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Towards the architectural heritage information infrastructure: a UML-based information model linking HBIM, smart point clouds, and 3D Gaussian splatting

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ABSTRACT

This paper presents the Architectural Heritage Information Infrastructure (AHII), a standards-operational framework for maintaining identity, semantics, and traceability across three complementary representations used in heritage workflows: Smart Point Clouds (SPC), HBIM/IFC, and Smart 3D Gaussian Splatting (S3DGS). AHII is centered on a compact UML information model and governed code lists, and it operationalizes cross-representation continuity through a shared alignment transform and an explicit identifier crosswalk. This design supports task-driven switching between evidence-grade inspection (SPC), standards-based querying and exchange (IFC), and lightweight photorealistic dissemination (S3DGS), while maintaining auditable correspondence across iterative updates. We validate AHII on two Dutch case studies using a reproducible protocol with fixed evaluation splits and independent checkpoints, complemented by an online, task-anchored user study ($N = 200$). Results provide evidence of cross-representation interoperability, together with task-appropriate technical performance: intrinsic SPC segmentation reaches macro-mIoU ≈ 0.88, cross-representation co-location achieves 3D RMSE on the order of 1–3 cm, and IFC4 round-trip checks preserve GUIDs with near-lossless property-set retention. Together, these findings show that AHII can be implemented in practice as a traceable information infrastructure linking documentation, modeling, standards-based data and semantic exchange, and dissemination across heterogeneous representations.

1. Introduction

Architectural heritage is vital to human cultural heritage, reflecting the notion of human legacy emphasized by UNESCO.[1] These structures and sites are relics of the past and vibrant testimonies of historical narratives, architectural ingenuity, and cultural continuity [1,2]. Beyond their intrinsic cultural and aesthetic value, architectural heritage is crucial in fostering a deep sense of local identity and pride [3–5]. It connects communities to their past and educates future generations about their history and traditions [6,7]. Furthermore, well-preserved heritage sites can be significant economic assets by attracting tourists, boosting local economies, and promoting sustainable development. Protecting these treasures, therefore, is essential to preserving historical integrity, nurturing cultural diversity, and driving economic vitality worldwide [8–10].

Information-driven techniques are integral to architectural heritage conservation, conferring notable strengths in data standardization, semantic consistency, and system interoperability, thereby improving the quality and efficiency of integration and sharing [11]. However, digital conservation still faces substantial challenges across the heritage

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[1] UNESCO. World Heritage Convention. Available online: https://whc.unesco.org/en/conventiontext/ (Accessed on 16 July 2025).

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information lifecycle, largely due to the heterogeneity, complexity, and sheer volume of heritage-related information [12–14]. Across the architectural heritage information lifecycle (e.g., data collection, transmission, curation, and archiving), numerous technical modalities such as point clouds and Smart Point Cloud (SPC) for documentation, as well as integrative digital environments including Geographic Information Systems (GIS), Building Information Modeling (BIM), and Heritage Building Information Modeling (HBIM), 3D Gaussian Splatting (3DGS), supported by platforms such as Docomomo International, have been introduced and continuously refined [15–23]. Although several review studies have mapped application scenarios, traced technological trajectories, and examined possibilities for cross-technical integration [24,25], these efforts still fall short of achieving truly integrated information systems [26,27]. In practice, the field continues to struggle to move from isolated or loosely coupled tools to integrated information systems that maintain information continuity across representations and stakeholders [7].

The observed integration gap can be attributed to three interrelated factors that jointly undermine information continuity and reliable exchange. Firstly, the fragmented nature and lack of interoperability among existing digital technologies hinder efficient integration and seamless data exchange, compromising comprehensive heritage management [28,29]. Secondly, current systems lack sufficient interaction and user engagement capabilities, thereby failing to meet the diverse and dynamic needs of stakeholders, including heritage experts, researchers, policymakers, and the general public [30,31]. Lastly, the absence of standardized frameworks leads to insufficient semantic enrichment and inconsistent data standardization, limiting clear and effective information dissemination [32,33].

In summary, the practical bottleneck in architectural-heritage digitization is increasingly not acquisition or model creation itself but maintaining continuity of identity and semantics when information is transferred, updated, and used across heterogeneous representations and platforms. These limitations reduce information continuity across the heritage information lifecycle, because element identity and semantics often become inconsistent when information is transferred across heterogeneous representations and platforms. This motivates a central research question: *How can we enable interoperable use and conversion of heterogeneous heritage representations while preserving the persistent identity of elements, consistent semantics, and traceable exchange?* To address this question, we further formulate three specific research questions.

RQ1: What design factors and requirements are necessary to establish such an infrastructure in architectural heritage contexts, given fragmentation, limited interoperability, and inconsistent standardization?
RQ2: How can these factors be operationalized into a unified framework and formal specification that links documentation modalities, semantic models, and visualization within a traceable workflow?
RQ3: How can the resulting infrastructure be evaluated reproducibly on real projects in terms of cross-representation interoperability, semantic consistency during transfer, and practical utility for users?

To address these questions, this paper responds to **RQ1** by summarizing where today's heritage digitization workflows break when moving across representations, responds to **RQ2** by defining AHII with a concise UML specification and code lists, and responds to **RQ3** by validating it through case studies and a reproducible evaluation. The contributions are: (a) a standards-aligned AHII specification (UML plus controlled code lists), (b) a practical interoperability mechanism using a shared transform and an explicit ID crosswalk (IfcGUID–patch_id–cluster_id) with integrity audits, and (c) evidence from an evaluation protocol covering semantic transfer, geometric co-location, exchange integrity, and user-facing utility, with a focus on end-to-end information continuity rather than isolated accuracy gains.

2. Foundations for AHII: Insights from literature

Digital technologies have introduced a wide range of tools and workflows for the preservation of architectural heritage [34,35]. In this section, a PRISMA-guided[2] review and bibliometric mapping are used to identify the dominant technology families and their coupling patterns, and to locate the recurring integration gaps that motivate the AHII requirements and its theoretical model.

2.1. Review protocol and corpus construction

A PRISMA-guided review was conducted to map dominant technological dimensions in architectural heritage digitization. English-language, peer-reviewed articles were retrieved from Web of Science and Scopus, including the Science Citation Index Expanded, Social Sciences Citation Index, and Arts and Humanities Citation Index. The search query combined heritage terms, TS = ("architectural heritage" OR "heritage building*" OR "historic* building*" OR "cultural heritage" OR "built heritage" OR "monument*"), with digital-technology terms, TS = ("digital technolog*" OR "digital tool*" OR "digital method*" OR "digital platform*" OR "information infrastructure"). Using PRISMA 2020, we identified 1,913 records from Web of Science (n = 886) and Scopus (n = 1027). After removing duplicates and ineligible items, and following automated filtering, manual screening, and quality assessment, 227 publications were retained for bibliometric and technical analyses. Technology-specific keywords were cleaned and normalized, retaining terms such as photogrammetry, laser scanning, point-cloud processing, BIM, HBIM, GIS, semantic segmentation, and immersive interaction. VOSviewer was then used to construct a keyword co-occurrence network, where node size represents frequency and link strength indicates co-occurrence intensity.

The resulting clustering reveals four major technology families that organize the landscape of architectural heritage digitization. The first family centers on immersive interaction, where AR and VR connect to intelligent processing and engagement-related themes, reflecting an increasing focus on stakeholder-facing interpretation. The second family focuses on documentation and reconstruction, where photogrammetry, laser scanning, and point-cloud processing anchor the capture and preprocessing workflow [36–38]. The third family concentrates on BIM and HBIM, which support semantic enrichment and object-based information organization and frequently co-occur with acquisition terms, indicating the consolidation of scan-to-model practices in heritage contexts [39–41]. The fourth family relates to platform-scale management and spatial context, where GIS, remote sensing, and digital platforms support multi-scale organization and analysis [5,42].

Beyond the four-family structure, the network identifies several bridging nodes that connect multiple families and thus serve as integration pivots. In particular, point cloud-based acquisition, BIM or HBIM information modeling, AR or VR interaction, and GIS show comparatively dense cross-family links in the network, as can be observed from the link thickness in Fig. 1. Where needed, this observation can be quantified using VOSviewer[3] outputs by reporting total link strength for these nodes and summarizing the strongest cross-family links (co-occurrence intensity in Appendix A1). For single-building heritage workflows, the prominence and coupling of point clouds, BIM or HBIM, and AR or VR suggest that these technologies constitute a practical core for infrastructure construction. At the same time, GIS provides an important bridge for contextualizing and connecting assets to broader

[2] PRISMA: An evidence-based reporting guideline (comprising a checklist and flow diagram), designed to ensure transparent, complete reporting of systematic reviews and *meta*-analyses. Last search date: [09–09–2025].

[3] VOSviewer: A software for constructing and visualizing bibliometric networks from bibliographic data, including coauthorship, cocitation, and keyword cooccurrence maps.

