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LEVEL OF HISTORY (LOH) IN HBIM-T: A METHODOLOGY FOR MODELING AND VISUALIZING HISTORICAL UNCERTAINTY IN DIGITAL MODELS OF ARCHITECTURAL HERITAGE

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SUMMARY: *This paper presents a methodology for applying the Level of History (LoH) parameter to describe and visualize historical uncertainty in Historic Building Information Modeling with a temporal dimension (HBIM-T). The research is motivated by the identified gap between existing BIM standards—such as Level of Development (LOD) and Level of Information (LOI)—and the need to represent source reliability and the degree of certainty in the reconstruction of heritage buildings. A five-level LoH scale is developed, integrating the hierarchy of historical sources with BIM model parameters. The study proposes principles for assigning LoH levels and their implementation through the extension of the IFC schema with a dedicated property set. A key element of the methodology is the integration of the LoH parameter with temporal modeling, enabling the linkage of certainty levels to successive phases of a building's development. The results indicate that the application of LoH improves the transparency of HBIM models, supports the distinction between evidence-based data and hypothetical reconstructions, and facilitates the interpretation and management of knowledge related to historical objects. The proposed approach operationalises an epistemological dimension within HBIM-T by embedding source reliability and uncertainty directly into BIM element attributes and temporal phases. Validation is currently qualitative and design-science oriented; future work will include empirical user studies and comparative benchmarking against existing frameworks such as LOK, GoG and Source-Feature Matrix.*

KEYWORDS: *HBIM-T, historical uncertainty, temporal modeling, architectural heritage, Level of History, digital heritage.*

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1. INTRODUCTION

In recent years, a dynamic development of digital methods for the documentation, analysis, and management of built assets has been observed (La Guardia et al., 2025). One of the key tools supporting these processes is the Building Information Moel/Modelling/Management (BIM) methodology, which enables the development and management of a digital representation of a building throughout its entire life cycle (Kraus et al., 2022).

In the context of historical buildings and cultural heritage, this concept has been extended into the approach known as Historic Building Information Modelling/Management (HBIM), which integrates geometric, historical, and material data within a single information environment (Lucchi & Fayez, 2024).

Historic Building Information Modeling (HBIM) constitutes a key methodology for the documentation, analysis, and management of architectural heritage, integrating advanced surveying technologies with semantic parametric modelling (Ripp et al., 2025). Unlike BIM applied to new construction, where geometric and material parameters are based on design documentation with a high level of certainty, HBIM must address historical uncertainty resulting from the fragmentary nature, ambiguity, and varying reliability of documentary sources (Murphy et al., 2009; Pocobelli et al., 2018).

Historic buildings are characterized by complex geometry, irregular forms, and often limited availability of archival documentation (Salah et al., 2025). Consequently, the development of HBIM models relies heavily on modern spatial data acquisition techniques, such as terrestrial laser scanning (TLS) and digital photogrammetry (Xu et al., 2025). These technologies enable the generation of accurate point clouds, which form the basis for further geometric modeling of the objects.

Uncertainty in HBIM manifests at three levels:

- geometric uncertainty, resulting from limitations of measurement technologies and material degradation;
- historical information uncertainty, related to the dating of construction phases and functional transformations;
- interpretative uncertainty, concerning the reconstruction of non-existing or poorly documented elements based on indirect sources, typological analogies, and research hypotheses (Mazzei et al., 2024; Pocobelli et al., 2018).

Despite the growing number of studies on the application of HBIM in the documentation of cultural heritage, the literature primarily focuses on issues related to data acquisition and the development of detailed geometric models. Much less attention is given to the optimization of model levels of detail in the context of their practical use. In particular, there is a lack of clear guidelines for selecting appropriate levels of detail (LOD – Level of Development/Detail) for HBIM models, taking into account both the accuracy of measurement data and the intended applications of the models, such as conservation documentation, facility management, or technical analyses (Lo Brutto et al., 2026).

Existing standards defining model maturity levels, such as LOD (Level of Development) and LOI (Level of Information) (Sacks et al., 2018), focus exclusively on geometric and informational aspects, neglecting source reliability, which is crucial in the context of heritage. Although concepts such as LOK (Level of Knowledge) and LoH (Level of History) have been introduced in the literature, there is still a lack of systematic methodologies for their operationalization within HBIM processes and their integration with temporal modeling (HBIM-T) (Banfi et al., 2021; Brumana et al., 2018). In this study, LoH is therefore not introduced as a new conceptual construct, but as a systematic, five-level, rule-based and IFC-implemented operationalisation of the Level of History idea within HBIM-T workflows.

This issue has significant practical implications, as excessive model detail may increase model complexity, hinder usability, and generate high development costs. Conversely, an insufficient level of detail may limit the applicability of the model in processes related to the conservation and management of cultural heritage. Therefore, it is necessary to define optimal levels of detail for HBIM models that ensure a balance between accuracy and functionality (Kwast-Kotlarek & Szóstak, 2026).

The practical implementation of transparency principles in HBIM models faces several significant challenges, including:

- the lack of standardized methods for documenting source evidence for individual model elements;
- limited interoperability between BIM tools and historical documentation management systems;
- insufficient visualization mechanisms enabling intuitive differentiation of certainty levels within 3D environments (Pocobelli et al., 2018).

In response to these challenges, the aim of this paper is to define and evaluate the Level of History (LoH) in HBIM models for historical buildings, taking into account data acquisition methods, geometric accuracy, and their practical applications.

To achieve this objective, the following research questions were formulated:

1. How can LoH levels be defined and categorized to reflect the varying reliability of historical sources used in HBIM?
2. How can LoH parameters be linked with geometry, attributes, and temporal phases in HBIM models?
3. What benefits (and limitations) result from the application of LoH in reconstruction processes, scenario analysis, and conservation decision-making?

The scientific contribution of this paper lies in the systematic analysis of HBIM model levels of detail in relation to historical buildings and in proposing an approach that enables the selection of an appropriate level of detail depending on available data and the intended use of the model.

2. STATE OF THE ART

2.1 Fundamentals of HBIM and the challenge of uncertainty

Early research on HBIM primarily focused on the scan-to-BIM process, involving the transformation of data acquired from terrestrial laser scanning (TLS) and photogrammetry into parametric digital models (Rocha et al., 2020). In this approach, the main emphasis was placed on the accuracy of geometric representation and the efficiency of processing measurement data (Alshawabkeh & Baik, 2023).

In recent years, however, a significant shift in the perception of HBIM has been observed (Javier Sánchez Aparicio et al., 2025). Increasingly, HBIM models are treated not merely as three-dimensional representations of objects, but as comprehensive information environments integrating geometric, material, historical, and interpretative data (Lovell et al., 2023). In this context, the key issue becomes not only the representation of an object's form, but also the way in which knowledge about its history, and the degree of certainty of that knowledge, is encoded (Şentürk & Şimşek, 2025).

As noted by Pocobelli et al. (2018), the development of HBIM is associated with three main challenges:

1. automation of data acquisition and model generation;
2. updating and managing information throughout the model lifecycle;
3. modeling data affected by uncertainty.

Among these, the issue of uncertainty is particularly significant in the context of heritage objects, due to the limited availability of sources, ambiguity of historical data, and the need for interpretation of the building's condition.

In standard BIM practice, a set of parameters is used to describe model "maturity," such as Level of Development (LOD), which defines the degree of detail and refinement of model elements, and Level of Information (LOI), referring to the scope of non-geometric information. These standards were primarily developed for new construction and assume the availability of unambiguous design data (Borrmann et al., 2018). Consequently, they do not account for situations typical of heritage objects, where knowledge about the building is incomplete, fragmentary, reconstructed from indirect evidence, or sometimes contradictory (Abualdenien & Borrmann, 2022).

