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Research on Value-Chain-Driven Multi-Level Digital Twin Models for Architectural Heritage

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Abstract

As a national treasure, architectural heritage carries multiple value dimensions such as history, technology, art, and culture. With the increasing demand for architectural heritage protection and utilization, the traditional static digital model of architectural heritage based on geometric expression can no longer meet the practical application of multi-stage and multi-level scenarios. To this end, this paper proposes a value-chain-driven multi-level digital twin model of architectural heritage. Based on the three-stage logic of protection, management, and dissemination of value-chain classification, it integrates four types of models: geometry, physics, rules, and behavior. Combined with different hierarchical application levels, the digital model of architectural heritage is refined into a VCLOD (Value-Chain-Driven Level of Detail) detail hierarchy system to achieve a unified expression from spatial form restoration to intelligent response. Through the empirical application of three typical scenarios: the full-area guided tour of the Forbidden City, the exhibition curation of the central axis and the preventive protection of the Meridian Gate, the model shows the following specific results: (1) the efficiency of tourist guidance is improved through real-time personalized path planning; (2) the exhibition planning and visitor experience are improved through dynamic monitoring and interactive management of the exhibition environment; (3) the predictive analysis and preventive protection measures of structural safety are realized, effectively ensuring the structural safety of the Meridian Gate. The research results provide a theoretical basis and practical support for the systematic expression and intelligent evolution of digital twins of architectural heritage.

Keywords: architectural heritage; digital twin model; digital twin system; value-chain theory; level of detail

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1. Introduction

Architectural heritage, as a tangible carrier of the evolution of human civilization, embodies historical memory, artisanal wisdom, and regional culture, possessing irreplaceable historical, artistic, and scientific value [1,2]. In contemporary society, it not only fulfills multiple functions such as cultural identity, academic research, and public education but

also plays a significant role in urban renewal and cultural revitalization [3–5]. However, with the diversification of social demands and increasing urban spatial pressures, architectural heritage faces multifaceted challenges in practice [6–8]. On the one hand, its limited physical capacity struggles to accommodate growing demands for exhibition, visitation, and research [9–11]; on the other hand, the complex multi-stakeholder management mechanisms result in inefficient resource integration. Additionally, there is an inherent conflict between the utilization of architectural heritage for public engagement and its long-term preservation [12,13]. While digital technologies have been widely adopted for modeling and visualization [14], the lack of unified standards in content representation, data sharing, and continuous updates hinders their deeper application and value realization in real-world operational scenarios [15].

In this context, digital twin technology offers a novel solution for the intelligent representation and systematic management of architectural heritage [16]. By constructing virtual models that correspond one-to-one with physical entities, digital twins enable real-time state mapping and data-driven dynamic interactions, demonstrating potential for multi-source data integration [17], system operation simulation, and user behavior feedback [18]. However, current digital models of architectural heritage generally lack unified twin-scenario support, with fragmented functionalities and disconnected information, making it difficult to establish coherent operational workflows [19]. Furthermore, inadequate interactive linkages and real-time feedback mechanisms hinder the models' ability to adapt to evolving usage demands in practical applications, ultimately limiting their capacity to support collaborative operations and intelligent services within existing operational frameworks. Therefore, there is an urgent need to re-examine the representational methods of digital twin models from a holistic architectural perspective, promoting their evolution toward systematic, hierarchical, and semantically enriched frameworks to enhance their comprehensive adaptability in complex heritage scenarios.

To address the above issues, this paper divides the value realization process of architectural heritage into three core stages—protection, management, and dissemination—based on the value-chain theory. Focusing on the functional requirements and business scenarios of each stage, a value-chain-driven digital twin model hierarchy for architectural heritage is constructed. This system, built upon the concept of LOD (Level of Detail) layering, incorporates physical attribute data, parameter specifications, and behavior feedback mechanisms, overcoming the traditional modeling logic primarily focused on geometric complexity. It places greater emphasis on the functional value and semantic adaptability that the model carries throughout the lifecycle of architectural heritage. By constructing a multi-level model structure from low-dimensional overview to high-precision components, the value-chain-driven digital twin model hierarchy for architectural heritage not only supports the expression needs from static display to dynamic perception but also helps to bridge the model calls and semantic interlinkages across different business segments. This enables a transformation from a "geometry-driven" to a "value-driven" modeling paradigm, further enhancing the adaptability, scalability, and decision-support capabilities of digital twins in architectural heritage scenarios.

2. Design of the Value-Chain-Driven Digital Twin Framework for Architectural Heritage

2.1. Value-Chain Analysis of Architectural Heritage

Value refers to the positive significance and usefulness that an object demonstrates to a subject. Architectural heritage itself carries multiple values, such as artistic value, which reflects the building's design, decorative techniques, and aesthetic styles [20]; scientific value, which embodies the structural system, construction techniques, and restoration

studies; historical value, which reflects the cultural characteristics and evolutionary traces of a specific era [21]; educational value, which serves knowledge dissemination and public awareness [22]; and social value, which supports cultural identity, community involvement, and cultural tourism. The digital model of architectural heritage effectively supports the preservation, protection, display, and dissemination of these values. However, during the transformation of architectural heritage into digital twins, a single static model is no longer sufficient to meet the demands for multidimensional expression and dynamic response in complex business scenarios.

To enhance the model's support for real business processes and its ability to reflect the value of architectural heritage, we divide the value realization process of architectural heritage into three continuous and mutually supportive core stages: protection, management, and dissemination [23]. The value-chain theory was initially designed to analyze how various business activities within an enterprise work together to create value [24]. In the context of architectural heritage, value-chain theory helps us understand how the value of architectural heritage is continuously realized through the interaction and coordination of different stages. The protection stage focuses on the perception, analysis, and preservation of heritage status. It constructs a digital twin system for architectural heritage health monitoring through methods like health detection of the heritage body and its surrounding environment [25] and dynamic monitoring, providing decision support for architectural heritage protection and management. The management stage optimizes resource allocation and operational strategies, integrating digital archives of architectural heritage [26], health monitoring management, and daily display maintenance data to build a digital twin system for architectural heritage management at different levels, such as exhibition curation and heritage health maintenance. The dissemination stage aims to enhance the social value and public engagement of architectural heritage by integrating visitor tourism information, transportation routes, data on ancient buildings and cultural relics, meteorological data, and sensor data. This stage builds a digital twin system for public service, optimizing public tourism services, improving online and offline experiences, and promoting cultural dissemination.

Figure 1 illustrates the interdependent relationships among the three functional modules—protection, management, and dissemination—of architectural heritage throughout its lifecycle from the value-chain perspective. It also emphasizes that in the design of the digital twin framework for architectural heritage, the model must not only meet the requirements for static display but also possess the ability for cross-stage data flow and business interaction.

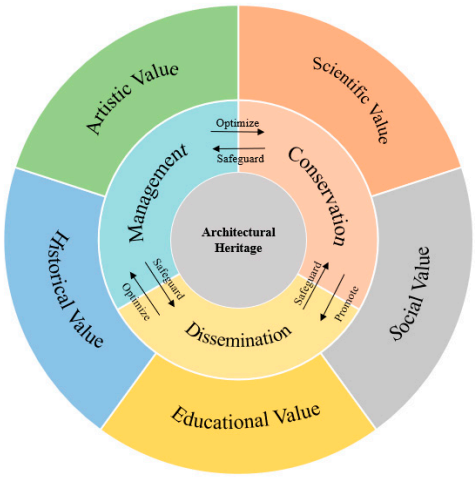


Figure 1. Value-Chain Analysis of Architectural Heritage.

