D2.2 - BIM Family ontologies for materials, components, HVAC equipment in renovation

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BIM-SPEED
Harmonised Building Information Speedway for Energy-Efficient Renovation

This research project has received funding from the European Union's Programme H2020-NMBP-EEB-2018 under Grant Agreement no 820553.

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Publishable executive summary

This report summarizes the results of Task 2.2 *BIM Family ontologies for materials, components, HVAC equipment in renovation projects*. In the context of new buildings, procedures, tools and workflows in the design, planning and execution stages are usually well established, in contrast, renovation projects are performed often by small-scaled participants with highly segmented processes. Renovation projects encounter diverse challenges such as capturing reliable information about the current building condition, and the lack of dedicated tools and clear data management structures. This scenario calls for the development of specialized workflows and tools for renovation. Dedicated tools for this field may support the small and medium-sized companies to enhance the performance of renovation management activities and reduce re-work over costs, errors, and delays in delivery times. This can be achieved by enabling better processes, which are essential to achieve the multiple sustainable goals set by the 2030 Agenda and other international and local agreements. Additionally, more clear knowledge models and data structures may also improve the conventional processes, tools and workflows to exploit the potential that comes with technologies such as Building Information Modelling (BIM).

This deliverable describes three ontological models covering knowledge from different fields of the planning and execution of deep renovation projects. The models comprise: 1) Reno-Inst Ontology: An ontology for installation of components in building renovation projects, 2) LCA-C Ontology: An ontology for LCA/LCC assessments in renovation projects, and 3) BEM-Reno Ontology: An ontology for Building Energy Models (BEM) development in renovation projects. The proposed ontologies were developed to define a common knowledge representation of the building renovation domain. The ontologies aim at mapping a complete and minimal set of information required to support diverse tasks involved in specific renovation workflows related to planning activities, LCA/C assessments, and the development of BEM for renovation. These ontological models can support the development of a shared understanding of the domains they represent and the development of future tools to automate and facilitate the collection, retrieval and inference of information, enhancing the performance of multiple building renovation activities. The final models implemented in Protégé are available at the DepositOnce TU Berlin repository[1].

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[1] http://dx.doi.org/10.14279/depositonce-10630.2

List of acronyms and abbreviations

AEC: Architecture, Engineering and Construction

BEM: Building Energy Model

BIM: Building Information Model

BOT: Building Topology Ontology

BPO: Building Product Ontology

DHW: Domestic Hot Water

EEB: Energy Efficient Building

EPD: Environmental Product Declaration

ETICS: External Thermal Insulation Composite System

HVAC: Heating Ventilation Air Conditioning

LCA: Life Cycle Analysis

LCC: Life Cycle Costing

MEP: Mechanical, Electrical, and Plumbing

OWL: Web Ontology Language

QUDT: Quantities, Units, Dimensions and Data Types Ontologies

RDF: Resource Description Framework

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1. Introduction

Buildings account for 40% of the EU's energy consumption, 36% of its CO_2 emissions and 55% of its electricity consumption (Artola et al. 2016), therefore they play an important role in implementing energy efficiency objectives at the urban level. The rate at which new buildings either replace the old stock or expand the total stock is about 1% a year in the EU. This implies that the largest opportunity to make this sector more sustainable comes from the renovation of existing buildings. Nevertheless, the current renovation rate of existing buildings is low, even as renovation accounts for 57% of all construction activity, only about 1-2% of the building stock is renovated each year (Artola et al. 2016). Renovation activities currently taking place include mainly the replacement of windows, heating, cooling, lighting systems or roof insulation (Saheb 2016).

Diverse tools for design and project management are usually developed for new construction and later adapted or modified to support renovation projects, or at least attempt to do so. This might be due to the lack of structured knowledge of the specific needs in the field of building renovation. Renovation projects deal with specific challenges that demand a better understanding of their associated processes and call for specialized tools to address them. These challenges are often related to the uncertainty of as-built conditions, the presence of occupants during the diverse stages of the project, limitations on the design and assessment of renovation alternatives due to restrictions imposed by the current status of the building, local regulations, technological compatibility, and other aspects. Therefore, diverse processes in the building renovation field should be studied more in detail to identify specialized knowledge, gaps, and opportunities to improve them, especially by developing new tools dedicated to renovation projects, the stakeholders involved and their needs.

In general, the lack of a shared understanding can lead to difficulties in identifying requirements from a system, an approach to solving this problem is to develop formalized knowledge representations (Uschold and Gruninger 1996). A data model as a set of symbols and text that describe some information landscape. The data model is a wayfinding tool that helps developers and analysts better understand a set of attributes and business rules (Kent 2012). Particularly, an ontology is concerned with the knowledge of engineers about physical and abstract objects, their relations, and events influencing them. Ontological representation allows for a commitment with respect to the model of the specific domain that is required as the basis for any computational method (Hartmann and Trappey 2020). An ontology is a representation which provides an explicit specification of concepts, terminologies and relationships that are known in a particular domain (Gruber 1995). It includes a set of concepts/classes, relations/properties, instances/individuals, and axioms. For instance, for a database or knowledge base, ontology determines the categories of things that exist or may exist in an application domain. Those categories represent the ontological commitments (Sowa 2000). An ontology can map and represent knowledge from a specific domain, it can also support tasks related to information collection, processing, reuse, and retrieval. Depending on the complexity and rigor required, these elements can be described based on different approaches including RDF and RDF Schemas, Simple Knowledge Organization System (SKOS), Web Ontology Language (OWL), and among others.

Many industries have developed ontologies for efficient knowledge management. In the construction industry, ontologies are introduced and studied widely because building projects involve many collaborative works from multiple professionals, stakeholders and phases (Zhong et al. 2019). The use of semantic web technologies in the architecture, engineering and construction (AEC) industries has been focused on supporting: a) interoperability, b) linking information across domains such as BIM-GIS, manufacturer data-building data, and building performance analysis; and c) logical inference to check model consistency and completeness, compliance, construction safety, and perform cost estimation and home automation (Pauwels et al. 2017).

Well-known and established ontologies on the context of building-related knowledge include EEPSA[2], SAREF4BLDG[3], ifcOWL[4], and BIMSO/BIMDO[5] ontologies. Other proposed models have focused on domains related to the building environment (Zhong et al. 2018), cost estimation (Lee et al. 2014), and certification labels (Kamsu-Foguem et al. 2019). Most of these efforts are developed around the construction process of new buildings or the operational phase of existing buildings, while building renovation seems to be a neglected area in the AEC ontology field. Nevertheless, ontologies may also contribute to illustrate requirements and address challenges of building renovation projects. More clear and structured knowledge and data models may pave the way to adequate conventional building renovation processes to facilitate the implementation and exploitation of technologies such as BIM modelling. According to Lenat and Feigenbaum (1991), a great deal of real-world knowledge is a prerequisite for an intelligent program to perform complex analytical tasks accurately, therefore, a representation with machine-readable data for building renovation domains may contribute to developing tools to support and make easier information collection, processing, reuse and retrieval in the context of renovation projects. Therefore, the purpose of Task 2.2 is to develop a set of ontological models to support different tasks of renovation projects.

This report presents three ontologies focused on the installation of renovation elements, LCA/LCC assessments, and Building Energy Model (BEM) development for renovation. The installation procedures for energy efficiency elements in new buildings are well established, nevertheless, renovation projects address specific limitations and constraints that have not been properly studied and represented. Hence, the first ontology seeks to map this unexplored domain to identify particularities of the installation of renovation elements and support stakeholders during the planning and construction coordination phases. On the other hand, LCA and LCC assessments are increasingly becoming essential in the evaluation of buildings performance. The second ontological model maps LCA/LCC information in the context of building renovation project, this representation may enable and facilitate the implementation of these approaches in this field, allowing stakeholders to evaluate renovation scenarios according to comprehensive and up-to-date assessment strategies in the building industry. Moreover, the development of this ontology allows

[2] https://iesnaola.github.io/eepsa/EEPSA/index-en.html
[3] https://saref.etsi.org/saref4bldg/v1.1.2/
[4] https://technical.buildingsmart.org/standards/ifc/ifc-formats/ifcowl/
[5] https://core.ac.uk/download/pdf/213087401.pdf

identifying relevant product and building information that will support the development of BIM-SPEED tasks such as T2.3 *BIM Object Library and Product LCA* and T7.3 *BIM-based Lifecycle Cost and Asset Management*. Finally, some approaches to enhance the development of BEM models have been developed as presented in BIM-SPEED deliverable *D3.1 Analysis of BIM-to-BEM critical parameters and recommendations to solve the current bottlenecks*, however, existing procedures still require a high intervention from experts and manual activities. An ontology capturing BEM model information may support some of the manual tasks involved in BEM models development procedures and data collection, especially in the context of renovation projects where information comes from diverse sources in different formats and structures. Therefore, the third proposed ontology covers the domain of BEM development for renovation. The proposed models can be summarized as follows:

- Reno-Inst Ontology: An ontology for installation of components in building renovation projects
- LCA-C Ontology: An ontology for LCA/LCC assessments in renovation projects
- BEM-Reno Ontology: An ontology for BEM development in renovation projects

It is important to notice that the proposed ontological models are intended to map and represent the knowledge from specific areas of the building renovation domain which seems to be an unexplored are in the semantic technologies field. The presented models are not a final implementation or final computational application, they are a potential starting point to initiate the dialogue amongst experts in the industry to encourage the development of more dedicated models and tools for building renovation projects. As mentioned previously, formalized knowledge representations can address the lack of a shared understanding and difficulties in identifying requirements from a system. Therefore, our main goal was to identify relevant areas from the building renovation domain, explore and study their knowledge, and map and represent that knowledge. Since ontologies help humans and computers understand and fully utilize domain knowledge (Hartmann and Trappey 2020), the proposed ontologies can be the starting point to develop dedicated computational tools for renovation projects to support and enhance different processes. They can also trigger the development of semantic and knowledge management applications such as information retrieval, question answering, pattern identification, and knowledge reuse, which have been already explored in other areas of the AEC industry.

1.1 Interaction with other work packages and tasks

Figure 1 represents how the proposed ontologies integrate with other BIM-SPEED work packages and tasks. In general mapping the proposed domains can support the capturing data activities performed in work package 1 since the ontologies represent a clear structure of relevant data required for different purposes during the renovation, these representations facilitate to identify which information should be collected during initial stages of the renovation project. The LCA-C ontology is closely related to task 7.3 – *BIM-based Lifecycle Cost and Asset Management*, the concepts mapped in the ontology are a starting point for the task to define LCC information requirements from products and buildings. The challenges and bottlenecks identified in D3.1 – *Analysis of BIM-to-BEM critical parameters and recommendations to solve the current bottlenecks* motivated the development of the BEM-Reno ontology and enable the identification of some of the main concepts included in it. Finally, the concepts mapped by the ontologies represent valuable input for tasks 2.3 – *BIM Object Library and Product LCA* and 2.4 – *As-built BIM Passport of existing building stock*. The former aim at creating a BIM library of the most common building materials and components, which is highly required for planning the renovation of existing buildings. The latter intends to develop an As-Built BIM passport of existing residential buildings, to ensure that owner companies can collect and evaluate the completeness of all necessary data properly.

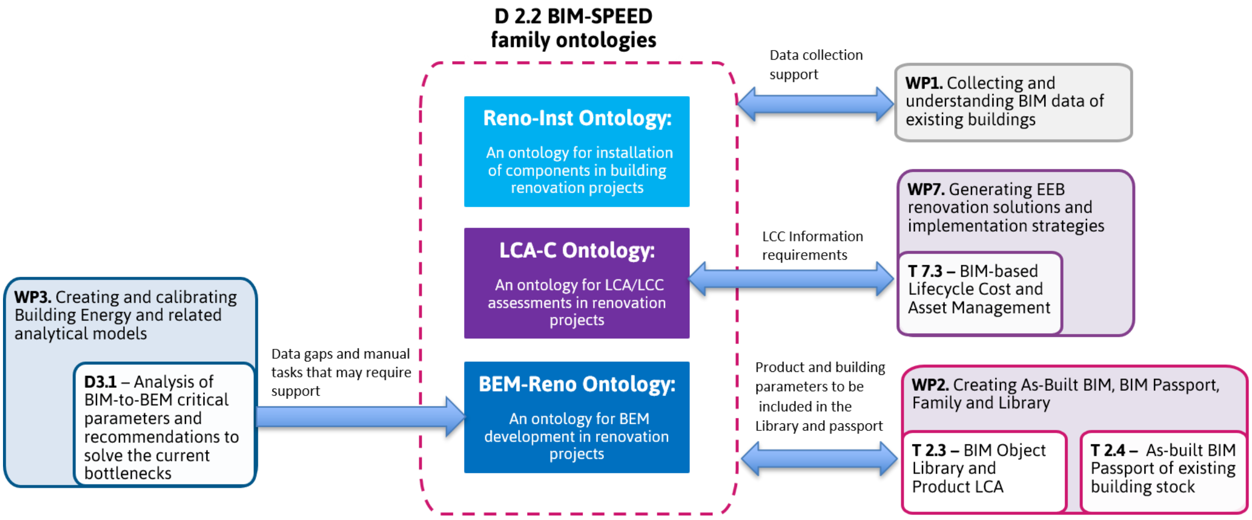

Figure 1. D2.2 integration with other BIM-SPEED tasks

1.2 Outline of task and deliverable 2.2.

The workflow of task 2.2 followed the steps presented in Figure 2. This document is structured as follows: Section 2 presents the methodology that was implemented to develop the three proposed ontological models. Sections 3, 4, and 5 introduce the development of the ontologies and the final models; each of the sections includes the motivation to develop the model and the current state of the art of the three specific domains: installation of renovation elements, LCA/LCC assessments, and BEM development for renovation. Moreover, a verification section is included for each of the models. Section 6 presents the relation of the proposed models with existing ontological resources. Finally, Section 7 summarizes the conclusions. In this report, *renovation* will be used as a general term comprising building improvements in the form of rebuilding, refurbishing or retrofitting.

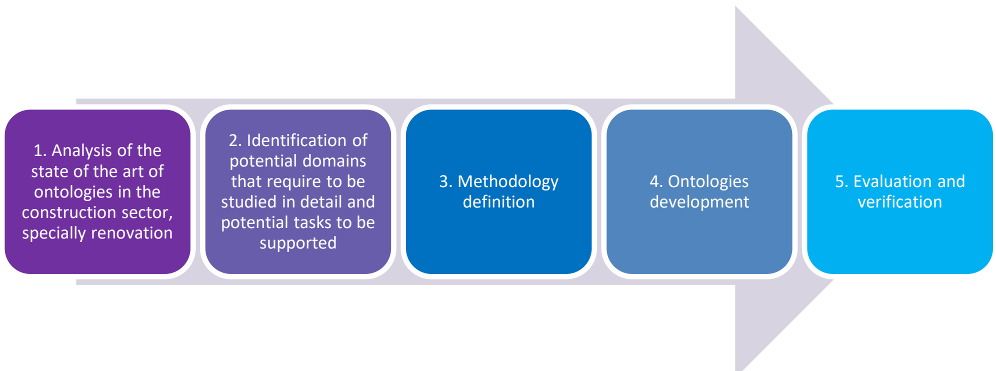

Figure 2. D2.2 workflow

2. Ontology development methodology

This section presents the methodology that was followed to develop the three proposed ontologies, modelling the knowledge from the domains of installation of renovation elements, LCA/LCC assessments, and BEM development for renovation. The methodology presented in Figure 3 is based on the guidelines presented in (Noy and Mcguinness 2001) and the Methontology approach (Fernández-López et al. 1997). These methodologies enable documenting the motivation for the development of the ontologies, their use and purpose in natural language.

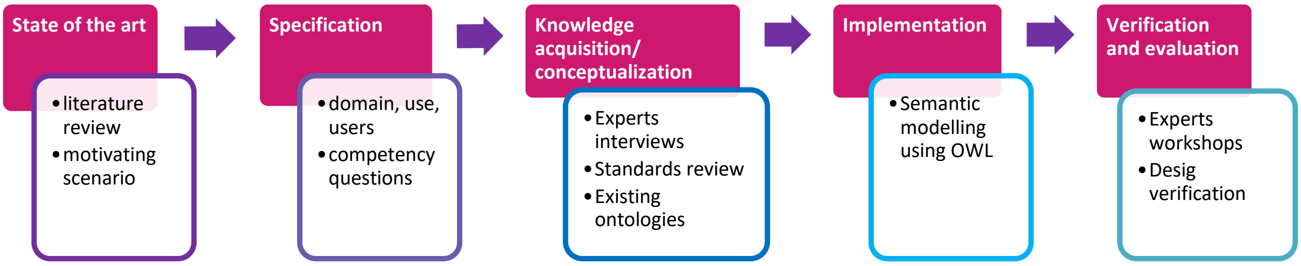

Figure 3. Methodology for ontologies development

The initial review of the state of the art was also informed by BIM-SPEED deliverables such as D2.1 *Method and Online Tool for Defining the Feasibility and Scope of BIM Implementation for Renovation Projects* (BIMSPEED 2019a), D1.1: *Methods for architectural, structural, thermal 3D data acquisition of existing buildings*, and D4.1 *Baseline and Use Cases for BIM-based renovation projects and KPIs for EEB renovation* (BIMSPEED 2019c). The three identified domains covered by the proposed ontologies and the motivation to develop them are related to some of the Use cases presented in these deliverables.

In the ontology specification stage, for each of the ontologies, we answer the following questions: what is the purpose? What is the scope? Who are the intended users? And what is the intended use of the ontology? To guide the identification of relevant terms, a set of competency questions is presented for each ontology. The capture of knowledge and conceptualization stage relies on different sources depending on the domain. These include catalogues from manufacturers, experts' interviews, standards, existing ontologies, related scientific literature, and others.

Once the main concepts for each domain are identified, it is necessary to study how these diverse concepts can be gathered in a knowledge network including different classes, relationships, and properties. Classes provide an abstraction mechanism for grouping individuals with similar characteristics, while properties can link individuals to individuals or individuals to data values to represent relationship between them. The ontologies are implemented using OWL/RDF in the Protégé environment (Musen 2015). The models are presented to experts in a series of workshops to validate the proposed ontological models, identify potential adjustments, and evaluate whether each model is coherent with its specific domain. The models are adjusted according to the experts' feedback. The final ontologies are checked thoroughly to verify the concepts description, their hierarchy, object properties, data properties, and the relations between them. As part of the verification process, the final models implemented using OWL/RDF in Protégé are reviewed extensively, the hierarchy is revisited and the relations of each class and sub-class are checked. The following list of common errors made during the ontological development process is used as a guideline to check the models:

- A class defined as a sub-class and super-class at the same time
- An excessive use of the isA property (ontological structure with a merely classificatory approach)
- Incomplete existing classes
- Non-disjoint classes
- Lack of exhaustivity
- Concepts or terms represented multiple times
- Lack of specification and limitation of the properties

The proposed methodology was implemented for each ontology. The following sections present individually the results for each model.

3. Reno-Inst ontology

3.1 Motivation and current state of the art

While installation and commissioning procedures for energy efficiency elements in new buildings may be well established, renovation projects address specific challenges that call for specialized supporting tools and procedures. A review of existing literature demonstrates that renovation projects face different challenges, especially during the construction stage and the installation of new elements, when multiple limitations and constraints appear. These particularities are mainly related to existing conditions of the building, the presence of occupants, and space limitations. One of the major renovation constraints is the uncertainty of unforeseen and varying conditions related to unknowns in pre-existing conditions, which can impact the performance of construction activities (Singh et al. 2014). Renovation projects encounter deteriorated existing conditions of materials and structural elements and additional decommissioning activities of previous elements, which could affect construction and installation activities. Moreover, in residential buildings, the construction process is performed, in most of the cases, while the building is occupied. The presence of occupants may modify conventional practices, in these cases, the execution of renovation activities should consider potential impacts on occupants and implement measures to mitigate them. For instance, approaches for envelope refurbishment need scaffolding on the outer facade for very long periods of time (12 to 24 months), requiring occupants to keep windows locked and introduce safety issues (Salvalai et al. 2017).