In response to these limitations, several concepts extending the classical BIM approach in the context of cultural heritage have been proposed in the literature. Grades of Generation (GoG) refer to the level of geometric accuracy depending on the type and quality of available measurement data, while Level of Knowledge (LOK) integrates the quality control of both graphical and descriptive information (Banfi et al., 2021; Brumana et al., 2018). The concept of Level of History (LoH), in turn, emphasizes the importance of historical information and source evidence underlying modeling assumptions. Despite growing interest in these concepts, existing studies are largely theoretical or conceptual in nature.

Existing frameworks such as LOK and GoG (Banfi et al., 2021; Brumana et al., 2018) address knowledge quality and geometric generation but remain only partially operationalised within mainstream BIM tools. The Source Feature Matrix proposed by Liu et al. (2025) offers a powerful mapping between sources and features in virtual reconstructions, while paradata oriented initiatives, including the London Charter and work by Bentkowska Kafel and Denard (Bentkowska-Kafel & Denard, 2012), emphasise epistemological transparency and the explicit documentation of interpretative steps. Additional contributions, such as Napolitano et al. multi source confidence models for heritage structures (Napolitano, Scherer & Glisic, 2018), CityGML heritage LOD extensions (Pepe et al., 2020, Lasorella & Cantatore, 2025), Brusaporci's 'Ideal Model' concept (Brusaporci et al., 2018) and research related to the methodology for the creation of the HBIM model conducted by Borkowski (Borkowski, 2023; Borkowski & Wyrzykowska, 2025), further highlight the need for integrated representations of uncertainty and transparency in digital heritage.

In particular, there is a lack of coherent methodologies for implementing parameters such as LoH within BIM environments and linking them to geometric modeling processes and information management over time. There are also no clear guidelines for integrating levels of detail (LOD) with the level of certainty of historical data.

The problem of uncertainty in HBIM can be considered within the broader context of scientific modeling, where three main types of uncertainty are typically distinguished:

1. parametric uncertainty, resulting from limited measurement accuracy;
2. structural uncertainty, related to the assumptions adopted in model construction;
3. scenario uncertainty, concerning incomplete knowledge about past or future states of the object.

All these types of uncertainty are present in heritage objects and directly affect the quality and reliability of HBIM models (Abd ElWahab et al., 2024).

The literature includes attempts to address the issue of uncertainty in HBIM. Mazzei et al. (Mazzei et al., 2024) propose the use of parametric modeling and a 4D approach to analyze changes over time, enabling model updates as new data become available and structuring historical information within a temporal framework. Liu et al. (Liu et al., 2025), on the other hand, developed the Source-Feature Matrix (SFM) concept for virtual reconstruction, which links data sources (such as in situ remains, archival documentation, graphical materials, written records, or analogies) with model elements and allows for the assessment of their reliability.

Despite these advancements, existing approaches do not provide a unified and scalable system for categorizing uncertainty that is directly linked to BIM model parameters and allows integration with temporal analysis of object evolution. In particular, there is a lack of solutions enabling the simultaneous consideration of model level of detail (LOD), data quality, and historical reliability.

Addressing this gap by developing an approach that links HBIM model levels of detail with the level of historical uncertainty constitutes one of the key objectives of this paper.

2.2 Temporal modeling (4D) in HBIM

Temporal modeling in HBIM (HBIM-T) extends the traditional three-dimensional model by incorporating the time dimension, enabling the representation of changes in an object across successive phases of its development, reconstruction, and conservation (Boton et al., 2022; Grazianova & Mesaros, 2023). Unlike 4D BIM used in new construction, where the temporal dimension refers to the construction schedule, HBIM-T often operates retrospectively, reconstructing earlier historical states of the building (Stober et al., 2018).

An example of this approach is the work of Bacci et al. (Bacci et al., 2019), in which a BIM model was structured into temporal phases within the Autodesk Revit environment. For the former church of San Quirico in Lucca, each model element was assigned parameters defining the moment of its creation (Phase Created) and, if applicable, its removal (Phase Demolished). This enables the analysis of the building's evolution over time and the visualization of selected historical periods.

Despite the availability of tools supporting temporal modeling, the literature highlights significant limitations of this approach (Awe et al., 2025). First, phasing systems do not account for the level of uncertainty associated with individual phases, treating all stages of a building's development as equally reliable. Second, there is often no clear linkage between model elements and specific historical sources, making it difficult to assess the basis of adopted assumptions. Third, available visualization tools do not allow for intuitive representation of differences in certainty levels among elements within the same phase.

Therefore, there is a need to develop an approach that enables the integration of historical uncertainty information with temporal modeling in HBIM environments. This study addresses this issue by linking parameters describing the level of historical knowledge with the temporal phases of the model.

3. RESEARCH METHODOLOGY

3.1 Research approach and process structure

This study adopts the design science research (DSR) approach, which is widely used in information systems and engineering research, particularly when the objective is to develop a novel artifact addressing an identified practical problem. In the context of this study, the artifact is the Level of History (LoH) scale, together with procedures for its implementation and application within the Historic Building Information Modelling–Temporal (HBIM-T) environment.

The primary aim of the adopted methodology is to develop a coherent, operational, and implementable framework for modeling and communicating historical uncertainty in digital models of architectural heritage.

The research process was structured into four main phases:

1. problem analysis and requirements identification;
2. artifact design in the form of the LoH scale;
3. implementation within a BIM environment and demonstration of functionality;
4. evaluation and validation of the proposed solution.

In the first phase, the problem of uncertainty in HBIM modeling was analyzed, with particular emphasis on its temporal dimension. It was demonstrated that, unlike BIM models used in contemporary construction, where data are typically well-defined and reliable, HBIM models operate on data characterized by varying levels of reliability due to incomplete sources, interpretative processes, and hypothetical reconstructions.

Existing standards, such as Level of Development (LOD) and Level of Information (LOI), do not systematically address this issue. This gap provided the foundation for defining the design assumptions of the LoH scale. The adopted research structure enables a direct linkage between theoretical considerations and practical implementation, which is essential for method- and tool-oriented engineering research.

Within the adopted design-science framework, the success of the LoH artifact is assessed against four criteria:

1. logical consistency of the five-level scale and assignment rules;
2. readability and interpretability of LoH-based visualisations by heritage professionals;
3. technical feasibility of implementing LoH as an IFC property set and integrating it with HBIM-T phasing;
4. compatibility with existing HBIM workflows and standards such as LOD/LOI, LOK and GoG.

Replicability is supported by providing a detailed description of Pset_LoH_Heritage, the decision flowchart for LoH assignment, and the element classification procedure used in the Szewska 49 case study, together with supplementary machine-readable files.

3.2 Conceptual assumptions of the LoH scale and value assignment

The development of the Level of History (LoH) scale is based on four key assumptions derived from literature analysis and conservation practice.

The first assumption is the hierarchy of source reliability, according to which primary sources, such as physical evidence, direct measurements, and preserved material substance, have the highest epistemic value. In contrast, secondary and tertiary sources require interpretation and are associated with a higher degree of uncertainty.

The second assumption is the continuum of knowledge certainty, which spans from full confirmation (e.g., a preserved element in situ) to pure speculation. To enable operational use within a BIM model, this continuum is divided into clearly defined, discrete categories.

The third assumption concerns the multi-source nature of information, which is characteristic of HBIM. A single model element is often created based on a synthesis of multiple data sources of varying quality. Therefore, it is necessary to account for the relationships between these sources and their influence on the resulting level of certainty.

The fourth assumption is transparency, understood as the ability to clearly distinguish between confirmed data, interpreted information, and hypothetical reconstructions within the model (Banfi, 2020).

To ensure consistent application of the scale, a set of operational rules has been defined.

