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# OntPreHer3D: Ontology for Preservation of Cultural Heritage 3D Models

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## Abstract

This work addresses issues related to digital 3D models of cultural heritage in the context of FAIR data. It introduces OntPreHer3D, an ontological extension of the CIDOC CRM for the comprehensive preservation of 3D models. OntPreHer3D semantically maps the intricate relationships between 3D models, their components, and their real-world equivalents. Through specialised classes and properties, it provides a robust framework for documenting diverse 3D models, including digitised objects, hypothetical reconstructions of lost heritage, and visualisations of never-built architectural projects. The paper highlights various documentation challenges and scenarios, underscoring the crucial need for data protection and the ability to re-model content in case of loss of the original 3D data. The presented ontology is rooted in the application ontology OntSciDoc3D, developed by the Institute of Architecture at Mainz University of Applied Sciences (AI MAINZ), for the scientific documentation of hypothetical 3D digital reconstructions. This further development included assessing the current limitations of the OntSciDoc3D, and official extensions of the CIDOC CRM family in the context of documenting 3D models. Crucially, given the inherent interpretative nature of hypothetical reconstructions, the presented framework integrates Inference to the Best Explanation (IBE) to transparently capture the human reasoning, choices, and uncertainties driving reconstruction decisions. It facilitates the semantic documentation of not only what was modelled, but also why and how confident we are in the interpretation, including the systematic quantification of uncertainty. Finally, the paper briefly presents results of a case study of the hypothetical reconstruction of the ruins of the Synagogue in Speyer (Germany) conducted by four different modellers equipped with the same source package, and predefined granularity and scope of the research. The study empirically examines how varying technical decisions made at the 3D software level impact the final models, demonstrating the critical role of such detailed process documentation in ensuring the long-term preservation and future reusability of 3D cultural heritage content.

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## Introduction

3D models of cultural heritage are invaluable resources. They enable detailed analysis without compromising the physical integrity of artefacts (Bossema et al., 2021) and provide virtual access to objects that are typically inaccessible to both site visitors and researchers (Efkleidou et al., 2022). In addition, 3D models can be used to virtually reconstruct lost cultural heritage (Kuroczyński et al., 2021) or digitally visualise architectural projects that were never built (Apollonio et al., 2023a). The academic community has also acknowledged the importance of 3D models as digital documentation for archaeological (Brandolini et al., 2021) and architectural research (Argasiński & Kuroczyński, 2023). Despite their growing importance, a standardised approach for the long-term storage and preservation of 3D models has yet to be established (Golubiewski-Davis et al., 2021). The rapid obsolescence of digital data poses a serious risk, potentially resulting in so-called "digital graveyards" where all knowledge invested in 3D representation of the past becomes inaccessible (Kuroczyński, 2017).

One potential solution to this issue lies in adhering to current standards in the context of Web 3.0 and Open Science, particularly through ontological data documentation that allows for machine processing and the use of Linked Open Data (LOD) technology (Berners-Lee & O'Hara, 2013). This approach fosters the creation of accessible, transparent, and interoperable data, thereby enhancing the usability and preservation of published 3D assets. The process of translating heritage documentation into structured, machine-readable documentation requires a data modelling approach grounded in ontology. In this approach, the various entities are represented as classes, while the relationships between them are defined as properties. An ontology serves as a formal, shared vocabulary—a kind of dictionary accessible to both humans and machines—that clearly defines the meaning of each entity or relation. Once the ontology is established, it enables the classification of data and the creation of semantic links both within the dataset and across external resources, allowing for more effective integration, querying, and long-term preservation.

The cultural heritage sector has already developed a standardised, universal formal ontology for this purpose: the CIDOC Conceptual Reference Model (CRM) (Doerr, 2005). The CIDOC CRM is currently the most widely used model in cultural institutions (Münster, 2022). It is a well-balanced model, limited to general classes and properties that can be applied across a wide range of scientific fields. However, in cases of extensive documentation, the same classes may need to store different types of information, which can complicate the model's readability and hinder proper data retrieval. Given the complexity and multi-layered nature of 3D, attempts to use the CIDOC CRM base for documenting digital models (Nevola et al., 2022) may fall short of providing the complete information needed for model re-construction in the event of data loss.

Sometimes application ontologies, which offer a minimal terminological structure tailored to the needs of specific communities, can provide useful concepts for broader applications (Menzel, 2003) and fill the gaps not covered by formal ontologies. But what specific gaps exist in the CIDOC CRM base model when it comes to the documentation of 3D models?

## Requirements for an ontology documenting 3D models of cultural heritage

Cultural heritage includes both tangible and intangible aspects, reflecting a society's beliefs, traditions, and customs. The line between tangible and intangible heritage often fades, whether through the decay of physical relics or the abstract preservation of unrealised ideas. The CIDOC CRM framework draws a sharp line between physical and conceptual entities. In practice, though, 3D reconstructions often work with hybrid entities, bridging physical remains ('*E18 Physical Thing*') and conceptual designs ('*E28 Conceptual Object*'). General classes, such as '*E70 Thing*', enable coverage of both types but restrict relational complexity, making it difficult to articulate the transition from preserved evidence to informed inference. It is precisely at this juncture that Inference to the

Best Explanation (IBE) emerges as a primary methodological approach. As theorised by Fogelin (2007), IBE operates as a non-deductive form of reasoning where conclusions are drawn based on their ability to provide the most plausible and coherent explanation for existing, often incomplete or ambiguous, evidence. For 3D reconstructions, this means that the decision to represent a 'partly existing' element or to fully reconstruct a 'non-existing' component relies heavily on an IBE-driven process, where modellers evaluate various hypotheses to arrive at the 'best' possible interpretation given the available archaeological, historical, and architectural data. Therefore, adequately documenting 3D models, particularly their materialisation spectrum and the underlying interpretive choices, requires supplemental frameworks. This framework has to surpass rigid typological boundaries and facilitate detailed property mapping that captures the results of such essential inferential reasoning. By maintaining these distinctions, we can identify three primary categories of cultural heritage 3D models:

1. **Reality Capture (current phase)**: representing the physical form of a preserved object, captured directly through processes like 3D scanning or photogrammetry.
2. **Recreation of the Past (past phase)**: representing past forms of heritage that have been altered, partially lost, or destroyed, constructed through the analysis of archaeological traces or archival records.
3. **Concept Reconstruction (conceptual phase)**: representing heritage that exists only in design form—ranging from historical plans to contemporary proposals—rather than tangible structures.

Each of these model types presents its own set of challenges, which have been organised based on the author's practical experience in Table 1.

**Table 1** - Overview of the challenges associated with three categories of 3D cultural heritage models—**Reality Capture**, **Recreation of the Past**, and **Conceptual Reconstruction**. A solid circle indicates a challenge that applies in all cases to a given model type; a half-filled circle shows that it applies to some cases; and a cross marks challenge that do not apply to the case.

| Challenges | Reality Capture | Recreation of the Past | Concept Reconstruction |
|---|---|---|---|
| Documentation of the physical counterpart | ● | ● | ✕ |
| Accuracy of 3D representation | ● | ◐ | ◐ |
| Documentation of the primary heritage carrier | ✕ | ◐ | ● |
| Documentation of sources used | ✕ | ● | ● |
| Uncertainty of the 3D representation | ✕ | ● | ● |
| Incorporation of hypothetical components | ✕ | ● | ● |
| Distinction between material and conjectural parts | ◐ | ● | ● |
| Machine-driven data acquisition processes | ● | ◐ | ✕ |
| Human-driven data interpretation processes | ◐ | ● | ● |
| Technical specification of the creation workflow | ● | ● | ● |
| Semantic segmentation of the object into documentation units | ◐ | ● | ● |
| Versioning of work | ◐ | ● | ● |
| Various variants of work | ✕ | ◐ | ◐ |
| Distinction between raw data, information model and its derivatives | ● | ● | ● |

**Legend**

- ● challenge that applies in all cases to a given model type
- ◐ challenge applies to some cases to a given model type
- ✕ challenge that do not apply to the case to a given model type

## CIDOC CRM family extensions for the documentation of the 3D cultural heritage

The first challenge was related to blending the tangible and intangible parts of the heritage object within one 3D model. This issue is addressed within the scope of the CRMba ontology (CIDOC CRM extension for Buildings Archaeology). It allows for the division of a '*B1 Built Work*' into '*B2 Morphological Building Sections*'—discrete architectural components like walls, roofs, foundations, or others (Ronzino et al., 2016). This segmentation aligns directly with the methodology of the Scientific Reference Model (SRM), which advocates for a rigorous semantic division of heritage objects into documentation units, the first step towards detailed and complex object documentation (Kuroczyński et al., 2023). Secondly, CRMba further refines this classification by distinguishing between real, remaining parts ('*B3 Filled Morphological Building Section'*) and missing or theoretically reconstructed elements ('*B4 Empty Morphological Building Section'*). This distinction also serves as one of the foundations of documentation practices for archaeological 3D models, as described in the Extended Matrix (EM) method (Demetrescu & Ferdani, 2021). It formalises archaeological reconstruction by classifying entities into three stratigraphic node types:

- US (Stratigraphic Unit) — actual physical remains still in situ;
- USV/s (Structural Virtual Stratigraphic Unit) — virtual components reconstructed to fill a structurally inferred absence, grounded in physical evidence;
- USV/n (Non-Structural Virtual Stratigraphic Unit) — hypothetical elements reconstructed without direct archaeological traces, based solely on secondary sources.