Ward et al. (2017) analyse the challenges to maintain a balance between building operations and completing a renovation project. Changes in the conventional construction practices comprise including the occupants' schedule in the activity planning, changes on the definition of egress pathways and other routes in the construction site, as well as adjustments of the material storage and waste management plans. In addition, special measures should be implemented to guarantee occupants' safety and reduce pollution such as noise, dust, and debris production. A representation of these and other particular conditions for the installation of different elements may support stakeholders to plan construction activities in the context of building renovation.

According to Singh et al. (2014), by studying the constraints of renovation projects, it is possible to better plan for these constraints and to minimize their impacts on construction activities and overall performance of the project. The authors identify a set of critical activities that may have an impact on the final performance of renovation projects:

- Preparation of plans and specifications,
- site investigation by contractor,
- preparation of site logistics plan,
- mobilization and demobilization,
- temporary construction,
- selective demolition,
- material and equipment procurement,
- demolition waste management,
- mechanical, electrical, and plumbing (MEP) rough-ins.

There are some previous ontology models that have focused on building construction process. Bilal et al. (2017) propose a building materials database based on an ontology which captures semantically diverse data of building materials to establish the core of a building waste analysis tool. Niknam and Karshenas (2017) present a shared ontology approach for semantic representation of building information, which is used to integrate information from different sources such as design, cost estimation and scheduling concepts. Díaz et al. (2013) introduce an ontology that describes the structure of the building, the distribution and connectivity of its systems, objects, and spaces, the functionality and characteristics of the energy-consuming devices, and energy efficiency metrics corresponding to the building and its components. On the other hand, Zhong et al. (2015) present an ontological approach to support the definition and verification process of a construction plan. The authors model the construction plan domain including tasks, methods, resources, and constraints and present a case focused on a deep foundation pit excavation. Nevertheless, the installation of renovation elements seems to be an unexplored area in the field of ontological representations. To the best of our knowledge, there is not a common representation or understanding of the particularities and critical aspects of the installation procedure of different elements in the renovation of residential buildings.

An ontology covering the domain of the installation of components in renovation projects may contribute to developing a shared understanding of this domain, supporting stakeholders during the activity planning and construction processes. Common renovation activities are mainly related to the replacement of windows, envelop insulation, and HVAC systems. Therefore, the Renovation products Installation (Reno-Inst) ontology focuses on the installation of windows, external thermal insulation composite systems-ETICS panels, and radiators in the renovation of residential buildings, considering different requirements and constraints. The structure of the ontology is designed to facilitate the integration of additional renovation elements. Structuring a representation of the installation procedure and constraints for the three mentioned elements can facilitate the activity planning and material, tools, and workforce estimation process. The purpose of the Reno-Inst ontology is to support stakeholders such as project managers and site-directors during the planning and construction coordination phases, in tasks such as identifying the activities with the greatest number of constraints, defining particular requirements to guarantee the occupants' safety during the performance of a specific task, and checking activities coordination, materials and tools.

3.2 Reno-Inst Ontology specification

The goal of the specification phase is to produce a general description of the ontology comprising the minimum information regarding the purpose, use, users, and domain covered by the model (Fernández-López et al. 1997). This section presents the specification of the Reno-Inst ontology using natural language and a set of competency questions.

- **What is the purpose?** The Reno-Inst ontology was developed to represent concepts related to the installation of renovation elements to support planning tasks and the execution of residential building renovation projects.
- **What is the scope?** The ontology will cover concepts and relations regarding the installation of windows, ETICS panels, and radiators, which are common renovation elements. The ontology includes information on physical features, general installation procedures, constraints that should be considered, and additional elements such as workforce, time, and tools requirements.
- **Who are the intended end-users?** The intended end-users are project managers, site-directors and other stakeholders which may be involved in the planning and scheduling of construction activities in residential building renovation projects.
- **What is the intended use?** The intended use of the ontology is to facilitate reasoning over the installation information for different purposes. The set of competency questions presented in Table 1 was developed to identify some of the concepts that users may be interested in. For instance, a user may list the tools and materials required to install a window. This information can be used to schedule the procurement of specific supplies. A user may also verify whether a specific construction task can be performed in the presence of occupants. This kind of information can help the stakeholders to identify which installation activities require special measures and coordinate them accordingly. Hence, the ontology will support the end-users to plan the installation activities of renovation elements considering time schedules, required tools, materials and workforce, and constraints related to the existing conditions in the building and occupants.

Table 1. Competency questions and answer examples for the Reno-Inst Ontology

Competency questions	Example answers
What are the *tools* required to install an ETICS panel?	Drill, cutting tool, mixing and delivery machine, scaffolding

What *regulation* should be considered when installing ETICS panels?	ETAG 004, EN 13162, EN 13163
What *activity* should be finished before driving rain-proof connection of a window?	To Install the air-tight joint closure
What kind of *pollution* should be controlled when *anchoring* an ETICS panel?	Noise, dust, and vibration
What is the material of the wall where a specific radiator will be installed?	Clay brick
Which activities require a *high* level of *safety* to avoid potential impacts on the occupants?	Lifting of a window from indoor, materials transportation through the staircase

As presented in Figure 4, the proposed ontological model can leverage information from different sources such as general documents, communication plans, building operational schedules, etc. When as-built and the renovation design information are in the form of BIM models, related data can be extracted easily to instantiate the corresponding classes from the ontology.

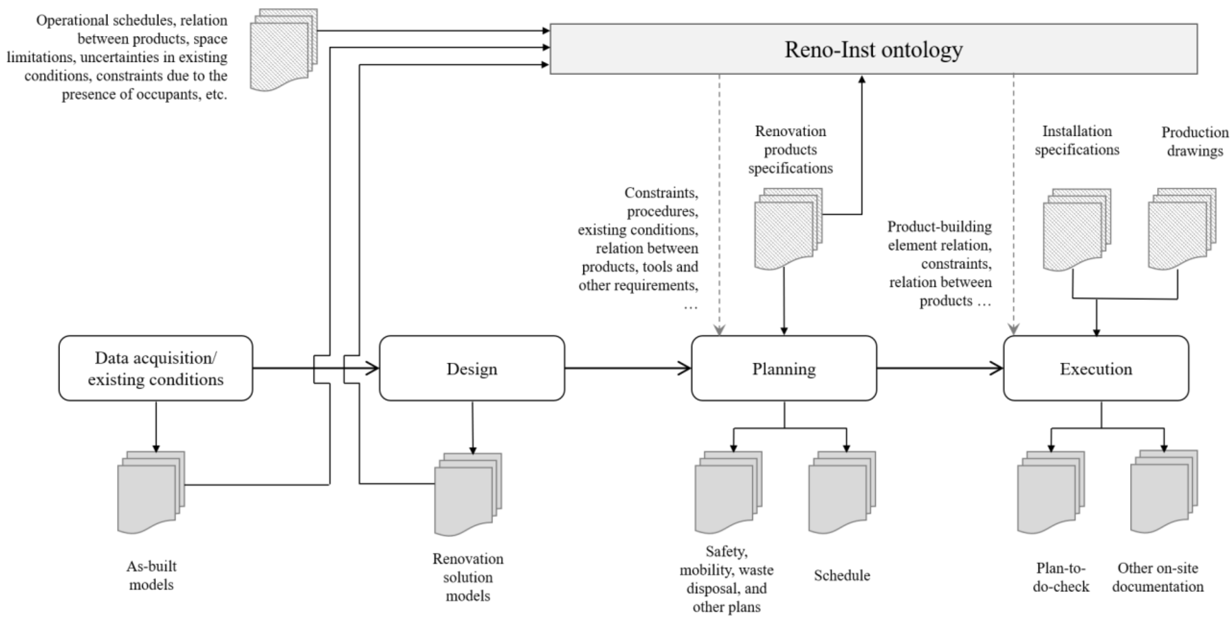

Figure 4. Potential use of the proposed Reno-Inst ontology

While planning and executing renovation activities, stakeholders can retrieve relevant information in a structured way. For instance, a user can list the tools and materials required to install a window. This information can be used to schedule the procurement of specific supplies. A user can also verify whether a specific construction task can be performed in the presence of occupants. Such information can help the stakeholders to identify which installation activities require special measures to coordinate them accordingly. Other information includes constraints related to the operational schedule of the building, space limitations, and the state of existing building elements. This information is relevant to establish process outputs such as the schedule of renovation activities, safety, mobility, waste disposal, other plans, and additional documents.

3.3 Knowledge Capture and Conceptualization

The knowledge acquisition includes identifying the relevant concepts in the ontology, developing a class hierarchy, and establishing class properties. The main goal is to identify what is the information required for the installation of each renovation element and how these diverse concepts can be gathered in a knowledge network including different classes, relationships, and properties. The specification and competency questions presented in the previous section are used to guide the identification of relevant terms. These terms focus on physical features of the component and the building element where it will be installed, tools and external requirements to complete the installation, and other aspects. The capture of knowledge relies on literature review, catalogues from manufacturers, guidelines from regional associations, as well as input from experts on the subject as summarized in Table 2. The input from experts was collected through a workshop and semi-structured interviews. The experts involved in this task comprise two architects, a BIM coordinator, and an R&D director from four construction companies, members of the BIM-SPEED consortium. They are responsible for four of the BIM-SPEED demonstration projects, including the Gdynia, Warsaw I and II cases, in Poland and Victoria-Gasteiz, in Spain. Special attention was given to physical features of the renovation element and the building interface where it will be installed, and constraints imposed by the presence of occupants and other aspects.

Table 2. Sources for the Reno-Inst ontology knowledge

Main Concepts	Terms Examples	Source
Renovation elements	Functional component, interface component, material	Darup et al. (2015), ift (2016), Joint Research Centre (2012)
Installation procedure	Main installation activity, tools, construction material, activity description	EAE (2011), ift (2016), and experts' input
Existing conditions and Constraints	Building interface, opening, pollution constraint, activities coordination	Singh et al. (2014), Ward et al. (2017) and experts' input

3.4 Reno-Inst Ontology Description

3.4.1 Reno-Inst Ontology Overview

Reno-Inst covers the installation of windows, ETICS panels, and radiators in the context of renovation projects. These three elements have diverse concepts associated with them and different requirements regarding their installation. Developing an ontology to represent each of these procedures separately could derive in a complex, large and probably unpractical approach. In order to address this challenge, the main classes of Reno-Inst comprise the general concepts which are common for the installation of diverse renovation elements. As shown in Figure 5[6], each *RenovationElement* has *Component*, *Documentation* and *InstallationActivity*, and is linked to a *BuildingInterface*. The *InstallationActivity* of each renovation element requires *WorkforceAndTools* and *MaterialsAndResources* and has *Constraint* regarding existing conditions, coordination, and safety. Moreover, the *BuildingInterface* where a *RenovationElement* will be installed is

[6] The outline colors are differentiated to facilitate the interpretation process, they do not have a specific meaning in the figure. For all the figures representing sections of the proposed ontological models, a similar approach with similar colors was implemented.

located at a *BuildingElement* and has *InterfaceState* to represent the current state of the interface. *Component*, *BuildingInterface*, and *BuildingElement* are described by *Attribute*. The entire hierarchy and list of properties extracted from Protégé describing the complete ontology are presented in Appendix A. The following sections describe in detail each of the concepts, the reasoning behind the proposed structure, sub-classes, and relations between them.

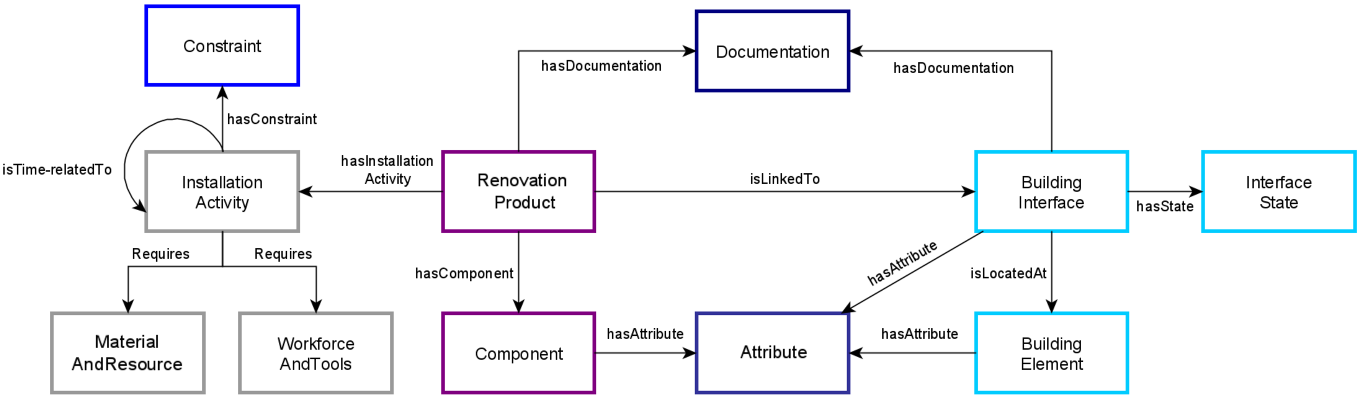

Figure 5. Reno-Inst ontology overview

3.4.2 Building Interface and attributes

In a deeper level of abstraction, as presented in Figure 6, each *RenovationElement* will be linked to a *BuildingInterface*, which may be a *ConstructiveInterface* or a *SystemInterface*. Architectural elements where a *RenovationElement* may be installed such a specific point in a wall, an opening, or an area in a floor correspond to *ConstructiveInterface*. In contrast, *SystemInterface* gathers building elements that link one of the building systems to a *RenovationElement*, e.g. an existing hot water pipeline that will be connected to a new radiator. As mentioned previously, the as-built conditions may impact the way the construction activities are performed in renovation projects. The class *InterfaceState* is included to represent the current state of the *BuildingInterface* and provide information regarding any requirement that should be fulfilled before installing the new *RenovationElement*.

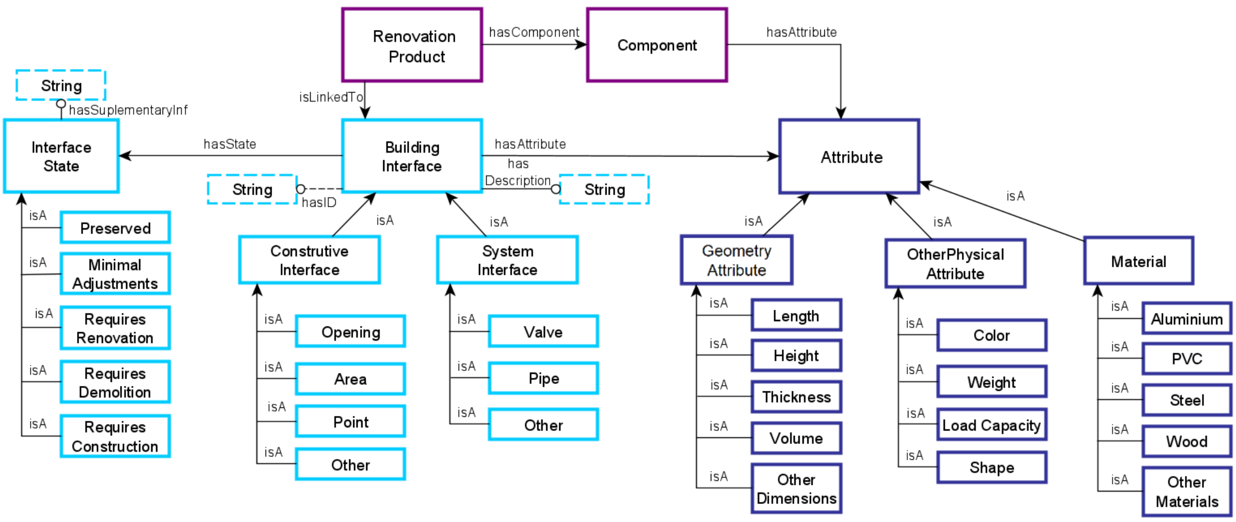

Figure 6. Major classes BuildingInterface, RenovationElement, Component, and Attribute

On the other hand, the concept *Attribute* gathers the features that can be used to describe a *Component* of a *RenovationElement*, a *BuildingElement* or a *BuildingInterface*. For instance, the frame of a window can be described by *Length*, *Height*, *Thickness* and the *Material Wood*. Moreover, an *Opening* where a *Window* will be installed can be described by *Length*, *Height* and *Material* ClayBrick.

3.4.3 Renovation products

Specific knowledge related to different renovation elements can be added to the model as blocks of concepts. A *Window*, a *Radiator* and other elements can be represented under the concept *RenovationElement* as presented in Figure 7. The existing BPO: Building Product Ontology[7] could have been used to model the different renovation elements, nevertheless it does not categorize the components of a certain product. Therefore, an alternative approach is proposed to classify the components of a certain *RenovationElement* in two classes *FunctionalComponent* and *InterfaceComponent* to identify explicitly the components that will be directly linked to the *BuildingInterface*. This allows checking possible compatibility requirements between the renovation elements and the building interfaces where they will be installed. The concept *FunctionalComponent* represents the main components of a *RenovationElement*, which perform the main function of it, e.g. the core of a radiator. In contrast, *InterfaceComponent* represents the components that will be directly linked to the *BuildingInterface*, e.g. a radiator has a fixing mechanism that will be linked to a point in a wall. Individual blocks with the components for each renovation element can be added to the model.

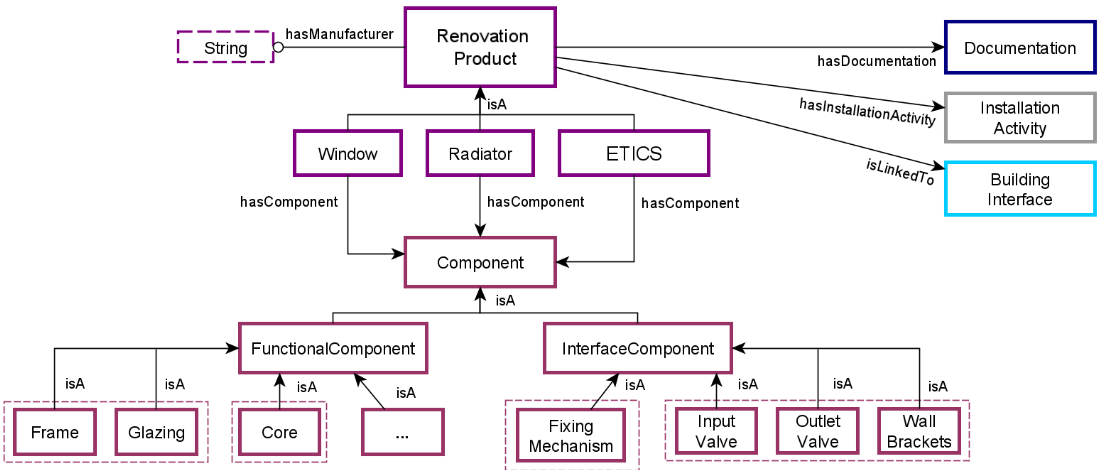

Figure 7. *RenovationElement* class and knowledge blocks for different renovation elements

3.4.4 Installation activities

In a similar fashion, in Figure 8, the *InstallationActivity* class includes *RemovalActivity*, *WorkAreaPreparationActivity*, *InsituTransportActivity* and *InstallationVerificationPhase* which are concepts shared by different renovation elements. A block with a concept *WindowMainInstallationActivity* and the associated activities *FixingActivity*, *AirtightClosureActivity*, *RainProofConnectionActivity*, and *ThermalInsulationActivity* can be added to represent specific tasks for the installation of windows. Equivalent blocks can be used for ETICS panels and other elements. This proposed ontology structure may facilitate the integration of new renovation elements, contributing to extend Reno-Inst for future

[7] https://www.projekt-scope.de/ontologies/bpo/

applications. The property isTime-relatedTo and its sub-properties allow considering the sequence of the activities during the installation procedure. For instance, for the installation of a window, the *ThermalInsulationActivity* hasPreviousActivity *FixingActivity* which is performed in advance, and hasFollowingActivity *AirthightClosureActivity*, which is performed afterwards.

