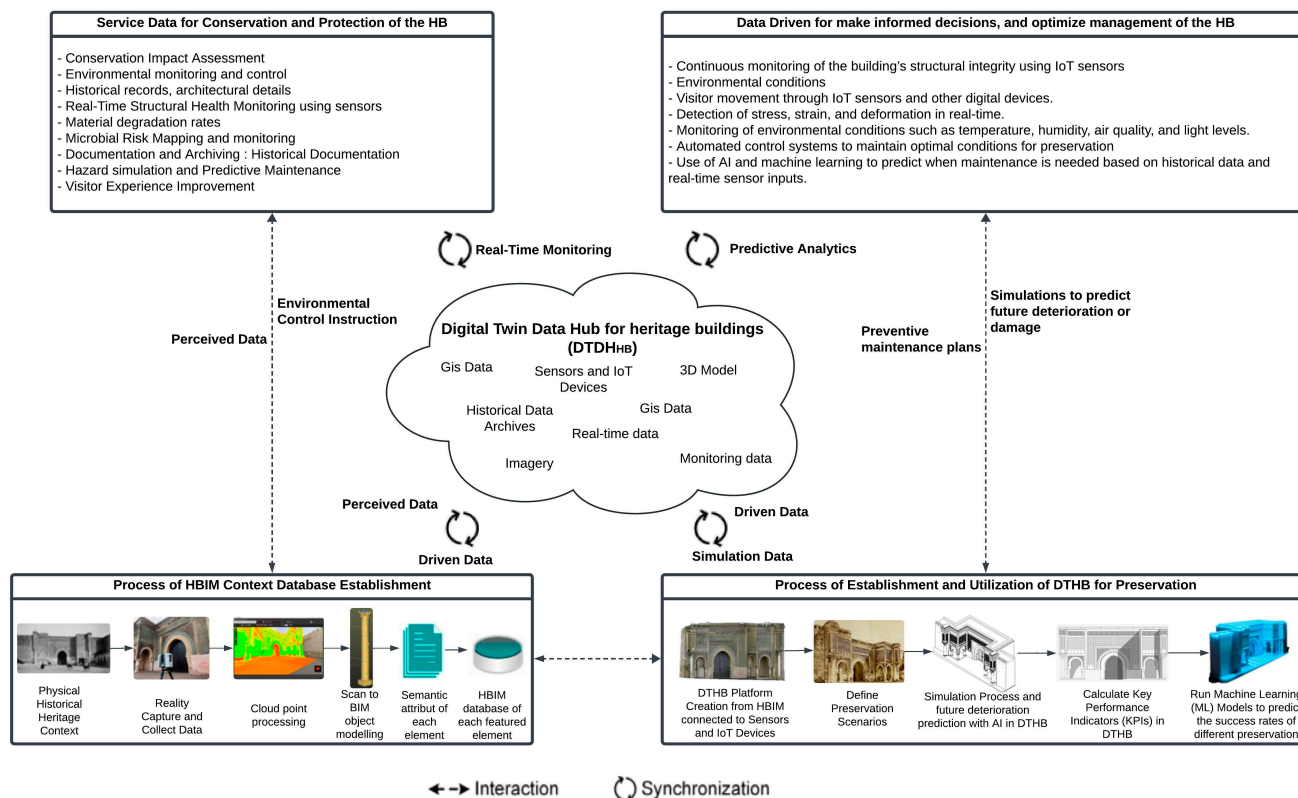


Figure 12. General framework illustrating the integration of HBIM, DT_{HB} , and data hub DT_{HB} .

3. Results and Discussion

3.1. Textural and Structural Information Extraction from Point Cloud Data

Figure 13 illustrates the integration of high-resolution point cloud data in creating a Digital Twin model of the Al-Mansour Gate, with a focus on both structural precision and textural detail. Figure 13a captures the entire architectural composition of the gate, including its main archway, supporting columns, and surrounding decorative panels. The point cloud data enables the construction of an accurate 3D mesh, onto which realistic textures are applied using photogrammetric mapping. This process ensures that the model accurately represents the physical structure's weathering patterns, color variations, and material textures. By capturing these essential characteristics, the Digital Twin becomes a valuable resource for heritage conservation, providing insights into the gate's current state and informing potential restoration efforts. This digital representation preserves the architectural integrity of the Al-Mansour Gate, serving as a precise reference for future conservation interventions and enabling comprehensive documentation and analysis over time.