- Rule 1: Weakest link principle. According to the "weakest link" principle, when multiple sources are used, the assigned LoH value should correspond to the least reliable source that is critical for interpreting a given element (in terms of geometry, location, or material). This approach prevents overestimation of certainty;
- Rule 2: Element decomposition. Based on the principle of decomposition, complex elements should be divided into components with different levels of reliability. This allows for a more precise representation of uncertainty within the model;
- Rule 3: Justification documentation. Each LoH assignment must be supported by explicit source references and properly documented. This includes a list of sources (e.g., attachments or links within a Common Data Environment—CDE), a brief textual justification of the interpretation process, and an assessment of the level of agreement between the sources;
- Rule 4: Priority of preserved substance. This rule states that physically existing elements should take precedence over hypothetical reconstructions. In multi-phase objects, preserved material substance (LoH 1) has priority over reconstructed elements (LoH 4–5).

Rules 1 (weakest link) and 4 (priority of preserved substance) can, in principle, point to different LoH values for the same element. Consider a load-bearing wall at Szewska 49 whose lower two-thirds consist of original medieval masonry preserved in situ (LoH 1, per Rule 4: preserved substance takes priority) and whose upper third is a reconstructed parapet based on regional typological analogies (LoH 4, per Rule 1: the weakest contributing source). If the wall were modelled and classified as a single, non-decomposed element, Rules 1 and 4 would suggest different outcomes: LoH 4 for the whole element under Rule 1, versus an implicit claim of LoH 1 authenticity for the wall under Rule 4.

This conflict is resolved by applying Rule 2 (element decomposition) first: whenever a single BIM element combines portions of clearly different reliability, it is split into two sub-elements the preserved masonry core (LoH 1) and the reconstructed parapet (LoH 4) each individually classified. Rule 2 therefore takes precedence over a direct application of Rules 1 and 4 to a composite element. Only when decomposition is not technically feasible does Rule 1 (weakest link) govern the single assigned value, in order to avoid overstating certainty; Rule 4 is then used only as a secondary, qualitative justification recorded in the LoH_Justification attribute, not as a basis for overriding the weakest-link value. This decision order decomposition first, weakest link second, preserved-substance priority as justification rather than override is applied consistently throughout the Szewska 49 case study.

3.3 Structure and definition of the Level of History (LoH) scale

Based on the above assumptions, as well as an analysis of source classification and conservation practices, a five-level Level of History (LoH) scale was developed. The scale ranges from LoH 1 to LoH 5, corresponding to increasing levels of uncertainty:

- LoH 1 – High certainty. Refers to elements supported by direct physical evidence, documented through high-precision measurements (e.g., TLS ≤ 5 mm) or preserved material substance in situ. In this case, uncertainty is limited to measurement tolerance;
- LoH 2 – Medium-high certainty. Includes elements based on primary sources that require interpretation, such as archival drawings, historical photographs, or dendrochronological analyses. There is high certainty regarding the existence of the element, with partial geometric uncertainty;
- LoH 3 – Medium certainty. Applies to elements based on secondary sources or expert analysis. While the existence of the element is confirmed, its form may be reconstructed with limited accuracy, resulting in moderate geometric uncertainty,
- LoH 4 – Medium-low certainty. Covers elements derived from typological analogies, comparative studies, or indirect reasoning. In this case, geometric uncertainty is high, and reliability relates primarily to the general type of the element rather than its specific form;
- LoH 5 – Low certainty. Refers to speculative reconstructions based on minimal evidence, representing one of several possible interpretations.

The defined scale enables the systematic assignment of certainty levels to elements within HBIM models and supports their comparison across different historical phases:

- LoH 1 – High certainty.
  Definition: A model element represents a preserved physical structure documented through high-accuracy direct measurements.
  Sources: Terrestrial Laser Scanning (TLS) with accuracy ≤ 5 mm; photogrammetry with a point cloud density > 1000 pts/m²; preserved in situ elements in an undisturbed condition; dendrochronological measurements with a complete tree-ring sequence.
  Uncertainty range: Geometric uncertainty limited to measurement tolerance; full certainty regarding the existence of the element.
- LoH 2 – Medium-high certainty.
  Definition: A model element is based on original historical sources from the period of construction or use, which require interpretation but do not involve speculation.
  Sources: Original design drawings and technical specifications; historical photographs from the period of use; dendrochronological measurements with incomplete sequences; archaeological investigations of stratigraphic layers.
  Uncertainty range: Geometry may require interpolation; high certainty regarding the existence and general form of the element.
- LoH 3 – Medium certainty.
  Definition: A model element is based on secondary sources (e.g., conservation reports, scientific publications) or expert analysis of material traces.
  Sources: Conservation reports and as-built documentation; analysis of construction traces (e.g., carpenter’s marks, assembly holes); scientific publications analyzing the object; interpreted archaeological stratigraphy.
  Uncertainty range: Moderate geometric uncertainty; high certainty regarding the existence of the element, but moderate certainty concerning its detailed form.
- LoH 4 – Medium-low certainty.
  Definition: A model element is based on typological analogies, comparisons with similar objects, or

logical inference derived from indirect evidence.
Sources: Analogies to preserved objects of the same type, region, or period; architectural treatises and historical pattern books; inference based on structural context; low-reliability iconographic sources (e.g., representational paintings).
Uncertainty range: High uncertainty regarding detailed geometry; moderate certainty concerning the general type of the element.

- LoH 5 – Low certainty.
  Definition: A model element representing a reconstruction hypothesis based on minimal evidence and constituting one of several possible interpretations.
  Sources: Minimal archaeological traces with ambiguous interpretation; speculation based on general architectural principles of a given historical period; interpolation of gaps within discontinuous structural remains.
  Uncertainty range:: Very high uncertainty in all aspects; the reconstruction requires validation by an expert panel.

3.4 Evaluation of the approach

The final stage of the research involved the evaluation of the proposed methodology. The analysis was qualitative in nature and focused on assessing:

- the consistency of LoH value assignment;
- the feasibility of integration with temporal modeling;
- the readability and clarity of visualization;
- the usefulness of the approach for interpreting historical data.

The results of the evaluation confirm that the proposed approach enables a systematic treatment of uncertainty in HBIM and significantly enhances model transparency. This is of particular importance for both academic research and conservation practice, supporting more informed interpretation and decision-making processes.

4. RESULTS AND ANALYSIS

The main outcome of the conducted research is the development and implementation of a five-level Level of History (LoH) scale, which constitutes a coherent mechanism for quantifying historical uncertainty in HBIM-T models. The proposed solution integrates the epistemological foundations of historical source classification with the technical structures of BIM models, thereby addressing the identified research gap between existing LOD/LOI standards and the need for explicit modeling of uncertainty in cultural heritage objects (Table 1).

In contrast to approaches that treat uncertainty primarily in descriptive form (e.g., textual reports or external matrices), the LoH scale embeds source reliability directly into BIM element attributes. Table 1 summarises the relationship between LoH and selected existing concepts such as LOD, GoG, LOK and Source-Feature Matrix.

The proposed LoH framework builds upon existing concepts such as LOD, GoG, LOK and Source-Feature Matrix, as well as Apollonio's colour-coding schemes (Apollonio et al., 2017) and Demetrescu's Extended Matrix for documenting uncertainty (Demetrescu, 2015; Demetrescu & Ferdani, 2021). In contrast to these approaches, LoH embeds source reliability and historical uncertainty as an ordinal attribute directly within HBIM-T elements, integrates it with temporal phasing, and implements it through a dedicated IFC property set (Pset_LoH_Heritage), enabling exchange and analysis across different BIM platforms

As a result, the model evolves from a purely representational tool into an information system that explicitly communicates the epistemic status of its components. This integration allows users to identify, at the level of individual elements, whether a given part of the model is based on direct evidence, interpreted sources, or hypothetical reconstruction. Consequently, the LoH scale enhances both the analytical potential and the interpretative transparency of HBIM-T models.

Table 1: Comparison with existing concepts.

