

Article

Optimizing H-BIM Workflow for Interventions on Historical Building Elements

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Abstract: Intervention projects for historical buildings depend on the quality of multidisciplinary data sets; their collection, structure, and semantics. Building information model (BIM) based workflows for historical buildings accumulate some of the data sets in a shared information model that contains the building's geometry assemblies with associated attributes (such as material). A BIM model of any building can be a source of data for different engineering assessments, for example, solar and wind exposure and seismic vulnerability, but for historic buildings it is particularly important for interventions like conservation, rehabilitation, and improvements such as refurbishment and retrofitting. When the BIM model is abstracted to a semantic model, enabling the use of semantic technologies such as reasoning and querying, semantic links can be established to other historical contexts. The semantic technologies help historic building experts to aggregate data into meaningful form. Ontologies provide them with an accurate knowledge representation of the concepts, relationships, and rules related to the historic building. In the paper, we are proposing an improved workflow for the transformation of a heritage BIM model to a semantic model. In the BIM part the workflow demonstrates how the fully parametric modelling of historical building components is relevant, for example, in terms of reusability and adaptation to a different context. In the semantic model part, ontology reuse, reasoning, and querying mechanisms are applied to validate the usability of the proposed workflow. The presented work will improve knowledge-sharing and reuse among stakeholders involved in historic building projects.

Keywords: heritage building information modelling (H-BIM); algorithmic design; semantic model; ifcOWL; Erlangen CRM/OWL; SPARQL



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1. Introduction

Heritage building domain research co-develops information modelling and semantic modelling domains. Semantic technologies are methods and tools associated with data and the information that can be retrieved from it, enabling both human and machine “understanding” of the topic they focus on, e.g., taxonomies, glossaries, knowledge graphs, and ontologies.

The roots of the term “ontology” can be found in philosophy, where it has different conceptions. One of the definitions describes ontology as a philosophical discipline that focuses on the study of what there is, the general features of what there is, and the study of what is involved in settling questions about what there is in general [1]. In 1993, Thomas Gruber defined ontology as an “explicit specification of a conceptualization” [2], i.e., a semantically structured description of concepts and of the connections between them. Ontologies are essentially composed of classes, subclasses, properties, restrictions, and instances. In the computer and information science, heavily connected to the architecture, engineering, construction, owner and operator (AECCO) industry, an ontology can be

viewed as a representation vocabulary and the conceptualizations of the terms it contains, often specialized to some domain or subject matter [3].

The multidisciplinary applicability of semantic technologies, like ontologies, assists in improving interoperability, especially in fields where a reliable and precise knowledge of concepts is vital but often dispersed. However, due to the myriad of ontologies being developed, the principles of orthogonality (reusing definitions already created), cross-ontology compatibility, and sustainability [4], should be considered when extending or building a new ontology. The reuse of existing ontologies also prevents the duplication of prevalent terms, with the additional benefit of guaranteed usability and applicability [5].

1.1. Heritage Buildings Interventions

Heritage or historic buildings are integrated in the cultural tangible immovable category of the heritage domain. When the value of their physical, historical, cultural, or ecological features is considered significant, buildings can be classified as heritage which assists in their safeguarding for posterity. The broad spectrum of possible measures spans from raising awareness (among communities, authorities, and decision makers) of the importance and benefits of their protection to highly technical localized structural interventions. Any considered measure is based and heavily depends on knowledge (contextual, detailed, technical, etc.) of the asset to be preserved. When the study of these buildings is on focus, numerous charters, standards, and guidelines serve as unavoidable references, namely:

- International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter) (1964) [6];
- Athens Charter for the Restoration of Historic Monuments (1931) [7];
- Washington Charter for the Conservation of Historic Towns and Urban Areas (1987) [8];
- The Charter on the Built Vernacular Heritage (1999) [9];
- The Charter of Krakow—Principles for Conservation and Restoration of Built Heritage (2000) [10];
- ICOMOS Charter—Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage (2003) [11];
- The Burra Charter: The Australia ICOMOS Charter for the Conservation of Places of Cultural Significance (2013) [12].

The previous references provide recommendations for the safeguard of heritage buildings and detail the types of interventions that assist in their protection, conservation, and rehabilitation. Table 1 summarizes the main types of interventions and their definitions, retrieved from the Burra Charter [12] and the Getty Research Institute vocabulary [13]. As research confirms, the following presented definitions, taken from specialized references are recognized and accepted amongst specialists and therefore were introduced in the extended ontology, later presented in Section 4. Results.

The importance of the use of ontologies in the heritage buildings project domain is justified by several factors. Foremost, the connection with construction, where the terminology, materials, processes, actors is vast and frequently complex. The particularities associated with interventions in heritage buildings, terminology, techniques, and the multidisciplinary teams (often from fields not usually directly associated to construction projects, e.g., history, biology, archaeology, tourism, and sociology), suggests that a connection between the concepts specific to the application domain, for example, heritage buildings interventions projects, should be established.

Building information modelling (BIM) has an already robust and established important role in the heritage building domain. As a set of technologies, processes, and policies capable of incorporating quantitative and qualitative information about an asset, BIM has been proven adequate for projects related to heritage buildings, commonly designated heritage or historic building information modelling (H-BIM).

Table 1. Heritage buildings interventions and definitions.

Intervention	Definition
Conservation	“Conservation means all the processes of looking after a place so as to retain its cultural significance.”; “Conservation may, according to circumstance, include the processes of: retention or reintroduction of a use; retention of associations and meanings; maintenance, preservation, restoration, reconstruction, adaptation and interpretation; and will commonly include a combination of more than one of these.” [12].
Maintenance	“Maintenance means the continuous protective care of a place, and its setting.” [12]
Preservation	Preservation means maintaining a place in its existing state and retarding deterioration.” [12].
Restoration	“Restoration means returning a place to a known earlier state by removing accretions or by reassembling existing elements without the introduction of new material.” [12].
Reconstruction	“Reconstruction means returning a place to a known earlier state and is distinguished from restoration by the introduction of new material.” [12].
Adaptation	“Adaptation means changing a place to suit the existing use or a proposed use.”, “Adaptation may involve additions to the place, the introduction of new services, or a new use, or changes to safeguard the place. Adaptation of a place for a new use is often referred to as ‘adaptive re-use’.” [12].
Demolition	Demolition of significant fabric of a place is generally not acceptable. However, in some cases minor demolition may be appropriate as part of conservation. Removed significant fabric should be reinstated when circumstances permit.” [13].
Rehabilitation	“The act or process of making possible a compatible use for a property through repair, alterations, and additions while preserving those portions or features which convey its historical, cultural, or architectural values. Refers also to the activity of returning to good condition deteriorated objects, structures, neighborhoods, or public facilities; and may involve repair, renovation, conversion, expansion, remodeling, or reconstruction.” [13].
Repair	“Repair involves restoration or reconstruction.”: “Repair involving restoration: returning dislodged or relocated fabric to its original location.”, “Repair involving reconstruction: replacing decayed fabric with new fabric.” [13].
Renovation	“Process of making changes to objects, especially buildings or other structures, with the intention of improving their physical condition and returning them to a good state of repair.” [13].
Additions	“Refers to parts added onto an object or structure. In architecture, if a modification does not substantially increase a structure’s volume, use alterations.” [13].
Remodeling	“Changes undertaken with the intention of altering the style or decorative appearance of rooms, spaces, or buildings or other structures, without regard necessarily to historically accurate forms or periods.” [13].
Refurbishment	“The process of updating and redecorating a building or other work, particularly with the implication of making it more energy efficient, eco-friendly, or sustainable. Used primarily in the context of built works.” [13].
Retrofitting	“Adding something new to the original building or structure to improve functionality, structural stability, and/or energy efficiency. These can be new technology, building systems, or equipment. The process of furnishing a building or other object with new parts or equipment not available at the time of its manufacture.” [13].