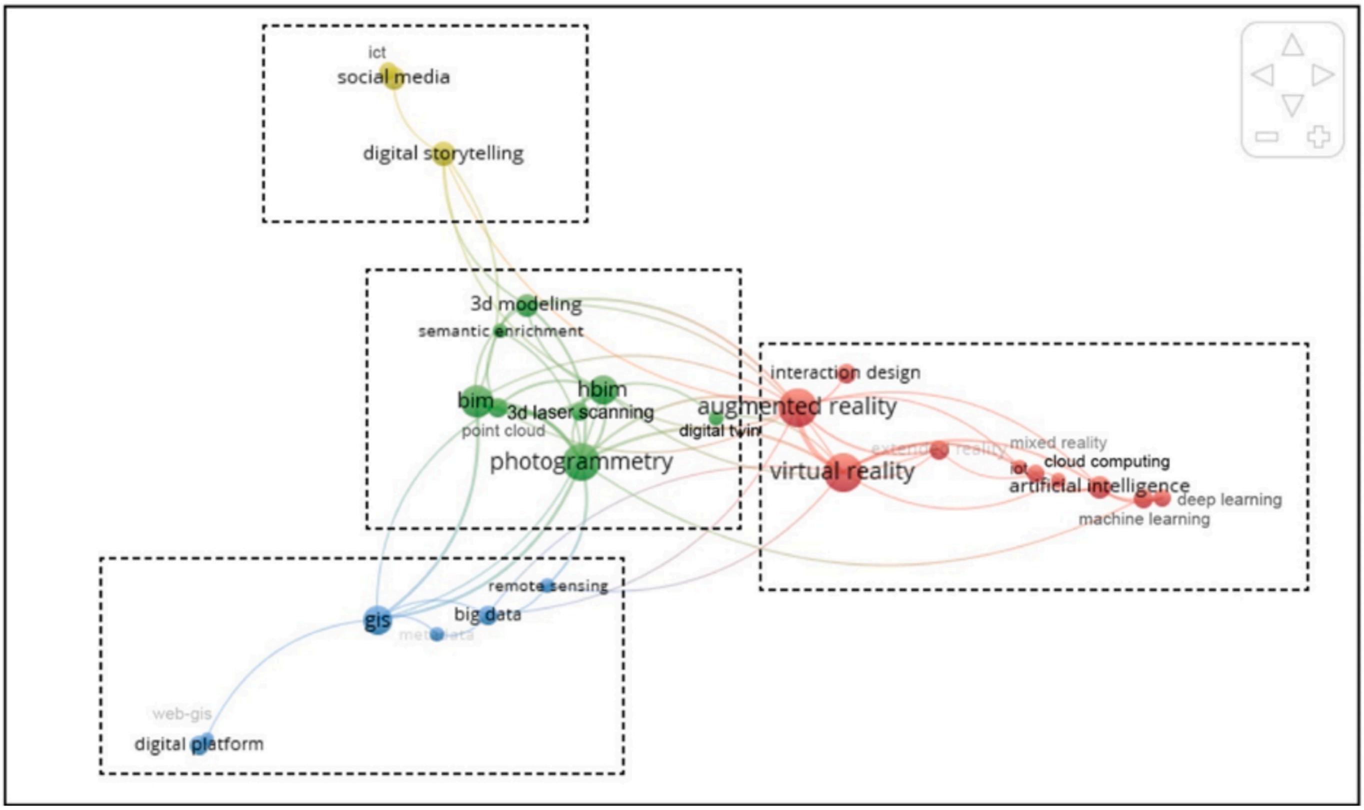

Fig. 1. Network Analysis: the review for the methodological foundation of AHII.

management environments. This evidence establishes the central technology pivots for AHII design and also leaves room for later extensibility toward platform-scale and multi-asset applications.

However, identifying these technology families and coupling pivots is only a first step. To motivate AHII as an information infrastructure rather than a loose combination of tools, it is also necessary to examine what functional roles these technologies are expected to support jointly in a closed-loop workflow, and where recurring integration difficulties arise when information moves across representations. The next section therefore translates the review findings into functional needs and recurring integration challenges.

2.2. Functional needs and recurring integration challenges in closed-loop workflows

Building on the technology families and integration pivots identified, we next consider what these coupled technologies are expected to achieve within a closed-loop heritage workflow. Architectural heritage digitization is iterative rather than one-off (Fig. 2). New surveys, corrective updates, annotations, and reinterpretations repeatedly propagate backward to refine upstream representations and forward to dissemination and engagement, forming a closed-loop workflow over the heritage information lifecycle [43]. In such a workflow, integration quality is determined by whether a set of functional needs can be satisfied consistently at handoff points between documentation modalities, information models, platform-scale environments, and interactive visualization [10,44,45]. The literature indicates that these needs are repeatedly undermined by recurring integration challenges, which motivates an infrastructure-level response rather than ad hoc tool coupling [19,45].

A first functional need is identity continuity, so that the same heritage element can be tracked across point-based documentation, object-based information models, and visualization or dissemination assets. A recurring challenge is that element-level correspondence often becomes

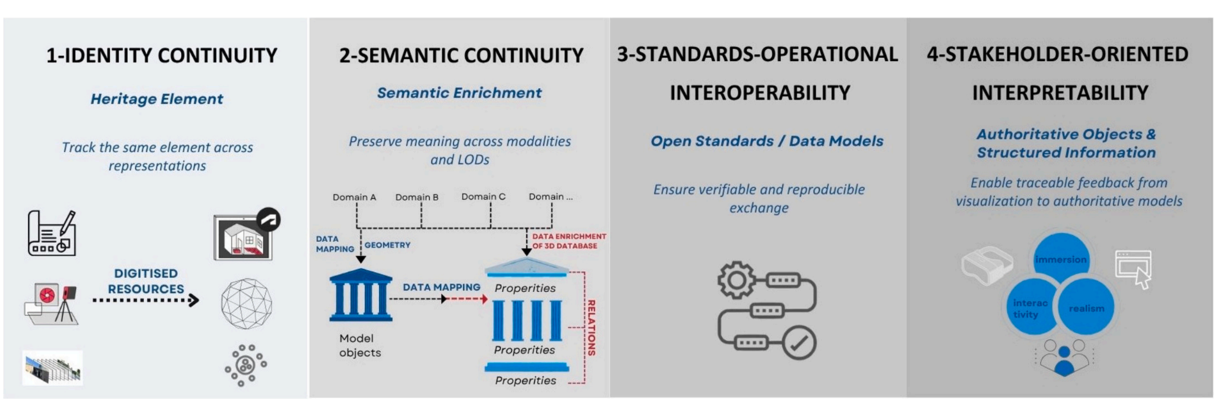

Fig. 2. Functional needs for an AHII framework.

project-specific or is lost when information is transferred across tools and software ecosystems with different granularity and representation units [46]. This weakens lifecycle traceability and makes closed-loop propagation of updates and feedback difficult.

A second functional need is semantic continuity, so that meanings introduced during enrichment remain interpretable and consistent when transferred across modalities and levels of detail [47]. A recurring challenge is semantic drift during enrichment and transfer. HBIM supports structured semantics and attributes, while point clouds remain semantically sparse unless segmentation and labeling are introduced [48,49]. Even when labeling exists, differences in granularity, uncertainty, and representation constraints can lead to semantic inconsistency when semantics are transferred across modalities or simplified for delivery, limiting coherent cross-representation interpretation and query [50].

A third functional need is standards-operational interoperability, so that exchange across toolchains is not only possible but verifiable and reproducible. A recurring challenge is inconsistent standardization and limited auditability of the exchange. Standards and open models are increasingly referenced, yet mappings are often undocumented, extensions are handled inconsistently, and property sets and code lists may be treated differently across pipelines. Without explicit exchange logic and verification procedures, integration becomes fragile and hard to reproduce or extend beyond single projects.

A fourth functional need is stakeholder-oriented interpretability with traceable feedback, so that interactive and immersive environments can support communication and engagement while remaining anchored to authoritative objects and structured information [51,52]. A recurring challenge is the decoupling between visualization assets and structured information at the stakeholder interface. Visualization outputs and interaction records often lack stable links to authoritative objects and semantics, which limits their contribution to expert review and closed-loop update.

2.3. Requirements for an operational AHII focusing on single-building heritage

For an operational AHII focused on single-building architectural heritage while remaining extensible, the preceding review suggests that many of the recurring integration challenges emerge at representation handoffs. Based on this synthesis, we distill a small set of implementation-oriented requirements that translate the functional needs identified above into concrete design targets. Table 1 summarizes the literature-derived requirements for an operational AHII and translates them into design implications. Their concrete realization is presented in **Sections 3-4** and evaluated in **Sections 5–6**.

Table 1
Literature-derived requirements for operational AHII and their design implications.

Requirements	What it demands in practice	Design implication for AHII
Identity persistence	Stable identifiers across formats and updates	Preserve authoritative identity and explicit cross-representation links
Auditable transforms	Repeatable, traceable transforms	Make alignment and conversion inspectable artifacts
Semantic authority and transfer policy	Defined semantic authority and transfer rules	Separate authoritative, proposed, and propagated semantics
Delivery decoupling	Independent evolution of visualization outputs	Preserve links between delivery interfaces, evidence, and semantics
Exchange integrity	Verifiable exchange of identifiers and properties	Pair standards-based exchange with validation checks
Closed-loop updateability	Traceable revision propagation	Maintain versioned mappings and update pathways

3. Towards a UML-based AHII framework

Building on the requirements identified above, this section operationalizes AHII as a closed-loop information infrastructure for single-building architectural heritage (Fig. 3). It first defines the core layers and cross-layer artifacts of the framework, and then consolidates them into a UML-based information model.

3.1. Layer specifications and minimum requirements

AHII is operationalized through three complementary layers, SPC, HBIM/IFC, and S3DGS (Table 2), together with a small set of cross-layer artifacts that support alignment and correspondence across representations [53,54]. Each layer is defined not only by its conceptual role but also by a minimum set of required artifacts and deliverables that enable reproducible exchange and linkage (Table 3).

(a) SPC layer: evidence and semantic proposal.

Within AHII, SPC functions as the evidence layer and carries patch-level instance structure together with traceable semantic proposals. Here, “smart” denotes that geometry is coupled with persistent identifiers, sidecar semantics, and provenance/version records, so that interpretations can be revised and audited over time rather than fixed as final authority. Because architectural interpretation may evolve, AHII treats SPC semantics as revisable proposals, with manual refinement restricted to boundary-guided merge/split edits recorded in a revision log. The minimum requirements and deliverables of the SPC package are summarized in Table 3.