2.2. Five-Dimensional Digital Twin Model for Architectural Heritage

To comprehensively support the multi-stage business needs of architectural heritage from monitoring and protection to operational management and public dissemination from the value-chain perspective [27–29], this paper proposes a Five-Dimensional Digital Twin Model Framework for Architectural Heritage (see Figure 2). Based on the traditional concept of digital twins, this model integrates the diverse characteristics of architectural heritage scenarios and constructs a structural system composed of five core dimensions: Physical Entity (HBPE), Digital Twin Model (HBDT), Physical–Digital Connection (HBCN), Twin Data (HBDD), and Application Services (HBSS). This model not only clarifies the information mapping relationship between the physical and digital entities but also lays the foundation for dynamic perception and intelligent interaction in the system.

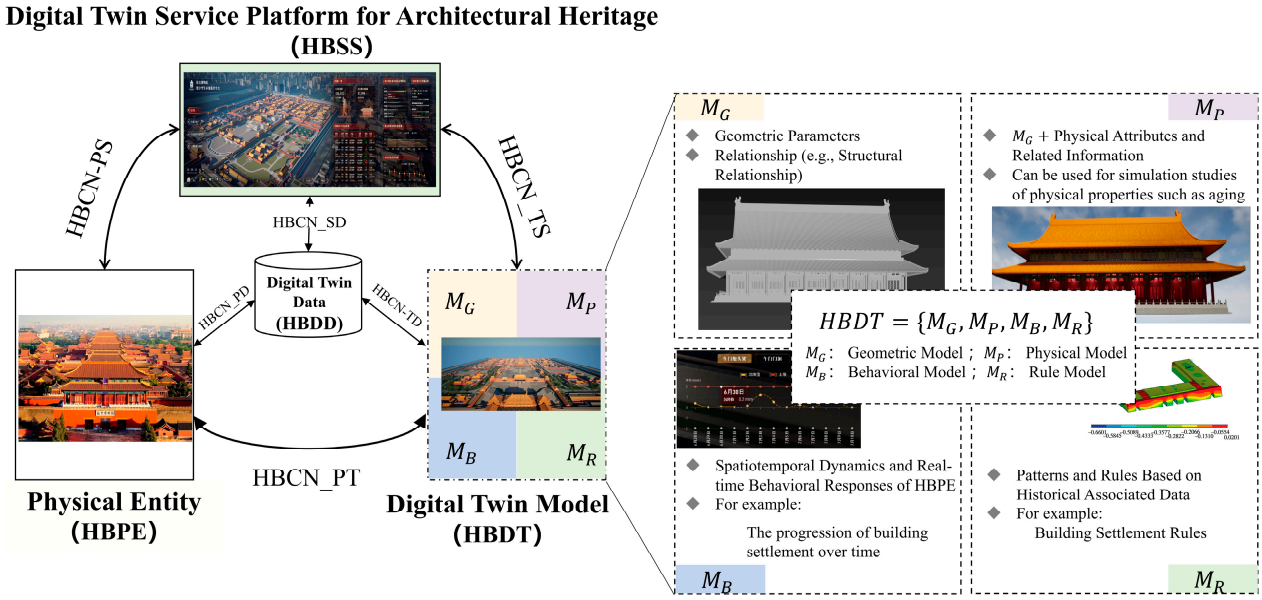


Figure 2. Design Diagram of the Five-Dimensional Digital Twin Model Framework for Architectural Heritage.

In this framework, the Physical Entity (HBPE) represents the real existence of architectural heritage in physical space, serving as the starting point and foundation of the entire digital twin system. Its structure, scale, material, and environmental conditions determine the original basis for subsequent model expressions. Correspondingly, the Digital Twin Model (HBDT) in the virtual space carries the full-dimensional mapping of the physical entity, including geometric shape, attribute information, state responses, and evolution mechanisms. It serves as the core carrier for realizing intelligent expression and behavior simulation. To ensure the data pathway between the physical and digital entities, the Physical–Digital Connection (HBCN) component, based on sensing devices, edge computing, and communication networks, achieves real-time synchronization between physical states and the digital model. Twin Data (HBDD) aggregates multi-source heterogeneous information resources, such as structural monitoring [30], environmental sensing, management behaviors [31], and public feedback, which serve as the supporting foundation for system operation analysis and service inference. Finally, the Application Services (HBSS) are tailored to specific application scenarios, providing functionalities such as deformation analysis [32], operational decision-making, and cultural dissemination. This reflects the business implementation capability of the digital twin model and represents the ultimate point of convergence for the twin system in the business domain.

2.3. Digital Twin Model

In this five-dimensional model system, the Digital Twin Model (HBDT), as the core expression entity in virtual space, is no longer limited to static display [33]. It not only carries the geometric restoration and attribute mapping of the physical entity but also takes on the task of modeling the complex behaviors, physical mechanisms, and rule-based logic of architectural heritage. To achieve multidimensional expression and business interaction of architectural heritage across different value stages, this paper divides the digital twin model into four components: geometric model, physical model, rule-based model, and behavioral model.

Figure 3 illustrates the relationships between the four models. The geometric model, as the foundational layer of the digital twin model, is responsible for describing the spatial form and component structure of the heritage, providing the geometric support for other sub-models to attach data and conduct semantic analysis. The physical model focuses on the expression of the physical properties of component materials, structural performance, and environmental responses, serving as the key foundation for structural analysis and operational monitoring. The rule-based model defines the institutional logic and operational standards for various management and protection behaviors, acting as the core logical layer that supports automated decision-making and process-driven workflows. Meanwhile, the behavioral model simulates the interactive behaviors and dynamic evolution of the heritage system across multiple roles and scenarios, serving as an essential engine for proactive response and intelligent scheduling.

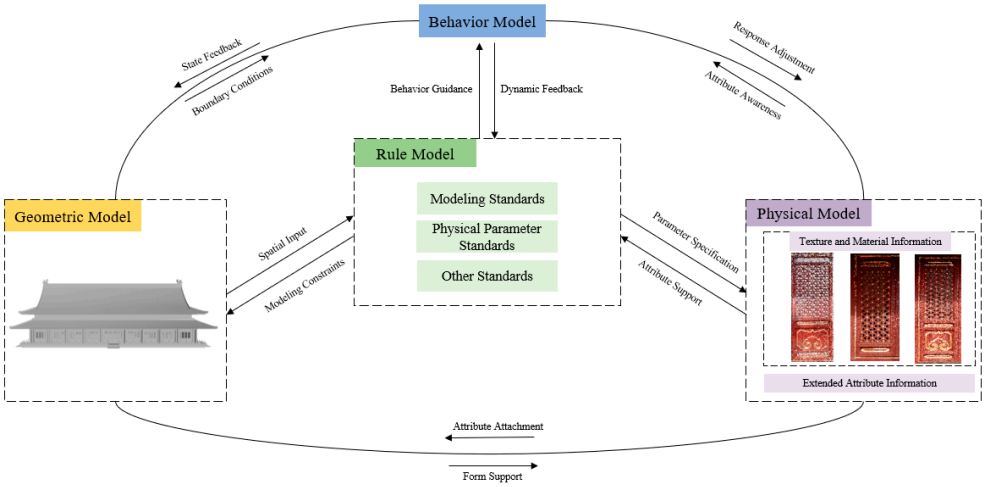


Figure 3. The Interactions Between the Geometric, Physical, Rule-Based, and Behavioral Models.