Figure 13b provides a close-up view of the ornamental details, specifically highlighting the intricate lattice patterns and architectural reliefs that embellish the gate's façade. This LoD captures the craftsmanship of the original structure, allowing even subtle variations in depth and form to be represented in the digital model. The texture mapping retains the esthetic features, from carved decorations to the natural patina of aged stone, offering a rich visual context that honors the cultural and historical significance of the gate. The results of this study demonstrate the scalability of the DT_{HB} framework, identifying challenges specific to heritage buildings with complex architectures, and validating the data hub DT_{HB} as a central repository for real-time data integration. By integrating these technologies, the Digital Twin offers significant potential for adaptive preservation, ensuring the longevity of heritage structures.



Figure 13. (a) Structural representation of Al-Mansour Gate for Digital Twin modeling and (b) textural information modeling from cloud point of Bab Al-Mansour.

3.2. Al-Mansour Gate Elements' Real-Time Monitoring and Choice of the Best Location for the Sensors

Exposure to weather, pollution, and human activities can accelerate the degradation of Bab Al-Mansour. Real-time monitoring and predictive analytics help in mitigating these effects, ensuring timely conservation actions. One of the unique challenges in preserving Bab Al-Mansour is the need for continuous monitoring to detect structural issues, environmental impacts, and potential damage. Digital Twin technology integrates real-time data from sensors placed around the monument, allowing for constant monitoring of structural health, environmental conditions, and visitor interactions. This proactive approach enables timely interventions and predictive maintenance, significantly reducing the risk of irreversible damage.

The scalability of the DT_{HB} framework is highlighted in this study by its ability to incorporate diverse data streams into a unified platform, as exemplified by the integration of IoT sensors and environmental monitoring tools in the case of Bab Al-Mansour. Additionally, the study demonstrates how the data hub DT_{HB} consolidates these data streams into a cohesive system, providing actionable insights for preservation efforts. This capability validates the broader applicability of the framework for other heritage buildings with similarly complex architectures and environmental challenges.

To create a Digital Twin of this structure, several key aspects need to be considered for effective monitoring and preservation. Structural integrity monitoring involves strategically placing sensors at critical points such as pillars, arches, and load-bearing walls to detect any shifts, deformations, or stress points, thereby providing data on the building's overall stability. Environmental sensors distributed throughout the building measure temperature,

humidity, and pollutant levels, helping assess the impact of environmental factors on the building's materials and structural health over time. Ensuring historical accuracy, the Digital Twin should incorporate detailed architectural features visible in the cross-sections, including intricate designs on arches and pillars, maintaining the building's historical and cultural significance. Additionally, a centralized data integration platform is essential to collect and process data from all sensors, enabling real-time monitoring, predictive analytics, and simulation tools, thus providing a comprehensive and dynamic view of the building's condition.

Finding strategic points for the location of the sensors is a comprehensive monitoring system that captures data on the structural health, environmental conditions, and overall stability of the heritage building must be created. In this section we used the meshing model to do the comparison of 3D scans to conduct technical analyses and deduce, for example, the occurrence of changes in the digitized object over time. The use of 3D scanning as a method of monitoring existing works or sites thus makes it possible to trace sensitive information from the field before the emergence of certain events that could have catastrophic repercussions. We conducted the verticality analyses of the monumental pillars based on their meshes model (Figure 14a). Then, we were able to generate a map indicating the most critical areas (Figure 14b). This analysis highlights the framework's capability to identify and overcome technical challenges in heritage preservation while demonstrating the effectiveness of data integration through the data hub DT_{HB} platform. These findings suggest that the DT_{HB} framework can serve as a replicable model for heritage conservation.