(b) HBIM/IFC layer: semantic container and adjudication

HBIM/IFC serves as the standards-oriented semantic adjudication layer in AHII, anchoring authoritative identity and structured attributes for exchange and downstream query. When semantics derived from SPC are introduced into HBIM, they are treated as proposed semantics until confirmed through adjudication, so that discrepancies remain explicit rather than being silently overwritten. In this way, HBIM/IFC acts not simply as a model container, but as the layer where semantic normalization and concordance checking become auditable. The minimum requirements and deliverables of the HBIM/IFC package are summarized in Table 3.

(c) S3DGS layer: queryable visualization

S3DGS serves as the queryable visualization layer in AHII. It is not treated as an independent semantic authority; instead, semantics are propagated from SPC under a shared spatial reference and remain traceable through cluster-level identifiers and cross-layer correspondence. This allows S3DGS to support lightweight interaction and dissemination while remaining linked to evidence and adjudicated semantics. The minimum requirements and deliverables of the S3DGS package are summarized in Table 3.

(d) Cross-layer artifacts and linkage mechanisms

Cross-layer traceability in AHII is maintained through two explicit artifacts: a shared alignment transform and an identifier crosswalk (Table 3). The transform records the shared spatial reference used to align SPC, HBIM/IFC, and S3DGS, so that correspondence can be reproduced across tools and revalidated after updates. The crosswalk records explicit correspondences among IfcGUID, patch_id, and cluster_id, including relation types for non-1:1 mappings and confidence or reason codes where correspondence is ambiguous.

Together, these artifacts support the closed-loop logic of AHII. Semantics attached to S3DGS are propagated from SPC under the shared spatial reference, while HBIM serves as the adjudication layer in which injected SPC proposals are checked against object-level semantics and attributes. In this way, the transform record, crosswalk mapping, and propagation provenance form a minimal exchange bundle that can be

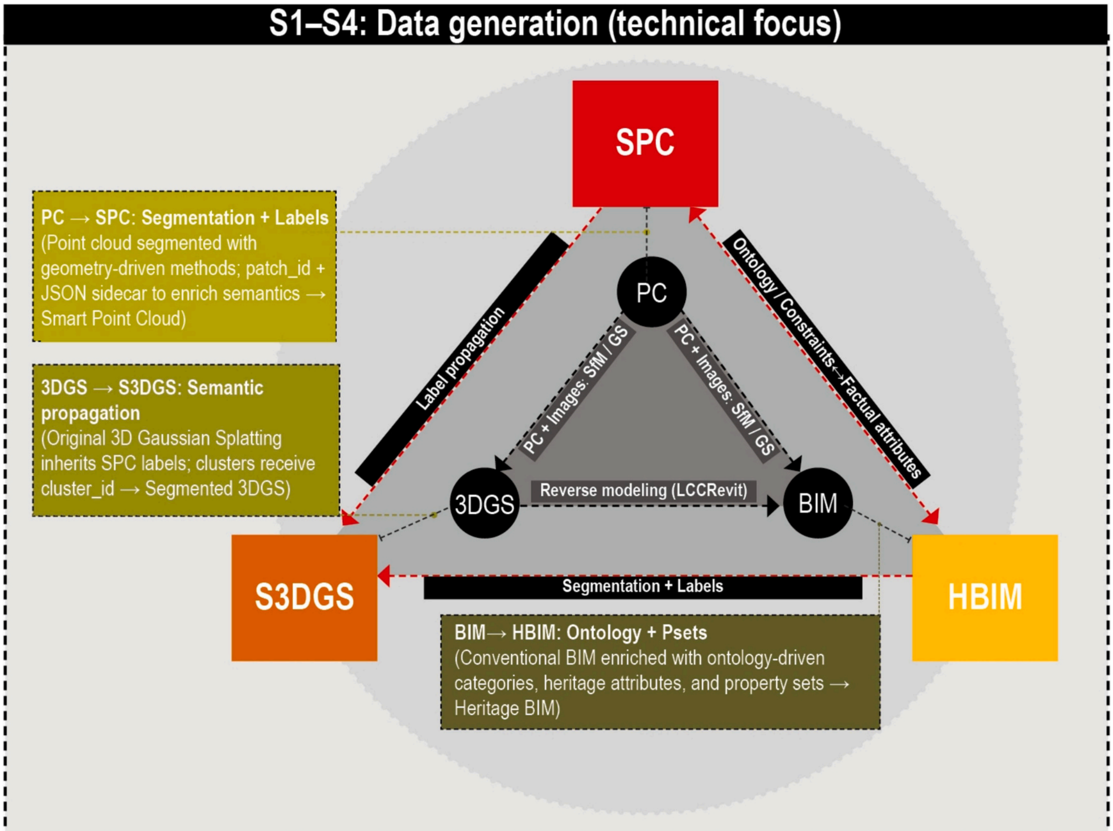

Fig. 3. Workflow of the proposed AHII.

Table 2
Operational definitions of AHII layers.

Layer	Operational definition in AHII	Primary identifier	Role in the closed loop
SPC	Evidence layer with patch-based structure, semantic proposals, and provenance	patch_id	Segmentation and revisable evidence-linked semantics
HBIM/ IFC	IFC-aligned object model for semantic normalization and structured attributes	IfcGUID	Authoritative semantics and adjudication
S3DGS	Cluster-based Gaussian splatting layer with propagated semantics	cluster_id	Queryable visualization and dissemination

packaged, transferred, and revalidated across tools.

3.2. UML consolidation and alignment to standards

Building on the layer specifications and cross-layer artifacts defined in Section 3.1, the UML information model formalizes the entities, relations, and controlled vocabularies that AHII uses to maintain cross-representation continuity, as summarized in Fig. 4; the complete UML model is presented in Appendix A2. Rather than duplicating detailed geometry schemas already covered by existing standards, the model captures the integration logic that is often left implicit in project-specific workflows, including identity management, correspondence, provenance, and versioning.

At its core, the model represents the three layers and their associated artifacts through entities such as SmartPointCloud, IfcHBIM, SemanticGaussianSplatting, and Presentation, together with a HeritageObject abstraction for project-level grouping and metadata. Its key contribution is the explicit representation of linkage entities that encode correspondences among IfcGUID, patch_id, and cluster_id, together with relation

Table 3
Minimum requirements and minimal deliverables for AHII artifacts.

Artifact	Minimum requirements	Minimal deliverables
SPC package	Reference/transform, persistent patch_id, patch membership, semantic_label, provenance, optional revision record	Point cloud file plus versioned patch sidecar table
HBIM/IFC package	IfcGUID, consistent classes, required Psets, IFC4-preserved GUIDs, adjudication status	IFC4 exchange file plus optional metadata summary
S3DGS package	Reference/transform, persistent cluster_id, cluster membership, propagated_label, provenance	S3DGS model plus versioned cluster sidecar table
Crosswalk	IfcGUID–patch_id–cluster_id links, relation type, confidence/reason, version tag	Crosswalk CSV/JSON
Transform	Alignment transform, reference metadata, timestamp/version	transform.json is packaged with the exchange bundle.

Note: In this study, patches are defined at an interpretable component or surface-region granularity suitable for linkage to HBIM elements. Manual refinement is limited to merge and split edits guided by architectural boundaries and recorded in the SPC revision log.

types, confidence or reason codes, and version tags. Controlled vocabularies further support consistency in document types, spatial references, quality levels, and delivery formats across exchanged bundles.

In this way, the UML model functions as an operational integration layer anchored to IFC conventions for object identity and structured attributes, while allowing point-based evidence and visualization assets to remain in their native forms. It therefore aligns a core subset of concepts needed for traceability without attempting to replace IFC or city-scale models (Table 4).

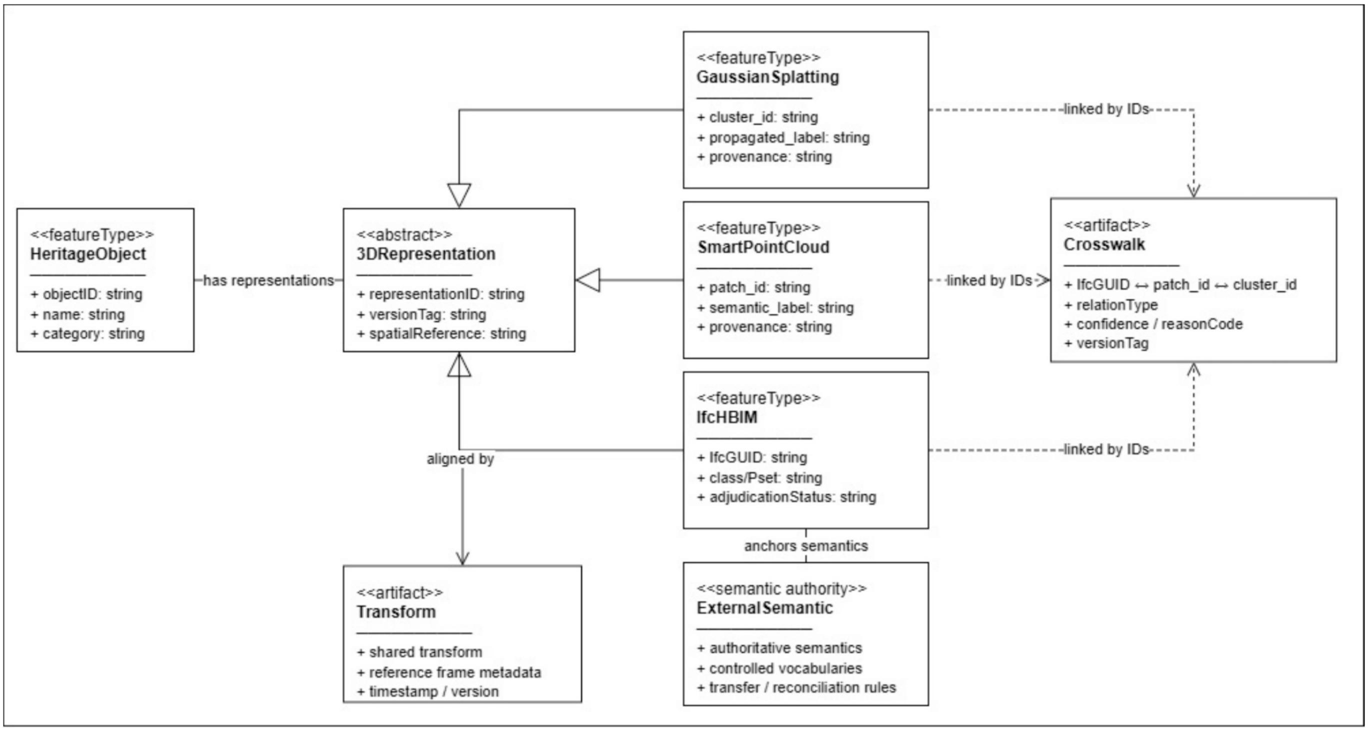

Fig. 4. Unified information model of AHII (UML schema).

