An Accelerometer Sensor-Based Digital Twin Framework For Structural Health Monitoring Of Cultural Heritage Buildings: A Case Study Of Jakarta Cathedral

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Abstract

The maintenance of cultural heritage buildings is gradually shifting from a curative approach toward preventive conservation supported by digital technologies. Although Heritage Building Information Modeling (HBIM) has been widely adopted, the resulting models are generally static and incapable of integrating real-time structural monitoring data. This study employs a qualitative case study approach combined with a literature review. The literature review was conducted to identify variables, subvariables, and indicators, which were subsequently validated by experts. In addition, benchmarking of previous frameworks was carried out to understand existing structures and methodologies. Based on these findings, a framework was developed according to the research requirements and further validated by experts to ensure its reliability and practical applicability. This study proposes a Digital Twin (DT) framework for cultural heritage buildings by integrating geometric building models, historical information, and dynamic data obtained from accelerometer sensors. The framework consists of four main layers: the information source layer, the BIM model layer, the integration layer, and the application layer for visualization and decision-making support. The framework was implemented in the Jakarta Cathedral to evaluate the integration of sensor data into the HBIM environment. Expert validation results indicate that the proposed framework provides a systematic approach to supporting preventive conservation for cultural heritage buildings with complex geometries.

Keywords: Digital Twin, Heritage Building Information Modeling (HBIM), Cultural Heritage Buildings, Structural Health Monitoring System (SHMS), Accelerometer Sensor, Preventive Conservation.

INTRODUCTION

The preservation of historical sites has become a global challenge for governments and site managers, as progressive deterioration can reduce structural strength and stability (Kong & Hucks, 2023). In Jakarta, the Provincial Government of DKI Jakarta recorded 305 cultural heritage objects between 2020 and 2024, including heritage objects, buildings, structures, sites, and heritage areas. Of these, 253 are classified as heritage buildings. One of the heritage buildings that remains actively utilized today is the Jakarta Cathedral, which serves both as a place of worship and a historical tourism destination. The building has stood since 1901 (Trisno et al., 2022).

In addition to aging-related deterioration, Indonesia's geographical location within the Ring of Fire significantly increases the risk of damage to heritage structures. This vulnerability is further amplified considering that many heritage buildings are more than a century old. Moreover, revisions to the Indonesian seismic design standard (SNI 1726) from 2002 to 2024 indicate increasing earthquake response spectrum design values in the Jakarta region. This trend suggests that buildings, including heritage structures, face greater seismic risks and therefore require closer attention to their structural conditions. The Jakarta Cathedral features towers approximately 60 meters high at the front and 45 meters high at the rear. The tall and slender configuration of these towers makes their upper sections particularly sensitive to structural changes and vibrations. Tower slenderness can be expressed through the slenderness ratio, defined as the ratio between the total tower height and the minimum external dimension of its base cross-section. Higher slenderness ratios generally correspond to lower natural frequencies, making structures more susceptible to dynamic loads, including earthquakes (Bartoli et al., 2017).

Recent developments in Digital Twin technology have demonstrated significant potential in various applications, including structural health monitoring, environmental condition control, and preventive conservation planning (Hosamo & Mazzetto, 2024). Within this context, Structural Health Monitoring Systems (SHMS) play a crucial role by providing continuous and real-time information regarding structural conditions. Consequently, SHMS has become an increasingly important research topic, particularly in civil structures and infrastructure requiring ongoing condition monitoring (Beskhyroun & Aghakouchaki Hosseini, 2025). Various types of sensors can be employed within SHMS, including accelerometer sensors. However, the implementation of Digital Twin technology for heritage buildings in Indonesia remains limited due to the absence of a standardized framework capable of accommodating the complex geometries and unique historical semantic data associated with cultural heritage structures. Therefore, this study aims to design and validate a Digital Twin framework that systematically integrates accelerometer data with an HBIM model.

Literature Review

Heritage Building

In Indonesia, the protection of cultural heritage buildings is regulated under Law No. 11 of 2010 concerning Cultural Heritage. This law states that cultural heritage constitutes a national cultural asset that reflects the thoughts and lives of past societies and plays an important role in the development of history, science, and culture within social, national, and state life. According to the law, an object, building, or structure may be proposed as a Cultural Heritage Object, Cultural Heritage Building, or Cultural Heritage Structure if it meets the following criteria:

1. It is at least 50 years old;
2. It represents a style period that is at least 50 years old;
3. It possesses special significance for history, science, education, religion, and/or culture; and
4. It has cultural value that contributes to strengthening national identity.

Over the past few decades, efforts to preserve and enhance the quality of heritage buildings have received increasing attention due to their significant contributions to economic, social, cultural, and environmental aspects (Rossi & Bournas, 2023). Heritage building conservation encompasses a series of activities aimed at protecting, maintaining, and preserving the architectural, historical, social, cultural, and environmental values embedded within historic structures (Revaldi et al., 2025). Referring to the Burra Charter (1999), several principal conservation actions can be identified (Rubiantoro, 2018), including:

1. Conservation, encompassing all maintenance activities undertaken to preserve the cultural significance of a place;
2. Preservation, involving the retention of existing materials and conditions while slowing deterioration;
3. Restoration/Rehabilitation, aimed at returning a building to its former physical condition by removing later additions and reinstating missing original elements without introducing new components;
4. Reconstruction, involving the restoration of a place to a known earlier state using either original or new materials and distinguished from restoration;
5. Adaptation/Revitalization, referring to modifications that enable a place to serve an appropriate contemporary function; and
6. Demolition, involving the dismantling or removal of a building that has become severely damaged or hazardous.

Digital Twin (DT)

The term *digital twin* was first introduced in 1997 in the context of interactive urban design. Its development began in the aerospace and astronautics sectors, then expanded into the manufacturing and automotive industries, and eventually came to be used in the development and management of virtual products based on real-world data (Lucchi, 2023). According to Wang et al., (2019) digital twin is a dynamic digital model that uniquely represents a physical system and is supported by various enabling technologies, such as multiphysics simulation, machine learning, augmented reality/virtual reality (AR/VR), and cloud computing services. According to He et al., (2018) digital twin is a dynamic digital representation of assets, processes, and physical systems used to comprehensively monitor, analyze, and manage the condition of an object throughout its lifecycle. A digital twin can be defined as a digital representation of a physical object, system, or process that functions as a virtual twin.

A digital twin can be defined as a digital representation of a physical object, system, or process that functions as a virtual counterpart. The primary objective of its implementation is to improve performance, operational efficiency, and cost-effectiveness through the integration of various technologies such as virtual modeling, simulation, blockchain, edge computing, cloud computing, and various optimization methods (Khan et al., 2022). In the development of a digital twin, a framework serves as a guideline that helps organize all important components in a structured manner so that the relationships among elements can be clearly understood and well integrated (Johnson, 1997). In general, a framework can also be viewed as a fundamental structure that explains the arrangement of technical components within a system, including how data flows and how each element interacts to support the overall functionality of the system (Kang & Mo, 2024). In this study, there are 14 digital twin frameworks used as initial benchmarks, as listed in Table 1.

Table 1. List of 14 initial benchmark frameworks

Description		
FW1	Heritage Building Information Modeling (HBIM) for Heritage Conservation: Framework of Challenges, Gaps, and Existing Limitations of HBIM	(Penjor et al., 2024)
FW2	Digital Twin in Construction: An Empirical Analysis	(Piskernik et al., 2020)
FW3	A Comprehensive Digital Twin Framework for Building Environment Monitoring with Emphasis on Real-Time Data Connectivity and Predictability	(Kang & Mo, 2024)
FW4	A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry	(Zhang et al., 2024)
FW5	Edge Computing Application, Architecture, and Challenges in Ubiquitous Power Internet of Things	(Liu et al., 2022)
FW6	Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus	(Xu et al., 2023)
FW7	Digital Twins for the Automation of the Heritage Construction Sector	(Lucchi, 2023)
FW8	Data Fusion for Smart Civil Infrastructure Management: A Conceptual Digital Twin Framework	(Hakimi et al., 2023)
FW9	A Review of Digital Twin Applications in Civil and Infrastructure Emergency Management	(Cheng et al., 2023)
FW10	An Integrated HBIM Framework for the Management of Heritage Buildings	(Khan et al., 2022)
FW11	Digital Twins in Construction: Architecture, Applications, Trends and Challenges	(Yang et al., 2024)
FW12	Review of Digital Twin in Structural Dynamics to Improve Condition Monitoring	(Adimass & Żak, 2026)
FW13	A Digital Twin Architecture for Real-Time and Offline High Granularity Analysis in Smart Buildings	(Hadjidemetriou et al., 2023)
FW14	From HBIM to Digital Twins: An Interoperable Framework for Semantic Knowledge Integration and Dynamic Monitoring of Historic Buildings	(Becker et al., 2025)

