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Date of secondary publication: 20.04.2026

Version of Record (Published Version), Conferenceobject

Persistent identifier: urn:nbn:de:bvb:473-irb-114784x

Primary publication

Salzer, L.; Arera-Rütenik, T.; Stenzer, A. (2026): Semantic Topologies for Complex Medieval Buildings and their Annotation : Basic Considerations for the Description of Historic Architecture in the Semantic Web, in: W. Börner and H. Rohland (Ed.), The World’s Heritage in the Digital Age : New Technologies Towards Sustainable Research, Conservation and Communication, Heidelberg: Propylaeum, pp.91–102, doi: 10.11588/propylaeum.1449.c20737.

Long Paper

Semantic Topologies for Complex Medieval Buildings and their Annotation

Basic Considerations for the Description of Historic Architecture in the Semantic Web

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Abstract: Semantic technologies can be used not only to create ontologies as controlled vocabularies for historical architecture. Rather, they also make it possible to map the spatial and structural relationships within a building. Using an OWL ontology developed for the use in the MonArch system with a lean, non-event-oriented data model, the example of the Gothic church of St. Lorenz in Nuremberg shows how the relationships between the individual elements of a building (buildings parts, spatial units, structural components, architectural surfaces) have to be set. For this, a spatial breakdown of the building must be combined with a structural breakdown, with the architectural surfaces representing the interface between these two approaches. The result is a consistent structure graph and, derived from it, a basic rule for a semantic topology as an object-related data infrastructure that can also be applied to other buildings and enables the interaction of different disciplines in heritage conservation in everyday practice. Furthermore, the structure graph can be extended with additional specific information, such as the localisation of artistic furnishing or archaeological findings. At the same time, it is connectable to other data models, such as CRMba. The structurally detailed and networked storage of specialist information offers the possibility for a continuously updatable, Linked Data-capable recording of historic buildings, which can be used both as a building information system for the long-term preservation of a historic building and, in the case of indexing the historic building stock through the Semantic Web, would facilitate comparative research in architectural history, building archaeology, art history and restoration sciences.

Keywords: *Ontologies—Linked Data—Semantic Topology—Heritage Conservation—Architectural History*

CHNT Reference: Salzer, L., Arera-Rütenik, T. and Stenzer, A. (2025). ‘Semantic Topologies for Complex Medieval Buildings and Their Annotation: Basic Considerations for the Description of Historic Architecture in the Semantic Web’, *Proceedings of the 26th International Conference on Cultural Heritage and New Technologies*, Vienna and online, November 2021. Heidelberg: Propylaeum. doi: 10.11588/propylaeum.1449.c20737.

Semantic Web and semantic topologies – present approaches

In recent years, there has been an increase in the number and intensity of initiatives to develop ontologies as controlled vocabularies respectively scientific thesauri that describe the phenomenology of historical architecture in general and can be used for Linked Data.[1] In contrast, the semantic modelling of individual existing historical buildings received less attention. Initial approaches to modelling historical architecture as an ontology focused more on certain events associated with the architecture by using CIDOC CRM and thus put the creative process of architectural design as well as the realisation at the construction site in the foreground (Guillem, Bruseker and Ronzino, 2017). With CRMba as an extension of CIDOC CRM for building archaeological use, considerations were made how the structural fabric of a building can be represented within the event-oriented approach of CIDOC (Ronzino, Niccolucci, Felicetti and Doerr, 2016; Ronzino, 2019). While quite impressive possibilities for modelling stratigraphic relationships and building-historical knowledge were achieved, a descriptive system for highly differentiated spatial and structural relationships of the individual elements of buildings has not yet been fully carried out. If one realises that a structural breakdown of buildings is the outline structure for the analogue documentation procedures established in heritage conservation to enable exact localisations of findings,[2] it becomes clear that spatial semantic ontologies of individual architectural monuments would open up a digital turning point for the recording and preservation of cultural heritage, as will be shown at the end.

CIDOC CRM – originally developed for objects of limited size in museum collections – has a large number of classes and properties. In addition, the system has been supplemented by numerous extensions, e.g. CRMba or CRMarch. Its consistent application is essentially reserved for experts. However, professionals working in heritage conservation, such as architects, restorers, architectural archaeologists, civil engineers, must be able to enrich such systems with their specialised information even without having experience in complex semantic modelling. It therefore seems questionable whether CIDOC is suitable for everyday use in heritage conservation. For a widespread use in heritage conservation, leaner data models adapted to main contents and generally valid guidelines for its application are necessary. In the following, a different, not event-oriented approach of semantic modelling of historic architecture is presented. The data model does not reject CIDOC at all. It is rather simplified on one hand and more detailed on the other to meet the requirements of complex built objects in particular. Finally, its complete reverse mapping to CRMba is possible as will be shown at the end.

The aim of the modelling is especially the exact description of the status quo of the spatial building structure – the exact topologic localisation of findings and other information – and thus the integration of the different approaches of object-oriented disciplines to historic building fabric within a common semantic graph. Some disciplines are focused on the architectural surfaces, such as wall and surface restoration or to some extent building archaeology, while others deal primarily with structural components, such as civil engineering or are focused on the enclosed space, as indoor climate monitoring does. The challenge is to describe the relationships among the individual elements of the building

[1] Initiatives in Germany include the Gemeinsame Normdatei (GND) developed from the library system, the idai.vocab of the German Archaeological Institute (available at: https://archwort.dainst.org/de/vocab/, Accessed: 05 January 2022) or the Wortnetz Kultur of the Landschaftsverband Rheinland (LVR) (available at: http://lvr.vocnet.org/wnk, Accessed: 05 January 2022).

