

Article

Modeling Ontology-Based Decay Analysis and HBIM for the Conservation of Architectural Heritage: The Big Gate and Adjacent Curtain Walls in Ibb, Yemen

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Abstract

The conservation of architectural heritage (AH) in regions threatened by natural and human-induced factors requires interdisciplinary approaches that integrate physical documentation with semantic modeling. This study introduces a comprehensive framework combining Historic Building Information Modeling (HBIM) with ontology-based modeling aligned with the CIDOC Conceptual Reference Model (CIDOC CRM). Focusing on the Big Gate and adjacent curtain walls in Ibb, Yemen, where the gate is entirely lost, the study reconstructs the structure using historical photographs, eyewitness accounts, and analogical references. The methodology incorporates UAV and terrestrial photogrammetry surveys, point cloud generation, and semantic enrichment using Autodesk Revit V. 2024 and Protégé V. 5.5. Decay phenomena such as cracks, efflorescence, and disintegration were ontologically classified and spatially linked to the HBIM model, revealing deterioration patterns concerning historical phases and environmental exposure. The resulting system enables dynamic documentation, facilitates strategic conservation planning, and enhances data interoperability across heritage platforms. The proposed framework is transferable to other heritage sites, supporting both the conservation of extant structures and the reconstruction of lost ones.

Keywords: HBIM; CIDOC CRM; semantic-enrichment; ontology; conservation



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1. Introduction

Architectural heritage (AH), as a key component of cultural heritage (CH), includes historic cities, towns, monuments, and ruins that embody the shared memory and identity of societies [1–4]. These cultural assets possess significant historical, artistic, and social value, serving as tangible links to the past and providing insight into the evolution of

human settlements and architectural traditions [3,4]. However, AH faces increasing threats from both natural and anthropogenic factors. Recurrent natural disasters, climate-induced stresses, rapid urbanization, neglect, and improper restoration practices continue to undermine the structural integrity and authenticity of historic assets [5–8]. The gap between traditional conservation methods and the sophisticated understanding required to address complex deterioration processes highlights the urgent need for systematic, science-based, and digitally supported conservation frameworks [9]. The documentation and management of AH involve large volumes of interdisciplinary data, including historical records, architectural details, material characteristics, and conservation interventions [10]. However, these datasets are often fragmented, inconsistent, and distributed across different organizations, leading to difficulties in integration, analysis, and long-term reuse [11,12]. To overcome this fragmentation, semantic networks have been introduced to interconnect and organize diverse heritage knowledge, but the absence of unified and interoperable data management strategies continues to impede informed decision-making in conservation workflows [13,14].

In response to these challenges, digital frameworks integrating Historic Building Information Modeling (HBIM) and three-dimensional Geographic Information Systems (3D GISs) have gained prominence [15–17]. HBIM has become a crucial tool for systematically documenting the entire lifecycle of heritage assets, including historical background, geometric configuration, material properties, and previous restoration measures [18–20]. Unlike traditional 2D documentation, HBIM provides a parametric and information-rich environment, enabling not only detailed modeling but also linking of non-geometric attributes, such as historical context and maintenance records [21,22]. Nevertheless, conventional HBIM implementations often lack semantic depth and fail to support automated reasoning or advanced data interoperability. To address these limitations, ontology-based approaches have been introduced, leveraging semantic web technologies to structure and interlink heritage data [23,24]. Over the past decade, research efforts have expanded HBIM applications beyond geometric modeling to include semantic enrichment and multi-source data integration. Early studies focused primarily on point cloud-based 3D modeling [25,26], while subsequent works established semantic bridges between BIM and ontologies to enhance knowledge exchange [27,28]. Quattrini et al. [29] demonstrated the integration of HBIM with historical documentation and structural monitoring through customized plug-ins, while Simeone et al. [30] extended HBIM to encompass both geometric and non-geometric elements for better knowledge management. Recent advancements have also explored the integration of HBIM with the Internet of Things (IoT) systems [31], structural health monitoring, and big data platforms, thereby enabling preventive conservation and intelligent management of historic structures [32–36].

The fusion of smart sensing technologies with HBIM has become a significant area of development. Gara et al. [37] developed a structural health monitoring system combined with swarm intelligence-based model updating techniques to evaluate the seismic resilience of historical masonry buildings. Similarly, Nagy and Ashraf [38] presented an HBIM platform enhanced with smart sensors and big data, which enables real-time visualization of energy performance and environmental conditions of heritage buildings. These studies highlight how IoT sensors, when integrated with HBIM, allow continuous tracking of dynamic parameters such as temperature, humidity, and structural strain, thereby facilitating predictive maintenance and risk assessment. By coupling live data streams with semantically structured 3D models, HBIM can evolve from a static documentation tool into a proactive decision-support framework for heritage management. In addition to advancements in digital modeling, the semantic representation of heritage knowledge has been significantly strengthened through the adoption of the International Committee

for Documentation (CIDOC) Conceptual Reference Model (CRM). As an ISO standard since 2006, CIDOC-CRM provides a robust ontological framework for describing CH entities, events, and relationships [39–41]. Its extension, CRMba, focuses on architectural and construction-related information, enabling a more granular understanding of historical building processes. Projects such as ARMOS, MONDIS, and STAR have successfully employed CIDOC-CRM for cataloging heritage elements, documenting damage, and implementing automated reasoning [42–45]. Recent studies have expanded these foundations by incorporating diagnostic data, material deterioration patterns, and rule-based reasoning into extended ontology frameworks [14,46–50]. Despite these advances, the absence of dedicated semantic modules for representing progressive degradation and context-specific conservation measures remains a limitation, especially in regions with underdeveloped digital infrastructure [51].

These challenges are particularly evident in the Middle East, where cultural assets face a combination of natural hazards, urban encroachment, and conflict-related destruction [5,51]. Yemen's AH is under severe threat from earthquakes, floods, and prolonged environmental exposure [52]. Political instability, neglect, and rapid urban expansion further complicate the implementation of effective conservation strategies [53,54]. Traditional surveying and recording methods alone are insufficient to address these issues, underscoring the need for digitally integrated, semantically enriched approaches that can manage both existing and vanished heritage elements. The Big Gate and adjacent curtain walls in Ibb, Yemen, provide a compelling case study that reflects these challenges. Although the Big Gate has been completely lost, its historical and spatial importance as a vital urban gateway and defensive feature remains conserved through archival records, local oral histories, and contextual urban studies. Recent reconstructions and replacements have failed to maintain the authenticity and integrity of the city's historic urban fabric. This scenario demonstrates the importance of not only protecting the remaining structures but also virtually reconstructing lost elements in a manner that conserves their historical and cultural significance for future generations.

This study introduces a hybrid framework that integrates ontology-based decay analysis with HBIM to document, analyze, and virtually reconstruct the Big Gate and adjacent curtain walls of Ibb. The key innovations of this study were as follows: (1) develops an ontology-based model grounded in the CIDOC-CRM framework to semantically reconstruct the historical footprint of the Big Gate and trace the processes leading to its deterioration; (2) integrates this semantic model into an HBIM environment for managing both geometric and non-geometric heritage data in a unified digital ecosystem; and (3) establishes an interoperable platform for multi-source data integration, collaborative workflows, and long-term conservation planning. By merging ontology-driven knowledge representation with HBIM and sensor-based monitoring concepts, this research contributes to the advancement of digital heritage documentation and offers a scalable methodology for digitally reconstructing lost architectural elements based on spatial logic, historical evidence, and analogical reasoning.

2. Materials and Methods

This study employed a structured methodological framework that integrates four inter-related components: (1) multidisciplinary data collection, (2) photogrammetric modeling, (3) ontology-based semantic analysis, and (4) data enrichment through HBIM integration, aimed at supporting the conservation of AH in Ibb. As shown in Figure 1, the first phase involved gathering data from multiple sources (the black arrows), including historical archives, old city maps, architectural drawings, construction records, and building material documentation (e.g., material stratigraphy, past interventions, and surface decay

analysis), alongside on-site surveys conducted using Unmanned Aerial Vehicles (UAVs) and Terrestrial Digital Photogrammetry (TDP). The UAV data were acquired using a DJI Mavic 3 Classic (DJI Technology Co., Shenzhen, China), while ground-level images for TDP were captured using a Nikon D810 DSLR camera (Nikon Corporation, Tokyo, Japan) equipped with a 35 mm lens. These combined datasets form the foundation of an organized 2D/3D environment, which, while not strictly required for generating point clouds or constructing digital models, proves essential for managing, structuring, and retrieving multi-source data and ensuring consistency throughout analysis and dissemination. In the next stage, both spatial and non-spatial datasets were processed and integrated into a geospatial platform, where structural characteristics, material conditions, and historical context are analyzed concurrently. A core component of this workflow is the application of CIDOC CRM and ontology-based modeling, which enables the semantic analysis of deterioration patterns and the creation of a structured knowledge database tailored to the conservation of both existing and lost architectural features. This integrated methodology establishes an enhanced data environment that strengthens the understanding of both physical and semantic attributes of the cultural asset, while providing a scalable foundation for informed decision-making and sustainable, long-term heritage management.

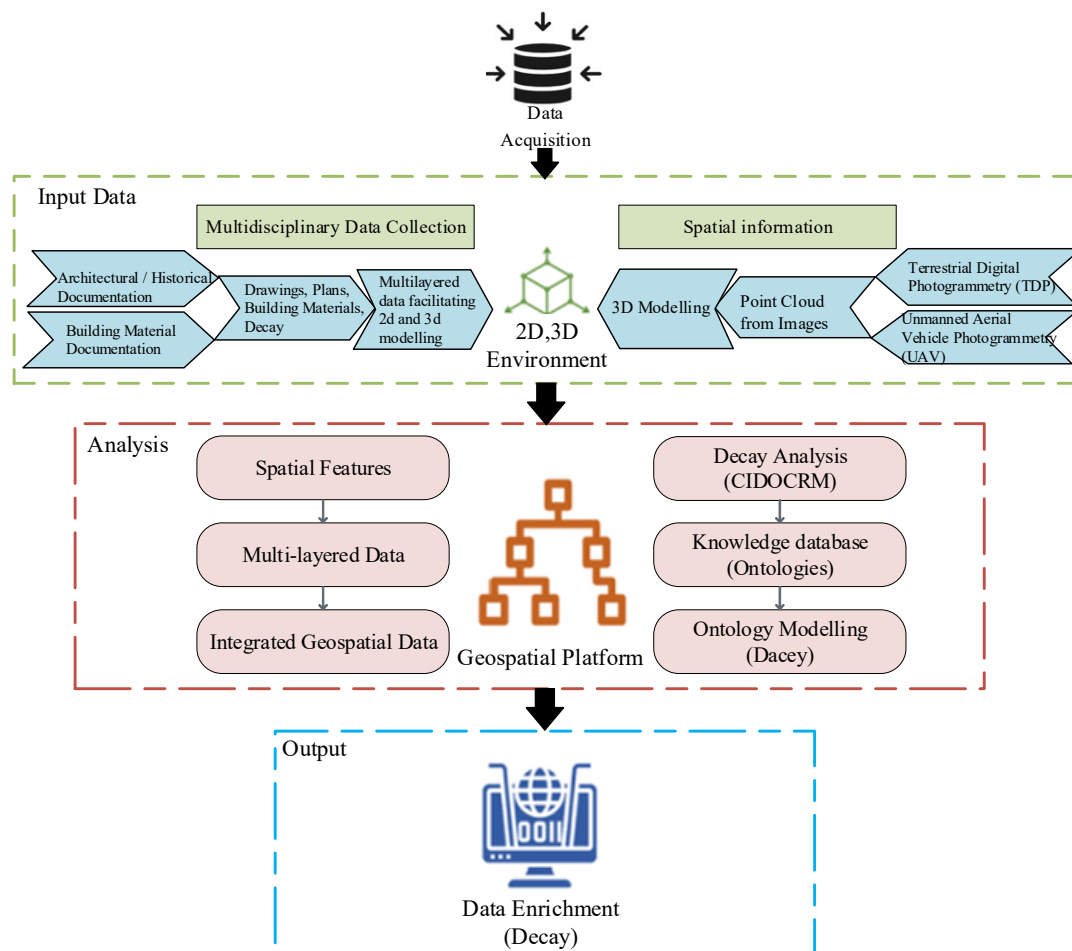


Figure 1. Conceptual framework of the study methodology.