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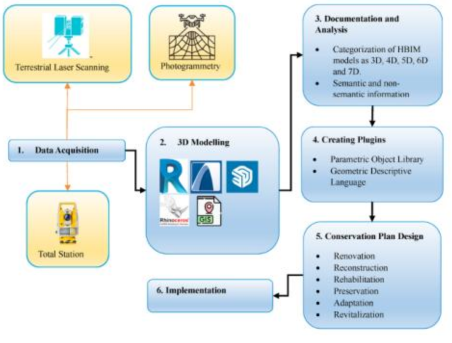
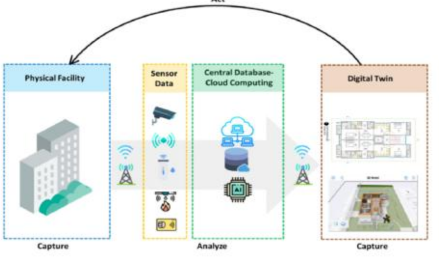
Table 2. Explanation of the 14 reference frameworks

Code	Framework image	Explanation
FW1		Framework consist of: 1. Data acquisition: The first stage involves recording the current condition of historic buildings using various measurement tools such as TLS and photogrammetry. 2. 3D model: Converting the raw data into intelligent digital models using BIM software such as Revit, ArchiCAD, or Rhinoceros. 3. Documentation & analysis: The digital model is enriched with semantic information. The use of HBIM is expanded from 3D to 7D 4. Plugin: Development of plugins to build a specialized library of parametric objects representing historical architectural motifs. 5. Conservation plan design: These conservation plan options include strategies for Renovation, Reconstruction, Rehabilitation, Preservation, Adaptation, or Revitalization 6. Implementation: This implementation ensures that all stakeholders work with synchronized data, thereby minimizing the risk of information errors.
FW2		Framework consist of: 1. Physical Facility: The process begins with physical assets or buildings in the physical world. These objects serve as the primary source of information whose condition must be monitored throughout their lifecycle.

<table>
<tr>
<td></td>
<td></td>
<td>2. Capture/Sensor Data: Data from the physical facility is captured in real time using various sensor technologies.
3. Central Database - Cloud Computing: The raw data captured is then sent to a data processing center. At this stage, technologies such as Cloud Computing, Big Data, and Data Mining are used to store and organize large volumes of information.
4. Analyze/AI: Within this data center, Artificial Intelligence (AI) algorithms work to predict the building's future behavior and support informed decision-making
5. Digital Twin: The results of the analysis and predictions are then displayed in a virtual model that serves as a digital replica of the physical object. This model is typically BIM-based.
6. Act: There is a two-way data flow where information from the virtual model is fed back to the physical facility.</td>
</tr>
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<td>FW3</td>
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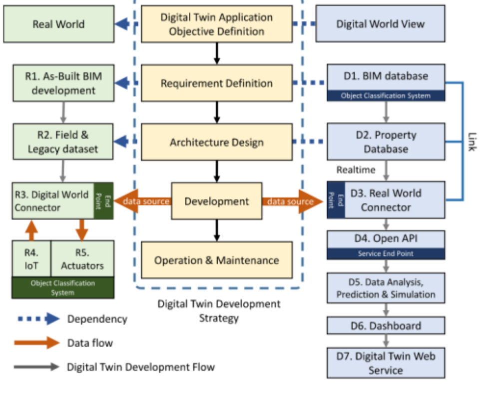
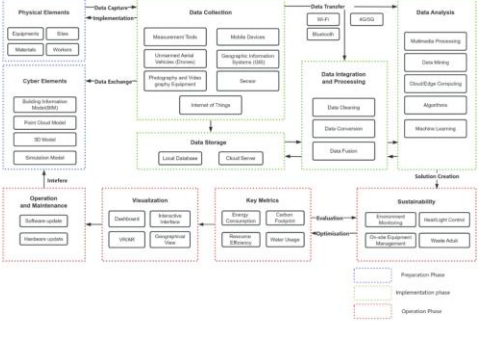


</td>
<td>Framework consist of:
1. Real World: This is the primary data source in a digital twin system. R1 builds a digital model of the building's actual condition, R2 provides field and historical data, R4 collects real-time data via sensors, R3 connects physical assets to the digital world, and R5 executes physical actions based on instructions from the digital system.
2. Digital twin development strategy: Organizes the system development process from goal setting, needs identification, architectural design, and system development through to operation and</td>
</tr>
</table>

		maintenance to ensure the digital twin functions sustainably. 3. Digital World: Functions as the data management and analysis hub within the Digital Twin system. D1–D2 manage BIM data and asset attributes, D3–D4 support data exchange with the physical world, D5 performs analysis and predictions, D6 displays results via a dashboard, and D7 provides Digital Twin services to users. 4. Connectivity and Predictability Mechanisms demonstrate the real-time data flow from sensors (R4) to databases (D1/D2) via connectors (R3/D3), which is then analyzed by D5 and displayed on D6 to support decision-making and actions through R5.
FW4		Framework consist of: 1. Preparation phase: This is the initial stage of Digital Twin implementation, aimed at mapping physical elements (equipment, locations, materials, and labor) to cyber elements such as BIM, point clouds, 3D models, and simulation models. 2. Implementation phase: This phase involves the acquisition, storage, integration, and analysis of data using IoT, sensors, the cloud, and intelligent analytics to generate information and predictions that support decision-making. 3.Operation phase: Utilizes the results of the analysis for monitoring, controlling, and optimizing assets, with evaluations based on energy, carbon emissions, resources, and water. Information is presented through visualization, then supported by

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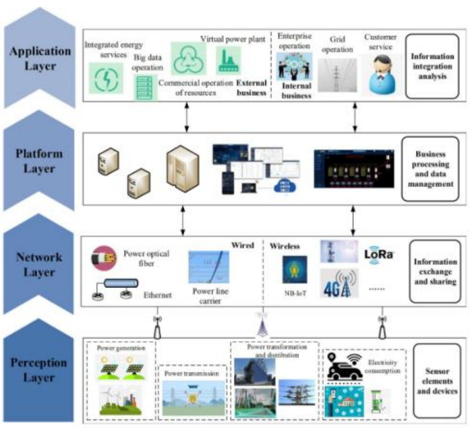
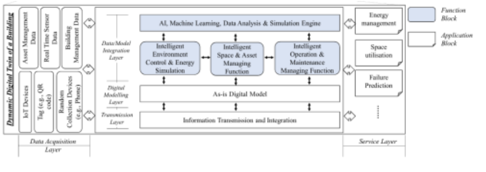
		operations and maintenance to sustain system performance.
FW5		Framework consist of: 1. Perception Layer is the foundational layer that uses smart sensors to collect and monitor real-time data from physical assets. The devices used include sensors, cameras, inspection robots, and smart meters to obtain operational data directly. 2.Network Layer serves as a communication medium that transmits data between sensors and the Digital Twin system efficiently and securely via wired and wireless networks, such as Ethernet, fiber optics, NB-IoT, LoRa, 4G, and 5G. 3.Management Layer functions as a data storage and processing hub using cloud computing, big data, and deep learning. This layer manages information from the network in an integrated manner to support real-time analysis, collaborative computing, and system operational needs. 4. Application Layer is the topmost layer that provides control, analysis, and decision-making services for users and operators. This layer integrates information to support network

		operations, energy services, and new business models such as virtual power plants and energy management.
FW6		Framework consist of: 1. Data acquisition layer collects data from the building's physical environment via sensors and IoT devices, asset identification tags (e.g., QR codes), and manual user input. The collected data includes asset information, environmental conditions, and building operational data, which serve as the foundation for Digital Twin management. 2. Transmission layer serves as the communication infrastructure that bridges the physical and digital worlds. 3. Digital modeling layer represents the building in the form of a digital model, typically based on BIM (Building Information Modeling). This model not only includes accurate 3D geometry but is also enriched with parametric data on building elements. 4. Data/model integration layer is the core of the Digital Twin, processing and integrating data using AI, Machine Learning, and simulation to support energy management, asset management, and predictive building maintenance.. 5. Service Layer serves as the interface where the results of data processing are presented to end-users in the form of practical services.