2.3.1. Geometric Model

In the value-chain-driven digital twin framework for architectural heritage, the geometric model serves as the foundational layer, carrying the expression of the building's spatial form, component structure, and their interrelationships. The construction of the geometric model is one of the key steps in the digital twin system, aimed at accurately transforming the physical form of architectural heritage into a virtual model through digital means [34]. This process not only needs to efficiently represent the external form of the building but also requires flexibility to accommodate the varying demands for model accuracy and detail at different application stages.

The core of geometric modeling lies in obtaining accurate three-dimensional spatial data from the real world. Common data collection methods include LiDAR scanning [35], photogrammetry [36], and UAV data acquisition. These technologies provide the foundational data for the model, enabling the digital representation of the building's spatial

form, component distribution, and relative positional relationships. During the geometric modeling process, methods such as Irregular Triangle Networks (TIN), polygonal meshes, or raster-based modeling are often used [37]. The most appropriate method is selected based on the data complexity and application scenario to restore the building's three-dimensional structure.

Level of Detail (LOD) is an important concept in geometric modeling, used to describe the performance of a model under different precision requirements [38]. The LOD levels range from LOD0 to LOD4, corresponding to geometric representations from low to high precision, as shown in Table 1. In different value-chain stages of architectural heritage, the LOD levels of the geometric model vary. LOD0 typically represents the most simplified 2D representation, used to express the spatial position and outline of buildings or heritage areas. This level is suitable for large-scale heritage area planning, positioning, and navigation systems, especially in the dissemination stage, where it provides basic spatial structure and path guidance. LOD1 introduces the basic volume of buildings, using uniform-height block models to represent the macro spatial structure of the building. In the management stage, LOD1 models can be used for spatial management of heritage areas [39], volume control, and formulation of skyline protection lines. However, due to the lack of detail, it cannot be used for more precise restoration or damage monitoring. LOD2, based on LOD1, adds structural features like the roof, enhancing the authenticity of the building's appearance. This level can be used for facade management and historical heritage evaluation [40]. In the dissemination stage, LOD2 models provide the public with a more realistic representation of the building's external form, suitable for digital tours, online displays, and other applications. LOD3 is a detailed building model that includes external details such as doors, windows, and other key components. It is the most commonly used level for building quality monitoring, deformation analysis [41], damage monitoring, and restoration design. In the protection stage, LOD3 provides the necessary geometric detail support for structural analysis, damage detection, and restoration design. It also helps with fine monitoring and asset management during the management stage. LOD4, the highest precision level, fully represents the internal structure and components of the building. It is suitable for virtual restoration [42], detailed preservation, and spatial analysis tasks. In the protection stage, LOD4 supports comprehensive digital restoration and structural safety assessment, and provides an immersive experience for the public. Particularly in the dissemination stage, it enables realistic virtual exhibitions and interactive displays.

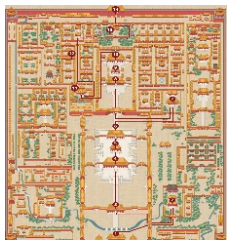
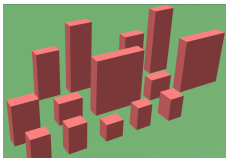
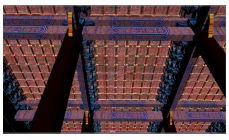
2.3.2. Physical Model

In the value-chain-driven digital twin framework for architectural heritage, the physical model serves as an intermediary layer that connects geometric structure and behavioral logic. It plays a core role in simulating the material properties of the architectural entity and its environmental response characteristics. The physical model not only injects real-world material properties, structural performance, and environmental impact parameters into the digital heritage model but also provides real, dynamic data support for the subsequent behavior simulations and management responses. The construction of the physical model relies not only on the precise expression of geometric form but also emphasizes the integration and expression of multi-source physical data, such as material information, component status, and external conditions [43]. As the value realization activities of architectural heritage gradually unfold through the three stages of protection, management, and dissemination, the content and functionality of the physical model also present multi-layered, scenario-specific expression characteristics.

In the protection stage, the physical model is primarily used to support structural analysis and damage identification for the safety assessment of the heritage entity [44].

Its data typically include the physical properties of component materials (such as density, elasticity modulus, and aging resistance), parameter expressions of construction nodes and stress systems, texture reconstruction of surface weathering and crack information [45], as well as long-term monitoring data of external environmental conditions. These data are often obtained through methods such as ground laser scanning [46], structured light scanning, experimental testing, and Internet of Things sensors, and can be further used to construct finite element analysis models, simulate damage expansion trends, and evaluate repair intervention strategies. This enables the scientific understanding of heritage status and provides support for early-stage interventions.

Table 1. LOD System and Its Applications in Architectural Heritage.

LOD Level	Detail Characteristics	Model Example	Typical Applications
LOD0	2D plan		Guiding maps
LOD1	Simplified building block model		Large-scale heritage area management
LOD2	Simplified model with roof and structure		Skyline and façade management
LOD3	Detailed building model		Damage monitoring and restoration design
LOD4	Detailed interior and exterior model		Virtual restoration and immersive experience

In the management stage of architectural heritage, the role of the physical model shifts towards real-time perception of asset operational status and lifecycle monitoring, emphasizing the acquisition of dynamic data and the linkage mechanism for management responses. The model content includes structural response information (such as displacement, tilt, and crack propagation), environmental monitoring data (such as temperature, humidity, PM2.5, and rain/snow), as well as parameter configurations and behavior-triggering rules that support daily operations and maintenance scheduling. By deploying sensor networks and edge computing devices, the physical model not only enables continuous updates of the operational status but also integrates with the rule-based model to drive automated actions such as early warnings, inspection scheduling, and resource allocation, thereby enhancing the response capabilities and visualization support of the digital twin system in the heritage management stage.

In the dissemination stage, the physical model takes on the role of visual representation and interactive experience, with the core focus on enhancing the realism and immersion of the model. The data for this stage includes high-precision texture maps, PBR (Physically Based Rendering) material parameters, lighting, and environmental reflection information, and even multimedia elements related to audience interaction. Through detailed material representation and dynamic light–shadow simulations, the physical model is widely used in Web 3D display platforms, virtual reality environments, and online exhibition spaces, supporting the visual dissemination of cultural heritage and multi-terminal interactive presentations. Additionally, the integration of historical documents, blueprints, and photographic materials enables the physical model to simulate the building's condition during different historical stages, thus achieving a unified expression of cultural imagery and authenticity.

2.3.3. Rule-Based Model

In the value-chain-driven digital twin framework, the rule-based model plays a key role in logically constraining and institutionally expressing various operational behaviors of architectural heritage, serving as the core mechanism for the twin system's transition from "state expression" to "intelligent decision-making." In contrast to geometric and physical models that focus on the spatial form and material properties of objects, the rule-based model focuses on the boundary conditions, evaluation standards, and operational norms for behavior, constructing a semantic system that drives, limits, and controls the system's operations. The essence of the rule-based model is to formalize and structurally embed the regulations, technical requirements, and response logic inherent in cultural heritage protection and management activities into the twin system, thus enabling automated judgment and process-driven actions.