Table 4
Alignment boundary of AHII UML concepts with existing standards (core subset).

AHII UML concept	IFC anchor (typical)	CityGML anchor (typical)	AHII addition for traceability
IfcHBIM element	IfcElement (IfcGUID as identity)	Building installation or thematic feature (as applicable)	Concordance status and cross-representation links
SmartPointCloud patch	n/a (evidence-level object is external to IFC)	n/a	patch_id, semantic proposal, provenance, revision log
SemanticGaussianSplatting cluster	n/a	n/a	cluster_id and propagated semantics via crosswalk
Crosswalk relation	IfcGUID-based correspondence	External correspondence	Relation types, confidence/reason codes, versioning
SpatialReference / Transform	IfcMapConversion / IfcCoordinateReferenceSystem	CRS metadata	Shared transform for reproducible alignment
Presentation interface (optional)	n/a	n/a	Traceable VR/AR/Web interaction
GIS connector (optional)	IfcSite / IfcMapConversion / IfcCoordinateReferenceSystem	CRS and geospatial context metadata	GIS linkage via shared reference and crosswalk

Fig. 5. Case studies: (a) left: HK, captured by phone by the author; (b) right: Aula building (Delft) (drone photo), taken by the author.

4. Case studies

To demonstrate applicability across different scales and levels of complexity, the AHII workflow is instantiated in two case studies in the Netherlands. Case A, *Herdenkingsmonument Kartuizerklooster* **(HK, Fig. 5a)**, is a compact public monument marking the former Carthusian monastery "St. Bartholomew in Jerusalem" (1469–1572), destroyed during the Eighty Years' War. Its small footprint, public accessibility, and rich municipal archives make it suitable for multi-sensor documentation, multilayer modeling, and public-facing dissemination. Case B, the Aula building **(Aula, Fig. 5b)**, is a Dutch national monument and a canonical example of post-war Dutch Brutalism by Van den Broek & Bakema. At the building scale, limited ground-level capture, the need to fuse supplementary point clouds, and complex geometry make it a more demanding test of segmentation and processing.

This section documents how AHII is deployed in these two cases to produce aligned representations for subsequent evaluation (Fig. 6). Quantitative validation and human-factor validation are reported in

Fig. 6. Comprehensive Flow Diagram of closed-loop AHII with feedback loop.

Sections 5-6, respectively.

4.1. Documentation

Both cases followed the same documentation protocol, combining multi-source imagery, SLAM-based point clouds, and curated semantic sources (Table 5). HK used 30 UAV/mobile images (0.11 GB) and a GeoSLAM/iPhone point cloud (~0.6 M points; 0.01 GB), with semantic metadata curated from municipal records and stored as JSON. Aula used 412 UAV images (1.52 GB), a GeoSLAM ZEB Horizon RT building-scale cloud (LAZ; 4.90 GB), and the national LiDAR AHN5 tile 37EN2.11 (LAZ; 1.08 GB), with semantics curated from Kunstwacht documentation and stored as JSON.

For both cases, these inputs were organized into the same minimal AHII exchange bundle, comprising the three core representations, SPC, HBIM/IFC, and S3DGS, together with the crosswalk and shared transform needed for reproducible alignment and correspondence. The case-specific datasets are summarized in Table 5, while their alignment, identifier linking, and assembly are described in Sections 4.2–4.4.

4.2. Pre-processing, alignment, and identifier linking

To prepare the case data for cross-representation alignment and identifier linking, we standardized pre-processing and metadata logging across the three formats before the validation reported in Section 5. In the SPC representation, semantic anchors were organized as non-overlapping patches, each assigned a persistent patch_id and a semantic_label drawn from the project label set. When patches were merged or split during refinement, parent–child relationships were recorded in the revision log so that changes remained versioned and auditable.

For SPC (.ply/.laz), semantic patches and patch_id anchors were derived using the workflow and parameter ranges summarized in Table 6. Statistical outlier removal was first applied to suppress isolated points, followed by voxel downsampling to normalize point density. Dominant planar structures, such as walls and floors, were extracted using RANSAC-based plane fitting, while curved or continuous surfaces, such as roofs, were separated using normal-based region growing. Where discrete small objects were present, Euclidean clustering was used to isolate them from surrounding structures. When boundary ambiguity was unavoidable, for example in ornaments, occlusions, or eroded areas, lightweight manual refinement was allowed but restricted to boundary-preserving merge/split edits guided by architectural edges, with all edits recorded in the revision log.

Patch-level provenance was treated as part of the data product. For each patch, we recorded the method chain and key parameters in a sidecar metadata table (JSON), together with revision information for post-processing edits. To preserve stable membership between full-resolution points and patches across exports and tools, patch membership was then written back to the original SPC resolution via a KD-tree nearest-neighbour pass. This ensured that subsequent spatial joins, sampling operations, and visualization exports maintained a consistent point-to-patch association even when intermediate processing was performed on a reduced cloud.

All representations were then brought into a shared coordinate frame using a rigid or similarity transform estimated by least-squares registration to the project coordinate reference system (CRS), using the Dutch national CRS where georeferenced data were available and otherwise a local project CRS. The resulting 4×4 transform was recorded in transform.json and reused unchanged across SPC, S3DGS, and HBIM. An independent set of checkpoints, excluded from transform estimation, was reserved for downstream geometric validation in Section 5. Traceability across representations was maintained through an explicit crosswalk among IfcGUID, patch_id, and cluster_id, supporting semantic transfer, entity-level comparison, and IFC round-trip checks.

Table 5
Overview of data used in the two cases.

Dataset	Type	Source	Format	Data volume/ result
HK images	Image set	UAV (DJI Mini 3) + iPhone (Polycam)	JPG	[30 images; 0.11 GB]
HK point cloud	Point cloud	GeoSLAM ZEB Horizon + iPhone (Polycam app)	LAZ, PLY	[~0.6 million points; 0.01 GB]
HK semantics	Metadata table	Hand annotation; heritage documents	JSON	
Aula images	Image set	UAV (DJI Mini 3)	JPG	[412 images; 1.52 GB]
Aula point cloud	Point cloud	GeoSLAM ZEB Horizon RT	LAZ	[975 million points; 4.90 GB]
AHN5 tile 37EN2.11	Point cloud	GeoTiles.nl (colored AHN5)	LAZ	[153 million points; 1.08 GB]
Aula semantics	Metadata table	Hand annotation, Kunstwacht	JSON	

4.3. Multi-representational assembly of the AHII bundle

Using the patch_id anchors produced in Section 4.2 and Table 6, we assembled the aligned AHII bundle for each case by linking SPC, S3DGS, and HBIM/IFC under a shared spatial reference. High-resolution imagery was processed to generate dense S3DGS reconstructions, while IFC4 export preserved HBIM identity and structured attributes for downstream audit and query.

For semantic interoperability between SPC and S3DGS, patch_id labels were propagated from the labeled SPC to the S3DGS representation using a deterministic k-nearest-neighbour (kNN) transfer. A KD-tree was built on the SPC xyz coordinates. For each Gaussian center, the k nearest SPC points were queried ($k = 3$), and the Gaussian was assigned the majority patch_id among these neighbours. Ties were resolved deterministically: when votes were split (1–1–1), the patch_id of the single nearest SPC point was assigned. To limit long-range label bleeding, a fixed distance gate was applied: if the nearest-neighbour distance exceeded $\tau = 3 \times$ voxel_size (voxel_size as in Table 6, Step 2), the Gaussian was left unassigned. The labeled S3DGS points were then exported as patch-wise PLY subsets to support visualization, inspection, and metric computation under a shared identifier scheme.

Geometric interoperability across SPC, S3DGS, and HBIM was maintained through the shared transform recorded in transform.json (Section 4.2). Under this common frame, spatial joins and identifier links could be executed consistently across patch_id, cluster_id, and IfcGUID. Fig. 7 illustrates the coordinated alignment across the three representations.

4.4. Integration with external viewers and delivery modes

AHII supports multiple delivery configurations derived from the same aligned bundle, depending on audience and task (Fig. 8). In this study, these include SPC-based semantic inspection, S3DGS-based interactive visualization, and IFC-based querying and exchange. Because all viewers consume the same shared transform (transform.json) and identifier crosswalk (IfcGUID, patch_id, cluster_id), cross-representation referencing remains consistent across delivery interfaces. The viewers used here therefore function as reference implementations rather than as the core contribution of the framework. In particular, a VR client is used as the reference implementation for the S3DGS modality in the human-factor evaluation reported in Section 6, while other clients, such as AR, GIS, or web viewers, can be connected in the same manner.

