A Knowledge Service System for Cultural Heritage Integrating Knowledge Graph and Semantic 3D Model

Jiadong Zhang[1,2,3], Miaole Hou[4,5,*], Jun Chen[2,3,*], Xiaoguang Zhou[1], Jiaxin Ren[3,6], Shunxi Yin[2,7], Huiqiang Zhao[5], Zhihua Zhang[8], Bingliang Cui[9]

[1] School of Geosciences and Info-Physics, Central South University, Changsha 410083, China - zjdgis@csu.edu.cn, zxgcsu@foxmail.com
[2] National Geomatics Center of China, Beijing 100830, China - chenjun@ngcc.cn
[3] Moganshan Geospatial Information Laboratory, Huzhou 313299, China - jaycecd@foxmail.com
[4] School of Land Engineering, Chang'an University, Xi'an 710054, China - houmiaole@bucea.edu.cn
[5] School of Geomatics and Urban Spatial Informatics, Beijing University of Civil Engineering and Architecture, Beijing 100044, China - 1108140024005@stu.bucea.edu.cn
[6] School of Earth Sciences, Zhejiang University, Hangzhou 310058, China
[7] School of Environment and Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China - yshunxi@gmail.com
[8] Shanxi Cultural Relics and Museum Industry Group Co., Ltd., Taiyuan 030001, China - sxwenbojituan@163.com
[9] Guangzhou Alpha Software Information Technology Co., Ltd., Guangzhou 510060, China - cui_bl@163.com

Keywords: Cultural Heritage, Semantic 3D Model, CityGML, Knowledge Graph, Knowledge Service.

Abstract

Cultural heritage (CH) digitization currently suffers from fragmented multi-source heterogeneous data, insufficient knowledge organization, and limited semantic expression in 3D CH models. Existing knowledge graphs and HBIM in CH field lack unified semantic representation and effective GIS integration, thus restricting intelligent knowledge services. To overcome these issues, a knowledge service approach integrating knowledge graph and semantic 3D models is proposed, enabling the transformation from data process to knowledge-driven services. An extension model for CH (CHADE) is developed using the CityGML ADE mechanism to support the construction of semantically enriched 3D geospatial scenes. Meanwhile, A domain ontology (CHOnto) based on CIDOC CRM is constructed to formalize CH knowledge, and multi-source heterogeneous data are organized into a Cultural Heritage Knowledge Graph (CHKG). By establishing semantic connections between knowledge graph and 3D models, the proposed method achieves integrated representation of geometry, spatial context, and domain knowledge. A prototype system (3DCHKS) is implemented and validated through multiple heritage scenarios. Results demonstrate that the approach enhances semantic connectivity, knowledge organization, and scenario-based representation, supporting intuitive visualization and intelligent application. Although limitations remain in generalizability and knowledge extraction robustness, this study provides a novel framework for integrated CH knowledge services and lays a foundation for scalable, knowledge-driven heritage applications.

1. Introduction

Cultural heritage (CH), as a vital carrier of human civilization, embodies rich historical information and cultural value. With the rapid advancement of digital technologies and geospatial information technologies, the preservation, management, and dissemination of CH are progressively evolving toward greater intelligence and refinement. However, the current process of CH digitization is generally characterized by an emphasis on data acquisition over data utilization. Although large volumes of multi-source data have been collected, they are often stored in fragmented forms such as texts, images, maps, and 3D models, exhibiting significant heterogeneity in structure and format (Soler et al., 2018). This fragmentation leads to a lack of unified semantic organization and association mechanisms, thereby hindering in-depth knowledge mining and efficient dissemination of cultural content. Meanwhile, conventional 3D models primarily represent geometry (Blut et al., 2018), offering limited capacity for semantic and attribute representation, and thus failing to meet the requirements for scene understanding and knowledge services of complex heritage objects. Consequently, how to achieve the integrated organization and knowledge-based representation of multi-source heterogeneous heritage data has become a critical issue in CH digitization.

Traditional CH information systems still exhibit notable limitations in terms of knowledge representation and interactive services. On the one hand, existing heritage management and visualization systems struggle to capture semantic relationships among heritage resources, making it difficult to comprehensively access relevant information and knowledge, thereby impeding heritage cognition (Wang et al., 2018). On the other hand, conventional 3D models focus primarily on geometric visualization, lacking semantic description capabilities and thus failing to support structured knowledge representation and intelligent application. Although knowledge graph technologies have been increasingly applied in the CH domain to organize entities, relationships, and attributes, most approaches neglect the semantic representation of spatial dimensions while existing information model such as HBIM enables detailed reconstruction of heritage objects in both geometry and attributes but lacks a unified and standardized semantic representation framework for CH and is difficult to integrate with Geographic Information Systems (GIS). The fragmentation between these approaches in terms of

* Corresponding Author

methodologies and data structures limits their synergistic potential and constrains the advancement of CH knowledge services.

To address these challenges, this paper proposes a knowledge service approach for cultural heritage that integrates knowledge graphs with semantic 3D models, enabling a transition from "data representation" to "knowledge service." The structured knowledge representation capabilities of knowledge graphs are combined with the spatial visualization strengths of semantic 3D models. The knowledge graph provides a unified semantic framework for multi-source heterogeneous data, supporting the systematic organization and semantic alignment of entities, attributes, and relationships. The semantic 3D model serves as a spatial carrier of knowledge, offering intuitive 3D representations that enhance users' understanding of heritage spatial structures and their underlying cultural connotations. Through this integration, a knowledge service framework that combines "semantic association–spatial representation–online application" is established.