1.2. Objective of the Paper

In the paper, we present an improved workflow for the transformation of H-BIM models to semantic models. The paper validates the proposed workflow with the support of a case study: an existing heritage building in Krekova Street, Maribor, Slovenia. Designed by Gustav Zornik, built in 1913, and formerly a branch of the Austrian and Hungarian Bank, the building currently serves as the location of the Faculty of Civil Engineering, Transportation Engineering and Architecture of the University of Maribor. In 2016, a renovation and revitalization project allowed the adaptation to a new use, preserving and protecting the identity of the building. The building is listed on the Register of Immovable Cultural Heritage of Slovenia.

The starting point of the presented research was the development of the building's BIM model. The proposed workflow, presented in more detail in Section 3, includes both H-BIM and semantic modelling, and intends to improve the retrieval of relevant information connected to the building through reasoning and querying mechanisms, facilitating knowledge-sharing between all stakeholders.

2. Related Work

2.1. Ontologies for the Construction Domain

There are numerous examples of the development of ontologies for the construction domain, with diverse objectives. In 2019, Zhong et al. [14] identified in their review the top ten frequently co-occurring keywords in articles related to this topic, specifically, project management, construction industry, semantics, BIM, architectural design, information theory, knowledge management, knowledge-based system, construction management and semantic web. The review also identified the top research themes: domain ontology, Industry Foundation Classes (IFC), automated compliance checking and BIM. These results clarify that the research community is aware of the multiple applications and advantages of ontology technologies.

Recent scientific publications illustrate the extensive application of ontologies in construction. Mohammadi et al. [15] developed an ontological inference engine to configure construction processes, define activities and manage resources of concrete construction works, representing construction planning knowledge through an ontology and several semantic rules. Guven et al. [16] adapted an ontology based on Unifomat and Master-Format (two major construction classification systems) to perform material take-offs and identify prospects to improve their efficiency. The management of concrete bridges and the improvement of information integration and searching in such projects was the focus for Wu et al. [17], which justified the development of an ontology capable of calculating procedures' delays, tasks, and constraint removal, identifying critical constraints, and evaluating the project participants performance. Zheng et al. concentrated on the information related to construction systems, connected to activities, agents, equipment, locations, building objects, and other participating entities, to develop an ontology focused on the digital construction workflow [18]. Corry et al. presented a performance assessment ontology and correspondent framework devoted to the energetic and environmental management of buildings, where the focus was the integration of relevant datasets, data integration and analysis [19]. Concerning renovation projects and related product installation activities, the Reno-Inst ontology by Amorocho and Hartmann [20] focused on the installation of windows, ETICS panels and radiators, which are considered for renovation. The authors highlight the advantages of ontologies as facilitators for mapping and knowledge representation, collection and retrieval of relevant information.

2.2. Ontologies for Heritage Buildings

Equivalently, the cultural heritage domain benefits from the application of semantic technologies, such as ontologies, supporting information systems, and extending data models. When cultural heritage tangible assets are considered, particularly heritage buildings, ontologies support the qualitative collection of related data and its meaning, connecting concepts and clarifying the relationships between them.

The importance of using ontologies in the heritage buildings project domain is justified by several factors, for example, the connection with construction, where the terminology, materials, processes, and actors are vast and frequently complex. The particularities associated with interventions in heritage buildings, terminology, techniques, and multidisciplinary teams (often from fields not usually directly associated to construction projects, e.g., history, biology archaeology, history, tourism, and sociology), suggests that a connection between the concepts specific to the application domain, for example, heritage buildings interventions projects, should be established. Ontologies provide a way of understanding the relationships between the concepts in what can be called a federated, structured way.

Concerning ontologies for the cultural heritage domain, the International Committee for Documentation Conceptual Reference Model (CIDOC-CRM, ISO 21127: 2014—Information and documentation: A reference ontology for the interchange of cultural heritage information) stands as one primary reference. Promoting information integration in the field of cultural heritage, the CIDOC-CRM is often used as a base for research in the built cultural heritage domain, integrated and expanded in the development of specialized ontologies.

The Cantabria's Cultural Heritage Ontology [21] and the Built Cultural Heritage (BCH) ontology for preventive conservation [22] are examples of ontologies that use the CIDOC-CRM. The latest presents the development of an ontology by merging three ontologies, CIDOC-CRM, a CityGML-based data model obtained through a dedicated Application Domain Extension (ADE) and the Monument Damage ontology (Mondis), a method that was also used in this paper. Dedicated to 3D semantic annotations of the building conservation states, Messaoudi et al. [23] presented an ontology with classes mapped to the CIDOC-CRM, opening their research work to a broader research community. Acierno et al. use the CIDOC-CRM to derive a catalogue of architectural heritage, the Architecture Metadata Object Schema (ARMOS) [24].

A particularly relevant ontology for the present research (as it was chosen for extension) is the Erlangen CRM/OWL (ERCM), an implementation of the CIDOC-CRM, which includes detailed restrictions and is kept as close as possible to the CIDOC-CRM in terms of the text specification [25]. Developed at the Friedrich-Alexander-University of Erlangen-Nuremberg, the ERCRM presents 85 classes and 283 properties.

Current technological developments such as 3D scanning, BIM, machine learning, and semantic web technologies, assist in obtaining, reasoning, and structuring data referent to heritage buildings. Ontologies provide needed support for their development [26–30].

2.3. Heritage Building Information Modelling and Semantic Technologies

Relevant for heritage buildings is the connection between the building and its historical background, the multidisciplinary collaboration (extended to areas not traditionally connected to construction) and the often specific techniques to perform interventions to the building, which makes H-BIM a good candidate for the management of all this information (geometric, alphanumeric, and documentation). Antonopoulou and Bryan [31] present a diagram that describes the H-BIM life cycle principle, connected to the H-BIM workflow, that can be summarized as a cyclic process: 1—identification of asset strategy; 2—research legislation; 3—preliminary survey; 4—determining options, 5—define detailed survey, 6—determining intervention; 7—physical intervention; 8—handover and 9—operation and future.