Concept	Scope	Main limitations	Contribution of LoH
LOD (Level of Development)	Degree of completeness of geometry and information at different project stages	Does not account for source reliability; assumes a design-oriented (future-focused) approach	Introduces an epistemological dimension independent of LOD
GoG (Grades of Generation)	Geometric accuracy as a function of the quality of measurement data	Focus limited exclusively to metric aspects	Extends the approach to include non-metric sources (e.g., archival data, typological analogies)
LOK (Level of Knowledge)	Holistic control of graphical and alphanumeric information	Lack of operationalization and integration with BIM systems	Provides implemented IFC parameters and a defined workflow
Source-Feature Matrix	Mapping of source support for features of virtual reconstruction models	External matrix relative to the BIM model; lack of automation	Embeds reliability directly as an attribute of model elements
Apollonio's colour-coding scheme	Visual encoding of hypotheticality/reliability levels through colour-coded 3D reconstruction elements (Apollonio et al., 2017)	Provides a visualisation convention only; not linked to a formal, machine-readable attribute structure; reliability assigned qualitatively, outside the BIM data schema	Retains the colour-based visual logic but embeds it as a discrete, rule-based IFC attribute (LoH_Value) linked to explicit assignment criteria, rather than a purely graphical convention
Demetrescu's Extended Matrix	Formal, flowchart-based notation linking sources, interpretative processes and reconstruction hypotheses (Demetrescu, 2015; Demetrescu & Ferdani, 2021)	Operates as an external documentation/notation system, generally outside the BIM/CAD environment; not natively embedded as an attribute of 3D model elements	Translates the source-to-hypothesis logic of the Extended Matrix into a compact ordinal attribute embedded directly in HBIM-T elements, integrated with temporal phasing and exchangeable through a dedicated IFC property set

The proposed LoH framework was demonstrated on the historic complex at Szewska 49 in Wrocław, currently housing the Institute of History of the University of Wrocław. The HBIM-T model integrates TLS and photogrammetric surveys, archival drawings and photographs, conservation reports, archaeological stratigraphy and typological analogies. For each model element, LoH values were assigned according to the four rules (weakest link, element decomposition, justification documentation, priority of preserved substance) and linked to temporal phases representing major historical stages of the building's development. In the current implementation, LoH primarily signals accumulated uncertainty based on these rules; advanced propagation mechanisms (e.g. fuzzy-logic inheritance across element hierarchies) are identified as future research directions

4.1 Level of History (LoH) scale in HBIM-T

As part of the research, a five-level LoH scale was defined in the methodological section, ranging from LoH 1 (high certainty based on direct physical evidence) to LoH 5 (low certainty, speculative reconstruction). In the Results, this scale is applied to concrete elements and historical phases within the HBIM-T model of Szewska 49.

Figures 1–5 illustrate representative examples of elements classified at LoH 1–5, showing how direct measurements, archival documents, conservation reports, typological analogies and speculative reconstructions are encoded in the model. This application demonstrates that the scale is operational: each element is assigned a single LoH value per phase according to the four rules (weakest link, element decomposition, justification documentation, priority of preserved substance).

The LoH framework was demonstrated on the historic complex at Szewska 49 in Wrocław, currently housing the Institute of History of the University of Wrocław. The site comprises multi-phase masonry structures evolving from medieval plot development through early modern palace transformations to twentieth-century adaptations.

The HBIM-T model integrates terrestrial laser scanning (TLS) and photogrammetric surveys for the existing fabric, archival drawings and photographs, conservation reports, archaeological stratigraphy and typological analogies for non-extant elements. For each model element, LoH values were assigned according to the four rules and linked to temporal phases representing major historical stages of the building's development. In the current implementation, LoH primarily signals accumulated uncertainty based on these rules; advanced propagation mechanisms (e.g. fuzzy-logic inheritance across element hierarchies) are identified as future research directions rather than present features. All LoH values reported in this study were assigned by a single researcher (the corresponding author), following the four rules defined in Section 3.2; no independent second assessor cross-checked the assignments. Inter-rater reliability testing is identified as a priority direction for future work (Section 4.7).

4.1.1 LoH 1: High certainty – direct physical evidence

Example (Figure 1): A preserved load-bearing wall documented using TLS and visual inspection. The western wall contains traces of original openings with arched lintels, fragments of stonework, and recesses from former electrical installations. The southern wall shows traces of an original doorway opening with an arched lintel; condition as of April 2024.

Figure 1: LoH 1: High certainty.

4.1.2 LoH 2: Medium-high certainty – indirect primary sources

Example (Figure 2): Reconstruction of a non-existing building based on archival municipal records dating to approximately 1350. The comparison concerns the building volume at Szewska Street 49 in Wrocław (ca. 1350) and the present-day Institute of History. The medieval structure occupied approximately 80% of the current building volume, characterized by thick masonry walls and a simple form without later extensions.

4.1.3 LoH 3: Medium certainty – secondary sources and expert analysis

Example (Figure 3): Reconstruction of a historical spatial layout based on architectural research conducted in the 1990s, developed as part of project documentation for the University of Wrocław (architectural study of the building at Szewska 49, 1999). Based on the analysis of research results, the form of the earliest masonry development on the site was defined, including the number and size of buildings existing in the first half of the 14th century, prior to their acquisition as a ducal residence and subsequent transformation into a palace. Identified remains of medieval foundations within the current buildings along Uniwersytecka Street indicate the presence of one or two narrow, non-basemented structures forming a continuous service building frontage along Rycerska Street.

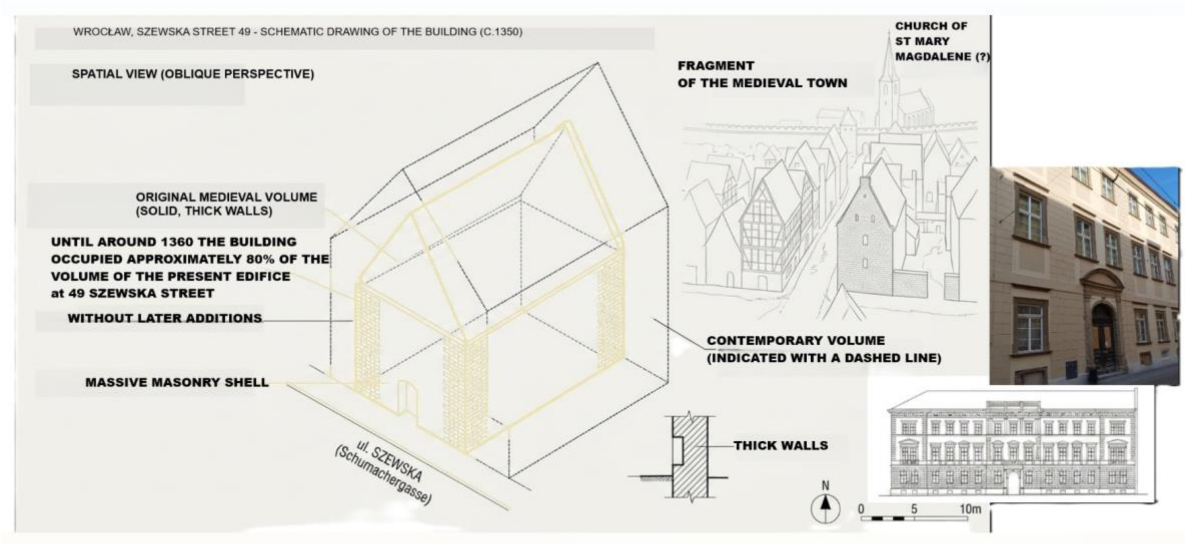

Figure 2: LoH 2: Medium–high certainty.