Specifically, a domain ontology (CHOnto) covering key concepts such as CH and geospatial entities is constructed based on CIDOC CRM. Entities and relationship triples are extracted from multi-source heterogeneous data to build a Cultural Heritage Knowledge Graph (CHKG), enabling structured organization of heritage knowledge. For semantic 3D representation, a CH-oriented semantic extension model is developed based on the Application Domain Extension (ADE) mechanism of CityGML. This facilitates the construction of 3D geospatial scenes for CH and establishes semantic mapping and association between heritage entities and 3D models, thereby achieving an integrated representation of geometric forms, spatial contexts and knowledge.

To validate the effectiveness of the proposed approach, a 3D Geospatial Scene Knowledge Service System for Cultural Heritage (3DCHKS) is designed and implemented, and experimental applications are conducted across multiple heritage scenarios. The results demonstrate that the system effectively integrates knowledge graphs and semantic 3D models, enhancing the organization and representation of CH knowledge, and providing a novel technical pathway for knowledge sharing, reuse, and intelligent services in the cultural heritage domain.

2. Related Work

2.1 CityGML ADE for Cultural Heritage

CityGML is an open standard for representing 3D urban objects, enabling unified modeling of geometric, topological, and semantic information of urban geographic features (Gröger & Plümer, 2012). Application Domain Extension (ADE) is an extension mechanism of CityGML, designed to incorporate domain-specific object types and attributes tailored to particular application needs (Biljecki et al., 2018). CityGML ADE in CH aims to extend the semantic expressiveness of CityGML by integrating the geometric representation of 3D heritage models with their historical and cultural semantics, thereby providing standardized framework support for the digital preservation, management, and dissemination of cultural heritage.

In the CH domain, early studies primarily focused on specific heritage types such as historic buildings, enriching the attributes of CityGML core classes (e.g., the Building module) to meet cadastral or real estate management requirements. Subsequent research shifted toward multi-level semantic extensions, leveraging the ADE mechanism to define both component-level and holistic attributes in accordance with heritage characteristics. This led to the development of extension modules tailored to different heritage types, enabling semantic 3D modeling of specific components such as traditional building roofs (Li et al., 2017), as well as heritage entities like grottoes (Yang et al., 2023) and Buddha statues (Pan et al., 2025).In recent years, research has increasingly emphasized multi-scale scene adaptation and standardization. By defining Levels of Detail (LoD), studies have realized LoD-based modeling for grottoes (Yang et al., 2024) and historic buildings (Zhang et al., 2024), while also achieving interoperability with systems such as GIS and BIM, thereby enhancing data sharing and spatial analysis capabilities. However, existing heritage ADEs remain limited in their ability to model and represent complex cultural heritage scenes. They lack formalized representations of CH knowledge and contexts, making it difficult to establish associations with heterogeneous semantic entities. Moreover, the absence of unified extension standards across different heritage types hinders their capacity to provide structured semantic inputs required for fine-grained management and simulation of complex heritage scenarios.

2.2 Integration of BIM and GIS

The integration of BIM and GIS aims to combine the fine-grained building information provided by BIM with the macro-scale geospatial context of GIS, thereby overcoming the limitations of using either system independently in complex application scenarios (Amirebrahimi et al., 2016). This integration provides critical technical support for domains such as smart cities, digital twins and CH. Existing research has primarily focused on cross-standard transformation and semantic mapping between BIM (e.g., IFC) and GIS (e.g., SHP or GML), addressing key challenges such as geometric transformation, semantic alignment, LoD mapping, and georeferencing (Arroyo et al., 2018). Additionally, ADEs have been developed to preserve semantic and attribute information from IFC as much as possible (Biljecki et al., 2021).

In the CH field, Historic Building Information Modeling (HBIM) was proposed as an approach tailored to historical structures (Murphy et al., 2009). The integration of HBIM with GIS/HGIS enables the reconstruction and simulation of the spatiotemporal evolution of heritage environments at regional and urban scales (Mu et al., 2024), providing technical support for multi-scale analysis, risk assessment, conservation, and simulation of CH (Colucci et al., 2020). More recently, graph-based technologies have introduced new pathways for semantic transformation between BIM and GIS. The adoption of ontologies and the semantic web effectively supports mapping, transformation, and integration from IFC to CityGML (Karan et al., 2015; Ji et al., 2024), enabling efficient information retrieval while reducing information loss during the conversion process (Tan et al., 2023). Nevertheless, for culturally diverse and structurally complex heritage objects, there is still a lack of unified transformation methods and standardized mapping mechanisms. Furthermore, current approaches remain insufficient in terms of geographic registration and multi-source data integration for heritage scenes, making it difficult to meet the demands of fine-grained representation and comprehensive applications in complex, multi-scale heritage scenarios.

2.3 Semantic Web and Knowledge Graph

In recent years, ontology, Semantic Web, and knowledge graph technologies have witnessed significant growth in research and applications within the AEC, BIM, and GIS domains. These technologies are employed to address interoperability and information exchange across different domains (Pauwels et al., 2017), and to enable the formal representation of domain concepts and entities, as well as the associative modeling of complex spatiotemporal relationships (Zhang et al., 2022). Early studies primarily adopted ontology-based Semantic Web technologies to achieve semantic interoperability of multi-source heterogeneous data by standardizing domain-specific concepts. With the increasing demand for knowledge integration and the expansion of data scale, research has gradually shifted toward knowledge graphs as a structured knowledge representation framework, aiming to integrate fragmented multidisciplinary data and construct graph-based models encompassing both entities and their relationships. At present, research on CH knowledge graphs relies on relevant standards such as CIDOC CRM as the core ontology to define key concepts and relationships such as heritage objects and events, while CRMgeo extends it to the geospatial domain, and GeoSPARQL supports geospatial queries, thereby offering a unified specification for semantic and spatial representation of CH. Existing studies have developed domain-specific CH knowledge graphs, such as those for grottoes (Yang & Hou, 2023) and intangible cultural heritage (Fan & Wang, 2022), which integrate multi-source data to extract heritage entities and relationships, and exploring their applications in heritage conservation and knowledge integration. However, current research lacks a knowledge representation framework oriented toward spatiotemporal scenarios of CH. It remains insufficient in modeling spatiotemporal relationships within heritage scenes, and its application in the organization, management, and visualization of 3D heritage scenes is still limited. A complete and practically deployable application system has yet to be established.