Scianna et al. [32] suggest a workflow for the construction of a H-BIM model with 1—acquisition of information; 2—categorization of building elements; 3—survey; 4—3D modelling; 5—output. The authors highlighted that the main difficulties were found in the modelling phase and that the creation of parameterized objects is complex and not always necessary. For example, for some structural analyses, a geometrical simplification sometimes must be carried out for calculation purposes. In the present paper, different modelling approaches are mentioned, e.g., connected to different types of parametric modelling, based on photogrammetric input data and scan-to-BIM. The decision on which to use should be taken by all project participants, mainly based on the intended use(s) of the model and objectives of the project, availability of equipment, software, and expertise of the BIM modelers. Detailed parametric modelling of individual parts of buildings (including deformations) is a time consuming and demanding task. Translating complex building components to parametric objects is therefore not common practice. It is also important to mention, though not the focus of the paper, that for the analysis of structural deformations in heritage buildings, as-is H-BIM models obtained through laser scanning can be crucial for the assessment of deviations and displacements, as detailed in [33]. León-Robles et al. [34] presented a similar use, applied to a stone bridge.

Dedicated to the review of the semantic enrichment of H-BIM, Cursi et al. [35] present an investigation on how semantic and knowledge management can elevate the quality of non-geometric information associated with H-BIM models. The authors define two approaches, the relational and the ontological, and detail their main differences. For the relational approach, the semantic enrichment makes use of an external database. The ontological approach uses external knowledge representation models. One of the mentioned differences is that the ontological approach focuses on specific processes, where the exchange of information is streamlined to the essential. The authors conclude that there is no single way to integrate data across all the resources involved, and specific workflows are often better supported than an overall approach.

The previously described references confirm the relevance of associating H-BIM with semantic technologies. BIM is highly connected to the use of standards, particularly open standards, such as the IFC, proposed by buildingSMART [36]. One of the development efforts for a complete representation of the IFC standard in a Web Ontology Language (OWL) is also connected to buildingSMART [37]. The ifcOWL ontology is automatically generated, using the EXPRESS schema [38] (currently up to the IFC 4X3 RC1) and can be described, in a very summarized way, as an ontology for the representation of construction data. The process results in a very rich ontology (1326 classes, 1596 properties, 1162 named individuals), which can pose issues related to its management, reuse, and understandability. Aware of these and other “disadvantages”, Terkaj and Pauwels [39] proposed a modularization approach to the ifcOWL ontology. The conversion of the H-BIM IFC model to IfcOWL will be explored in the present paper.

3. Workflow for H-BIM and Semantic Model

The proposed workflow (Figure 1) is divided in two parts, the H-BIM modelling part and the semantic modelling part.

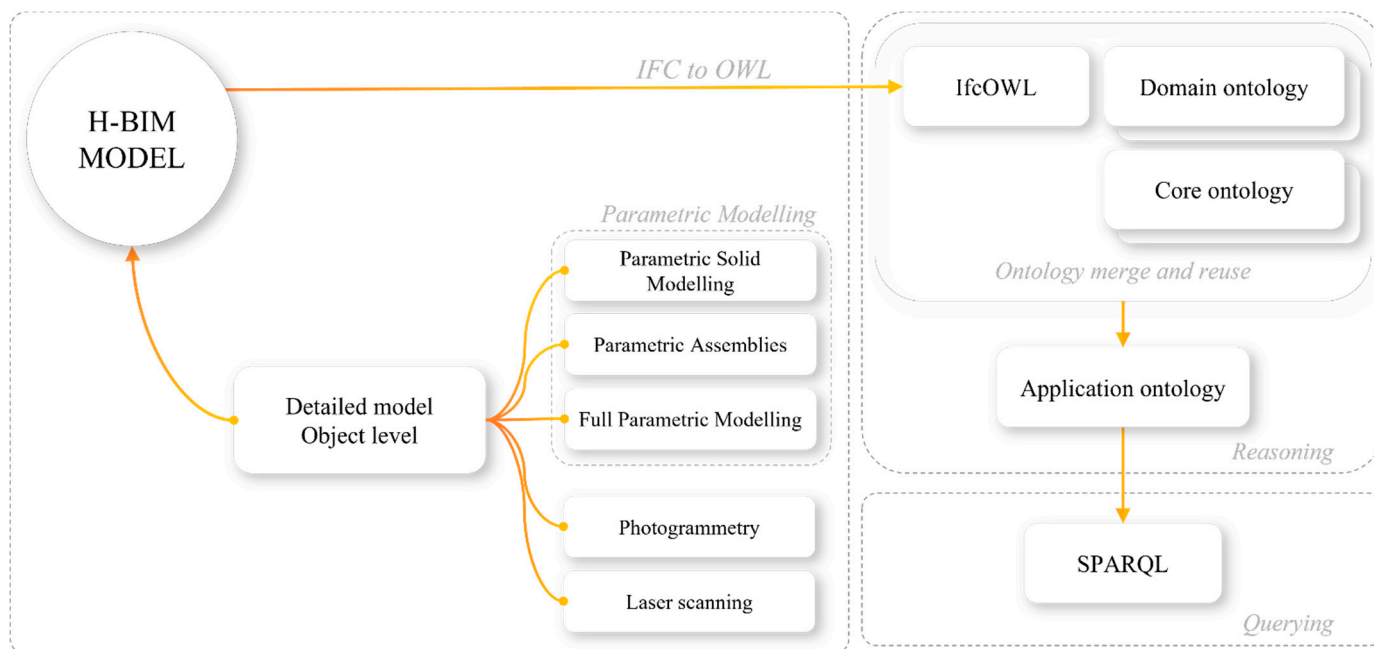


Figure 1. Concept of the H-BIM to semantic model workflow for heritage buildings.

3.1. H-BIM

In the H-BIM part, the workflow demonstrates how parametric modelling of reusable historical building components can be advantageous when integrated to create model objects. Parametric modelling refers to the creation of digital models, which can be further differentiated as parametric solid modelling (complex shapes defined by a few parameters), parametric assemblies (that automatically update when any of the parameters are changed),

or full parametric modelling (when parameters defining one shape are linked to parameters of another shape and the system automatically updates them) [40]. As mentioned before, it should be up to the participants involved in the heritage building project to decide which modelling technique to employ.

The collection of data for the detailed information model of the building (H-BIM) is usually the starting point. Data collection techniques range from the 3D point cloud data laser scanning, photogrammetry 3D scanning, manual measurements, CAD to BIM conversion, and improvement of previous inaccurate BIM models, associated with research on historical documentation and records concerning previous interventions on the building.

The development of a H-BIM project involves multidisciplinary teams, including BIM designers and therefore, the use of common data environments (i.e., BIM clouds) is key. They provide support when the model is being jointly developed (collaborative workflow) and assist in correcting modelling issues (e.g., wrong elements, inaccurate dimensions, overlapping elements, misplaced elements, and elements not properly identified) that can then be managed, assigned, and resolved.

