Towards a smart heritage information infrastructure: integrating multiple geometric representations and sharing semantics

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Abstract

Architectural heritage is increasingly documented and managed through point clouds, photogrammetry, Heritage Building Information Modelling (HBIM), Geographic information system (GIS), machine learning, and immersive media. Yet these technologies often remain fragmented, with weak continuity of identity, semantics, and spatial alignment across representations. This paper argues that heritage digitization should be reframed as a 3D smart-data integration problem rather than a sequence of isolated 3D representations. Building on recent analyses of digital heritage technologies and their multi-stage application trajectory, we propose the Architectural Heritage Information Infrastructure (AHII) as a standards-oriented framework that links Smart Point Clouds (SPC), IFC, and 3D Gaussian Splatting (3DGS) through persistent identifiers, a shared spatial reference, explicit crosswalks, and controlled vocabularies. In this architecture, SPC acts as the evidence layer and semantic proposal space, Heritage Building Information Modelling / Industry Foundation Classes (HBIM/IFC) provides authoritative object semantics and structured attributes, and 3DGS supports lightweight, queryable photorealistic visualization for expert review and public interaction. Two Dutch pilot cases illustrate how the framework can support cross-representation interoperability, semantic propagation, and audience-specific delivery while preserving traceability. The paper contributes a concise conceptual and operational model for smart heritage data, positions architectural heritage within broader information infrastructures, and outlines how building-scale heritage assets can become interoperable components of future smart-city information ecosystems.

1. Introduction

Architectural heritage has become a data-rich domain. Laser scanning, photogrammetry, HBIM, GIS, machine learning, VR, AR, and digital twins now support documentation, modelling, analysis, and communication (Yu et al., 2026a). Yet the field remains dominated by tool-based workflows in which geometry, semantics, and interpretation are repeatedly fragmented when data move between platforms (Garcia and Cardoso, 2019, Niang et al., 2017, Penjor et al., 2024). In smart-city contexts, this is a critical limitation, because heritage assets should function as interoperable urban information objects rather than isolated visual models (Peng et al., 2026c).

Recent reviews show two important shifts in the field. First, digital heritage technologies have expanded from single-task applications toward multi-stage workflows spanning documentation, modelling and visualization, analysis and management, and public engagement (Mazzetto, 2024, Lian and Xie, 2024). Second, target users have broadened from experts alone to include citizens, visitors, and decision-makers. These shifts suggest that the next step is not simply more tools, but a smart data infrastructure able to preserve continuity across heterogeneous representations (Yu et al., 2025a).

This paper addresses that need through the concept of the Architectural Heritage Information Infrastructure (AHII). Building on the broader vision of integrated heritage information systems, AHII is repositioned here providing the evidence, object semantics, and visualization remain explicitly linked. The framework integrates Smart Point Clouds (SPC), HBIM/IFC, and 3D Gaussian Splatting (3DGS) through persistent identifiers, shared spatial referencing, and traceable semantic mappings.

The paper makes three specific contributions. First, it identifies a remaining integration gap in current architectural heritage digitization workflows: existing point-cloud, HBIM/IFC, GIS, and visualization approaches often support pairwise data exchange, but they rarely preserve a single auditable chain of object identity, semantics, spatial correspondence, and provenance across evidence, authoritative modelling, and visual dissemination layers. Second, it proposes AHII as an operational linkage model that coordinates Smart Point Clouds, HBIM/IFC, and 3D Gaussian Splatting through persistent identifiers, a shared spatial reference, versioned transformation metadata, and the crosswalk IfcGUID ↔ patch_id ↔ cluster_id. Third, it demonstrates the feasibility of the model through two Dutch pilot cases and reports initial evidence on cross-representation semantic propagation, geometric alignment, identifier persistence, and task-based inspection.

2. From digital heritage tools to smart 3D Information Infrastructure

The recent evolution of digital technologies in architectural heritage indicates a clear shift from isolated documentation tools to increasingly interconnected digital ecosystems (Jiang et al., 2023). While earlier applications often focused on single technical tasks such as surveying, recording, or visualization,

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contemporary heritage workflows are progressively characterized by the integration of multiple digital technologies across different phases of conservation, interpretation, and communication (Angeloni et al., 2023). This transition is particularly relevant from a 3D information infrastructure, because heritage information is no longer handled as a set of disconnected files, but increasingly as a multi-representational information environment in which geometry, semantics, analysis, and interaction need to remain coordinated (Yao et al., 2023).