2.4 Spatio-temporal Intelligence

Spatiotemporal information is not only a fundamental medium for describing natural phenomena and human activities, but also a critical support for the protection and restoration of CH. It provides a scientific basis for disaster management, risk assessment, and preventive conservation of CH, thereby facilitating its sustainable utilization and dissemination. Efficient processing and intelligent mining of spatiotemporal information are key components of spatiotemporal intelligence. Hybrid intelligence (Ren et al., 2024), as a novel paradigm integrating human intelligence and machine intelligence, has emerged as a crucial pathway for their deep integration and for empowering spatiotemporal information applications.

Early approaches to spatiotemporal information processing mainly relied on manual interpretation and single-algorithm methods, which suffered from limited generalization capability and were difficult to transfer to domain-specific applications. Subsequently, research has gradually shifted toward hybrid intelligence-driven approaches, enabling intelligent upgrades in spatiotemporal information processing and providing technical support for related studies. Existing research focuses on multi-scenario spatiotemporal information mining, including map annotation extraction (Ren et al., 2025a, 2025b, 2026), spatiotemporal scene understanding (Yin et al., 2025, 2026), and generation (Ren et al., 2024). These techniques can be adapted to CH applications, such as spatial distribution monitoring and historical scene reconstruction, and can assist in tasks like heritage entity annotation and conservation monitoring. Nevertheless, current methods still face challenges when applied to CH scenarios, including insufficient integration of multi-source spatiotemporal information and limited adaptability to complex scenarios. Research should further integrate the hybrid intelligence paradigm, explore its applicability in CH contexts, and incorporate domain knowledge to enhance the generalization capability of spatiotemporal intelligence, thereby promoting its application in CH conservation and utilization.

3. 3D Geospatial Scene Modeling and Knowledge Representation of Cultural Heritage

3.1 Semantic 3D Modeling of Cultural Heritage

3.1.1 Extending CityGML ADE for Cultural Heritage: Figure 1 illustrates the overall structure of cultural heritage ADE (CHADE). The model adopts *core::CityObject* as the top-level abstraction, and organizes spatial objects hierarchically through *core::Site* and *AbstractCityObject*. The geometric information of heritage objects is represented using *gml::MultiSurface*. On this basis, *ch::CulturalHeritage* is introduced as the core extension class to incorporate heritage-specific attributes, including identifier, name, geographic location, historical period, protection level, and preservation status, among others, thereby addressing the limitations of native CityGML in CH semantic representation. Furthermore, the model refines heritage categories by deriving subclasses such as *Grotto*, *AncientTomb*, *HistoricBuilding*, *AncientSite*, and *HistoricLandscape*, forming a unified representation framework for diverse heritage types. Each heritage class can be further decomposed into component-level structures through compositional relationships. For example, historic buildings can be detailed into components such as Roof, Wall, and Window, enabling multi-scale semantic modeling from macroscopic heritage scenes to individual entities and down to microscopic components. It should be noted that the heritage types and attributes are not limited to those mentioned above, but can be flexibly extended and iteratively refined according to specific application requirements.

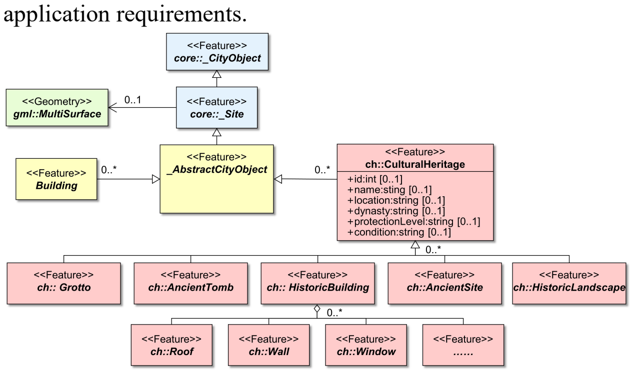

Figure 1. Schematic diagram of CHADE.

3.1.2 Transformation of 3D Models into CHADE: Due to the heterogeneity of data structures in CH 3D models, different data extraction strategies are adopted for various heritage and data types to obtain geometric and attribute information (if available), which are then encoded into semantic 3D models compliant with the proposed CHADE. For HBIM data (primarily historic buildings), such models are typically acquired through field measurements and manual modeling, containing geometry, attributes, and partial semantic information, but lacking realistic texture appearance. We extract geometric and attribute data and convert them into CityGML ADE-based semantic 3D models according to component types. For mesh models containing only geometric information, which are usually generated via 3D laser scanning or photogrammetry and may include real-world textures, we extract geometric data

https://doi.org/10.5194/isprs-archives-XLIX-B4-2026-745-2026 | © Author(s) 2026. CC BY 4.0 License.

and map them into semantic 3D models based on their semantic interpretation, while computing geospatial coordinates and geometric parameters as attributes. On this basis, the CityGML Appearance module is employed to assign materials and textures to the models. For mesh models with texture information, texture mapping is applied to preserve realistic surface appearances, thereby enhancing visual fidelity. For all models, regardless of whether texture is available, materials can be used to distinguish different semantic categories through color encoding.