Often different parts of heritage building models have different requirements regarding the level of information need and the level of parametrization. For example, when elements are created manually and are partially parametrically connected, a change of an object parameter in the model does not necessarily cause the adaptation of geometrically connected objects. This can lead to misaligned or disconnected objects (i.e., poor geometry definition, gaps in the model), which requires a systematic manual model correction. Because heritage buildings are usually “one-of-a-kind” buildings, with complex geometry and specific elements, parametric solid modelling, and parametric assemblies are of common use. Alternatively, our BIM workflow integrates the possible use of full parametric modelling for heritage building objects. The use of full parametric modelling is gaining attention for new buildings with repetitive model patterns due to better scalability and model control. For heritage buildings we propose the use of full parametric modelling when heritage artefacts of the same type (e.g., parts of heritage building, as doors and windows) that share common geometrical features (e.g., door clad with rectangular wooden panels) can be used as the instrument for duplication and adaptation to other buildings within the similar architectural context.

3.2. Semantic Modelling

The semantic part of the workflow is based on transforming BIM’s relational data structures (closed world assumption) to semantic data structures (open world assumption) contained in an ontology and best explained as knowledge graphs. Ontologies enhance the quality and relevance of the information about the heritage asset. In the process, an IfcOWL model is derived from the IFC model. In the semantic space the IfcOWL model can be extended with the reuse of general-purpose core ontologies (e.g., Person core ontology) as well as with the combination with ontologies specifically built for the heritage building domain (e.g., ECRM HBO). The process of combining the IfcOWL ontology with other ontologies (domain specific and core) can result in multiple linked ontologies or in a single merged ontology. Both solutions allow an improved knowledge modelling of the heritage asset. The ontology merge process integrates complementary ontologies into a single ontology as a union of conceptualizations from different namespaces. The resulting ontology contains conceptualizations as well as instances (individuals) and thus is a domain specific application ontology engineered for a specific use case or application focus. Individuals in the ontology represent common IFC values (e.g., enumerations, objects ids, material data), concrete geometrical object information (e.g., locations, dimensions) but also other heritage building specific information (e.g., intervention dates, actors involved, administrative data for heritage register, measurements, and classifications).

To improve its quality, the ontology can be evaluated. Simple evaluation includes check for inconsistencies (e.g., contradicting cardinality restrictions leads to unsatisfiability of class), individuals checking, and empty entities. IfcOWL ontologies are always coherent

with BIM domain knowledge since the IFC-to-OWL process is driven by the IFC schema of the IFC model. More complex evaluation includes different metrics like interoperability, aggregability, composability, etc. Testing of the ontology on fulfilling specific goals (e.g., information retrieval, querying). Querying mechanisms can be applied to retrieve information, using SPARQL queries. For example, if the project is focused on the management of maintenance operations, the user can query about the upcoming dates for interventions or about interventions on specific components of the building; if one participant is mainly interested in the buildings' windows the querying can be restricted to those elements; the leading conservator can query the identification of the person assigned to a specific intervention, etc.

4. Results

When applying the proposed workflow to an existing building, as previously mentioned, an initial effort to collect information about the heritage building, focus of the project, is needed.

Although recent capturing techniques are available, the BIM model presented in Figure 2 was prepared (in terms of the geometrical part) based on CAD 2D plans and on-site measurements, in a reverse engineering process. The model was built using the correct definitions and identification to all elements, following the IFC specification format.

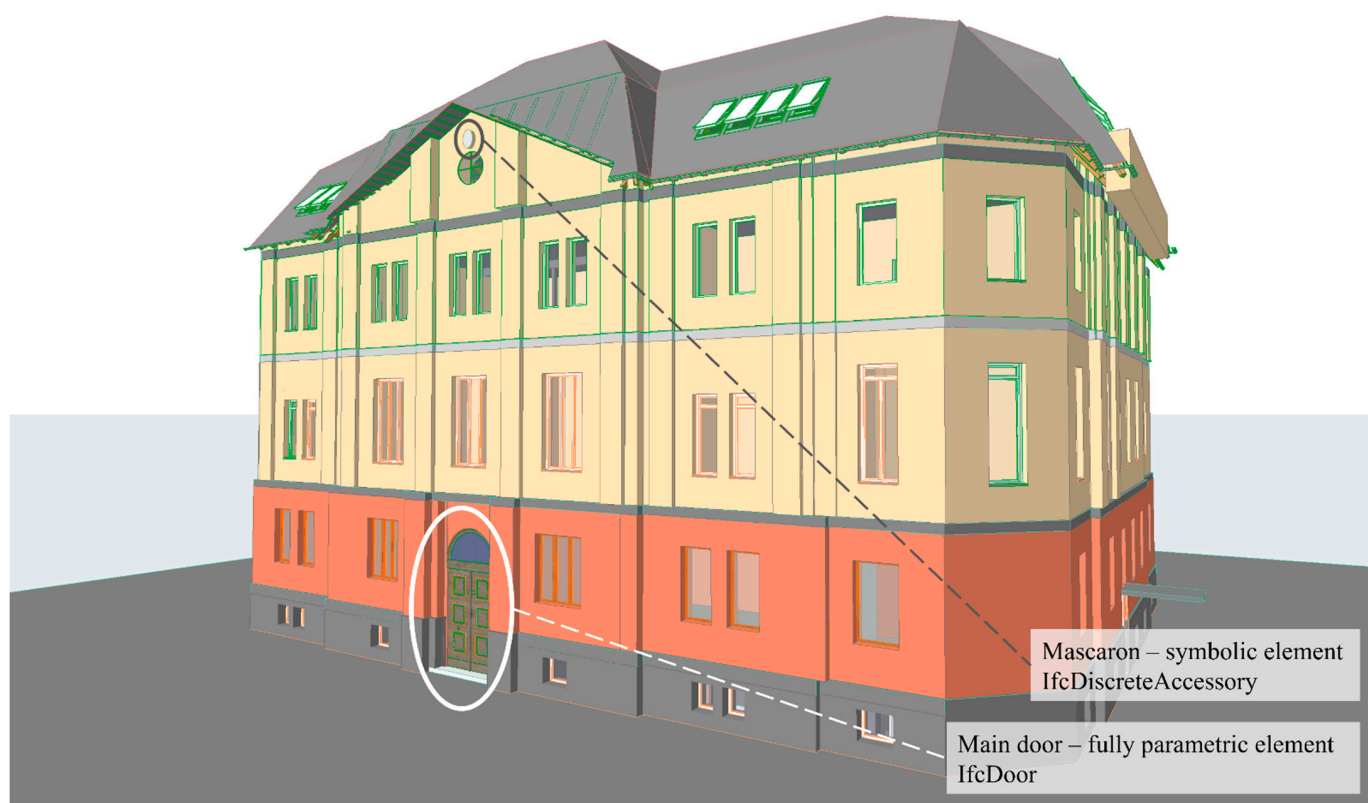


Figure 2. Overview of the H-BIM model of the faculty building with the integrated detailed main door element and the symbolic mascaron element.

To streamline the adoption of the proposed workflow, particular attention was given to two elements located in the main façade of the building: the main entrance door (IfcDoor) and a decorative façade element, mascaron (IfcDiscreteAccessory).