5. Technical evaluation protocol

We evaluate AHII using a reproducible multi-stage protocol executed

Table 6
SPC patch extraction workflow.

Step	Algorithm	Purpose	Key Parameters	Values Used	Output	Notes
1	Statistical Outlier Removal	Noise removal	k-neighbors, std_ratio	k = 20–50, std = 1.0–2.0	Cleaned SPC	Removes isolated points
2	Voxel Downsampling	Density normalization	voxel_size	0.02–0.05 *m*	Reduced SPC	Preserves geometry
3	RANSAC Plane Fitting	Extract dominant planar elements (walls, floors)	distance_threshold, ransac_n, iterations	0.01–0.03 m, n = 3, iter = 1000–5000	Plane segments	Sensitive to threshold
4	Normal-based Region Growing	Surface clustering	normal_radius, angle_threshold	0.05–0.15 m, 15–25°	Curved/ continuous surfaces	Works for roofs
5	Euclidean Clustering	Object separation	cluster_tolerance	0.05–0.2 *m*	Discrete objects	Used for street furniture
6	Manual Patch Refinement	Correct over/under segmentation	—	Visual inspection	Final patch_id assignment	No strict quantitative rule

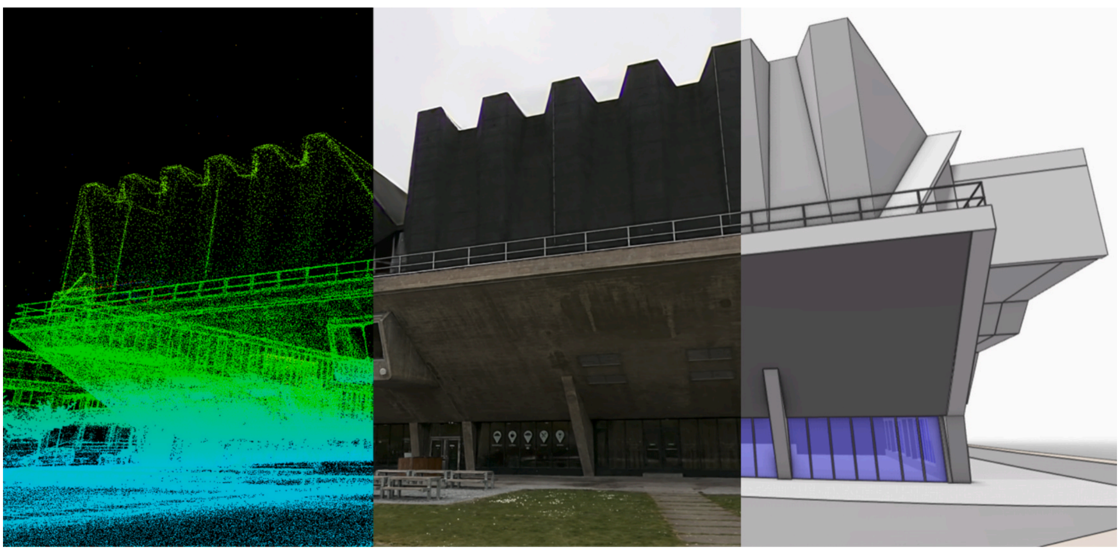

Fig. 7. Coordinate alignment and transformation across three AHII representations: SPC (left), S3DGS (middle), and HBIM (right).

consistently across both case studies (Fig. 9). The protocol covers cycle efficiency and update propagation, semantic accuracy and label transfer, geometric co-location, IFC4 exchange integrity, and S3DGS visual fidelity. All scores are recomputable from fixed splits, independent checkpoints, and archived artifacts.

5.1. Evaluation matrix and baselines

We assess AHII with a compact, representation-agnostic evaluation matrix aligned to its infrastructure goals (Fig. 10), covering end-to-end cycle efficiency, semantic accuracy and cross-representation transfer, geometric co-location, exchange integrity, and S3DGS visual fidelity. The implementation steps that enable these evaluations, including SPC patch_id generation and SPC-to-S3DGS label propagation under a shared transform, are described in Sections 4.2–4.3; here we define the evaluation protocol, reference data, and baselines.

Ground truth for semantics is provided by a blinded SPC reference subset in which stratified patch_id units are labeled using SPC-only cues. The subset is generated using a fixed sampling rule and recorded patch_id lists, allowing exact reconstruction. We evaluate intrinsic SPC segmentation on this subset and the fidelity of label propagation from SPC to S3DGS clusters via spatial joins under transform.json.

Registration accuracy is computed on independent checkpoints excluded from transform estimation, reporting RMSE_X, RMSE_Y, RMSE_Z, RMSE_3D, P95_3D, and mean absolute 3D error for HBIM–SPC and SPC–S3DGS. Exchange integrity is examined through an IFC4 round-trip, auditing GUID persistence, entity and count agreement, and property-set retention. Cycle efficiency is quantified using wall-clock time, manual editing time, and update-propagation latency, while visual fidelity is assessed on held-out camera views using PSNR and SSIM. We compare AHII against two practical baselines:

(a) Semantic baseline: voxel-grid majority voting assigns labels by per-voxel class counts on a shared grid for SPC and S3DGS (optionally followed by light CRF smoothing), reflecting a common non-learning strategy for cross-representation label transfer.

(b) Geometric baseline: FPFH + RANSAC followed by point-to-plane ICP provides a competitive geometry-only registration pipeline representative of standard practice.

All methods use the same input data, evaluation splits, and scoring scripts. Each registration method estimates its own transform, but all transforms are evaluated on the same independent checkpoints. The reported results can be recomputed from the archived artifacts and recorded evaluation configuration.

5.2. End-to-end cycle transfer efficiency and manual-effort audit

Beyond isolated accuracy metrics, AHII is intended to support a closed workflow in which semantics and identifiers can be propagated across representations without repeated re-authoring. We therefore assess transfer efficiency in two complementary ways: the reduction of manual effort achieved by labeling once and reusing those labels across representations, and the latency incurred when updates are propagated through SPC, HBIM, and S3DGS.

For each case, we record compute time for denoising, registration,

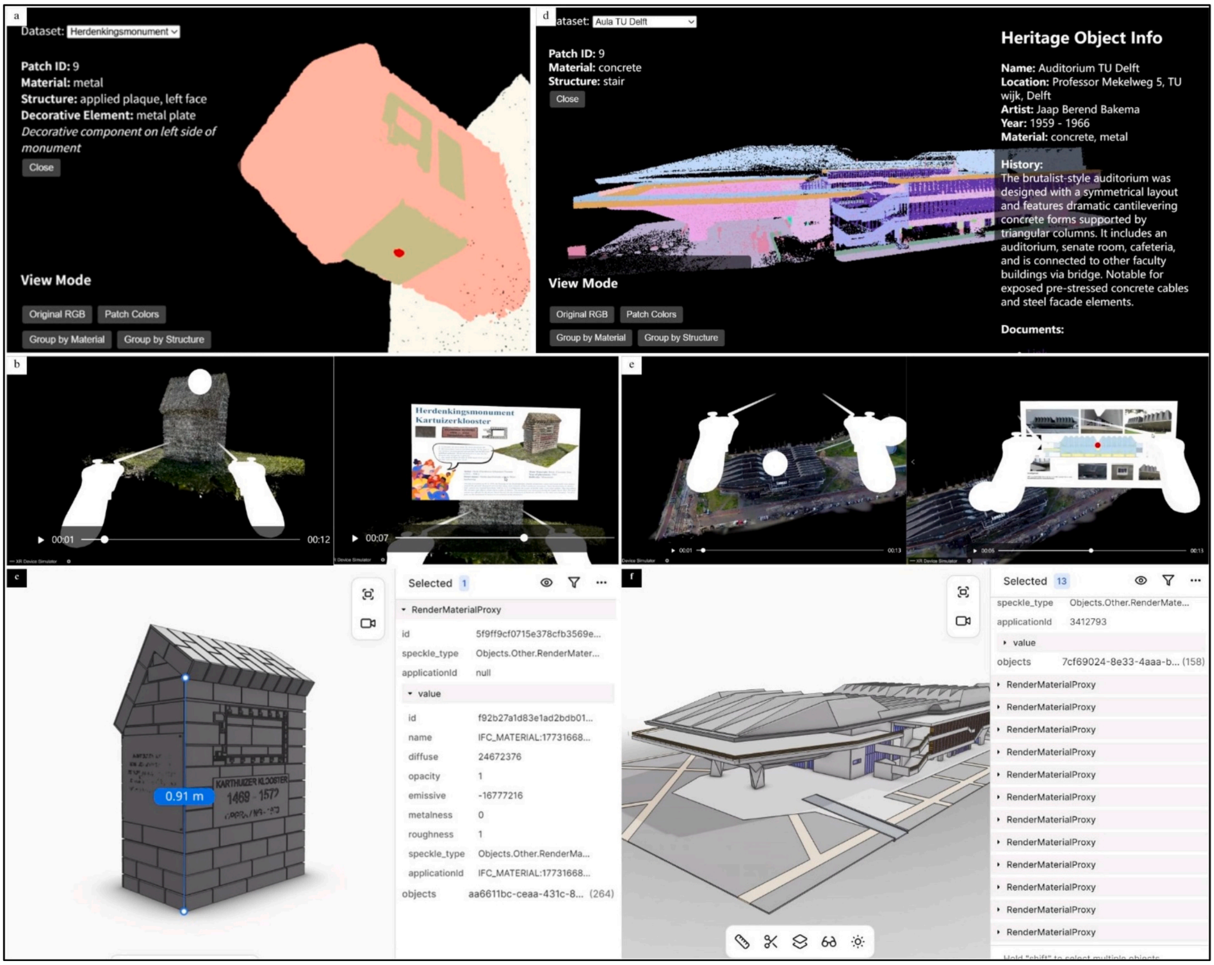

Fig. 8. Interactive visualization and semantic inspection across AHII representations: (a)–(c) HK case: SPC, S3DGS, and HBIM layers presented in immersive and web-based viewers; (d)–(f) Aula building case: corresponding layers illustrating material inspection, measurement, and semantic query functions.