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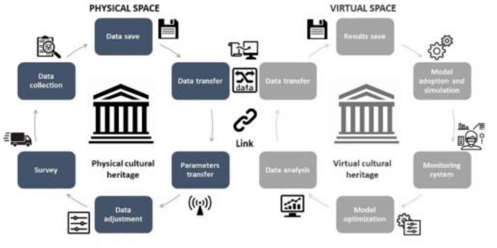
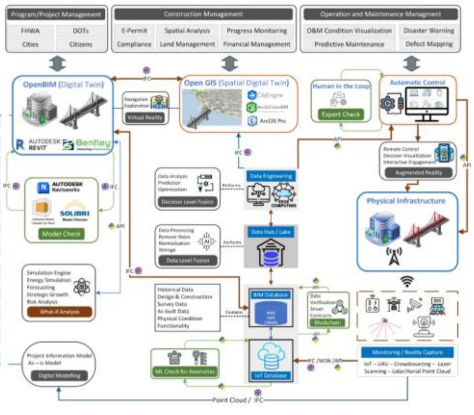
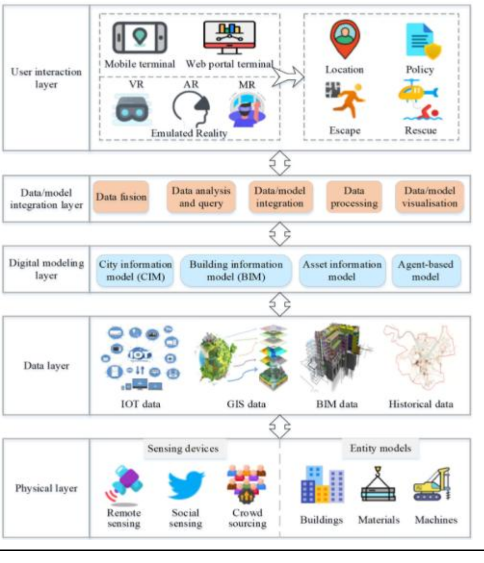
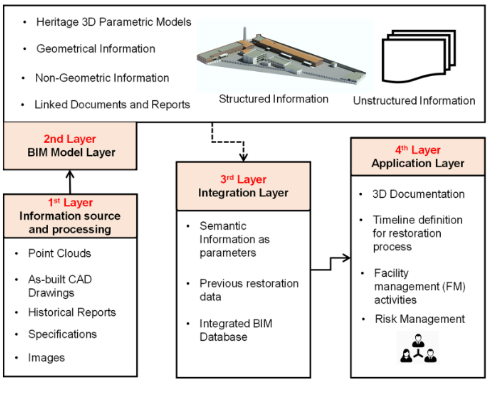
FW7		Framework consist of: 1. Physical space process begins with an initial survey to assess the condition of the building, followed by data collection and storage in the field, and concludes with the transfer of data to the Digital Twin system for further analysis. 2. Link is a two-way connection that automatically bridges the physical and virtual worlds, enabling continuous data synchronization and the exchange of feedback between real-world objects and digital models. 3. Virtual Space functions as the Digital Twin's intelligence hub, managing cultural heritage data digitally. The process includes data storage, simulation and modeling of object conditions, real-time monitoring, and data analysis to generate model optimization, condition predictions, risk detection, and accurate recommendations for restoration interventions. 4. This cycle is closed with feedback to the real world through the transmission of decision parameters and data adjustments or restoration interventions. This process is circular, sustainable, and dynamic, thereby transforming a static HBIM into an adaptive Digital Twin capable of continuously optimizing data to maintain the integrity of cultural heritage buildings.

FW8		Framework consist of: 1. Data Acquisition and Physical Infrastructure layer captures real-time data using IoT, sensors, LiDAR, drones, and scanning technologies to generate as-built models. 2. Data Management and Security (Blockchain) integrates IoT–BIM databases, ML-based anomaly detection, and data security via blockchain. 3. The Multi-Level Data and Fusion Center serves as a data hub that performs data fusion, analysis, prediction, and optimization using AI and edge/cloud computing. 4. The Immersive Visualization Layer (OpenBIM and GIS) presents analysis results through OpenBIM and GIS with VR/AR support. 5. Validation, Simulation, and Human-in-the-Loop ensure decisions are validated through expert review and scenario simulation. 6. The Services and Stakeholders Layer provides Digital Twin applications for project management, construction, and operations and maintenance.
FW9		Framework consist of: 1. Physical Layer serves as the foundation of the system, collecting data from real-world objects through remote sensing, social media, and crowdsourcing. 2. Data Layer integrates cloud computing and big data to manage and integrate various data sources such as GIS, BIM, IoT, and historical data using the cloud and big data.

		3. Digital Modeling Layer contains various digital models to support control and decision-making, such as CIM (city scale), BIM (building scale), asset information models, and agent-based models for simulating various scenarios. 4. Data/Model Integration Layer is the core of the Digital Twin system, functioning as the central component that processes and analyzes data using AI, machine learning, and simulation for early detection and warning. 5. User Interaction Layer serves as the user interface via web, mobile, and VR/AR to support decision-making and disaster response.
FW10	 	Framework consist of: 1. Information source and processing is the foundation of HBIM, which collects raw data such as point clouds, as-built CAD drawings, historical reports, technical specifications, and documentary photos. This data is then classified into geometric (building geometry) and non-geometric (component attributes) categories to build an integrated model. 2. BIM Model Layer represents physical assets as an Asset Information Model (AIM) in the form of a parametric 3D model equipped with geometric and non-geometric data as well as links to related documents. Each element is assigned a unique ID to facilitate classification and collaboration among stakeholders.

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<td></td>
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<td>3. Integration Layer serves to combine semantic data, restoration history, and IFC-based BIM databases for data interoperability.
4. Application Layer serves as the user interface for 3D documentation, restoration simulations, facility management, and risk management for historic buildings.</td>
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<td>FW11</td>
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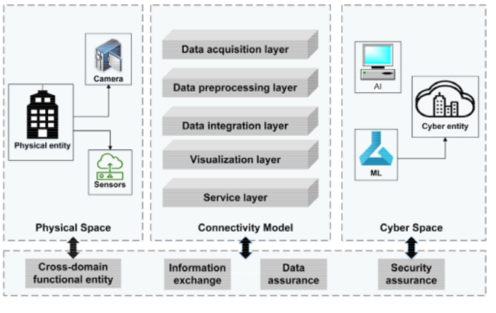

</td>
<td>Framework consist of:
1. Physical Space refers to tangible assets in the field, such as buildings or construction projects, that are monitored directly. These spaces are equipped with IoT sensors to collect real-time data on building geometry, materials, and equipment conditions.
2. Virtual Space is a digital representation of physical objects that uses simulation models or data to replicate and analyze real-world systems. These models are dynamic, as they are continuously updated based on field data to ensure accuracy and timeliness.
3. Connectivity model & data processing form a two-way connection between physical and virtual spaces. Data is processed using AI, Machine Learning, and Data Mining, then visualized through dashboards, VR, and AR. The analysis</td>
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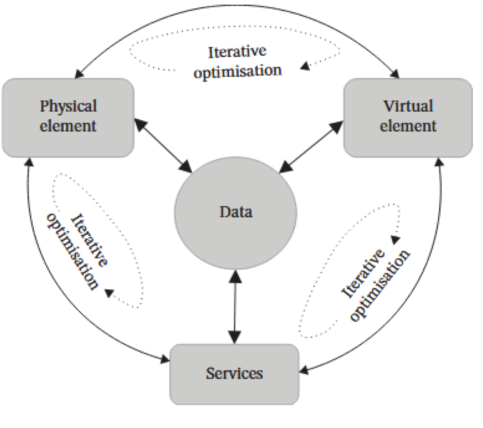
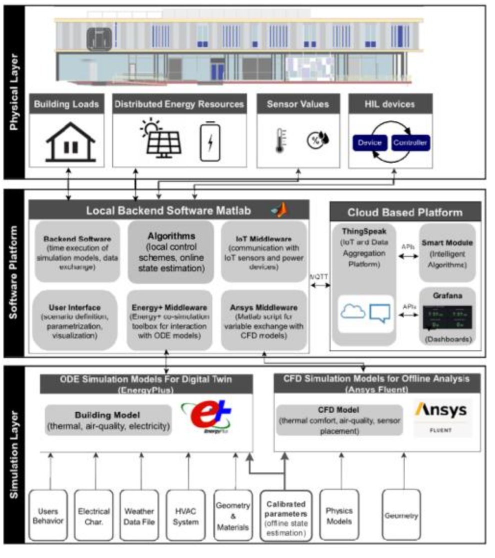
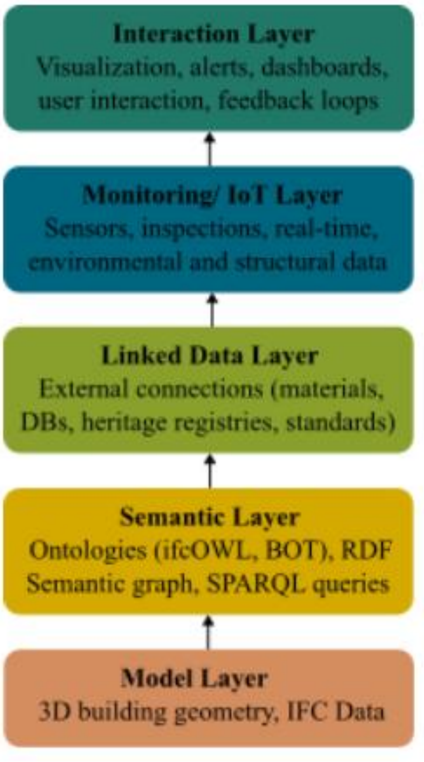
</table>