With visual programming language (VPL), software can now assist in the algorithmic design of elements, facilitating and enhancing the control of their overall geometry within a dynamic graphical interface. This allows the creation of custom parametric library objects, that can then be imported and connected to the BIM model within a fully parametric

environment. The main door of the building, which undoubtedly assists in the definition of the buildings' character and identity, was modelled as a fully parametric object.

Figure 3 presents the environment interface of the parametric design tool used, PARAM-O. In Figure 4, a close-up on the definition of the parameters used to model the interior panels of the entrance door is presented.

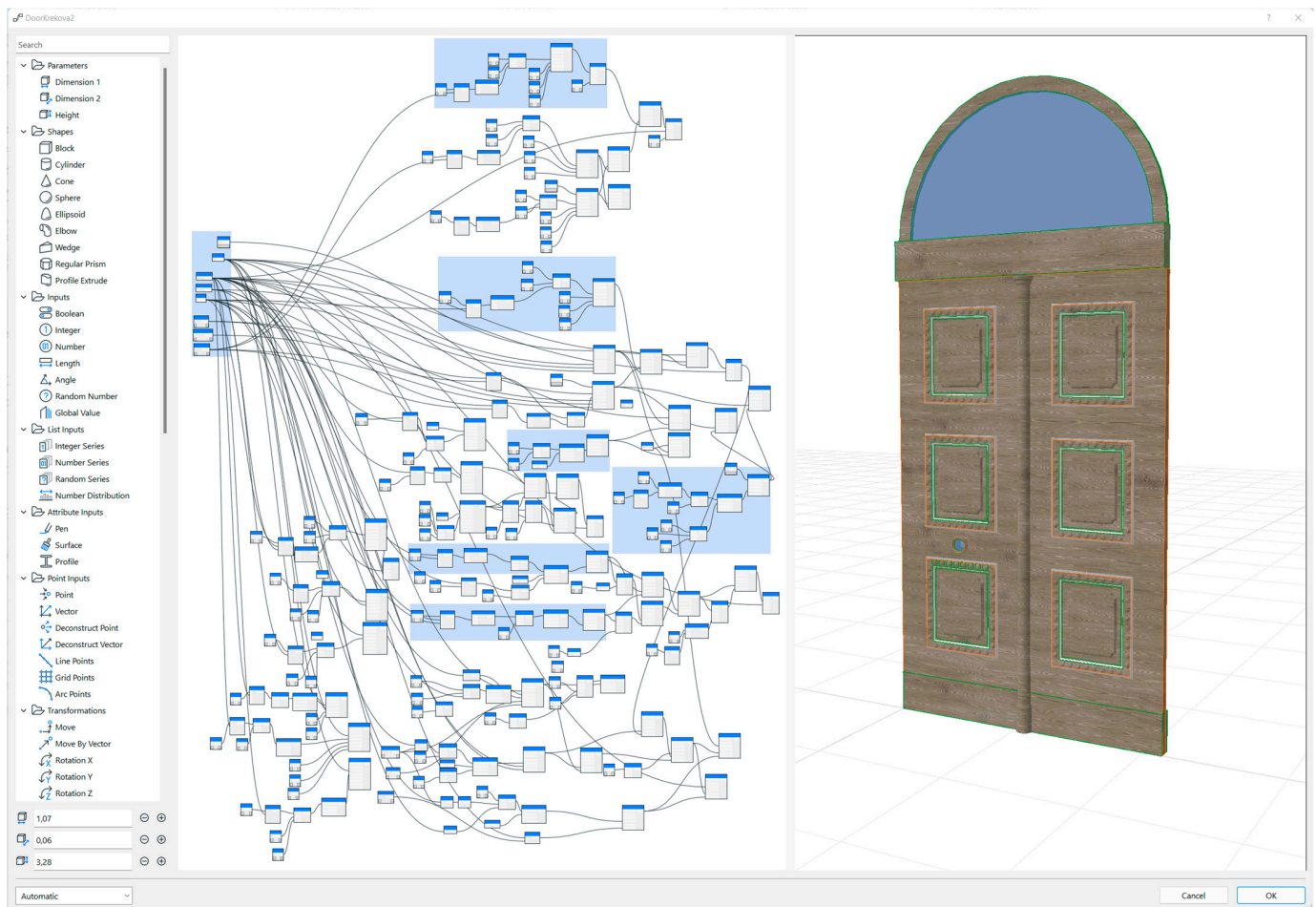


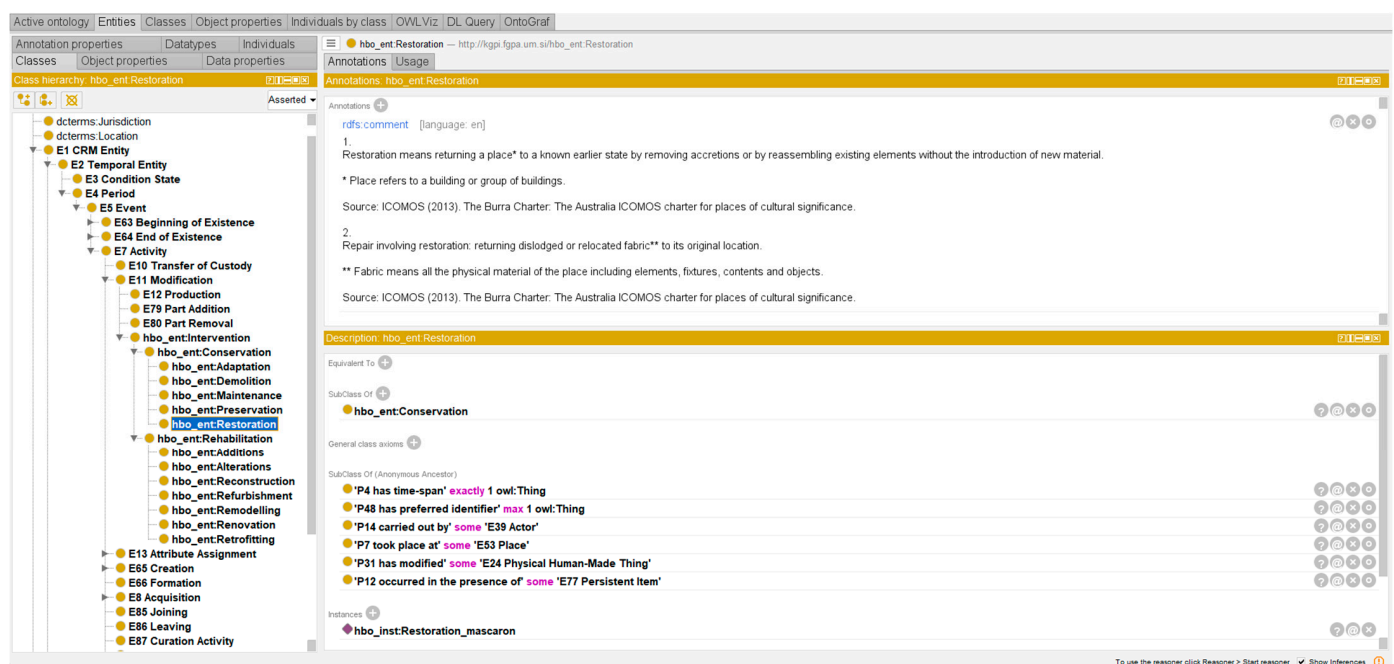
Figure 3. Algorithmic design for parametric model of the main entrance door.