By explicitly differentiating what is real, evidenced, and imagined, this method enables transparent tracking of the materiality and evidential basis of each component in a 3D heritage reconstruction. But to fully capture the EM approach, CRMba should be enhanced with CRMarchaeo—CIDOC CRM extension for archaeological excavation process. It introduces concepts of stratigraphic units that fully align with the concept of EM. The combined capabilities of CRMba and CRMarchaeo excel at representing both physical heritage and archaeological evidence, yet fall short when it comes to purely conceptual heritage - unbuilt designs, theoretical plans, and intellectual constructs. For ontology developers specialising in digital reconstruction, this remains a notable gap in the current framework.

Materiality and immateriality are just part of the puzzle - 3D heritage reconstruction faces an equally critical challenge: how to handle uncertainty. Fragmentary preservation necessitates interpretive reconstruction. However, the CIDOC CRM's fact-based paradigm is unable to capture conjectural processes or levels of certainty. For virtual reconstructions based on historical evidence, this absence of certainty-qualifying mechanisms potentially undermines their academic value. This issue is addressed by the official CRMinf extension, providing a formal argumentation model (Doerr et al., 2023). It solves the problem via the introduction of the event '*I5 Inference Making'*, which can document an action of introducing the hypothesis into 3D model, which can be documented with use of the class '*I1 Argumentation*', which signifies the reasoning activity leading to a belief linked via the property '*J2 concluded that*' to an '*I2 Belief'* which encapsulates the conclusion. This can be further enriched by using the class '*I3 Inference Logic'* to describe the logic behind the hypothesis.

Uncertainty issue leads to another topic: hypothetical 3D models are also subject to versioning. As reconstructions rely on imperfect evidence, successive studies—through archival research, fieldwork, or comparative analysis—frequently yield multiple, equally plausible variants of the same model, or different versions based on various stages of research on the source material. Each variant or version represents a hypothesis that must be documented, tracked, and preserved. This is crucial not only for transparency but also for the long-term stability and reuse of digital assets. The LRMoo ontology (Library Reference Model object-oriented extension of CIDOC CRM) (Bekiari et al., 2023) is designed to capture and represent the underlying semantics of bibliographic information. It offers a formal structure for representing such versions, as it was explicitly designed to model editions, translations, and variant forms of bibliographic works. While its original scope is bibliographic, LRMoo's mechanisms—such as handling different expressions or manifestations of a work (e.g., '*R75 incorporates/is incorporated in*', '*R74 uses expression of*')—can be adapted to manage 3D model versions. However, it may require extensions or specialisation, since it was not designed to capture the semantics of virtual heritage model publication or the specific needs of 3D model lifecycle management.

In addition to addressing uncertainty and versioning, virtual 3D reconstructions also need to account for the provenance of digital 3D models. Some 3D data result from fully automated workflows, such as laser scanning or photogrammetry, while others are generated through manual modelling and editing. Documenting these processes requires a level of granularity in event classes that are not included in the CRM base model. This topic is addressed by the official CRMdig extension (Doerr et al., 2022), which focuses on the digitisation process of any object. It introduces classes related to the actual object capture ('*D2 Digitization Process'*, '*D11 Digital Measurement Event'*, '*D8 Digital Device'*, '*D9 Data Object'*), data processing ('*D7 Digital Machine Event'*, '*D10 Software Execution'*, '*D1 Digital Object'*), and the creation of derivatives ('*D3 Formal Derivation*', '*D9 Data Object*'). These enable modelling of both machine-driven capture and manual processing, such as who performed a scan, which device was used, what software and parameters were applied, and how derived assets were produced. However, while CRMdig is well-suited for general digital objects provenance, it may require further extension to fully represent the intricacies of human-centred 3D modelling workflows, particularly where human interpretation or creative input plays a significant role.

The CRM family effectively supports detailed documentation of 3D models, particularly those based on reality capture methods (Catalano et al., 2020). There are emerging approaches that leverage the CIDOC CRM family to document virtual reconstructions by representing the process as a reasoning chain of propositions using CRMinf as the core model (Bruseker et al., 2015). However, the heritage community has raised concerns about its applicability in manual 3D modelling, highlighting the missing granularity in CRM extensions for modelling reconstruction workflows (Veggi & Cerato, 2025).

## Evaluation of application ontologies for virtual reconstructions

The application ontology paradigm may provide a solution to fill the still-open questions. These specialised ontologies adapt foundational frameworks, such as CIDOC CRM, through selective concept reuse and refinement, creating purpose-built systems for specific implementation contexts. Their scenario-driven design ensures alignment with operational requirements while maintaining ontological rigour (Katsianis, 2023).

Therefore, two application ontologies have been selected for evaluation in terms of their usefulness in preserving the knowledge carried by 3D models. The first is OntSciDoc3D - Ontology for Scientific Documentation of source-based 3D reconstruction of architecture (Kuroczyński & Große, 2020). It was designed for the needs ot documentation of the digital 3D reconstruction project of "New Synagogue in Brerslau". The ontology implements a CIDOC CRM derivation strategy, where core classes, such as E21 Person, are mirrored (as osd21a Person) and extended with task-specific subclasses. All property definitions maintain consistency with the CRM model's relational logic. It describes the process of digital 3D reconstruction based on human interpretation of collected data, expressing the links between historical sources ('*osd 31b Source*'), the reconstructed object ('*osd 22a Object'*), and the process of human interpretation ('*osd 7a Research Activity*') (Kuroczyński et al., 2021). This research-oriented framework successfully accommodates both art historical documentation and reconstruction methodology. While effective for these purposes, it lacks substantive engagement with fundamental 3D modelling principles—a significant omission given their importance in digital preservation. The current OntScidDoc3D implementation treats the 3D model as a finalised output rather than examining the sub-processes behind its creation. This represents a missed opportunity, as the modelling workflow itself constitutes an artistic practice worthy of documentation, particularly given the evolving technical approaches employed in the field.

The second evaluated application ontology for virtual reconstruction is the Conceptual Reference Model for Virtual Reconstruction (CRMvr*)*,[1] introduced in Elisabetta Giovannini's doctoral dissertation. This ontology is the first among those analysed to deconstruct 3D modelling process into two components: a 2D profile defining the cross-section of the element ('*V14 Profile*') and a path indicating the extrusion trajectory to generate the final solid ('*V15 Path*'), as shown on Figure 1. However, this approach is inherently limited to classical architectural orders (Giovannini, 2018), where solids are conceptualised through cross-sections (e.g., capitals, cornices), and struggles to accommodate organic or complex forms.