[2] E. g. the “Raumbuch” (“room book”) as a documentation system of monuments in German heritage conservation is subdivided into rooms and then into wall surfaces. Petzet and Mader, 1995, pp. 178–179.

– building sections, structural components, spatial units and surfaces – in such a way that despite the diversity of approaches an ontological consistency is maintained.

As part of the research project “Die Nürnberger Großkirchen” (“The Large Parish Churches of Nuremberg”), computer scientists from the University of Passau and researchers from the fields of building archaeology, art history and restoration sciences from the University of Bamberg developed such a spatial ontology, using the example of the St. Lorenz Church in Nuremberg. The development took place within the framework of a general upgrading of the MonArch system, a software that was designed at the University of Passau for the data management of historical buildings.[3] The structure of this application is made up of four components: The graphical representation of the object – a 2D plan or a 3D model – is linked to an ontology, which describes the object in its spatial and constructive structure as a semantic graph. Hereafter this ontology is called topology or structure graph. The individual entities of the specific building represented by the nodes of the structure graph can be described by a controlled vocabulary that contains generalizable information, hereafter called concept graph. Furthermore, several documents such as archival records, architectural plans, documentations of restoration measures or building research as well as visual material from different periods can exactly be attached to the nodes of the structure graph and thus automatically also to the graphic representation in detail (Figure 1). Their exact location is thereby ensured (Freitag and Stenzer, 2017; Stenzer, Ehrlinger and Schmid, 2019, pp. 383–386). An insight into the ontology of St. Lorenz will illustrate how a semantic topology of a building should be structured. First, some technical basics especially the definition of nodes and edges are explained. Afterwards, the practical application is examined in more detail with the help of some specific examples.

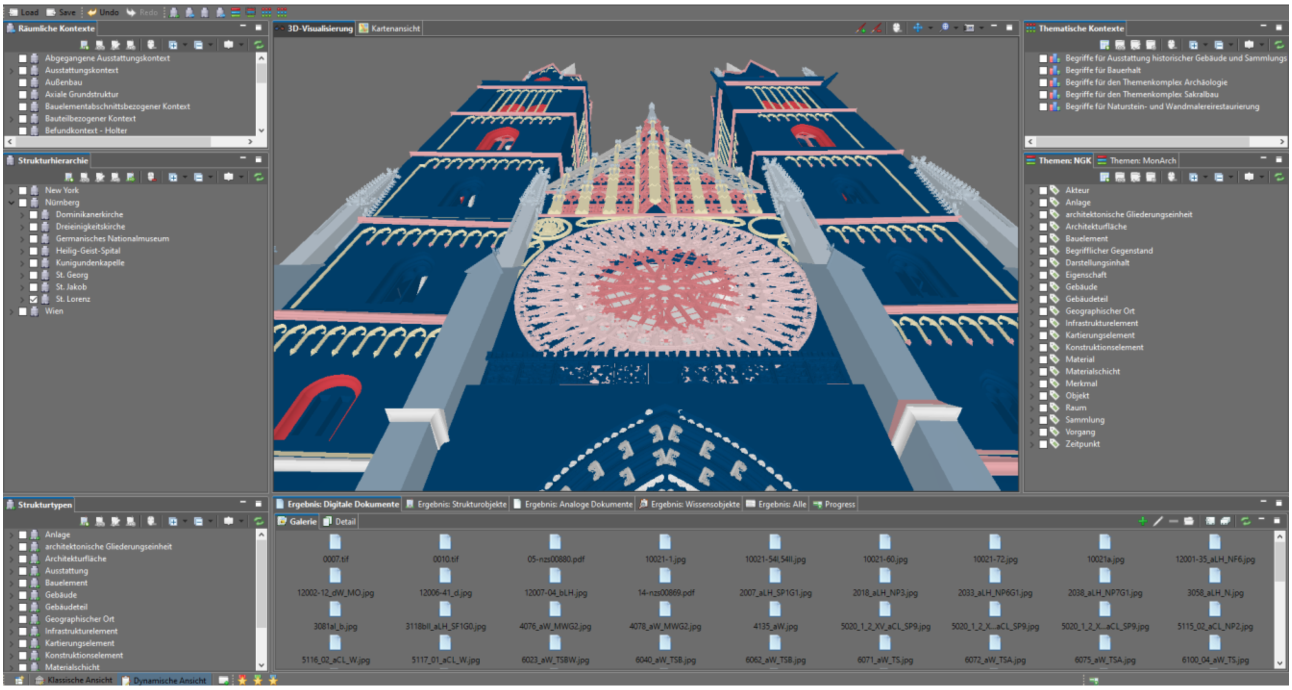

Fig. 1. The MonArch system: The left column shows the semantic topology linked to the graphical representation in the middle. The topology can be labelled with terms from a controlled vocabulary shown in the right and bottom left columns. (© Alexander Stenzer).

[3] Further information on the MonArch system is available at the following homepage: https://openmonarch.org/ (Accessed: 28 June 2023).

Technical foundations of the ontology

The semantic topology of St Lorenz was modelled as an OWL ontology consisting of only one class of nodes – the *spatial symbolic entities*. Each entity represents a particular spatial or structural element of St. Lorenz. The network of the spatial symbolic entities reflects the spatial and constructive features of the building. For the interconnection of the spatial symbolic entities, the number of edge types is deliberately limited and specifically adapted to the description of architecture. A distinction is made between two directed relationships: a *part of*- and a *belongs to-relationship*. The *part of-relationship* represents an existential dependency of the child node on the parent node and can therefore only be used once. The *belongs to-relationship*, on the other hand, expresses a weaker relationship between two spatial symbolic entities and can be used for multiple assignments. This is especially important for modelling Gothic architecture, which is characterized by the spatial overlap of individual elements (Nöbauer and Stenzer, 2019, p. 74). In addition to these hierarchising edges, mutual *connects-relationships* can be used to define adjacencies or a constructive connection of two spatial symbolic entities.