After the finished model is ready, as a custom fully parametric object, it is then placed and connected to the corresponding elements of the building's model.

It is not always necessary that elements are modelled at such high detail level. The modelling requirements (both geometrical and semantical) should always be aligned with the objectives of the project. Therefore, we also present as an example the model of one façade decorative element, a mascarón, with a symbolic level of geometrical representation. The inclusion of this example serves to validate that the benefits from the connection with ontologies is not exclusive to highly detailed objects/models. It was also interesting to semantically model the planning of a laser scanning survey connected to that element. Some historical buildings are composed of elements as ornated moldings, statues, mascarons, that are complex or even impossible to model natively (in dedicated software). The creation of objects based on meshed elements, allowing accurate geometrical representations, obtained from laser scans are one possible solution to overcome this difficulty.

Table 2. New classes, subclasses, and instances of the ECRM HBO ontology.

Classes/Subclasses						
hbo_ent:Heritage_Building	hbo_ent:Intervention	hbo_ent:Conservation	hbo_ent:Adaptation hbo_ent:Demolition hbo_ent:Maintenance hbo_ent:Preservation hbo_ent:Restoration			
hbo_ent:Ornament	hbo_ent:Doors	hbo_ent:Rehabilitation	hbo_ent:Reconstruction hbo_ent:Renovation hbo_ent:Remodelling hbo_ent:Alteration hbo_ent:Addition hbo_ent:Addition hbo_ent:Refurbishment hbo_ent:Retrofitting			
Instances						
hbo_inst:MainDoor; hbo_inst:Mascaron; hbo_inst:Conservator-restorer; hbo_inst:Cleaning; hbo_inst:Crack_Repair; hbo_inst:Repointing; hbo_inst:Lubrication_of_hinges_and_ironmongery; hbo_inst:3Dscanning; hbo_inst:Terracotta; hbo_inst:Wood; hbo_inst:Photogrammetry.						

**Figure 5.** Restoration class as defined in ECRM HBO, screenshot of the Protégé Editor.

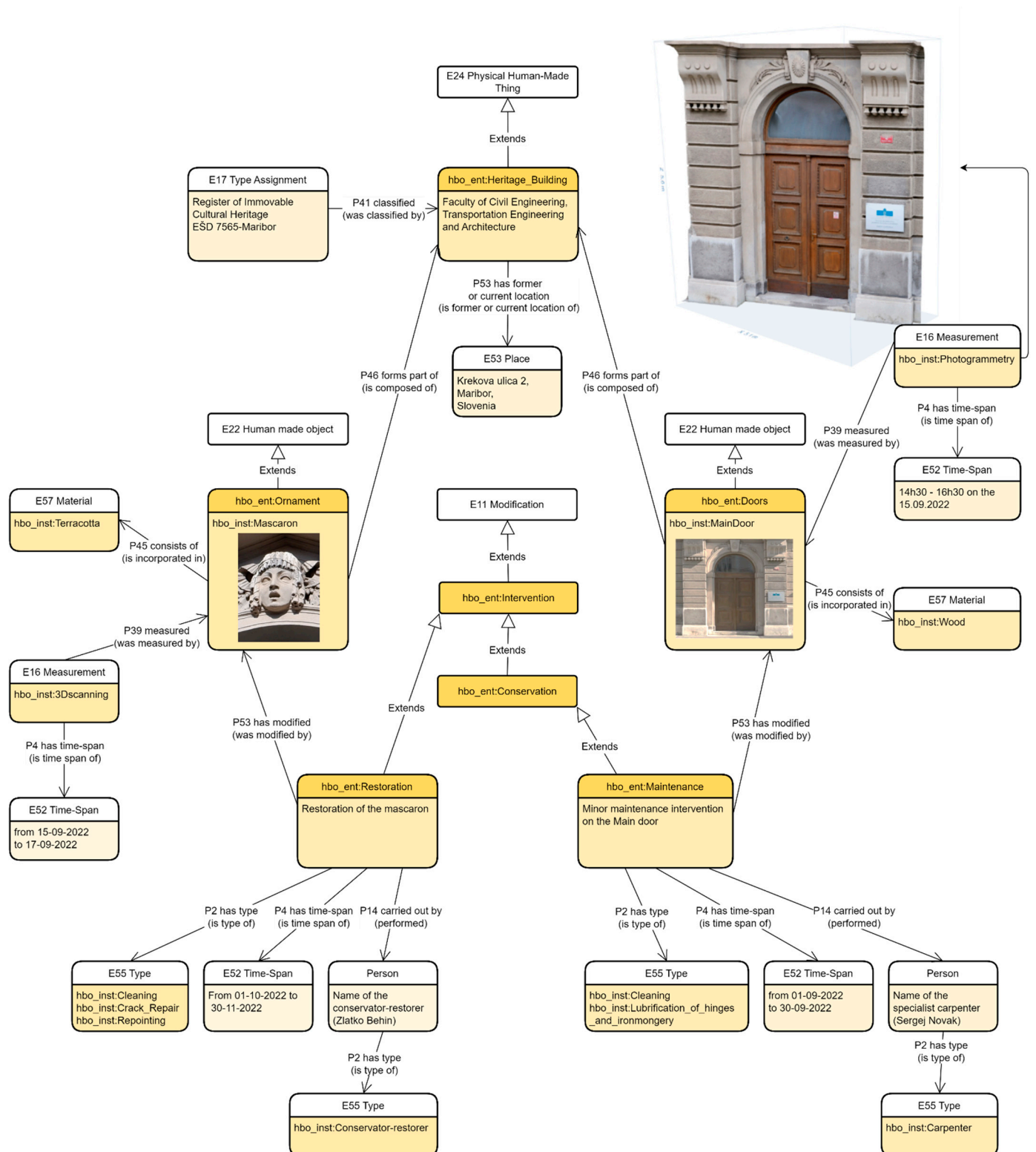


Figure 6. Example of the modelling of the restoration of a façade decorative element (mascaron) and of a minor maintenance intervention to the main door of the building.

The ontology contains 115,798 internal (base) resources and 72,465 external resources in axioms out of which there are 1400 concepts, 1880 object properties, 18 data properties, and 1964 usages of direct properties.

The resulting HBK2O ontology was assessed using an ontology evaluation framework OQuaRE, based on the SQuaRE standard for software quality evaluation that proposes 14 metrics, which was extended in previous research [5]. The ontology evaluation benchmarks applicability and reusability of the ontology by examining its structural quality characteristics calculated from explicit ontology document content. Results of the ontology evaluation are single value metrics aggregated in higher metrics that rank an ontology. Results of the evaluation are presented in Table 3. The evaluation consists of the eight main quality characteristics [41]: quality of the ontology structure, functional adequacy, transferability, reliability, compatibility, interoperability, maintainability, and operability.