The rule-based model is primarily used to guide daily monitoring, early warning responses, and intervention processes. It involves numerous constraint conditions based on national or local cultural heritage protection standards, such as damage warning level classifications, permissible structural crack propagation values [47], repair material usage ranges, and intervention permission conditions. These rules are often embedded into the twin system in the form of threshold logic, event-triggered mechanisms, or expert experience rules, driving the system to assess, classify, and trigger corresponding response mechanisms based on the results of physical state recognition. With the involvement of the rule-based model, the digital twin system simulates the judgment logic of human experts in heritage protection, facilitating the transition from "passive perception" to "proactive intervention".

The rule-based model also forms the scheduling basis and decision-making foundation for system operations. Its content covers heritage asset classification standards, routine inspection and maintenance cycles, personnel authority configuration, emergency response processes, and multi-department coordination mechanisms. The rule-based model in this stage emphasizes the logical integrity of business processes and the automation of system responses, exhibiting clear process flow and event-driven characteristics. By transforming management systems into machine-readable rule chains, the twin system can automatically assess risk levels based on real-time sensory data, generate task lists, and link other models to implement actionable instructions. This enables the system to perform and provide feedback on heritage management tasks without manual intervention.

During immersive visitor tours, the rule-based model focuses on supporting user interaction and content adaptation, primarily involving user behavior restrictions, display logic control, and immersive experience management. Typical rules include hierarchical authorization mechanisms for display content, tour path recommendation algorithms [48],

interactive event triggers, and audience preference adaptation logic. In this stage, the rule-based model often relies on knowledge graphs, user profiles, and content tagging systems, supporting adaptive display strategies across multiple terminals and roles, making dissemination activities more contextually relevant and culturally accurate. Through rule-driven content distribution and interactive responses, the digital twin system evolves from a "passive browsing" mode to an "active guidance" mode of dissemination.

Overall, as the institutionalized expression mechanism of the value-chain logic, the rule-based model enables the architectural heritage digital twin system to not only express states and physical characteristics but also execute logical tasks such as behavior restrictions, process scheduling, and strategy control, playing a crucial role in driving the system's intelligent evolution.

2.3.4. Behavioral Model

The behavioral model is a core component of the architectural heritage digital twin system that expresses dynamic responses and interaction logic. It is primarily responsible for simulating the operational mechanisms, state evolution, and multi-party behaviors of the heritage system under specific rule-driven conditions [49]. Unlike the rule-based model, which emphasizes institutional constraints and process settings, the behavioral model focuses more on behavior changes over time, feedback loops, and event response mechanisms. It not only reflects the dynamic evolution characteristics of the heritage system in the virtual–physical mapping but also forms an important support for the digital twin system to achieve proactive prediction, intelligent scheduling, and multi-party collaboration.

In the digital twin system for architectural heritage protection, the behavioral model is mainly used to simulate the state evolution of heritage under environmental disturbances, structural degradation, or human intervention, supporting the prediction, verification, and evaluation of intervention strategies. The behavioral model at this stage is typically built on multi-physics simulations [50], mechanical analysis [51], or state transition logic, such as simulating the impact of temperature and humidity fluctuations on the cracking of wooden components, the linkage mechanism of crack propagation [52] and load redistribution, or predicting the differences in structural responses under different restoration plans. These behavioral models often work in conjunction with physical and rule models. By inputting real-time monitoring data, they dynamically simulate the risk evolution path of the heritage entity, thus providing proactive support for intervention decisions.

In the management system, the behavioral model serves as an intermediary that connects perception input with operational execution, realizing the digital mapping of management behaviors such as resource scheduling, task execution, and cross-departmental collaboration. The content expressed by the model includes multi-role operation processes, daily operation and maintenance behavior patterns, device linkage rules, and response feedback mechanisms. For example, automatic inspection path generation [53] for specific abnormal events, personnel group scheduling, sensor linkage detection, and response priority judgments all require the behavioral model to achieve system-level behavior planning and response control. The behavioral model in this stage emphasizes logical feedback loops and is often constructed using flowcharts, event chains, or state machine models. It can be further optimized through the mining of historical behavior data, achieving a fusion of experience-driven and data-driven strategies.

In the visitor tour system, the behavioral model focuses on designing and responding to user interaction logic and experience behaviors. It guides user participation, controls interaction rhythm, and simulates audience paths, thereby linking cultural content with experiential behavior. Common behavioral models include virtual tour interaction processes, user preference-triggering mechanisms, interactive node feedback logic, and immersive

behavior mapping. For example, the system can adjust the tour content in real time based on the viewer's browsing path, push relevant semantic information, or trigger audiovisual feedback, thereby enhancing user engagement and cultural acceptance. The behavioral model in this system often works in conjunction with the rule-based model to implement customized dissemination strategies for different audience groups, supporting the transition from one-way display to two-way interactive dissemination.

In summary, as the dynamic semantic expression carrier within the digital twin system, the behavioral model not only supports the "action generation" and "response evolution" of architectural heritage in virtual space but also, through its collaboration with geometric, physical, and rule models, constructs an intelligent system with perception capabilities, decision logic, and feedback responses. This significantly enhances the proactivity, adaptability, and service capability of the architectural heritage digital twin system.

3. Construction of the Value-Chain-Driven Digital Twin Model Hierarchy

3.1. Methodology

In the construction of the digital twin model for architectural heritage, traditional models are typically categorized based on geometric complexity, focusing primarily on the visualization of spatial entities and data load. However, in the face of the multiple demands of architectural heritage protection, management, and dissemination, the model must not only accurately represent static forms but also meet functional requirements in different business scenarios, such as structural monitoring, operation and maintenance management, and public dissemination. Therefore, based on the digital twin framework, this paper proposes a value-chain-driven digital twin model hierarchy structure, aiming to achieve a transformation in modeling paradigms from "geometry-driven" to "value-driven."

In the process of constructing the digital twin model for architectural heritage, a variety of software tools may be used at different stages depending on project requirements and data characteristics. For geometric modeling, commonly used tools include 3ds Max2024, Blender4.3, Autodesk Revit2024, or Bentley ContextCapture10.20 for point cloud processing, 3D reconstruction, and component refinement. For interface and interactive experience design, Unreal Engine 5.4.1 or Visual Studio Code1.99 may be adopted to support immersive visualization or web-based interaction. GIS platforms such as ArcGIS Pro3.0 and QGIS3.40 can be applied for spatial data management and VCLOD level integration. For physical simulation and behavioral model computation, MATLAB R2020a and Python3.14 are frequently employed. The selection of these tools is based on their compatibility with multi-source heritage data, ability to support high-precision modeling, and flexibility in integrating geometric, physical, rule-based, and behavioral models into a unified digital twin framework.

Figure 4 presents the overall workflow of our value-chain-driven digital twin model, which adopts the level of geometric detail as the classification criterion, drawing on the LOD hierarchy of CityGML. However, since our focus is on architectural heritage, we take a palace structure as an example: the first level is essentially consistent with LOD0, representing a two-dimensional plan; the second level corresponds to LOD1, depicting a simplified block model of the heritage building; the third level adds basic structures such as the roof; the fourth level represents a detailed model of the heritage building, including features such as the roof, dougong, beams, and columns; and the fifth level further incorporates interior details, such as furniture, stairs, and cultural relics. Other physical, rule-based, and behavioral models are integrated into these geometric levels to form a complete digital twin hierarchy, which is then validated within a value-chain-oriented digital twin system for conservation, management, and dissemination, playing a pivotal

role in its operation. In other words, the degree of geometric detail determines the spatial resolution of the digital twin model, while the adaptability of the physical, rule-based, and behavioral models endows it with functional capacity across different value stages, thereby enabling a transition from "spatial representation" to "intelligent collaboration."