2.1 Multi-stage digital heritage

A useful way to understand the development of digital technologies in architectural heritage is to distinguish four linked stages in the digital heritage lifecycle: documentation, modelling and visualization, management and analysis, and interaction. These stages should not be understood as strictly separate phases. Rather, they describe recurrent functions within an integrated information workflow, where heritage data are captured, structured, analysed, managed, and communicated across different platforms and user groups.

The documentation stage concerns the acquisition and recording of heritage assets, including geometric, visual, and contextual information (Cursi et al., 2022). The modeling stage transforms raw observations into more structured, navigable, or interpretable forms, such as surface reconstructions, semantic models, or visual scene representations (Crisan et al., 2024, Peng et al., 2026a). The management and analysis stage supports activities such as condition assessment, monitoring, comparison, information retrieval, and decision-making. Finally, the interaction stage addresses communication, dissemination and visualization, education, and public engagement, while also serving professional uses through more accessible and intuitive interfaces (Wang and Meng, 2024).

This lifecycle perspective is important because heritage information is repeatedly transformed rather than simply stored. Survey data are cleaned, registered, segmented, and interpreted; models are enriched with semantic attributes; analytical results are used for conservation or management; and simplified visual products are created for expert review or public communication. When these transformations occur without stable links, the same wall, column, roof element, inscription, or decorative feature may acquire different identifiers, inconsistent labels, or ambiguous spatial positions across platforms. This is the key reason why architectural heritage digitization should be treated as an information-continuity problem, not only as a data-production problem.

The timeline in Fig. 1 was synthesized from a PRISMA-informed literature review of digital technologies applied to architectural heritage. English-language peer-reviewed publications were retrieved from Web of Science and Scopus using two keyword groups: one related to architectural and cultural heritage, and one related to digital technologies, tools, platforms, and information infrastructures. The initial search identified 1,913 records, including 886 from Web of Science and 1,027 from Scopus. After duplicate removal, eligibility screening, keyword cleaning, manual review, and quality assessment, 227 publications were retained for analysis. Keyword co-occurrence mapping in VOSviewer was then used to identify major technology clusters and their changing interconnections. Fig. 1 therefore does not aim to provide a complete technical history of each technology, but to show the broader transition from isolated digital tools toward increasingly integrated and multi-stage digital heritage workflows.

Overall, the review indicates that digital heritage technologies have progressively moved from single-purpose documentation and visualization tools toward interconnected information environments. Technologies such as point clouds, photogrammetry, HBIM, GIS, VR/AR, machine learning, digital twins, and more recently 3D Gaussian Splatting now operate across several lifecycle stages. This overlap creates new opportunities for heritage documentation and communication, but it also creates a coordination problem: identity, semantics, spatial alignment, and provenance must remain traceable when information moves between different representations. This problem motivates the AHII framework introduced in the following sections.

Previous integration efforts in digital heritage have mainly followed three directions: scan-to-HBIM workflows that convert survey evidence into structured object models; HBIM–GIS or HBIM–digital twin integration for urban-scale management; and HBIM/photogrammetry/VR/AR workflows for visualization and public communication (Yu et al., 2026b). These works are important, but they are often pairwise. They usually connect two data forms at a time and do not explicitly maintain a persistent identity–semantics–provenance chain across evidence, authoritative semantics, and lightweight photorealistic visualization. AHII is positioned in this remaining gap by coordinating SPC, HBIM/IFC, and 3DGS through a minimal cross-representation linkage model.