The spatial symbolic entities do not contain any characterising specific information in the pure structure graph initially. They receive their content-related qualification through matches to the concept graph, a controlled vocabulary based on SKOS (Simple Knowledge Organisation System). It was also elaborated in the context of this research project by merging different specialised vocabularies existing only as printed publications into a joint ontology. It contains a variety of detailed technical terms for historic architecture and heritage conservation and cannot be commented on further here due to limited space.[4] Regarding the mentioned matches between the structure and concept graph the *type-relationship* expresses what kind of object the respective spatial symbolic entity actually *is*. In contrast, the *topical reference-relationship* determines, which detailed properties a spatial symbolic entity further *has*. For example, the spatial symbolic entity, that represents a pillar in St. Lorenz, is clearly defined by the *type-relationship*, whereby multiple assignments are possible: thus the entity receives three types, which represent a specialisation of the term "*pillar*" in the vocabulary: "compound pier", "arcade pillar" and "free-standing pillar". In order to describe the material of the pillar, its spatial symbolic entity receives the *topical reference* "middle Keuper sandstone". One could assign further terms here, like terms for stone damages or for processing traces etc.

The semantic topology as a description of the spatial and structural relationships

The use of the part of- and belongs to-edges will be illustrated by specific examples in the following. The first one represents a typical use-case from the field of building archaeology – the exact localisation of findings: a piece of a Romanesque round arch frieze, which remained from a predecessor building. As a spolia it is integrated into the northern central nave wall of the subsequent Gothic basilica. For the exact localisation of the wall surface containing the spolia, two indications have to be semantically expressed: First, the spatial unit (empty space) where the wall surface with the spolia is to be found, in this case the *northern side aisle roof space*. Secondly, the limiting wall and thus the structural component to which the wall surface with the spolia is attached, in this case the *northern central nave wall*. Two basic variants of the breakdown for the semantic topology of St. Lorenz

[4] The SKOS vocabulary mentioned above is available at https://hist-arch-vocab.org/ (Accessed: 28 June 2023) and has a SPARQL endpoint.

can be derived from this. For the presentation of the following examples, it should be noted in advance that, for the sake of clarity, the type-relationship to the vocabulary, which expresses in machine-readable form what kind of object the spatial symbolic entity represents, is not shown. In the examples, only the labels of the concepts of the structure graph are given, which, however, imply to the reader what kind of object the spatial symbolic entity represents.

For the spatial breakdown of St. Lorenz (Figure 2, left), the interior of the building is continuously subdivided into its individual spatial units (empty spaces). This alternating subdivision finally ends e. g. at the northern side aisle roof space on one side and at bay X of the central nave on the other. The two wall surfaces of the corresponding section of the northern central nave wall are assigned to their respective spatial unit: the concept “northern central nave wall, surface roof side section nX” to the concept “northern side aisle roof space” and the concept “northern central nave wall, surface nave side section nX” to the concept “bay X of the central nave”. For this purpose, a belongs to-relationship is used, because it is not an existential dependency. The finding, the Romanesque spolia, is at the same time assigned to the corresponding spatial unit via its allocation to the adjacent wall surface. This space-orientated structure corresponds to analogous documentation standards in heritage conservation, such as the so called ‘Raumbuch’ (room book). However, the two wall surfaces are located at two separate points within a strict hierarchy, without an explicit structural relationship between these two surfaces having been defined. Thus, it lacks the essential statement that the Romanesque spolia is part of a physically existing wall and that the two wall surfaces shown in this example are part of a common wall section.

The structural breakdown (Figure 2, right), on the other hand, separates the building or its individual parts into its structural components. A structural component, such as the wall, the vault or the pillar, is defined as an individual architectural element made of construction material (filled component). It is three-dimensional, has a material volume, however, it does not enclose a spatial volume by its own, but only in combination with other components. The structural breakdown finally leads to the concept “northern central nave wall” and – since it can be divided into individual sections according to the given spatial units – finally to the concept “northern central nave wall section nX”. Its two wall surfaces, one facing the roof space, the other the central nave, represent child nodes of the latter. In this way, the finding is also assigned to the wall via the relationship to the wall surface. The interconnection between the two wall surfaces and thus the physical existence of the superordinated wall, which was missing in the previous example, is now semantically expressed. However, the spatial references of the individual wall surfaces to the adjacent (empty) spatial units are missing now.