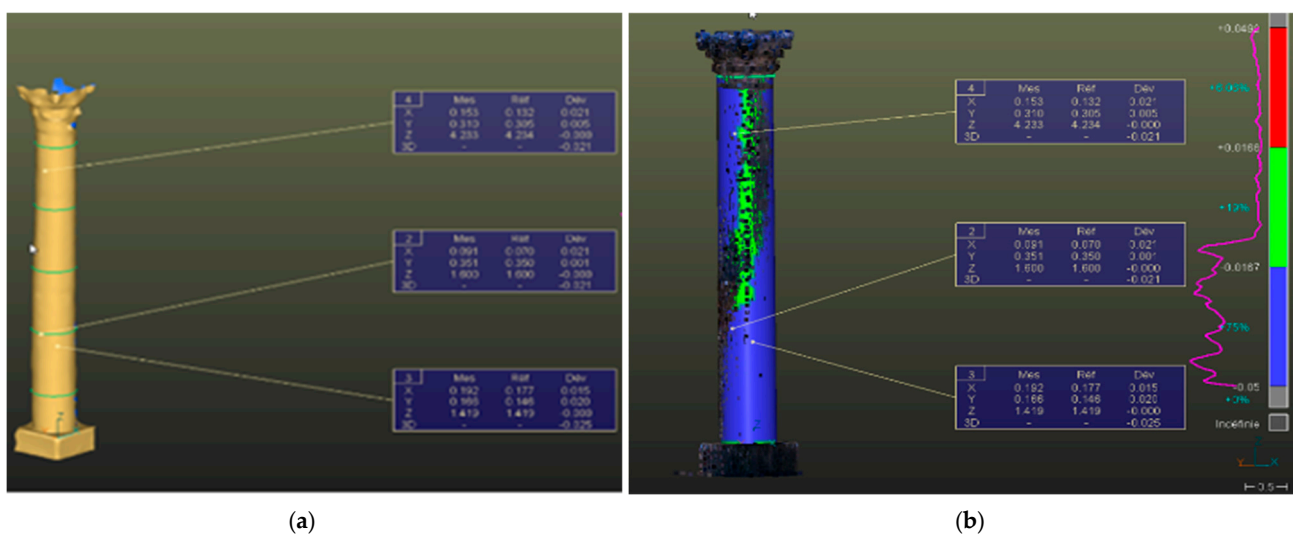


Figure 14. (a) IFC-based 3D mesh classification of Bab Al-Mansour pillar and (b) verticality analysis with decay property set.

The verticality analysis of the pillar reveals that it is generally well-aligned with minor deviations. The top and bottom sections show slight misalignments within acceptable limits, while the middle section exhibits a small bulge, indicating potential structural deformation or settling. Color-coding on the pillar highlights areas of deviation, with green indicating proper alignment and red/blue showing deviations. Regular monitoring and potential restoration of the middle section are recommended to maintain the pillar's structural integrity and prevent further misalignment. To effectively monitor a heritage building, sensors should be strategically placed at various points along the structure. Near the top of the column, sensors at the capstone or capital will monitor structural integrity and detect any potential tilt or movement at the highest point. In the mid-section, sensors should be installed around the middle of the column to track bending or

deformation in this critical load-bearing area, helping to identify structural changes over time. At the base, sensors should be positioned to monitor ground stability, any shifts in the foundation, and vibrations that might impact the entire structure. Additionally, environmental sensors should be distributed along the height of the column to measure factors such as temperature, humidity, and exposure to pollutants, which can affect the material condition. This comprehensive sensor placement ensures continuous and detailed monitoring of the heritage building's condition.