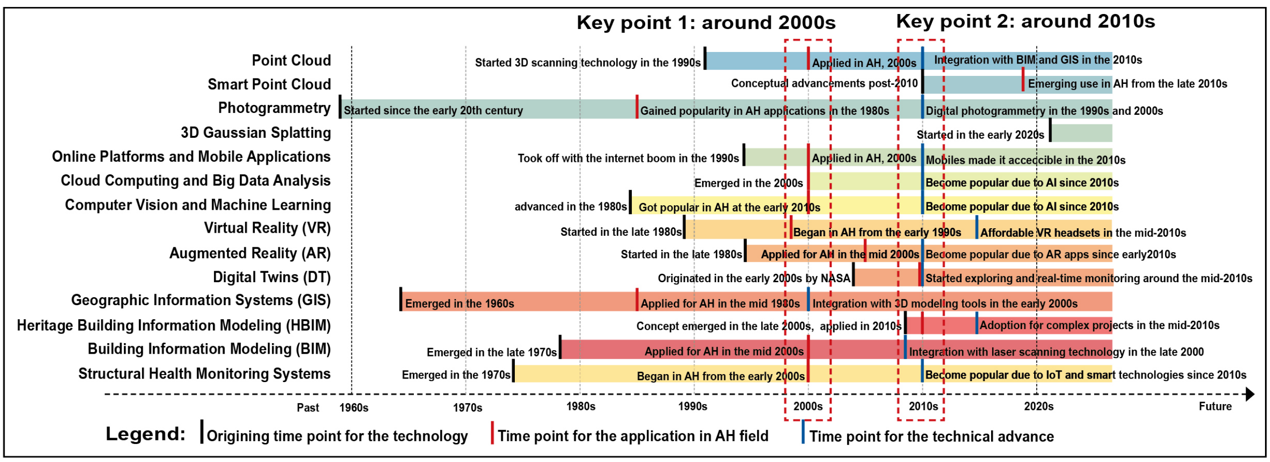

Figure 1. Timeline of the digital technologies' applications in architectural heritage.

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2.2 Digital technologies applied across the four stages

To further clarify this transition, the selected digital technologies and platforms are grouped into four functional categories: representation, computing technologies, visualization and interaction, and information systems. These categories cut across the four lifecycle stages described above. This mapping shows that current technologies are rarely confined to a single application stage. Instead, many of them now span multiple stages, while integrated platforms increasingly support workflows that extend across the entire heritage information lifecycle.

This pattern is especially visible in technologies primarily associated with representations. Point clouds, Smart Point Clouds, photogrammetry, and 3DGS are all rooted in the recording of heritage assets, yet they already support more than mere data capture (Yunisya et al., 2026). Point cloud and Smart Point Cloud technologies enable scan-based storage, preliminary visualization, inspection, and preparation for subsequent 3D modelling (Buldo et al., 2024, Zhang and Yuyang, 2024). Photogrammetry similarly supports image-based reconstruction and visual documentation (Javadi Moghadam et al., 2026, Peng et al., 2026b). 3DGS, although also derived from image-based acquisition, extends beyond documentation by enabling lightweight and photorealistic scene representation, thereby forming a bridge between recording, visualization, and interactive exploration (Yu et al., 2025b). Nevertheless, more advanced semantic management and structured analysis usually require connection to other interoperable environments.

A second cluster consists of computing type based on information technology and the Internet, including online platforms and mobile applications, cloud computing, big data analysis, and computer vision and machine learning. These technologies are applicable throughout the architectural heritage workflow, from data acquisition and processing to modelling, analysis, management, and dissemination. Computer vision and machine learning can, for example, support the cleaning, segmentation, and classification of point cloud data during documentation, while also contributing to semantic modelling, condition assessment, and predictive analysis at later stages. Online platforms and mobile applications support collaboration, portable scanning, public dissemination, and maintenance workflows, whereas cloud computing provides infrastructure for large-scale storage, exchange, and computation across nearly all stages.

A third group includes VR and AR technologies, whose primary role lies in visualization and interaction. These technologies transform how architectural heritage is perceived, interpreted, and experienced, especially in public-oriented settings. They help bridge historical knowledge and contemporary experience, thereby contributing not only to preservation, but also to education, communication, and engagement (Malik, 2024). At the same time, their intuitive visual interfaces are also useful for researchers, designers, and heritage managers in professional contexts (Almeraj et al., 2026, Zhang et al., 2025).

Finally, there are integrated digital technology information systems, including GIS, HBIM, BIM, digital twins, and structural health monitoring systems (Kong and Hucks, 2023, Argasiński and Tomczak, 2025, Parente et al., 2025). These platforms typically combine modelling, management, analysis, and interaction functions, and in some cases also incorporate data acquisition or monitoring workflows. In particular, standards-based environments such as BIM and HBIM depend on cleaned, structured, and semantically explicit data to support formal exchange and interoperability. This highlights an important point: as heritage workflows become more integrated, the challenge is no longer simply to generate digital data, but to ensure that the meaning of these data remains understandable and transferable across both human users and computational systems (Ma et al., 2025).

Taken together, this mapping shows that digital heritage technologies increasingly overlap in function and operate across multiple stages of the information lifecycle. The practical implication is that heritage projects now require more than isolated software tools; they require a stable logic for coordinating heterogeneous but complementary representations.