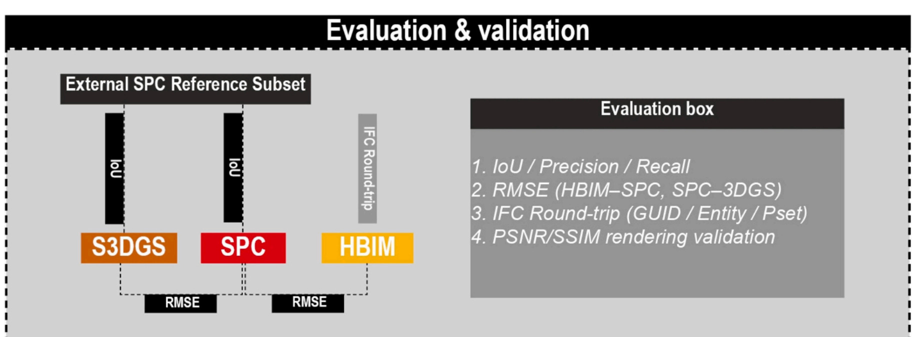

Fig. 9. Evaluation protocol for the AHII.

and segmentation; manual refinement time during SPC editing; the time required to rebuild the IfcGUID–patch_id–cluster_id crosswalk and inject updated labels into HBIM property sets and S3DGS clusters; and delivery performance in end-user viewers, including loading time and interactive FPS (Table 7). Update-propagation latency is measured from the moment a patch label is revised in SPC to the moment the updated semantics become visible in both HBIM property sets and S3DGS clusters. To contextualize the savings, we compare this workflow against a counterfactual manual scenario in which the same labels are authored independently in each representation. As part of the manual-effort audit, we report manual time, edit counts, and rework time as complementary proxies for labor, workload, and quality risk. Because consistent expert logging is required, the manual-effort audit is reported for the HK case only in this revision.

5.3. Semantic consistency, geometric co-location, and exchange integrity

To examine whether AHII achieves cross-representation interoperability beyond parallel visualization, we evaluated its semantic and geometric performance against the two baselines introduced above: voxel-grid majority voting and FPFH + RANSAC → ICP. These metrics are interpreted as evidence of interoperability and consistency rather than as standalone performance claims.

(a) Semantic accuracy: For the HK monument (Table 8), intrinsic

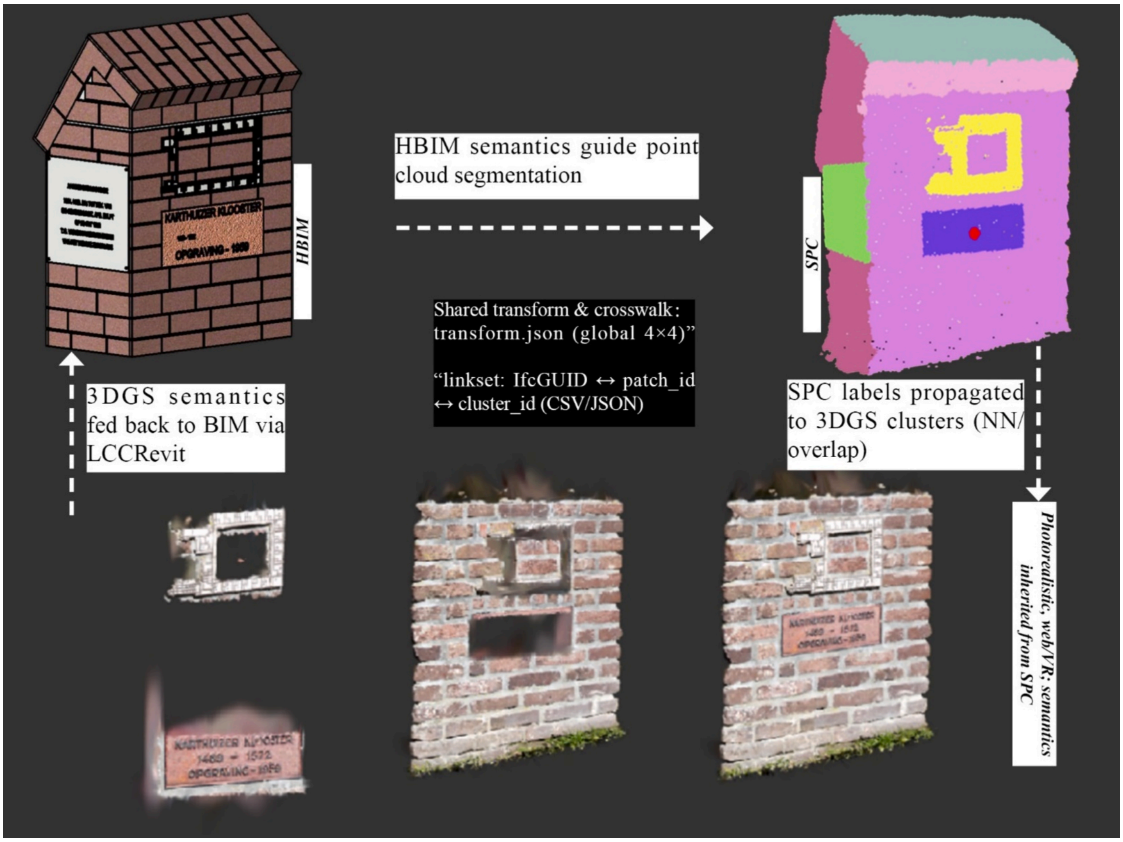

Fig. 10. Semantic and geometric interoperability within the AHII.

Table 7
Delivery performance and manual-effort audit across AHII representations.

Platform	Model Type	Device	Avg FPS	Loading time (s)	Rendering Layer	Manual refinement (min)	Atomic edits	Quality check/ rework (min)
Unity-based VR (S3DGS)	S3DGS	Desktop PC (RTX 4070 Ti)	80	4.1	S3DGS	–	–	–
Unity-based VR (S3DGS)	S3DGS	VR Headset (Meta Quest 2 via Link)	37	5.8	S3DGS	–	–	–
Web-based IFC Viewer	IFC (BIM)	Laptop/Desktop (Mid GPU)	38	3.6	HBIM	–	–	–
WebGL-based Viewer (SPC)	SPC (Smart Point Cloud)	Browser (HK case)	28	5.2	SPC	18	75	4

Table 8
Semantic and geometric performance of the AHII workflow for the HK case.

(SPC vs Ref) Class	Performance of the HK case						Baselines	
	TP	FP	FN	Precision	Recall	IoU		
wall_body (4)	4	0	0	1.00	1.00	1.00		
Decoration (2)	1	0	1	1.00	0.50	0.50		
plaque_inscription (1)	1	0	0	1.00	1.00	1.00		
top (1)	1	0	0	1.00	1.00	1.00		
(3DGS vs Ref) Class	**TP**	**FP**	**FN**	**Precision**	**Recall**	**IoU**	**IoU (Voxel-vote)**	
wall_body (4)	3	1	1	0.75	0.75	0.60	0.60 (3, 1, 1)	
Decoration (2)	1	0	1	1.00	0.50	0.50	0.00 (0, 1, 1)	
plaque_inscription (1)	0	0	1	0.00	0.00	0.00	0.00 (0, 1, 1)	
top (1)	1	0	0	1.00	1.00	1.00	1.00 (1, 0, 0)	
Pair (n = 8)	**$RMSE_X$**	**$RMSE_Y$**	**$RMSE_Z$**	**$RMSE_{3D}$**	**$P95_{3D}$**	**$mean\_abs_{3D}$**	**$RMSE_{3D}$**	**$P95_{3D}$**
HBIM–SPC (m)	0.0062	0.0059	0.0032	0.0092	0.0108	0.0091	0.0230	0.0252
SPC–S3DGS (m)	0.0171	0.0150	0.0102	0.0249	0.0296	0.0247	0.0412	0.0468

Notes: macro-mIoU = 0.88, obtained as the unweighted mean of four per-class IoUs. Each class contributes equally.

SPC segmentation reached a macro-mIoU of 0.88, with per-class IoUs of 1.00 for wall_body, 0.50 for decoration, 1.00 for roof_top, and 1.00 for plaque_inscription. After propagation to S3DGS, macro-mIoU decreased to approximately 0.53, compared with approximately 0.44 for the voxel-vote baseline. For the Aula building (Table 9), intrinsic SPC segmentation reached a macro-mIoU of approximately 0.86, while propagated S3DGS semantics retained a macro-mIoU of approximately 0.62, compared with approximately 0.50 for the baseline. These results indicate that large, contiguous structures transfer reliably, whereas small or occluded details remain the main sensitivity points.

The observed drop in mIoU is mainly attributable to representation mismatch and the sensitivity of fine details. First, S3DGS is optimized for view-consistent appearance rather than explicit surface representation, so class boundaries are often spatially diffuse and therefore more prone to label bleeding, especially near patch edges. Second, the spatial-join transfer amplifies residual registration errors and non-uniform sampling, which disproportionately affect thin structures and partially occluded cavities. Third, class imbalance biases nearest-neighbour assignment toward densely sampled roof and wall regions, reducing recall for smaller decorative classes. Together, these factors explain why large structures transfer well while fine-detail semantics remain the dominant failure mode.