		results are used as feedback for real-time decision-making and system optimization in the physical world.
FW12		Framework consist of: 1. Physical element is a real-world entity or system that is the subject of monitoring, such as a bridge, an offshore platform, or an aerospace system. 2.Virtual element is a digital representation based on physical equations or data algorithms that replicates a physical asset. This model evolves in parallel with the real-world object and is updated in response to changing conditions or damage. 3. Data acts as the central hub or primary connector in the diagram. Data encompasses information flows from the data acquisition layer (IoT sensors) as well as operational feedback that bridges the physical and virtual domains. 4. Services include analytical tools, simulations, and predictive algorithms that support condition monitoring and operational decision-making processes. 5. Iterative Optimization is a continuous feedback process between the physical and virtual worlds,

		where the results of Digital Twin analysis improve the performance of physical assets, while field data continuously updates the digital model.
FW13		Framework consist of: 1. Physical Layer encompasses the physical building and its operational systems, such as electrical loads, distributed energy (PV and batteries), environmental quality sensors, and HIL devices for direct system monitoring and testing. 2. Software Platform serves as a data bridge between the physical system and the simulation, including MATLAB for control and simulation, middleware for IoT and model integration, a UI for configuration and visualization, and the cloud (ThingSpeak and Grafana) for storage and dashboards, with MQTT-based communication. 3. Simulation Layer is the core of the Digital Twin intelligence, utilizing two main models: EnergyPlus (ODE) for real-time simulation of energy, thermal, and air quality behavior, and Ansys Fluent (CFD) for detailed offline analysis of airflow and temperature. Simulation accuracy is enhanced through parameter calibration based on field data to align with real-world conditions.

FW14		Framework consist of: 1. Model Layer stores 3D geometry and IFC data from TLS, drones, and LiDAR with unique GUIDs for interoperability. 2. Semantic Layer converts IFC into a knowledge graph (RDF) using ifcOWL and BOT to represent spatial relationships, history, and damage, which can be accessed via SPARQL. 3. Linked Data Layer connects the model to external sources via URIs, such as cultural heritage registries and international standards, to enrich the information. 4. Monitoring/IoT Layer provides real-time data from environmental and structural sensors based on SSN/SOSA standards to form a living digital twin. 5. Interaction Layer presents information through dashboards, visualizations, VR/AR, and automated alerts to support decision-making and on-site actions.

In this study, the benchmarking process was conducted using eight criteria: digital twin, BIM/HBIM, sensor integration, data integration, Structural Health Monitoring System (SHMS), heritage buildings, real-time monitoring, and visualization. These criteria were determined based on the research objectives and the results of a literature review on digital twins, HBIM, SHMS, and heritage buildings. The selection of these criteria aims to represent the key components and characteristics required in the development of an accelerometer-based digital twin framework for monitoring the structural health of heritage buildings so that it can be used to evaluate the characteristics, strengths, and limitations of the frameworks found in the literature review.

Structural Health Monitoring System (SHMS)

Structural Health Monitoring Systems (SHMS) refer to monitoring processes conducted continuously or periodically on structures such as buildings, bridges, dams, and other infrastructure with the aim of evaluating the level of integrity and identifying potential damage or performance degradation (Xu et al., 2023). The implementation of effective structural health monitoring for cultural heritage buildings focuses on monitoring changes in modal parameters relative to baseline structural conditions because significant changes in these modal parameters indicate the need for intervention. This is because each cultural heritage structure possesses different material characteristics, inherent defects, and structural responses, meaning that modal parameters considered "safe" cannot be standardized (Rossi & Bournas, 2023). There are various types of SHMS sensors used to monitor the structural condition of a building, one of the most commonly used being accelerometer sensors. These sensors capture the dynamic response of structures to various environmental loads, particularly earthquakes. In practice, accelerometers work by detecting changes in structural acceleration and converting them into digital data for further analysis. The measurement data are then transmitted to a data acquisition system, servers, and visualization platforms through specific communication networks (Sivasuriyan et al., 2021). The monitoring system at Jakarta Cathedral uses a combination of several types of accelerometers, namely three uniaxial accelerometers, three biaxial accelerometers, and two data loggers (located in the attic and on the ground floor), each equipped with one internal triaxial accelerometer. An Ethernet switch located on the second floor functions to connect both data loggers to the network for data transfer and time synchronization. The junction box (SEN-JB-GMB) functions as a connection box between the sensor cables (AC-42H and AC-41H) and the data logger (GMSplus).

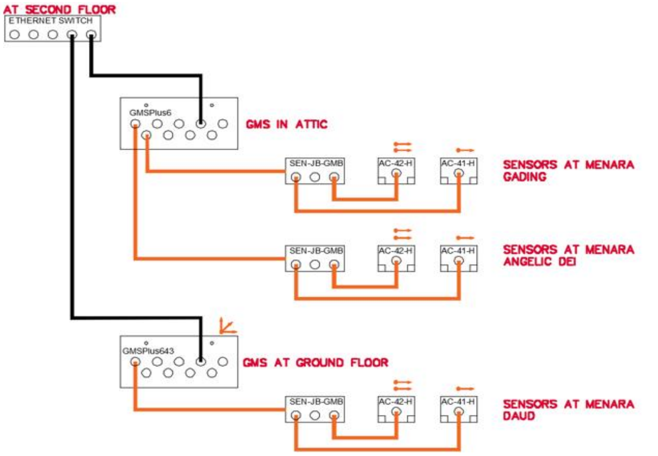


Figure 1. Schematic Diagram of an Accelerometer

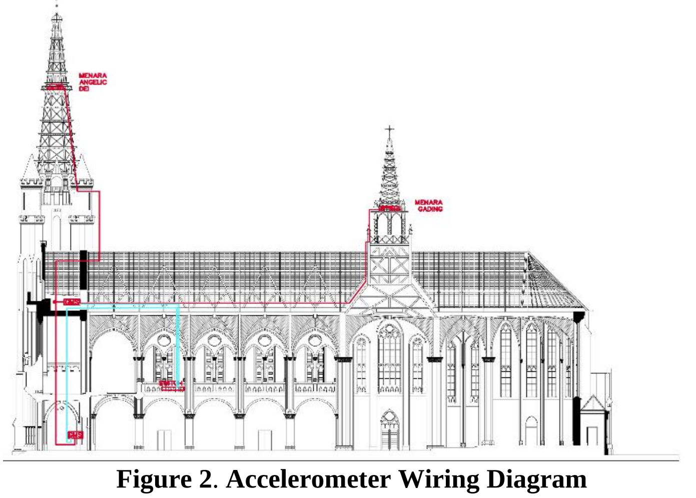


Figure 2. Accelerometer Wiring Diagram

Heritage Building Information Modeling (HBIM)

HBIM can be defined as an extension of BIM applied to built cultural heritage assets while maintaining consistency with its concepts and methodologies. HBIM is understood as an interdisciplinary approach to support the sustainable management of heritage buildings (Castellano-Román & Pinto-Puerto, 2019). Its primary objective is to integrate all information related to cultural heritage assets into a single unified digital model that can be accessed and utilized by various stakeholders. In general, the HBIM approach is similar to conventional BIM and includes several major stages (Suprobo & Jatmiko, 2025) as part of its process, namely:

1. Data Collection

   The most commonly used methods for collecting geometric data are photogrammetry and Terrestrial Laser Scanning (TLS). Typically, TLS is used to capture data from ground surfaces, while Unmanned Aerial Vehicles (UAVs) or drones equipped with photogrammetric equipment are used to access unsafe structures or hard-to-reach areas (Lovell et al., 2023).

2. Filtering
   The collected data, particularly point clouds, are processed through alignment, cleaning, and filtering stages to facilitate management. In addition, a process is conducted to build a knowledge base from semantic data, which can then be integrated into three-dimensional models through Industry Foundation Classes (IFC) or directly into BIM platforms.
3. Model Development
   This stage begins with the integration of point cloud and semantic data into a BIM platform. Modeling is performed manually or semi-automatically through point cloud segmentation and delimitation based on historical patterns and principles to identify objects. Subsequently, objects are modeled parametrically using available BIM libraries or externally developed components.

In HBIM modeling, the Level of Detail (LOD) is an important aspect that determines the level of complexity and depth of information contained in the digital model (Brumana et al., 2022).