2.3 Core requirements for smart heritage data

The increasing overlap among digital technologies raises a more fundamental question: how can heritage information remain coherent as it moves across different stages, tools, and audiences? A smart heritage data infrastructure must therefore satisfy at least four conditions.

First, it must preserve identity continuity, so that the same wall, roof element, column, or decorative feature can be traced across evidence, object models, and viewer-oriented assets. Second, it must maintain semantic continuity, allowing labels and attributes to move across representations without uncontrolled drift. Third, it must support reproducible spatial alignment and auditable exchange, so that correspondences between different representations are explicit rather than assumed. Fourth, it must enable audience-aware delivery, allowing professionals and the public to interact with different interfaces without breaking links to authoritative information.

These requirements suggest that the central problem is not the absence of digital data, but the lack of infrastructure-level coordination among heterogeneous data forms. In other words, the challenge is not only technical conversion between formats, but the preservation of identity, meaning, and spatial correspondence across a multi-stage heritage information lifecycle.

From a 3D GeoInfo perspective, this is precisely where the concept of AHII becomes relevant. Its practical value lies in coordinating heterogeneous yet complementary representations within one traceable information environment. This requires more than geometric conversion between formats; it requires an explicit and stable logic for preserving object identity, semantic meaning, and spatial correspondence as information moves between capture, modelling, management, and interactive visualization. For this reason, AHII is structured as a multi-representation framework in which different layers perform different functions, but all remain connected through explicit linkage rules. The following section therefore introduces the three principal layers that form the operational core of the framework.

This matrix (Table 1) clarifies that no single representation satisfies all AHII requirements alone. The infrastructure value lies in assigning different responsibilities to SPC, HBIM/IFC, and 3DGS while maintaining explicit links among them.

AHII condition	**SPC**	**HBIM/IFC**	**3DGS**

Identity continuity	patch_id identifies evidence segments	IfcGUID anchors authoritative objects	cluster_id identifies visual regions
Semantic continuity	proposes labels from segmentation / annotation	stores curated object semantics and property sets	displays propagated semantic labels
Spatial alignment	preserves survey geometry	positioned in shared coordinate reference	aligned by transformation metadata
Audience-aware delivery	expert evidence inspection	structured query and management	lightweight visual exploration

Table 1. Mapping AHII requirements to SPC, HBIM/IFC, and 3DGS

3. AHII 3D representation type

The following subsection therefore introduces the three principal 3D representation types that implement AHII.

3.1 Three complementary 3D representation types

AHII does not seek to collapse all heritage information into a single monolithic model. Instead, it coordinates three complementary 3D representation types (Fig. 2).

The first is the Smart Point Cloud (Poux et al., 2016). In AHII, SPC functions as the evidence layer. It preserves high-density survey geometry and supports patch-level semantic proposals derived from segmentation, annotation, or machine learning. Its strength lies in remaining close to the captured reality while allowing iterative refinement.

The second is the HBIM/IFC layer. This is the authoritative semantic container. Object identities are anchored through IfcGUIDs, and structured properties are stored in a standards-oriented format suitable for documentation, exchange, and management. HBIM is therefore not merely another visualization model; it is the layer in which semantics are normalized, attributes are curated, and authoritative object-level interpretation is maintained.

The third is 3D Gaussian Splatting. In AHII, 3DGS acts as a lightweight, photorealistic, queryable visualization layer. It is especially valuable for inspection, communication, and immersive access, but it is not treated as an independent semantic authority. Instead, it receives traceable semantic attachments propagated from the evidence and object layers (Lee et al., 2025). In Fig. 2, S3DGS refers specifically to the semantically enriched 3DGS layer generated after semantic labels are linked through the AHII framework.

Operationally, the relation among SPC, 3DGS, and IFC is not implemented as a single geometry-only conversion, but as a traceable cross-representation transformation workflow. The SPC layer is first standardized, denoised, and segmented, and each semantic segment is assigned a persistent patch_id linked to an external metadata record containing HBIM-oriented attributes such as material, structural role, decorative information, and conservation notes. In parallel, the 3DGS model is reconstructed from calibrated image sets and aligned to the same shared spatial reference through an explicit transformation, while the HBIM model is exported as IFC and positioned within the same coordinate framework. This common spatial reference establishes the geometric basis for inter-representation correspondence.