Table 3. Evaluation results for the HBK2O.

Characteristics	Score
1. Structural	3.00
2. Functional adequacy	3.80
3. Transferability	2.25
4. Reliability	5.00
5. Compatibility	3.25
6. Interoperability	1.50
7. Maintainability	2.78
8. Operability	2.83
Total ontology quality	2.93

Each characteristic is mapped to the scale: 1—“Not Acceptable”, 2—“Not Acceptable, Improvement Required”, 3—“Minimally Acceptable”, 4—“Acceptable”, and 5—“Exceeds Requirements”. The total ontology quality (2.93) is calculated as an average of the quality characteristics.

The individual characteristics vary between 1.50 and 5.00.

The structural characteristic refers to quality factors such as: classes are strongly related (cohesion), the existence of multiple inheritance (tangledness), annotation richness (redundancy), and relationship richness (formal relations support).

The functional characteristic presents the degree of accomplishment of functional requirements, considering, for example: consistent search and query, knowledge acquisition, clustering and similarity, indexing and linking, classifying instances, guidance and decision trees, knowledge reuse, and inferencing.

The transferability characteristic presents the degree to which the ontology can be adapted for different specified environments (languages and expressivity levels). The reliability characteristic measures capability of an ontology to maintain its level of performance under stated conditions (recoverability and availability).

The compatibility characteristic measures the ability to which the ontology can be used in place of another specified ontology for the same purpose.

The interoperability characteristic is calculated from the number of external ontologies used not considering the standard namespaces (XSD, RDF, RDFS, OWL), the composability of the maintained ontology by exploiting the quality of the composition when external ontologies are used through the name-spacing mechanism and the aggregation size of the sets of the external ontologies in the maintained ontology (aggregability).

The maintainability characteristic presents the capability of ontologies to be modified for changes in namespaces, in requirements, or in functional specifications.

The operability characteristic presents effort needed for using an ontology (learnability). The evaluation assessment and the results are further analyzed in Section 5.

For the retrieval of information, the ontology can be queried using SPARQL. The following queries were executed, intended to demonstrate how information can be retrieved:

1. Who is responsible for the restoration of the mascaron?

```
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
prefix ecrm: <http://erlangen-crm.org/211015/>
prefix person: <http://www.w3.org/ns/person#>
```

```
SELECT ?intervention ?person
WHERE {
    #intervention of type restoration
    ?intervention rdf:type owl:NamedIndividual;
                  rdf:type <http://kgpi.fgpa.um.si/hbo_ent:Restoration>.

    # person
    ?person rdf:type owl:NamedIndividual.
    # intervention carried out by the person
    ?intervention ecrm:P14_carried_out_by ?person.
}
```

Results of the query:

```
?intervention = <http://kgpi.fgpa.um.si/hbo_inst:Restoration_mascaron>
?person = http://kgpi.fgpa.um.si/hbo_inst:Person_ZlatkoBehin
```

2. What is the height of the main door of the building?

```
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX ifc: <https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL#>
PREFIX inst: <http://kgpi.fgpa.um.si/ke4aeco/hbk2o/>
PREFIX express: <https://w3id.org/express#>
```

```
SELECT ?door ?doorHeight
WHERE {
    #criteria for main door
    ?x rdf:type owl:NamedIndividual;
       express:hasString "MainDoor".
    # door height
    ?y rdf:type owl:NamedIndividual;
       rdf:type ifc:IfcPositiveLengthMeasure;
       express:hasDouble ?doorHeight.
    # door
    ?door rdf:type owl:NamedIndividual;
          rdf:type ifc:IfcDoor;
          ifc:name_IfcRoot ?x;
          ifc:overallHeight_IfcDoor ?y.
}
```

Results of the query:

```
?door = inst:IfcDoor_4131
?doorHeight = "4650.0"^^xsd:double
```

Figure 7 presents the adaptation of the workflow diagram to our specific validation use case, and the involved steps.

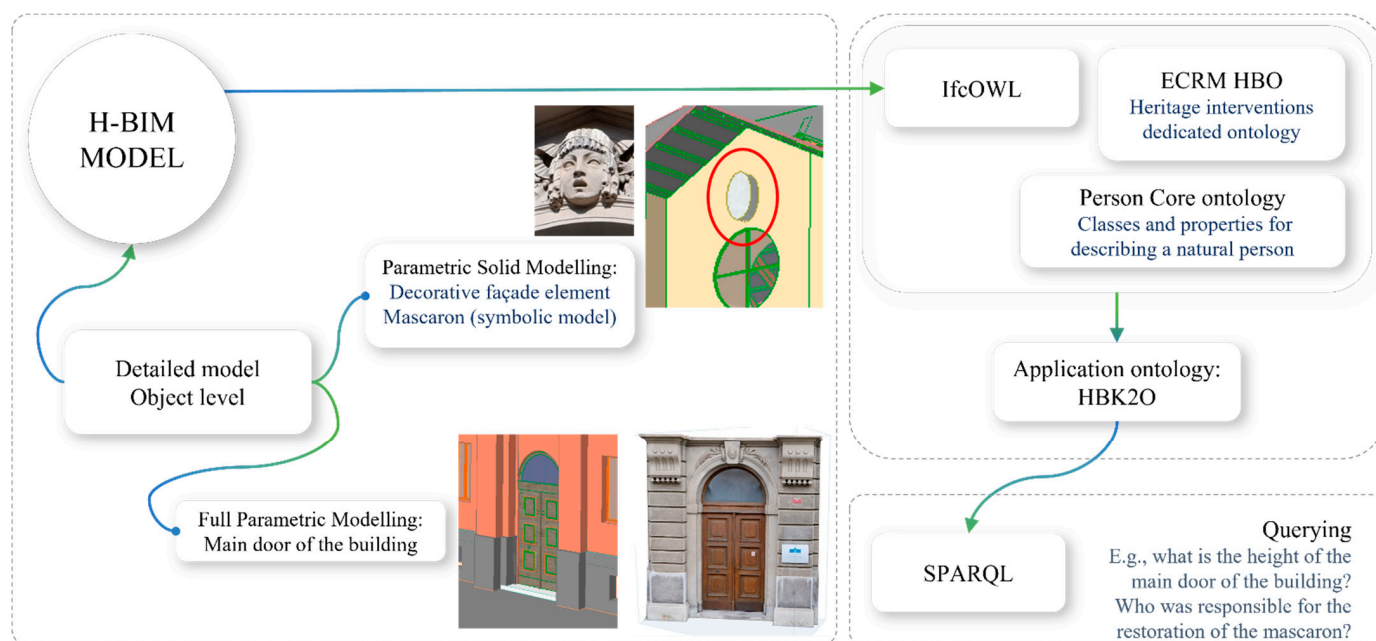


Figure 7. Use case workflow summary.

5. Discussion

The proposed workflow follows through what can be described as a sequence of operations to achieve the best possible representation of a heritage building and its custom elements. The connection between BIM and semantic technologies allows researchers, practitioners and specialists involved in the project to have more control on the data quality, relevance, and accuracy.