3.3. Al-Mansour Gate Model

The 3D model of Bab Mansour, shown in Figure 15a, is a highly detailed representation based on point cloud data collected from reality capture technologies. This model accurately reflects the intricate architectural features of the historical gate, including its elaborate geometric patterns, decorative tilework, and structural elements such as arches and columns. The use of point cloud data allows for precise modeling of the gate's complex geometry, ensuring that even the finest details, such as the reliefs and ornamental carvings, are faithfully captured. This digital model serves as a foundational element for further analysis and conservation efforts, enabling heritage preservation experts to visualize, assess, and monitor the condition of Bab Mansour in a digital environment. The following texture has been applied on the mesh based on the panoramic imagery captured on site by an optical sensor, as shown in Figure 15b.

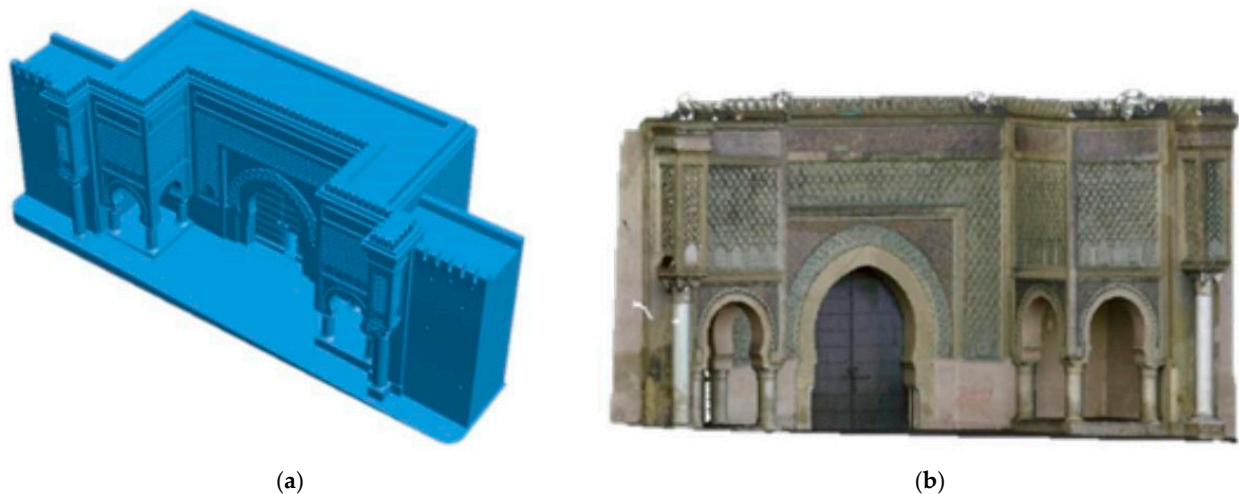


Figure 15. (a) Point cloud-based 3D model of Bab Al-Mansour and (b) textured optical sensor model of Bab Al-Mansour.

3.4. General Schema for Using the Developed Framework in Heritage Preservation

The developed framework, illustrated in Figure 16, for heritage preservation begins with the systematic collection and integration of critical data related to heritage structures. This includes structural integrity data obtained from IoT sensors, environmental conditions such as humidity, temperature, and pollution, historical and cultural records, and visitor impact metrics, such as foot traffic and physical wear. By consolidating these diverse data streams, the framework establishes a robust foundation for modeling, analysis, and decision-making. Preservation and restoration scenarios are then outlined to address specific risks and challenges, with simulations conducted to evaluate their effectiveness. A key component of the framework are KPIs such as Structural Integrity Score, Environmental Impact Assessment, and Restoration Longevity, derived from sensor data. These metrics provide quantitative insights into the current condition of the heritage structure, enabling data-driven decisions for its preservation. For instance, crack and deformation sensors contribute to the Structural Integrity Score, while humidity and temperature data inform

the Environmental Impact Assessment, allowing for the precise evaluation of external factors on material longevity.