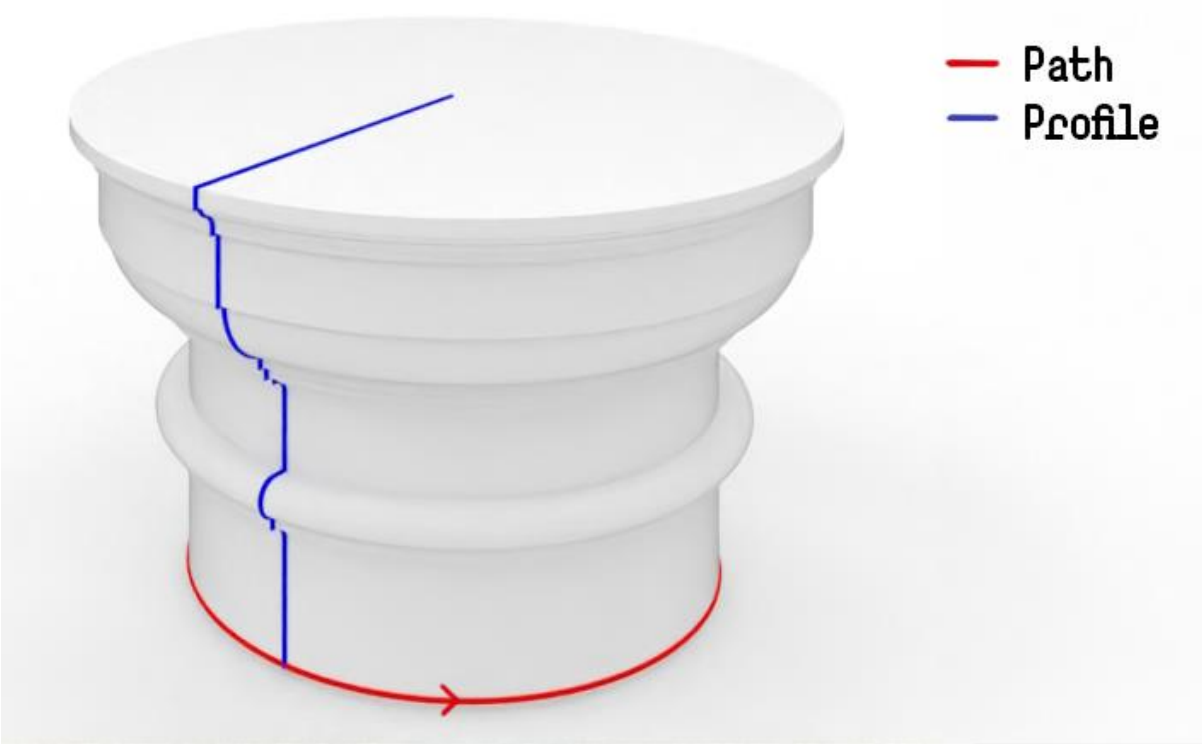


**Figure 1 –** Schematic diagram showing the modelling concept based on the division of a 3D solid into a path (red outline) and a profile (blue outline), following the principles of CRMvr ontology.

The ontology also conceptualises 3D models as constrained virtual representations, with explicit recognition of their geometric and morphological parameters. For this purpose, Giovannini created two classes: '*V16 Morphological Representation*' for morphological composition representing materials, and '*V11 Geometrical Representation'*, which refers to the geometric form of an object. While this representational framework lacks extensive elaboration, it importantly identifies the need to document geometric volume (V11) and surface materiality (V16) as distinct yet complementary components that collectively shape a model's interpretive fidelity.

Ultimately, CRMvr provides a structured evaluation framework for virtual reconstruction, encompassing five key metrics. Level of Elements (LoE) documents architectural components down to their basic geometric parts, while Level of Measures (LoM) records precise dimensions with values and units. The Level of Reference (LoR) systematically tracks source materials, and the Level of Uncertainty (LoU) qualifies measurement reliability. Finally, Level of Accuracy (LoA) synthesises both morphological and dimensional precision from available evidence. This method demonstrates particular strength in documenting classical architecture, where its methodical approach aligns well with clearly defined elements and measurements. However, some limitations emerge in practice. The evaluation of uncertainty and accuracy inevitably involves subjective

[1] Some documentation related to CRMvr is publihsed under Giovannini GtiHub Repository: https://github.com/elisabettacaterina/CRMvr (last accessed 28 June 2025).

judgments, especially when working with incomplete evidence. Additionally, the framework's current lack of digital implementation restricts its application in collaborative projects. While exceptionally thorough for well-documented, geometric structures, the metrics prove less adaptable to organic forms or cases requiring more flexible interpretation.

While CRMvr introduces valuable documentation concepts, its development has stalled at the theoretical phase. Available documentation exists only as written specifications without proper implementation. Additionally, its foundational premise of decomposing models into profiles and paths implies a specialised modelling methodology that diverges from conventional 3D modelling practices. Therefore, a more flexible documentation approach, one not predicated on a specific modelling technique, would prove more broadly applicable.

## Definition of classes and properties in OntPreHer3D

The analysis of existing ontological solutions revealed several gaps in the documentation of 3D models, leading to the development of Ontology for Preservation of Cultural Heritage 3D Models (OntPreHer3D) (Bajena, 2025).[2] The ontology has already undergone several iterations: version 0.9.0 was a preliminary draft, version 1.0.0 marked the first implementation and practical testing, and version 1.0.1 (described in this paper) is currently used within WissKI-based Virtual Research Environment[3] for 3D models, developed for the CoVHer[4] project (Bajena et al., 2025). The ontology continues to evolve, adapting to the needs of users, with version 2.0.0 gearing up for its planned release in July 2025**.** The OntPreHer3D has been developed to extend the functionality of OntSciDoc3D, a complementary ontology from the former research group team. While OntSciDoc3D replicates CIDOC CRM classes within its dedicated namespace, OntPreHer3D diverges by introducing exclusively novel classes. It explicitly incorporates extensions from the CRM ecosystem—including CRMdig, CRMinf, and LRMoo—to address specialised needs. The ontology employs a structured naming convention: classes are prefixed with 'M' (denoting '3D Model') followed by a numeric identifier, while properties use 'R' prefix ('Relationship').

The application of the ontology depends significantly on the classification of the 3D content. 3D models of cultural heritage can be grouped according to various criteria, each requiring specialised documentation (Münster et al., 2016). Examples could include the condition of the object (damaged, preserved, destroyed, never realised), the reconstructed time phase (present, past, or conceptual phase), or the scale of the object (artefact scale, architectural scale, or urban scale). The complexity of the documentation scheme also varies depending on the target audience and the specific needs of the data publisher (Bajena & Kuroczyński, 2023). Thus, the OntPreHer3D supports several levels of complexity while incorporating modelling efficiencies where applicable.

The ontology introduces 19 classes (see Figure 2) and 22 properties. It is grounded in the principle that documentation of 3D data involves identifying the relation between digital 3D objects and their real-world equivalents, which should occur through the dedicated event, the core of the event-centred CIDOC CRM approach. The OntPreHer3D followed this principle through three core classes that form a triple, serving as the backbone of the digital 3D documentation process. The first is the '***M1 3D Model***', a subclass of '*D1 Digital Object*' from CRMdig. This specialised class is necessary to distinguish differences between digital objects representing raw data and 3D models representing the final product obtained through human verification. The second class, '***M26 Cultural Heritage Thing***', is a specialisation of '*E70 Thing*' from CRMbase. This class was introduced to connect conceptual objects (used for visualising never-realised designs) with physical objects (preserved and destroyed) while emphasising their significance in human culture. The third class is '***M25 Digital Reconstruction***', which is a specialised activity event, and a subclass of '*osd 7a Research Activity*' from OntSciDoc3D and '*D7 Digital Machine Event*' from

[2] The development of ontology as well as archival versions can be found on GitHub: https://doi.org/10.5281/zenodo.15771797 (last accessed 23 June 2025).
[3] See WissKI Homepage: https://wiss-ki.eu/ (last accessed 24 September 2024).
[4] A repository for the publication of 3D models using the described ontology for documentation was opened to the public in July 2024 as part of the CoVHer project, which aims to standardise the methodological approach to hypothetical digital reconstructions. The repository is available at: https://repository.covher.eu/ (last accessed 24 September 2024).

CRMdig. This class describes the creation of a 3D model, combining historical and archival research with both automatic and manual 3D data acquisition methods. This allows for the proper classification of reconstructions, whether they are hypothetical or based on real-world data. The relation between those classes is illustrated in Figure 3.