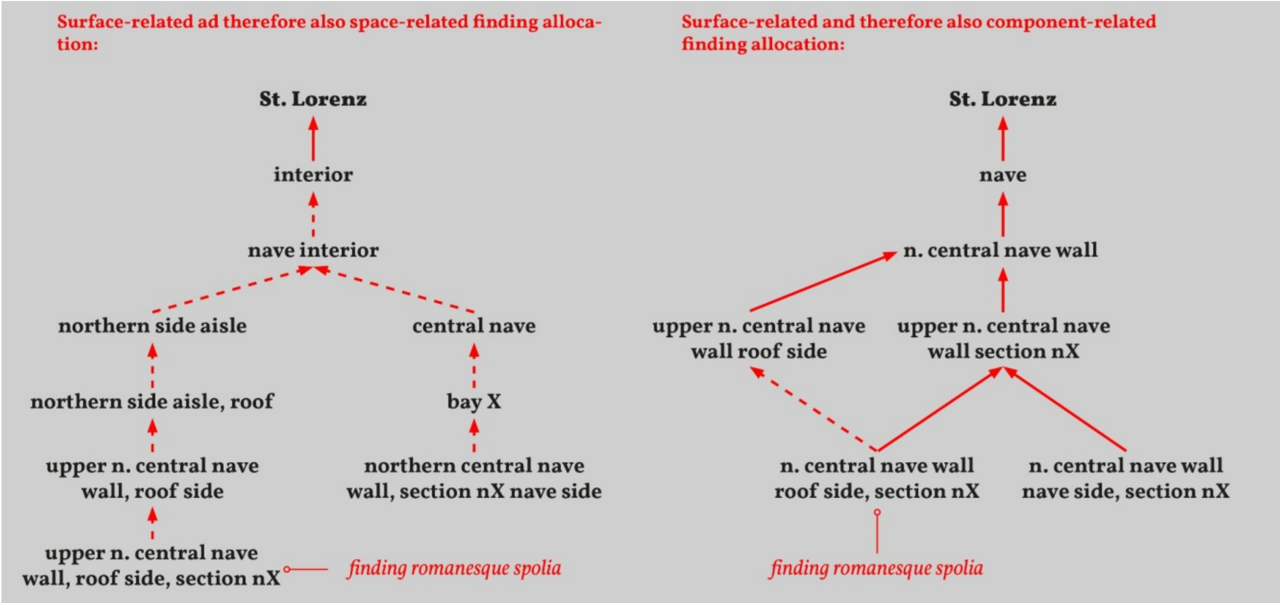

Fig. 2. Semantic topology and building archaeology: The left column shows the space-related breakdown, the component-related breakdown is depicted on the right. Part of-relationships are symbolised by solid arrows while belongs to-relationships are represented as dashed lines. (© Tobias Arera-Rütenik, University of Bamberg).

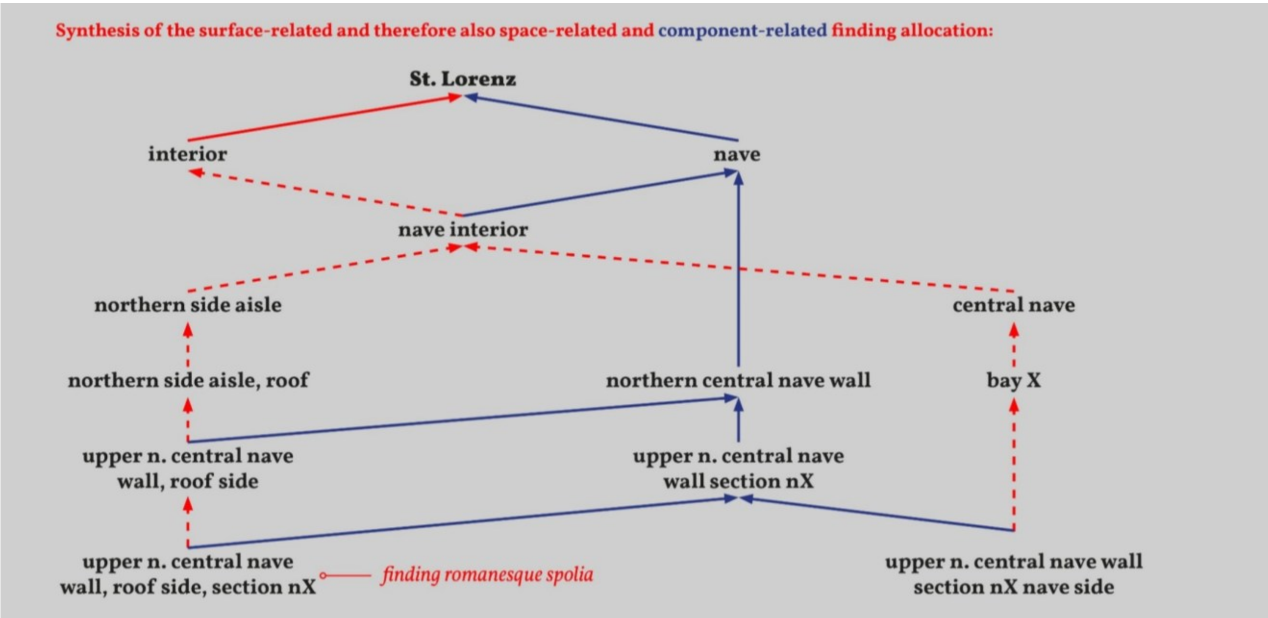

Fig. 3. Semantic topology and building archaeology: The structure graph of St. Lorenz allows a combination of the space-related (red) and the component-related perspective (blue), which were shown seperately in Fig. 2. Part of-relationships are symbolised by solid arrows while belongs to-relationships are represented as dashed lines (© Tobias Arera-Rütenik, University of Bamberg).