3.1.3 Construction of Semantic 3D Geospatial Scenes for Cultural Heritage: The Delaunay triangulation algorithm is utilized to convert DEM raster data into a TIN model. High-resolution remote sensing imagery is then applied for texture mapping, overlaying realistic surface textures onto the TIN model to restore the actual geomorphological characteristics of CH sites and improve scene realism. Semantic encoding of terrain information is achieved using the CityGML Terrain module. Subsequently, the semantic 3D models of CH are geospatially registered with the terrain model by transforming local coordinate systems of individual models into a unified geospatial reference system, ensuring spatial consistency. This integration enables the construction of 3D geospatial scenes for CH, supporting applications such as 3D visualization and spatial analysis.

3.2 Construction of Cultural Heritage Knowledge Graph

3.2.1 Cultural Heritage Domain Ontology Modeling Based on CIDOC CRM: The cultural heritage domain ontology (CHOnto) is constructed using the seven-step method, with the CIDOC CRM (Conceptual Reference Model) reused as the foundational ontology. As a widely acknowledged conceptual reference model in the CH domain, CIDOC CRM effectively encompasses the core concepts, attributes, and inter-concept relationships of CH, thereby providing a solid theoretical and practical foundation for ontology construction. Considering the limitations of the base ontology in representing geospatial information, extension standards such as CRMgeo are further integrated to complement and refine the model. This effectively addresses deficiencies in describing spatial location and geographic relationships of CH, leading to the construction of a domain ontology model (CHOnto) that accommodates both CH objects and geospatial representation requirements (Figure 2). The ontology is stored in the form of OWL (Web Ontology Language) and serves as the schema layer of the cultural heritage knowledge graph (CHKG), explicitly defining the conceptual system, attribute specifications, and constraint relationships. It establishes a unified formal representation framework for domain knowledge, providing standardized support for subsequent knowledge extraction, integration, and application, and facilitating effective knowledge sharing and reuse within the CH domain.

3.2.2 Data Layer Construction of CHKG via Knowledge Extraction: Knowledge extraction aims to transform unstructured CH data into structured entities and relationships. A hybrid approach combining manual extraction and deep learning is adopted to extract CH-related knowledge triples from multi-source web texts. Considering the significant differences among various types of heritage data in terms of data scale, textual standardization, and semantic complexity, a single extraction method is insufficient to balance accuracy and generalization capability. Therefore, differentiated knowledge extraction strategies are employed for different heritage types. For architectural heritage, which typically features abundant textual resources, relatively homogeneous types, and standardized descriptions, deep learning methods are prioritized by training a BERT-BiLSTM-CRF model for entity recognition, thereby enhancing automation and scalability. In contrast, for grotto temples and heritage landscapes characterized by limited data, scarce samples, and complex types, manual extraction is adopted to ensure the accuracy and reliability of knowledge acquisition.

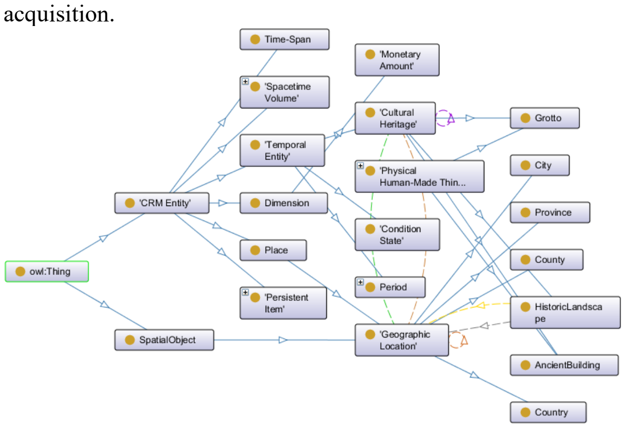

Figure 2. Visualization of partial main structure of CHOnto in Protégé.

3.2.3 Visualization of Cultural Heritage Knowledge Graph: To address the multidimensionality and semantic complexity of CH knowledge, this study proposes a knowledge graph visualization method oriented toward heritage knowledge representation. Through visual encoding, multidimensional knowledge is effectively represented, transforming the knowledge graph from a simple combination of nodes and edges into a visual carrier enriched with semantic information. For entity representation, a multi-attribute visual encoding mechanism is adopted, where multiple visual variables such as color, size, transparency, and shape are collaboratively used to characterize entity features. For instance, node color is utilized to distinguish heritage types, enabling clear visual differentiation among categories such as ancient architecture and grottoes, while node size is mapped to heritage level or significance, thereby enhancing the information capacity and expressive power of the CHKG. For relationship representation, a similar multi-attribute encoding strategy is applied to edges in the knowledge graph to characterize relationship types, strengths, and spatial properties. For example, edge color and textual annotations are used to differentiate relationship types, while edge thickness represents relationship strength or spatial distance, thereby enabling intuitive and comprehensive expression of relational semantics.

4. 3D Geospatial Scene Knowledge Service System for Cultural Heritage

Taking multiple types of CH, such as ancient architecture and grottoes, as the primary objects, multi-source heterogeneous data including texts, images, maps, and 3D models are collected. On this basis, domain knowledge of CH is condensed to construct a comprehensive domain knowledge system. Guided by this knowledge system, geometric information, geospatial information, semantic relationships, and attribute features are extracted from multi-source data and organized into structured triple data, thereby enabling the construction of CHKG and a knowledge base for the formal representation of heritage knowledge.