2.1. Case Study

The historic city of Ibb in Yemen's central highlands is one of the best examples of a fortified Islamic city. The old city was built along a sloping terrain that made its natural and man-made defenses stronger. It is surrounded by a defensive stone wall that made an irregular quadrilateral shape [5]. The wall is about 1450 m long and 6 to 9 m high. It played

a key role in controlling access and making trade easier, marking the historical borders of Ibb and shaping its urban structure [54], as illustrated in Figure 2.

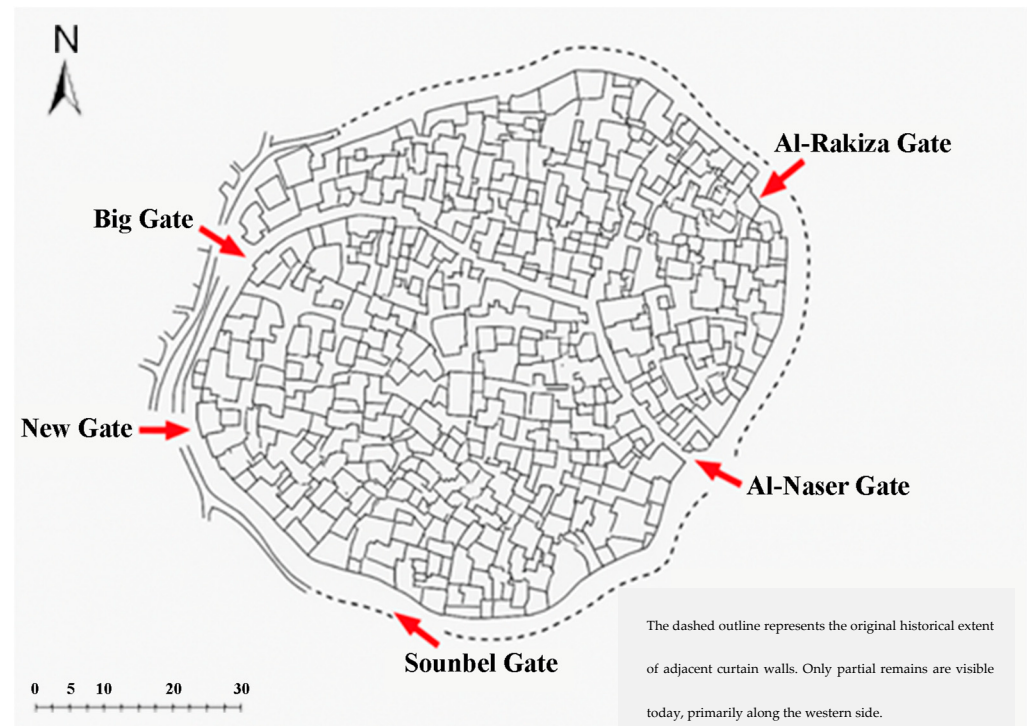


Figure 2. Study area location.

There are four sides to the wall, and each one used to have a main gate. The southern side, which is 313 m long, has four turrets (nubahs) and connects to both the Sounbel gate and the New Gate (also called Al-Jadeed or Al-Hukoomah gate). This is the point where the southern and western walls meet. The western side, which is 425 m long, used to have the huge Big Gate (Al-Bab Al-Kabir), which was the main entrance to the city. The northern side, which is the shortest at 283 m, has the Al-Rakiza gate, which is still the only gate that is completely intact. The eastern side, which is 429 m long, has the Al-Naser gate, which is only partially collapsed and has only one turret still standing [55]. Figure 2 shows that the five gates, Al-Naser, Sounbel, Big Gate, New Gate, and Al-Rakiza, gave people access to different parts of the city and were built in a way that was typical of Islamic defensive urbanism. The gates were part of semi-circular towers with narrow slits for watching over and defending the area. Field surveys and archival records show that many of them used the same materials and building methods [56].

In 1962, when the city started to grow beyond its historic borders, big changes were made to the adjacent curtain walls next door. During this time, several changes were made, such as making new openings, tearing down parts of walls, and building a new entrance for cars, the New Gate, to accommodate more traffic and the growth of the city. These changes made it easier for the city to grow and become more integrated, but they also changed the original enclosure's defensive and architectural integrity in a big way. The city went from being a fortified settlement to a more open and urbanized area. Even though the wall has changed a lot over time, a lot of it is still visible today, especially on the western and southern sides. These parts of the wall are still there to show how the city has changed in terms of architecture and space over time. It is interesting to note that the last major renovation of the wall before these modern changes was carried out in the 18th century (1120 AH) by Ministers Mohsen bin Ali Al-Hubaishi Al-Harbi and his

brother [57]. This restoration is the last known pre-modern effort to keep the structural integrity of the defensive boundary intact before modern changes began.

The Big Gate was the most prominent and architecturally refined of all the gates, serving as the main entrance to the city and featuring intricate wood carvings and inscriptions from the Rasulid period [54]. Over time, the gate deteriorated due to multiple stressors. The 1941 earthquake caused severe structural cracking, and subsequent flooding events in 1972 and 1982 further eroded its foundations [58]. It deteriorated more rapidly because of ongoing weathering and inadequate maintenance. Political instability, particularly the civil wars of the 1960s and the conflicts continuing since 2015, halted conservation efforts. By the early 2000s, the gate had been completely lost. Instead of reconstructing it at its original site, new gates were built in other sections of the wall using materials and designs inconsistent with the city's historic architecture and urban fabric. Although the Big Gate was physically lost, its cultural and spatial significance was reconstructed through archival sources, spatial analysis, and oral testimonies. Field measurements indicate that its original location is 149 m from the starting point of the western wall at the New Gate. The adjacent curtain wall section, extending 171.8 m beyond the former Big Gate site to a drainage outlet and another 133.2 m to the northern wall, remains partially intact. Five massive arched stone buttresses are anchored along a stone-paved alley running parallel to the wall, providing structural support. The northern wall, though fragmented due to urban encroachment, still retains the Al-Rakiza gate, located 200 m from the western junction [59]. This gate is 1.5 m wide and 2.4 m high, with its original wooden door intact, and is connected to Wadi Al-Sahool by a staircase of 44 steps. Conversely, the eastern side has undergone significant alterations; an 8 m-wide road now replaces the Al-Naser gate opening, and the remaining turret is currently repurposed for residential and commercial use. As part of this study, a comprehensive architectural and structural analysis of the wall and its gates was undertaken, documenting construction techniques, historical transformations, and dimensions. Appendix A presents these findings, supported by field surveys and archival records. The digital modeling and semantic interpretation of the adjacent curtain walls were based on this analysis. Table 1 indicates that the total length of the adjacent curtain walls is 1450 m, confirming that the current perimeter of the walls is approximately 1.5 km².

Table 1. Measured dimensions of the adjacent curtain walls of Ibb.

	Side	Length (m)
1	Southern side	313
2	Western side	425
3	Northern side	283
4	Eastern side	429
The total		1450 (1.5 km)

These metric measurements, as presented in Table 1, are not merely descriptive but form a foundational dataset for the HBIM and ontology-based modeling processes. They enable precise geometric alignment of the wall segments and gates within the 3D environment and ensure that structural elements, deterioration phenomena, and historical phases are semantically mapped with accuracy. By linking these dimensions to the ontology (CIDOC CRM), the model can establish spatial references for decay patterns and conservation scenarios, enhancing both the analytical depth and interoperability of the heritage database.

2.2. Data Acquisition and Processing

2.2.1. Survey Technology

The initial phase of the survey involved an on-site inspection to assess the terrain, identify potential obstructions, and prepare the area for photogrammetric acquisition. To achieve a high level of spatial coverage and resolution, a hybrid photogrammetric approach was adopted, combining dynamic UAV flights with TDP. UAV imaging provided a comprehensive aerial perspective, capturing vertical and oblique views of the curtain walls from multiple heights and angles, thereby ensuring continuous coverage of the upper sections that are inaccessible from the ground. At the same time, TDP uses a high-resolution DSLR camera to document the lower sections and areas requiring fine detail, such as cracks, stone joints, and surface textures.

This hybrid strategy effectively merged the strengths of both techniques: UAV flights ensured a broad spatial overview and reduced occlusions, while TDP captured fine geometric and textural details at a sub-centimeter resolution, critical for accurate 3D reconstruction and decay mapping. The workflow began with establishing a topographic control network, followed by dividing the wall perimeter into overlapping sectors, each captured through UAV passes with 80% forward and 60% side overlap. Control points and natural features visible in both the UAV and TDP datasets were used for precise co-registration. The UAV data were complemented by close-range TDP captures, which increased the accuracy of surface detail and allowed for the detection of localized deterioration patterns. While HDRI techniques were not feasible due to dynamic conditions, post-processing enhancements corrected image inconsistencies, ensuring that the generated orthophotos and dense point clouds provided both geometric accuracy and high visual fidelity.

2.2.2. Data Acquisition

To document the remaining segments of Ibb's adjacent curtain walls, a hybrid photogrammetric strategy integrating UAV imaging and TDP was implemented. This dual-method approach balanced large-scale spatial coverage with high-resolution detail, enabling accurate 3D reconstruction and fine-grained decay analysis. UAV flights provided nadir and oblique imagery covering the full vertical and horizontal extents of the walls, including rooflines and inaccessible upper sections. In parallel, TDP offered close-range, high-resolution imagery of masonry textures, joints, and decay phenomena (e.g., cracks, efflorescence, biological growth) not captured adequately by UAV images. The two datasets were merged using Structure-from-Motion (SfM) and dense matching algorithms to minimize occlusions and achieve sub-centimeter accuracy in critical areas.

The UAV survey utilized a DJI Mavic 3 Classic with a 4/3 CMOS Hasselblad camera (20 MP, 5280 × 3956 pixels) and a mechanical shutter to avoid rolling distortions. The 24 mm lens (35 mm equivalent) with adjustable aperture (f/2.8–f/11) ensured high-quality imagery (Figure 3). Multiple flight plans vertical (nadir), horizontal, and oblique guaranteed full masonry coverage (Figure 4). Images were acquired in JPEG format at maximum quality for consistent datasets and reduced post-processing complexity.