To represent both necessary breakdowns, the two variants have to be combined in one structure graph so that the two parallel breakdowns into spatial units and structural components have a common beginning – the whole building – and a common end – the wall surfaces (Figure 3). Ultimately, a modelling scheme as a basic rule for a semantic topology can be seen in this single example (Figure 4): Thus a building is composed of rooms / (empty) spatial units and (filled) structural components. Depending on the size, the building can first be broken down into individual building sections as superordinate units, before the subdivision into structural components and spatial units follows. Building sections are made up of both spatial units and the building components that enclose them. Examples would be “the choir” or “the nave”. Analogous to the building and its sections, structural components and spatial units can also be continuously subdivided, which is usually expressed for structural components with a part of-relationship, for spatial units with a belongs to-relationship. On the lowest level in the structure graph are the architectural surfaces. They are existentially dependent on the structural component by a part of-relationship but are assigned to the respective room / spatial unit via a belongs to-relationship. In contrast, there are no direct belongs to-relationships between the spatial units and the adjacent structural components. Since most of the structural components separate several spatial units from each other, they would therefore receive belongs to-relationships to at least two spatial units. Such an approach could cause incorrect transitive spatial assignments of the architectural surfaces and in consequence wrong query results. However, the user does not have to worry about a correct distinction between spatial units, structural components and architectural surface in detail. In the controlled vocabulary developed within the framework of the same research project, the five classes of objects listed in the mentioned modelling scheme are defined as top concepts. Individual technical terms used to describe the quality of the spatial symbolic entities of the structure graph via the type-relationship are ontologically subordinate to these top concepts. If, for example, a heritage expert uses the term “arcade pier” as usual to specify an element, the superclass “structural component” is automatically inherited as well. This provides a validation mechanism in the data model with which the semantic structure scheme presented here can be consistently implemented on each individual building in practice.

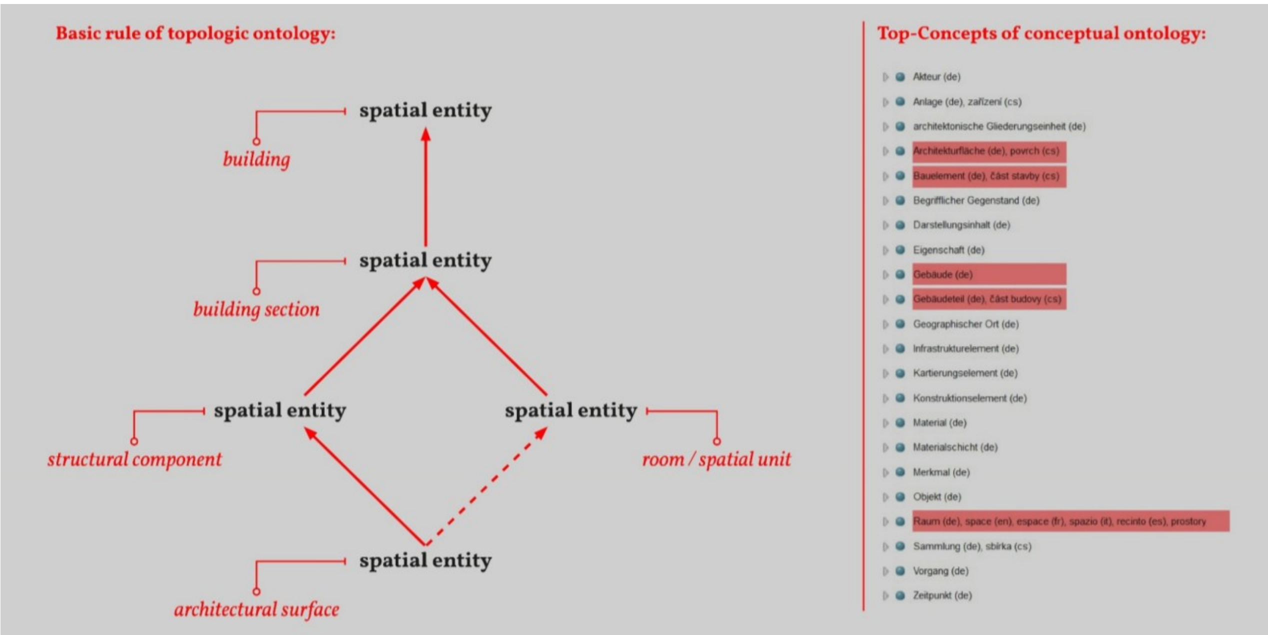

Fig. 4. Semantic topology: The modelling scheme as a basic rule defines the relationships between the five basic types of spatial symbolic entites on the left. They are also represented as top concepts of the controlled vocabulary used to annotate the conceptual values of the spatial symbolic entites. Part of-relationships are symbolised by solid arrows while belongs to-relationships are represented as dashed lines (© Tobias Arera-Rütenik, University of Bamberg).

The structure graph for St. Lorenz can be extended to include further specialist content with further spatial symbolic entities, for example the pieces of artistic furnishing. Recommendations can be made for a stringent semantic modelling, as will be shown with the three sculptures “Martyrdom of St. Sebastian”, “Apostle James minor” and “St. Anthony” (Figure 5).