On this basis, semantic transfer is achieved through identifier crosswalks rather than through direct substitution of native data structures. SPC-derived observations are injected into IFC property sets, where IfcGUIDs serve as authoritative object identifiers for structured documentation and exchange, while the same SPC semantics are propagated to aligned 3DGS clusters assigned stable cluster_ids for lightweight visualization and interactive inspection. A lightweight crosswalk (IfcGUID ↔ patch_id ↔ cluster_id), together with recorded transformation metadata, therefore preserves identity continuity, semantic traceability, and auditable correspondence across the evidence, semantic, and visualization layers.

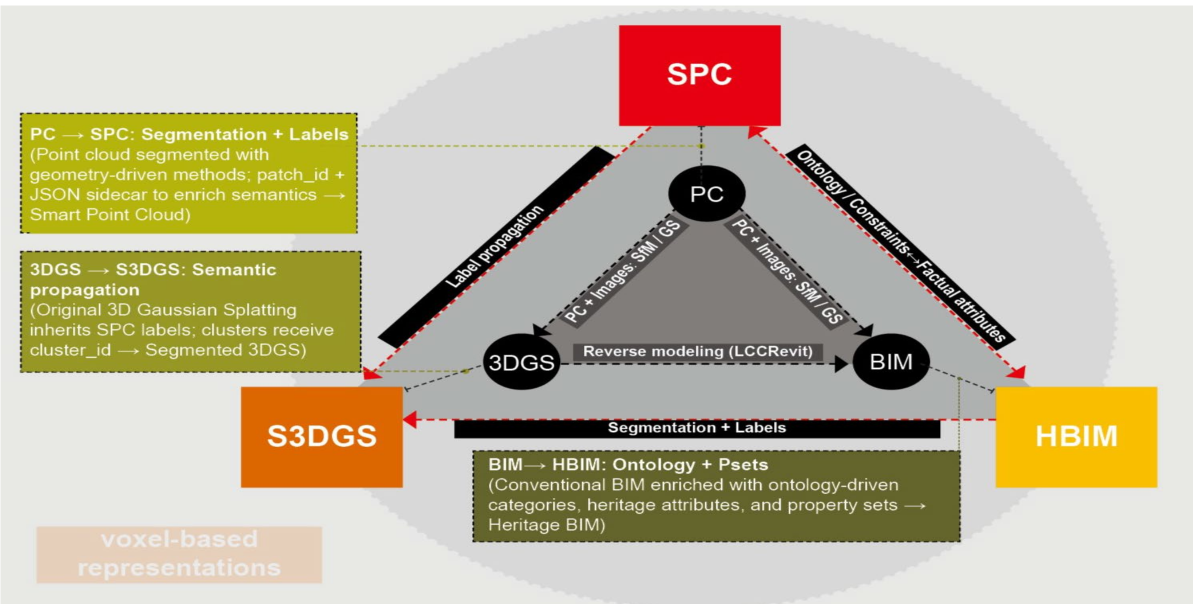

Figure 2. Workflow of three complementary 3D representations.

3.2 Cross-3D representation linkage

What makes AHII an infrastructure rather than a collection of files is the explicit linkage between these types. The framework uses a shared spatial reference, an alignment transform, and an identifier crosswalk. In practical terms, correspondence is recorded between IfcGUIDs in HBIM, patch identifiers in SPC, and cluster identifiers in 3DGS. This means that semantic transfer is explicit and inspectable rather than implicit.

A lightweight UML-based coordination model can formalize these relationships without replacing existing standards (Fig. 3). Its purpose is not to duplicate IFC or geospatial schemas, but to define the minimum entities and relations needed for continuity: identities, correspondences, provenance, versioning, semantic labels, and exchange metadata. In this way, AHII is standards-oriented in an operational sense. It uses common formats where possible, but adds the traceability logic that is often missing in project-specific workflows.

3.2.1 Crosswalk establishment and validation

The crosswalk is established through five steps (Table 2). First, all three representations are transformed into a shared project reference system, and the transformation parameters are stored as metadata. Second, the SPC is segmented into semantic patches, each assigned a persistent patch_id. Third, candidate links between SPC patches and IFC objects are generated by spatial overlap, proximity, and semantic compatibility, using IfcGUID as the authoritative object identifier. Fourth, aligned 3DGS splats are grouped into visual clusters and assigned cluster_id values; these clusters are linked to SPC patches through spatial overlap and visual inspection. Fifth, each accepted or rejected correspondence is recorded in a crosswalk table with provenance, version, confidence, and validation status.