To minimize geometric distortions, standard photogrammetric practices were followed, maintaining 80% forward overlap and 60% side overlap. The Ground Sampling Distance (GSD) was calculated using Equation (1):

$$\text{GSD} = \frac{(\text{Focal Length} \times \text{Image Width})}{(\text{Sensor Width} \times \text{Flight Height})} \quad (1)$$

As shown in Figure 5, a maximum flight height of 22.85 m was used to achieve 0.01 m GSD for 1:100-scale modeling. UAV flights at lower altitudes enhanced detail capture of stonework and joints, while higher passes documented urban context. The UAV gimbal

tilt ($\pm 90^\circ$ to $+30^\circ$) ensured effective imaging of vertical surfaces. Ground-based imaging with a Nikon D810 DSLR (35 mm lens, 7360×4912 pixels) captured cracks, joints, and surface erosion. These images complemented UAV data, improving high-resolution decay mapping. Challenges such as narrow streets and vegetation were mitigated by strategic camera positioning. Ground Control Points (GCPs) and natural landmarks visible in both datasets enabled precise georeferencing and scaling of the 3D model.



DJI Mavic 3 Classic drone

(www.dji.com/mavic-3-classic)

- UAV (Unmanned Aerial Vehicle) equipped with Hasselblad 4/3 CMOS camera.
- Automatic or manual flight configuration via DJI Fly app or RC controller.
- Obstacle sensing system enabled with omnidirectional sensors (can be disabled when needed).
- Calculation of GSD (Ground Sample Distance) down to 1.77 cm/pixel at 10 m altitude.
- Recommended for 1:100 mapping scale with

Aircraft specifications	
Take-off weight (g)	895
Dimensions (mm)	221×96.3×90.3 (folded)
Max flight time (min)	46
Operating temperature range (°C)	0–40
Maximum work range (km)	Up to 15 km (O3+)
Satellite Positioning System	GPS/GLONASS/Galileo
Hover accuracy range – Horizontal (m)	±0.1
Hover accuracy range – Vertical (m)	±0.1
Camera specifications	
Sensor format	4/3 CMOS
Sensor	20 MP Effective Pixels
Lens	FOV 84°, 24mm equivalent, f/2.8 to f/11
ISO	Photo: 100–6400, Video: 100–6400
Image resolution (px)	5280 × 3956
Pixel size (µm)	3.3
Focal length (mm)	24 (equivalent)
Diagonal crop factor	1.0
Flight Plan parameters	
Near to far façade flying distance (m)	10–50
Near to far GSD (mm)	3.5–17.7
Area covered by near image (m)	14 × 10
Area covered by far image (m)	70 × 51
Vertical overlap (along flight line)	80 %
Lateral overlap	80 %

Figure 3. Specifications and photogrammetric setup of the UAV.

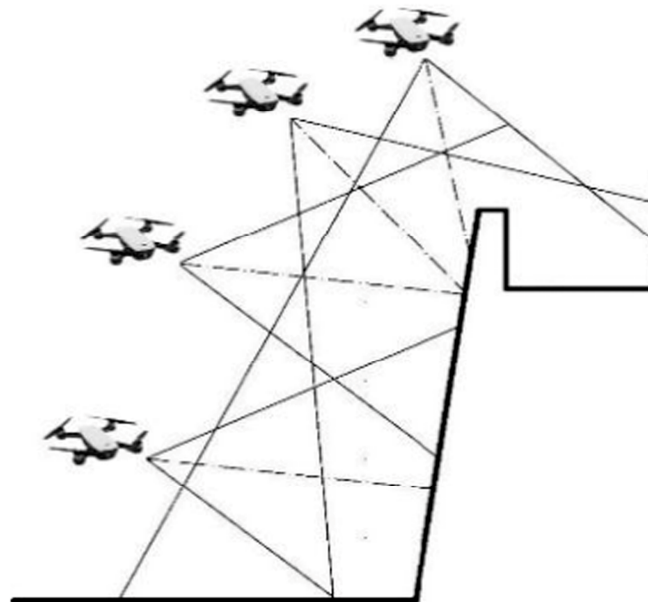


Figure 4. UAV flight paths for documenting the wall.

2.2.3. Post-Processing

Following data acquisition, a multi-software photogrammetric workflow was implemented to generate high-resolution dense point clouds and 3D textured meshes, which form the foundation for subsequent HBIM and semantic modeling tasks. The processing

was carried out using RealityCapture (<https://www.capturingreality.com> (v1.5, accessed on November 2024)) and Agisoft Metashape (<https://www.agisoft.com/> (v2.2.1, accessed on 13 July 2025)), both of which are state-of-the-art photogrammetry platforms optimized for Structure-from-Motion (SfM) and dense image matching. The combination of these two tools allowed for efficient handling of large datasets, parallel batch processing, and refinement of geometric accuracy while conserving fine surface details. To ensure spatial consistency, the resulting point clouds were aligned and georeferenced using CloudCompare (v2.13, accessed on 7 July 2024), where GCPs and natural features served as reliable spatial anchors. This step was essential for eliminating drift errors, harmonizing vertical and horizontal alignments, and accurately situating the model within the local coordinate system (WGS 84/UTM Zone 38N). Additional manual noise filtering and segmentation were conducted in CloudCompare to clean the dataset and improve the reliability of subsequent modeling processes. Following point cloud generation and refinement, ContextCapture (v23.0, accessed on 20 May 2023) was utilized for mesh generation and texturing, transforming the dense point clouds into triangular meshes with photorealistic textures. This step provided high-quality 3D visual outputs that accurately represented the surface features, materiality, and visual integrity of the curtain walls. Textures were applied to maintain natural color fidelity, enabling precise visualization of deterioration phenomena such as cracks, efflorescence, and biological growth. The workflow outputs included 3D textured meshes, orthophotos, and dense point clouds as primary datasets for HBIM integration. Since the Big Gate no longer exists, the reconstructed 3D model served both to document the existing western curtain wall and to digitally reconstruct the lost gate using historical images, eyewitness accounts, and architectural comparisons with similar gates like Sounbel and Al-Rakiza. The processed datasets were imported into Autodesk Revit and CAD platforms for semantic modeling, decay mapping, and 2D projections (plans, elevations, cross-sections).

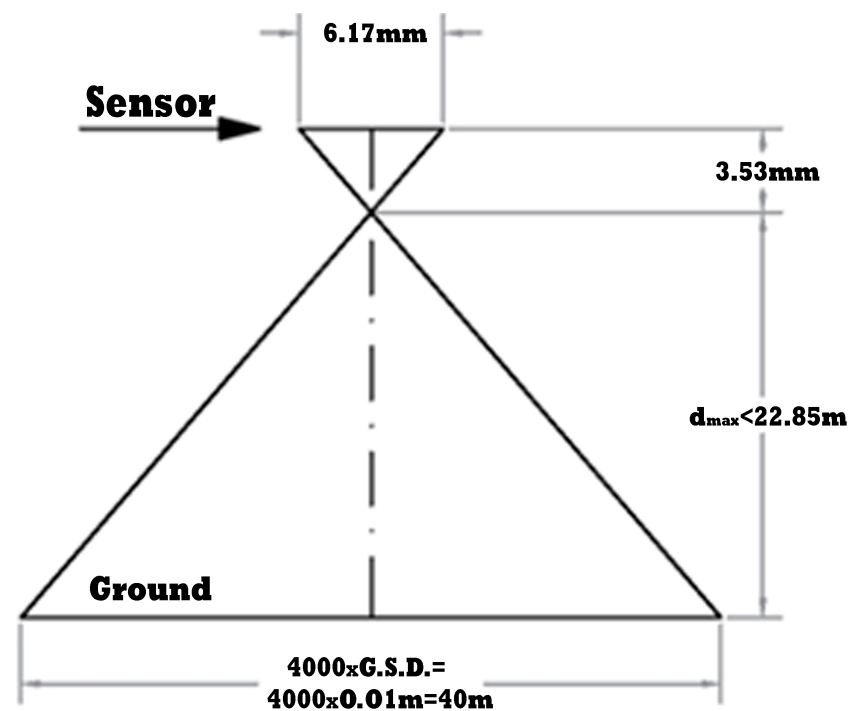


Figure 5. GSD-based maximum image acquisition distance.

The geometric and metric information obtained from UAV and TDP surveys, including the detailed measurements of wall segments and gate dimensions, directly supports the ontology-based modeling phase. These accurate spatial datasets provide the foundational

geometry for HBIM integration, enabling semantic annotations of structural elements, deterioration patterns, and historical interventions. The precise 3D models ensure that the ontology-driven analysis, particularly the mapping of decay phenomena such as cracks, efflorescence, and material disintegration, is both spatially consistent and metrically reliable. Thus, the survey and metric data are not standalone results but form a critical basis for the semantic enrichment and digital reconstruction of the Big Gate and adjacent curtain walls.

2.3. Decay Analysis

This study employed an ontology-driven approach to analyze decay phenomena, combining semantic structuring with field-based observations to support long-term conservation planning. The approach enabled the systematic classification, spatial mapping, and temporal tracking of various deterioration types, while also analyzing their underlying causes, both environmental (e.g., weathering, moisture) and human-induced (e.g., neglect, inappropriate restoration).

In heritage documentation, ontology provides a formalized framework for organizing and standardizing terms, relationships, and analytical workflows. By adopting ontology, heterogeneous knowledge (e.g., historical records, material data, and decay events) can be structured in a way that enhances semantic interoperability across digital heritage platforms. This study employs the CIDOC Conceptual Reference Model (CIDOC CRM, version 7.1.3) as the core ontology framework for semantic structuring and decay documentation (<http://www.cidoc-crm.org/> (accessed on 13 February 2024)) was adopted as the primary ontological framework. CIDOC CRM allowed for the encoding of critical heritage information, such as deterioration phenomena, environmental conditions, conservation interventions, and spatiotemporal attributes, in a consistent and queryable semantic structure.

The Protégé ontology editor (<http://protege.stanford.edu/> (v 5.5, accessed on 14 March 2019)) was used to create and refine the semantic schema. Protégé enabled the modeling of relationships between decay types, such as efflorescence, cracking, disintegration, and biological growth, providing a formal semantic mapping that links each phenomenon to its associated CIDOC CRM entities and properties. For example, E14 Condition Assessment was used to document efflorescence, while E3 Condition State represented cracks (see Table 2). Each decay class was enriched with metadata, including location, severity level, temporal occurrence, and causal factors, which were recorded during field inspections. The analysis also explored interdependencies among decay phenomena, for instance, cracks facilitating moisture ingress and thereby accelerating efflorescence or biological colonization. The ontology-based system was deliberately designed to be dynamic and extendable, enabling updates with newly observed data or refined diagnostic insights. By combining CIDOC CRM for standardized semantic management with Protégé for ontology creation, the study established a scalable and interoperable framework for documenting and monitoring decay processes. This enriched semantic dataset serves as a foundation for HBIM integration, allowing both current conservation needs and future interventions to be addressed through data-driven decision-making and predictive deterioration analysis.

This ontology-based decay analysis provided the semantic foundation for HBIM integration. By linking each deterioration phenomenon to CIDOC CRM classes and spatial attributes, the data could be embedded into the 3D Revit model as queryable attributes, enabling both visualization and data-driven conservation planning. This ensured a seamless transition from semantic analysis to integrated HBIM documentation, as detailed in the next section.