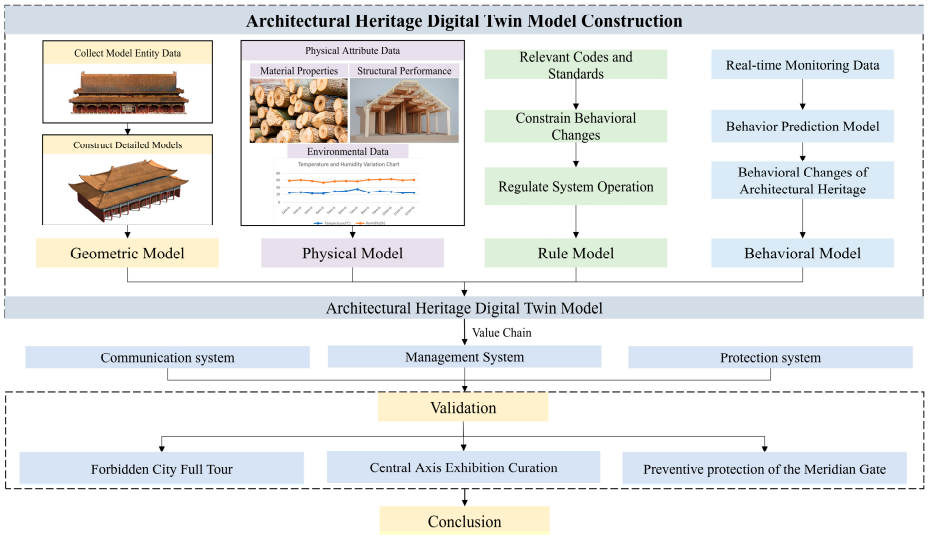


Figure 4. Overall flow chart of building and verifying digital twin models of architectural heritage.

3.2. Construction of the Digital Twin Model Hierarchy

Through the above discussion, we understand that constructing a digital twin model hierarchy begins with the geometric model hierarchy, followed by the integration of physical, rule-based, and behavioral models, depending on the specific application scenario. Therefore, we constructed a digital twin geometric model hierarchy based on the architectural heritage value-chain, referencing LOD0-4, as shown in Figure 5. To distinguish it from the existing LOD, we refer to it as VCLOD (Value-Chain-Driven Level of Detail). We define the architectural heritage model hierarchy, VCLOD, to consist of four levels: VCLOD0, VCLOD1, VCLOD2, VCLOD3, and VCLOD4. Below is a detailed introduction:

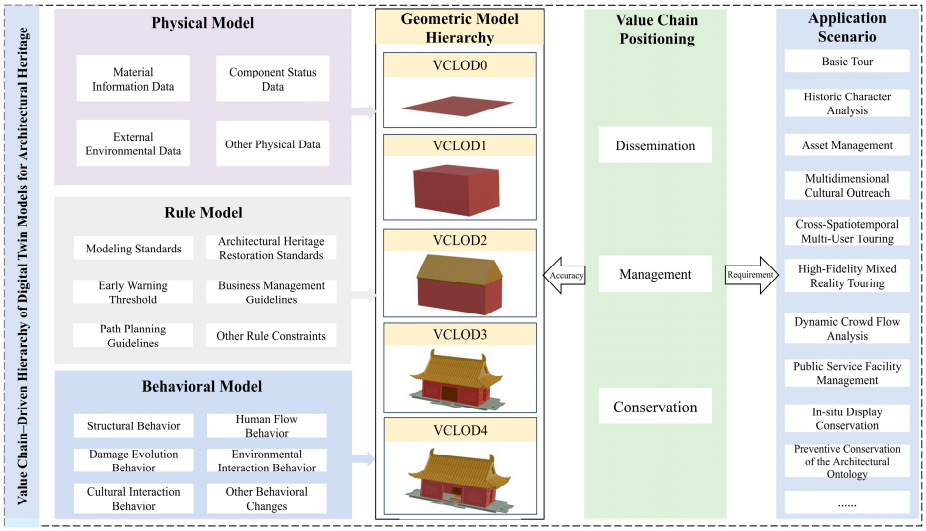


Figure 5. Value-Chain-Driven Digital Twin Model Hierarchy for Architectural Heritage.

VCLOD0: This is the most basic level in the architectural heritage geometric model hierarchy. It uses a 2D plane format to express the geometric outline and spatial location of heritage objects, without involving three-dimensional structures or building height. It

primarily serves tasks such as spatial positioning, boundary definition, and navigation for architectural heritage. This level is suitable for foundational management scenarios like heritage cataloging, location mapping, route planning, and functional zoning. It also serves as the underlying support for public dissemination interfaces and navigation systems. In practical applications, VCLOD0 is often used to create interactive maps, WebGIS platforms, or mobile navigation systems, providing users with intuitive heritage distribution information and path guidance. Its data mainly comes from GIS geographic databases, orthophotography images from aerial surveys, architectural floor plans, or manual survey results, with low processing costs and high update efficiency. Although VCLOD0 lacks three-dimensional expression capabilities and cannot meet the needs of detailed protection and complex analysis, it acts as the "touchpoint layer" of the architectural heritage model system, providing a foundational framework for the scheduling, positioning, and organization of higher-level models. It plays a vital role in the visual dissemination and basic management of heritage information.

VCLOD1: This is a simplified block model, primarily used to support macro tasks in the architectural heritage management stage. It is suitable for scenarios such as heritage site cataloging, protection zone division, asset statistics, visibility analysis, and façade control, and can serve as the foundational model for management layers and spatial analysis. The data required for constructing this model includes building boundary outlines, standardized or estimated height information, topographic elevation data, and building attribute information. The data acquisition cost is relatively low, making it suitable for large-scale, rapid modeling and management deployment. It provides structural support for the integration of more precise models in subsequent applications.

VCLOD2: This level further introduces roof structures based on the VCLOD1 block model, enhancing the building's appearance, realism, and spatial recognition capabilities. By adding roof forms (such as pitched roofs, flat roofs, etc.), VCLOD2 not only retains the management functions of VCLOD1 in heritage zoning, asset management, and façade analysis but also enables more detailed tasks such as visibility analysis, skyline control, and historical façade restoration. This level is suitable for management and dissemination scenarios where moderate accuracy in the expression of architectural heritage form is required, particularly in heritage display, planning assessments, and façade model construction. The modeling of VCLOD2 relies on the existing building outlines, height, and attribute data from VCLOD1, while also requiring additional information on roof types and shapes, which can be obtained through elevation drawings, real-life photographs, oblique photogrammetry, or laser point clouds. This level achieves a significant improvement in model expressiveness and management applicability while maintaining relatively low data costs.

VCLOD3: This level is designed for high-precision expression of architectural heritage geometry. It builds on VCLOD2 by further introducing component-level details such as doors, windows, dougong (bracket sets), eaves, and plinths, enabling the fine restoration of the building's external form. This level primarily serves both the protection and dissemination stages of architectural heritage, particularly suited for specialized tasks such as damage monitoring, deformation analysis, component recognition, 3D documentation [54], and restoration design. The VCLOD3 model is highly accurate and operational, supporting the digital preservation of heritage components while providing a realistic visual foundation for digital exhibitions, interactive tours, and virtual restoration [55]. In terms of data requirements, VCLOD3 relies on high-precision data sources, including terrestrial laser scanning (TLS), structured light 3D scanning, photogrammetric point clouds, high-definition images, and architectural as-built drawings, all of which require complex modeling and refinement processes. As one of the most accurate and semantically rich levels in architectural

heritage 3D models, VCLOD3 bridges the gap between component-level management and public dissemination, making it a key model layer that integrates both protective and expressive elements.