Field	Meaning
IfcGUID	Authoritative HBIM/IFC object identifier
patch_id	SPC semantic patch identifier
cluster_id	3DGS visual cluster identifier
transform_id	Spatial transformation record
relation_type	one-to-one, one-to-many, many-to-one, partial
semantic_label	shared or mapped semantic class
confidence	high / medium / low, or numeric score
validation_status	accepted, rejected, ambiguous, pending
method	automatic, semi-automatic, manual
version/date	crosswalk version and update time

Table 2. crosswalk record

The crosswalk allows one-to-many and many-to-one relations, because a single IFC object may correspond to multiple SPC patches, and a visually coherent 3DGS cluster may cover more than one architectural element. Ambiguous correspondences are not forced; they are explicitly recorded as partial or unresolved links.

Fig. 3 should be read as a minimal coordination schema rather than a replacement for IFC, GIS, or 3DGS-native data structures. The central class 3DRepresentation records the version, coordinate reference, transformation metadata, and validity period of each representation. HeritageObject provides the project-level anchor, while IfcHBIM, SmartPointCloud, and GaussianSplatting specify the three representation layers. SemanticGaussianPatch and BIMElement implement the cross-representation semantic links, whereas ExternalSemantic and Document classes store controlled vocabularies, historical references, conservation records, and supporting documents. This structure makes semantic propagation auditable: a user can move from a 3DGS visual cluster to the corresponding SPC evidence patch and then to the authoritative IFC property set, while preserving the provenance of each link.

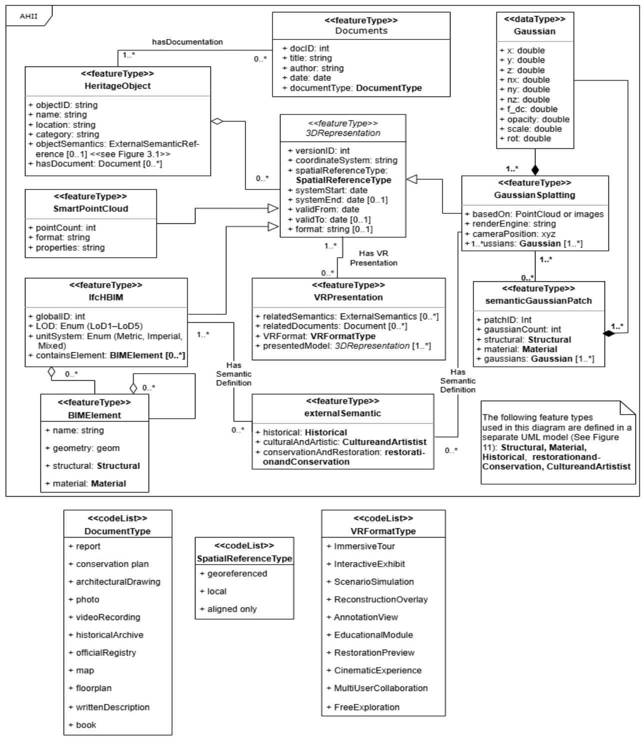

Figure 3. Unified information model of AHII (UML schema): Shows the core feature types.

3.3 Relevance to 3D smart cities

AHII treats heritage assets as interoperable spatial objects with persistent identity, explicit semantics, and multiple valid representations. This is directly relevant to smart-city information ecosystems. Urban heritage is rarely only a conservation issue; it also intersects with planning, tourism, public communication, urban memory, risk assessment, and long-term asset management. A heritage information infrastructure that can connect building-scale evidence and semantics to broader geospatial systems is therefore more valuable than a stand-alone model.

4. Illustrative implementation and early evidence

4.1 Two pilot cases

The framework has been explored through two Dutch pilot cases at different scales: a compact public memorial and a larger, architecturally complex monument building. The contrast between these cases is important. The smaller case tests whether the infrastructure can work cleanly on a limited, interpretable object, while the larger case tests whether the same logic remains useful under higher geometric complexity and larger data volumes (Table 3).