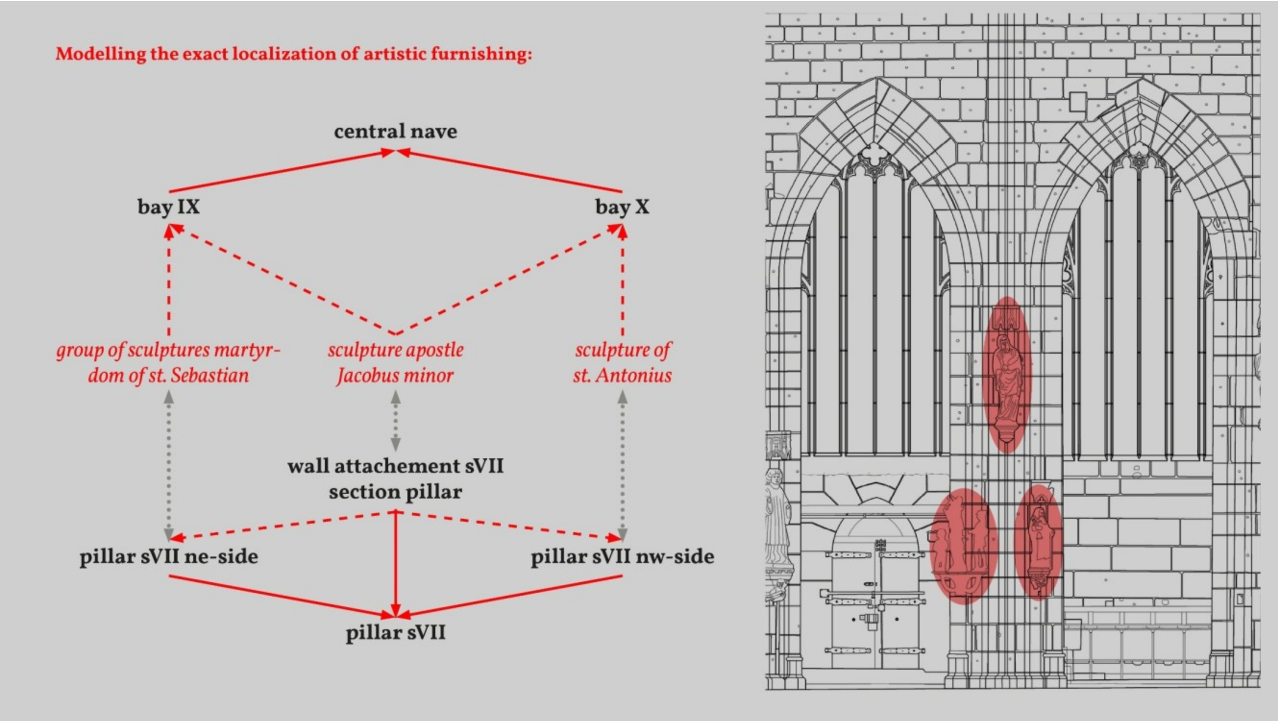

Fig. 5. Semantic topology and artistic furnishing: Sculptures are not attached via part of-relationships to structural components directly but linked to corresponding spatial units with belongs to-edges. Instead, connects-relationships express the binding to the structural component which are represented by dashed grey arrows in the Fig. (© Tobias Arera-Rütenik, University of Bamberg).

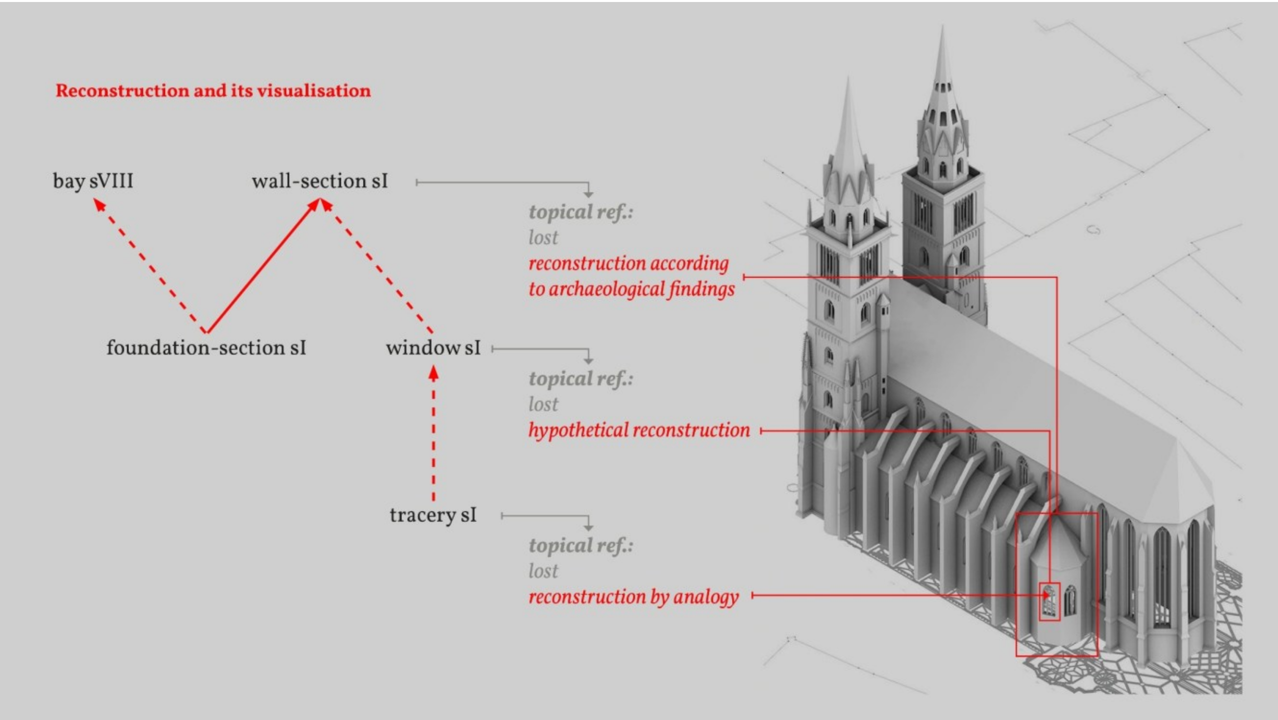

Fig. 6. Semantic topology and archaeological reconstruction: Even lost, only reconstructed components can be located in the semantic graph and consistently linked to the existing archaeological findings. Topical references provide information about the reliability of the reconstruction (© Tobias Arera-Rütenik, University of Bamberg).