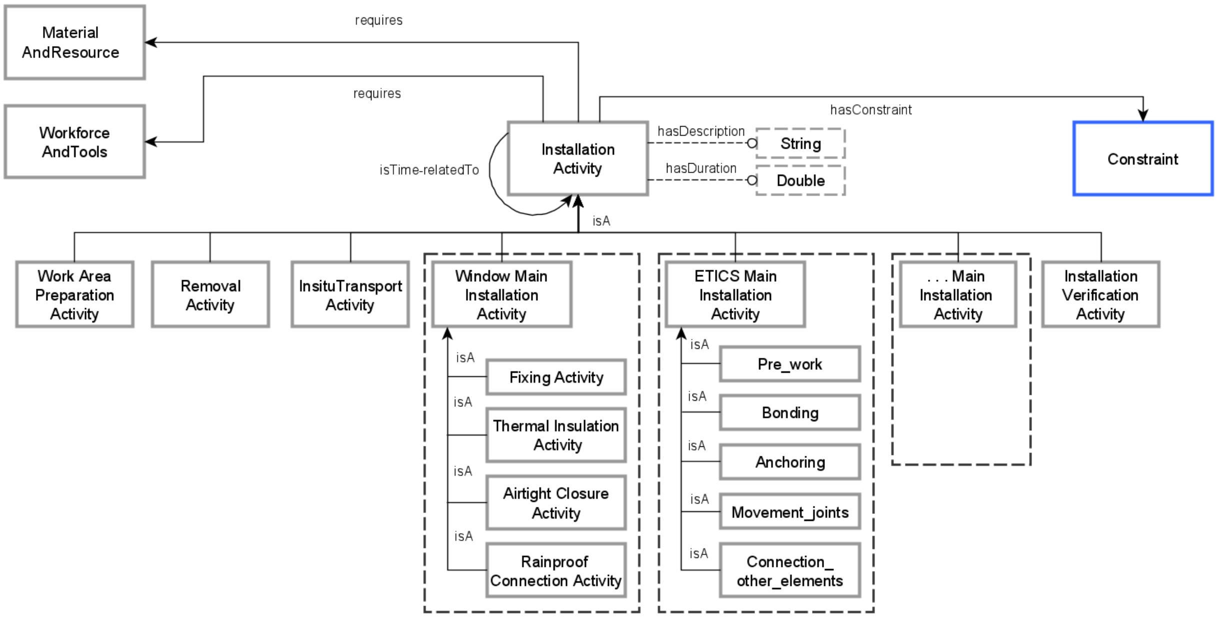

Figure 8. *InstallationActivity* class and knowledge blocks for different renovation elements

3.4.5 Constraints

As shown in Figure 9, the *Constraint* class includes five main concepts named *PhysicalConstraint, UncertaintyConstraint, CoordinationConstraint, PollutionConstraint*, and *SafetyConstraint*. Including these diverse constraints contributes to getting a better understanding of the particularities of the construction processes in renovation projects. The sub-classes *PhysicalConstraint* and *UncertaintyConstraint* represent restrictions due to physical limitations and lack of information from the existing building. The sub-class *CoordinationConstraint* is related to limitations imposed by the building operational schedule or coordination required with the occupants, for instance, to perform construction activities inside the dwelling units. On the other hand, *PollutionConstraint* is related to situations such as large dust production during the activity, the handling of building materials containing contaminants, or high noise production during long periods, which may affect occupants. These constraints require the constructor to implement strategies to mitigate the kind of pollution produced during the activity and/or to prevent the occupants to be exposed to it. The last sub-class *SafetyConstraint* represents the level of impact of each activity on occupants' safety. A High *SafetyConstraint* means that the activity cannot be performed in the presence of occupants and special measures should be taken into consideration to execute this task. For instance, an activity such as lifting and transporting large elements (e.g. windows) through the building staircase may have a High or Medium *SafetyConstraint* since it represents a risk for the inhabitants, and occupants transit through the staircase should be completely or partially restricted while performing this task to avoid potential accidents.

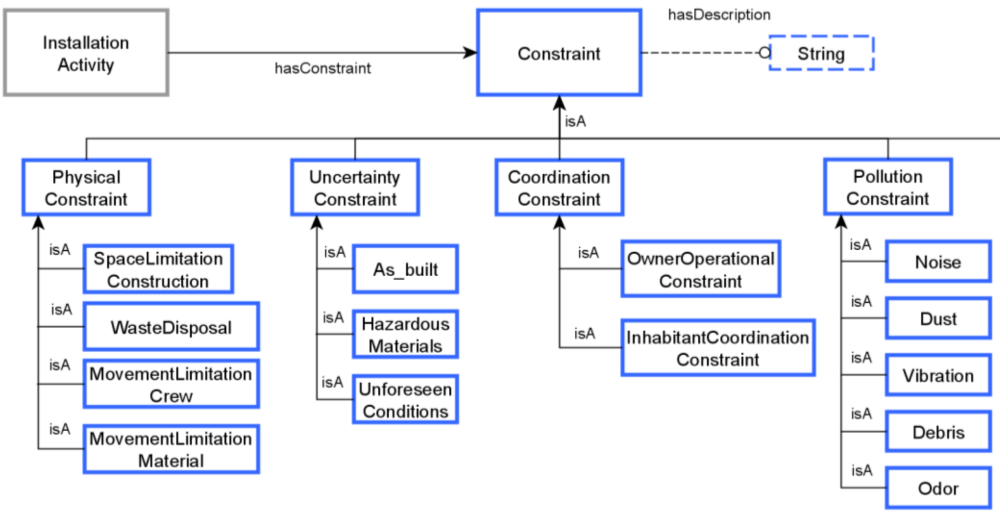

Figure 9. *Constraint* class representation

3.4.6 Other concepts

Finally, the major classes *Documentation*, *MaterialsAndResources*, *BuildingElement* and *WorkforceAndTools* are depicted in detail in Figure 10. These concepts can be extended to include other tools, resources and materials that are relevant for the installation procedure of other renovation products.

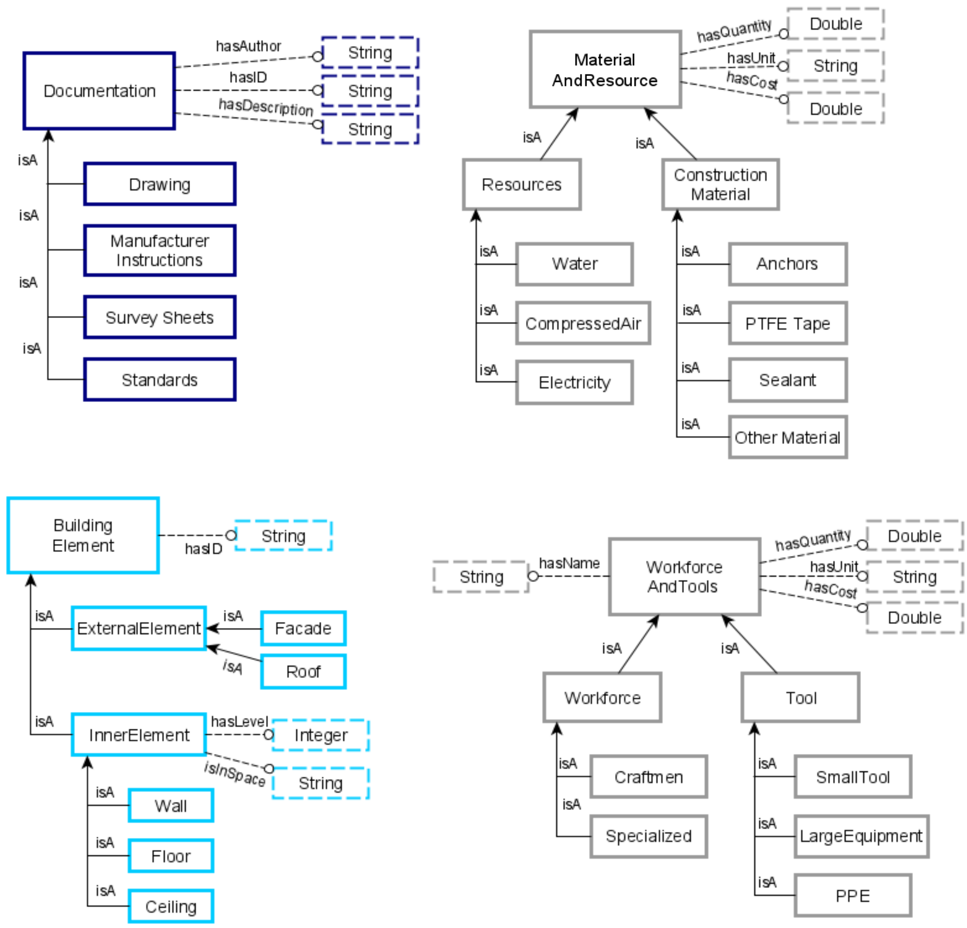

Figure 10. Major classes *Documentation, MaterialsAndResources, BuildingElement* and *WorkforceAndTools*

3.5 Reno-Inst Ontology evaluation

3.5.1 Workshop with experts

A workshop with a set of practitioners of the BIM-SPEED consortium was conducted to evaluate the proposed Reno-Inst ontology and identify potential adjustments. The group comprised two architects and an R&D director from three different construction companies. The goal was to evaluate if the model is coherent with the domain **Installation of renovation elements**. The specific questions leading the workshop were:

- Does the model cover all the concepts and attributes required to fulfil its intended use?
- Does the taxonomy and hierarchy of concepts represent the terms and structure of the elements in the real world?
- Are the relations between concepts according to the real-world interactions?

The ontology specification was presented to the experts, then the general model and the details of each concept were introduced. After discussing each of the concepts and their relationships, the model was modified according to the experts' comments. At the last stage of the workshop, a fictional case was presented to the experts. The case includes the replacement of 12 main windows and 4 general windows of an occupied four-story residential building, with eight apartment units. While the author of the ontology was verifying whether if the information required by the experts was represented in the ontology, the experts discussed the activities required to implement the task. After analysing the comments and results from the workshop, the following adjustments were made to the model:

- To include resource requirements as part of the class Workforce,ToolsAndMaterials. The class was split into two main classes *WorkforceAndTool* and *MaterialsAndResources*, the latter including resources such as water, electricity, and compressed air.
- To include a concept to represent the waste disposal constraints under the class *PhysicalConstraint*. Waste management is one of the main aspects that requires a high level of attention during renovation activities in existing buildings due to the lack of space and presence of occupants. The subclass *WasteDisposalConstraint* was created.
- To include other attributes of the interface and renovation elements such as shape, position, load capacity. Additional subclasses were created under the class *OtherPhysicalAttributes*. A data property was included to specify the position, regarding the interface, where the renovation element will be installed. For instance, a window can be installed to the inside or outside of the building, or in the centre of a certain opening.
- Experts pointed out that some activities should be coordinated with the inhabitants. For instance, occupants should often adequate the space around the work area in advance, when construction activities will be performed inside the dwelling units. To represent this requirement an additional subclass *InhabitantsCoordinationConstraint* was created under the class *CoordinationConstraint*.
- To consider the fact that it is often required to perform some demolition activities on the building interface where an element will be installed (e.g. enlargement of window openings), a

subclass was created under the class *InterfaceState* to indicate if the building interface requires demolition.

- Certain renovation elements require close coordination such as a window and solar protection system, and radiators and pipelines. The symmetric property *InstalledInConjunctionWith* was created to represent this relation between renovation elements.

3.5.2 Ontology design verification

The final Reno-Inst model implemented using OWL/RDF in Protégé was reviewed thoroughly according to the list of common errors presented in Section 2. The review process allowed identifying the errors presented in Table 3. Proper adjustments were implemented to solve the issues identified, some of them are mentioned explicitly where necessary.

Table 3. Errors and actions for the Reno-Inst ontology verification

Description	Related error
The hasState property was defined but not linked to the BuildingInterface and the InterfaceSate classes	Lack of specification and limitation of the properties
The class FunctionalComponent was not disjoint with the InterfaceComponent class	Non-disjoint classes
The sub-class FloorBasedRadiator was not disjoint with the WallRadiator sub-class	Non-disjoint classes
Functional object properties such as hasState and isLocatedAt were not declared explicitly as functional	Lack of specification and limitation of the properties
Object properties such as requiresMaterial_Resource were no specific enough. Adjustment: sub-properties requiresMaterial and requiresResource were created. A similar approach was followed with other object properties	Lack of specification and limitation of the properties
The data property hasInstallationPosition was defined but not assigned to the RenovationElement class	Lack of specification and limitation of the properties
The data property hasType was defined but not assigned to the RenovationElement class	Lack of specification and limitation of the properties
Adjustment: All data properties were defined as functional	Lack of specification and limitation of the properties

4. LCA-C Ontology

4.1 Motivation and current state of the art

Worldwide there is a growing concern about the environmental, economic, and social impacts of the built environment. Buildings consume high shares of final energy, extracted materials and water, and produce large amounts of CO_2 emissions. These and additional impacts are no longer considered as single values produced at a single point in time but as the set of multiple impacts throughout the lifetime of a building. The standards EN 15978 and ISO 15686-5 introduce the concepts and methodologies to assess the life cycle impacts and cost in the context of buildings. However, the application of Life Cycle Assessment (LCA) to buildings is a complex problem since buildings are designed for a long life span and they may perform different functions, moreover, LCA was initially developed for the assessment of simpler products (Joint Research Centre, 2018). On the other hand, Life Cycle Costing (LCC) may encounter some challenges related to the uncertainties and assumptions linked to parameters such as future inflation and discount rates due to the long lifetime of buildings.

Particularly, LCA is very popular among the scientific community; however, in practice, the evaluation of sustainability in the built environment usually relies on certification systems such as BREEAM, LEED, HQE, SBTool, DGNB, etc (Joint Research Centre, 2018). According to the reviews conducted by Buyle et al. (2013) and Cabeza et al. (2014), most of the LCA studies assessing residential and commercial buildings have dealt mainly with new buildings. On the other hand, there have been some efforts to integrate LCA and LCC with semantic technologies, for instance, Schwartz et al. (2016) present a framework that integrates BIM with LCA components by utilizing different data inventories to support the decision rationale for achieving sustainable designs. The authors present an Environmental Product Declaration (EPD) ontology. This ontology is re-used as part of the LCA-C ontology proposed in this BIM-SPEED report.

Regarding LCA/C and Building Information Modelling (BIM), Santos et al. (2019a) use BIM as a repository for the LCA and LCC information and show how that information should be used for environmental and economic analysis, using the industry foundation classes (IFC) schema for the integration and exchange of information within a BIM-based environment. In a further development of the concept, Santos et al. (2019b) present a BIM-based environmental and economic life cycle assessment (BIMEELCA) prototype tool to improve the integration of BIM with LCA and LCC. Potrč Obrecht et al. (2020) review different integration approaches between BIM and LCA/C. In most of the cases the data exchange is performed manually, and the workflow is associated to a specific BIM or LCA software, or a plug-in between them, which can be a disadvantage, particularly in the context of renovation projects where the stakeholders usually do not have large experience using this specialized software. The review also suggests that gathering all the LCA information in the BIM model may lead to complex and rigid models that usually cannot be handle by the existing BIM software. In any case, the information must transfer in such a way that the semantics is preserved, this task is very demanding because it requires standardization, which could be supported by an ontology covering the domain. It is important to notice that the reviewed studies are focused on new buildings were most of the information from the building is available, and the LCA studies focus on the entire life cycle. For renovation projects, the workflows and integration may vary since information from the building is usually missing, and the LCA assessment usually focuses on the new products to be added to the building and the operational stage of the building after renovation, as explained below.

Even though the previously mentioned models and tools may be applied in the renovation field, the domain of LCA and LCC for renovation has some particularities that should be considered thoroughly. For instance, according to the EN 15978 standard, the lifecycle of the building includes the stages presented in Figure 11. The standard states that for an existing building, the system boundary shall include stages representing the remaining service life instead of the full building life cycle. This does not mean that Product and Construction A1-A5 modules should be discarded, actually, according to Thibodeau et al. (2019), it is common to assume that the renovated building has its own building life cycle starting with the building renovation. This means that the addition of renovation elements is distributed throughout the life cycle modules from A1 to D and not only the rehabilitation stage B5 module. Other particularities may be related to the fact that usually many of the existing components of a building (eg. main structure) are not modified during the renovation and design alternatives are based on packages of renovation measures in contrast to design options as in new building processes. Therefore, the LCA and LCC assessments usually focus on the newly added renovation products that would be installed as part of a certain renovation alternative and on the building s' performance after the installation.

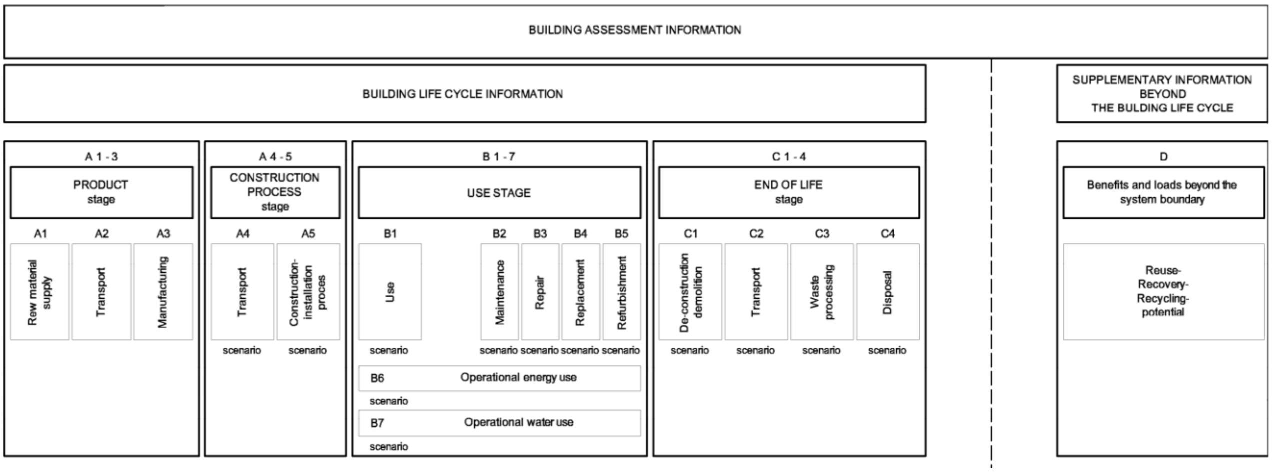

Figure 11. Building lifecycle stages

Moreover, literature reviews show that not all LCA and LCC studies follow recognized standards and that both embodied and operational energy play a key role in contributing to potential environmental impacts of renovated buildings. The International Energy Agency (2017) presents the Annex56 methodology that integrates a life cycle perspective with an environmental LCA methodology next to an LCC assessment focused only on buildings renovation. The methodology was applied to multiple cases and is mentioned in the scientific literature as one of the common guidelines to perform LCA/C assessment in the context of building renovation. According to the review conducted by Thibodeau et al. (2019), studies following guidance documents such as the Annex 56 and EeBGuide present more homogeneous methodological choices, while this relation does not seem to exist for the studies that follow standards such as ISO 14044 or EN 15978. This may be related to the more practical approach of the guidance documents which facilitates the implementation of the methodology by practitioners.