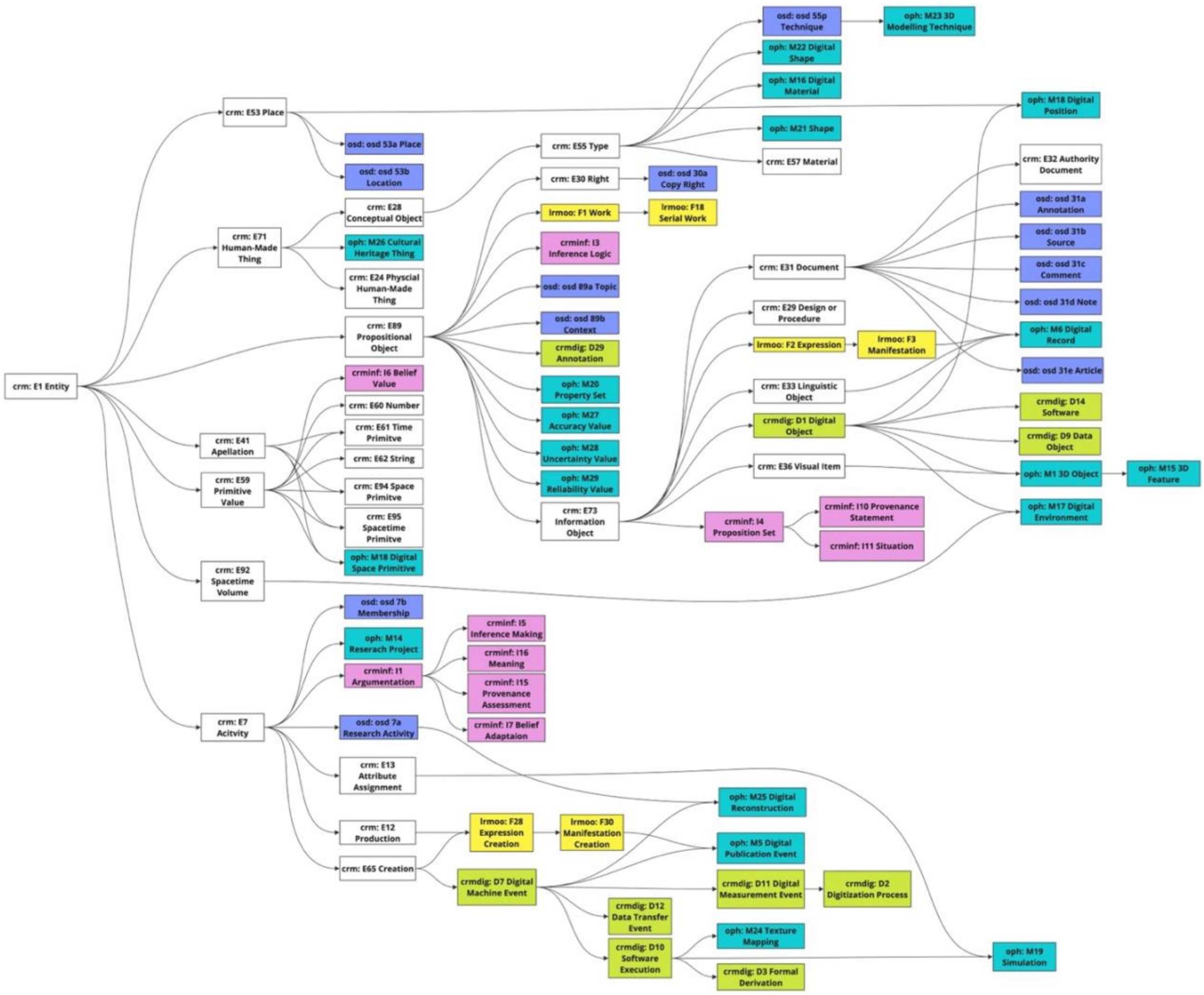


**Figure 2 –** Diagram illustrating the class hierarchy in OntPreHer3D. Boxes in white colour represent classes from CRMbase (version 7.2.2), in pink from CRMinf (version 1.0), in green from CRMdig (version 3.2.1), in yellow from LRMoo (version 0.9.6) in blue from OntSciDoc3D (version 2.0) and in turquoise new classes from OntPreHer3D (version 1.0.1).

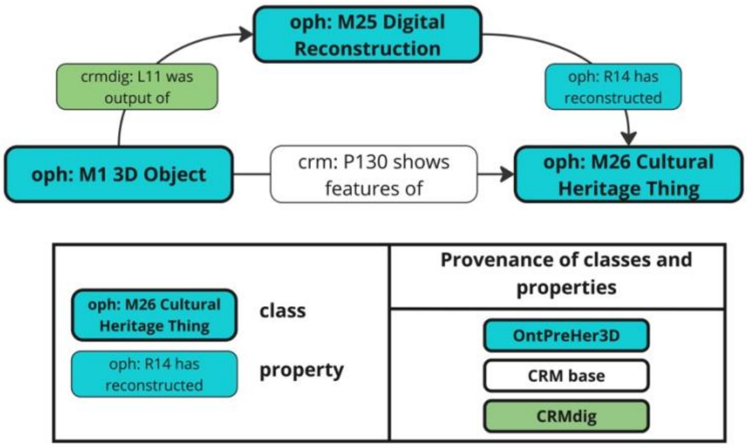


**Figure 3 –** The core triple of the data model in the OntPreHer3D ontology for documenting the virtual reconstruction process.

When dealing with hypothetical virtual 3D reconstructions, specifying the temporal phase of the reconstruction is imperative. Unlike digitised objects, where the focus often lies on the dating of their physical origin, particularly in an archaeological context, hypothetical reconstructions aim to visualise past phases that may represent lost, altered, or conceptual stages in the lifecycle of the cultural object. To document this, OntPreHer3D introduces a new property, '***R18 simulates time***'. This property links the reconstruction activity to the class that defines time in CRMbase: '*E52 Time Span'*.

Research shows that semantic segmentation of 3D models is a foundation for the documentation of virtual 3D reconstructions (Apollonio, 2019; Grellert et al., 2018). The OntPreHer3D supports this approach by enabling the division of a physical object into semantic parts using the '*E25 Human-Made Feature'* class from CRMbase. The digital equivalent of physical semantic parts can be modelled using the newly introduced '***M15 3D Feature'*** class. Since the segmentation of a physical object typically relies on available sources, existing patterns from the OntSciDoc3D ontology are applied to document the fact that individual features, or segments of the object, are defined by the '*osd24a Physical Source'* class and the '*P62 depicts'* property from CRMbase. It should be noted, however, that object segmentation on sources is most often carried out for hypothetical reconstructions. In the case of digital documentation of preserved objects in architecture, segmentation is an integral part of the Historic Building Information Modelling (HBIM) process. In this approach, 3D modelling is object-oriented, and segmentation comes naturally. As HBIM software serves as an internal database, all segments of the 3D model have defined specific properties (Murphy et al., 2009). In hypothetical reconstructions, historical sources serve as the carriers of information about the reconstructed segment. However, these sources may not always be reliable. They could be damaged or inconsistent with other materials. The process of segmenting and reconstructing from such ambiguous sources (evidence) inherently involves an Inference to the Best Explanation (IBE), as modellers must determine the most plausible segmentation based on fragmented or conflicting data. As Campanaro (2021) elaborates, applying an IBE-based model directly contributes to improving transparency in 3D reconstruction processes by building better arguments for interpretive decisions, particularly concerning how sources inform the definition of segments. OntPreHer 3D introduces the ability to document the level of reliability of a source by specialising the '*E55 Type'* class and applying the following path: '*osd24 Physical Source'* -> '***R22 has reliability level***' -> '***M30 Reliability Level***'.

The principal limitation identified in most ontologies studied in previous chapters is the perception of the 3D model as a singular entity, with no differentiation between the original model and its derivatives. This leads to a common misconception in online repositories with web-based viewers, where the visible model is assumed to be the actual state of the digital object from the modelling program. This is inaccurate, as 3D viewers only support a limited range of 3D formats.[5] Exporting these formats involves compression and conversion, which alter how 3D data is stored and displayed (Europeana Network Association, 2019) .[6] Consequently, the geometry and material mapping visible in these viewers are often modified, creating a distorted representation of the model. Furthermore, the virtual space in which the model is displayed can also influence the perception of the model due to variations in coordinate systems or environmental settings, such as lighting or camera positioning (Haynes, 2023). To address this issue, it was determined that each 3D model (‘***M1 3D Object***’) should be viewed as a digital object component in the form of a file (‘*D1 Digital Object*’). The other component is the software or viewer that interprets the data, acting as an intermediary between the computer screen and the user, which is defined as the ‘***M17 Digital Environment***’. Depending on the settings of this digital environment, the model can be represented in different ways, as indicated by the ‘***R17 has representation type***’ property, which is linked to the ‘*E55 Type*’ class from CRMbase. A diagram illustrating the data model and the logic of the ontology of source-based digital reconstruction is presented in Figure 4.