1. LOD 100 (Concept Design)
   The initial conceptual stage in which the BIM model represents only the general form of the building. The information modeled consists of basic parameters such as area, volume, location, and building orientation without specific element details.
2. LOD 200 (General Modeling with Schematic Design)
   The general modeling stage in which building elements begin to be modeled with dimensions, shapes, and locations that approximate actual conditions. The information at this stage remains estimative and is used for schematic design development and initial interdisciplinary coordination.
3. LOD 300 (Accurate Modeling & Detailed Design)
   The detailed modeling stage in which building elements are modeled accurately according to their actual dimensions, shapes, locations, and orientations. At this stage, the model can be used for construction drawings, technical coordination, and construction analysis.
4. LOD 350 (Greater Detail & Construction Documentation)
   The construction detail development stage in which the relationships and interfaces among building elements are modeled more clearly. This stage supports construction coordination and minimizes potential conflicts among building systems in the field.
5. LOD 400 (Fabrication & Assembly)
   The fabrication modeling stage in which building elements are modeled in detail to the manufacturing and assembly level. The model at this stage can be used for production, prefabrication, and construction assembly processes.
6. LOD 500 (As-Built Models)
   The final stage in which the model represents the actual condition of the building after construction has been completed. The information contained in the model corresponds to real field conditions and can be used for operation, maintenance, monitoring, and digital twin development.

There are various conceptual frameworks for managing heritage buildings. According to (Khan et al., 2022), the conceptual framework for heritage building management consists of four main layers: information source layer, BIM modeling layer, integration layer, and application layer.

1. Information Source Layer
   This layer focuses on collecting data from various sources, including historical documents, CAD drawings, reports, photographs, and field survey results obtained through techniques such as photogrammetry or laser scanning.
2. BIM Modeling Layer
   At this layer, collected data (such as point clouds or CAD drawings) are converted into object-based parametric BIM models. Each building element is assigned a unique identification number

(ID) to facilitate classification, access, and future information updates. The model is developed using the IFC (Industry Foundation Classes) standard to ensure interoperability, enabling data sharing among stakeholders without software barriers.

3. Integration Layer
   This layer functions to consolidate all heterogeneous information into a single BIM environment. Structured information (semantic parameters) and unstructured information (external reports in PDF format linked via URLs) are integrated into model elements. This process involves collaboration among organizational owners, management teams, and BIM modeling teams.
4. Application Layer
   This final layer provides practical functions for users to manage buildings throughout their life cycle, including:
   a. 3D Digital Documentation
      Provides comprehensive visualization containing asset details, structural conditions, and material specifications.
   b. Facility Management (FM)
      Supports planned and corrective maintenance by monitoring component performance and updating their status within the BIM database.
   c. Restoration Planning
      Utilizes 4D simulation (time attributes) to visualize reconstruction or structural strengthening processes, helping estimate project costs and duration more efficiently.

In practice, data interoperability is an important factor in supporting data exchange processes among HBIM, monitoring systems, and digital twins. Effective data exchange capabilities enable building information to be utilized across various platforms without losing data relationships or meanings, thereby supporting monitoring, analysis, and heritage building management processes (Bonini et al., 2021). One of the standards commonly used to support BIM interoperability is Industry Foundation Classes (IFC). In HBIM implementation, IFC plays an important role in integrating geometric data, object parameters, building metadata, and relationships among elements within heritage buildings. The use of IFC enables HBIM models to be exchanged and utilized across various digital platforms in a more interoperable and integrated manner (Ioannides, Baker, et al., 2025; Ioannides, Issini, et al., 2025; Oostwegel et al., 2022)

Furthermore, data synchronization is an aspect related to a system's ability to update and align information across platforms periodically and continuously. This synchronization includes periodic data updates, consistency of information with actual building conditions, and latency in the data exchange process. The integration of SHMS sensor data with HBIM models enables changes in structural conditions to be visualized more dynamically, in real time, and closer to the actual condition of heritage buildings (Becker et al., 2025).

In addition to data exchange, HBIM and digital twin implementation also require semantic information and semantic interoperability. Semantic information relates to the ability of a model to represent the meaning, characteristics, and relationships among building elements in a structured and informative manner. Meanwhile, semantic interoperability refers to the ability of systems not only to exchange data but also to understand and interpret the meaning of exchanged information so that the data can be used consistently across various digital platforms (Argasiński & Tomczak, 2025)

Data security is an aspect related to access protection and data management within HBIM and digital twin systems. This aspect is important because digital twin implementation involves continuous data exchange and storage of monitoring information, requiring appropriate access management and data protection mechanisms to maintain the integrity, confidentiality, and sustainability of digital systems (Brumana et al., 2022).

Cost Component

Socio-Technical System (STS) theory views a system not merely as a collection of technical devices but as an entity consisting of complex interactions among humans, machines, and workplace environmental aspects (Baxter & Sommerville, 2011). The hardware component represents physical elements that interact directly with the environment. In the context of Structural Health Monitoring Systems (SHMS), this includes sensor networks installed on building structures. Meanwhile, software serves as the digital “brain” that processes data generated by hardware. This includes machine learning algorithms and digital twin simulation models (Chadha et al., 2022). Hardware and software constitute the core of the technical subsystem.

In addition, brainware represents the human and organizational elements that form the heart of the social subsystem. This component involves various stakeholders such as managers, engineers, and operators. According to (McKeen & Smith, 2010), Total Cost of Ownership (TCO) is defined as a holistic view of the costs associated with an asset (such as IT systems or infrastructure) throughout the organization over time, categorized into direct and indirect cost elements.

Direct costs are cost components that are explicit, objective, and easily identifiable because they are directly related to the acquisition and operation of the asset. In contrast, indirect costs are often hidden, more difficult to quantify, and highly subjective because they depend on user experience or operational impacts that arise.

Within TCO analysis, hardware represents initial direct costs and physical operational costs. Hardware costs constitute one of the fundamental components in the development of digital twin systems because they are directly related to the system’s capability to capture and represent the physical condition of an object in a realistic manner.

Table 3. Hardware Components

No.	Hardware Component	Function	Reference
1	Structural Health Monitoring System sensors (e.g., accelerometers, tilt meters, strain gauges)	Monitor structural response and structural health of buildings	(Pallarés et al., 2021)
2	Heritage building geometry acquisition equipment (e.g., LiDAR, laser scanners)	Document and develop digital models of heritage buildings	(Su et al., 2025)
3	Data acquisition and communication devices (e.g., data loggers, Ethernet switches)	Collect, temporarily store, and transmit monitoring data to servers/cloud platforms	(Muttillo et al., 2020)
4	Sensor and network installation components (e.g., sensor cables, equipment racks)	Support the installation and connectivity of SHMS within heritage buildings	(Pallarés et al., 2021)
5	Server and network infrastructure (e.g., local/cloud servers)	Provide storage infrastructure and connectivity for Digital Twin systems	(C. Wang et al., 2012)

Software costs may be classified as either direct costs or indirect costs. Software can be categorized as a direct cost when the expense can be clearly identified and directly attributed to the IT asset. Conversely, software may be categorized as an indirect cost when the associated costs are difficult to quantify.

Table 4. Software Components

No.	Software Component	Function	Reference
1	HBIM/BIM platform (e.g., Revit)	Develop digital models of cultural heritage buildings	(Lovell et al., 2023)
2	Monitoring and visualization platform (e.g., Figma)	Create dashboard layout designs and user interface/user experience (UI/UX) wireframes	(K.-J. Wang & Lee, 2024)
3	Development tools (e.g., Python)	Support Digital Twin system development and data analysis	(Albayrak, 2026)
4	Data integration and communication platform (e.g., HiveMQ)	Connect sensors, databases, and Digital Twin dashboards	(Bono et al., 2025)
5	Database and cloud platform (e.g., Amazon Web Services)	Store, manage, and process monitoring data	(Repetto, 2026)
6	AI/analytics tools (e.g., Fast Fourier Transform, Isolation Forest)	Predict structural damage and analyze structural conditions	(Kustiana et al., 2024)
7	Security systems (e.g., end-to-end encryption)	Ensure data and system security	(Repetto, 2026)

Brainware is part of the social subsystem, involving various stakeholders. Brainware encompasses a range of stakeholders who interpret sensor data and make appropriate maintenance decisions for buildings. Examples include project managers, system engineers, hardware/software engineers, and installation technicians.

Table 5. Brainware Components

No.	Brainware Component	Function	Reference
1	HBIM Modeler	Develop HBIM models of buildings	(Lovell et al., 2023)
2	Structural Engineer	Analyze structural health and structural performance	(Li et al., 2024)
3	IoT Engineer	Integrate sensors and monitoring systems	(Bhatta & Dang, 2024)
4	Digital Twin System Developer	Develop Digital Twin platforms and workflows	(Talasila et al., 2026)
5	Data and AI Specialist	Manage data analysis and structural condition prediction	(Bagerzadeh Karimi, 2026)
6	Field Technician	Perform maintenance, calibration, and troubleshooting of equipment	(Pallarés et al., 2021)
7	Trainer/Training Personnel	Enhance user competency in operating the system	(Shojaei et al., 2023)

RESEARCH METHODS

This study uses Jakarta Cathedral as a case study. Jakarta Cathedral is a cultural heritage site designated by the government since 1993 and is located at Jalan Katedral No. 7B, Pasar Baru, Central Jakarta. As one of the historic religious buildings still in active use, this church was selected as the subject of this study because it holds significant historical value and requires ongoing monitoring of its structural condition. The building's structure features three main towers that are the focus of monitoring: Ivory Tower and Turris Davidica Tower, each approximately 60 meters tall and Angelus Dei Tower, approximately 45 meters tall.