The lack of a common agreement regarding methodological choices related to the functional unit, requested service life, life cycle stages, impact assessment indicators, etc. may impact the implementation of LCA and LCC for renovation. A common understanding of the standardized methodologies may encourage practitioners to implement them and make more homogeneous assumptions and choices when performing LCA and LCC for building renovation. Therefore, the LCA-C ontology proposed in the following sections aims at developing an LCA/C representation closer to the field of building renovation. The ontology focuses on the LCA and LCC assessment for renovation to support stakeholders such as designers and architects at the design stage, when multiple renovation alternatives are evaluated. The aim of this representation is two-fold: 1) To establish a clear structure of the information related to LCA and LCC in renovation; 2) to support the retrieval and inference of information to analyse different renovation alternatives and make comparisons between them, enabling easier extraction of information from large amounts of data gathered, calculated and reported during the performance of an LCA or LCC assessment.

4.2 LCA-C Ontology specification

This section presents a general description of the LCA-C ontology comprising information regarding the purpose, use, users, and domain covered by the ontology. A set of competency questions is also presented to facilitate the identification of potential concepts that should be modelled by the ontology.

- **What is the purpose?** The LCA-C ontology was developed to represent concepts related to the LCA/C assessments to support the comparison of different renovation alternatives in residential buildings.
- **What is the scope?** The ontology will cover concepts and relations regarding the LCA and LCC assessments for buildings under renovation. The ontology includes information on physical features, environmental and cost indicators, renovation products, and general information describing the goal and other aspects of the assessment.
- **Who are the intended end-users?** The final intended users are designers, architects and other stakeholders which may be involved in the LCA/C analysis of residential building renovation alternatives.
- **What is the intended use?** The intended use of the ontology is to facilitate reasoning over the LCA/C information of different renovation alternatives. The ontology will support the end-users to evaluate and compare the environmental impacts and cost indicators of the different renovation alternatives considered for the renovation of a certain building. The set of competency questions presented in Table 4 was developed to identify some of the concepts that users may be interested in. For instance, a user may query the ontology to check how many replacements have been considered for a specific renovation product, which are the products included in a certain renovation alternative, or what is the total global warming potential of a renovation alternative in the operational stage B6.

Table 4. Competency questions and answer examples for the LCA-C Ontology

Competency questions	Example answers
What is the reference study period of the LCA assessment?	50 years
What is the Global warming potential indicator of the renovation alternative A in the use stage B6?	24.5 kgCO2/m2
How many replacements for the window D are considered during the reference study period?	1 replacement
Which products are included in the renovation alternative A?	Window double glazing Ref. 123, ETICS panel Ref. 456, PV panels Ref. 789
What is the maintenance cost of the renovation scenario A?	-------- [€]
What is the acquisition cost of the products included in the renovation scenario A?	-------- [€]

Figure 12 depicts a potential use of the proposed LCA-C ontological model. As mentioned previously, one of the goals of this ontology is to provide a clear knowledge structure that can support the users to manage the large amounts of data related to LCA and LCC assessments, hence, the LCA-C ontology can be leveraged in the initial stages of the renovation projects to gather and store in a uniform way the heterogeneous information capture from the existing building and the new potential products to be installed. This information usually comes in the form of EPD sheets, drawings, tables, and different formats that can make its management a complex task prone to errors. Particularly, during the design and analysis of different potential renovation alternatives, users can retrieve information related to particular renovation products, scenarios of the life cycle of the products or building, or check specific cost or environmental indicators for each of the stages of the life cycle of the building in order to make better informed decisions.

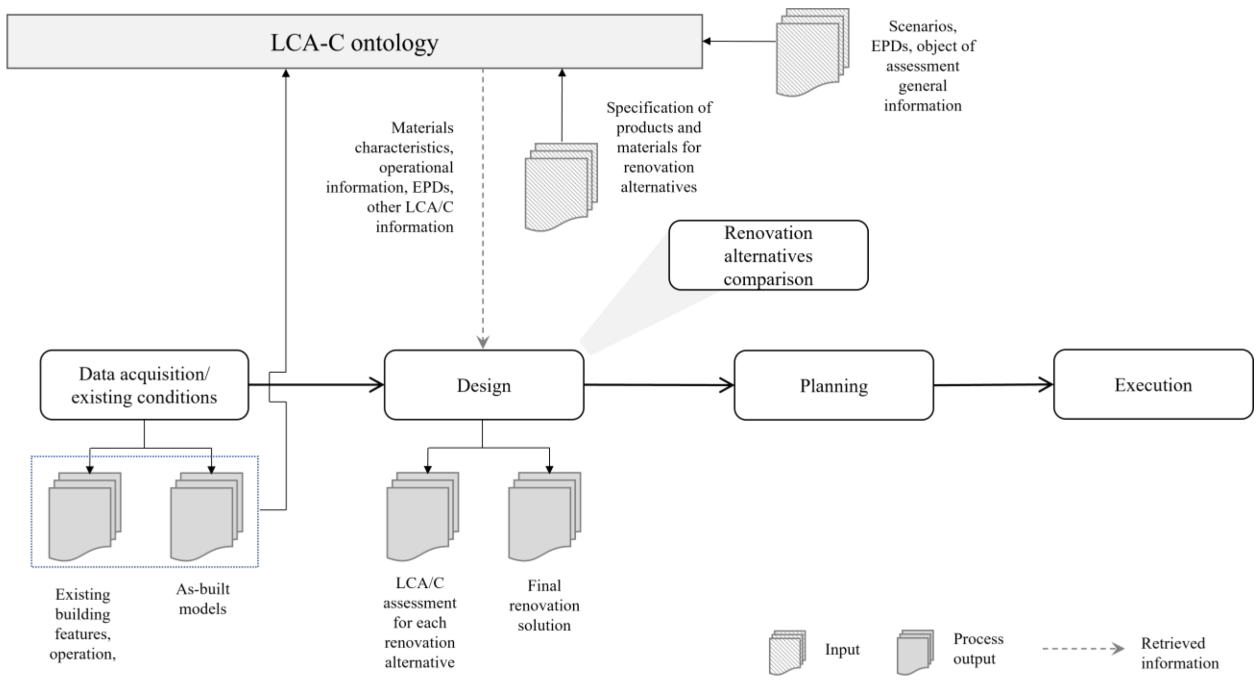

Figure 12. Potential use of the proposed LCA-C ontology

4.3 Knowledge Capture and Conceptualization

The knowledge acquisition includes identifying the relevant concepts in the ontology and the diverse relations between them. The main goal is to identify what is the information linked to LCA and LCC assessments in building renovation, which concepts should be modelled and how they can be represented in a knowledge network. The concepts identification and proposed structure for the ontological model rely on the specification and competency questions presented in the previous section. The capture of knowledge is based on a literature review related to tools and the implementation of LCA and LCC for renovation, and general standards for buildings as summarized in Table 5. The terms focus on information related to general features of the building, the materials and renovation products included in the renovation alternatives, operational characteristics of the building, cost and environmental parameters; especially, information from the renovation products, the general structure of LCA and LCC data, and the characteristics of the data itself.

Table 5. Sources for the LCA-C ontology knowledge

Main Concepts	Terms Examples	Source
General concepts and particularities of LCA/LCC for renovation	Renovation alternative, renovation product, quality of data	(International Energy Agency 2017), (Joint Research Centre 2018), (P2ENDURE 2018)
LCA Assessment	Environmental indicator, boundary, waste category, functional unit	(BSI Standards 2011), (BSI Standards 2014)
LCC Assessment	Cost variable, built asset level, cost type	(BSI Standards 2017)

4.4 LCA-C Ontology Description

4.4.1 LCA-C Ontology Overview

The LCA-C ontology gathers concepts related to LCA and LCC assessments, the object of assessment (the building being renovated), and the products and materials included in a renovation alternative. As mentioned previously, design alternatives for renovation are usually specified as packages of renovation elements, therefore, a big share of the LCA and LCC gathered information, calculations and results depends on the products and materials included on each renovation alternative and the operation of the building according to that alternative.

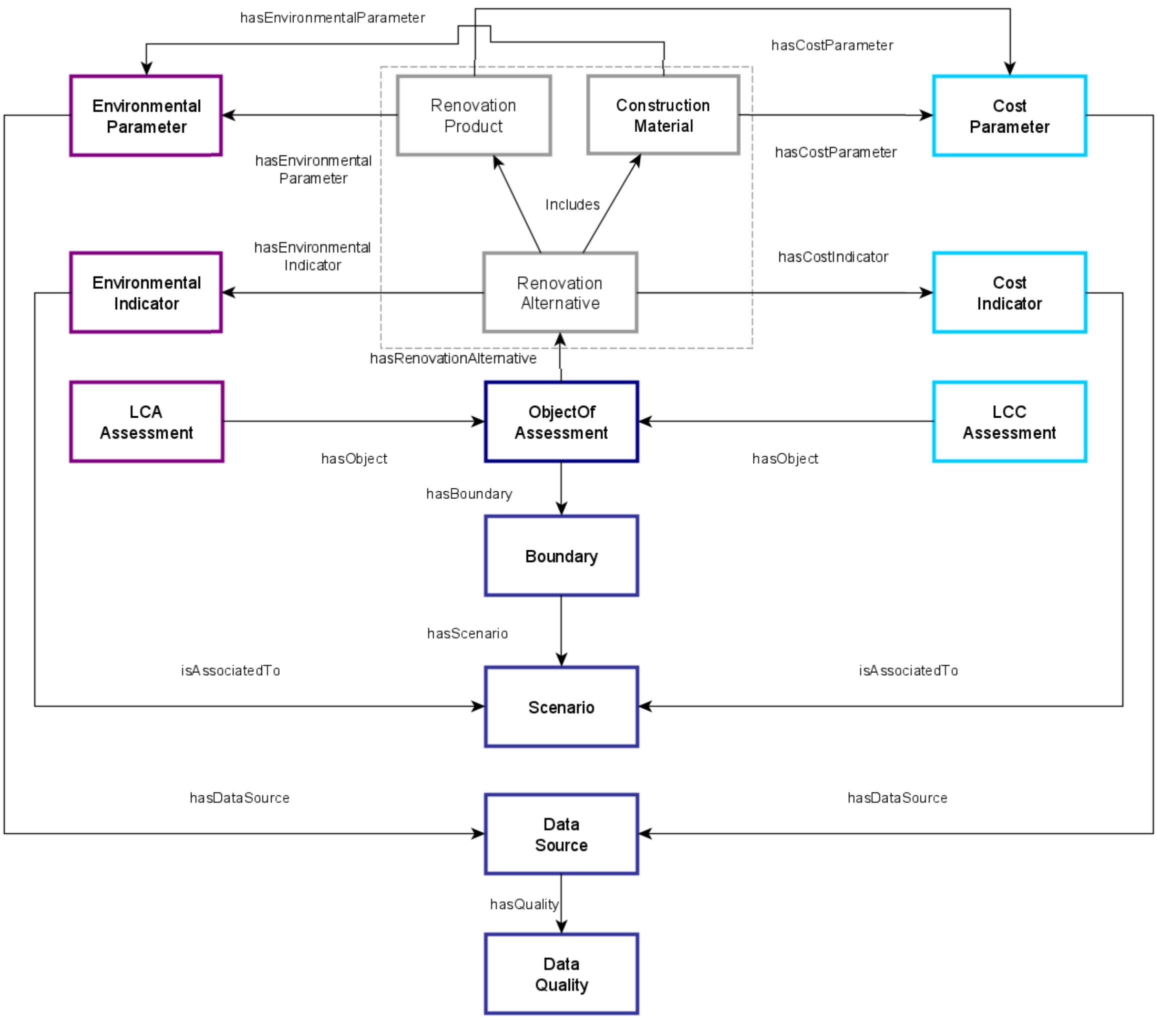

Figure 13. LCA-C ontology overview

As shown in Figure 13, the *ObjectOfAssessment* is the core concept of the model, it is shared by the LCAAssessment and LCCAssessment. The *ObjectOfAssessment* has *Boundaries* which represent the different stages of the life cycle of the building considered in the assessments: product (A1-A3), construction (A4-A5), use (B1-B7), end-of-life (C1-C4), beyond the system (D). These boundaries have *Scenarios*, representing assumptions (or, where known, real information) that can be applied to models for construction, use, and end-of-life stages (modules A4 to C4) of the object of assessment. The *ObjectOfAssessment* has *RenovationAlternatives* as shown in the shaded box in the upper section of the model. Each *RenovationAlternative* includes a set of *RenovationProducts* and *Materials* that would be installed in the building as part of the renovation activities. For each *RenovationAlternative*, *EnvironmentalIndicators* and *CostIndicators* quantify environmental impacts and costs that would be caused by the object of assessment and the products and materials included in the renovation alternative, during their life cycle. When different scenarios are established for the boundaries of the object of assessment, these indicators may have different values associated to each scenario.

On the other hand, the *RenovationProducts* and *Materials* included in each renovation alternative have *EnvironmentalParameters* and *CostParameters* related to their respective impacts. The *DataSource* concept represents the different information sources used in the LCA and LCC assessments, which may be an EPD from the manufacturer, a Database or other. Being able to trace data is essential to evaluate the consistency and uncertainties associated with the results of the assessments. Finally, the concept *DataQuality* is included to represent the quality features introduced in EN 15804, EN 15978, and ISO 14044 standards, including *Completeness*, *Geographical coverage*, *TechnologicalCoverage*, and *Time-relatedCoverage* of the *DataSources*. The following sections describe in detail all the concepts and additional secondary classes and properties that were included to develop the entire ontological model. The entire hierarchy and list of properties extracted from Protégé describing the complete ontology are presented in Appendix A.

4.4.2 General Information

Three classes were included to represent the general information related to the object of assessment, and the LCA and LCC assessments. As presented in Figure 15, the *ObjectOfAssessmentGeneralInformation* includes sub-classes describing the main concepts related to the object of assessment such as *DesignLife* and *FunctionalUnit*, most of these concepts were extracted from Section 7 of the EN 15978 standard. The *InitialBuildingLifeTime*, *YearOfPreviousRefurbishment* and *YearOfCommissioning* are essential for establishing a partial picture of the current state of the object of assessment and defining the expected remaining life span of the building and the *RequestedServiceLife*.

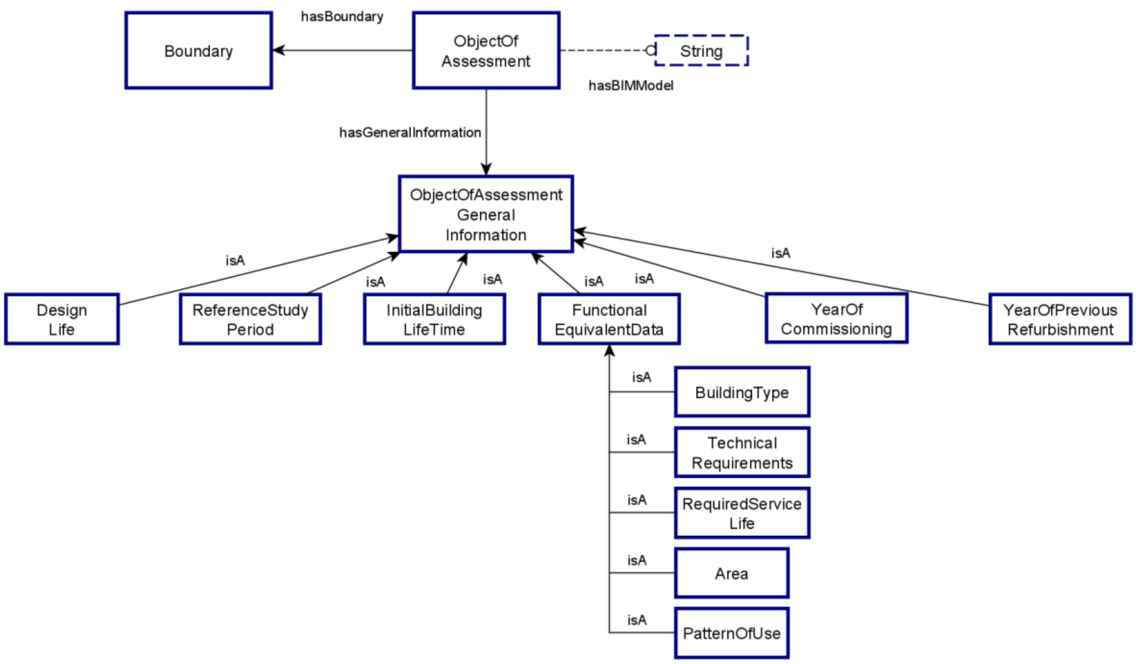

Figure 15. ObjectOfAssessmentGeneralInformation class

Figure 14 shows the sub-classes associated to the *LCAAssessmentGeneralInformation*. some of the terms were extracted from Sections 5 and 6 of the EN 15978 standard. The sub-class *Standard-Guideline* was included to gather the different available approaches used by practitioners. In a similar fashion, Figure 16 represents the general information of the LCC assessment. These concepts were extracted from Sections 4 and 5 of the ISO 15686-5 standard. The LCC level options presented in that section correspond to detailed, system and strategic level, nevertheless, the levels included in the ontological model correspond to the levels proposed in Annex E of the same standard, which are described in detail on the same document. This modelling decision was made based on experts' recommendations made during the validation workshop and the approach used by LCC tools for renovation such as the one developed in the P2ENDURE project (P2ENDURE 2018).

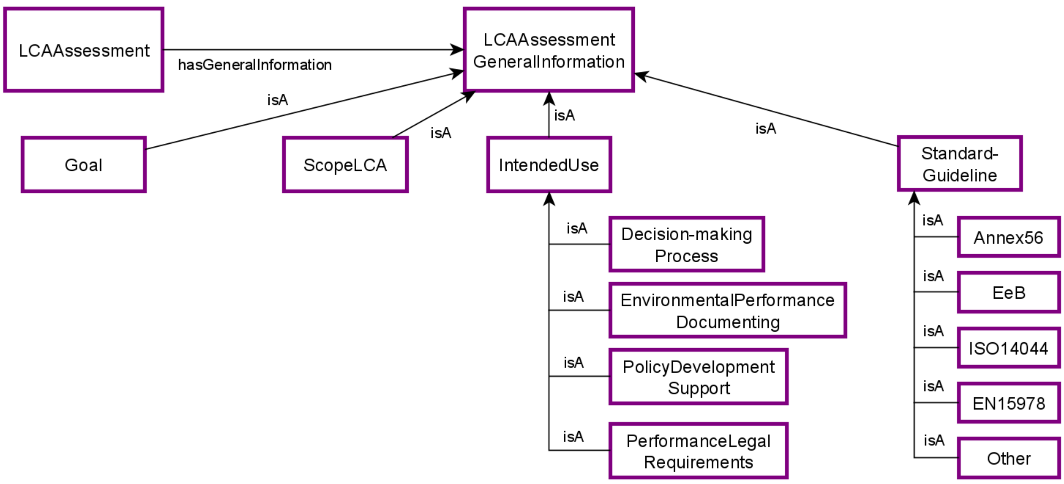

Figure 14. LCAAssessmentGeneralInformation class

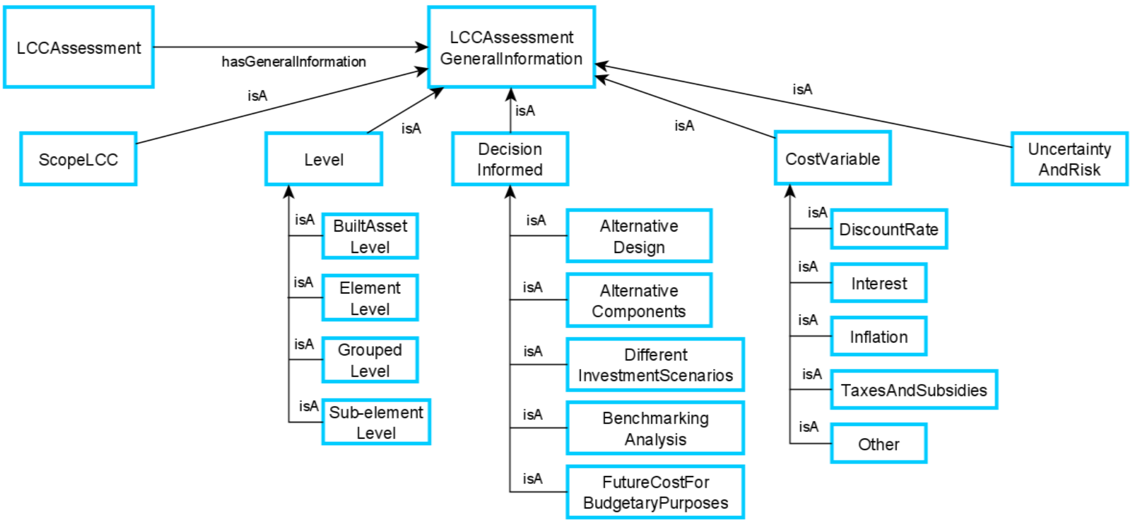

Figure 16. LCCAssessmentGeneralInformation class

4.4.3 Boundaries and Scenarios

The system boundary determines the processes that are taken into account for the object of assessment. The system boundaries follow the "modularity principle": where processes influence the building's environmental performance during its life cycle, they shall be assigned to the module in the life cycle where they occur (BSI Standards 2011). As shown in Figure 17, boundaries are classified in five modules *ProductStage*, *ConstructionProcess*, *UseStage*, *EndOfLife* and*BenefitsAndLoadsBeyondTheSystem-Boundary*, the sub-classes correspond to the traditional life cycle modules described in Figure 6 of the EN 15978 standard. Modules B6 and B7 in the *UseStage_Module* correspond to the operational use of energy and water, for this reason, an additional class *Resource* was created to represent the energy and water consumption of the building in those two modules.