VCLOD4: This level further introduces a high-precision model layer for the interior structure and spatial configuration of buildings, building on VCLOD3, achieving an integrated expression of both the interior and exterior spaces of cultural heritage. This level not only retains external details such as doors, windows, dougong (bracket sets), and plinths but also fully presents the interior layout, partition walls, beams, stairs, and other key structural elements. It is suitable for application scenarios requiring fine expression of both the overall building form and internal spaces. VCLOD4 primarily serves high-precision preservation, in-depth management, and immersive dissemination tasks, such as damage identification of interior components, structural safety assessments, building load analysis [56], fire evacuation simulations, virtual restoration displays, and digital twin interactions. In terms of data acquisition, VCLOD4 requires the integration of multiple high-precision data sources, including interior laser scanning, BIM modeling results, structural drawings, photogrammetry, and on-site surveying, with high modeling accuracy and complex processing workflows. However, it provides the most complete restoration of the spatial appearance and structural logic of cultural heritage. As the highest level of 3D models for cultural heritage, VCLOD4 not only provides comprehensive data support for professional preservation and structural research but also offers the public an immersive virtual experience platform, serving as the key foundation for realizing heritage as "readable, usable, and tourable."

To further clarify the operational mechanism of the digital twin model framework, we here supplement the technical details of the underlying data fusion process. In practical applications, the integration of multi-source data is achieved through a unified spatial–temporal database that supports both real-time streaming access and batch data ingestion. Real-time sensor data (such as structural monitoring outputs and environmental sensing information) are first pre-processed to remove noise and standardize formats; subsequently, these data streams are aligned with historical archives through metadata matching and spatial–temporal indexing, thereby enabling direct comparison and integrated analysis across temporal scales. For critical safety monitoring applications, the data update frequency can reach near real-time; whereas archival data enrichment follows a scheduled cycle (e.g., quarterly or annually, depending on the data type). The standardized protocols adopted include the OGC SensorThings API (for sensor data management) and CityGML (for 3D spatial representation), ensuring interoperability and scalability among heterogeneous systems.

4. Implementation of Multi-Level Digital Twin Models

The Forbidden City, as China's most iconic architectural heritage, has a rich and complex range of business activities that involve architectural preservation, cultural relics management, visitor experience, scientific research, education, and more [57–60]. Figure 6 shows the satellite map of the entire Forbidden City from our point cloud visualization system, which illustrates the full scope of the palace complex. To meet these diverse demands, the Forbidden City urgently needs to build a multi-level digital twin model. Through a value-chain-driven digital twin model, it is possible to meet the detailed requirements for preservation, management, and dissemination at different levels. For example, in the geometric model hierarchy, VCLOD0 can be used for regional planning and navigation functions, VCLOD1 is suitable for large-scale spatial management and facade protection, VCLOD2 enhances the authenticity of external structures, VCLOD3 provides precise component-level data support, and VCLOD4 offers a comprehensive representation

of both the interior and exterior structures, supporting high-precision virtual restoration or immersive experiences. The multi-level digital twin model not only improves the management efficiency of the Forbidden City but also provides the public with a richer interactive experience and cultural dissemination platform, promoting the digital preservation and sustainable development of cultural heritage.



Figure 6. Satellite Map of the Entire Forbidden City in the Point Cloud Visualization System.

4.1. Implementation of the Digital Twin Model for the Entire Forbidden City Tour

The Forbidden City, with its vast area and rich historical and cultural significance, requires an efficient and intuitive tour system to enhance the visitor experience [61] and support the management and preservation of architectural heritage. This study, based on digital twin technology, has developed a flat navigation system for the entire Forbidden City. Relying on the map of the entire Forbidden City, the system integrates spatial data, navigation paths, and relevant cultural information through the value-chain-driven digital twin model. It aims to provide visitors with accurate and convenient navigation services while assisting managers in efficiently overseeing the heritage. The construction process is shown in Figure 7.

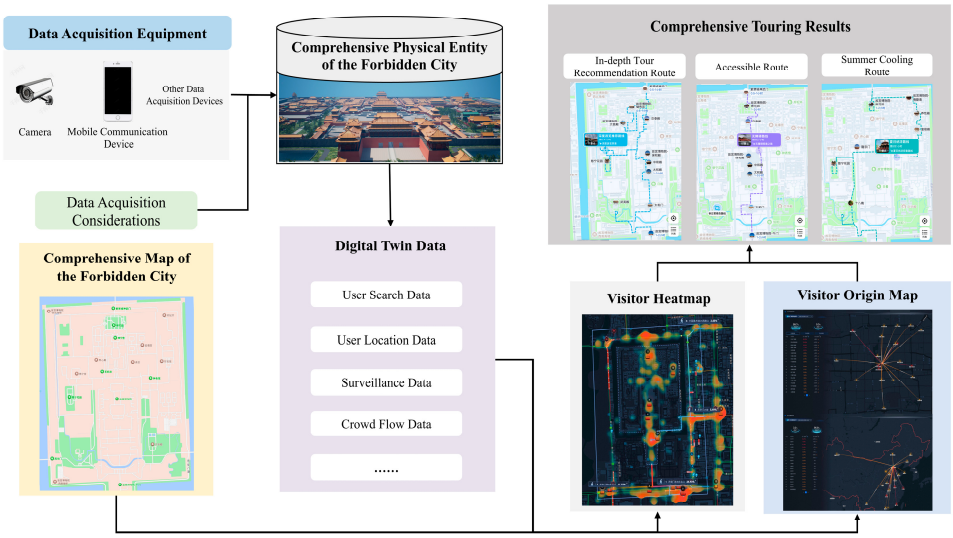


Figure 7. Construction Flowchart of the Digital Twin Model for the Entire Forbidden City Tour.

When constructing the digital twin system for the entire Forbidden City tour, we use the VCLOD0 level for the geometric model. If an immersive full-scale tour is required, VCLOD3 may be needed, and if indoor navigation is also necessary, VCLOD4 would be

required to meet the demand. The VCLOD0 geometric model includes the spatial outlines of the major palaces, courtyards, gatehouses, and other buildings in the Forbidden City, along with their locations on the global map, providing visitors with a clear overview of the Forbidden City area. The data sources for this model include architectural floor plans, satellite images, and GIS geographic information, ensuring the fundamental accuracy for tour path planning and area location.

Through cameras across the entire Forbidden City, visitors' mobile phones, and other devices, we collect data on visitors' searches, their location, and monitoring data. Using this data, we analyze the entire Forbidden City map to generate a visitor heat map, allowing us to identify the most crowded areas for real-time path planning by guides. With this data, visitors can also personalize their tour experience while adhering to the Forbidden City's visiting guidelines and ensuring their safety. For example, they can choose personalized routes, such as deep-dive tours, accessible routes, or summer cooling tour routes. In this context, the collected data serves as the physical model of the digital twin model for the Forbidden City tour, the management rules and safety regulations that visitors need to follow form the rule-based model, and the path planning behavior based on the data and regulations is represented by the behavioral model.