Table 2. CIDOC CRM class hierarchy (organizing decay phenomena).

E1	CRM Entity					
E2	-	Temporal Entity				
E3	-	-	Condition State			
E14	-	-	-	-	-	Condition Assessment
E5	-	-	-	Event		
E7	-	-	-	-	Activity	
E11	-	-	-	-	-	Modification
E18	-	-	-	-	Physical Thing	
E29	-	-	-	-	-	Design or Procedure
E41	-	-	-	-	-	Appellation
E39	-	-	Actor			
E52	-	Time-Span				
E53	-	Place				

3. Application

3.1. Ontological Model for Decay Records

After the survey and analysis of the decay state were finished, an ontology was created to accurately show how the heritage site's structure and degradation processes work. Even though the Big Gate is no longer there, it was rebuilt using old photos, eyewitness accounts, and comparisons with other gates that are still standing and look similar. This method made it possible to make a conceptual model of the gate, which ensured it was included in the larger heritage context. The ontology was based on well-known research frameworks, especially the CIDOC CRM. It provides a conceptual base for understanding, protecting, and managing the heritage site over the medium to long term. Figure 6 shows how the ontology was broken down into four main semantic domains: the artifact, the lifecycle, the investigation process, and the people who were involved. These domains were changed to fit the project's needs while still following logical frameworks from past research and accepted guidelines for conserving CH.

The artifact domain was split into classes that included both the construction and spatial parts. The spatial classes were made up of the spatial complexes (the whole structure), the spatial units (the different parts of the wall), and the spatial components (the smaller architectural details). Construction classes included the types of technology and materials used, such as foundations and walls. Each construction component was also described in terms of the materials used, which were mostly stone, lime mortar, and wood. In the investigation process domain, a lot of attention was paid to the direct and indirect analysis methods used to figure out how much decay there was. Geometric surveys, stratigraphy, material testing, and diagnostic procedures were all examples of direct analyses. Iconographic research and archival studies were examples of indirect analyses. These efforts made it possible to look closely at decay events like efflorescence, cracks, disintegration, and biological growth. The CIDOC CRM entities were used to further sort these decay records into groups within the ontology. Then, each type of deterioration was linked to the right CIDOC CRM entities (Table 3). For example, cracks were shown as instances of "E3 Condition State," and their assessment events were shown as "E14 Condition Assessment." Additionally, human-caused deterioration was explicitly modeled, taking into account human factors like neglect, urban encroachment, poor restoration, and damage caused by conflict. The model used "E5 Event" and "E7 Activity" to show these, which showed how socio-political events caused observed patterns of decay. New buildings that do not fit in with the historic fabric, especially near the old site of the Big Gate, were recorded as "E11 Modification" events that were linked to sequences of deterioration. These groups

were formalized by organizing them, matching each observed decay phenomenon with its CIDOC CRM category, semantic representation, and functional description. This was carried out to facilitate modeling and alignment (see Table 3).

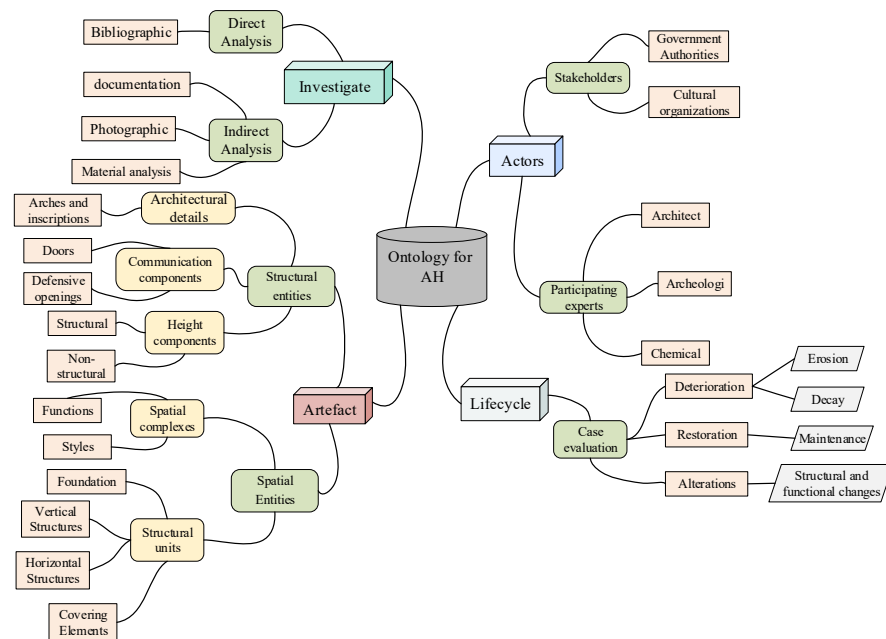


Figure 6. Conceptual ontology model for Architectural heritage.

Table 3. Semantic classification of observed decay phenomena according to CIDOC CRM.

Ontology Class Type	CIDOC CRM Class	Decay Phenomenon/ Representation	Cause	Description
Condition State	E3 Condition State	Cracks	Thermal expansion, mechanical stress, or foundation settling.	Visible fractures in stone or wood, ranging from hairline cracks to structural splits.
Assessment	E14 Condition Assessment	Disintegration	Erosion due to weathering, prolonged water exposure, and aging of materials.	Loss of material cohesion, causing crumbling or flaking of stone surfaces, leading to structural instability.
Material Entity	E18 Physical Thing	Efflorescence	Water infiltration through cracks or pores is followed by evaporation and salt crystallization.	Material loss (powdering/flaking) or salt crystallization on surfaces.
Process	E29 Design or Procedure	Erosion	Prolonged exposure to wind, rain, and other natural weathering agents	Gradual surface loss due to exposure to environmental agents (wind, rain, etc.).

Table 3. Cont.

Ontology Class Type	CIDOC CRM Class	Decay Phenomenon/ Representation	Cause	Description
Event	E5 Event	Biological Growth	Prolonged moisture exposure, poor drainage, and limited sunlight foster the development of moss, algae, and lichen colonies.	Visible green, black, or white biological patches appearing on stone or mortar surfaces, especially in shaded, damp, or poorly ventilated areas.
Event	E5 Event	Concretion	Hard mineral deposits form on surfaces due to prolonged water interaction.	Accumulation of mineral salts into hardened crusts or nodules on the stone surface.
Event	E7 Activity	Human-induced factors	Neglect, inappropriate restoration, war damage, and urban encroachment.	Structural deterioration resulting from human activities, such as collapse, erosion, or alteration of the original fabric due to neglect, conflict, or uncontrolled development.
Intervention	E11 Modification	Restoration Efforts	Post-decay interventions aiming to stabilize, clean, or reconstruct affected areas	Alterations to the original structure, either documented or inappropriate.
Records	E41 Appellation	Restoration Records	Not applicable (temporal metadata)	Documentation of prior interventions, field reports, and visual archives.
Human Action	E39 Actor	→Restoration teams/Urban planners/War agents	Decision-making errors, poor planning, and war-related interventions.	Linked to actions causing or mitigating deterioration.
Temporal Link	E52 Time-span	→Time of observation or event	Not applicable (temporal metadata)	Enables tracking degradation over time.
Place	E53 Place	→Spatial location of decay	Not applicable (temporal metadata)	Spatial indexing of decay locations across wall sectors.

An ontological network diagram was developed to clearly illustrate the semantic relationships and CIDOC CRM properties (P-numbers) that connect various types of decay phenomena, materials, assessments, and restoration activities. As shown in Figure 7, all relevant P-properties (e.g., P2 has type, P34 is concerned, P44 has condition) are represented, facilitating the visualization of how deterioration events such as Cracks, Erosion, Disintegration, and Restoration are interconnected within spatial and temporal contexts. In particular, the connector between “Condition Assessment” (E14) and “Disintegration” (E18) represents the CIDOC CRM property P35, which has been identified, indicating that the condition assessment process formally recorded and identified the disintegration phenomenon. This semantic linkage ensures traceability and standardization of deterioration documentation within the HBIM framework. To improve readability, Figure 7 uses color coding where red nodes represent observed decay phenomena (e.g., Cracks, Erosion, Disintegration), blue nodes represent CIDOC CRM classes (e.g., Condition Assessment, Time Span), and light brown nodes represent intermediate elements such as materials, cultural periods, artisans, and restoration events. Additionally, line styles have been standardized, with solid lines indicating semantic relationships represented by CIDOC CRM properties (P and dashed lines indicating class instantiation or indirect contextual relationships. Table 4 provides a detailed mapping of the relationships between environmental and structural conditions and the corresponding decay phenomena, helping to model the causes and progression of deterioration.

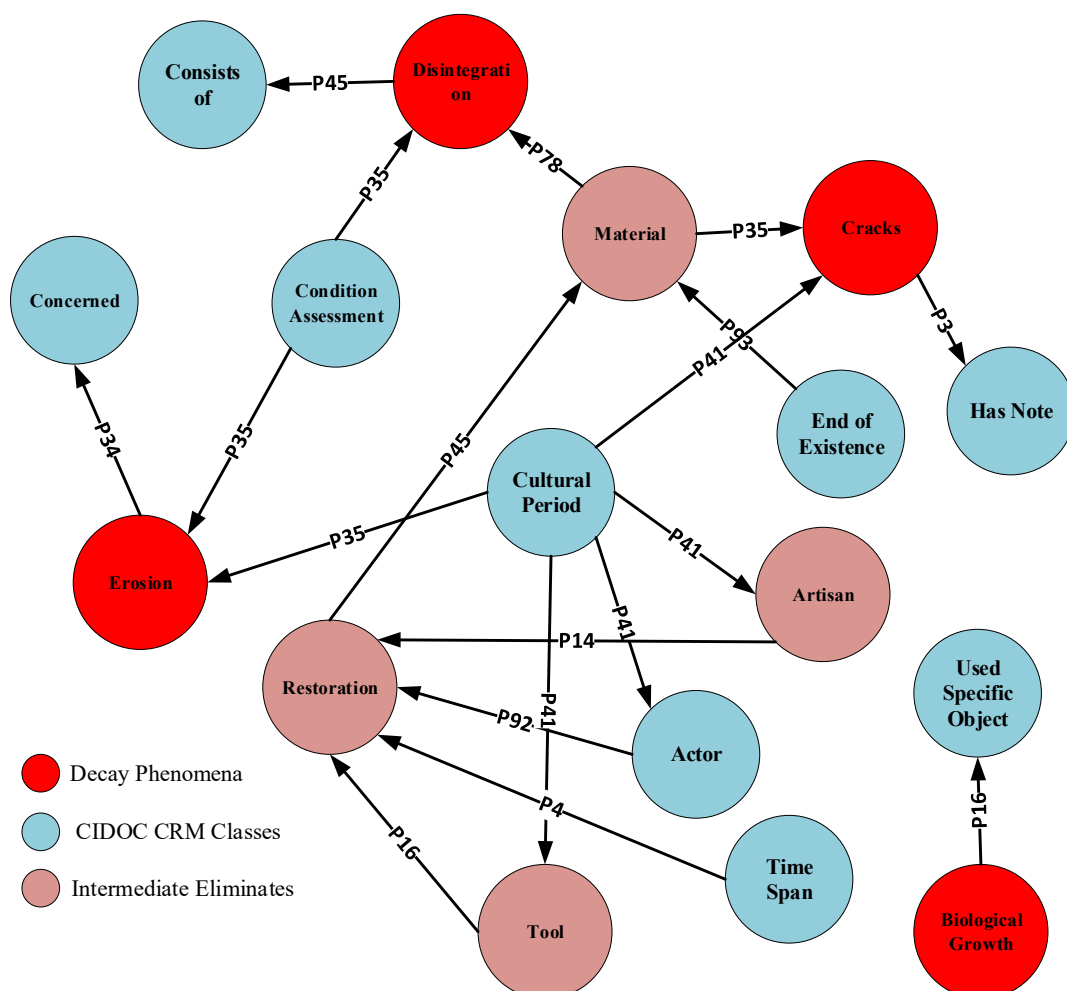


Figure 7. An ontology model showing semantic links and CRM properties between decay, materials, and restoration.