To clarify the empirical role of the two pilots, the cases were selected not only because they differ in size, but because they stress different parts of the AHII workflow. Case A, Herdenkingsmonument Kartuizerklooster (HK), is a compact public monument with a limited footprint, clear object boundaries, and rich municipal archival information. It therefore provides a controlled setting for testing whether persistent identifiers, semantic patches, IFC objects, and 3DGS clusters can be linked in a clean and interpretable manner. Case B, the Aula building in Delft, is a building-scale Dutch national monument with more complex geometry, larger data volume, limited ground-level capture conditions, and the need to fuse supplementary point clouds. It therefore tests whether the same AHII logic remains operational when the number of architectural elements, occlusions, and partial correspondences increase.

The contrast between the two cases is important for evaluating AHII. HK mainly tests semantic clarity, object-level correspondence, and public-facing interpretation at a small scale. Aula tests scalability, geometric alignment, semantic consistency, and cross-representation inspection under more complex architectural conditions. Together, the two cases show that AHII is not tied to a single object size or documentation setting, but can coordinate evidence, authoritative semantics, and visualization across different levels of heritage complexity. In both cases, the workflow followed the same logic. Images and point clouds were acquired and aligned to a shared project reference (Fig. 4). SPC packages were segmented into patches and enriched with semantic labels. HBIM models were exported in IFC and used as the authoritative object-semantic layer. 3DGS models were reconstructed from image sets and aligned to the same reference. Cross-layer correspondences were then recorded so that labels, queries, and inspection results could be transferred between representations.

Aspect	HK case	Aula case
Type	Compact public memorial	Building-scale national monument
Scale	Small object / site	Large, complex building
Data	30 images; approx. 0.6M-point cloud	412 images; approx. 975M-point cloud + AHN5 LiDAR
Semantic source	Municipal records + manual annotation	Kunstwacht records + manual annotation
Main test	Clean object-level linkage	Scalability under complex geometry
AHII value	Links visual interpretation to evidence and semantics	Maintains identity, semantics, and provenance at building scale

Table 3. Comparison of the two pilot cases

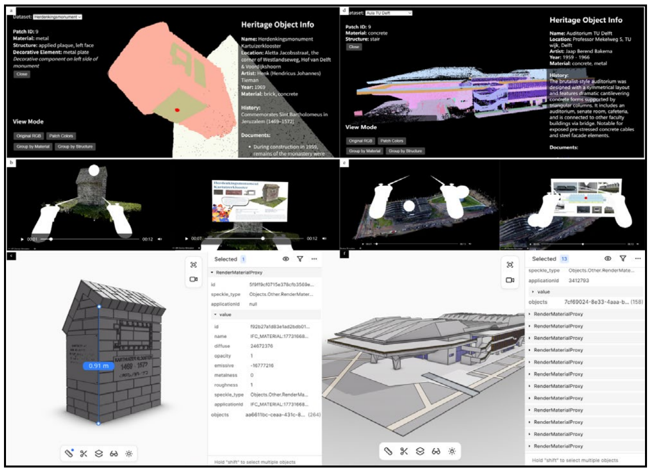

Figure 4. Interactive visualization and semantic inspection across AHII representations.

4.2 Initial evidence

To assess whether AHII supports task-driven switching among SPC, HBIM/IFC, and 3DGS, we conducted an online task-based formative evaluation. After quality control, including attention checks, minimum completion-time screening, and duplicate-response removal, the final sample included 200 participants: 101 participants with heritage-related academic or professional backgrounds and 99 members of the general public. Participants accessed the three representations in counterbalanced order and completed guided tasks related to inscription information, facade material recognition, and overall spatial-structure understanding (Table 4).

The evaluation included both objective task performance and subjective perception ratings. Objective performance was measured through three verifiable questions: identifying the inscription date range, identifying facade material categories, and recognizing the number of building floors. Subjective perception was measured using nine 7-point Likert-scale items grouped into three dimensions: system usability, cognitive interpretability, and operational value. Dimension scores were computed as the mean of the corresponding items. Reliability was checked using Cronbach's alpha, and representation effects were examined using marginal means and pairwise comparisons.

The results indicate that 3DGS provided the most fluent interface for navigation and public-facing interpretation, whereas SPC and HBIM/IFC remained important for evidence inspection and structured semantic query. In terms of subjective perception, 3DGS scored higher than SPC and HBIM/IFC for system usability and cognitive interpretability, while perceived operational value remained comparatively stable across the three representations. Objective task accuracy was high for inscription information and material recognition, reaching 98.5% and 91.5%, respectively, while the spatial-structure task was more difficult, with an accuracy of 66.5%. This suggests that AHII can support complementary task performance across representations, but that global spatial understanding may require clearer navigation aids or level indicators in future viewer implementations.