Data collection was conducted through a benchmarking approach against previous studies discussing digital twins, BIM/HBIM, the Internet of Things (IoT), and Structural Health Monitoring Systems (SHM), as well as through a literature review to identify relevant variables, sub-variables, and indicators. The results of the benchmarking and literature review were used as the basis for developing an accelerometer-based digital twin framework that integrates sensors, HBIM models, data communication systems, databases, and digital twin visualization platforms. The framework was then organized into four main layers—the information source layer, the HBIM model layer, the integration layer, and the application layer—to illustrate data flow and interconnectivity among system components.

The framework that was developed was then validated using a questionnaire distributed to experts. The selected experts had at least five years of professional experience in the field of modeling and held at least a bachelor's degree. The results of the expert validation were analyzed using a qualitative descriptive approach to evaluate the suitability of the variables, subvariables, indicators, and the design of the developed framework. Input and recommendations from the experts were used to refine the framework so that it could support the digital and real-time monitoring of the structural health of Jakarta Cathedral.

RESULTS AND DISCUSSION

Data Processing and Analysis

Data processing and analysis were conducted in two stages. In the first stage, data collection was carried out using a benchmarking framework, wherein the reference frameworks were analyzed and utilized to develop the research framework. In the second stage, data collection was conducted through expert validation using a questionnaire survey. The questionnaire results were then analyzed to support the refinement and improvement of the developed framework. The initial stage of analysis was conducted by benchmarking the 14 reference frameworks previously compiled in Table 1. Subsequently, the fourteen frameworks were compared using a benchmarking table based on a set of predetermined criteria. The benchmarking criteria were formulated based on the requirements of the system to be developed in this study, ensuring that each criterion represents the components, functions, or capabilities necessary for building an SHMS-based digital twin framework for cultural heritage buildings.

Table 6. Benchmark framework table with research criteria

No	Kode framework	Digital Twin	BIM/HBIM	SHMS	Heritage building	Sensor integration	Data integration	Real time monitoring	Visualization
1	FW1	ü	ü	ü	ü	-	ü	-	ü
2	FW2	ü	ü	ü	-	ü	ü	ü	ü
3	FW3	ü	ü	-	-	ü	ü	ü	ü
4	FW4	ü	ü	ü	-	ü	ü	ü	ü
5	FW5	ü	-	-	-	ü	ü	ü	ü
6	FW6	ü	ü	ü	-	ü	ü	ü	ü
7	FW7	ü	ü	ü	ü	ü	ü	ü	ü
8	FW8	ü	ü	ü	-	ü	ü	ü	ü
9	FW9	ü	ü	ü	-	ü	ü	ü	ü
10	FW10	-	ü	ü	ü	-	ü	-	ü
11	FW11	ü	ü	ü	-	ü	ü	ü	ü
12	FW12	ü	ü	ü	-	ü	ü	ü	ü
13	FW13	ü	ü	-	-	ü	ü	ü	ü
14	FW14	ü	ü	ü	ü	ü	ü	ü	ü

The results of the benchmarking of 14 frameworks indicate that several frameworks are relevant to the research context, particularly regarding cultural heritage buildings, HBIM, and Structural Health Monitoring Systems (SHMS). The framework developed by Khan et al., (2022) with the code FW 10 was selected as the basis for developing this research framework because it provides a practical, systematic, and context-appropriate HBIM-based cultural heritage building information management structure. However, this framework does not yet accommodate the integration of accelerometer sensors, IoT communication, and real-time structural condition monitoring. This study adds sensor integration components to support the implementation of an SHMS-based digital twin for cultural heritage buildings. The research framework is then structured using an input–process–output approach to clarify the data flow, starting from building information and sensor data (input), through data integration and processing within the HBIM and digital twin environments (process), to visualization, structural health monitoring, and decision-making support (output).

The developed framework consists of four primary layers: Information Source Layer, BIM Model Layer, Integration Layer, and Application Layer. In First layer: Information Source Layer, the process serves as the primary data source for HBIM development. At the input stage, various types of information are collected, including 3D scanning data, SHMS sensor data such as accelerometers, OIR and AIR documents, and supporting information such as material specifications, maintenance histories, and building inspection reports. During the processing stage, data acquisition is conducted using technologies such as LiDAR, followed by data cleaning, validation against OIR and AIR requirements, building element classification, and the addition of non-geometric information to model objects. This stage aims to transform raw data into structured information ready for modeling. The outputs include point clouds as the basis for 3D modeling, a semantic database integrating geometric and non-geometric data, validated documentation in the form of verified technical documents, and an asset inventory equipped with unique identifiers (GUIDs) to support future building lifecycle management.

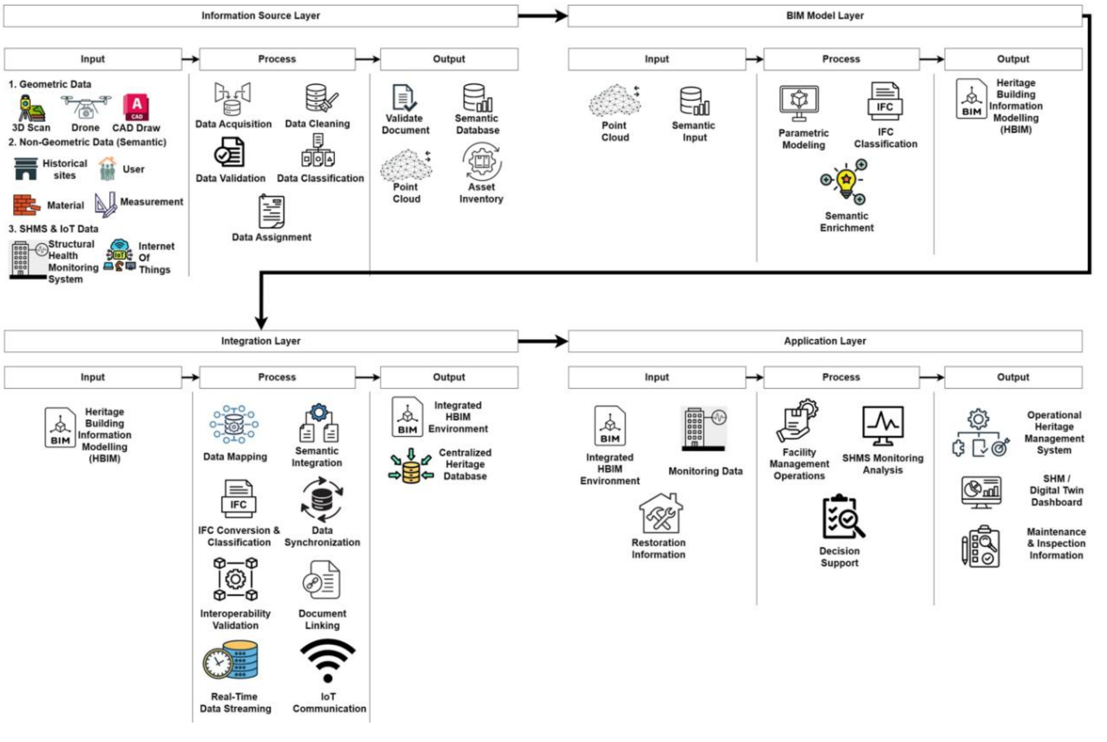


Figure 3. Research Framework

In Second layer: BIM Model Layer, the objective is to develop a digital representation of the building based on the point cloud and semantic data generated in the previous phase. These data serve as the foundation for ensuring that the model accurately represents the building's physical and historical conditions. During processing, parametric modeling is performed by converting point clouds into BIM objects such as walls, columns, and other building elements with defined dimensions and technical attributes. Subsequently, semantic enrichment is conducted by adding non-geometric information, such as material characteristics and damage conditions. The resulting objects are then classified using IFC standards (e.g., IfcWall and IfcColumn) to maintain interoperability and ensure compatibility with various BIM software platforms. The output of this phase is an integrated HBIM model ready to support the management, conservation, and operation of heritage buildings.

Third layer: Integration Layer functions to integrate the HBIM model with semantic information, supporting documents, and sensor data, thereby creating a connected digital environment. The primary inputs at this stage include the HBIM model, semantic information, and external documents such as archival photographs, historical reports, and technical documentation. During processing, data mapping and conversion into IFC format are performed to ensure interoperability among software platforms. Semantic integration is then carried out by adding metadata and linking supporting documents to model elements, enabling information to be accessed directly through 3D objects. The model subsequently undergoes interoperability validation to ensure compliance with standards and AIR requirements. Data synchronization is then implemented to maintain data consistency automatically, and SHMS sensor data are integrated through IoT technologies such as MQTT and HiveMQ to enable real-time building condition monitoring. The outputs of this phase are an Integrated HBIM Environment, which provides an integrated platform for visualization, access, and management of building information throughout its lifecycle, and a Centralized Heritage Database/Asset Information Model (AIM), which functions as a centralized repository for geometric, semantic, documentation, and monitoring data within a standardized system.