By integrating the geometric model, path planning [62], physical adaptation, and safety management, the digital twin system for the entire Forbidden City tour successfully transitions from static map display to dynamic path guidance. Through this system, visitors can not only receive accurate route directions but also enjoy a personalized tour experience based on points of interest and real-time data. At the same time, managers can use the system to monitor visitor flow in real time, adjust tour strategies, and ensure the safety and comfort of visitors.

4.2. Construction and Implementation of the Digital Twin Model for the Central Axis Exhibition Curation of the Forbidden City

In the digital twin applications for architectural heritage, particularly in exhibition curation scenarios, the digital twin model must not only reflect the physical structure of the building but also support various display, interaction, and management functions. The exhibition curation of ancient buildings involves requirements such as exhibition design, visitor and fire evacuation route planning [63], visitor management, and cultural relic protection monitoring [64], among others related to management and dissemination. The central axis exhibition curation of the Forbidden City, as an important part of architectural heritage display, requires the construction of a digital twin model that integrates geometric, physical, rule-based, and behavioral models to achieve efficient exhibition layout [65], dynamic management, and audience interaction.

In constructing the digital twin model for the central axis exhibition curation of the Forbidden City, we used the UE5 engine for design, as shown in Figure 8. First, we constructed the geometric models of the buildings along the central axis of the Forbidden City and the interior exhibits of the curation rooms, referencing historical archives and design standards. We also incorporated measurement data obtained from 3D laser scanning devices to create detailed models of the buildings along the central axis. Since exhibition curation also involves displaying details such as interior cultural relics, we used the VCLOD4 detail level for modeling, as shown in Figure 8.

In terms of the physical model, we collected three types of data using sensors and other devices:

(1) Exhibit Data: This includes physical data of cultural relics, historical information, preservation requirements, etc. These data are used for exhibition layout design, relic protection, and display introduction.

(2) Exhibition Hall Environmental Data: This includes information such as the functional zoning of the exhibition hall, main entrances and exits, fire safety facilities, and surveillance facilities. These data are used for exhibit layout design, visitor and fire evacuation route planning, personalized exhibition hall layouts [66], and virtual tours.

(3) Other Curation Support Data: This includes various sensors such as surveillance cameras, temperature and humidity sensors, and visitor data such as online reservation numbers, on-site ticket checking data, and group visitor numbers. These data are used for on-site exhibition management and visitor flow management.

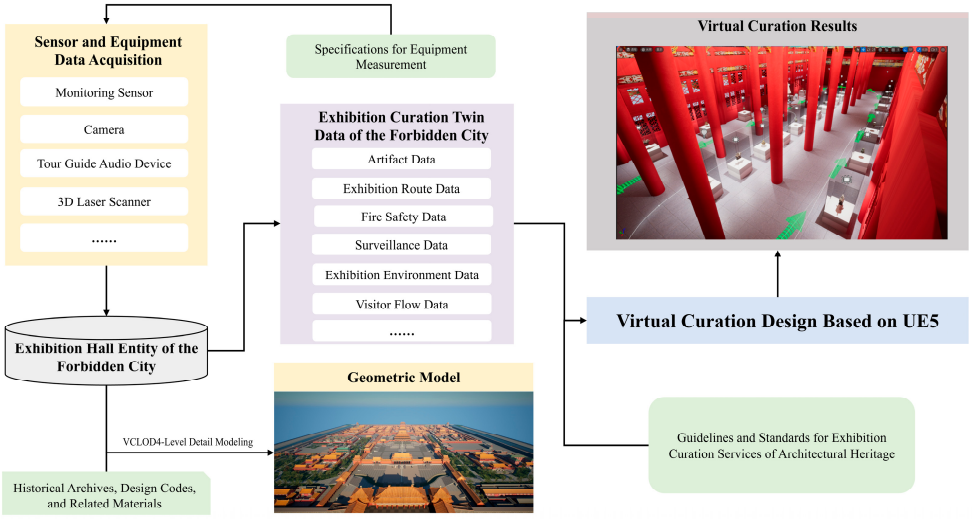


Figure 8. Virtual Exhibition Digital Twin Model Construction Flowchart.

These data provide fundamental support for behavior prediction and route planning in UE5. Through these physical models, the digital twin system can provide real-time feedback on environmental changes in the exhibition space and offer scientific support for relic display and preservation.

The rule-based model is reflected in multiple aspects, such as the precautions in data collection, historical references for modeling, or the integration of exhibit data, exhibition hall environmental data, and curation design rules, along with requirements for fire safety, surveillance, and more, to conduct virtual curation. It helps plan visitor tours and fire evacuation routes, providing support for on-site exhibition layout and display. These elements are responsible for defining the logic of various operational and management behaviors during the exhibition process. They ensure that visitors follow the pre-set paths during their tour and automatically adjust the exhibition path if deviations occur, even offering real-time interactive feedback.

In terms of the behavioral model, analyzing visitor flow data in UE5 helps optimize the exhibition path. Real-time data, such as temperature and humidity, collected by IoT sensors, monitors the environment of physical display cabinets, automatically issuing warnings and adjusting air conditioning/lighting systems to ensure the safety of cultural relics, effectively reducing energy consumption in the exhibition hall, and improving management response speed. Additionally, visitor flow data, including crowd density and visitor behavior data (such as dwell time and interaction frequency), help with on-site crowd management and control, enhancing the on-site visitor experience. The system also supports interactive features such as virtual tours and cultural relic information queries, providing visitors with a more immersive tour experience. Through this design, the digital twin system achieves a seamless transition from static display to dynamic interaction, significantly enhancing the interactivity and engagement of the exhibition.

By integrating the digital twin model, the digital twin system for the central axis exhibition curation of the Forbidden City not only accurately reflects the physical and environmental characteristics of the architecture and cultural relics but also enables intelligent exhibition management and audience interaction, ensuring an efficient and immersive display experience.

4.3. Construction and Demonstration of the Digital Twin Model for Preventive Protection of Meridian Gate

As the highest-ranking and most complex palace gate building on the central axis of the Forbidden City [67], the Meridian Gate has both significant historical and cultural value and public service functions, and is a typical high-risk, high-intensity ancient building. Its structure has long been subjected to the combined effects of natural aging [68], human traffic loads, and climate change, and there are potential hazards such as the aging of wooden components and uneven settlement of the base. In the context of the current emphasis on "prevention" as the core concept of architectural heritage protection [69], the realization of real-time monitoring and trend prediction based on the digital twin model is of great significance for the long-term safety management of the Meridian Gate, an important heritage entity.

This study focuses on the structural characteristics and protection needs of the Meridian Gate and constructs a digital twin model for preventive protection of the Meridian Gate. It integrates geometric models, physical models, behavioral models, and rule models to form a structural expression and response system for preventive protection, as shown in Figure 9. In terms of geometric models, the VCLOD3 level is selected to complete the three-dimensional fine modeling of the Meridian Gate platform, archways, main building and other components to ensure that the model has a real structural structure, scale ratio and component topology to support subsequent loading and analysis; in terms of physical models, the mechanical parameters of masonry and wood materials are integrated, combined with the deadweight of the main building of the Meridian Gate, the density of blue bricks and the live load of tourists, to establish a finite element simulation model to simulate the structural stress and vertical deformation process under various load conditions, focusing on analyzing the deformation distribution characteristics of the vault nodes and their load sensitivity, and evaluating the stability and response threshold of the structure.