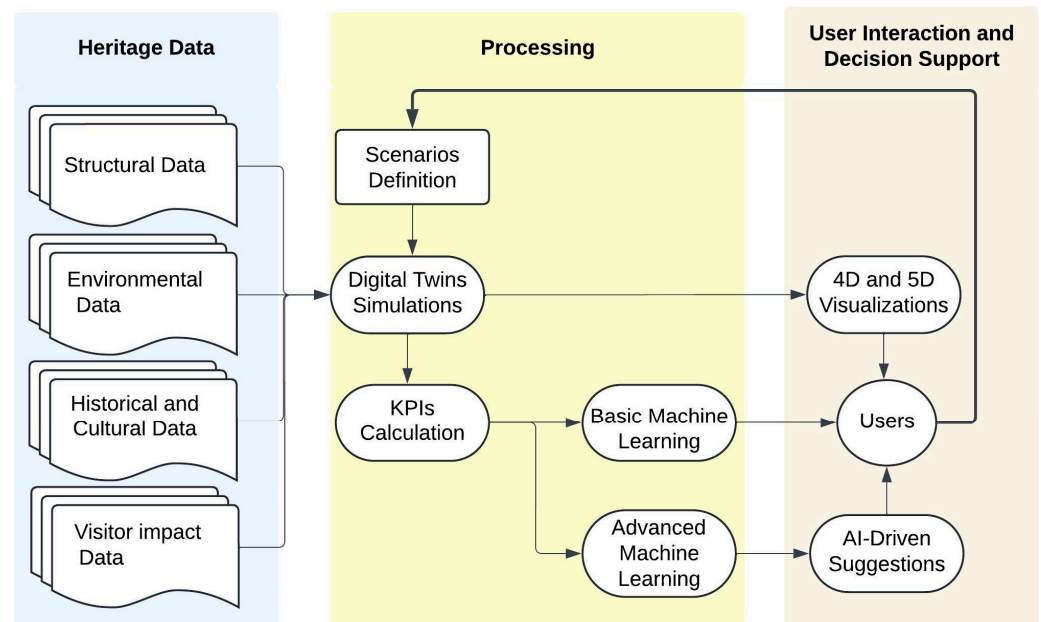


Figure 16. Framework for AI-Enhanced Digital Twin simulations and user interaction in heritage preservation.

The integration of ML algorithms enhances the analytical depth of the framework. Basic ML algorithms, such as linear regression and decision trees, identify patterns in structural degradation and predict future risks. Advanced ML techniques, including neural networks and support vector machines, refine these insights by optimizing preservation strategies customized to the historical and cultural context of the structure. These models also incorporate user-defined constraints, such as budgetary limits and sustainability objectives, ensuring practical and context-specific conservation approaches. Additionally, the framework emphasizes user engagement through time-enhanced (4D) visualizations, which allow users to explore real-time changes and simulate the impacts of various interventions over time. Sustainability-integrated (5D) visualizations expand this capability by incorporating factors such as environmental impact and cost analysis, providing a comprehensive understanding of the long-term effects of preservation strategies. These interactive interfaces enable decision-makers to assess scenarios dynamically, fostering data-driven and informed heritage management processes.

The framework also addresses the unique challenges associated with African heritage sites, which require context-specific solutions. Extreme weather conditions, such as arid climates and sandstorms, accelerate material degradation, while vulnerabilities inherent to materials like mudbrick and zellige tiles demand specialized preservation techniques. Limited conservation resources, urban encroachment, and socio-economic pressures compound these challenges, underscoring the need for adaptive and resource-efficient methodologies. By addressing these challenges, the framework ensures that African heritage sites, including Bab Al-Mansour, can be preserved with approaches that respect their cultural, material, and environmental specificities.

3.5. Framework of DT_{HB} Difficulties, Limitations, and Future Directions of Development

Table 3 provides a detailed framework for advancing DT_{HB} , systematically organized across eight critical stages: survey, mapping, and data integration; semantic and HBIM modeling; IoT sensor integration; DT_{HB} construction; data hub DT_{HB} implementation; KPIs

calculation; bidirectional online communication; and real-time decision support. Each stage addresses unique technical challenges and outlines specific future-oriented solutions to bolster Digital Twin applications in heritage conservation.

Table 3. Overview of key steps, challenges, and future developments for the DT_{HB} framework.