In Fourth layer: Application Layer, the data are utilized to support operational activities and decision-making processes. Inputs include the Integrated HBIM Model containing geometric and semantic building information, real-time IoT monitoring data obtained from sensors, and restoration-related information such as historical documents, maintenance reports, and material specifications. During processing, SHMS and monitoring analysis are conducted to monitor structural conditions and detect anomalies at an early stage based on sensor data. Furthermore, facility management operations are employed to manage both preventive and corrective maintenance activities. In addition, decision support utilizes available data to provide recommendations for conservation actions and more effective asset management. The outputs include a Digital Twin Dashboard for real-time visualization of building conditions, an Operational Heritage Management System as a central information and documentation platform for heritage assets, and Maintenance and Inspection Information, which provides maintenance records, inspection reports, cost information, and intervention histories throughout the building lifecycle.

After the framework had been developed, the next stage involved conducting a validity analysis. The validation process engaged experts as evaluators to ensure that the developed framework was appropriate and relevant to the research objectives. Data obtained from the validation process included assessments of framework suitability, recommendations for improvement, and comments regarding the research outcomes. Through this approach, the framework could be evaluated objectively by individuals possessing expertise in the relevant field, thereby enhancing its completeness, interconnectedness, and complexity.

Table 7. Expert Validation Results

No	Statement	Evaluation		
		Expert 1	Expert 2	Expert 3
1	The framework systematically represents the stages of Digital Twin development.	Very appropriate	Very appropriate	Less appropriate
2	The integration of geometric, semantic, SHMS, and IoT data within the framework is appropriate for structural monitoring.	Very appropriate	Very appropriate	Fairly appropriate
3	IoT Communication, Real-Time Data Streaming, and Data Synchronization components support the Digital Twin concept.	Very appropriate	Appropriate	Fairly appropriate
4	The structure and workflow of the framework are clear and easy to understand.	Very appropriate	Very appropriate	Less appropriate

Based on the expert validation results, several recommendations were proposed to refine the framework. The first expert suggested the addition of sensor data validation mechanisms, threshold warning values, and follow-up procedures when structural anomalies are detected. The objective is to ensure that the Digital Twin functions not only as a visualization tool but also as a platform supporting early detection and decision-making. Meanwhile, the third expert considered the framework sufficiently comprehensive but suggested that the workflow and integration among components should be clarified further. Therefore, recommendations included improving relationships among phases and data flows, as well as utilizing BPMN (Business Process Model and Notation) diagrams to visualize processes in a more structured and systematic manner.

The researchers acknowledged the recommendations regarding sensor data validation, warning thresholds, and structural anomaly response workflows. These three aspects were considered important for the operational implementation of the Digital Twin–SHMS system. However, since this study focuses on the development of a conceptual framework, these features were not integrated into the main framework and were instead proposed as recommendations for future research. Similarly, the suggestion to utilize BPMN was considered but not adopted because the primary focus of this study is the development of a framework and the integration of Digital Twin–HBIM–SHMS systems rather than detailed business process modeling. The layered framework approach was deemed more appropriate for representing system architecture and data integration flows.

CONCLUSIONS

Based on the analysis and expert validation results, the accelerometer sensor-based Digital Twin framework developed in this study can serve as a foundation for the integrated development of a Structural Health Monitoring System (SHMS) for the Jakarta Cathedral. The study also highlights the importance of Organizational Information Requirements (OIR) and Asset Information Requirements (AIR) documents as references for determining the data that need to be collected and managed within an HBIM environment. These documents play a critical role in ensuring that the information gathered aligns with the needs of both the organization and building managers, thereby improving the efficiency of the development process in terms of time and cost. Considering that OIR and AIR documents are currently unavailable, it is recommended that cultural heritage building managers develop these documents as guidelines for data collection and 3D model development to support future Digital Twin implementation.

REFERENCES

Adimass, S. A., & Żak, A. (2026). Review of Digital Twin in Structural Dynamics to Improve Condition Monitoring. *Structural Control and Health Monitoring*, *2026*(1), 2777297. https://doi.org/10.1155/stc/2777297

Albayrak, A. (2026). A multi-layered digital twin framework for smart agriculture and livestock: System architecture and implementation challenges. *Information and Software Technology*, *195*, 108139. https://doi.org/10.1016/j.infsof.2026.108139

Argasiński, K., & Tomczak, A. (2025). Enhancing Semantic Interoperability of Heritage BIM-Based Asset Preservation. *Heritage*, *8*(10), 410. https://doi.org/10.3390/heritage8100410

Bagerzadeh Karimi, M. R. (2026). Real-time structural health monitoring using IoT-enabled affordable sensors and unsupervised anomaly detection. *Discover Civil Engineering*, *3*(1), 2. https://doi.org/10.1007/s44290-025-00397-4

Bartoli, G., Betti, M., Marra, A. M., & Monchetti, S. (2017). Semiempirical Formulations for Estimating the Main Frequency of Slender Masonry Towers. *Journal of Performance of Constructed Facilities*, *31*(4), 04017025. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001017

Baxter, G., & Sommerville, I. (2011). Socio-technical systems: From design methods to systems engineering. *Interacting with Computers*, *23*(1), 4–17. https://doi.org/10.1016/j.intcom.2010.07.003

Becker, S., Niño, L. V., & Rüppel, U. (2025). From HBIM to Digital Twins: An Interoperable Framework for Semantic Knowledge Integration and Dynamic Monitoring of Historic Buildings. *Digital Heritage*. https://doi.org/10.2312/DH.20253357

Beskhyroun, S., & Aghakouchaki Hosseini, S. E. (2025). *A Novel Methodology for Structural Health Monitoring of Buildings Subjected to Earthquakes*. SSRN. https://doi.org/10.2139/ssrn.5087890

Bhatta, S., & Dang, J. (2024). Use of IoT for structural health monitoring of civil engineering structures: A state-of-the-art review. *Urban Lifeline*, *2*(1), 17. https://doi.org/10.1007/s44285-024-00031-2

Bonini, J. A., Mandelli, A., De Gennaro, S. M., & Banfi, F. (2021). BIM INTEROPERABILITY: OPEN BIM-BASED WORKFLOW FOR HERITAGE BUILDING INFORMATION MODELLING (HBIM). A MULTIDISCIPLINARY APPROACH BASED ON ADVANCED 3D TOOLS AND EXCHANGE FORMATS. *Proceedings ARQUEOLÓGICA 2.0 - 9th International Congress & 3rd GEORES - GEOmatics and pREServation*, 1–11. https://doi.org/10.4995/arqueologica9.2021.12104

Bono, F. M., Polinelli, A., Radicioni, L., Benedetti, L., Castelli-Dezza, F., Cinquemani, S., & Belloli, M. (2025). Wireless Accelerometer Architecture for Bridge SHM: From Sensor Design to System Deployment. *Future Internet*, *17*(1), 29. https://doi.org/10.3390/fi17010029

Brumana, R., Stanga, C., & Banfi, F. (2022). Models and scales for quality control: Toward the definition of specifications (GOA-LOG) for the generation and re-use of HBIM object libraries in a Common Data Environment. *Applied Geomatics*, *14*(S1), 151–179. https://doi.org/10.1007/s12518-020-00351-2

Castellano-Román, M., & Pinto-Puerto, F. (2019). Dimensions and Levels of Knowledge in Heritage Building Information Modelling, HBIM: The model of the Charterhouse of Jerez (Cádiz, Spain). *Digital Applications in Archaeology and Cultural Heritage*, *14*, e00110. https://doi.org/10.1016/j.daach.2019.e00110

Chadha, M., Hu, Z., & Todd, M. D. (2022). An alternative quantification of the value of information in structural health monitoring. *Structural Health Monitoring*, *21*(1), 138–164. https://doi.org/10.1177/14759217211028439

Cheng, R., Hou, L., & Xu, S. (2023). A Review of Digital Twin Applications in Civil and Infrastructure Emergency Management. *Buildings*, *13*(5), 1143. https://doi.org/10.3390/buildings13051143

Hadjidemetriou, L., Stylianidis, N., Englezos, D., Papadopoulos, P., Eliades, D., Timotheou, S., Polycarpou, M. M., & Panayiotou, C. (2023). A digital twin architecture for real-time and offline high granularity analysis in smart buildings. *Sustainable Cities and Society*, *98*, 104795. https://doi.org/10.1016/j.scs.2023.104795

Hakimi, O., Liu, H., Abudayyeh, O., Houshyar, A., Almatared, M., & Alhawiti, A. (2023). Data Fusion for Smart Civil Infrastructure Management: A Conceptual Digital Twin Framework. *Buildings*, *13*(11), 2725. https://doi.org/10.3390/buildings13112725