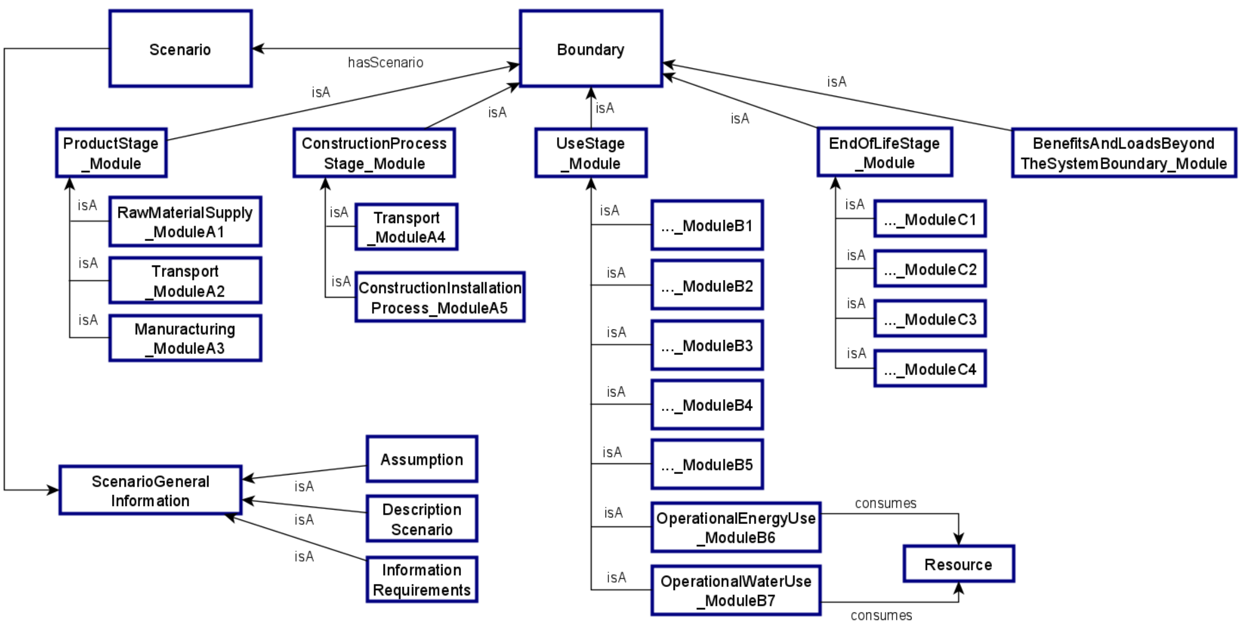

Figure 17. *Boundary* and *Scenario* classes

To provide a complete description of the object of assessment, time-related characteristics of the building need to be added to the physical description, this is made through the concept *Scenario*. Different scenarios may be created to specify different options of construction, transport, maintenance, repair, replacement, water and energy use, reuse, recycling, and energy recovery. Each *Scenario* has *Assumptions* and *InformationRequirements* that should ensure that scenarios developed for the boundaries are consistent with any product information and general scenarios defined at the building level.

4.4.4 Environmental and Cost Indicators

The environmental and cost indicators gather the main results of the LCA and LCC assessments. Since each renovation alternative includes different renovation products and materials, and the building will perform in different ways according to the measures implemented, each renovation alternative have its own environmental and cost indicators results aggregating the impacts of the renovation products, materials and building operation. In a similar fashion, since different scenarios can be established according to products and materials included in the renovation alternative and operation of the building, each set of environmental and cost indicators can be associated to a specific scenario. Figure 18 shows the *EnvironmentalIndicator* class and its hierarchy. The main categories *EnvironmentalImpacts*, *ResourcesUse*, *OutputFlows* and *WasteCategories* and sub-classes in the lowest levels correspond to the indicators presented in Section 11 of the EN 15978 standard. Not all the indicators are presented in Figure 18 to facilitate the representation of the model. Focusing on the *EnvironmentalImpacts* category, each indicator has instances for each of the life cycle modules, e.g. the *GlobalWarmingPotential_GWP* has instances *GWP_A1* for the *RawMaterialSupply_ModuleA1*, *GWP_A2* for the *Transport_ModuleA2*, etc. The same structure is used to model the other indicators from the different categories. Datatype properties of unit definitions according to the QUDT catalogue[8] can be re-used to describe the units of the indicators.

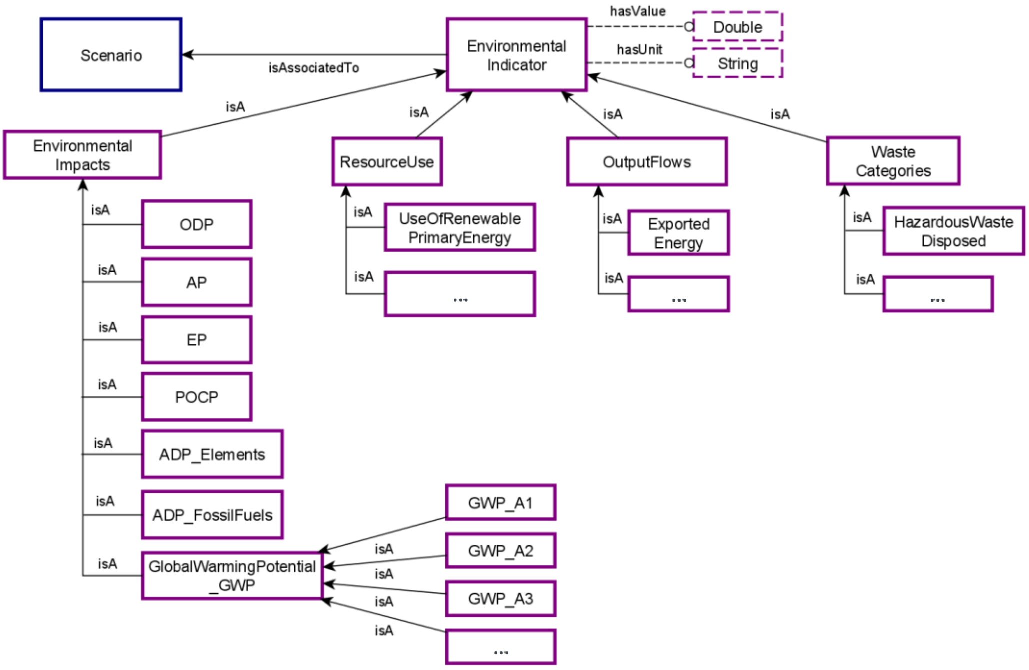

Figure 18. EnvironmentalIndicator class

[8] https://qudt.org/

There are multiple existing ontological resources including concepts related to cost from a social or technical perspectives. Since the LCA-C ontology intends to map and represent the knowledge from the existing LCC standards related to buildings, we followed the definition and classification presented in the ISO 15686-5 standard. The *CostIndicator* class is depicted in Figure 19, the cost categories *GlobalCostIndicator*, *Construction*, *Operation*, *Maintenance* and *EndOfLife* and their sub-classes were extracted from Sections 4-5 and Annex B of the ISO 15686-5 standard. Cost indicators have a type that can be present or discount, and real or nominal. According to the standard, real and discounted costs should be used, ideally. *EnergyAndUtilitiesCost* includes electricity, hot water, district heating and other services. Some of the cost concepts represented in the model can be aligned and complemented with classes such as om:cost and om:quantity from the Ontology of Units of Measure[9] or ifc:costValue, ifc:costItem, ifc:replacementCost among others from the ifc standard.

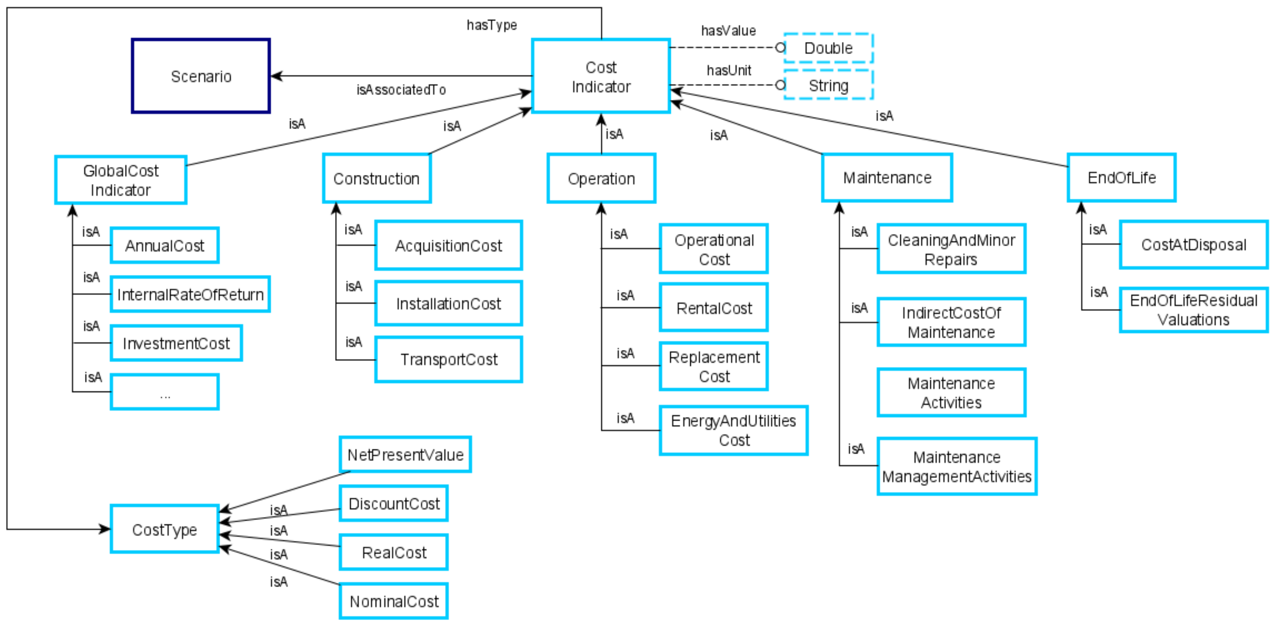

Figure 19. CostIndicator class

4.4.5 Renovation Alternatives

One of the goals of the LCA-C ontology is to facilitate the comparison of multiple design alternatives in the context of building renovation projects, to do this, the class *RenovationAlternative* was included in the model. As presented in Figure 20, each *RenovationAlternative* includes multiple *RenovationProducts* and *Materials* that constitute the final package of measures that would be implemented as part of the renovation project. These products and materials have their own *EnvironmentalParameter* and *CostParameter* that represent their impacts through their life cycle. These indicators are aggregated to obtain the final environmental and cost indicators introduced in the previous section. The EPD ontological model presented by Schwartz et al. (2016) was re-used to model the *EnvironmentalParameter*, following the same structure used to model the *EnvironmentalIndicator* presented in the previous section, this structure is based on the EPD data approach.

[9] http://www.ontology-of-units-of-measure.org/page/om-2

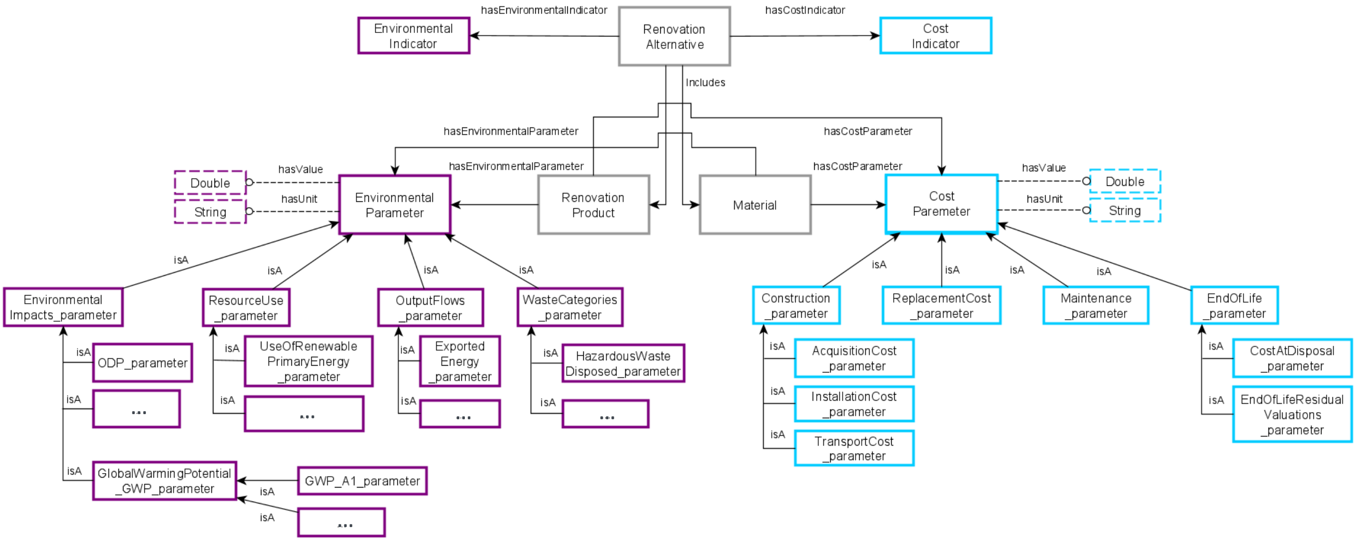

Figure 20. *RenovationAlternative*, *EnvironmentalParameter* and *CostParameter* classes

On the other hand, the *CostParameter* class follows a similar structure to the class *CostIndicator* presented in the previous section. Nevertheless, categories related to global and operational costs are not included in the hierarchy of the *CostParameter* since those concepts are related to the whole *RenovationAlternative* and the operation of the object of assessment while the *CostParameter* class focuses on the parameters of the individual *RenovationProducts* and *Materials*. Finally, a set of Data properties were added to describe information related to the *RenovationProduct*, these properties are not shown in Figure 20 for the sake of clarity. They include hasDescription, hasNumberOfReplacements, hasReferenceServiceLife and hasYearOfReplacement, which are essential to analyse and compare different products and understand better their performance through their life cycle and the life cycle of the building where they would be installed.

4.5 LCA-C Ontology evaluation

4.5.1 Workshop with experts

Following a similar approach as the one implemented for the Reno-Inst ontology, a workshop with a set of practitioners of the BIM-SPEED consortium was conducted to identify potential adjustments and evaluate the proposed LCA-C ontology. The group comprised two LCA experts and an LCC expert from two different construction companies, which are responsible for the BIM-SPEED demonstration cases Frigento, in Italy and Warmond, in the Netherlands. The goal was to evaluate if the model is coherent with the domain **LCA/LCC assessment for renovation**. The specific questions leading the workshop were:

- Does the model cover all the concepts and attributes required to fulfil its intended use?
- Does the taxonomy and hierarchy of concepts represent the terms and structure of the elements in the real world?
- Are the relations between concepts according to the real-world interactions?

After the ontology specification was presented to the experts, the general model and the details of each concept were introduced. Due to the large size of the model, the discussions focus mainly on the concepts of the upper layers of the ontology and the relations between them. After analysing the comments and results from the workshop, the following adjustments were made to the model:

- To include the reference service life for the products proposed in each renovation alternative. Moreover, to specify at which point during the reference study period each product required replacement. This is important, especially for the cost indicators calculations. A set of data properties was created to represent some more concepts associated to the products in detail, including hasDescription, hasNumberOfReplacements, hasReferenceServiceLife and hasYearOfReplacement.
- To check the level definition for the LCC assessment. The ISO 15686-5 standard includes different categories. Initially, the ontology included the levels: detailed, system, and strategic. However, the experts proposed to use the levels presented in Annex E of the standard, which are more descriptive and understandable. Therefore, the *Level* concept in the *LCC_AssessmentGeneralInformation* class were modified and adjusted to the categories proposed in Annex E of the standard.
- To include a concept related to the methodology for the life cycle inventory since it is important to know how the environmental parameters were aggregated. Some subclasses could be EPD methodology, European footprint methodology and among others. Since the focus of the ontology lies at the building level and creating a structure covering these different methodologies at the product level may be difficult and impractical, the structure of the ontology was not modified and the hierarchy under the EPD data was preserved.
- To check the relation between *Scenario* and *Boundary*, it could be represented inversely. The EN 15978:2011 was reviewed again to check other possible approaches to represent the relation between the *Scenario* and *Boundary* classes. However, the standard states in Section 8 that scenarios are created "for" the different stages (here represented by the concept Boundary), therefore the definition of the property hasScenario was preserved to represent the relation as: *Boundary* hasScenario *Scenario*.
- To describe better the concept "Scenario", it requires a better characterization, as it is a main element in the LCA and LCC assessments. More detailed characteristics and other sub-concepts related to this concept should be included. A new class *Scenario_GeneralInformation* was created to represent more in detail the concepts associated to scenarios developed for the boundaries of the assessment.

4.5.2 Ontology design verification

The hierarchy and relations of each class and sub-class of the final ontology were checked extensively following the list of common errors presented in Section 2. Adjustments were implemented to solve the errors identified, some of them are mentioned in Table 6 when necessary.

Table 6. Errors and actions for the LCA-C ontology verification

Description	Related error
The sub-classes from the concept GlobalCostIndicator were not disjoint	Non-disjoint classes
The sub-classes from the class CostVariable were not disjoint	Non-disjoint classes

Adjustment: The data property hasDescription was assigned to the class Boundary to complement the description of this concept	Lack of exhaustivity. Lack of specification and limitation of the properties
Adjustment: The properties hasValue and hasUnit were assigned to the class CostVariable	Lack of exhaustivity. Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasBoundary were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasCostIndicator were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasCostParameter were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasEnvironmentalIndicator were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasEnvironmentalParameter were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property consumesResource were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property includes were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Functional object properties such as hasCostType, hasDataSource, isAssociatedTo, and among others were not declared explicitly as functional	Lack of specification and limitation of the properties
Adjustment: All data properties were defined as functional	Lack of specification and limitation of the properties

5. BEM-Reno Ontology

5.1 Motivation and current state of the art

Since energy use is one of the major contributors to the environmental impacts produced along the life cycle of buildings, it is important to estimate it accurately during the design stage to guarantee that different renovation scenarios are compared in a reliable way and to reduce the gap between the design and real performance after renovation. Therefore, the third proposed ontological model focuses on the development of BEM models for renovation projects.