The growing interest in H-BIM justifies research in the field, particularly on the exploration of practical issues related to heritage buildings. In terms of the development of the H-BIM models, the heritage field does not diverge from the “original” BIM modelling workflows involved. However, it is a domain with very specific terminology, special construction elements (not so common in current architecture), subject to higher restriction in terms of interventions for their conservation, open to multidisciplinary teams involving fields not traditionally connected to construction. As with new construction projects, it is particularly important to always keep the objective of the project in mind, and adjust, optimize, and select the technologies that better suit its achievement.

When debating the methods applied to geometrically model the building and its elements, some considerations can be retrieved from the work presented in Section 3. With H-BIM, digital modelling involves mostly parametric modelling. The geometrical detail of H-BIM elements should always depend on the intended use of the model. For example, the studied mascaron decorative element was integrated into the model with a symbolic level of representation which did not affect the later demonstration of querying of the ontology. However, if our querying referred to precise geometrical details, the results would be poor as the element was not rigorously detailed. A contrasting case can be found when we analyze the door element. Developed as a fully parametric element, it can be considered a geometrical digital twin of the door of the building, and queries on its geometrical characteristics can be made.

During the preparation of the H-BIM model, when modelling and identifying elements using the IFC standard (e.g., IfcSlab, IfcColumn, IfcWindow, IfcDoor) we noticed that specific heritage elements are difficult to classify. For example, the IfcDiscreteAccessory entity (representation of different kinds of accessories included in or added to elements) was chosen to identify the mascaron. Extending the ECRM to include details on interventions for the protection of heritage buildings was one of the objectives, so as to integrate specific

classes and instances to better model semantically these often not well-defined events. Aware of the lack of specificity in that case, we used the semantic model to accurately identify the decorative element, creating `hbo_ent:Ornament` and `hbo_inst:Mascaron`. The use of semantic models (ontologies) expands, then, the possibilities in terms of associating domain specific concepts. Moreover, as a structured representation of knowledge, through knowledge graphs, users can get a fast visual representation of the connection between them. The most internationally relevant standards, charters, and guidelines in the heritage field served as the reference for the definitions included in the ECRM HBO.

The example presented in Figure 6 of planned interventions to the decorative façade element (mascaron) and to the main door of the building illustrated the capabilities of the extended ontology, structuring data, and enabling a reliable level of detail for the characterization of the restoration and maintenance interventions. Additionally, measurement surveys were modelled semantically. Two subclasses were defined for the class E16 Measurements to semantically model a photogrammetry scan (to the main door of the building) and planned laser scanning campaign (to the mascaron).

The HBK2O was the resulting application ontology from the merging of IfcOWL, the ECRM HBO and the Person Core Vocabulary ontology. One of the main advantages of the HBK2O is that when all information is integrated, the models can then be queried, in terms of the records connected to interventions on a specific element or even the entire building (e.g., when did the last intervention to the main door of the building occur, what was the person in charge of carrying out the work, is there any future planned maintenance planned, etc.). Other advantages were identified in the use of ontologies for heritage building related projects, as the organization of the domain knowledge (connected to the structure and categorization of concepts) easily retrieved, extended, reused, and improved. The possibility to create the conceptual representation of the knowledge included is also advantageous, as project participants can view the basic complete ontology structure or a specific representation. This is particularly useful when the interest is focused (e.g., administrative details on the classification register of the building, information on one specific type of intervention planned or completed). Although not explored in the paper, ontologies can include the translation of the concepts included to different languages. Working within this domain gave us also an insight on some disadvantages, as with the memory footprint (i.e., memory requirements can be high), and absence of different open-source software tools. It is a complex engineering domain that includes logic and reasoning and often presents difficulties when handling different namespaces.

The application ontology HBK2O was assessed using an ontology evaluation framework OQuaRE. The ontology evaluation presented an average value of the quality characteristics of 2.93. Significant are the low values of interoperability and transferability but as the HBK2O is a specific use case application ontology, this result requires explanation. These values are determined by the nature of the HBK2O application ontology creation workflow. The IFCOWL ontology creates the conceptualization of all the resources from the latest official IFC4 ADD2_TC1 schema which composes 68% of all the external resources in the final HBK2O after import of the ECRM HBO. The relevance of the interoperability ontology characteristics therefore has a different meaning for application ontologies when compared to domain and core ontologies. It is not expected that the HBK2O ontology will be used to describe another heritage building. On the contrary, the schema of the extended ECRM HBO presented in the paper can be extended and reused for similar projects.

Specific information retrieval is possible when querying mechanisms were applied to the HBK2O. The first query “Who is responsible for the restoration of the mascaron?” exemplified how the semantic information, initially defined in the ECRM HBO, could be retrieved. The second “What is the height of the main door of the building?” allowed us to retrieve geometrical information, initially defined in the H-BIM model. This step served as another validation for the usability of the HBK2O.

6. Conclusions and Future Developments

Semantic technologies, such as ontologies, enhance the quality of information on interventions in historical buildings. In the paper, we propose a workflow for the transformation of a H-BIM model to a semantic model.

The H-BIM part of the workflow focused on the methods for digitally modelling elements that are part of the building. Different modelling approaches were discussed. After the model was considered complete (including the identification of the elements according to the IFC standard) it was converted to IfcOWL, an OWL based ontology for the representation of construction data included in the H-BIM model. Additionally, the ontology was then merged with a domain ontology (ECRM HBO) and the Person Core Vocabulary ontology.

The use of semantic technologies paired with H-BIM enhances the management of specialized information about the assets. Conservation actions or other type of interventions can then be further detailed combining geometric, alphanumerical, documentation, and operational data, supported with reliable representations, naming, and definition of the involved concepts, classes, and relationships between them.

With the integration of BIM workflows into legislation (e.g., digital building permit) BIM is becoming de-facto standard for the AECOO industry. The demand will progressively make BIM mandatory. In Slovenia, it is now requested for all public investment projects, regardless of the project value. It is therefore important that research in semantics of BIM models continues to develop best practice workflows for the IFC to OWL transformation. This guarantees semantically consistent OWL models for buildings but also deals with problems related to large ontologies. Modularization of IFC schemas, which in the current conversion process are entirely and heavily populating resulting IfcOWL models, must be researched in the future. Another important aspect is the choice of standardized quality core ontologies for reuse, such as the Person Core Vocabulary ontology and the Time and Location ontology.

Reasoning and querying are powerful features often integrated in semantic tools (like Protégé) and important for validation, consistency, and compliance checks of IfcOWL models and thus indirectly. H-BIM models. General purpose software tools for ontologies often come with below-optimal performance for reasoning and querying of large ontologies. Therefore, the use of programming APIs for manipulating ontologies (like Owlready2 for Python) is often recommended.

The presented use case encourages the application of the workflow in the modelling of a large-scale conservation and rehabilitation project.

The connection between the semantic technologies and H-BIM, mainly when open standards such as the IFC are applied, calls for further connection to other open standards, such as the Information Delivery Manual (IDM) and Model View Definitions (MVD), as a desired future development of the presented study.

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