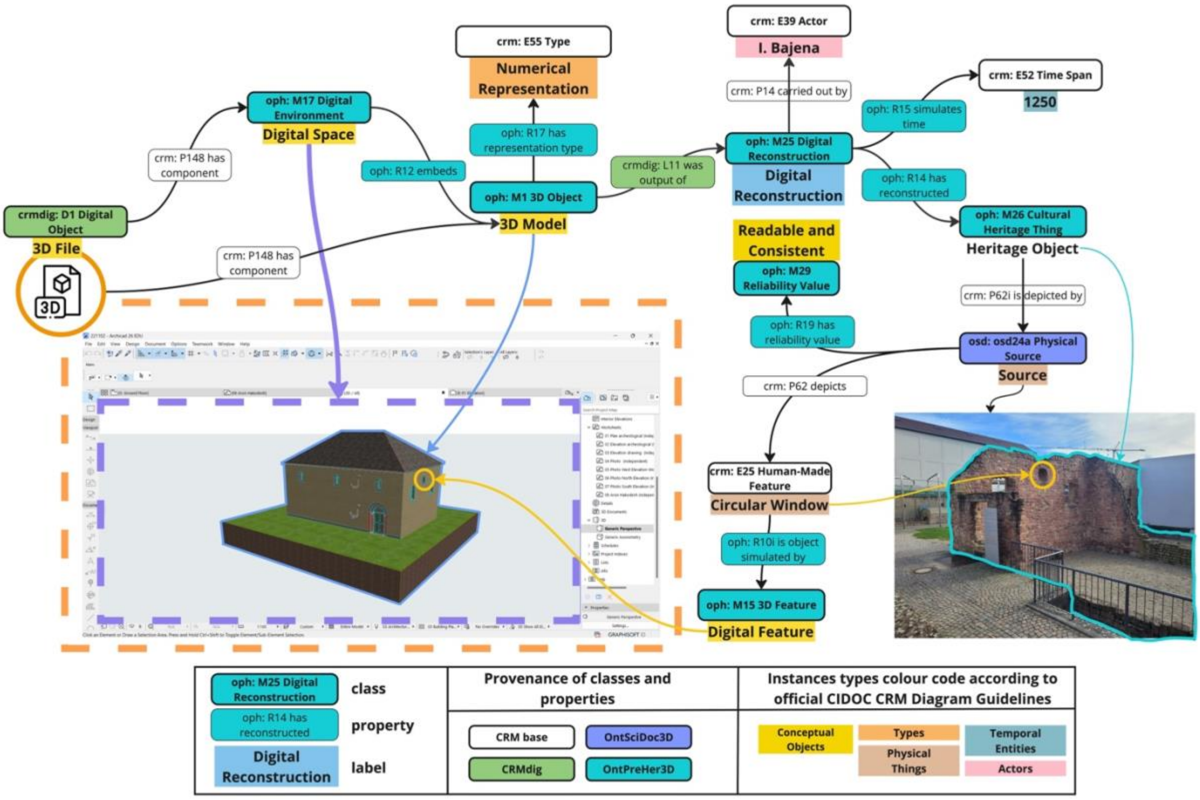


**Figure 4 –** Diagram illustrating the basic data model using the OntPreHer3D ontology for the digital reconstruction process with the use of a shortcut property.

[5] Online 3D viewers like Sketchfab support a broad, but finite, list of formats—e.g. OBJ, FBX, STL, PLY, COLLADA, glTF/GLB, VRML, 3DS, USD, IGES, and others—by converting uploads into glTF/GLB for display. Heritage-focused viewers like 3DHOP rely on the multi-resolution NEXUS format (derived from OBJ/PLY) and do not accept raw modelling files. Similarly, lightweight components such as Google’s <model-viewer> natively render only glTF/GLB, while institutional platforms like the Smithsonian Voyager serve glTF/WebGL-compatible outputs. Consequently, the visible model in web viewers often does not reflect the original file from the modelling software but may have been converted—potentially altering geometry, materials, or structure.

[6] According to the Europeana 3D Taksforce (2019), at least 14 distinct formats are commonly used for publishing 3D models on the web: OBJ, STL, PLY, FBX, COLLADA/DAE, glTF/GLB, VRML/WRL, 3DS, NXS/NXZ, E57, LAS, IFC, XYZ/PTS, and proprietary CAD/BIM formats. This list excludes native proprietary formats specific to 3D modelling software (e.g., .blend, .max). The formats vary not only by geometry type—meshes, solids, point clouds—but also by support for attributes like materials, cameras, animations, and textures. Transferring a model between formats typically necessitates recalculation or conversion, which risks altering parts of the model (such as geometry, UV maps, or material fidelity) to meet each format's technical constraints.

The diagram presents a simplified view of the documentation through the use of a shortcut property – ontological constructs that condense complex semantic relationships into single, more manageable relations while preserving underlying structural integrity (Fichtner & Ribaud, 2012). Here, the shortcut property '***R19i is object simulated by***' directly connects the '*E26 Physical Feature'* to its digital representation ('***M15 3D Feature***'*)*. The extended version contains intermediate steps with a focus on the event '***M19 Simulation***'. It refers to the machine process of simulating a physical attribute using computer visualisation techniques. Although it is a machine-driven process, its execution requires human input to define the parameters by which the object should be virtually simulated. The parameters can define the accuracy of the representation, the level of form simplification or the general style of artistic 3D model expression. The extended path is shown in Figure 5.

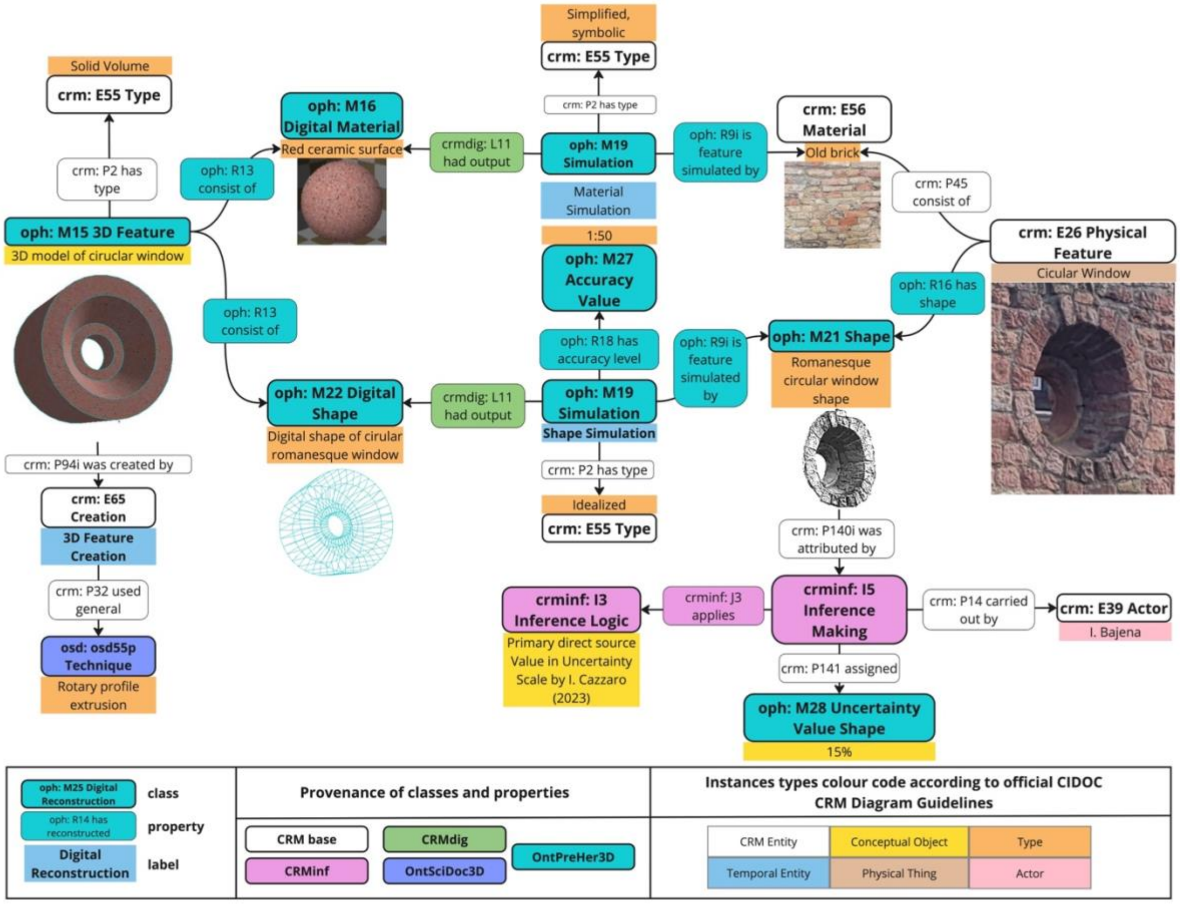


**Figure 5 –** Diagram illustrating the extended data model using the OntPreHer3D ontology for the hypothetical virtual 3D reconstruction process with the use of a simulation event.

The extended path divides the reconstruction process into two phases: the reconstruction of the object's geometry and the reconstruction of the object's materials. A similar separation occurs in the 3D modelling process, where, in some cases, materials are not developed at all, and the 3D model is based solely on its geometric form and a default surface finishing. Especially in the case of hypothetical digital reconstructions, when material information is absent or uncertain, researchers attempt to convey it through unified, neutral, abstract material applied to the entire model (Apollonio et al., 2023b). This approach follows standard practice in the 3D modelling workflow, allowing for the documentation of geometry and materials separately.