In general, the creation of a BEM model from scratch is a process that is often prone to human error. The current building energy performance simulation tools require a great deal of time and effort because data from multiple sources must be properly combined (e.g., building/urban models, renovation measures catalogues, occupancy, weather condition files) to create a BEM model (Gonçal Costa et al. 2020). Managing these data in an inefficient way may lead to re-work, additional costs, errors, and delays in delivery times. Some works have tried to address this issue, for instance, Corry et al. (2015) present a semantic web-based approach describing how heterogeneous building data sources can be transformed into semantically enriched information. A performance assessment ontology and performance framework (software tool) are introduced, which use this heterogeneous data as a service for a structured performance analysis. The SimModel (O Donnell et al. 2011) was created and designed as an interoperable XML-based data model to satisfy the information needs of building energy simulation tools (e.g., EnergyPlus) and facilitate the information modelling and exchange between different tools. The SimModel was also developed into an ontological model introduced by Pauwels et al. (2014). However, this approach may be strongly linked to the IFC schema, which has some drawbacks related to interoperability and covering different domains, supporting data integration, and linking and tracking at the data level.

In the AEC industry, the implementation of BIM technologies may support the modelling and management of different data related to the building environment. BIM was initially intended to support design and construction, although it has not been widely used for managing existing buildings and renovation projects (Ungureanu et al. 2016). In the context of renovation projects, defining information requirements and needs might be quite challenging, as there are usually no digital models of the building available. Most of the data is often available only as hard copies, outdated, poorly documented or not available at all. However, there have been some efforts to integrate the advantages of BIM technologies with the development of BEM models for renovation. Gonçal Costa et al. (2020) introduce a system using BIM technologies to integrate data from energy renovation measures into BEM models in an automated way. According to (Stegnar et al. 2019), around 75% of the information required to perform an hourly dynamic simulation may be already included in an IFC file, however, to include the missing information requires manual labour and is therefore prone to human errors.

As presented in the BIM-SPEED deliverable *D3.1 Analysis of BIM-to-BEM critical parameters and recommendations to solve the current bottlenecks*, some BIMtoBEM workflows have been established in practice. In the Revit – SketchUp (with Euclid plug-in) – EnergyPlus' BIMtoBEM procedure shown in Figure 22, the BIM model is developed with Autodesk Revit™ and completed with all the geometrical features and most of the thermophysical characteristics of the materials. Then, the model must be simplified eliminating unnecessary data to create an "Energy Model". This model needs to be converted into the IDF file format of the EnergyPlus simulation engine. Because of shortcomings in the above-mentioned conversion process, the IDF file has to be manually controlled and amended. In particular, for the building geometry, it is possible to manually inspect the IDF model for errors and to provide manual adjustments and corrections. As a final step, the BEM model is manually enriched with all the missing data concerning the non-geometric properties (HVAC specifications, operation schedules, etc.).

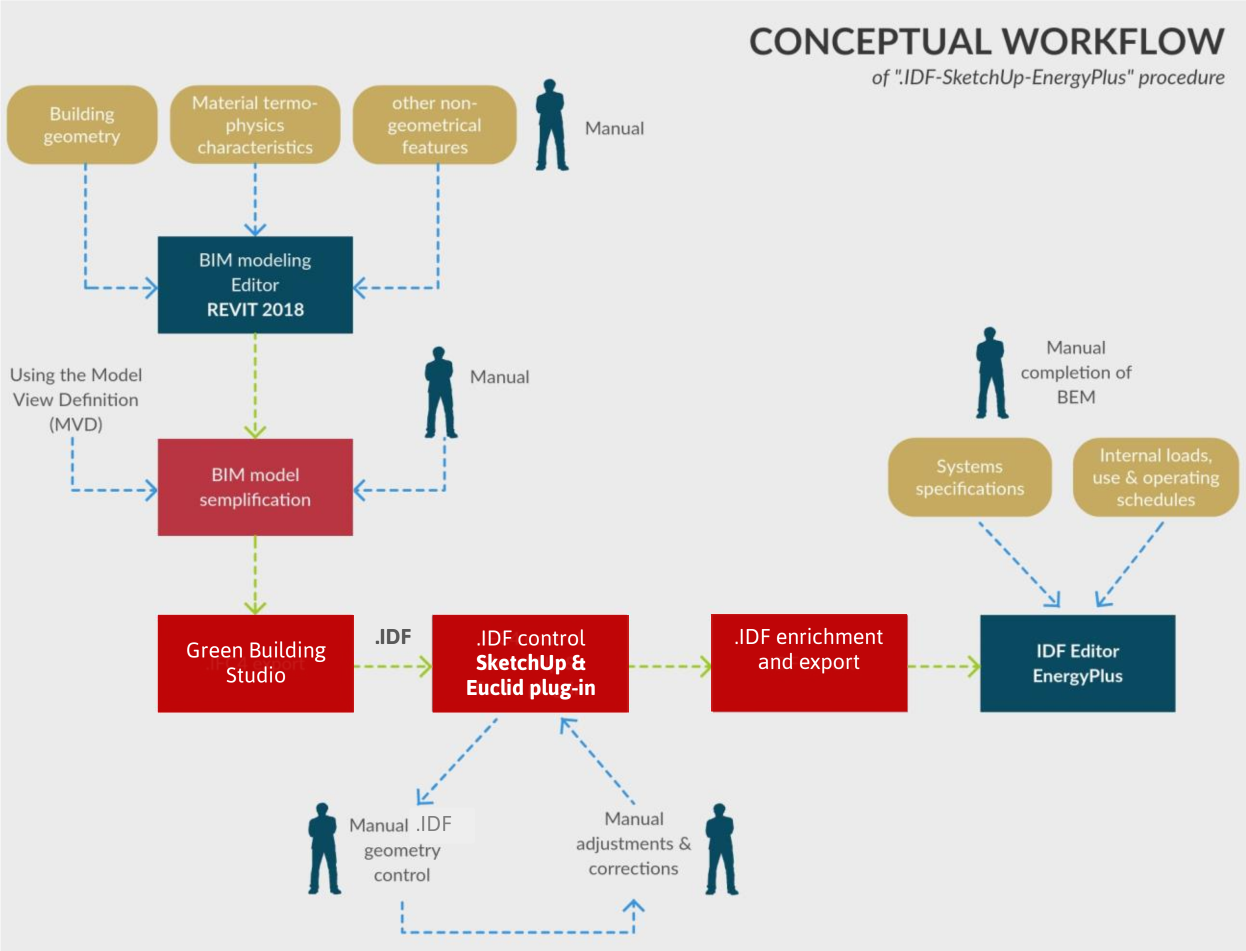

Figure 22.Revit – SketchUp (with Euclid plug-in) – EnergyPlus" BIM-to-BEM procedure (BIM-SPEED 2019b)

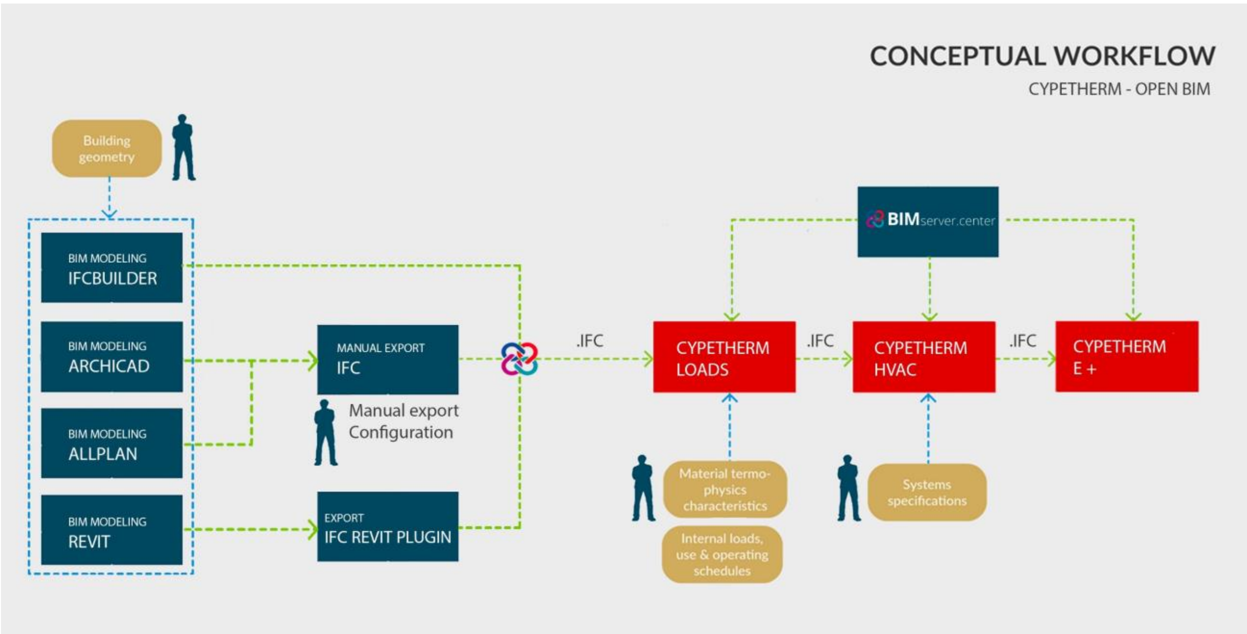

Figure 21. "IFC-CYPETHERM Suite" conceptual workflow of the procedure (BIM-SPEED 2019b)

On the other hand, in the ".IFC - CYPETHERM Suite" BIM-to-BEM procedure presented in Figure 21, the IFC geometry can be generated by different tools. Then, the IFC model is exported and thermal loads are calculated from the IFC geometry, which will lead to the calculation of the HVAC equipment and the energy efficiency using EnergyPlus as the calculation engine. Characteristics from the materials, internal loads, operating schedules, and HVAC system specifications are inserted manually.

It is clear that the two procedures still include activities that should be performed manually by experts, being time-consuming and prone to errors. Therefore, the goal of the BEM-Reno ontology is to support the tasks that should be performed manually as part of the diverse BEM development and BIMtoBEM procedures, including the manual geometry control and adjustments, and manual completion and enrichment of BEM (materials, HVAC system, and load characteristics). This information usually comes from diverse sources and is stored in different formats, especially in the context of renovation projects where data sources are rarely homogeneous, sets of information may be missing and therefore should be often assumed or estimated. Having an ontological model for the required information for BEM may facilitate 1) the collection of data with a more structured and standardized approach and 2) the retrieval of missing or lost information across the BIMtoBEM processes that need to be included manually into the BEM model being developed.

5.2 BEM-Reno Ontology specification

This section presents an overview of the proposed BEM-Reno ontology, comprising information regarding the purpose, use, users and domain covered by the ontology. A set of competency questions is also presented to enable the identification of potential concepts that should be modelled by the ontology regarding the building geometry, buildings systems, operation, and other aspects.

- **What is the purpose?** The BEM-Reno ontology was developed to represent concepts related to the building energy model of a building under renovation, the goal is to support the development of BEM models with the sufficient information required to perform building energy analysis in the context of renovation projects, especially to support the manual tasks that make part of BIMtoBEM approaches. The ontology can be also the starting point to develop an interface to support the BEM modelling.
- **What is the scope?** The ontology will cover concepts and relations regarding the existing conditions of the building, material features, building systems, operational schedules, and thermal characteristics.
- **Who are the intended end-users?** The intended end-users are architects, engineers and other stakeholders which may be involved in the development of BEM models for residential building renovation.
- **What is the intended use?** The intended use of the ontology is to support the development of BEM models for building renovation projects. Since the ontological model represents the information required to develop a BEM model, it can support the data acquisition process of the existing conditions of the building. Moreover, it can assist the manual enrichment, corrections and other activities related especially to BIMtoBEM procedures. For instance, the model can be used as a template that should be filled in, guiding the acquisition of the required existing conditions of the building to develop a BEM model. On the other hand, conventional and BIM-based BEM development

approaches usually require manual tasks and experts' interventions to simplify models, enrich them and correct the definition of thermal zones, operational schedules and many other aspects. A user may query the BEM-Reno ontology to compare the collected information with the data included in the BIM model associated with the building. The ontology can be queried to look for missing information related to schedules, material features, and HVAC systems, which usually gets lost during the BEMtoBEM processes. The set of competency questions presented in Table 7 was developed to identify some of the concepts that users may be interested in.

Table 7. Competency questions and answer examples for the BEMReno Ontology

Competency questions	Example answers
What is the description of the occupancy schedule for Zone 4?	Schedule:Week:Daily, Week room A, Weekday Sch3, Weekday Sch3, Weekday Sch3, Weekday Sch3, Weekday Sch3, Weekend day Sch3, Weekend day Sch1, Holiday Sch1, Summer design Sch1, Winter design Sch1.*.
Which material can be used as an alternative for a King brick?	Queen brick
What is the Solar transmittance of the glazing of window 8? And its data source?	89.5 %, Data source: Manufacturer datasheet
Which is the interface between zone 7 and zone 8?	Wall 31
What are the geometry attributes of wall 22?	Length: 6 m, Height: 2.30 m, Tilt angle: 90, Azimuth: 180
What is the equipment thermal load in zone 6?	50 Watts, Schedule: Equipment load zone 6

*According to Energyplus description, i.e. each schedule can be described by a schedule assigned to Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, and Sunday. Special day types that can be designated are: Holiday, SummerDesignDay, WinterDesignDay, CustomDay1, CustomDay2.

As presented in Figure 23, a potential use of the BEM-Reno ontology can be to guide the acquisition of the required existing conditions of the building to develop a BEM model during the first stages of the renovation project. Moreover, during the design stage, the ontology can support users to develop the BEM model for the building, helping the experts to perform the manual tasks discussed in the previous section, which are usually performed to simplify models, enrich them and correct the definition of thermal zones, operational schedules and many other aspects. For the enrichment and completion of the BEM model during the design stage, a user can retrieve (all from the same knowledge base) the collected information and data from the BIM model associated with the building, look for missing information related to schedules, material features, and HVAC systems, which usually gets lost during the BEMtoBEM processes. Therefore, making easier to gather, manage, and leverage the heterogeneous information available from the building.

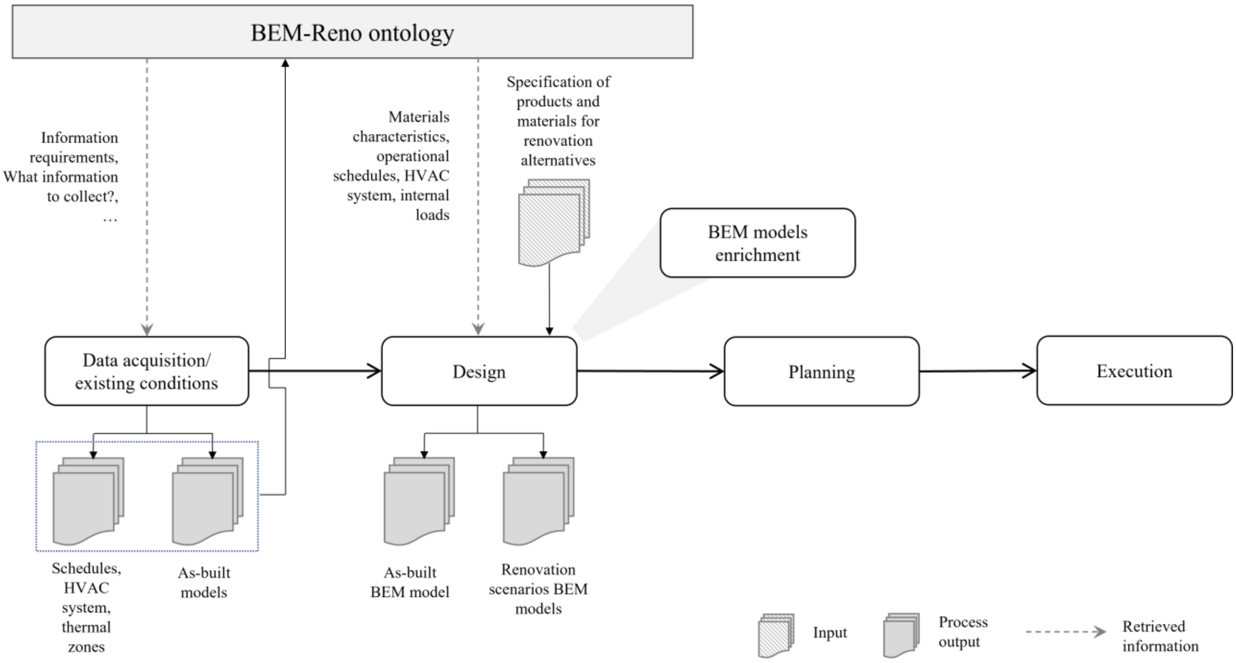

Figure 23. Potential use of the proposed BEM-Reno ontology

5.3 Knowledge Capture and Conceptualization

The main goal of the knowledge capture is to identify the information linked to the BEM model development for renovation, which concepts should be modelled, and which are the relations between them. The concepts identification and their proposed hierarchy are developed based on the specification and competency questions presented in the previous section. The knowledge capture relied on literature review related to building energy simulations, BEM models, tools requirements and bottlenecks of the BEM development process, as summarized in Table 8. The main source corresponds to the information requirements presented by Ungureanu et al. (2016) in the context of the P2ENDURE project[10], which is related to the implementation of BIM technologies for building renovation. The main concepts focus on general features of the building, geometry, building systems, materials, and operational information.

Table 8. Sources for the BEMReno ontology knowledge

Main Concepts	Terms Examples	Source
General requirements	InternalLoad, hasDayDescription, hasWeekDescription, hasAlternative	(BIMSPEED 2019b), (Ungureanu et al. 2016)
Building	Zone, Room_Space, Interface, BuildingElement, Material	(Rasmussen et al. 2020), (Ungureanu et al. 2016)
Operation	Schedule, RoomOperationalAttribute, BuildingSystem, EnvironmentalInformation	(U.S. Department of Energy 2015), (Ungureanu et al. 2016)

[10] https://www.p2endure-project.eu/en

5.4 BEM-Reno Ontology Description

5.4.1 BEM-Reno overview

Re-using previous ontologies and publishing modular ontologies are often mentioned as good practices for the ontological development in the AEC industry. Following these principles, we intended to re-use the Building Topology Ontology - BOT ontology[11]. The BOT ontology is a model for describing the core topological concepts of a building (Rasmussen et al. 2020 BOT), it was developed by the Linked Building Data Community Group[12]. This model is simpler and maybe more practical than approaches such as SimModel which is strongly linked to the IFC schema. The latter has some drawbacks related to interoperability and covering different domains, which play a key role in renovation projects that bring together different domains such as building, GIS, users surveys, and gathers data from different sources, with uncertainties and assumptions. Nevertheless, we encountered some differences between the concept bot:zone (a part of the physical world or a virtual world that is inherently both located in this world and having a 3D spatial extent) and what can be defined as Thermal zone in the domain of BEM modelling (an area of a building in which temperature is controlled by one thermostat). Since the concept bot:zone is the core of the BOT ontology, re-using the exact BOT ontology was not suitable, therefore, we use the conceptual model and structure of the BOT ontology only as a starting point to develop the proposed BEM-Reno ontology instead.