Step	Difficulties	Limitations	Future Developments
1. Survey, Mapping, and Integration	– Acquiring high-precision spatial data – Managing diverse data formats – Capturing climate and pollution data for comprehensive analysis	– Lack of standardized workflows – Limited automation tools for data cleaning – Absence of detailed climatic and pollution data	– AI-driven processing for data cleaning – Standardize geospatial formats – Integrate climate and pollution sensors
2. Semantic and HBIM Modeling	– Integrating semantic, historical, and structural data – Complex geometries in modeling	– Lack of comprehensive ontologies – Limited interoperability with monitoring systems	– Develop robust ontologies – Streamline HBIM with real-time data integration
3. IoT Sensors Integration	– Optimal sensor placement – Real-time data management from multiple sensors – Challenges in integrating pollution and climatic sensors	– Insufficient real-time IoT integration tools – Limited predictive capacity for long-term changes	– Wireless MEMS for non-invasive monitoring – AI-driven predictive analytics – Additional sensors to monitor NO_x, SO_x, PM_{2.5}, PM₁₀, humidity, temperature, and rainfall
4. DT _{HB} Construction	– Creating an accurate digital twin – Simulating environmental and structural stress	– Limited real-time updating – Lack of interactive, multi-user features	– Interactive Digital Twin platforms – Cloud-based collaboration for conservation
5. Data Hub DT _{HB} Construction	– Integrating diverse data sources – Standardizing data formats for consistency	– Limited capability for real-time data fusion – Lack of interoperability across platforms	– AI-driven predictive analysis – Advanced data fusion for comprehensive representation
6. KPI Calculation in DT _{HB}	– Defining balanced KPIs – Real-time KPI visualization across data streams	– Lack of heritage-specific KPIs – Insufficient automated KPI dashboards	– Universal KPI set for heritage preservation – Real-time KPI monitoring tools
7. Bidirectional Communication	– Data synchronization in real time – Latency and bandwidth constraints	– Lack of standardized protocols – Limited security for remote access	– Adaptive data synchronization – Blockchain for secure data transactions
8. Real-Time Decision Support	– Multi-criteria decision-making complexity – Data overload and interpretation challenges	– Limited predictive analytics – Absence of scenario simulation capabilities	– AI-driven decision support tools – Scenario-based simulation tools for proactive planning

In the first stage, survey, mapping, and data integration, the framework identifies obstacles such as handling large, high-precision datasets from UAVs, LiDAR, and pho-

togrammetry, often complicated by incompatible formats, varying resolutions, and dataset volume. To streamline this, the framework proposes AI-driven solutions for data cleaning and integration, in addition to standardized data formats to enable seamless data fusion across platforms. However, the current implementation lacks the inclusion of climate and pollution data, which are significant threats to heritage preservation. Future iterations will integrate additional sensors to monitor air quality, particulate matter (e.g., NO_x, SO_x, PM_{2.5}, and PM₁₀), and climatic parameters such as humidity, temperature, and rainfall, enabling a more comprehensive analysis of their impacts.

During the semantic and HBIM modeling phase, the primary challenge is integrating diverse semantic information, particularly historical, architectural, and structural data, into HBIM models, particularly for culturally rich but under-documented Moroccan heritage. The solution involves developing robust, culturally specific ontologies that encapsulate both tangible and intangible heritage elements and implementing software plugins to facilitate HBIM's interoperability with real-time data inputs from sensors.

IoT sensor integration is critical for real-time structural monitoring, yet it presents challenges in optimal sensor placement and efficient data flow management. Additionally, integrating environmental and pollution sensors remains a challenge, given the need for non-invasive technologies suitable for heritage structures. The framework advocates for advancements in MEMS-based (Micro-Electro-Mechanical Systems) non-invasive sensors and AI-driven predictive analytics to forecast structural deterioration, ensuring the effective and sustainable monitoring of heritage buildings.

In the DT_{HB} implementation stage, Table 3 highlights the need for dynamic, interactive interfaces capable of real-time data integration and simulation of environmental impacts on heritage structures. Current limitations, such as limited multi-user collaboration features and insufficient real-time update mechanisms, are addressed through cloud-based platforms that offer enhanced interactivity. This allows users to annotate, view, and actively engage in conservation planning in real time.