Item	Description
Participants	N = 200
Groups	101 experts; 99 public
Tested representations	SPC, HBIM/IFC, 3DGS
Protocol	Online task-based evaluation;

	counterbalanced order
Tasks	Inscription, material recognition, spatial structure
Measures	Objective accuracy + 7-point Likert ratings
Main finding	3DGS was best for fluent interpretation; SPC and HBIM/IFC remained useful for evidence inspection and structured query

Table 4. Task-based user evaluation

To provide empirical evidence of cross-representation continuity, the two pilot cases were assessed in terms of semantic propagation, geometric co-location, and IFC exchange integrity (Table 5).

Metric	**HK**	**Aula**
SPC macro-mIoU	0.88	0.86
3DGS propagated semantic macro-mIoU	approx. 0.53	approx. 0.62
HBIM–SPC RMSE3D	9.2 mm	16.4 mm
SPC–3DGS RMSE3D	24.9 mm	36.4 mm
IFC GUID persistence	100%	100%
IFC property-set retention	approx. 98%	approx. 98%

Table 5. Technical validation results

These results show that AHII does not only place SPC, HBIM/IFC, and 3DGS side by side, but maintains measurable semantic, geometric, and identifier continuity across them.

5. Discussion

The AHII perspective shifts attention from model production to information continuity. Many heritage projects already produce scans, BIMs, databases, viewer models, and public outputs. The persistent problem is that these assets are often linked only informally, through file naming conventions, manual interpretation, or one-off software scripts. AHII argues that heritage digitization should instead be organized through explicit, reproducible, and minimal infrastructure logic.

This also clarifies AHII's relation to existing standards. AHII does not compete with IFC, GIS, or other established schemas. HBIM/IFC remains the authoritative object-semantic anchor; geospatial systems remain essential for broader context and city-scale integration. AHII adds the layer of coordination that enables evidence, semantics, and visualization to remain traceably related across different tools and audiences.

For smart-city applications, this matters because built heritage is not peripheral data. Heritage assets are long-lived urban objects with legal, cultural, spatial, and social significance. They require condition assessment, maintenance planning, visitor communication, and sometimes integration with broader digital twins or geospatial platforms. A smart-city heritage workflow therefore needs data that are not only visually rich, but also semantically stable and interoperable.

Several limitations remain. The framework has so far been explored on only two cases, both within one national context. Some semantic population steps still depend on expert-guided refinement. Building-scale GIS integration remains more a direction than a fully implemented component. In addition, 3DGS semantics are still at development stage rather than fully standardized, which means long-term packaging and exchange conventions need further work. Even so, the framework provides a useful basis for future research on cross-standard mappings, automated semantic propagation, and city-scale heritage information services.

6. Conclusion

This paper argues that architectural heritage digitization should be understood as a 3D smart-data integration challenge. Based on the observed evolution of digital heritage technologies toward multi-stage, multi-audience, and increasingly interoperable workflows, it proposes AHII as a standards-oriented framework for maintaining information continuity across Smart Point Clouds, HBIM/IFC, and 3D Gaussian Splatting.

The central idea is simple but important: heritage information should remain traceable as it moves from captured evidence, to authoritative object semantics, to lightweight visual dissemination. By linking these layers through persistent identifiers, shared spatial reference, explicit crosswalks, and controlled vocabularies, AHII turns disconnected digital products into a coordinated information infrastructure.

The value of AHII lies in making architectural heritage interoperable, queryable, and audience-aware without sacrificing provenance. Future work should extend this logic toward broader GIS integration, stronger semantic automation, and more standardized exchange rules for emerging visual representations. A further direction for future work is to examine whether voxel-based representations could be incorporated as an intermediate semantic-spatial layer within AHII. Although voxel structures are not part of the current operational core, they may offer useful support for discretized analysis, multi-scale correspondence, and cross-representation mapping in more complex workflows. Their role, however, requires more systematic investigation before they can be integrated into the framework in a principled way. Moreover, this perspective opens the possibility that HBIM could, in the longer term, inform future standardization discussions within or across organizations such as OGC, ISO, and UNESCO. In this sense, AHII is not only a heritage framework; it is a pathway toward smarter cultural data infrastructures within future smart-city ecosystems.

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