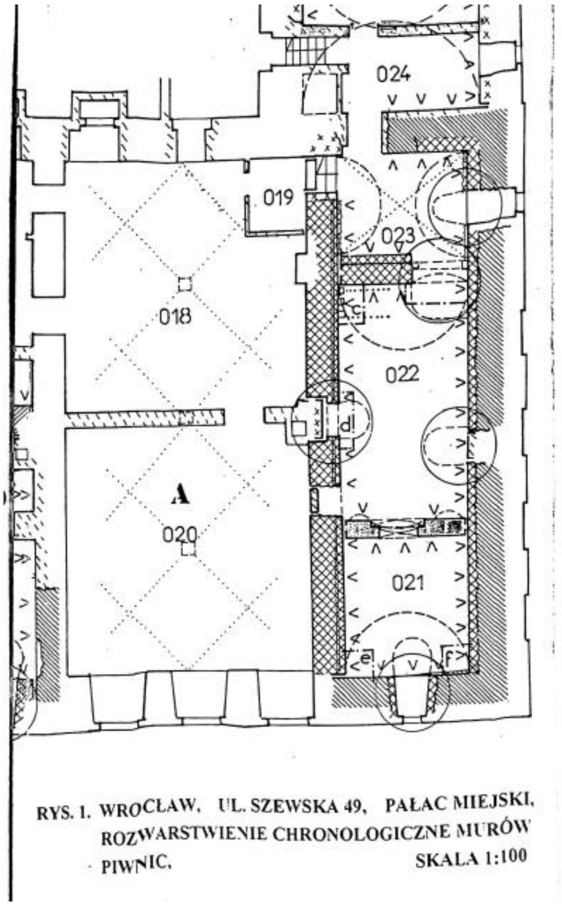

Figure 3: LoH 3: Medium Certainty.

4.1.4 LoH 4: Medium-low certainty – typological analogies and inference

Example (Figure 4): Reconstruction of ceiling details based on regional typologies for buildings from the given period. The reconstruction was developed using typological analysis of stucco ceiling systems in palace architecture in Lower Silesia, including Wrocław, from the 14th to 17th centuries. It was based on the study of preserved examples of ceilings and stucco decorations in regional palaces and manor houses. For the 14th and early 15th centuries, modest decorative schemes were assumed. In the late 15th and 16th centuries, flat coffered ceilings with simple stucco ornamentation were introduced, while the 17th century is characterized by more elaborate compositions of panels and frames with cornices and Baroque ornamental motifs, consistent with Silesian craftsmanship traditions.

Figure 4: LoH 4: Medium-Low Certainty.

4.1.5 LoH 5: Low certainty – speculative reconstruction

Example (Figure 5): Hypothetical reconstruction of a non-extant vault based on isolated traces of springing points. The reconstruction of the original vault was developed considering the preserved springing points identified within the masonry of the investigated structure. Based on the location and orientation of these springing points, the central axis, estimated number of bays, and a probable span ranging from 6–8 m were determined, in accordance with typical examples of Gothic rib vaults found in the Silesian region.

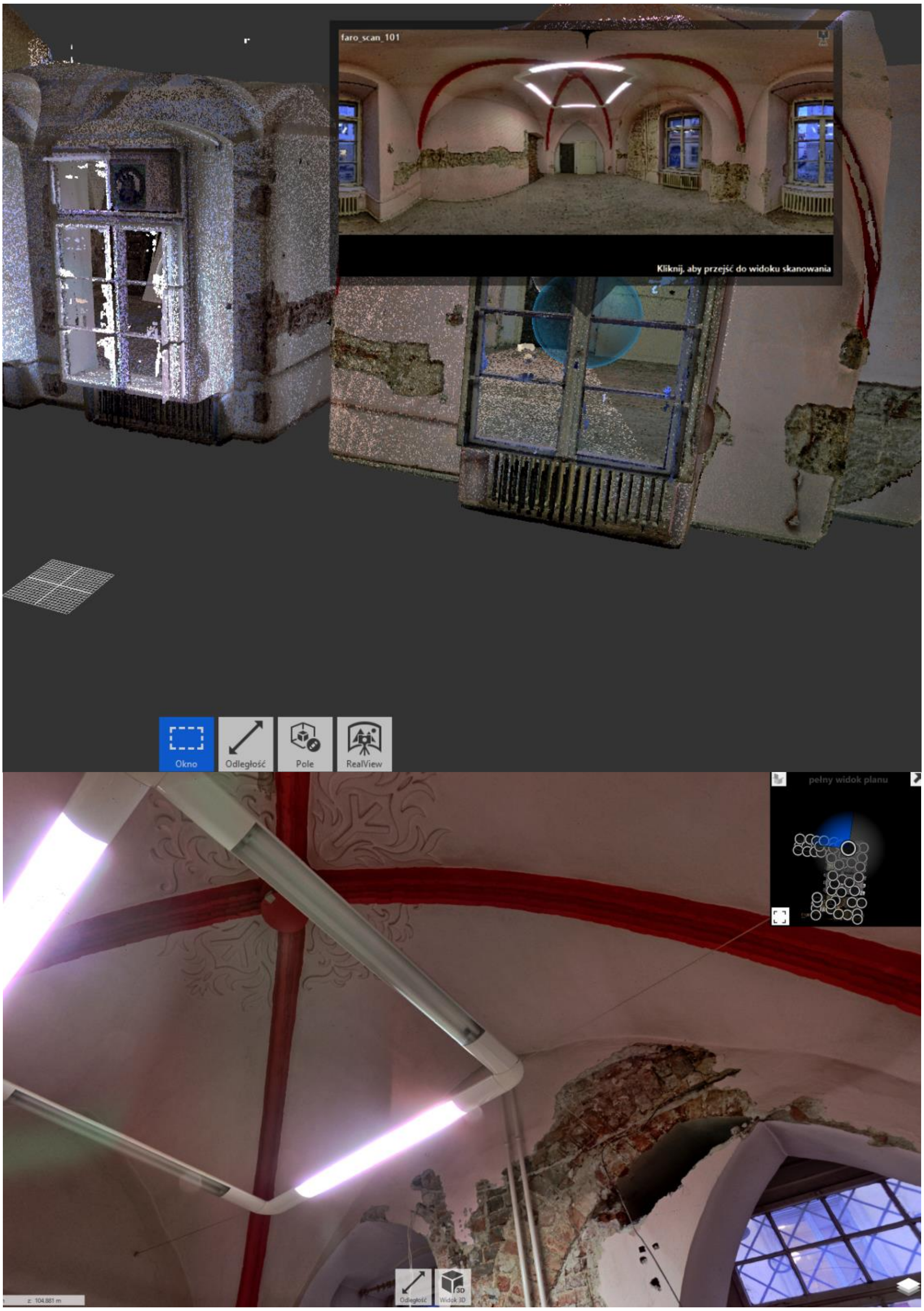

Figure 5: LoH 5: Low Certainty – Speculative Reconstruction.

4.2 Visualization of uncertainty levels

The clear representation of uncertainty levels is essential for maintaining methodological transparency. Section 3.3 defines the five-level LoH scale in full, including the Definition, Sources and Uncertainty range associated with each level. The present section applies this scale, without redefinition, to concrete elements and historical phases within the HBIM-T model of Szewska 49, illustrating LoH 1–5 through representative examples (Figures 1–5). Based on studies concerning user perception of different visualization methods, a simple two-dimensional visual scheme was proposed within this research framework, in which: color corresponds to the LoH level, i.e., the degree of certainty, while the level of transparency reflects the degree of uncertainty.

Recommended LoH color palette:

- LoH 1 (High certainty): Intense blue;
- LoH 2 (Medium-high certainty): Green;
- LoH 3 (Medium certainty): Yellow;
- LoH 4 (Medium-low certainty): Orange;
- LoH 5 (Low certainty – speculation): Red.

For LoH 5, an additional wireframe representation was introduced, in which the element is displayed only as an edge mesh rather than as a solid object.

The visualisation was implemented in Autodesk Revit using View Filters based on the LoH parameter, enabling users to quickly identify reliable and uncertain parts of the model.