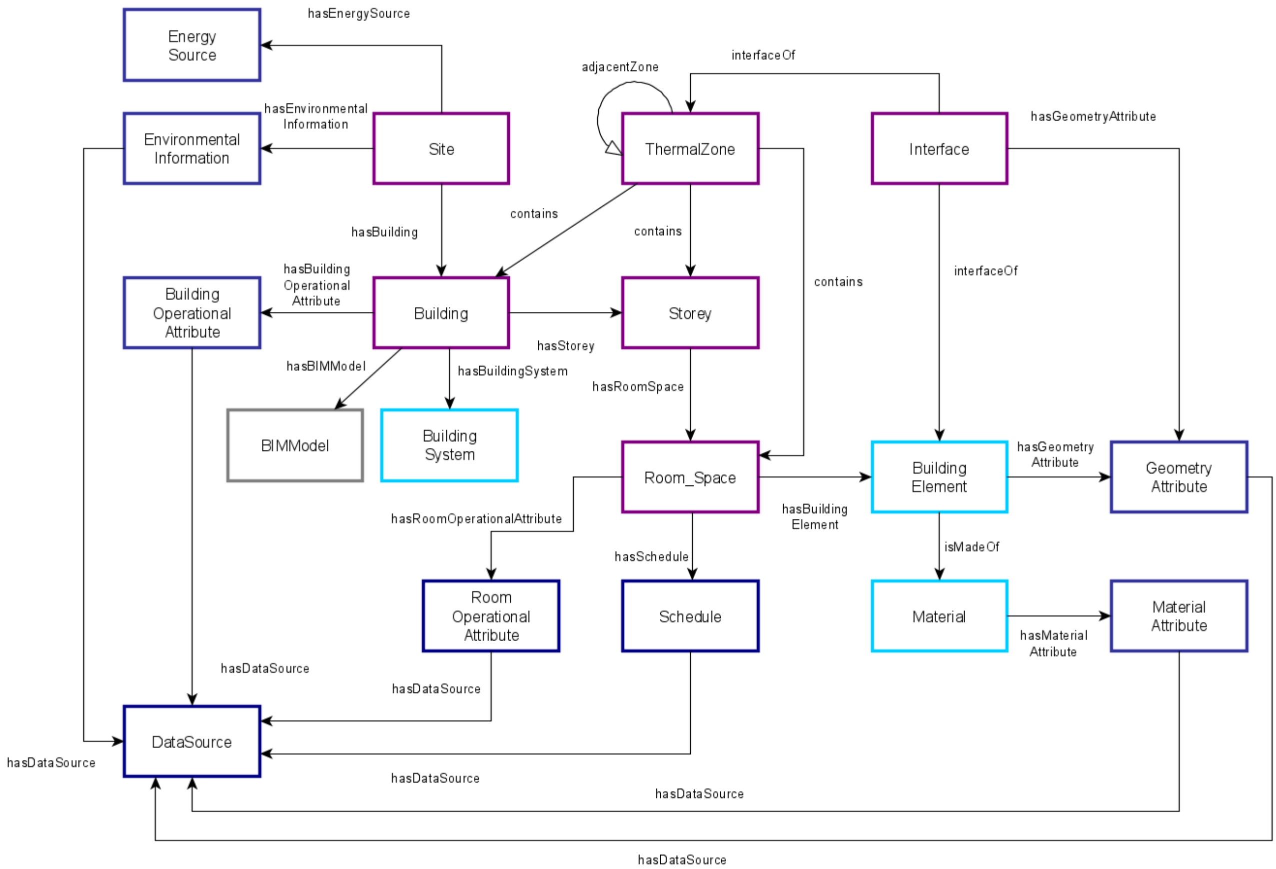

Figure 24. BEM-Reno ontology overview

11 https://w3c-lbd-cg.github.io/bot/#bib-rasmussen2020
12 https://www.w3.org/community/lbd/

Some potential alignments between the BEM-Reno and BOT ontologies are presented in Section 6. Multiple classes such as *EnvironmentalInformation*, *RoomOperationalAttribute* and *DataSource* were added to represent the additional relevant concepts from the BEM modelling domain as presented in Figure 24. The concepts and relations included in the proposed BEM-Reno ontology were extracted mainly from the P2ENDURE information requirements (Ungureanu et al. 2016), the BIM-SPEED deliverable *D3.1* (BIMSPEED 2019b), and an excel sheet that aims at supporting the BEM model data capturing in the context of renovation projects, which was developed by the BIM-SPEED partners RINA and CYPE.

The *Building* class is one of the main concepts in the model, it has *BIMmodel*, *BuildingSystems*, and *BuildingOperationalAttributes*. A *Building* has *Storey*, which has *Room_Spaces*, which in turn has *BuildingElements*. The concept *ThermalZone* can contain the entire *Building*, a *Storey* or *Room_Spaces*. This depends on the way the thermal zones are defined in the BEM model. The *BuildingElement* is described by *GeometryAttributes* and is made of *Materials* that are also described by some *MaterialAttributes*. On the other hand, each *Room_Space* has *RoomOperationalAttributes* and *Schedules*. The *DataSource* concept was included to facilitate the traceability of the information that will be used for the BEM model development. The *EnergySource* class gathers the energy sources available at the *Site* that supply the different building energy requirements. The *EnvironmentalInformation* class represents the weather and surrounding data which is essential to perform any energy simulation analysis. This concept is not described in detail in this report since a detailed ontological model is being developed in close collaboration to the prototype tool developed as part of BIM-SPEED deliverable *D1.4 IT solutions to couple environmental, surroundings and weather data to BIM*. The entire hierarchy and list of properties extracted from Protégé describing the complete ontology are presented in Appendix A. The following subsections describe in detail the general concepts, their subclasses and additional concepts that complement the representation of the domain.

5.4.2 Building elements and attributes

As shown in Figure 25, the *BuildingElement* concept includes inner and external elements. This classification facilitates the identification of elements that constitute the envelope and outer components, which play a key role during the development of BEM models since their physical and thermal characteristics have a big impact in the performance of the building. Each *BuildingElement* may have different *Layers*, both concepts are described by *GeometryAttributes* and are made of a specific *Material*, which has attributes such as *Absortance*, *Density*, *Specific Heat*, among others. A data type property hasAlternative is included to add alternative materials for each of the materials included in the model; often the name and specification of materials in BIM models and BEM simulation tools are not equivalent, therefore, it is necessary to have potential alternatives that could be used to represent the material according to the material description available in other databases. It is also important to notice that the purpose of the ontology is to support stakeholders during the BEM model development, especially in BIMtoBEM approaches, to verify irregularities. For this reason, only basic geometry information is represented in the ontology, instead of the whole 3D model specification, which can be checked on the *BIMModel* associated to the BEM model being developed. If a more complex geometry representation is necessary, strategies to align existing ontologies such as the Ontology for Managing Geometry (OMG)[13] may be pursued. In a similar fashion as in the previous ontological models, datatype properties of unit definitions according to the QUDT catalogue[14] can be re-used to describe the units of the different attributes included.

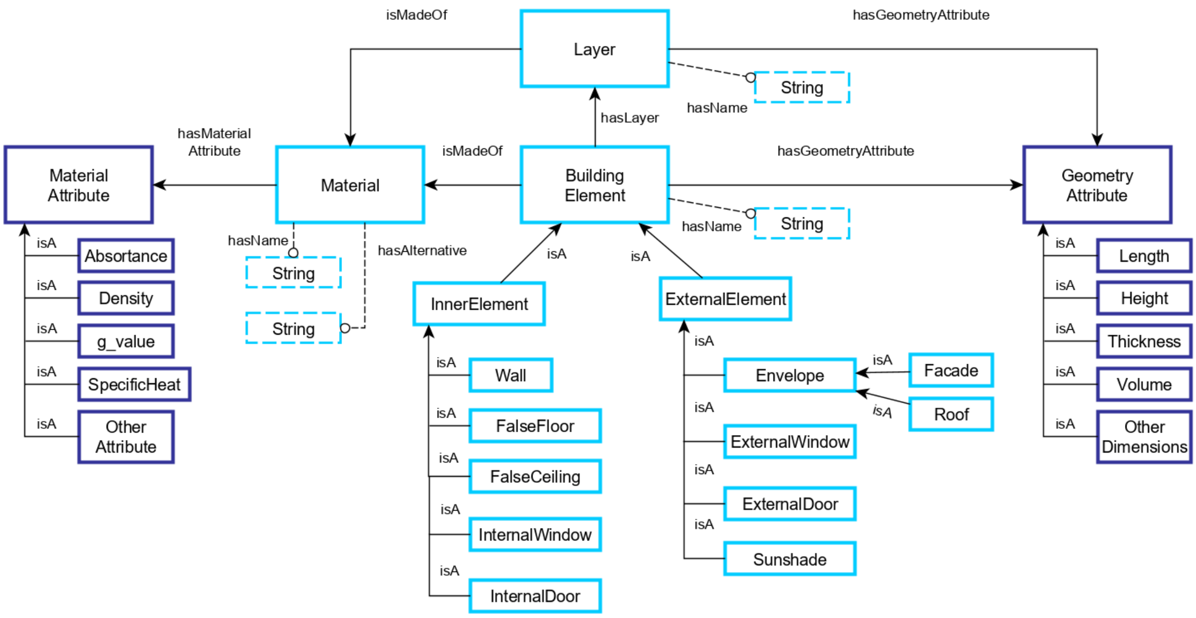

Figure 25. *BuildingElement*, *Layer*, *Material*, and attribute classes

5.4.3 Building systems

Building systems play a key role in the characterization and estimation of the building performance, HVAC and Lighting systems usually represent the major energy loads in buildings. They are specified explicitly in conjunction with the Domestic Hot Water (DHW) as presented in Figure 26.

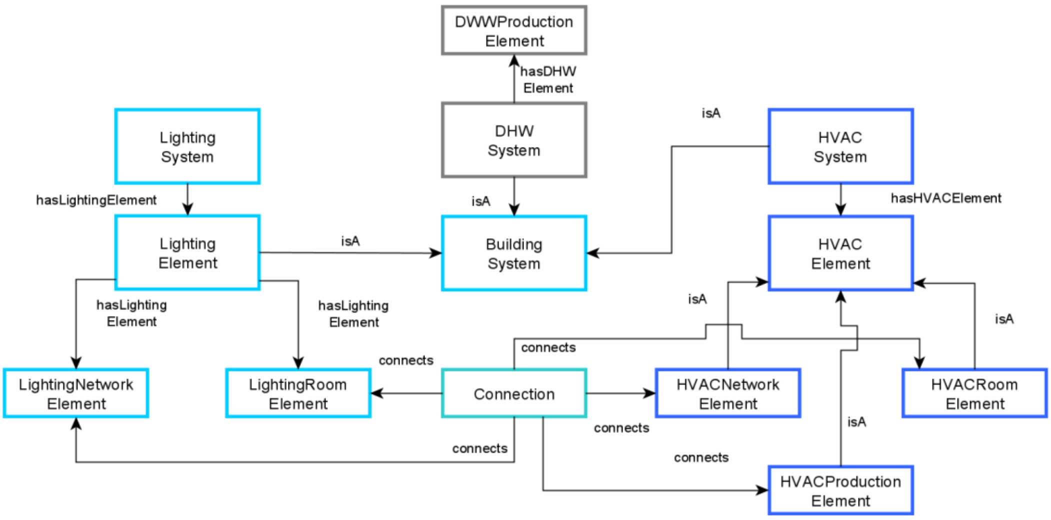

Figure 26. BuildingSystem class

The *HVACSystem* is composed by *ProductionElements*, representing the generation devices; *NetworkElements*, which correspond to the elements that distribute the heat, ventilation air and

13 https://www.projekt-scope.de/ontologies/omg/
14 https://qudt.org/

cooling fluids through the building; and *RoomElements*, being the final units installed in the diverse spaces of the building to supply the heating, cooling and ventilation requirements. For the *LightingSystem* only network and room elements are modelled. Representing production elements for the lighting system is not relevant since lighting devices consume electricity from the general network of the building, and other devices such as solar tubes use natural illuminance as the source. On the other hand, only the production element from the *DWHSystem* is included. For this system usually network elements are modelled as losses and final units are not considered. The class *Connection* is included to represent elements such as connectors, valves, and switches that connect the different system elements. Additional data type properties such as hasName, hasPowerDensity, and hasProvidedLightingLevel are included to represent the attributes of the lighting elements. The following section presents a more detailed representation of the HVAC elements and their attributes.

5.4.4 HVAC elements and attributes

In conventional and BIM-based BEM model development workflows there are challenges regarding the correct and complete transfer of information from one software tool to another. Even though some of the HVAC system information can be inserted in BIM models, often only a fraction of it gets transferred properly during the export processes to the energy simulation tools and therefore require time-consuming and error-prone manual data re-entry tasks. Therefore, as shown in Figure 27, the BEM-Reno ontology includes a detailed representation of the HVAC system to bring together relevant information that may be retrieved to support the above-mentioned manual data re-entry activities. As HVAC systems have multiple configurations, establishing an extensive HVAC system representation may lead to a large and unpractical approach. Therefore, the BEM-Reno ontology includes a pragmatic model of the HVAC system. Each of the general HVAC elements is classified as heating, cooling, or ventilation element. Each *HVACElement* has *HVACAttributes* that describe its functional features, including *EnergyFuel*, *MaxPartloadRatio*, *PerformanceCurves*, among others. These attributes are classified according to the three general HVAC element categories production, network, and room.

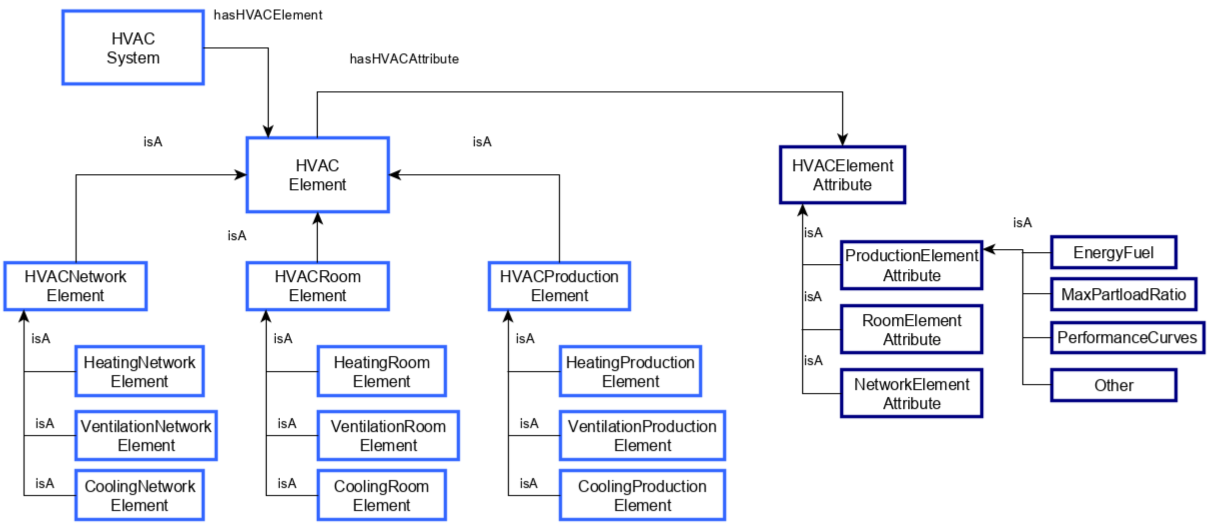

Figure 27. *HVACSystem* and *Element* classes

5.4.5 Room_space

The *Room_Space* concept shown in Figure 28 represents one of the basic functional units of the building. Rooms and spaces are the linking points of concepts such as *RoomOperationalAttribute*, *Schedule*, *BuildingElement*, and *ThermalBridge*, which are essential for the development of BEM models. As pointed out in the BIM-SPEED deliverable *D3.1* (BIMSPEED 2019b), in the context of BIMtoBEM procedures, *Schedule* information is one of the data sets that should be included manually in the BEM model since it cannot be directly inserted into BIM models. Hence, the *Schedule* class in the BEM-Reno ontology gathers all the typical schedules required to enrich the BEM model. On the other hand, the *RoomOperationalAttribute* class includes five main classes of attributes, each one has a set of subclasses that are not shown in the figure to facilitate the representation. The class *GeneralAttributes* comprises *UsageType*, *VentilationType*, *Position* (Inner or Perimeter), and other features. *AirAttribute* includes *AirchangesperHour*, *OutdoorAirMethod*, and additional attributes related to the air modelling of the room. *InternalLoads* has sub-classes to represent the *EquipmentThermalLoad*, *LightingThermalLoad*, and *OccupantThermalLoad*. *TemperatureAttribute* comprises *IndoorDesignTemperature*, *MaximumComfortTemperature*, *MinimumComfortTemperature*, and other relevant temperature characteristics.

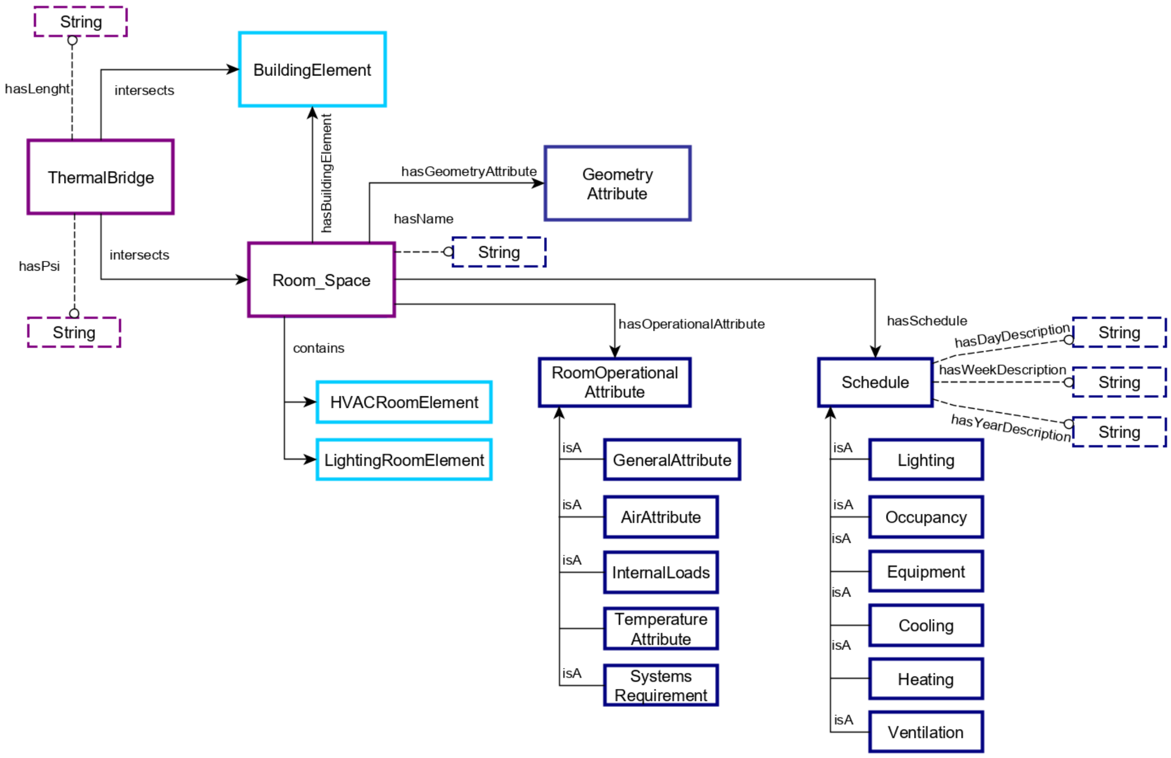

Figure 28. Room_Space, RoomOperationalAttribute, Schedule and ThermalBridge classes

The *SystemRequirement* concept includes the cooling, heating, ventilation, lighting and DHW levels required for the room. A *RoomSpace* has associated also different schedules to define the operational patters for the occupancy, heating, cooling, and other aspects. Each *Schedule* has data properties to describe its daily, weekly, and annual patter. They are usually described through pieces of information in the form of strings containing the name of each time slot (e.g. 11:00, 12:00,..., Monday, Tuesday,..., or January, February,...) and their value during that time. Finally, the *ThermalBridge* is included to represent the thermal bridges that may occur between different building elements and spaces. Here the model considers only linear thermal bridges, nevertheless, the concept can be extended to represent other thermal bridge categories.

5.4.6 Thermal zone and Interface

Defining thermal zones is a key task in the development of BEM models. A *ThermalZone* may include a single or multiple *Room_Spaces*. During the initial stages of design, the building may be even simulated as a single *ThermalZone*. Hence, as presented in Figure 29, a *ThermalZone* may contain *Building*, *Story* or *Room_Space*. Thermal zone boundaries and interfaces information is a sensitive aspect of the BEM model. Building energy simulation tools allow modelling surfaces heat exchange between thermal zones and through elements when a more detailed analysis is required. Therefore, the class *Interface* and the object properties interfaceOf and AdjacentZone (similar to the BOT ontology approach) are included to represent the characteristics of the boundaries between Thermal zones, and elements.