For a physical object, the class describing its material is taken from the CRMbase model, and it is a specialisation of the '*E55 Type'* class: '*E56 Material'*. Unfortunately, CRMbase does not have a class to express the concept of the shape or form of a physical object. That is why OntPreHer3D introduces for this purpose another specialisation of the '*E55 Type'* class: '***M21 Shape***'. To keep with the concept of separating physical and digital attributes, each class has a digital equivalent as a subclass*:* '***M16 Digital Material***' and '***M23 Digital Shape***', respectively. The digital and physical attributes are connected through the '***M19 Simulation***' event, a subclass of '*D10 Software Execution'* from CRMdig. '***M19 Simulation***' allows for the assignment of additional attributes determining whether a representation aims for realistic fidelity, artistic interpretation, or abstraction. It also allows for the indication of the degree of precision with which the model has been created. The following path represents this process: '***M19 Simulation***' -> '***R21 has accuracy level***' -> '***M27 Accuracy Level***'.

Given the inherently interpretive nature of the hypothetical virtual 3D reconstructions, OntPreHer3D explicitly assesses the uncertainty associated with the work. The assertion of the geometric form of an object is based on the interpretation of historical sources, which can vary in accuracy and reliability. As a result, the final shape may be subject to interpretative error. To systematically capture and evaluate these interpretive choices, OntPreHer3D leverages the IBE approach. Within this framework, each reconstruction decision represents an inference, where the chosen geometric form is considered the 'best explanation' for the available, often fragmented or ambiguous, evidence. To express this uncertainty and formalise the inferential process, OntPreHer3D utilises the CRMinf Argumentation Model, allowing for linking the declared shape of the model segment to the '*I5 Inference Making'* event. To further specify the level of imprecision and the epistemic status of these IBE-driven conclusions, the newly created '***M28 Uncertainty Value***' serves as an additional attribute of the inference process. Ultimately, this allows us to seamlessly incorporate uncertainty as a precise percentage value (Foschi et al., 2024). This integrated system ensures that both the reasoning behind our interpretive choices and their measurable uncertainty are documented clearly and systematically.

The ontology also introduces additional classes to address the process of digital model publication and file versioning. This section draws inspiration from the LRMoo model for bibliographic information. However, no classes were directly adopted from the LRMoo, as it was necessary to differentiate between the traditional publication of written material and the digital publication of data. Consequently, the '***M5 Digital Publication Event***' class was introduced as a subclass of LRMoo '*F30 Manifestation Creation*'. The event of digital publication results in the creation of instances of '***M6 Digital Record*** 'class, which is a subclass of up to four other classes: '*E31 Document'* and '*E33 Linguistic Object'* from CRMbase, '*D1 Digital Object'* from CRMdig, and '*F3 Manifestation'* from LRMoo. In this way, each publication of a new version or variant of the model triggers the '***M5 Digital Publication Event***', generating a corresponding '***M6 Digital Record***' capable of encapsulating diverse publication metadata.

## Strategy for the preservation of 3D data

The data model outlined above emphasises the decision-making aspects of the digital reconstruction and data interpretation process. It ensures that 3D models can be accurately reconstructed if a 3D file becomes corrupted or outdated. To validate this approach, a study was conducted to determine whether preserving assumptions about modelling and initial historical, architectural, archaeological, and archival research would allow for the reproduction of a 3D model. Four modellers using various 3D modelling software were chosen with different backgrounds (two architects and two archaeologists) and given a handout to prepare a reconstruction of the Synagogue in Speyer, Germany, in its 13$^{th}$-century phase (Bajena et al., 2022). Today, the building is part of the grounds of the local museum and is preserved in a state of ruin (see Figure 6). The handout included the sources collected, their classifications, and potential analogies. The building itself was segmented into architectural elements (documentation units) that the modellers had to consider. Sources included an archaeological research report about the site (Porsche, 2001), and some scholarly publications. The modellers were also given a packet of textures and guidelines concerning the surroundings of the building, which was to be set on a base 1 m deep. However, it was up to the modellers to determine the degree of accuracy of the model, or the level of simplification relative to reality.

**Figure 6 –** Picture of the current condition of the Synagogue in Speyer (Cazzaro, 2023).

The survey revealed significant differences in the proportions, sizes, and positioning of individual model segments that are easily noticeable to the naked eye (see Figure 7). It is important to acknowledge that much of the original substance of the building has not survived, and that features such as the windows on the longitudinal walls, the entrance portal, and the roof with its trusses are largely hypothetical. More surprisingly, even in reconstructions of elements where physical evidence exists, the interpretations vary greatly. These differences highlight the crucial role that human input plays in the reconstruction process, even when working with identical source materials, and in the classification of sources.

The apparent discrepancies between the models warrant closer examination. It was decided to study the problem using the example of the surviving round window element of the building's south facade. The main sources depicting round windowd included: (1) an archaeological report specifying a window aperture diameter of 0.29m (1 foot) (Porsche, 2001, p.11), accompanied by a scaled drawing from which the vertical position—approximately 5.1m between floor level and the window's centre—could be determined; and (2) photographic documentation providing crucial morphological details of the window. A combination of that information is summarised in Figure 8. To fully comprehend the form of a virtual 3D representation, we must retain detailed information about the decision-making process at each stage of the work. This begins with the classification of sources into primary, secondary, and tertiary categories, followed by the modeller's interpretation of the object's form. Subsequent steps involve determining the appropriate level of simplification for the virtual representation, selecting a suitable 3D modelling technique, and creating the model itself—a process inherently influenced by the modeller's skill, experience, and attention to detail. The workflow then progresses to applying materials to the object's form and positioning it within the broader model (though in some cases, objects may be roughly modelled directly at their point of occurrence). Notably, this workflow excludes the initial stages of source collection and on-site documentation, as these materials were already provided to the modellers in prepared form.

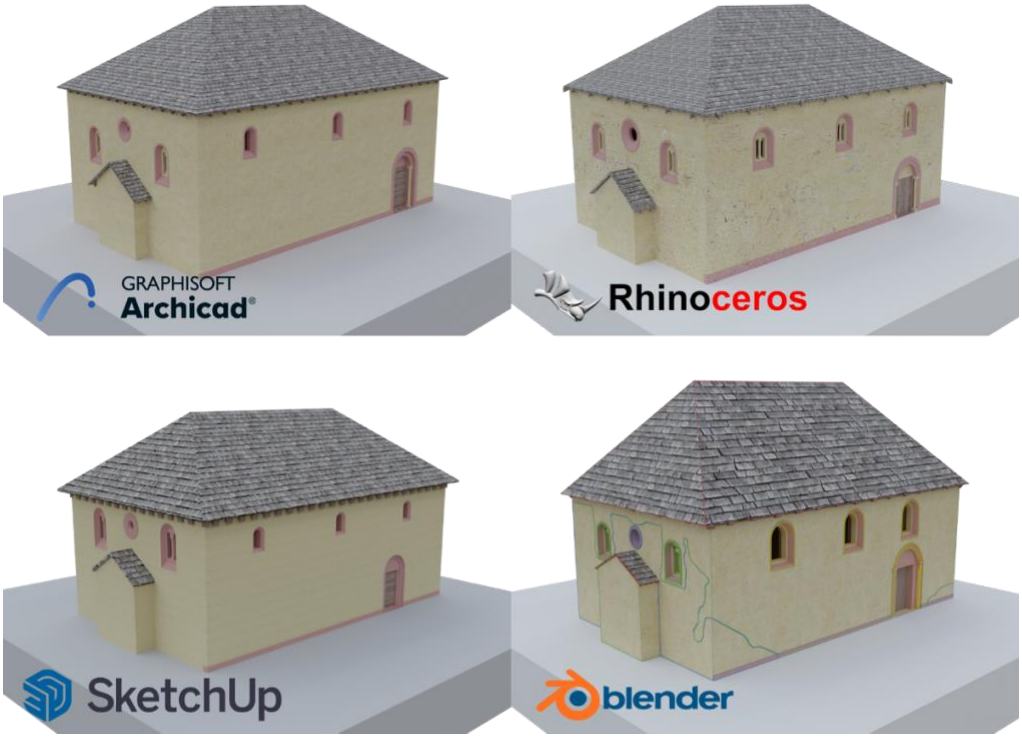


**Figure 7 –** Comparison of 3D modelling of a hypothetical digital reconstruction created in four 3D modelling software (Archicad, Rhino, Sketchup and Blender) by different modellers based on the same set of sources, their classification and featurisation in relation to object segmentation and detail development.


**Figure 8 –** Compilation of source materials for the round window: on the left, a photograph taken by Irene Cazzaro in March 2022; on the right, an archaeological drawing depicting the window's opening diameter and the height of its centre above the floor (Porsche, 2001). The unit of measurement is centimetres.