(b) Geometric co-location: Independent checkpoints excluded from registration yielded $RMSE_{3D} = 9.2$ mm (P95 = 10.8 mm) for HBIM–SPC and 24.9 mm (P95 = 29.6 mm) for SPC–S3DGS in the HK case (Table 8). For the larger Aula building, the corresponding residuals were 16.4 mm (P95 = 20.1 mm) and 36.4 mm (P95 = 42.7 mm) (Table 9). By comparison, the FPFH + RANSAC → ICP baseline produced $RMSE_{3D}$ values of approximately 23–32 mm for HBIM–SPC and 45–57 mm for SPC–S3DGS. AHII therefore reduces positional error by roughly 50–60% relative to the geometry-only baseline, supporting the effectiveness of shared-transform alignment within a traceable coordinate framework.

(c) Exchange integrity: Round-trip IFC4 validation confirmed 100% GUID persistence and approximately 98% property-set retention, indicating that the UML-based schema and open-standard mappings preserve interoperability and reproducibility across heterogeneous representations.

5.4. Quantitative visual assessment of S3DGS (PSNR and SSIM)

To quantify the image-domain reconstruction quality of S3DGS, we use full-reference metrics on held-out views. Calibrated photographs are split into training views used for optimization and test views reserved for evaluation. The reconstructed S3DGS scene is rendered from the test camera poses and compared with the corresponding photographs after resolution and color-space alignment. We report PSNR (dB) and SSIM, averaged across test views. These metrics complement runtime responsiveness by assessing visual quality rather than speed. The resulting scores are summarized in Table 10.

6. Human factors evaluation

We conducted an online, task-based human factors evaluation to examine whether AHII supports task-driven switching among S3DGS, SPC, and HBIM while maintaining interpretability and perceived operational value across representations. After quality controls, including attention checks, minimum completion time, and duplicate screening, the final sample comprised 200 participants: 101 heritage-related experts and 99 members of the general public (Table 11). Participants used their own mobile devices or personal computers, accessed the three representations in counterbalanced order, and completed guided tasks covering inscription facts, facade materials, and overall spatial structure.

6.1. Questionnaire and analytical approach

The questionnaire comprised two components: objective task performance and subjective perception ratings. Objective performance was measured using three verifiable questions covering inscription facts (Scene 1), facade materials (Scene 2), and floor count as a proxy for global spatial comprehension (Scene 3). Subjective perceptions were measured using nine Likert items on a 7-point scale, organized into three dimensions: Dimension 1 (D1), Perceived Learning and Engagement; Dimension 2 (D2), Cognitive Interpretability; and Dimension 3 (D3), System Usability. More specifically, D11–D13 measured whether the representation supported understanding, reuse intention, and interest in extended immersive experience; D21–D23 measured the clarity of spatial structure, semantic or attribute information, and trust in the representation as a faithful basis for understanding the real object; and D31–D33 measured ease of navigation, responsiveness of interaction, and the mental effort required to figure out how to use the representation. Full item wordings are provided in Appendix A3. Dimension scores were computed as the mean of their three items, and reliability was assessed using Cronbach's alpha. To test representation effects (S3DGS, SPC, HBIM) and group differences (experts, general public) while accounting for repeated measures within participants, we estimated cluster-robust marginal means with 95% confidence intervals, conducted omnibus tests, and performed planned pairwise comparisons with family-wise error control.

6.2. Evaluation results

Across groups, internal consistency was acceptable (Cronbach's alpha ranged from 0.69 to 0.80). Estimated marginal means (Fig. 11) indicate that representation choice influenced Perceived Learning and Engagement (D1) and Cognitive Interpretability (D2), while System Usability (D3) was comparatively stable across representations. For D1, S3DGS scored higher than SPC and HBIM in both groups (experts: S3DGS about 4.21, SPC about 3.24, HBIM about 3.18; general public: S3DGS about 4.52, SPC about 3.34, HBIM about 3.34), with a significant representation effect ($\chi^2 = 94.10$, $p < 0.001$) and a small overall group effect favoring the general public ($\chi^2 = 7.33$, $p = 0.0068$). D2 showed a similar representation pattern ($\chi^2 = 20.78$, $p < 0.001$), and the group effect was not significant ($p = 0.41$). In contrast, D3 did not vary by

Table 9
Semantic and geometric performance of the AHII workflow for the Aula case.

(SPC vs Ref) Class	Performance of the Aula building case						Baselines	
	TP	FP	FN	Precision	Recall	IoU		
Roof (84)	76	2	8	0.974	0.905	0.884		
Structural column (16)	14	1	2	0.933	0.875	0.824		
Basic wall (8)	7	0	1	1.000	0.875	0.875		
(3DGS vs Ref) Class	**TP**	**FP**	**FN**	**Precision**	**Recall**	**IoU**	**IoU (Voxel-vote)**	
Roof (84)	66	8	18	0.892	0.786	0.717	0.602 (59, 14, 25)	
Structural column (16)	10	2	6	0.833	0.625	0.556	0.421 (8, 3, 8)	
Basic wall (8)	6	2	2	0.750	0.750	0.600	0.455 (5, 3, 3)	
Pair (n = 8)	**$RMSE_X$**	**$RMSE_Y$**	**$RMSE_Z$**	**$RMSE_{3D}$**	**$P95_{3D}$**	**$mean\_abs_{3D}$**	**$RMSE_{3D}$**	**$P95_{3D}$**
HBIM–SPC (m)	0.0099	0.0104	0.0079	0.0164	0.0201	0.0156	0.0317	0.0379
SPC–S3DGS (m)	0.0221	0.0216	0.0193	0.0364	0.0427	0.0358	0.0568	0.0691

Notes: macro-mIoU = 0.86, obtained as the unweighted mean of three per-class IoUs. Each class contributes equally.

Table 10
Evaluation of S3DGS's visual quality.

Method	Dataset	Split	Images	PSNR ↑ (dB)	SSIM ↑	Quality
Depth Regularization	HK	test	77	25.91 *(25.907766)*	0.77 *(0.765587)*	Good
Depth Regularization	AULA	test	240	26.53 *(26.531886)*	0.78 *(0.776319)*	Good

Table 11
Participant summary (N = 200).

Group	n	Notes
Experts	101	Academic or professional background in architecture, landscape architecture, urban planning, or a closely related field (senior undergraduate or above).
General public	99	Nonspecialist participants were recruited for public-facing interpretation tasks.
Total	200	Online study with counterbalanced exposure order; records failing quality controls were excluded.

representation ($\chi^2 = 0.74$, $p = 0.69$), although the general public reported modestly higher values overall ($\chi^2 = 12.23$, $p = 0.0005$). Taken together, the results suggest that participants can switch among AHII representations without a loss in perceived operational utility, while interaction fluency and information presentation remain the main opportunities for improving SPC and HBIM modules.

Objective task accuracy was 98.5% for the inscription question, 91.5% for materials identification, and 66.5% for floor count (Table 12). The lower accuracy for floor count may reflect differences in floor numbering conventions (for example, whether the ground floor is counted as 0 or 1) and the higher cognitive demand of forming a global structural judgment from a brief interaction. For deployment, this points to a straightforward enhancement, provide clearer global structure cues (for example, a persistent level indicator or guided viewpoints) while keeping identifier linkage consistent across representations.

This human-based study prioritized ecological validity but did not measure task completion time or fine-grained error types. Future work can complement these results with timed tasks and more detailed error coding, especially for global-structure judgments.

7. Discussion and conclusion

In this section, the main findings are summarized and linked to previous research to highlight AHII's contributions. Based on the results, the limitations of the current work are discussed, followed by an outlook that outlines future directions for technical development, broader user engagement, and continued expansion of the AHII framework.

7.1. Core findings and contributions

This paper develops and validates AHII as a closed-loop, standards-operational framework for maintaining information continuity across the heritage lifecycle. Instead of collapsing all information into a single model, AHII retains three complementary representations, evidence-grade SPC, standards-based HBIM/IFC, and lightweight photorealistic S3DGS, and keeps them traceably linked for different tasks and audiences.

Concretely, AHII contributes: (i) a lightweight coordination schema expressed as a UML information model and code lists, (ii) an operational workflow that binds SPC-HBIM-S3DGS via persistent identifiers and a shared spatial reference, (iii) auditable exchange logic that leverages

Table 12
Objective task accuracy (N = 200).

Task	Correct answer	Accuracy
Q10 Inscription date range (Scene 1)	1469 to 1572	98.5% (197/200)
Q15 Facade materials (Scene 2)	1 to 2 material categories	91.5% (183/200)
Q19 Building floors (Scene 3)	Three floors	66.5% (133/200)