Furthermore, semantic 3D models are constructed based on CHADE. Centered on heritage entities, semantic entities in the

CHKG are linked and mapped with corresponding 3D models, promoting the deep integration of structured knowledge and 3D heritage scenes. This facilitates unified modeling and organization of spatiotemporal knowledge in CH scenarios. Building upon this foundation, a Cultural Heritage Spatiotemporal Knowledge Service System (3DCHKS) is constructed by integrating applications such as 3D scene visualization, interactive knowledge graph, 3D spatial analysis, intelligent question answering, recommendation, and reasoning. Through online services, the system supports application scenarios including heritage conservation, disaster management, urban planning, and sustainable development, forming an intelligent knowledge service framework that spans from data to knowledge and from models to scenarios. The overall framework of the spatiotemporal knowledge service for cultural heritage is illustrated in Figure 3.

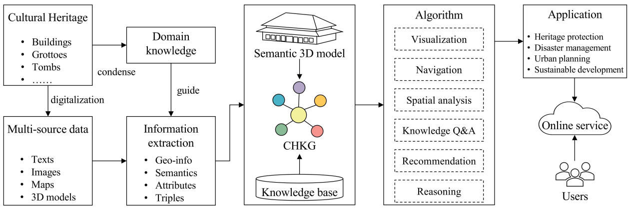

Figure 3. Overall framework of constructing 3DCHKS.

4.1 System Architecture

The system architecture of the proposed 3DCHKS is shown in Figure 4, aiming to support spatiotemporal analysis of 3D CH scenes, formal representation of related knowledge, and intelligent knowledge services. The system adopts a layered architecture consisting of the presentation layer, network layer, and application layer. The presentation layer serves end users who access and interact with the system via web browsers, supporting seamless interaction across various devices, including personal computers, mobile devices, and tablets. The network layer implements system access based on the TCP/IP protocol and leverages cloud platforms to provide cloud-native resources with Domain Name System (DNS) resolution capabilities. In terms of security and communication protocols, this layer enforces HTTPS standards and utilizes firewalls for port access control, ensuring secure data transmission and system operation. The application layer is responsible for coordinating the core application logic of 3DCHKS, as well as the implementation, deployment, and invocation of related functions and algorithms. It also manages diverse media resources, including 3D models, documents, images, and other CH assets. The knowledge base aggregates structured and interrelated triples supports associative queries of heritage entities, and facilitates knowledge discovery and heritage conservation workflows for both human experts and computational agents. This layered architecture decouples user-oriented services from backend data management, thereby enhancing modularity, scalability, and flexibility. It enables independent maintenance and iterative updates of each layer, reducing the complexity of system development and operation.

4.2 System Components and Functionalities

4.2.1 3D Geospatial Scene Visualization provides multiple browsing modes to meet diverse user requirements. The free mode allows users full control over the 3D heritage scene, supporting zooming, rotation, and panning for interactive exploration. The single-scene guided mode focuses on an individual heritage object, presenting detailed information of a single CH object from multiple perspectives, supplemented by textual and image descriptions. The multi-scene guided mode connects multiple related CH objects along predefined paths to form continuous navigation routes. In bird’s-eye mode, the system automatically navigates above the CH object and provides a 360° panoramic view, suitable for observing overall layouts. The cruise mode simulates a water-based touring perspective along predefined routes. The story mode integrates historical events or cultural themes, accompanied by images and textual narratives during the navigation process. These diversified modes accommodate both professional analytical needs and general user experiences.

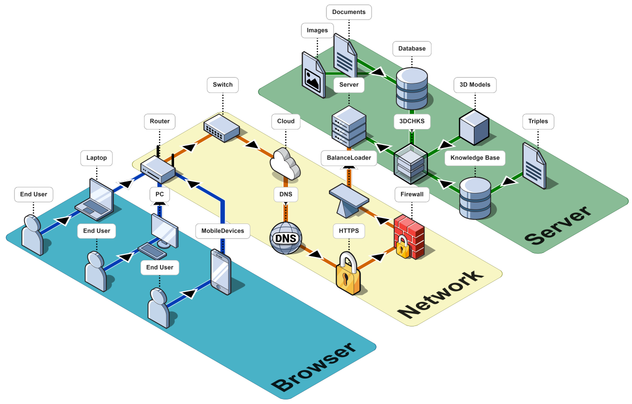

Figure 4. System architecture of 3DCHKS.

4.2.2 3D Geospatial Analysis provides quantitative analysis tools for CH research and conservation. Distance and area measurement tools support calculation of total distance, linear distance, XYZ components, area, and perimeter. Viewshed analysis evaluates visible ranges and occlusions based on user-defined parameters and selected viewpoints. Illumination analysis calculates sunlight duration and shadow distribution on CH surfaces at different times, supporting assessments of lighting conditions and orientation. Excavation analysis simulates terrain excavation to reveal foundation depth and underground structures, with adjustable excavation depth for observation. Flood simulation enables visualization of inundation processes based on specified water levels. Slope and profile analyses derive terrain gradients from elevation data to assess drainage conditions and site suitability. Cut-and-fill analysis calculates excavation and filling volumes based on selected areas and reference elevations, supporting restoration cost estimation. Model clipping allows users to inspect internal structures by slicing models along XYZ directions. The digital twin functionality integrates real-time sensor data from the physical world with 3D models, enabling risk monitoring and early warning for cultural heritage. Sensor locations (e.g., temperature and humidity sensors) are marked within the 3D scene, and real-time data are retrieved from IoT platforms via WebSocket. Popup windows display current sensor readings, while time-series curves visualize data dynamically. When parameters such as temperature, humidity, or deformation exceed thresholds, the system triggers visual and audio alerts, enabling timely intervention and providing real-time monitoring capabilities for heritage conservation.