The observed classes were set up as a semantic network using Protégé, which showed how decay agents were related to each other in terms of time and cause. One example diagram shows a typical degradation chain: cracks (“E3”) lead to disintegration (“E18 Physical Thing”), which leads to restoration (“E11 Modification”). The connections between states were made clear by logical connectors like “P46 is composed of” and “P31 has modified.” For each decay instance, metadata attributes like location, severity, time of occurrence, and causal factors were recorded for each node in the model. This made sure that all the factors that affected the structure’s degradation were fully understood. This ontology was flexible and could grow, so it could be updated as new data were collected and studied. A new ontological model was made to fix the semantic relationships in the old diagrams, especially the ones between restoration tools and biological growth. This was carried out to fix logical problems. This corrected structure makes sure that event-based causality and tool use are shown correctly according to CIDOC CRM logic (Figure 8).

Table 4. Classification of environmental and structural influences on decay phenomena using CIDOC CRM properties.

Type	CIDOC CRM Class	Decay Phenomenon/Representation	Description	Cause	Key CIDOC CRM Properties (P)
Efflorescence	E3 Condition State	Salt crystallization	White crystalline deposits form on stone or wood surfaces, leading to material weakening.	Water infiltration followed by evaporation and salt crystallization.	P2 has type: Moisture ingress; P44 has condition: Prolonged water exposure; P34 concerned: Structural instability
Cracks	E3 Condition State	Structural cracks	Visible fractures in stone or wood, ranging from hairline cracks to structural splits.	Thermal expansion, mechanical stress, or foundation settling.	P2 has type: Environmental stress; P44 has condition: Structural instability; P34 concerned: Moisture ingress, prolonged exposure
Disintegration	E3 Condition State	Material loss	Material breakdown leads to crumbling or flaking, causing structural instability.	Weathering, prolonged water exposure, and material aging.	P2 has type: Water exposure; P44 has condition: Structural instability; P34 is concerned: Structural failure, prolonged exposure.
Biological Growth	E3 Condition State	Moss/algae/lichen colonies	The growth of biological organisms on surfaces accelerates material decay.	Retained moisture and environmental conditions favoring growth.	P2 has type: Moisture retention; P44 has condition: Environmental conditions; P34 concerned: Structural instability

Table 4. Cont.

Type	CIDOC CRM Class	Decay Phenomenon/Representation	Description	Cause	Key CIDOC CRM Properties (P)
Erosion	E3 Condition State	Surface erosion	Gradual surface loss due to wind, rain, and weathering.	Wind, rain, and other environmental factors.	P2 has type: Environmental stress; P44 has condition: Water exposure; P34 is concerned: Moisture ingress, structural instability.
Concretion	E3 Condition State	Mineral deposit formation	Hard mineral deposits form on surfaces due to water interaction.	Retained moisture and prolonged water contact.	P2 has type: Moisture retention; P44 has condition: Water exposure; P34 is concerned: Structural failure.
Human-induced Factors	E7 Activity	Neglect, war damage, poor restoration	Deterioration caused by human actions like neglect or inappropriate repairs.	Human interventions, conflict-related damage, and urban encroachment.	P2 has type: Inappropriate actions; P44 has condition: Environmental degradation; P34 is concerned: Urban encroachment, neglect.
Restoration Records	E41 Appellation	Restoration documentation	Records of past interventions, repairs, and structural changes.	Conservation efforts have been documented over time.	P2 has type: Restoration interventions; P44 has condition: Conservation state; P34 concerned: Restoration efforts

Note: this table shows how CIDOC CRM groups different types of decay phenomena, along with their descriptions, causes, and the CIDOC CRM classes that are most relevant to them. It also shows how each phenomenon is connected to environmental and human-made factors using CIDOC CRM properly.

There were a lot of technical problems when trying to add decay analysis to the HBIM system. This was mostly because ontology-based systems and BIM software do not work together directly. Instead of being directly imported, the ontology was used as a guide for modeling the structure in Revit to get around these problems. The ontology's class > sub-class > entity hierarchy was used to organize the HBIM model. In Revit, elements were grouped into families, family types, and instances. This structure made it easy to move ontological data into the 3D modeling environment. In the Revit environment, each type of decay, like cracks, disintegration, or efflorescence, was shown by loadable families that were connected to the architectural parts they belonged to. These families were added as visual overlays on the base structural model, creating a parametric framework for keeping track of how materials break down. For example, cracks were put on separate parts of the wall, and efflorescence was used as semi-transparent textures on the surfaces that were affected. This method made it possible to see decay phenomena in a structured way, which made it easier to do targeted analysis and data queries in the HBIM model. This system also made the documentation process easier and less prone to mistakes by automating the flow of data with RDF exports from Protégé and Python-driven parameter mapping.

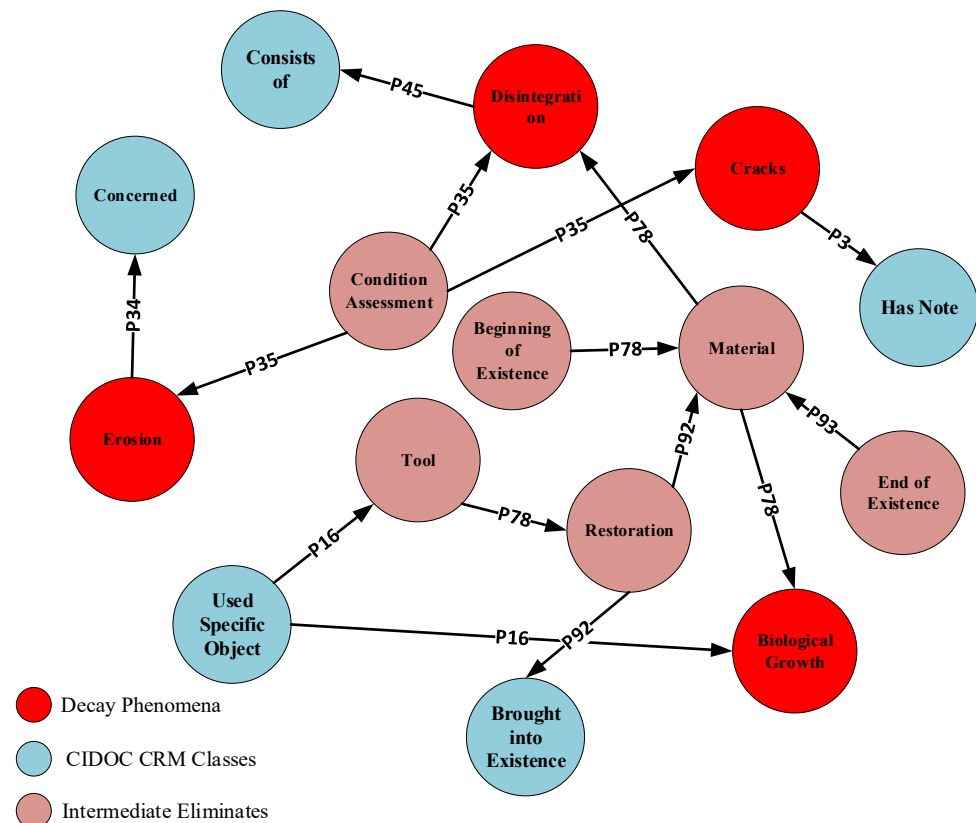


Figure 8. Refined ontology model illustrating semantic links for biological deterioration.

The integration of the ontological framework into the HBIM system was carried out through the following steps:

- (1) **Definition of Ontological Classes and IDs:** Ontological classes and identification codes (IDs) for all physical objects and forms of decay were defined in Protégé, aligning with BIM classifications to facilitate smooth data transfer into the HBIM environment.
- (2) **Export to RDF and Processing:** The defined classes and relationships were exported in RDF format and processed using Python (v 3.11.4) as shown in Supplementary Materials, and the Idlib (v 0.8.2) library to generate triples (subject, predicate, object). These were converted into JSON format for seamless handling within the BIM environment.
- (3) **Data Import into Dynamo:** The JSON data was imported into Dynamo (v 2.19.3) using ImportJSON nodes, ensuring structured organization and dynamic updates of the 3D model.
- (4) **Python Scripting for Decay Mapping:** Custom Python scripts within Dynamo mapped decay attributes (e.g., cracks, corrosion, material degradation) to the appropriate HBIM elements. The SetPropertyByName node was used to automatically populate element properties with ontology-driven decay information.
- (5) **LOD 350 Representation:** These steps ensured detailed integration of decay phenomena following the LOD 350 standard, enhancing both accuracy and visual representation.
- (6) **Creation of BIM Families:** New BIM “Families” were created to link host families (physical objects) with nested families representing specific types of decay. This allowed thematic mapping of deterioration directly within the 3D model.
- (7) **Structured Data Organization:** The classification and IDs for each decay type were cataloged (see Table 5a,b) to maintain data consistency and ensure easy integration into the HBIM system.
- (8) **Final HBIM Model:** The outcome was a dynamic and semantically enriched 3D database that documents the current condition of the Big Gate and adjacent curtain

walls. This model now serves as a flexible tool for ongoing monitoring, conservation planning, and future 3D data enrichment.

Table 5. (a,b) Decay Analysis and Structural Attributes.

(a)		
Family	Type	Instance (ID)
Decay	Efflorescence	DAn_D_Efflorescence_1
	Cracks	DAn_D_Cracks_1
	Disintegration	DAn_D_Disintegration_1
	Biological Growth	DAn_D_BioGrowth_1
	Erosion	DAn_D_Erosion_1
	Concretion	DAn_D_Concretion_1
	Human-induced factors	DAn_D_HumanFactors_1
	Squared Stone Masonry	DAr_M_SquaredMasonry_1
Base Wall	Squared Stone Masonry	DAr_M_SquaredMasonry_1
	Merlon	DAr_M_Merlon_1
Base Roof	Flat Roof	DAr_T_FlatRoof_1
Restoration Records	Documentation	DAn_R_RestorationRecords_1
Reconstructed gate	Architectural Features	DAn_Gate_Design_1
Reconstructed gate	Deterioration Analysis	DAn_Gate_Decay_Analysis_1
(b)		
ID-Code	Decay	Color Attributes
D-01	Efflorescence	Dark Green
D-02	Cracks	Yellow
D-03	Disintegration	Red
D-04	Biological Growth	Black
D-05	Erosion	Dark Orange
D-06	Concretion	Purple
D-07	Incongruous Elements	Light Blue/Cyan

3.2. Three-Dimensional Modeling and HBIM Integration

The ontology created in Protégé gave a structured way to organize both geometric and non-geometric data. This made sure that the 3D model would be complete and in line with long-term conservation goals. Although point cloud data collected via UAVDP and TDP surveys offered valuable insights into the structure's general shape and spatial context, these data came with inherent limitations. Point clouds are great for showing the outside shape of a building, but they are not as good for editing geometry or showing complex architectural details or changing patterns of decay, which are especially important for old buildings. To solve these problems, the point cloud data was brought into Autodesk Revit, where it could be turned into a 3D model that could be used and changed, as shown in Figure 9.