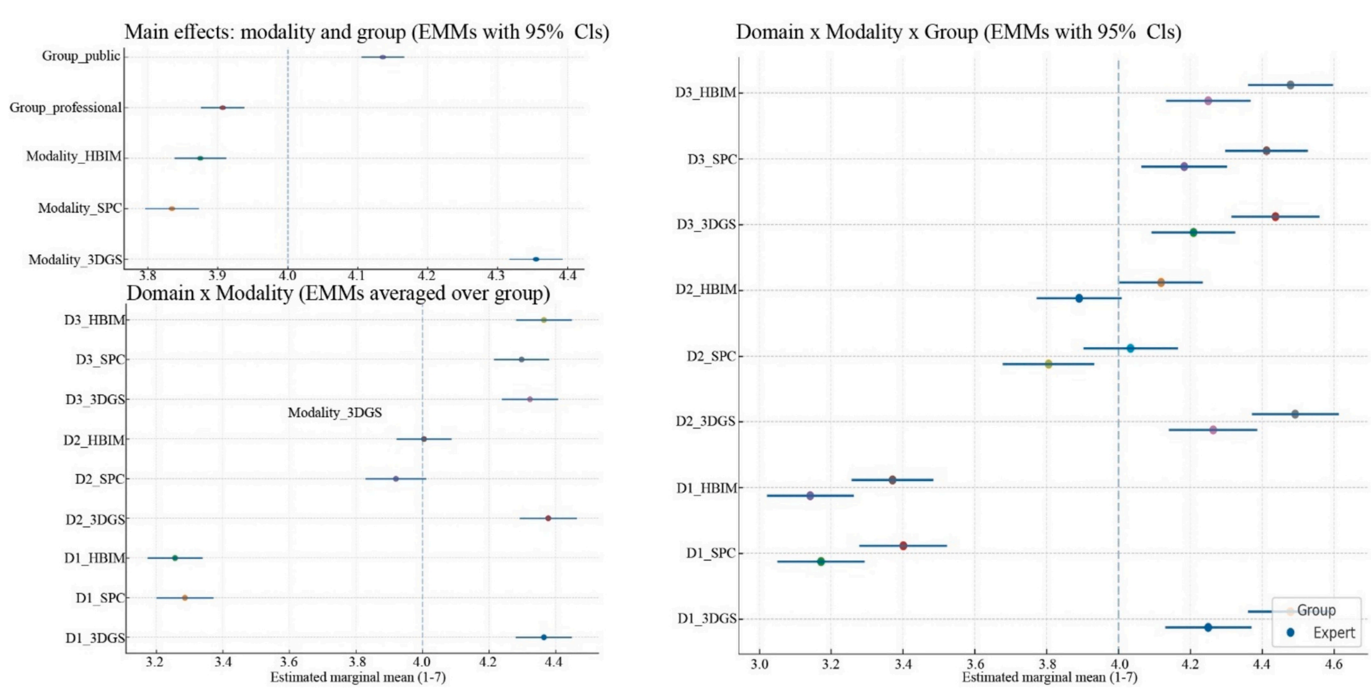

Fig. 11. Estimated marginal means (95% confidence intervals) for usability, interpretability, and operational value by representation and participant group.

open standards (IFC4) and round-trip checks, and (iv) a reproducible validation protocol that tests interoperability alongside usability. We position AHII relative to IFC and CityGML along practical interoperability dimensions to clarify what is inherited from standards and what AHII adds as an infrastructure layer (Table 13).

Empirically, we contribute representation-agnostic evidence that the infrastructure works in practice. The proposed evaluation matrix jointly measures semantic consistency, geometric co-location, and exchange integrity, complemented by operational performance (web/VR responsiveness) and a task-anchored user study. Across two Dutch cases at different scales, AHII achieves centimeter-level cross-model registration on independent checkpoints, preserves IFC identifiers and property sets under round-trip exchange, and retains usable semantics when propagating SPC-authored labels to S3DGS beyond simple voxel-vote baselines. Together, these results support AHII as an operational infrastructure for maintaining cross-representation continuity in single-building heritage workflows, while also highlighting the need for further improvement in fine-detail semantic transfer.

7.2. Practical applications

AHII is intended to support heritage documentation, coordination, dissemination, and long-term stewardship by allowing stakeholders to work in the representation best suited to their task while maintaining traceable links across evidence, semantics, and visualization.

For condition assessment and conservation planning, practitioners can measure, inspect, and annotate directly on SPC as the primary evidence source, then associate findings (e.g., decay types, extents, urgency) with corresponding IFC elements for structured reporting and intervention planning. This reduces ambiguity in interpretation by keeping observations tied to the original capture while still producing a standards-compliant deliverable suitable for project documentation [55].

For interdisciplinary coordination, AHII supports parallel communication modes: an IFC-centric model can be exchanged for technical integration and downstream use. At the same time, a photorealistic S3DGS layer provides rapid, intuitive visual review for non-expert stakeholders. This combination improves shared understanding during design discussions, site meetings, and approval workflows without forcing all participants to operate in the same tooling or representation.

For public dissemination and education, the S3DGS representation can be deployed as web-based or VR walkthroughs that are engaging and performant, while preserving transparent references back to IFC objects and SPC evidence [53,56]. This helps institutions communicate heritage value and conservation rationale to the public while maintaining an auditable connection to the authoritative model and the underlying survey data.

For update and revision workflows, AHII enables corrections or new labels introduced in SPC to be propagated to S3DGS clusters, while maintaining verifiable spatial consistency through shared transforms and independent checkpoints. This supports iterative documentation campaigns where new surveys, expert reviews, or evolving classification needs can be incorporated without breaking traceability across layers.

Finally, for data governance and archiving, AHII encourages a layered preservation strategy: keeping standard-compliant IFC deliverables for long-term interoperability, retaining SPC as the evidential record, and maintaining a responsive visualization layer for access. Audits across handoffs document what is preserved (e.g., identifiers, properties, alignment quality), strengthening accountability and supporting institutional requirements for reproducibility and long-term stewardship.

7.3. Limitations

The present study has four main limitations that also point to clear avenues for future work. (a) Validation is limited to two Dutch cases, a small monument and a large complex building, so transferability to other heritage typologies (e.g., cluttered interiors with heavy occlusion, archaeological fragments, linear or landscape assets) and governance contexts remains to be established; subsequent deployments should purposefully sample diverse typologies, data availability regimes, and regulatory settings to test AHII's portability and boundary conditions. (b) The semantic population of HBIM and SPC currently relies on semi-automatic, geometry-driven segmentation with manual refinement, rather than fully automated labeling; moreover, parts of the semantic reference and correction process remain expert-authored, which can introduce annotation bias and limit strict reproducibility. Future iterations should incorporate learning-based detectors for irregular elements, active learning loops to reduce annotation burden, uncertainty-aware labeling to expose confidence to end users, and multi-annotator protocols (e.g., inter-rater agreement) to better characterize label reliability. (c) While S3DGS is effective for photorealistic communication, it remains primarily a rendering-oriented representation; its geometry is implicit and view-dependent, and semantic attachment depends on clustering and spatial joins, which can degrade fine-detail transfer under occlusions, thin structures, specular materials, or uneven image coverage. Robust S3DGS would benefit from improved clustering and association strategies, uncertainty reporting, and more standardized packaging of S3DGS assets and metadata for long-term reuse. (d) Finally, our system-level validation is intentionally compact and toolchain-specific; broader conformance testing across multiple IFC authoring and viewer stacks, more explicit alignment with adjacent standards (e.g., CityGML and CityJSON where relevant), and longitudinal updates

Table 13
How AHII relates to IFC and CityGML across interoperability dimensions relevant to single-building heritage workflows.

Dimension	IFC	CityGML	AHII (this work)
Scope and scale	Building-scale object models for design, construction, and operation exchange.	Geo-referenced 3D city models for GIS-oriented, multi-asset contexts.	Single-building heritage workflows. Keeps native representations intact and adds cross-representation continuity and auditability.
Authoritative semantics	Authoritative container for object semantics via classes and property sets.	Thematic semantics for city objects typically support urban analysis at a coarser granularity.	Does not replace either semantic system. Operationalizes controlled vocabularies and mapping rules so SPC and S3DGS labels remain consistent with the chosen semantic authority, typically IFC for building elements.
Identity and correspondence	Identifies objects via IfcGUID.	Identifies features via gml:id.	Introduces explicit crosswalk links among IfcGUID, patch_id, and cluster_id with relation types and optional confidence, enabling inspectable traceability across representations.
Geometry and spatial reference	Supports parametric and boundary representations, often in local or project coordinates.	Typically uses surface-based geometries in a declared CRS.	Keeps geometry in each native format and adds a shared alignment artifact (transform.json) plus independent checkpoints so co-location is reproducible and verifiable.
Exchange and auditability	Supports exchange of building elements and properties, but does not prescribe validation of multi-tool handoffs.	Supports the exchange of georeferenced city objects with application-dependent validation practices.	Adds a compact audit protocol, including IFC4 round-trip checks (GUID persistence, entity and count agreement, property-set retention), registration error on independent checkpoints, and semantic transfer evaluation across SPC and S3DGS.

over time are needed. Together, these limitations point to the need for broader case diversity, lower annotation cost, stronger cross-standard alignment, and more comparable operational benchmarking in future work.

7.4. Conclusions and outlook

This work presents AHII as a standards-oriented, schema-level infrastructure that unifies HBIM, SPC, and S3DGS into a single, extensible, explicitly cyclical workflow. AHII formalizes an open information model with cross-ID traceability and shared transforms, so that evidence-grade geometry in SPC, authoritative semantics in IFC and HBIM, and lightweight interactive visualization in S3DGS can be linked at the element level and revisited repeatedly without losing provenance. In practical use, AHII supports a closed loop in which inspection and annotation start from SPC, semantic decisions are anchored and exchanged through IFC, and rapid stakeholder review happens in S3DGS, while corrections and updates can circulate back through the same links and transforms with checkpoints and audits that verify alignment and preservation across handoffs.

As an open infrastructure, AHII is designed for community-driven extension while maintaining a stable, measurable loop. New modalities such as neural radiance fields, semantic meshing, multi- or hyperspectral S3DGS, and sensor-level change detection can be connected through explicit interface contracts, extended code lists, and consistent transform propagation, preserving traceability as representations evolve. Operationally, the same cycle is supported by deployment telemetry and compact KPIs, including registration checks, exchange integrity across IFC tools, semantic agreement metrics such as IoU and mAP, and delivery latency and throughput for web or VR. Framed this way, AHII functions as a living, audience-aware platform that continuously preserves, updates, and validates evidence from the semantics-to-visualization loop and remains ready for broad community reuse and rollout.

CRediT authorship contribution statement

Yingwen Yu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Peter van Oosterom:** Supervision, Conceptualization. **Edward Verbree:** Supervision, Methodology. **Zhuoyue Wang:** Validation, Software, Methodology. **Uta Pottgiesser:** Supervision. **Abeer Abu Raed:** Data curation, Conceptualization. **Yuyang Peng:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aei.2026.105042.

Data availability

Data will be made available on request.

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