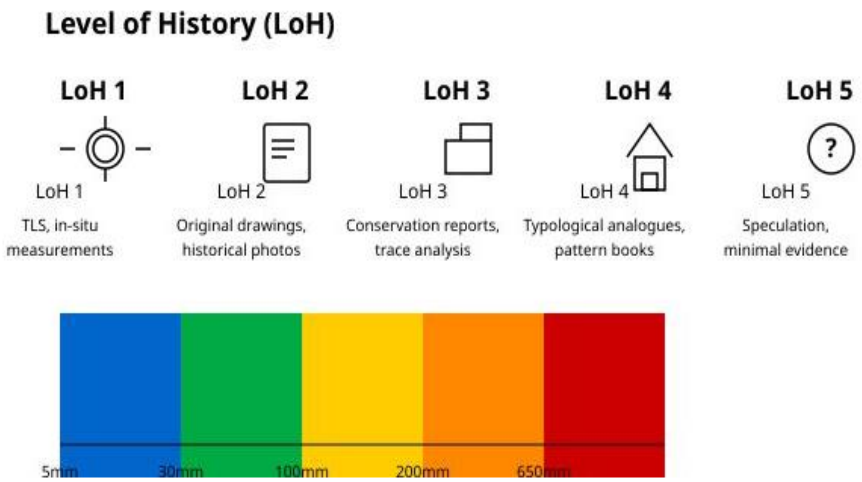

Figure 6: Five-level LoH scale with mapping of sources and uncertainty.

To systematize the process, a Phase–LoH decision matrix was developed, enabling an explicit correlation between historical phases and levels of uncertainty

4.3 Integration of LoH with temporal modeling (HBIM-T)

The implementation of the LoH scale was integrated with temporal modeling, which constitutes a key component of the HBIM-T approach. Each HBIM-T element is assigned both a creation phase and, where applicable, a demolition or disappearance phase, consistent with the phasing mechanisms in common BIM environments such as Autodesk Revit.

The LoH value is assigned independently for each phase, enabling the analysis of changes in certainty levels over time. For extant elements, LoH refers to the reliability of documentation describing the current condition, whereas for historical or non-extant elements it reflects the reliability of their reconstruction. Table 2 presents a Phase–LoH decision matrix, indicating typical LoH ranges and visualisation strategies (colour + opacity + wireframe) for different phase types (existing, documented, inferred, hypothetical).

Table 2: Phase–LoH decision matrix.

Phase Status	LoH Assignment Strategy	Visualization Approach
Existing (measured)	LoH 1–2 dominant	Standard color coding according to LoH
Historically documented (photographs, drawings)	LoH 2–3 typical	Color + reduced opacity (90%)
Historically inferred (material traces)	LoH 3–4 typical	Color + reduced opacity (70%)
Hypothetical reconstruction	LoH 4–5 required	Color + low opacity (50%) + wireframe option

A key innovative contribution of the research is the demonstration of the synergy between the LoH parameter and temporal modeling within the HBIM-T framework. In existing 4D BIM approaches, temporal phases generally serve only an organizational function, without considering variations in the certainty level associated with knowledge about particular stages of a building's historical development.

In the proposed approach, each temporal phase is enriched with an epistemological profile defined through the distribution of LoH values. As a result, the HBIM-T model ceases to function as a homogeneous representation of history and instead becomes a multilayered structure in which each layer (historical phase) possesses a defined level of reliability. Table 3 presents the epistemological categorization of historical phases.

Table 3: Epistemological categorization of historical phases.

Phase Type	Dominant LoH	Share of LoH 1–2	Share of LoH 3–5	Epistemological Characteristics
Existing phase (documented using TLS)	LoH 1	85–95%	5–15%	High certainty; uncertainty limited to elements inaccessible to scanning
Documented historical phase (photographs, drawings)	LoH 2	60–75%	25–40%	Medium-high certainty; uncertainty related to details and elements not visible in the documentation
Archaeological phase (stratigraphic traces)	LoH 3	20–40%	60–80%	Medium certainty; reconstruction based on material traces
Hypothetical phase (analogical reconstruction)	LoH 4–5	0–15%	85–100%	Low certainty; predominance of speculation

The analysis of the application of the LoH method revealed characteristic relationships between historical periods and levels of uncertainty:

- earlier historical phases are characterized by a greater proportion of elements classified as LoH 4–5;
- more recent phases demonstrate the predominance of elements with high reliability (LoH 1–2);
- intermediate phases exhibit a heterogeneous epistemological structure.

This phenomenon may be interpreted as a natural consequence of the availability of historical sources, the closer a period is to the present day, the greater the amount of highly reliable data available. This categorization enables the temporal stratification of reliability: the HBIM-T model ceases to function as a homogeneous representation of the past and instead becomes a multilayered palimpsest with explicitly communicated certainty levels assigned to each temporal layer.

The introduction of the Phase–LoH matrix (Figure 7) enables the formal representation of these relationships and the analysis of uncertainty distribution over time. This approach constitutes a significant extension of existing HBIM methodologies, as it allows the simultaneous analysis of:

- the spatial evolution of the building;
- the evolution of knowledge about the building.

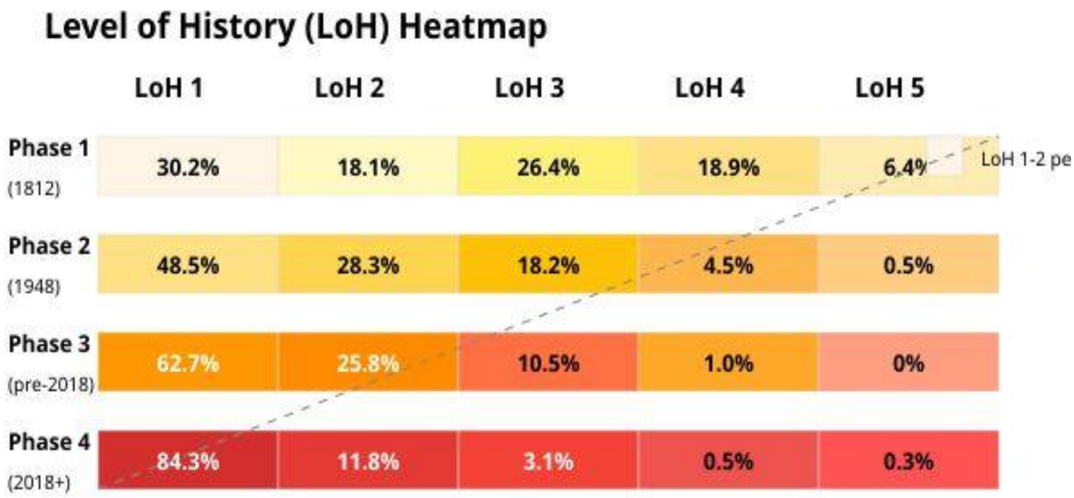

Figure 7: Phase–LoH matrix: distribution of uncertainty across temporal phases.

The conceptual matrix illustrates the percentage distribution of elements according to LoH levels across four temporal phases (1812→2018+). To derive the percentage distributions of LoH levels across temporal phases (Table 3; Figure 7), all model elements belonging to the HBIM-T representation of Szewska 49 were included in the analysis. The population comprised elements classified as IfcBuildingElement instances (walls, floors, roofs, columns, beams, openings, doors, windows and selected architectural details), excluding non-physical entities such as annotation objects and temporary construction aids. For each element, a single LoH value in the range 1–5 was assigned for each historical phase in which the element is present, according to the four rules defined earlier. In multi-phase cases, separate element instances were created per phase, so that LoH reflects the certainty of the element in that specific temporal context rather than a global value. Percentage shares were then computed by counting, for each phase, the number of element instances classified within the LoH 1–2 and LoH 3–5 ranges and dividing these counts by the total number of classified elements in that phase. For example, the statement "Phase 1 contains 25.3% elements classified as LoH 4–5" corresponds to the ratio of elements in the initial historical phase whose LoH is equal to 4 or 5 to the total number of elements present in Phase 1, expressed as a percentage and rounded to one decimal place. Figure 7 presents the resulting Phase–LoH matrix, which reveals a clear trend of increasing certainty over time: early phases contain a higher proportion of elements with LoH 4–5, whereas contemporary phases are dominated by elements with LoH 1–2. A clear trend of increasing certainty over time can be observed, Phase 1 contains 25.3% of elements classified as LoH 4–5, whereas Phase 4 reaches 96.1% of elements within LoH 1–2.