4.2.3 Interactive Cultural Heritage Knowledge Graph supports querying based on specific entities or relationship types and enables interactive and progressive exploration through operations such as panning, zooming, and dragging, facilitating the analysis of spatiotemporal relationships among heritage entities. Hovering over a node highlights its related entities, while double-clicking retrieves its one-hop neighbors, dynamically expanding the graph with newly revealed nodes and relationships. This allows users to incrementally explore areas of interest without being overwhelmed by the complexity of the entire graph.

5. Results

5.1 Study Area and Experimental Objects

To validate the applicability of the proposed method across diverse CH scenarios, this study selects 6 representative cases. Their basic information is listed in Table 1. These cases cover typical heritage categories, including individual historic buildings, architectural complexes, linear heritage landscapes, and grottoes. They exhibit significant differences in heritage type, historical period, spatial scale, and material attributes, thereby forming a representative and comparable experimental dataset. Figure 5 shows the geographical locations of the experimental objects.

5.2 Construction of Semantic 3D Models and CHKG

Considering the variations in data scale and precision across different types of CH models, a hierarchical semantic modeling strategy is adopted. For landscape-scale heritage, due to large data volume and relatively lower model precision, semantic modeling is conducted at the object level, such as buildings, rivers, and vegetation within the scene. In contrast, for individual heritage objects such as historic buildings and grotto caves, the modeling is refined to the component level to enable fine-grained representation at the micro scale.

Taking the Great Compassion Hall of Chongshan Temple as an example, the original HBIM model contains only 7 categories of semantic components. After conversion into a semantic 3D model encoded by the CHADE, it can represent 17 categories of components specific to traditional Chinese architecture, such as purlins, ridge beasts, and dougong brackets, significantly enhancing semantic expressiveness. For grottoes key semantic elements such as caves, main Buddha statues, and niches can be effectively modeled, thereby improving the representation of spatial structure and cultural connotation.

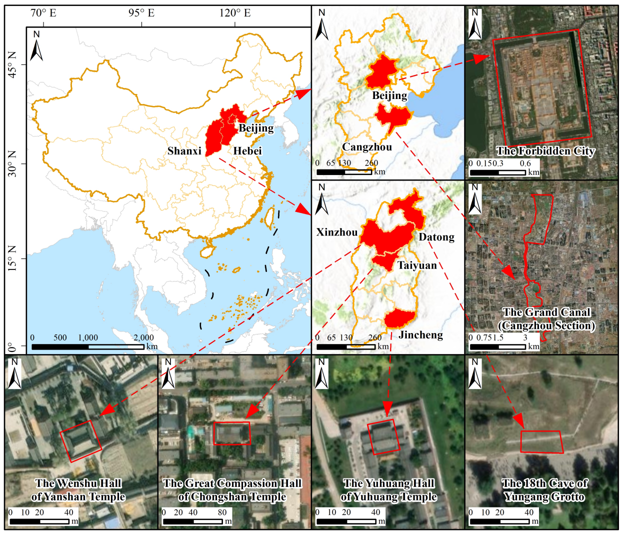

Figure 5. Geographical location of the experimental objects.

Cultural heritage	Type	Level	Location	Dynasty	Main material
The Great Compassion Hall of Chongshan Temple	Historic Building	China’s National Key Cultural Relic Protection Units	Taiyuan, Shanxi	Ming (1368–1644 CE)	Timber
The Wenshu Hall of Yanshan Temple	Historic Building	China’s National Key Cultural Relic Protection Units	Jincheng, Shanxi	Northern Song (960–1127 CE)	Timber
The Yuhuang Hall of Yuhuang Temple	Historic Building	China’s National Key Cultural Relic Protection Units	Xinzhou, Shanxi	Jin (1115–1234 CE)	Timber
The Forbidden City	Architectural Complex	World heritage	Beijing	Qing (1644–1912 CE)	Timber
The Grand Canal (Cangzhou section)	Linear Historic Landscape	World heritage	Cangzhou , Hebei	Sui-Qing (581-1912 CE)	Composite
The 18th Cave of Yungang Grottoes	Grotto	World heritage	Datong, Shanxi	The Northern Wei (386-534 CE)	Stone

Table 1. Basic information of experimental objects

The models with georeferenced coordinates are suitable for location-based visualization and applications (e.g., positioning and navigation). By selecting a CH model and linking it with corresponding entities in the CHKG, additional information such as attributes and semantics can be retrieved to support CH management, querying, and maintenance tasks. In terms of spatial accuracy, the planar RMSE of georeferencing is controlled within 0.09-0.40 m. This result is obtained based on feature point extraction from remote sensing imagery, without relying on field measurements. For macro-scale heritage scene modeling and analysis, this level of accuracy is acceptable. Moreover, the method effectively reduces the need for field surveying, significantly improving modeling efficiency and demonstrating engineering practicality.

For architectural heritage, a named entity recognition (NER) model based on BERT-BiLSTM-CRF is constructed and trained to extract knowledge triples from textual data. The model is trained on 2,519 samples derived from 2,342 manually annotated texts over 30 epochs, achieving a performance of 79% precision, 81% recall, and an F1-score of 80% on the test set. For other types of heritage, such as grottoes and heritage landscapes, due to limited annotated data and significant domain differences, direct model training is less effective. Therefore, 159 textual samples are selected from encyclopedic and official web sources, and relevant knowledge triples are manually extracted to compensate for data insufficiency.