One of the main advantages of using Revit is its capability to support the creation of parametric models based on point cloud data. While Revit does not directly “turn” point clouds into parametric models, it allows users to trace, interpret, and model structural elements (such as walls, floors, and openings) from the main geometric features extracted from the point cloud dataset. This approach ensures precise modeling, even in areas exhibiting wear and tear, by referencing the highly accurate measurements provided by the point cloud. The parametric environment further facilitates modifications and updates as new information becomes available, maintaining accuracy throughout the conservation process. The Family Editor in Revit played a key role in this work, enabling

the creation of custom families with tailored parameters for each structural element. These parameters included not only geometric and material properties but also specific patterns of deterioration, such as cracks, efflorescence, and disintegration. A Dynamo script was also implemented to automate the assignment of shared parameters to wall elements using external JSON data (Figure 10).

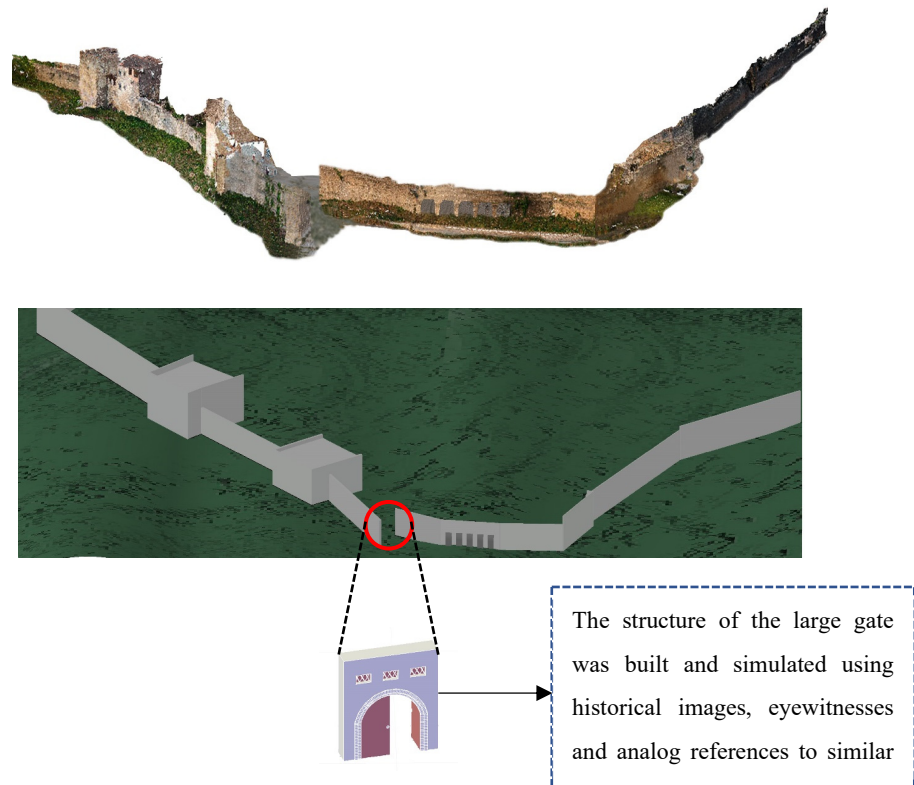


Figure 9. Geometrical appearance in BIM software is generated from a 3D point cloud.

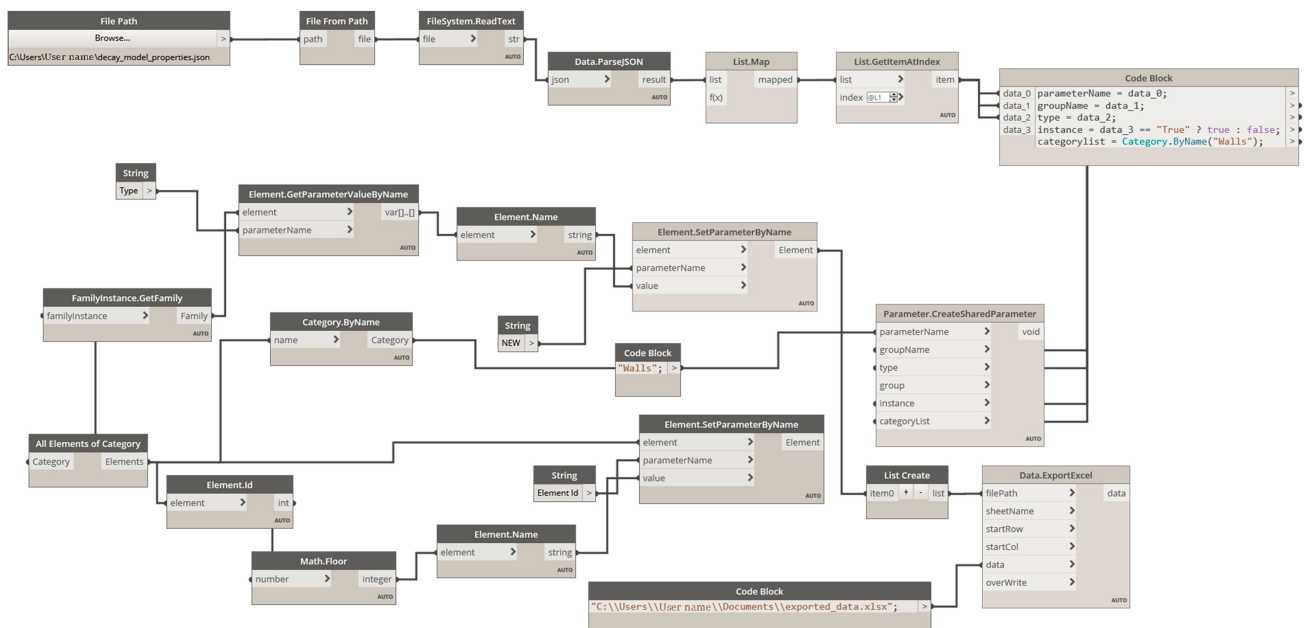


Figure 10. Automated Dynamo workflow mapping JSON attributes to shared wall parameters in Revit.

To address the challenge of representing the Big Gate’s deterioration despite its absence, historical data were carefully matched up with the geometric model. The custom families were used to add the different types of decay to the 3D model, and the decay patterns were linked to the right CIDOC CRM classes. A second Dynamo routine was added to give architectural parts specific attributes that show how they are deteriorating. This made it possible to integrate structured semantics into the HBIM model (Figure 11). These connections made it possible to figure out which parts of the wall and gate were decaying, using both direct and indirect methods like stratigraphy, material testing, and iconographic research. The model not only showed what was happening with the decay, but it also let the decay be mapped out in space very accurately. For instance, cracks that were seen in historical documents were linked to the right walls and parts in the 3D model, and efflorescence was shown as a clear layer on top of the affected surfaces. This method made it possible to show damage in great detail, which helped find and study areas that had gotten worse, even in hard-to-reach places. The HBIM model became a dynamic, multi-dimensional tool by adding Protégé’s ontology framework to it. The model changed from a simple geometric shape to a digital storage space that held both historical and structural data. This made it much more useful for conservation purposes. Revit’s BIM tools made it possible to create a variety of outputs, such as 2D drawings, exploded views, and detailed visual aids. These were very important for letting stakeholders like conservators, architects, engineers, and the public know about the building’s condition and what needed to be carried out to fix it.

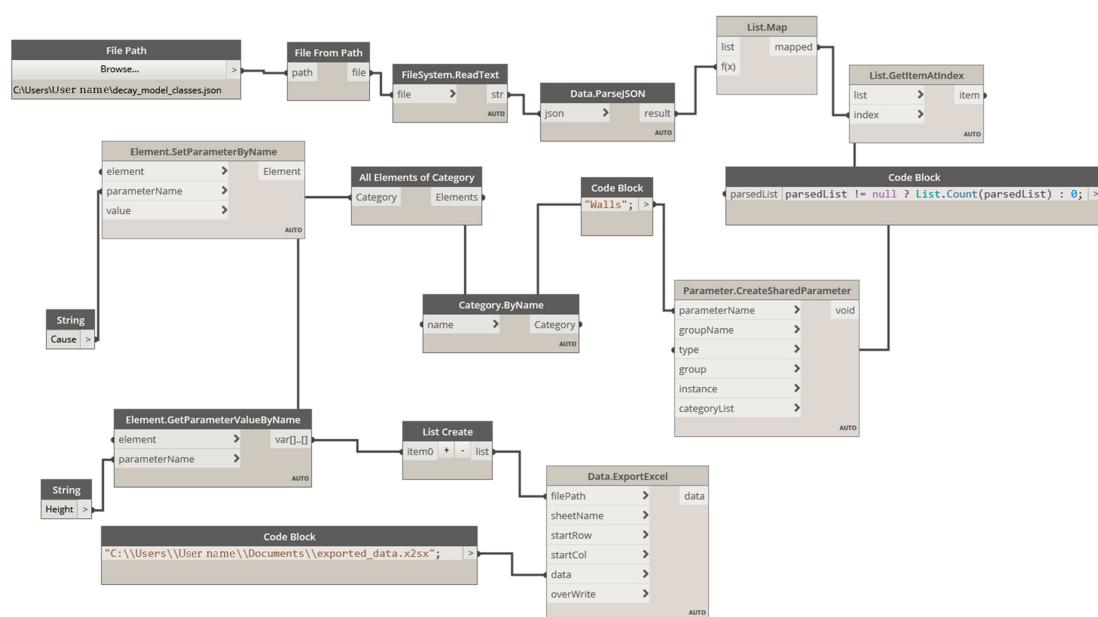


Figure 11. Dynamo routine assigning deterioration parameters to wall elements from JSON data.

The Revit environment is creating a family library, containing reusable components for future model updates. This library made it easy to add new structural elements, decay phenomena, or material updates, which made sure that the HBIM model could change as conservation efforts moved forward. This flexibility was necessary for the model to last a long time, as it made sure that the HBIM system would still be useful for future updates, inspections, and possible restorations. Also, the project was bigger than just making a 3D model that could be changed. The HBIM model became a 3D database when the Protégé-based ontology framework was added to it. This change was important because it allowed the model to record not only the building’s physical features but also important information about its history, material composition, structural integrity, and how it has changed over

time. The ontology helped organize and categorize non-geometric data by connecting each architectural element to historical, environmental, and decay-related information. For example, the ontology made sure that certain parts of a building were linked to past construction phases, repairs, material degradation, and exposure to environmental factors like weathering or human activity. This extra information made the HBIM model a useful tool for long-term conservation because it showed the current condition of the building and gave context for figuring out why it was getting worse. By putting this information into the 3D model, it became more useful and meaningful, offering insights that could guide future conservation strategies and actions.