Although the sculptures are attached to pillar sVII on the south side of the central nave, they are not a direct child node of the pier in the sense of a part of-relationship. Sculptures are in general always dismountable and can be moved to other locations. Furthermore, the subordination of the sculptures to a structural component would not indicate the spatial unit to which the sculptures are directed. For these reasons, an assignment of the sculptures to the bays via belongs to-relationships and a connects-relationship to the corresponding elements of pillar sVII is to be preferred. Sculptures at the interface between two bays, such as that of the apostle James minor here, refer via belongs to-relationships to both. In contrast, the lateral sculptures can only be assigned to one bay, which at the same time semantically models their orientation in space.

For archaeological excavations, this data model not only offers the possibility of detailed and consistent localisation of findings in the existing building. Furthermore, one can semantically model different hypotheses as regards how these archaeological findings can be interpreted and which reconstructions can be derived from them (Figure 6). This is of interest for St. Lorenz in so far as in previous research quite contradictory theories stand side by side. Some researchers have assumed that octagonal foundations found in the southern side aisle could be part of an isolated earlier Holy Sepulchre Chapel. Others again argue for an octagonal ending of the 14th century side aisle. In the semantic topology these different interpretations of the same finding could be modelled parallel to each other. Starting from the foundations, which undoubtedly exist in reality as excavation findings, two building parts represent the corresponding reconstruction variants and are linked as parent nodes via belongs-to-edges. They are marked by topical references as “not existing” or “gone”. So-called contexts, which could not be discussed in more detail here, allow their different chronological attribution. By linking the semantic topology and the references to the vocabulary with the virtual models, the substantive bases and the degrees of uncertainty for this reconstruction can furthermore be annotated in a machine-readable way. The linking of the semantic topology with a graphical representation already leads us to the point how the semantic topology can be used for heritage preservation and object related research within the MonArch System.

Semantic topologies as object-related data infrastructures – use and potentials

St. Lorenz’s topological building ontology intertwines two different systems of access to architecture and thus creates an interface for diverse disciplines that approach the existing building according to their own methods in their daily work practice or in their scientific focus. Thus, the examination of the individual rooms and spatial units is fundamental for the architect’s design issues, but also for room climate monitoring or the research of historical functional structures. The structural consideration of the individual building elements with regard to their load-bearing behaviour is in turn the approach of the civil engineer. The focus on architectural surfaces is one of restorers and also building archaeologists. Thus, semantic topologies – as developed for the MonArch system – can be seen as reference systems and infrastructures to store, retrieve and update the multimodal wealth of information of heritage conservation in an object-related manner and to make the objects accessible for Linked Data. The design of the structure graph is more than a one-dimensional filing system devised by a single user. Instead, by attempting to semantically reproduce the numerous relationships of the building elements in an ontology, a dense network of information is formed and object-related standard data graph for a certain building is created.

In order to preserve the greatest possible flexibility for different users and their respective points of view, the data model described strictly separates the purely topological ontology from the qualifying controlled vocabulary. In CIDOC CRM, the selection of a particular class to represent the morphological structure of an object always reflects a content statement to some extent. For data exchange, the system can nevertheless be mapped to CIDOC CRM (Figure 7). In order to automatically differentiate the always identical spatial symbolic entities in the structure graph of St. Lorenz with regard to different CIDOC classes, the qualifying type-relationships to the vocabulary are queried. These are selected as usual by the monument experts on the basis of the subject-related requirements and thus represent a wide variety of phenomena. However, their superordinate top concepts can be equated with CIDOC classes (here especially the morphological sections of CRMba). Thus, the concepts describing the whole building correspond to class B1 “Built Work”, the building parts to B2 “Morphological Building Section”, structural components to B3 “Filled Morphologic Building Section” and spatial units to B4 “Empty Morphologic Building Section” (Ronzino, Niccolucci, Felicetti and Doerr, 2016, p. 73, Ronzino, Niccolucci, Felicetti, Doerr et al., 2016, p. 9–10). Only for the architectural surfaces there is no adequate class in CRMba. Here, an extension would certainly make sense.

The described equivalences form the basis for a mapping of the structure graph of St. Lorenz with the help of simple conditions. For example for B2 a description logic axiom in Manchester syntax can be written as follows:

‘has type’ some (‘has broader transitive’ value ‘building section’) SubClassOf ‘B2 Morphological Building Section’.

This can be done for the other CRMba classes accordingly. If previous example is considered, the nave has class Spatial_Symbolic_Entity and the inferred class B2.

```
Individual: <http://www.monarch-project.eu/Spatial#nave>
  Types:
      <http://erlangen-crm.org/current/E24_Physical_Human-Made_Thing>,
      <http://erlangen-crm.org/current/E92_Spacetime_Volume>,
      <http://semanticweb.openmonarch.org/crmba#B1_Built_Work>,
      <http://semanticweb.openmonarch.org/crmba#B2_Morphological_Building_Section>,
      <http://www.monarch-project.eu/Spatial#Spatial_Symbolic_Entity>
```