This aggregate representation enables the simultaneous analysis of the spatial evolution of the building and the evolution of knowledge about the building, turning the HBIM-T model into a multilayered structure in which each temporal layer possesses a defined epistemological profile.

4.4 Implementation within the IFC standard

To ensure interoperability, an extension of the Industry Foundation Classes (IFC) schema was proposed through a dedicated property set named Pset_LoH_Heritage. This property set includes parameters enabling the storage of both LoH values and contextual information, such as data sources and justification of interpretation. These parameters are assigned to elements belonging to the IfcBuildingElement class, allowing their application across different BIM environments and Common Data Environment (CDE) systems. Figure 8 presents a UML diagram illustrating the IFC Property Set with nine attributes (LoH_Value, LoH_Category, LoH_Justification, etc.) and its relationships with IfcBuildingElement classes (walls, roofs, windows, doors, etc.).

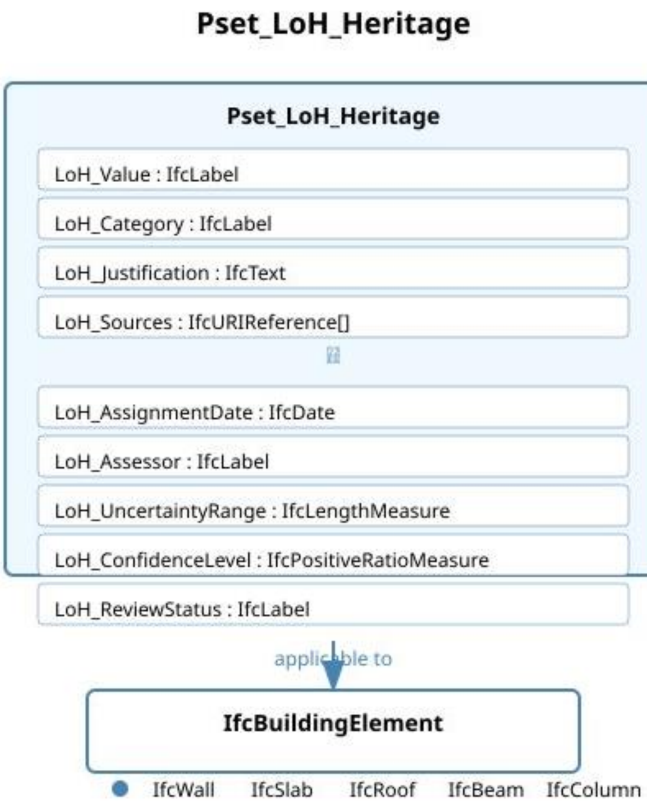

Figure 8: Pset_LoH_Heritage UML.

The complete attribute specification of Pset_LoH_Heritage is provided in Table 4, in a platform-independent, human- and machine-readable form (attribute name, IFC data type, description, example value), sufficient to reconstruct the property set in any IFC-compatible authoring environment.

Table 4: Pset_LoH_Heritage — attribute specification.

Attribute	IFC Data Tyype	Desription	Example value
LoH_Value	IfcInteger (1–5)	Assigned LoH value for the element in the given phase	2
LoH_Category	IfcLabel	Short textual label of the level	"Medium-high certainty"
LoH_Sources	IfcText	List/description of documentary sources supporting the assignment	"TLS_2024_W02; Archive_1350_map"
LoH_Justification	IfcText	Free-text justification of the interpretative process	"Wall geometry interpolated from 1350 cadastral outline"
LoH_AssessorID	IfcLabel	Identifier of the person who performed the assignment	"Researcher_01"
LoH_AssessmentDate	IfcDate	Date of assignment	2024-04-15
LoH_Phase	IfcLabel	Reference to the associated HBIM-T temporal phase	"Phase_2_1467-1550"
LoH_Rule	IfcLabel	Assignment rule(s) applied (R1–R4)	"R1, R4"
LoH_CrossChecked	IfcBoolean	Whether the value was independently cross-checked	FALSE

4.5 Benefits of applying LoH in HBIM-T

The implementation of the LoH parameter within HBIM-T models provides a range of significant benefits at both methodological and practical levels.

First and foremost, the LoH system operationalises one aspect of the fundamental principle of transparency formulated in the London Charter, by explicitly linking each model element with its documentary basis and associated level of certainty. In traditional documentation approaches (textual reports, appendices), information concerning reliability is often fragmented and difficult to assign unambiguously to specific spatial elements. In the proposed approach, such information is integrated directly into the geometric model itself.

An important aspect of the proposed solution is its interoperability. The implementation of LoH through standard IFC Property Sets enables its use within open BIM environments and supports data exchange between various design platforms (including Revit, Archicad, and Allplan). Furthermore, the possibility of exporting data to formats such as RDF and JSON-LD allows HBIM models to be integrated with heritage ontologies and linked open data systems:

- export to RDF formats enables integration with the broader linked open data ecosystem and heritage ontologies such as CIDOC-CRM;
- export to RDF (e.g., Turtle syntax) and JSON-LD enables semantic integration of the model with heritage ontologies and linked open data infrastructures.

From the perspective of practical applications, LoH significantly supports decision-making processes in conservation and heritage management. The LoH system enables filtering and analysis of model elements according to their level of reliability, which is particularly useful in three key scenarios:

- Conservation intervention planning – identification of elements with high LoH values (1–2) as critical for preserving the authenticity of the building;
- Reconstruction processes – identification of low-reliability elements (LoH 4–5) requiring additional research or specialist validation;
- Risk management - localization of areas characterized by high uncertainty as potential sources of decision-making errors.

An additional advantage of the system is its visual clarity. The application of a two-dimensional visualization scheme (color + transparency) enables intuitive interpretation of uncertainty levels by users with varying levels of expertise, ranging from specialists to stakeholders not directly involved in the research process.

4.6 Assessment of compliance with the London charter

The developed methodology was evaluated in terms of its compliance with the principles of the London Charter, which constitutes one of the most important reference frameworks for the digital documentation of cultural heritage. The analysis demonstrated that the proposed approach aligns with the key requirements of the Charter (Bentkowska-Kafel & Denard, 2012):

- Principle 1: Implementation. The LoH scale provides concrete and operational procedures for implementing transparency within HBIM-T models, in contrast to general declarative approaches. LoH delivers practical tools for transparency implementation, extending beyond the merely declarative character of many previous studies.
- Principle 2: Research Aims and Methods. The LoH system enforces the explicit articulation of research aims and interpretative assumptions for each reconstructed element.
- Principle 3: Research Sources. The LoH_Sources parameter establishes a direct relationship between model elements and source documentation stored within the CDE, ensuring traceability.
- Principle 4: Documentation. LoH reports and Phase–LoH matrices constitute comprehensive transparency records consistent with the documentation requirements of the Charter.
- Principle 5: Sustainability. The use of standard IFC mechanisms ensures long-term accessibility and interoperability; however, further development of dedicated heritage-oriented Model View Definitions

(MVDs) is required.

- Principle 6: Access. LoH color-based visualizations are intuitive for non-specialist users, supporting the requirement of accessibility for diverse audiences..

4.7 Limitations and future research directions

Despite its significant advantages, the proposed methodology also presents several limitations.