The data hub DT_{HB} construction phase focuses on data integration from diverse sources, including IoT, HBIM, and historical archives, emphasizing the importance of data standardization. This stage proposes advanced data fusion techniques that facilitate seamless interoperability across diverse data types, ensuring that legacy data and real-time inputs coalesce into a cohesive digital model.

KPI calculation and real-time decision support form the backbone of informed heritage preservation, suggesting dynamic dashboards for continuous KPI visualization. The framework advocates for AI-enabled decision-support systems and scenario-based simulation tools that allow heritage conservationists to assess the potential outcomes of different preservation strategies, fostering a proactive, data-driven approach to safeguarding cultural assets.

Finally, the bidirectional online communication and real-time decision support stages represent the most important and advanced levels in the construction of a DT_{HB}. These stages underscore the need for AI-optimized data synchronization and secure blockchain-based transactions to facilitate robust data sharing among users. By integrating these advanced tools, the framework envisions a collaborative, multi-user decision-making environment that enhances sustainable heritage preservation through innovative Digital Twin solutions, supporting seamless, synchronized updates and real-time, data-driven conservation efforts across multiple users.

4. Conclusions

This study demonstrates the transformative potential of Digital Twin technology in preserving and managing African heritage sites, with a focus on Bab Al-Mansour, a landmark of

profound historical and cultural value. By developing the Bab Al-Mansour DT_{HB} platform, we provide an integrated framework that combines advanced technologies, including HBIM, GIS, IoT sensors, and predictive analytics, to support a detailed and dynamic digital representation of this significant Moroccan monument. Through real-time monitoring, predictive maintenance, and interactive real-time decision-support capabilities, the Bab Al-Mansour DT_{HB} platform exemplifies how Digital Twin frameworks can proactively address the complexities of heritage conservation, extending beyond traditional preservation methods. The proposed DT_{HB} framework, illustrated through its application to Bab Al-Mansour, demonstrates significant potential for addressing critical challenges in heritage preservation. While this study focuses on establishing a detailed framework, the application highlights its ability to capture complex architectural features, integrate real-time monitoring data, and simulate potential deterioration scenarios. These capabilities provide a foundation for informed decision-making, proactive conservation, and scalable implementation across other heritage sites. By offering a structured approach to digitizing and preserving culturally significant monuments, the framework addresses pressing needs in heritage conservation, particularly in Africa, where resources for such initiatives are often limited.

The successful implementation of the Bab Al-Mansour DT_{HB} enhances the preservation efforts of Bab Al-Mansour while setting a new standard for sustainable conservation practices across Africa. By capturing intricate architectural features and environmental data, this framework supports a robust preservation strategy that balances technological innovation with respect for cultural heritage. As African landmarks like Bab Al-Mansour face challenges such as environmental degradation and limited conservation resources, the scalability of the Bab Al-Mansour DT_{HB} framework makes it a valuable model for other historic sites in Africa, supporting both local and global heritage conservation goals.

However, there are certain limitations to this study that present opportunities for future improvement. Challenges with data integration, due to the diverse sources and formats of information, as well as constraints on sensor durability and placement, highlight areas for development. Future advancements could focus on refining AI-driven analytics to enhance predictive capabilities and anomaly detection within the Digital Twin framework. Furthermore, improved sensor technologies that are less invasive and more resilient in extreme environmental conditions would enhance the reliability of real-time monitoring. The integration of cloud-based data storage and processing platforms could also facilitate scalability, making this framework adaptable to a wider range of African heritage sites with diverse preservation needs.

This research underscores the vital role of Digital Twin technology in heritage conservation, illustrating its capacity to foster sustainable, informed, and efficient preservation strategies for culturally significant structures. By merging advanced digital tools with traditional conservation principles, the Bab Al-Mansour DT_{HB} platform reinforces the importance of safeguarding cultural legacies, contributing to the enduring protection of African heritage sites.

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