The semantic topology, as applied in the MonArch system, enables the archiving and continuous updating of data on a building and thus a digital and networked monument management. The MonArch system as a store of knowledge for a historic building therefore becomes a useful tool for the planning of restoration measures and the long-term monitoring of damages. For example, maintenance intervals for furnishings and wall surfaces can be stored and queried for further planning of building maintenance. Or, through the semantic labelling of the different stone varieties occurring in an individual building or in a larger building stock, it could be determined where certain types of stone that cause certain damage patterns can still be found in order to initiate appropriate maintenance measures. Furthermore, indexing the historical building stock for the Semantic Web would offer new possibilities for research in architectural history, building archaeology, art history and restoration sciences since with a growing data base specific architectural phenomena could be better contextualised (Breitling, Arera-Rütenik, Giese and Salzer 2020, pp. 68–69). For example, comparisons for the use of Romanesque decorative elements as spolia in Gothic architecture could be determined automatically or semi-automatically and it could be decided via topological classification whether these spolia were installed in subordinate, non-visible areas, as in St. Lorenz. In order to answer such questions, the user of the software only has to call up the semantically annotated information by selecting a specific spatial symbolic entity, which is also possible via the graphic representation, or the terms of the vocabulary, whereby the relevant spatial symbolic entities are filtered. At the same time, it is possible to find out the relevant elements via SPARQL queries. Finally, the triad of structure graph, referenced controlled vocabulary and graphic representation in the MonArch system offers – as already emphasised elsewhere in the research (Kuroczyński, Brandt, Jara and Grosse, 2019; Stenzer, Ehrlinger and Schmid, 2019, pp. 387–390) – the basis for indexing the historical building stock for Building Information Modeling (BIM).

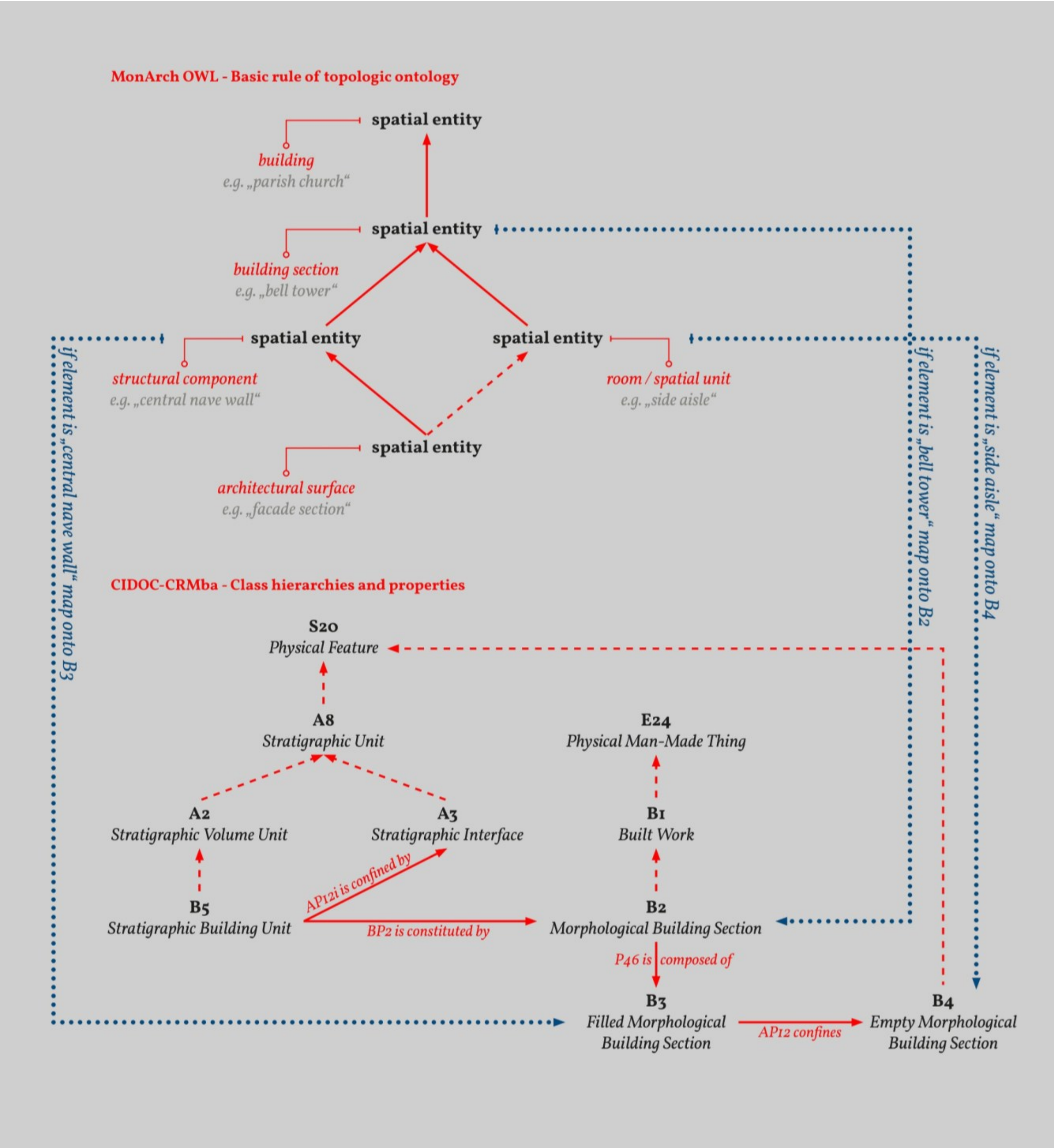

Fig. 7. Mapping of MonArch OWL (top) onto CIDOC-CRMba (bottom) by use of conditions accessing the top concepts of the referenced controlled vocabulary (© Tobias Arera-Rütenik, University of Bamberg).

Conflict of Interests Disclosure

No potential competing interests have been reported by the authors.

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Writing – original draft: Leonhard Salzer
Writing – review & editing: Tobias Arera-Rütenik, Leonhard Salzer, Alexander Stenzer

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