This case study engaged modellers to document their decision-making processes for virtual reconstruction and 3D modelling workflows in brief written paragraphs, accompanied by screenshots that illustrated the steps. Although modellers were equipped with documentation templates, the resulting documentation varied significantly in quality and depth, often comprising brief, fragmented comments that proved difficult to interpret without direct access to the models or specialised knowledge of each software's workflow. To synthesise these heterogeneous outputs, Table 2 was developed to compare systematically:

- The primary sources each modeller relied upon;
- Interpretations of the circular window's form derived from these sources;
- Decisions regarding geometric simplification for virtual modelling;
- Software-specific techniques employed in the reconstruction process.

By cross-referencing the written documentation with the 3D models themselves, this table reveals how software choices and interpretative approaches influenced the final reconstructions, despite the limitations of the original records.

**Table 2** - Comparative analysis of virtual reconstruction methodologies steps between modellers on the example of existing circular window from ruin of the Synagogue in Speyer, synthesising: (1) choice of primary source, (2) interpretation of the window form, (3) geometric simplification strategies, and (4) software-specific modelling techniques. Derived from participant documentation and final 3D model interrogation.

| | **Rhinoceros** | **Blender** | **Archicad** | **Sketchup** |
|---|---|---|---|---|
| Primary source | Close-up photo of west elevation showing windows | Araelogical report text<br>Archaelogical report drawing of the east elevation<br>Close-up photo of west elevation showing windows | Archaelogical report drawing of the east elevation<br>Close-up photo of east elevation showing windows | Archaelogical report drawing of the east elevation<br>En face photo of east elevation |
| Form interpretation | The window comprises two distinct elements: an outer ring projecting beyond the wall surface, and an inclined splayed interior. As the primary source depicts this window set within a neighbouring building's wall, it necessitated an opening at the termination point of the splayed section to connect with the adjacent space. | The window comprises two concentric circular elements: an outer ring featuring an irregular longitudinal hexagonal profile and an inner ring of contrasting material with a quadrangular cross-section. The composite form exhibits pronounced irregularity, lacking true verticals, level planes, or right angles. All edges display slight bevelling, evidencing material erosion over time. | The window can be geometrically defined as a uniform trapezoidal profile rotated about its central axis. This base profile incorporates rectangular extensions along its upper and lower edges, forming distinct inner and outer rings. Both rings maintain faces parallel to the wall surface, with the outer ring's face projecting slightly beyond the wall plane. | The circular window is observed on the west elevation, where it resembles a cylindrical form with a central opening. Its visible brick coursing maintains a uniform plane parallel to the wall surface. The opening's inner edge features a subtle bevel, creating a distinctive sheared-edge effect. |
| Simplification | The rings will be represented as geometrically perfect circles, with | This form derives from rotational geometry about a perfect circle's | The window's form has been simplified to a symmetrical configuration | The window has been conceptualised as an idealised |

| | | | | |
|---|---|---|---|---|
| | the profile's slope and the outer ring's projection beyond the wall treated as symbolic approximations. The cross-section is deliberately assumed to lack symmetry, while all specified dimensions are preserved intact. For modelling purposes, all edges are maintained as sharp intersections. Surface irregularities and brick divisions have been disregarded, treating the entire structure as a monolithic form. | radius, yet intentionally maintains organic imperfections through asymmetrical profiles and avoided right angles. A consistent micro-bevel softens all edges, replicating natural wear patterns. The assembly consists of two principal components: an outer hexagonal red sandstone ring and an inner quadrangular yellow sandstone ring, rendered as continuous elements without mortar joints. | composed of idealised circular geometry, with approximate vertical and horizontal alignments referenced to orthogonal relationships. Surface irregularities and brick divisions have been disregarded, treating the entire structure as a monolithic form. | cylindrical form with a central opening. To accentuate its architectural character, the transition between the ring's facade surface and the opening features a gently sloping surface of several centimetres. All brick divisions, surface irregularities, and minor imperfections have been omitted, resulting in a simplified, symbolic representation. |
| Technique | The solid was generated by first creating a window cross-section profile curve, then using Sweep1 command to extrude it along the prepared opening's boundary curve in the building wall. | The model was generated by modifying cylindrical primitives through two key operations: application of a bevel modifier to soften edges, followed by Boolean subtraction to achieve the desired profile shape. | The solid was created by developing a 2D window profile for profiles library and using beam tool to extrude profile trough the path which corrsponds to the beam axis which can be bended. | The 3D shape started as a flat circle with a hole cut out and an extra ring added to mark where the flat and curved parts meet. This 2D design was then extruded into 3D, and the inner ring was pushed down to create the sloped surface. |

A closer examination of the table reveals some significant divergences in interpretation and decision-making, which are reflected in the final output (see Figure 9). Why do these models differ so visibly when all modellers saw the same window? These differences emerge not from disagreements about the window's original form, but rather from the distinct simplification approaches each modeller adopted when translating it into 3D geometry. Put simply, the variations tell us less about medieval masonry and more about the invisible decision-making that shapes virtual reconstruction, where every strategic choice, from curve tolerance to edge handling, leaves an indelible mark on the outcome. This echoes broader debates in heritage visualisation, where subjective processes quietly but profoundly influence what we accept as 'accurate'.

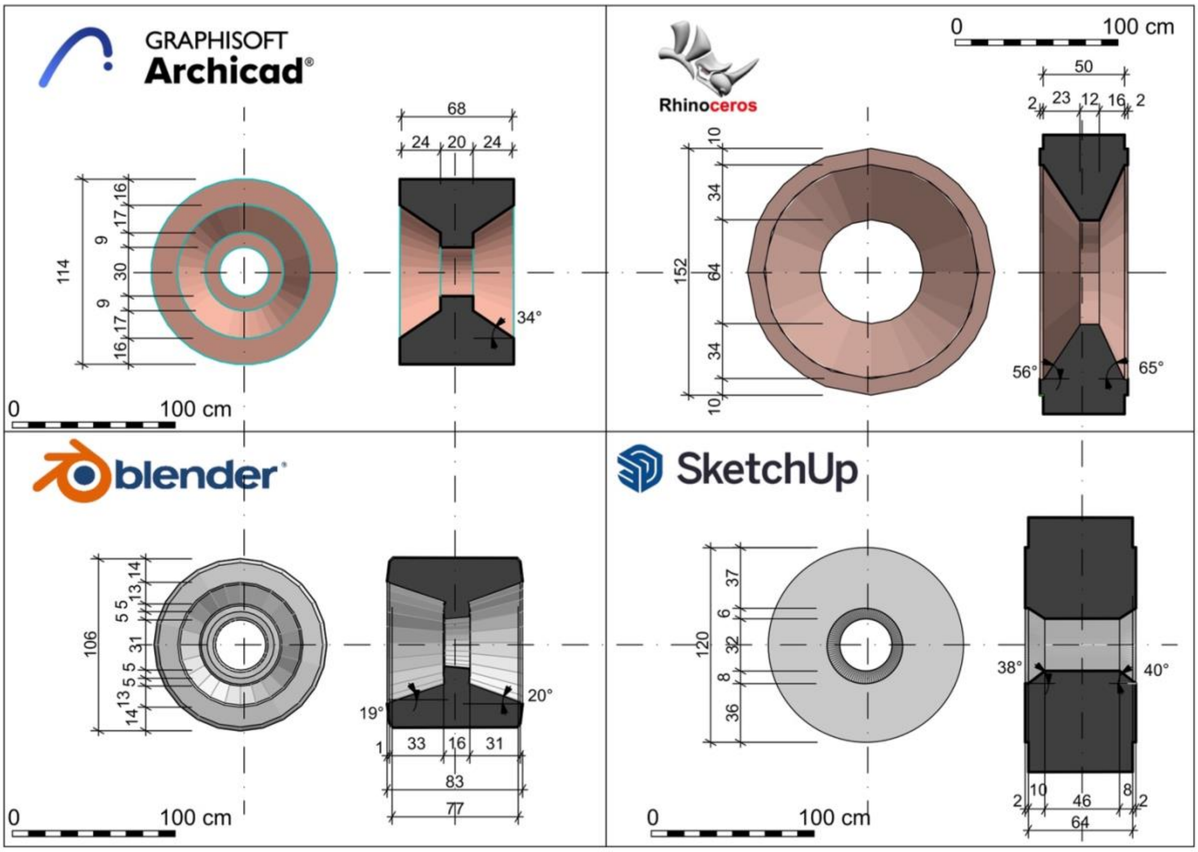


**Figure 9 –** Comparative views and cross-sections of the virtual reconstruction of the circular window of the Speyer Synagogue across all four modellers, revealing divergences in geometric interpretation and representation.