Spatial relationships between CH entities and geographic entities are identified and interpreted through map-assisted interpretation and rule-based extraction from textual data. Combined with the CHOnto constructed in Section 4, standardized representation and modeling of spatial relationships are achieved. Ultimately, through a combination of manual and automated extraction, a total of 1,146 entities and 5,077 relationships are obtained, covering 28 entity types and 16 relationship types. These are imported into the Neo4j graph database using Cypher, forming the data layer of the CHKG, which supports subsequent knowledge services such as question answering.

5.3 Implementation of 3DCHKS

The 3DCHKS adopts a browser/server (B/S) architecture with front-end and back-end separation. By decoupling interface rendering from application logic, the system improves scalability and maintainability, facilitates parallel development and modular iteration, and enhances cross-platform accessibility. Compared with client-based applications, web-based solutions offer platform independence, allowing the system to be accessed on any device with a web browser while ensuring a consistent user experience (Blut et al., 2019). Furthermore, the B/S architecture enables independent management of data and workloads: data storage, management, and querying are handled by the server, while the browser is responsible for rendering.

The front-end is developed using the Vue framework, integrated with Cesium for efficient rendering and interactive visualization of 3D geospatial scenes. A force-directed graph is employed to visualize the knowledge graph, enhancing the intuitive representation of relationships among cultural heritage entities. On the server side, the Neo4j graph database is used to store and manage knowledge graph data, while the Flask framework is adopted to build service APIs, enabling interaction between front-end components and core algorithms such as knowledge extraction and querying. This forms an integrated "data–knowledge–service" processing pipeline.

The 3D geospatial scene interface of 3DCHKS is shown in Figure 6. The interface adopts a multi-region coordinated design: the left panel provides 3D spatial analysis tools, including area measurement, viewshed analysis, and flood simulation; the central area displays the 3D geospatial scene for CH, supporting multi-scale browsing for immersive visualization of CH environments; the top panel offers environment and weather controls, enabling dynamic simulation of different time periods and weather conditions, as well as switching between navigation modes and CH scene; the right panel integrates multi-source information in the form of knowledge cards. The upper section visualizes semantic relationships between the selected heritage entity and its related entities through a knowledge graph, supporting interactive exploration; the middle section combines images and textual descriptions to provide a comprehensive introduction; the lower section presents structured attributes of entities, organized hierarchically into categories such as geospatial information, geometric parameters, and IFC properties, enabling multi-dimensional and multi-level knowledge representation and services.

Figure 6. The 3D geospatial scene of 3DCHKS.

To balance information completeness and interface clarity, a hierarchical visualization strategy is adopted for the CHKG. Within the knowledge cards in the 3D scene, only node color encoding is used to distinguish entity types and avoid visual overload, thereby highlighting core information and improving readability. In contrast, in the standalone knowledge graph page, the multi-attribute visualization strategy proposed in Section 3.2.3 is fully applied, enabling multi-dimensional encoding of nodes and relationships for comprehensive semantic representation and visualization of the overall structure.

6. Conclusion

To address key challenges in CH information modelling including the lack of unified semantic representation, the difficulty in effective integration with geospatial information, and the absence of structured and interconnected domain knowledge that limits intelligent and advanced applications, this paper proposes a cultural heritage knowledge service system that integrates semantic 3D models with knowledge graph. By constructing unified semantic 3D models and a knowledge graph, it enables organic integration of multi-source CH data, thereby supporting both 3D scene visualization and scenario-oriented intelligent knowledge services. The implementation confirms that the integration of semantic 3D models and knowledge graph enhances the scenario-based representation and semantic connectivity of CH knowledge. This facilitates a transition from "data visualization" to "knowledge-driven representation," and improves the organization and retrieval of complex heritage information to a certain extent. However, several limitations remain. The generalization capability across diverse heritage types and regions has not been fully validated, and the accuracy and robustness of knowledge extraction under complex conditions require improvement.

Future work should focus on applications and validations at larger spatial scales such as city, regional, and the national scales and across more heritage types (e.g., ancient tombs and archaeological sites) to assess the generalizability and scalability. Meanwhile, optimizing knowledge extraction and integration methods under large-scale and complex CH scenarios is essential to enhance cross-type applicability, accuracy, and robustness. In addition, promoting interdisciplinary integration with GIScience, architecture, and archaeology will be key to expand practical applications, including structural health monitoring and safety assessment of CH, disaster risk assessment, decision support, and virtual restoration. Moreover, developing multi-level, personalized knowledge services for public, researchers, and administrators will provide more efficient support for digital preservation, reuse, and knowledge dissemination of CH.

Acknowledgements

This work was supported by the National Natural Science Foundation of China under Grant 42394060 and the Shanxi Provincial Administration of Cultural Heritage under the Research Project under Grant 2023KT02. The authors sincerely thank all anonymous reviewers for their constructive comments and valuable suggestions.

References

Amirebrahimi, S., Rajabifard, A., Mendis, P., & Ngo, T. (2016). A BIM-GIS integration method in support of the assessment and 3D visualisation of flood damage to a building. *Journal of spatial science*, 61(2), 317-350.

Arroyo Ohori, K., Diakité, A., Krijnen, T., Ledoux, H., & Stoter, J. (2018). Processing BIM and GIS models in practice: experiences and recommendations from a GeoBIM project in the Netherlands. *ISPRS International journal of geo-information*, 7(8), 311.

Biljecki, F., Kumar, K., & Nagel, C. (2018). CityGML application domain extension (ADE): overview of developments. *Open Geospatial Data, Software and Standards*, 3(1), 13.