He, Y., Guo, J., & Zheng, X. (2018). From Surveillance to Digital Twin: Challenges and Recent Advances of Signal Processing for Industrial Internet of Things. *IEEE Signal Processing Magazine*, *35*(5), 120–129. https://doi.org/10.1109/MSP.2018.2842228

Hosamo, H., & Mazzetto, S. (2024). Integrating Knowledge Graphs and Digital Twins for Heritage Building Conservation. *Buildings*, *15*(1), 16. https://doi.org/10.3390/buildings15010016

Ioannides, M., Baker, D., Agapiou, A., & Siegkas, P. (Eds.). (2025). *3D Research Challenges in Cultural Heritage V: Paradata, Metadata and Data in Digitisation* (Vol. 15190). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-78590-0

Ioannides, M., Issini, G., & Oliveira, D. (Eds.). (2025). *3D Research Challenges in Cultural Heritage IV: Risk Prevention and Monitoring Methods* (Vol. 13577). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-93753-8

Johnson, R. E. (1997). Frameworks = (components + patterns). *Communications of the ACM*, *40*(10), 39–42. https://doi.org/10.1145/262793.262799

Kang, T. W., & Mo, Y. (2024). A comprehensive digital twin framework for building environment monitoring with emphasis on real-time data connectivity and predictability. *Developments in the Built Environment*, *17*, 100309. https://doi.org/10.1016/j.dibe.2023.100309

Khan, M., Khan, M., Bughio, M., Talpur, B., Kim, I., & Seo, J. (2022). An Integrated HBIM Framework for the Management of Heritage Buildings. *Buildings*, *12*(7), 964. https://doi.org/10.3390/buildings12070964

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

Kustiana, W. A. A., Trilaksono, B. R., Riyansyah, M., Putra, S. A., Caesarendra, W., Królczyk, G., & Sulowicz, M. (2024). Bridge Damage Detection with Support Vector Machine in Accelerometer-Based Wireless Sensor Network. *Journal of Vibration Engineering & Technologies*, *12*(S1), 21–40. https://doi.org/10.1007/s42417-024-01400-5

Li, X., Zhang, F.-L., Xiang, W., Liu, W.-X., & Fu, S.-J. (2024). Structural health monitoring system based on digital twins and real-time data-driven methods. *Structures*, *70*, 107739. https://doi.org/10.1016/j.istruc.2024.107739

Liu, D., Liang, H., Zeng, X., Zhang, Q., Zhang, Z., & Li, M. (2022). Edge Computing Application, Architecture, and Challenges in Ubiquitous Power Internet of Things. *Frontiers in Energy Research*, *10*, 850252. https://doi.org/10.3389/fenrg.2022.850252

Lovell, L. J., Davies, R. J., & Hunt, D. V. L. (2023). The Application of Historic Building Information Modelling (HBIM) to Cultural Heritage: A Review. *Heritage*, *6*(10), 6691–6717. https://doi.org/10.3390/heritage6100350

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

McKeen, J. D., & Smith, H. A. (2010). Developments in Practice XXXVII: Total Cost of Ownership. *Communications of the Association for Information Systems*, *27*. https://doi.org/10.17705/1CAIS.02732

Muttillo, M., Stornelli, V., Alaggio, R., Paolucci, R., Di Battista, L., De Rubeis, T., & Ferri, G. (2020). Structural Health Monitoring: An IoT Sensor System for Structural Damage Indicator Evaluation. *Sensors*, *20*(17), 4908. https://doi.org/10.3390/s20174908

Oostwegel, L. J. N., Jaud, Š., Muhič, S., & Malovrh Rebec, K. (2022). Digitalization of culturally significant buildings: Ensuring high-quality data exchanges in the heritage domain using OpenBIM. *Heritage Science*, *10*(1), 10. https://doi.org/10.1186/s40494-021-00640-y

Pallarés, F. J., Betti, M., Bartoli, G., & Pallarés, L. (2021). Structural health monitoring (SHM) and Nondestructive testing (NDT) of slender masonry structures: A practical review. *Construction and Building Materials*, *297*, 123768. https://doi.org/10.1016/j.conbuildmat.2021.123768

Penjor, T., Banihashemi, S., Hajirasouli, A., & Golzad, H. (2024). Heritage building information modeling (HBIM) for heritage conservation: Framework of challenges, gaps, and existing limitations of HBIM. *Digital Applications in Archaeology and Cultural Heritage*, *35*, e00366. https://doi.org/10.1016/j.daach.2024.e00366

Piskernik, M., Wien, T., & Nassereddine, H. (2020). *Digital Twin in Construction An Empirical Analysis.*

Repetto, M. (2026). Cybersecurity Digital Twins: Concept, blueprint, and challenges for multi-ownership digital service chains. *Journal of Information Security and Applications*, *96*, 104299. https://doi.org/10.1016/j.jisa.2025.104299

Revaldi, M. B., St. Trikariastoto, Wijaya, A., & Dewi, E. P. (2025). Penerapan Adaptive Reuse dan Infill Bangunan Untuk Konservasi Taman Kota Intan. *IKRA-ITH Teknologi Jurnal Sains dan Teknologi*, *9*(3).

Rossi, M., & Bournas, D. (2023). Structural Health Monitoring and Management of Cultural Heritage Structures: A State-of-the-Art Review. *Applied Sciences*, *13*(11), 6450. https://doi.org/10.3390/app13116450

Rubiantoro, E. A. (2018). *KAJIAN KONSERVASI BANGUNAN CAGAR BUDAYA PADA KORIDOR JL. KEPODANG KOTA SEMARANG*. *12*.

Shojaei, R. S., Oti-Sarpong, K., & Burgess, G. (2023). Leading UK Construction Companies' Strategies to Tackle BIM Training and Skills Challenges. *International Journal of Construction Education and Research*, *19*(4), 383–404. https://doi.org/10.1080/15578771.2022.2123071

Sivasuriyan, A., Vijayan, D. S., Górski, W., Wodzyński, Ł., Vaverková, M. D., & Koda, E. (2021). Practical Implementation of Structural Health Monitoring in Multi-Story Buildings. *Buildings*, *11*(6), 263. https://doi.org/10.3390/buildings11060263

Su, S., Nassehi, A., McClenaghan, A., Langridge, A., & Hicks, B. (2025). A methodology for estimating the cost of a digital twin. *Journal of Manufacturing Systems*, *80*, 841–858. https://doi.org/10.1016/j.jmsy.2025.04.004

Suprobo, F. P., & Jatmiko, A. D. (2025). *Heritage Building Information Modelling (HBIM): Kajian Studi Kasus untuk Konservasi Warisan Budaya Indonesia*. *4*.

Talasila, P., Tcherniak, D., Jensen, A. M. D., Mahato, S., Medom, J. V., Ulriksen, M. D., Abbiati, G., Schörghofer-Queiroz, A., Larsen, P. G., & Damkilde, L. (2026). A digital twin platform for structural health monitoring. *Computer-Aided Civil and Infrastructure Engineering*, 100086. https://doi.org/10.1016/j.cacaie.2026.100086

Trisno, R., Lianto, F., Liauw, F., Tangyong, D., Gelgel, I. M. W., & Hata, Y. (2022). Sacred Indicators of the Jakarta Cathedral Church, Indonesia, before the Second Vatican Council. *Journal of Hunan University Natural Sciences*, *49*(2), 23–33. https://doi.org/10.55463/issn.1674-2974.49.2.2

Wang, C., Wang, Q., Ren, K., Cao, N., & Lou, W. (2012). Toward Secure and Dependable Storage Services in Cloud Computing. *IEEE Transactions on Services Computing*, *5*(2), 220–232. https://doi.org/10.1109/TSC.2011.24

Wang, J., Ye, L., Gao, R. X., Li, C., & Zhang, L. (2019). Digital Twin for rotating machinery fault diagnosis in smart manufacturing. *International Journal of Production Research*, *57*(12), 3920–3934. https://doi.org/10.1080/00207543.2018.1552032

Wang, K.-J., & Lee, T.-L. (2024). Designing a digital-twin based dashboard system for a flexible assembly line. *Computers & Industrial Engineering*, *196*, 110491. https://doi.org/10.1016/j.cie.2024.110491

Xu, J., Shu, X., Qiao, P., Li, S., & Xu, J. (2023). Developing a digital twin model for monitoring building structural health by combining a building information model and a real-scene 3D model. *Measurement*, *217*, 112955. https://doi.org/10.1016/j.measurement.2023.112955

Yang, Z., Tang, C., Zhang, T., Zhang, Z., & Doan, D. T. (2024). Digital Twins in Construction: Architecture, Applications, Trends and Challenges. *Buildings*, *14*(9), 2616. https://doi.org/10.3390/buildings14092616

Zhang, Z., Wei, Z., Court, S., Yang, L., Wang, S., Thirunavukarasu, A., & Zhao, Y. (2024). A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry. *Buildings*, *14*(4), 1113. https://doi.org/10.3390/buildings14041113