The most important limitation concerns the subjectivity of the LoH assignment process, particularly in the case of elements based on multiple sources with varying levels of reliability. The adopted "weakest link" principle ensures interpretative caution; however, it may also lead to a conservative underestimation of certainty levels.

A second important limitation is the time-consuming nature of the process (e.g., for a model containing 5.000 elements, complete LoH documentation may require approximately 100 working hours). As the level of model detail increases (high LOD), the number of elements requiring individual LoH assignment grows significantly, potentially increasing the overall workload. In response to this issue, a hierarchical approach was proposed, based on prioritizing key structural elements.

Hierarchical LoH assignment strategy:

- Level 1 (required): LoH assignment for major structural elements (walls, roofs, vaults);
- Level 2 (optional): LoH assignment for decorative elements and architectural details. Another challenge is the limited practical interoperability resulting from the fact that not all BIM tools and heritage management systems fully support extended IFC property sets.

In the context of future research, the following directions appear particularly important:

- development of semi-automated LoH assignment methods (e.g., using fuzzy logic or expert systems);
- integration of LoH with quantitative risk analysis methods,
- extension of the methodology to the scale of entire urban complexes;
- development of heritage-oriented MVD standards.

The proposed LoH scale constitutes an important step toward the systematic modeling of uncertainty in HBIM. The integration of the LoH parameter with temporal modeling makes it possible not only to represent the historical evolution of a building over time, but also to explicitly reveal the level of knowledge associated with its individual phases. Consequently, the HBIM-T model becomes not merely a representation of geometry and history, but also a tool for epistemological analysis, which constitutes the principal contribution of this article to the development of research on the digital documentation of cultural heritage.

4.8 Data availability statement

The HBIM-T model of Szewska 49 and the associated Pset_LoH_Heritage definitions are available from the corresponding author upon reasonable request. Input datasets (terrestrial laser scanning surveys, photogrammetric point clouds, archival drawings and photographs, conservation reports and archaeological documentation) are held by the University of Wrocław and collaborating institutions and are subject to institutional access agreements. Derived, anonymised metadata necessary to replicate the LoH assignments and the Phase–LoH analyses will be provided as supplementary material upon request, allowing independent verification and reuse of the proposed framework.

5. DISCUSSION

The principal contribution of this study lies in shifting the HBIM paradigm from a purely representational approach, in which the model is treated as the most faithful possible reproduction of reality, toward an epistemological approach, where the model becomes a carrier of both knowledge and uncertainty regarding a historical object. Within this framework, the HBIM-T model is no longer understood solely as a geometric reconstruction, but rather as an information structure in which the certainty level of individual interpretations is explicitly encoded (Hussein & Ismaeel, 2020). This approach aligns with broader discussions in the field of digital humanities, where digital reconstructions are increasingly understood as scholarly hypotheses rather than unequivocal representations of historical facts.

The proposed Level of History (LoH) scale addresses a gap identified in the literature between existing BIM standards (LOD, LOI) and the specific nature of cultural heritage documentation, where uncertainty constitutes an inherent characteristic of the available data (Lombardi & Rizzi, 2024). In contrast to previous approaches such as GoG or LOK, which primarily focus on geometric accuracy or the scope of information, LoH integrates source reliability, interpretative processes, and temporal dimensions within a unified parametric assessment system. Consequently, the proposed methodology not only classifies levels of certainty but also enables their direct implementation within the HBIM-T environment.

One of the key aspects of the proposed approach is the formalization of uncertainty accumulation within historical inference processes (Vafaie et al., 2023). In heritage research practice, the reconstruction of architectural elements frequently relies on chains of reasoning in which subsequent model components are derived from previous interpretations. For example, if the reconstruction of element A is based on source X (LoH 2), and the reconstruction of element B depends on both element A and source Y (LoH 3), then element B inherits accumulated uncertainty. The introduction of the LoH parameter together with the "weakest link" principle enables the systematic representation of this dependency and allows uncertainty propagation within the model to be explicitly traced. As a result, the HBIM-T model ceases to function as a homogeneous structure in terms of reliability and instead becomes a multilayered knowledge system characterized by varying levels of certainty. This has significant implications both for heritage research methodology and for conservation and design practice, as it enables a clear distinction between evidence-based and hypothetical elements.

An important achievement of the study is the demonstration of the synergy between the LoH parameter and temporal modelling. Previous HBIM-T approaches focused primarily on representing successive phases of a building's development, yet they did not account for varying levels of certainty within those phases. The integration of LoH with the phasing system enables the assignment of an epistemological profile to each phase, significantly increasing the analytical value of the model (Janisio-Pawłowska et al., 2021). The obtained results indicate that the distribution of LoH values over time is not homogeneous, contemporary phases are generally characterised by a high level of certainty (LoH 1–2), whereas historical phases, particularly those that are poorly documented, exhibit a greater proportion of LoH 3–5 levels. Such an approach allows the HBIM-T model to be understood as a "palimpsest" of knowledge, in which each temporal layer possesses its own degree of reliability.

The application of the LoH parameter has direct implications for decision-making processes in heritage conservation. In particular, it enables:

- Prioritisation of interventions based on authenticity. Elements with high LoH values (1–2), representing preserved heritage fabric with confirmed authenticity, may be prioritised in the allocation of conservation resources. The analysis of LoH datasets enables a quantitative assessment of what proportion of the building consists of authentic elements versus reconstructions.
- Management of uncertainty in intervention design. When designing new interventions (e.g., installations or structural additions), the LoH parameter assigned to adjacent existing elements provides information regarding the level of certainty associated with their configuration, thereby influencing the choice of intervention strategy:
    a. High LoH values of adjacent elements → precise fitting strategies may be applied.
    b. Low LoH values → a minimal intervention strategy with tolerance buffers is recommended.
- Communication with stakeholders. Colour-based LoH visualisations provide strong support in communication with non-expert stakeholders (e.g., local authorities, communities, investors). They clearly indicate which parts of the reconstruction are based on well-documented sources (e.g., marked in blue or green) and which are more hypothetical in nature (e.g., marked in red). This method of presentation increases the transparency of the decision-making process and contributes to building trust.

From the perspective of information management, it is also significant that the implementation of LoH based on the IFC standard preserves model interoperability and enables integration with the broader data ecosystem, including linked open data approaches. This opens possibilities for the application of LoH not only in modelling processes, but also in heritage management systems and multi-criteria analyses.

6. CONSLUSIONS

The conducted research resulted in the development of a coherent methodology for the use of the Level of History (LoH) parameter for the explicit representation of historical uncertainty in HBIM-T models. The proposed five-level LoH scale organises levels of information reliability by integrating the hierarchy of historical sources with the geometric and semantic parameters of BIM models. In this way, it complements existing LOD/LOI standards while adapting them to the specific characteristics of heritage buildings.

An important outcome of the study is the demonstration of the practical implementation of LoH within the BIM environment through the extension of the IFC schema with dedicated property sets and its integration with temporal modelling. This enables certainty levels to be assigned not only to model elements, but also to their successive historical phases, leading to a more informed and multi-layered interpretation of the building's development over time.

The application of the LoH parameter increases the transparency of HBIM-T models, enabling a clear distinction between elements based on direct evidence and those representing hypothetical reconstructions. As a result, the models cease to serve solely as visualisation tools and instead become instruments supporting the analysis, interpretation, and communication of knowledge about the building.

Rather than claiming definitive superiority over existing frameworks such as LOK, GoG or Source-Feature Matrix, the present study proposes LoH as an operational complement that embeds source reliability and historical uncertainty directly into HBIM-T element attributes and temporal phases. The evidence presented is qualitative and design-science oriented, based on the internal coherence of the framework and its demonstration on the Szewska 49 case study. Future research will focus on empirical validation, including independent expert reviews of LoH assignments, inter-rater reliability tests, user studies on visualisation effectiveness, and comparative benchmarking against alternative approaches to uncertainty and transparency in heritage modelling.

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