Digital preservation is quite resource-intensive, and not every 3D asset of cultural heritage has to be preserved. For this reason, especially in hypothetical reconstructions, models should undergo rigorous quality assessment. While applying the CRMinf Argumentation Model within CIDOC CRM (Bruseker et al., 2015) helps preserve knowledge of interpreted shapes and inferred hypotheses, it does not address simplifications arising from technological constraints or a modeller's skill, factors that often lead to notable departures from the object's proper form. OntPreHer3D confronts this gap by treating simplifications as deliberate scholarly acts. Through '***M19 Simulation***' *events*, it documents not just the "what" of interpretation but the "how" of its digital execution—linking abstract hypotheses to concrete modelling decisions. When a '***M22 Digital Shape***' emerges, its associated '*E65 Creation*' event preserves the technical specification of its making: the tools, the shortcuts, and the modelling techniques used. Such detail is essential for recreating the model in the future. Looking ahead, developments in artificial intelligence (Silva & Oliveira, 2024) and the standardisation of 3D modelling concepts (Fallavollita et al., 2024) may eventually enable the automatic recreation of lost 3D cultural heritage resources through well-documented, ontological descriptions of the sources, their interpretations, decisions, and techniques (Münster et al., 2024).

An additional difficulty in properly preserving 3D models lies in the application of materials and textures—an aspect often overlooked in practice. This case study also revealed differences in this matter. Although all modellers used the same texture package, the sizing of the roof tiles varied significantly (see **Figure 7**). This discrepancy highlights the need to document not only the shape of each object but also the parameters related to the materials used to maintain complete information for the reconstruction of a 3D model. The current development of OntPreHer3D enables the documentation of attributes related to texturing methods, such as '***M20 Property Set***', '***M24 Texture Mapping***', and the property '***R19 has property value***' (see Figure 10).

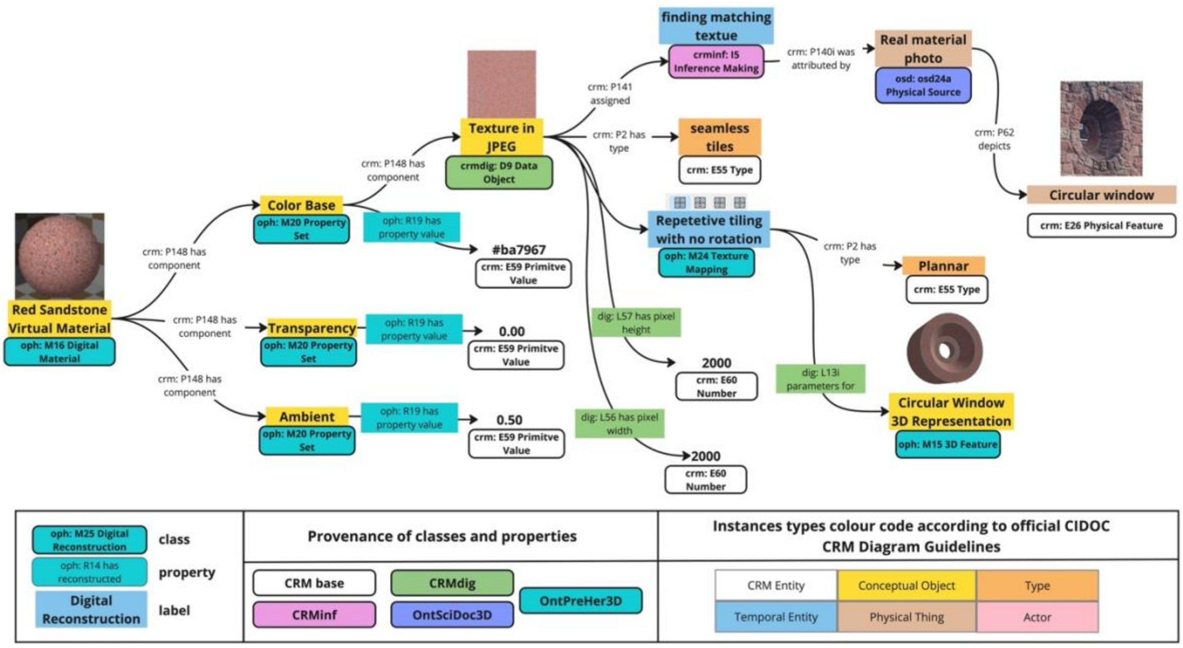


**Figure 10 –** Documentation scheme of selected compositional parameters of the red sandstone material used in the reconstruction of the Speyer Synagogue using OntPreHer3D ontology.

Digital model creation—both the geometry and the application of materials—relies heavily on the creator's interpretive decisions, which means that preserving a 3D model without capturing those decisions results in a superficial and incomplete record. As a scholarly community, we often value the object itself far more than the creative processes behind digital replica production, and this imbalance underpins the challenges of long-term 3D preservation. Initiatives such as aLTAG3D (Chayani, 2020), developed under France's CND3D/CINES programme, skillfully generate XML/XSD-based metadata packages to support the long-term archiving of final form of the 3D assets. Yet these tools focus on the 'what'—the finished model and its descriptive metadata—rather than the 'how' and 'why' of its creation. Indeed, aLTAG3D provides no explicit support for capturing interpretive workflows, documenting human decisions, or the uncertainties inherent in reconstruction.

This gap confirms the main hypothesis behind this paper: current solutions secure the final form of the 3D model but neglect the reasoning behind its creation. What is needed is an ontology-driven plugin that operates in real-time within 3D software, prompting brief user reflections at key interpretive moments. Such a tool would blend automation with lightweight, guided input, bridging the strengths of aLTAG3D's archive packaging and CIDOC-CRM/OntPreHer3D-based semantic richness. This approach would capture not only the outcomes but also the creative and epistemic processes behind digital reconstruction. While manually recording interpretive decisions, source evaluations, and semantic attributes for each 3D object is ideal in theory, it is often impractical in practice due to its time-consuming nature—even for experts. An intelligent, plugin-based tool could address this by automatically logging modelling steps, texture parameters, and material mappings, while prompting users to annotate key interpretive choices as they work. Recent advancements in AI and semi-automated tools offer significant potential for this integration (Silva & Oliveira, 2024). While these often focus on automating data acquisition and initial model generation (e.g., from laser scanning or photogrammetry), the principles can be extended to semantic annotation within the modelling process (Croce et al., 2023). This suggests that a 3D software plugin could leverage similar AI-assisted functionalities to automatically extract and semantically tag geometric attributes, material properties, or even identify components based on pre-trained models.

## Conclusion

The paper highlights the issue of the impermanence of 3D models, driven by rapid technological advancements and challenges in data integration. Presenting virtual reconstructions and digitised objects requires the development of a comprehensive ontological solution compatible with existing frameworks for digital objects and cultural heritage. The proposed OntPreHer3D ontology addresses these challenges by emphasising the importance of documenting the decisions made during research that influence the representation of an object's form and materials related to source interpretation, as well as simplifications related to virtual representations of the object. The paper emphasises the crucial importance of documenting the digital properties of simulated geometry and materials. Since human interpretation is inherently unreliable, it can yield different outcomes even when using the same source materials. This variability demonstrates that, despite having identical goals, source materials, and their classifications, different modellers can produce significantly different results. Digital preservation will only be achieved if the attributes of reconstructed models are documented in a standardised way. In an era of widespread automation of digital processes, requiring manual input of such information is inefficient and resource-intensive. Therefore, future developments in this area should focus on automating documentation methods directly from the 3D model, potentially with AI support,  and utilising available ontological tools such as the one presented in this paper.

While the ontology, as demonstrated by the presented case study, already exhibits significant potential for preserving knowledge surrounding 3D models, its development remains an ongoing process. Current efforts are focused on the forthcoming release of version 2.0.0, which aims to refine the precise categorisation of classes for tools that utilise a uniform data form across all elements of a given type within a database. This will involve the introduction of specialist classes for 3D derivatives, raw data, the semantic segmentation process of objects, and additional parameters crucial for ascertaining a model's scientific value and quality assessment. Furthermore, the necessity of integrating an extension to CRMba has been identified. This extension will enable a more nuanced distinction between physical remains and missing volume, particularly pertinent for the documentation of damaged, ruinous, or archaeologically excavated objects. Beyond internal ontological refinements, it is also planned to explore the critical process of harmonisation between the OntPreHer3D documentation method and the standardised 3D scene description in manifesto being developed by the IIIF 3D Technical Specification Group (TSG), with use of the new IIIF Presentation API 3.0.0, accommodating 3D models, officially published in June 2024 (International Image Interoperability Framework, 2025).

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## Conflict of interest disclosure

The author declares that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

## Data, scripts, code, and supplementary information availability

The latest citable version is available under the following namespace: https://www.ontscidoc3d.hs-mainz.de/OntPreHer3D/. Full documentation and OWL file of the OntPreHer3D ontology are available online: https://doi.org/10.5281/zenodo.15771797 (Bajena, 2025)

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