The integration of non-geometric data significantly enhanced the capabilities of the HBIM model, making it much more powerful than traditional CAD drawings, which only show geometry and do not include a lot of historical or condition-related data. The HBIM model's 3D nature, along with modern survey tools and integrated data, made it easier to understand the structure as a whole and in a more intuitive way. This helped historians, conservators, architects, engineers, planners, and other professionals from different fields work together more effectively, which made the whole conservation planning process better. Also, the model became a complete representation of the building when it could combine historical data with current survey data and decay analysis. It took into account not only the current state of things, but also how heritage conservation is always changing. This change from a digital geometric model to a 3D database format made the HBIM model a living document that could be updated, queried, and analyzed at any time to help with adaptive management strategies and long-term conservation goals. The HBIM model was improved even more by using thematic mapping techniques after it became a dynamic 3D database. These visual overlays added decay types like cracks, efflorescence, and disintegration directly into the 3D environment using parameterized and color-coded families. The model made it easy to see how damage was spread out and how bad it was across structural elements by combining semantic deterioration data with spatially explicit representations. This integration not only made it easier for conservation stakeholders from different fields to talk to each other, but it also helped prioritize restoration strategies based on spatial analysis and material vulnerability, as shown in Figure 12.

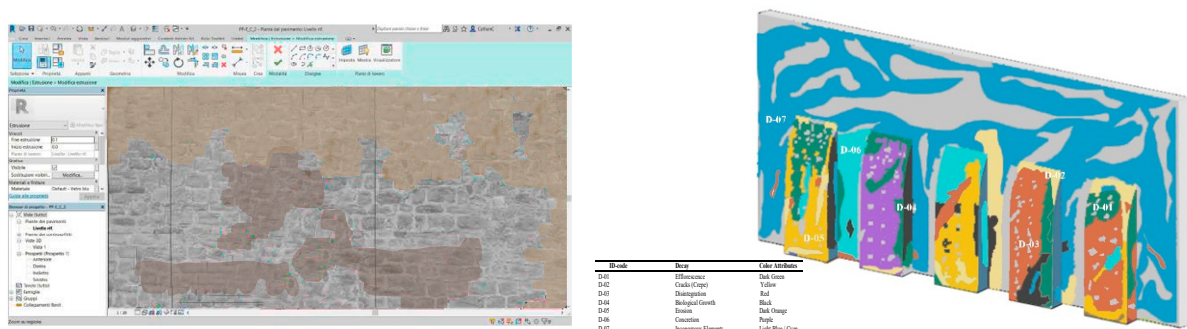


Figure 12. Thematic mapping of decay patterns within the Revit-based HBIM model.

3.3. Enrichment of 3D Models with Historical and Structural Data

Following the initial development of the HBIM model in Revit, the next step was to enrich the 3D model by integrating historical, structural, and semantic data. This enrichment process was designed to comprehensively address the decay phenomena affecting the Big Gate and the adjacent curtain walls. The integration of CIDOC CRM and the ontology developed in Protégé significantly enhanced the HBIM model by providing a structured semantic framework that systematically linked geometric components with non-geometric attributes, including decay typologies, historical phases, and conservation events. CIDOC CRM classes (e.g., E3 Condition State and E14 Condition Assessment)

and P-properties allowed deterioration phenomena, such as cracks, efflorescence, and biological growth, to be documented as structured, queryable entities connected to specific architectural elements. This semantic enrichment transformed the HBIM model from a static geometric representation into a dynamic 3D knowledge base, enabling advanced queries, historical context analysis, and predictive conservation planning.

CIDOC CRM served as the foundational ontology framework for connecting architectural, material, and historical data to individual elements of the HBIM model. This integration ensured a deeper linkage between the building's geometric structure and its historical context. As a result, the model evolved from a purely visual representation into a rich, multi-dimensional dataset necessary for informed conservation planning. A comprehensive ontological schema was constructed to unify existing models by merging CIDOC CRM class hierarchies, property definitions, and deterioration typologies into a single semantic framework (Figure 13). An important aspect of this enhancement involved systematically grouping different types of decay affecting the structure. The ontology developed in Protégé allowed the mapping of various deterioration phenomena—such as efflorescence, cracks, disintegration, and biological growth—directly onto the 3D model. This formalized system ensured consistent identification and classification of decay events. Each deterioration phenomenon was linked to specific CIDOC CRM entities, with E14 Condition Assessment and E3 Condition State playing central roles in standardizing condition documentation according to international heritage conservation practices. In addition to technical decay modeling, a broader ontological structure was developed to integrate cultural periods, artisan roles, and restoration contexts. As illustrated in Figure 14, this interconnected structure situates deterioration phenomena within a wider historical, social, and technological framework, supporting a holistic and context-aware approach to heritage management.

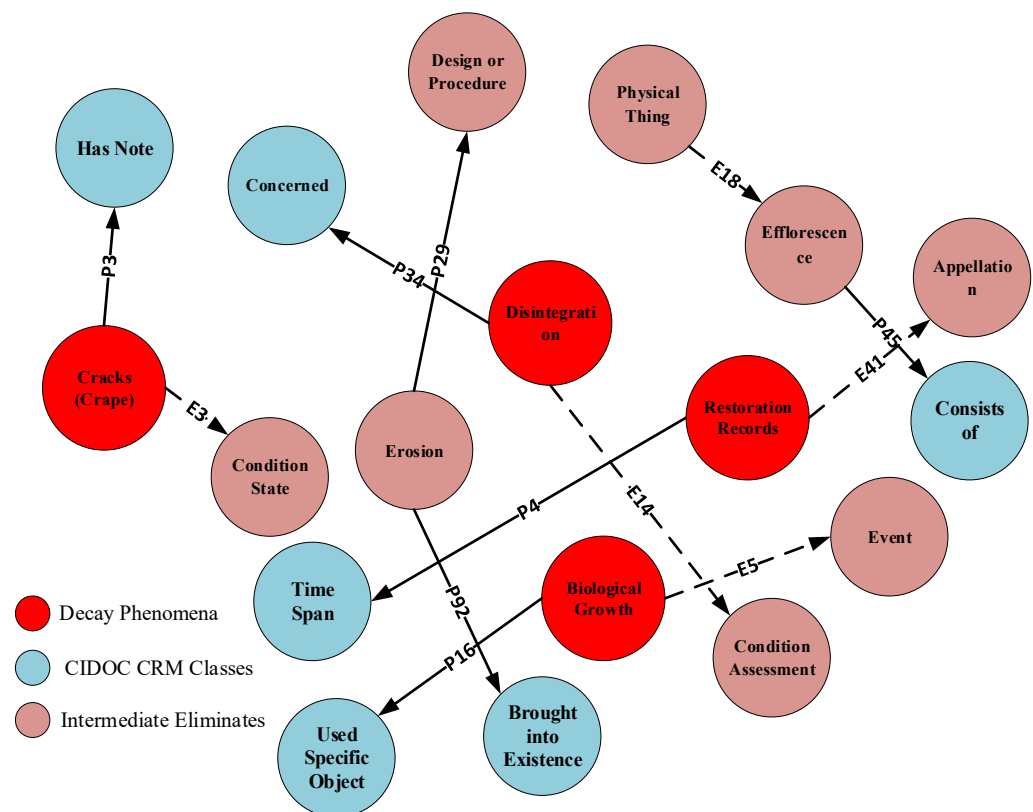


Figure 13. Integrated ontology model combining CIDOC CRM classes and properties for holistic decay representation.

The categorization process made it possible to accurately map the spatial distribution of decay phenomena within the 3D model. By linking each instance of decay to the architectural part that it affected, the model made it possible to accurately find and study areas that had gotten worse, even in parts of the structure that were hard to access or complicated. This process needed a lot of detail, including sub-centimeter accuracy, to find small and irregular deterioration that might not have been noticed otherwise. This level of accuracy was necessary to keep the model's integrity and make sure that there was a clear, accurate record of the current state of conservation. In the Revit environment, the enriched data was put into structured schedules to make it easier for people to work together and access it. These schedules showed the decay and condition of each part of the building in a way that was easy to understand and full of information. Also, the data was exported to more user-friendly platforms like Excel and Microsoft Access (v 2024) for stakeholders who were not as familiar with BIM software. This makes it easier for people who are not tech-savvy, like historians, conservators, and the general public, to use the data, help with analysis, and make smart choices about what to do next. Also, the use of external data-processing tools made it possible to create complex queries, reports, and databases from the data in the 3D model. These outputs encourage collaboration between different fields, allowing experts from different fields to use the same platform to query the database for specific insights, evaluate conservation needs, and plan interventions. A holistic, flexible management approach was possible because it was easy to obtain and change data. This meant that conservation efforts could change based on new or updated data.

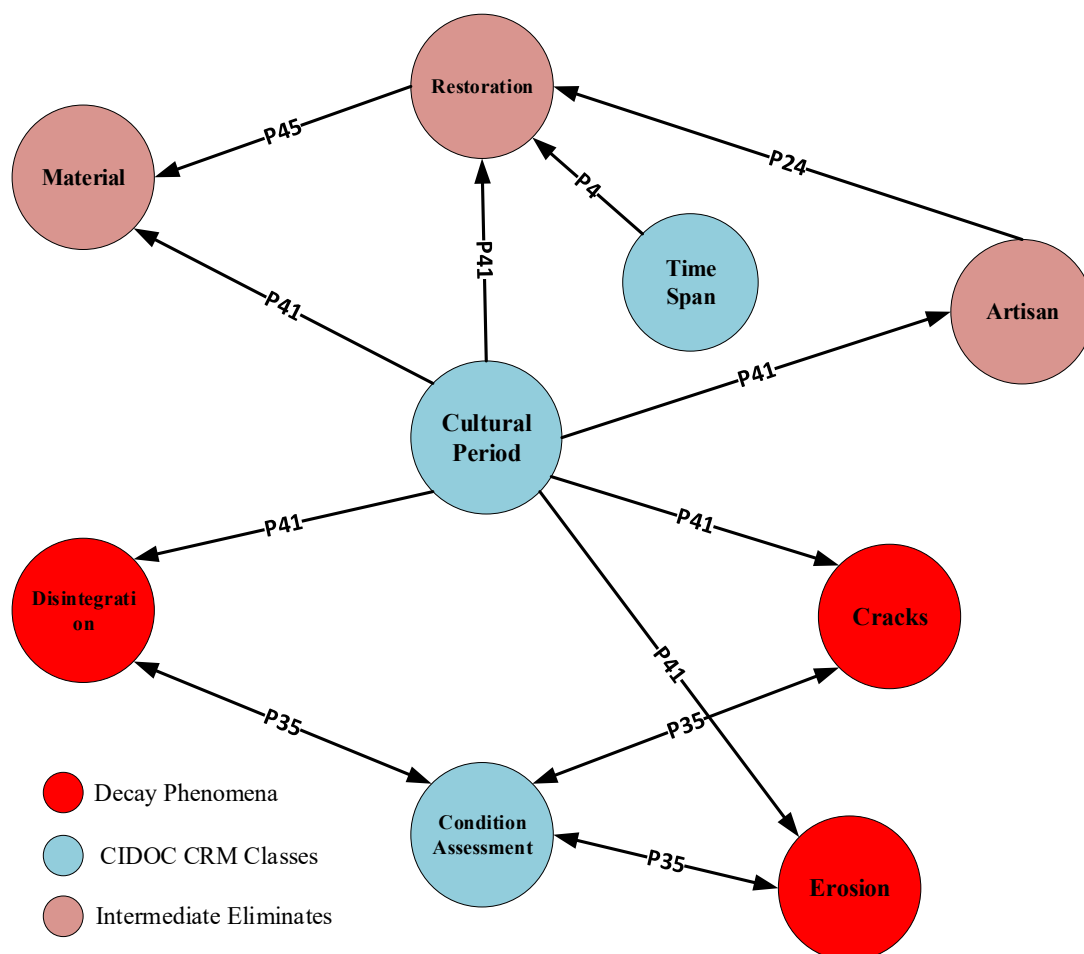


Figure 14. An ontology model linking decay to cultural context, restoration, and artisan roles.