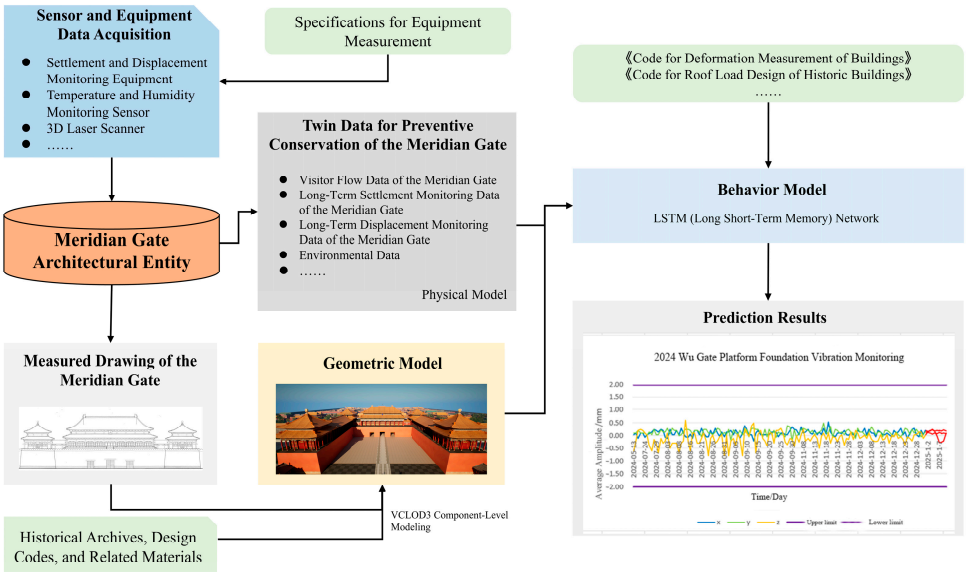


Figure 9. Flowchart of the construction of the digital twin model for preventive protection of the Meridian Gate.

In terms of behavioral models, the LSTM long short-term memory network is used to train the settlement and displacement monitoring data of the Meridian Gate from 2021 to 2024, and a short-term displacement prediction model for key component points is constructed, which can predict the structural deformation trend 7 to 10 days in advance, and output curve results for forward-looking judgment; in terms of rule models, according to the "Building Deformation Measurement Specifications", "Ancient Building Roof Load Specifications" and other cultural protection technical standards, the judgment criteria and response levels corresponding to each monitoring indicator (such as settlement rate, amplitude, and inclination angle) are clarified, and the early warning trigger logic is embedded to ensure that the system has rule basis and response path when judging abnormal conditions. The four types of models are associated and synchronized through a unified data interface, and a multidimensional expression and dynamic response mechanism of the real structure is constructed in the virtual space, laying the data foundation and model core for the early warning protection of the Meridian Gate.

Finally, the model system was fully integrated into the preventive protection system of the Meridian Gate, as shown in Figure 10, and interacted with the high-precision sensor network deployed on site in real time. The system can dynamically visualize the structural status of the Meridian Gate, identify abnormal trends and issue early warnings, and assist managers in formulating intervention measures such as flow control and reinforcement. The deployment of this system has enabled the preventive protection of the Meridian Gate to move from traditional static inspections to digital, intelligent, and predictive monitoring, providing effective technical support for the construction of a sustainable and stable protection mechanism for high-level ancient buildings.

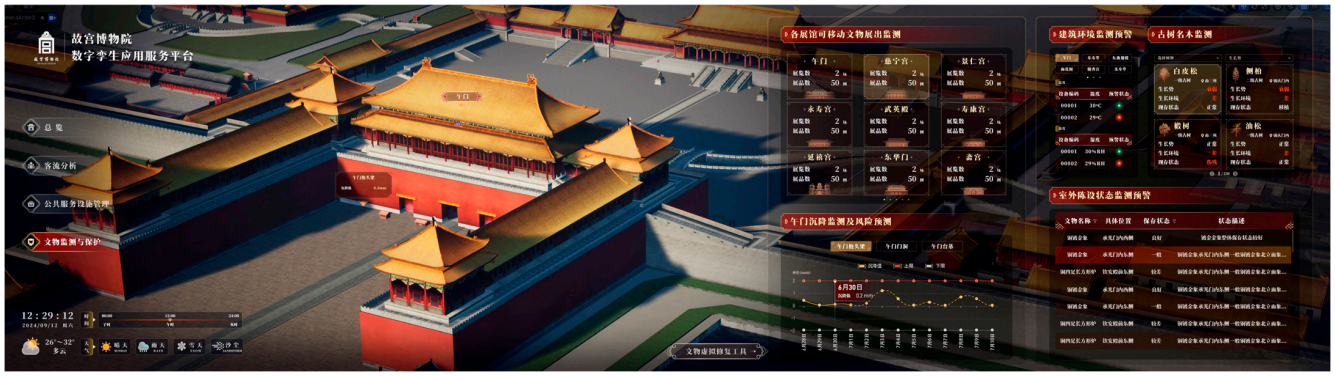


Figure 10. The Meridian Gate preventive protection digital twin system.

5. Conclusions and Outlook

In this study, we proposed a hierarchical system of digital twin models for architectural heritage driven by the value chain. Through the value-chain theory, we divided the value realization process of architectural heritage into three core stages: protection, management, and dissemination. Based on the functional requirements and business scenarios of these stages, we built a digital twin model covering geometric models, physical models, rule models, and behavioral models. This model not only helps to improve the adaptability of the digital twin system in architectural heritage but also promotes cross-stage data flow and business linkage, breaking through the limitations of traditional modeling methods.

Through digital twin models at different levels, we can accurately express the physical form, structural performance, historical value, and cultural characteristics of heritage according to the needs of architectural heritage at different value stages. At the same time, this system provides important support for heritage management and public communication, realizes the transformation from static display to dynamic perception, and can improve

the efficiency and sustainability of architectural heritage protection through intelligent monitoring and prediction.

However, this study also faces some limitations. Firstly, although we have proposed a value-chain-based digital twin model hierarchy, how to effectively integrate multi-source data and improve the real-time performance and accuracy of the model remains a challenge that requires further exploration in practical applications. Secondly, due to the diversity and complexity of architectural heritage, the digital twin model requirements vary between different heritage projects, and the construction methods may also vary. This requires us to consider a more personalized application of the model.

Compared with other heritage LOD and digital twin approaches (such as CityGML and HBIM), the digital twin model framework proposed in this study offers significant advantages. CityGML provides a standardized 3D city model framework with strong interoperability; however, its LOD concept is primarily oriented toward urban-scale representation and lacks domain-specific semantics for heritage conservation. HBIM excels in the fine-grained parametric modeling of building components, particularly for conservation and restoration projects, but often requires substantial manual modeling work and lacks the capability for real-time data integration. In contrast, VCLOD integrates historical archives with real-time monitoring within a multi-scale, semantically rich structural design, thereby enabling continuous and dynamic heritage management. Furthermore, the modular design of the VCLOD framework allows it to adapt to other types of heritage contexts, such as industrial heritage with complex machinery layouts or religious architecture characterized by elaborate ornamentation and symbolic spatial arrangements. This adaptability underscores its potential for broad application beyond the current case studies.

Future research can be deepened in the following areas: First, enhancing the real-time data collection and processing capabilities of digital twin systems to improve the response speed and accuracy of the models; second, exploring intelligent decision-making systems based on big data and artificial intelligence technologies, using model predictions and optimization to further improve the efficiency of architectural heritage applications; third, conducting more field applications and case studies to validate and refine the digital twin model system proposed in this research, promoting its widespread application in architectural heritage.

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