Biljecki, F., Lim, J., Crawford, J., Moraru, D., Tauscher, H., Konde, A., ... & Stouffs, R. (2021). Extending CityGML for IFC-sourced 3D city models. *Automation in Construction*, 121, 103440.

Blut, C., Blut, T., & Blankenbach, J. (2019). CityGML goes mobile: application of large 3D CityGML models on smartphones. *International Journal of Digital Earth*, 12(1), 25-42.

Colucci, E., De Ruvo, V., Lingua, A., Matrone, F., & Rizzo, G. (2020). HBIM-GIS integration: From IFC to cityGML standard for damaged cultural heritage in a multiscale 3D GIS. *Applied Sciences*, 10(4), 1356.

Fan, T., & Wang, H. (2022). Research of Chinese intangible cultural heritage knowledge graph construction and attribute value extraction with graph attention network. *Information Processing & Management*, 59(1), 102753.

Gröger, G., & Plümer, L. (2012). CityGML–Interoperable semantic 3D city models. *ISPRS Journal of Photogrammetry and Remote Sensing*, 71, 12-33.

Ji, Y., Wang, Y., Wei, Y., Wang, J., & Yan, W. (2024). An ontology- based rule mapping approach for integrating IFC and CityGML. *Transactions in GIS*, 28(3), 675-696.

Karan, E. P., & Irizarry, J. (2015). Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services. *Automation in Construction*, 53, 1-12.

Li, L., Tang, L., Zhu, H., Zhang, H., Yang, F., & Qin, W. (2017). Semantic 3D modeling based on CityGML for ancient Chinese-style architectural roofs of digital heritage. *ISPRS International Journal of Geo-Information*, 6(5), 132.

Mu, P. Y., Fraser, S. E., & Peng, M. (2024). Simulating urban evolution by H-GIS and H-BIM: a temporal and spatial study of Pingjiang map. *Heritage Science*, 12(1), 392.

Murphy, M., McGovern, E., & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey*, 27(4), 311-327.

Pan, Y., Hou, M., Yang, S., Li, H., Wei, S., & Fan, H. (2025). A CityGML ADE for modeling Buddhist statues in 3D with semantic information. *Journal of Cultural Heritage*, 76, 111-120.

Pauwels, P., Zhang, S., & Lee, Y. C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in construction*, 73, 145-165.

Ren, J., Liu, W., Chen, J., & Yin, S. (2025). HI4HC and AAAAD: Exploring a hierarchical method and dataset using hybrid intelligence for remote sensing scene captioning. *International Journal of Applied Earth Observation and Geoinformation*, 139, 104491.

Ren, J., Liu, W., Chen, J., Li, Z., Zhang, J., & Yin, S. (2026). SAFE: sensitive annotation finding and extraction from multi-type Chinese maps via hybrid intelligence and knowledge graph. *Geo-Spatial Information Science*, 1–26.

Ren, J., Liu, W., Chen, J., Yin, S., & Tao, Y. (2024). Word2Scene: Efficient remote sensing image scene generation with only one word via hybrid intelligence and low-rank representation. *ISPRS Journal of Photogrammetry and Remote Sensing*, 218, 231-257.

Ren, J., Liu, W., Chen, J., Zhu, X., Li, R., Zhao, T., ... & Wang, X. (2025). HI-CMAIM: hybrid intelligence-based multi-source unstructured chinese map annotation interpretation model. *Remote Sensing*, 17(2), 204.

Soler, F., Melero, F. J., & Luzón, M. V. (2017). A complete 3D information system for cultural heritage documentation. *Journal of Cultural Heritage*, 23, 49-57.

Tan, Y., Liang, Y., & Zhu, J. (2023). CityGML in the Integration of BIM and the GIS: Challenges and Opportunities. *Buildings*, 13(7), 1758.

Wang, B., Dane, G. Z., & De Vries, B. (2018). Increasing awareness for urban cultural heritage based on 3D narrative system. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 215-221.

Yang, S., & Hou, M. (2023). Knowledge graph representation method for semantic 3D modeling of Chinese grottoes. *Heritage Science*, 11(1), 1-26.

Yang, S., Chen, J., Hou, M., Fan, H., Li, S., & Sun, Y. (2024). The Concept of Levels of Detail for 3D Niche Models in CityGML. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 10, 419-425.

Yang, S., Hou, M., & Fan, H. (2024). CityGML Grotto ADE for modelling niches in 3D with semantic information. *Heritage Science*, 12(1), 1-18.

Yin, S., Liu, W., Chen, J., Ren, J., & Zhang, J. (2026). TopoFarm: A Topology-Annotated Panoptic Dataset for Unauthorized Farmland Excavation Scene Representation. *ISPRS International Journal of Geo-Information*, 15(3), 93.

Yin, S., Liu, W., Chen, J., Ren, J., Tao, Y., Wang, Y., & Zhang, J. (2025). HIUFE: Hybrid intelligence-based unauthorized farmland excavation scene cognition. *ISPRS Journal of Photogrammetry and Remote Sensing*, 227, 276-296.

Zhang, J., Chen, J., Fan, H., Zhou, X., Hou, D., Ren, J., … Hou, M. (2025). Shp2gml: semantic 3D model generation for Ming and Qing historical buildings at multiple LoDs using domain knowledge and multi-source data. *International Journal of Digital Earth*, 18(2).

Zhang, X., Huang, Y., Zhang, C., & Ye, P. (2022). Geoscience knowledge graph (GeoKG): Development, construction and challenges. *Transactions in GIS*, 26(6), 2480-2494.