The integration of decay made the model much more accurate. It went from being a static 3D picture to a dynamic, changing tool for managing the case study's conservation. The model now showed the structure's current state in great detail and was also a useful tool for making decisions and keeping an eye on things over time. This method made the HBIM model into a living database that could change with the building's condition in the future. It became an important platform for keeping an eye on the building's health and making sure that any new conservation work followed the rules and best practices that had already been set in AH conservation. The integration of photogrammetric modeling, multidisciplinary data acquisition, and ontology-based semantic analysis within the HBIM environment provides a comprehensive framework for both the documentation and long-term management of AH. High-resolution photogrammetric data ensure accurate geometric representation of existing conditions, while multidisciplinary datasets ranging from historical archives and material studies to environmental and structural analyses enrich the model with contextual and diagnostic knowledge. By embedding these heterogeneous data into a semantic ontology aligned with CIDOC CRM, the HBIM model evolves from a static 3D representation into an intelligent knowledge-based platform capable of querying, analyzing, and visualizing the spatial and temporal dynamics of deterioration. This integration not only supports predictive maintenance and proactive intervention planning but also enhances data interoperability and knowledge transfer across disciplines, ensuring that conservation strategies remain scientifically informed, historically accurate, and sustainable over time.

4. Conclusions

The rapid advancement of digital technologies has fundamentally reshaped the field of AH conservation, extending far beyond traditional practices of surveying, drafting, and documentation. This study highlights the transformative potential of integrating HBIM with semantic ontologies, particularly CIDOC CRM, as a means to enhance the documentation, interpretation, and conservation of heritage assets. Focusing on the Big Gate and the adjacent curtain walls of the historic city of Ibb in Yemen, a comprehensive framework was developed that combines geometric modeling through Autodesk Revit with ontology-based enrichment using Protégé and CIDOC CRM extensions. This dual-layered approach bridges the gap between spatial data and semantic knowledge, enabling a deeper understanding of the structural, material, and historical dimensions of the site. The resulting model not only captures the architectural geometry but also encodes deterioration phenomena such as efflorescence, cracking, and material loss by linking them to specific architectural elements and contextual records. This allows the model to serve as a dynamic conservation tool that can evolve, supporting ongoing monitoring, documentation, and decision-making processes. Importantly, the ontology-driven strategy transforms the HBIM model from a static record into a living system capable of accommodating real-time updates and supporting long-term maintenance planning. This adaptability ensures that both tangible and intangible heritage values are conserved coherently and sustainably. Beyond its specific application to the Big Gate and curtain walls, the proposed methodology is scalable and transferable to other historic structures, such as fortifications, religious buildings, and vernacular architecture. The interdisciplinary collaboration among architects, historians, engineers, and conservators further reinforces the model's robustness, ensuring a holistic conservation approach that respects both physical integrity and cultural significance. Additionally, the integration of photogrammetric modeling, multidisciplinary data, and ontology-based semantic analysis strengthens the HBIM framework as a proactive tool for heritage management. This synergy ensures accurate documentation, predictive maintenance, and sustainable conservation planning over time. Looking ahead, the framework offers a foundation for

future enhancements through the integration of artificial intelligence and machine learning techniques. These could facilitate predictive modeling of deterioration processes, thereby enabling more proactive and data-informed conservation strategies.

Supplementary Materials: The following supporting information can be downloaded at: <https://doi.org/10.5281/zenodo.16754977>, Code S1: Code for integrating ontology (Decay) model with CIDOC CRM property name hierarchy; Code S2: Python code to create RDF from class name hierarchy.

Author Contributions: B.Q.D.D.: Conceptualization, Methodology, Field investigation, Data curation, Formal analysis, Visualization, Writing—original draft, Writing—review and editing. D.J.: Conceptualization, Supervision, Methodology, review & editing, validation, resources. A.Q.D.: Methodology, Survey, Data curation, Validation, Writing—review and editing. Y.A.: Visualisation, writing—review & editing, validation, resources. S.A.: Review & editing, resources, visualization. A.H.: Review & editing, validation, resources. A.B.: Conceptualization, Supervision, Methodology, review & editing, validation, resources, Project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors state that they have no conflicts of financial interest or personal relationships that could potentially impact the objectivity or integrity of research findings.

Abbreviations

The following abbreviations are used in this manuscript:

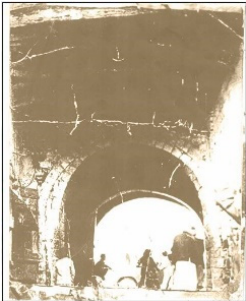
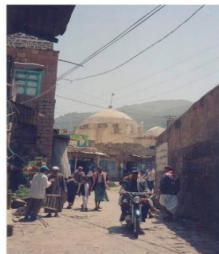
AH	Architectural Heritage
CH	Cultural Heritage
UAV	Unmanned Aerial Vehicle
TDP	Terrestrial Digital Photogrammetry
GCPs	Ground control points
HBIM	Historic Building Information Modeling
BIM	Building Information Modeling
3D GIS	Three-dimensional Geographic Information Systems
CIDOC	The International Committee for Documentation
CRM	Conceptual Reference Model
HDRI	High Dynamic Range Imaging
SfM	Structure-from-Motion
GSD	Ground Sampling Distance
IDs	Identification Codes
RDF	Resource Description Framework
IoT	Internet of Things
ARMOS	Architectural Data Object Schema
MONDIS	Monument Damage Description Information System
STAR	Semantic Technologies for Archaeological Resources

Appendix A

Table A1. Structural description, architectural analysis, and field measurements of the historic adjacent curtain walls and gates of Ibb.

	Description	Length (Field Measurements)	
The Southern Side and Sounbel gate	The southern part of the adjacent curtain walls starts at a turret (nubah) and goes to the eastern side, where it meets the New Gate, which is where the southern and western sides meet. At first, the southern side had four turrets, with one at the beginning and another at the middle, close to New Gate. The last two turrets surrounded Sounbel gate, which was named after Prince Senbel Al-Sadiq, who led Imam Al-Mansur Hussein bin Al-Mutawakkil Qasim’s army. There are only two turrets left of the Sounbel gate today, and the original wooden gate is gone. Modern homes have blocked off the area around the gate, making it hard to see what it used to look like. The way it is built is very similar to the round gates in Baghdad, which were mostly built to protect the city from attacks. It was noted during field visits that other gates, like the Big Gate, Al-Rakiza gate, and Al-Naser gate, were built in the same way. This will be talked about in more detail later.	The distance from the start of this side to the turret at Sounbel gate, which looks out over the street, is 87 m. The turret itself is 12 m wide. The distance between this turret and the one in the middle of the southern side is 60 m. The turret is also 9.40 m wide. The total length from the start of the southern side to its midpoint turret is 168.40 m. The distance from the middle of the southern side to the end point at New Gate is also 144.60 m. So, the southern side is 313 m long in total.	 Sounbel gate
The northern side and the Al-Rakiza gate	The northern side of the adjacent curtain walls, which is the shortest of the four sections, looks out over Wadi Al-Sahool (Al-Sahool Valley). Only small pieces of this wall are still standing because cities are growing and new buildings are going up. The Al-Rakiza gate, which is 200 m from the starting point of the northern side, is one of the most interesting things about this side. Even though it is small, it’s the only gate that is still standing. The wooden door that came with it is still there. The way Al-Rakiza gate was built is the same as the way Sounbel gate and the Big Gate were built, which makes it even more useful as a defense. There are 44 steps on a stone staircase that goes down from Al-Rakiza gate to Wadi Al-Sahool. This staircase used to be an important link between the city and the valley. The northern side goes past Al-Rakiza gate and eventually meets the eastern side of the wall at Dar Al-Hakim (Hakim’s House). At this junction, a turret is attached, marking the meeting point between the northern and eastern sides of the wall.	Al-Rakiza gate, which is 200 m from the starting point on the northern side, was an important reference point for the measurement. The gate’s size was carefully recorded, and it was 1.50 m wide and 2.40 m tall. After that, the measurement went from the Al-Rakiza gate to the point where the northern side meets the eastern side, which is 83 m away. So, the northern side is 283 m.	 Al-Rakiza gate

Table A1. Cont.

	Description	Length (Field Measurements)	
The Eastern side and Al-Naser gate	The eastern side starts at the turret near Dar Al-Hakim and goes all the way to the turret at the Al-Naser gate. Today, only one turret of the Al-Naser gate is still standing. It is 7 m wide, and the other turret has fallen. A street that is 8 m wide has taken the place of the original gate opening. The remaining turret has been turned into a home and business space. The eastern side goes on past the Al-Naser gate until it reaches the turret, which connects it to the southern side.	The measurement process started at the turret close to Dar Al-Hakim, which was the eastern side's starting point. The wall goes 234 m from this turret to the turret at Al-Naser gate, which is 7 m wide. The eastern side goes on for another 180 m past Al-Naser gate, ending at the turret that connects it to the southern side. So, the total length of the eastern section that has been recorded is 429 m.	 Al-Nasr Gate opening and its turret.
The Western side and the Big Gate	The wall's western side starts right at New Gate, which is where the southern and western sides meet. There is no longer a gate here; instead, there is a 10 m-wide path. Even though a lot of time has passed, a lot of the western side is still there, especially from its starting point at New Gate, which is 12 m long. Five big arched stone buttresses along the outside of this side help hold up and strengthen the wall. These buttresses sit on a stone-paved path next to the wall. The Big Gate, which was 149 m from the western side's starting point, is now completely gone, and there are no visible remains. The western side goes on past the Big Gate and ends at an opening that drains rainwater. The western side of the wall goes on past this drainage opening until it meets the northern side of the wall.	The western side starts at New Gate, which is a 10 m-wide path. A 12 m piece is still there from this point on. The distance between the New Gate and the Big Gate is 149 m. The western side goes on for 171.80 m from here until it reaches a hole for draining rainwater. The western side goes another 133.20 m past the drainage opening, where it meets the northern side of the wall. So, the total length of the western side, from New Gate to where it meets the western side, is 425 m.	 The western façade of the wall supported by buttresses.
			
	The lost Big Gate [60] (Archive)		
			
The Big Gate (Leaving only a 10 m-wide pathway)			

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