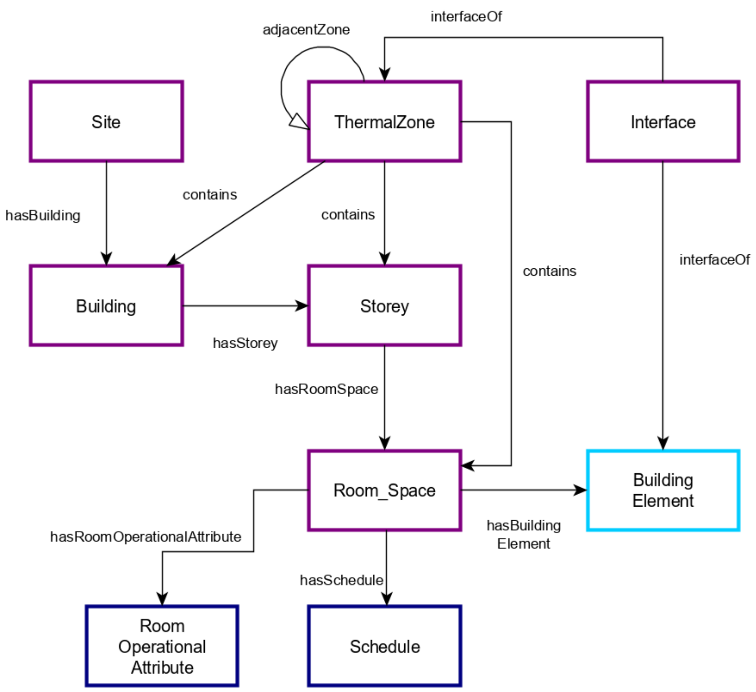

Figure 29. *ThermalZone* and *Interface* classes

5.4.7 Data source

The *DataSource* class shown in Figure 30 is included to represent explicitly the source of the information available to be included in the BEM model. In the context of new buildings, the information to develop a BEM model come from more homogeneous sources, while in renovation projects, multiple data is gathered, estimated, and assumed based on diverse sources such as *ExistingDrawing*, *HistoricalData*, *UserSurveys* and *DataBases*, making difficult to check traceability and consistency of the information, uncertainties and errors. Therefore, representing this aspect explicitly is essential to support the BEM development process in the context of renovation projects. All the classes representing attributes and specific information are linked to the *DataSource* class through the property hasDataSource. An additional data property includeInBimModel is included to specify whether a certain piece of information is included also in the *BIMModel* associated with the building. This can support the verification process in the BIMtoBEM procedures, which usually requires a comparison of the information in the BIM model with the information imported into the BEM model. The information to be checked and compared usually includes names of diverse elements, materials specification, geometry attributes, and others.

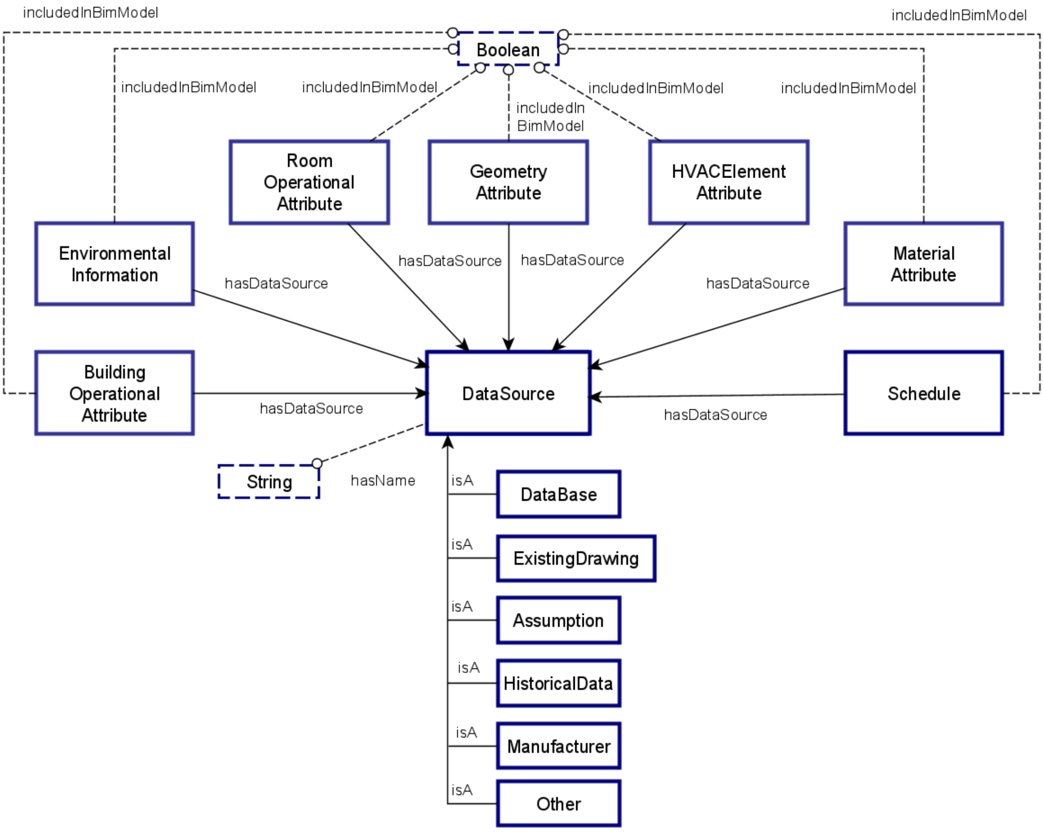

Figure 30. *DataSource* class

5.5 BEM-Reno Ontology evaluation

5.5.1 Workshop with experts

A workshop with a set of practitioners of the BIM-SPEED consortium was conducted to identify potential adjustments and evaluate the general ontological model proposed for the BEM model development. The group comprised two Architects, an Energy modelling expert, and a Computer Engineer from two different companies and a research institute. The goal was to evaluate if the model is coherent with the domain **BEM model development for renovation**. The specific subjects leading the workshop can be summarized as follows:

- Does the model cover all the concepts and attributes required to fulfil its intended use?
- Does the taxonomy and hierarchy of concepts represent the terms and structure of the elements in the real world?
- Are the relations between concepts according to the real-world interactions?

The purpose of the BEM-Reno ontology, its potential use and competency questions were presented to the experts. Then the general model and the details of each concept were discussed thoroughly, whereby special attention was given to the attributes describing the different classes and the relations between physical concepts such as thermal zones and rooms. Based on the discussions and results from the workshop, the ontology was adjusted according to the following experts' recommendations:

- To specify which of the information is already included in the *BIMModel* associated to the building. To do this, the data property includedInBimModel was included. The boolean value indicates whether or not a certain instance of the different classes is included in the *BIMModel*. As mentioned previously, this information may support the verification process of the diverse BIMtoBEM procedures.
- To include a concept to represent the DHW system. Even though the DHW demand is often represented as an aggregated value in many building energy analyses, the DHW production device is relevant for the analysis. Therefore, the classes *DHWSystem* and *DHWProductionElement* were created. Additional sub-classes were included under the *RoomOperationalAttribute* and *HVACElementAttribute* to represent the DHW requirements of each *Room_Space* and characteristics of the *DHWProductionElement*, respectively.
- To create a *HVACElement* concept to aggregate the concepts *HVACProductionElement*, *HVACNetworkElement*, and *HVACRoomElement*. This approach enhances the structure of the ontology and improves the way the model can be queried in future implemented applications. The class *HVACElement* was created and the three existing classes were assigned as sub-classes of it. A similar approach was applied to adjust the *LightingNetworkElement* and *LightingRoomElement*.

5.5.2 Ontology design verification

The review process allowed identifying errors in the ontology and implementing a set of adjustments as presented in Table 9.

Table 9. Errors and actions for the BEM-Reno ontology verification

Description	Related error
The external and inner element classes were not disjoint	Non-disjoint classes
The sub-classes from the class BuildingGeneralInformation were not disjoint	Non-disjoint classes
The sub-classes from the sub-class ProductionElementAttribute were not disjoint	Non-disjoint classes
Adjustment: The hasDescription data property was added to the Data Source class to complement the representation of that concept	Lack of exhaustivity
Adjustment: Sub-properties for the object property hasBuildingElement were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasBuildingSystem were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasHVACAttribute were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties

Adjustment: Sub-properties for the object property hasHVACElement were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasLightingElement were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasRoomOperationalAttribute were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Adjustment: Sub-properties for the object property hasSchedule were created to specify better this relation and facilitate inference over the model	Lack of specification and limitation of the properties
Functional object properties such as hasDataSource and isMadeOf, and among others were not declared explicitly as functional	Lack of specification and limitation of the properties
Functional data properties such as hasValue, hasDescription, hasProvidedHeatingLevel, and among others were not declared explicitly as functional	Lack of specification and limitation of the properties

6. Relation between the models, existing ontologies and data structures

The three proposed models cover different domains from the building renovation field, nevertheless, they share some concepts and elements. For instance, the *RenovationProduct* concept appears in the Reno-Inst and LCA-C ontologies. The concept *Material* is the same in BEM-Reno and Reno-Inst ontologies, it represents the material of which a certain element is made of. In a similar fashion, the concepts *ConstructionMaterial* and *Resource* included in the Reno-Inst ontology correspond to the same concepts included in the LCA-C model, the first one represents the construction material required to install the new *RenovationProduct* in the building and the second one relates to the resources such as water, energy, etc. required during the construction activities or the operation of the building. *DataSource* represents the same concept in the BEM-Reno and LCA-C ontologies. In certain scenarios, when the *ObjectOfAssessment* correspond to the entire building being renovated, the concept *Building* from the BEM-Reno ontology will be equivalent to the concept *ObjectOfAssessment* from the LCA-C ontological model.

An important aspect in the development of ontological models is the integration, re-use, and alignment with existing ontologies. Existing resources re-use and alignments allow to link or convert from datasets described with one ontology to another. For the LCA-C ontology, the ontological model presented by Schwartz et al. (2016) was re-used to model the *EnvironmentalParameter* and *EnvironmentalIndicator* classes, this approach is based on the EPD data structure.

For the Reno-Inst ontology, we studied the possibility to re-use the existing BPO: Building Product Ontology[15] to describe the *RenovationElement*, nevertheless, during the development of the ontology, it was noticed that an alternative approach would be more suitable to represent separately the components that would be linked to the building interface where the *RenovationElement* is installed. This facilitates to

[15] https://www.projekt-scope.de/ontologies/bpo/

infer information regarding specific details of these components to analyse the compatibility of materials and technologies between the *RenovationElement* and the *BuildingInterface*. For instance, information regarding the fixing mechanism of a window can be easily retrieved to check compatibility between the material of it and the material and state of the opening where the window would be installed. On the other hand, alignments with existing ontologies can be pursued. For instance, the BuildingElement concept can be mapped to the concept bot:BuildingElement from the BOT ontology[16], which provides a representation of additional concepts related to a building such as spaces, stories, and zones. Some efforts to integrate the BOT ontology with BIM authoring tools and IFC documents have been presented in (Rasmussen et al. 2020 BOT). Future integration of the knowledge mapped by the Reno-Inst ontology with these existing ontological resources can enable multiple stakeholders to exploit the potential that comes with technologies such as BIM modelling to support additional tasks in renovation projects.

For the BEM-Reno ontology, as mentioned in Section 5.4.1 the concept bot:zone was not entirely compatible with the understanding of *Zone* or *ThermalZone* in the BEM modelling domain. Nevertheless, many concepts from the BOT ontology were integrated into the BEM-Reno ontology, facilitating potential alignments between the models. The classes bem-reno:Site, bem-reno:Building, bem-reno:Storey, and bem-reno:Room_Space can be mapped to the concepts bot:Site, bot:Building, bot:Storey, and bot:Space. One of the advantages of using the BOT model as the starting point for the BEM-Reno ontology is that it has already defined an alignment with ifcOWL, facilitating a future integration of the BEM-Reno model with the IFC standard. For instance, the concepts ifc:IfcSite, ifc:IfcBuilding, ifc:IfcBuildingStorey and ifc:IfcSpace can be straightforwardly specialised from their respective BOT concepts, i.e. bot:Site, bot:Building, bot:Storey, bot:Space. More detailed information can be found in (Rasmussen et al. 2020 BOT). Finally, for the three proposed ontologies, datatype properties of unit definitions according to the QUDT catalogue can be re-used to describe the units of the different attributes, parameters, and indicators modelled to describe characteristics of the concepts from the domains.

On the other hand, the knowledge mapped through the three ontologies allows identifying general information, specific data, and parameters from the building, components, systems, and renovation products that may be relevant for the implementation of additional use cases, especially related to the employment of BIM technologies in the context of renovation projects. A segment of the mapped information may be embedded in BIM objects describing renovation products and building elements, allowing to develop a more complete BIM model including the sufficient information to perform different tasks along the renovation process. The W3C Linked Building Data Community[17] introduced the set of common data domain categories presented below to facilitate the structuring of data related to buildings and tag different use cases. Table 10 maps the domains covered by the three proposed ontologies, some of the classes of the models are mentioned to illustrate how the concepts represent the specific domain.

- **Building Product** (includes Geometry, excludes devices) (e.g. 2D, 3D, Zones/Spaces, materials, cost, durability, etc.)

[16] https://w3c-lbd-cg.github.io/bot/#bib-rasmussen2020
[17] https://www.w3.org/community/lbd/wiki/Seed_Use_Cases#Data_Domains

- **Building Devices** (e.g. HVAC, sensors, actuators, etc.)
- **Building Control** (e.g. Scheduled Automation, Intelligent automation [fuzzy reasoning, agent based, etc.])
- **Building Behavior** (e.g. inferred data like building state, user activities, etc.)
- **Building Communication** (e.g. communication protocols and interfaces, message structures, etc.)
- **Building Data** (e.g. measured data, set points, data structure, data storage etc.)
- **Energy** (e.g. predictive energy models, energy tariffs, etc.)
- **Geolocation and Weather** (e.g. location of building, relationship to district, predictive weather models, local weather data)
- **Historical Building Data** (e.g. historical data, heritage data, original plans, etc.)
- **Norms and Regulation** (Important terms and concepts related to norms and regulations.)
- **Best Practice Methods and Technologies** (Different technologies that could meet both district and building level requirements in terms of performance, energy efficiency, and sustainability)
- **Actors** (the actors who are involved in the activities related to all building life cycle stages)

Table 10. Relevant data domains covered by the proposed ontologies

Main Concepts	Reno-Inst	LCA-C	BEM-Reno
Building Product	RenovationProduct, PhysicalAttribute, FunctionalComponent, BuildingInterface	RenovationProduct, Material, CostParameter, EnvironmentalParameter, ObjectOfAssessment	BuildingElement, Material, ThermalZone, GeometryAttribute, MaterialAttribute
Building Devices			BuildingSystem, HVACElement, LightingElement, Connection
Building Control			
Building Behaviour	OwnerOperationalConstraint, InhabitantCoordination Constraint, SafetyConstraint	UseSate_Module, OperationalEnergyUse, OperationalWaterUse,	Occupancy, Schedule, RoomOperationalAttribute
Building Communication			
Building Data			DataSource, BIMModel
Energy		OperationalEnergyUse, Energy, Electricity, UseOF RenewablePrimaryEnergy	EnergySource, SolarThermal, HeatingRequiredLevel, EnergyFuel

Geolocation and Weather			EnvironmentalInformation, SiteLocationInformation, SharedCoordinates
Historical Building Data	InterfaceState, Documentation, Drawing, SurveySheets		DataSource, Schedule
Norms and Regulation		Standard-Guideline, EN15978, EPD	
Methods and Technologies			
Actors	WorkForce, OwnerOperationalConstraint, InhabitantCoordination		

According to Mcglinn et al. (2016), data models from these domains support multiple use cases in the field of building energy efficiency. Different use cases share common information, for instance, the geometry of the building elements and renovation products is required to be able to plan installation activities and to develop a BEM model. Mapping the knowledge covered by the proposed ontologies into more general data structures may facilitate the use of it for other purposes beyond the Installation activities, LCA/C assessments, and BEM models. In the context of BIM technologies and renovation products, integrating the knowledge covered by the Reno-Inst, LCA-C, and BEM-Reno ontologies into BIM objects and BIM models may support additional use cases. BIM-SPEED is developing different BIM use cases that share some of the information covered by the proposed ontologies. Table 11 lists a set of the BIM-SPEED BIM use cases that are under development and some of their information requirements that are shared with the three proposed ontologies. As presented, the information included in the models could support additional tasks of renovation projects procedures. For instance, the knowledge gathered in the Reno-Inst ontology is directly linked to the use case *4D scheduling*. The information contained in the LCA-C ontology is related to use cases such as *BIM Based LCC and Asset Management* and *Maintenance Scheduling*; and the concepts covered by the BEM-Reno ontology are closely linked to use cases such as *Assessing the as-built Thermal Comfort with simulated data* and *Post occupancy evaluation*.

Table 11. BIM use cases examples and shared data domains with the proposed ontologies

Use cases	Reno-Inst	LCA-C	BEM-Reno
BIM based Design coordination	Building Product, Historical Building Data	Building Product	Building Product, Building Devices, Historical Building Data

4D scheduling	Building Product, Actors	Building Product	Building Product
Assessing HVAC installation with norms			Building Devices
BIM Based LCC and Asset Management	Building Product, Building Behaviour, Actors	Building Product, Energy, Building Behaviour	Building Product, Energy, Building Behaviour
Assessing the as-built Thermal Comfort with simulated data	Building Product	Building Product	Building Product, Building Devices, Geolocation and Weather
Digital coordination on-site	Building Product, Actors	Building Product	Building Product, Building Data
Maintenance Scheduling	Building Product, Actors	Building Product	Building Product, Building Devices, Historical Building Data, Building Data
Post occupancy evaluation, Assessing the energy performance of buildings with measured data	Building Product, Building Behaviour	Building Product, Building Behaviour	Building Product, Building Devices, Geolocation and Weather, Historical Building Data, Building Behaviour

7. Conclusions

The models presented in this report are a potential starting point to initiate the dialogue amongst experts in the industry to encourage the development of more dedicated models and tools for building renovation projects. To develop and disseminate the use of an ontological model in the AEC industry is a long process that demands testing the ontology in multiple scenarios, looking for strategies to align it with existing standardized and well-established models, tools, and workflows. Therefore, populating and testing the three proposed models in different scenarios will be necessary to identify additional adjustments and potential integration opportunities with existing tools and models. As mentioned previously, formalized knowledge representations can address the lack of a shared understanding and difficulties in identifying requirements from a system. Therefore, our main goal was to identify relevant areas from the building renovation domain, explore and study their knowledge, and map and represent that knowledge.

Furthermore, the knowledge and concepts mapped by the three proposed ontologies related specifically to renovation products will be used as input to define information requirements for BIM objects in the BIM-SPEED task *2.3 BIM Object Library and Product LCA* that aims at developing a BIM library of the most common building materials, components and HVAC equipment used in the EU. Modelling strategies such as the representation of components as functional and interface components from the Reno-Inst, attributes such as the environmental and cost product parameters from the LCA-C ontology, and material and geometry attributes from the BEM-Reno ontology can be integrated to BIM models. Gathering this relevant information in a BIM objects library may facilitate the implementation of BIM technologies and BIM use cases on renovation projects.

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Appendix A – Ontologies hierarchy and properties

A1. Reno-Inst ontology

A1.1 Reno-Inst ontology hierarchy

Figure 31 presents the complete hierarchy of the Reno-Inst ontology, it was extracted from the model developed in Protégé.

Figure 31. Reno-Inst ontology hierarchy

A1.2 Property hierarchies

Figure 32 depicts the object and data hierarchies of the Reno-Inst ontology.

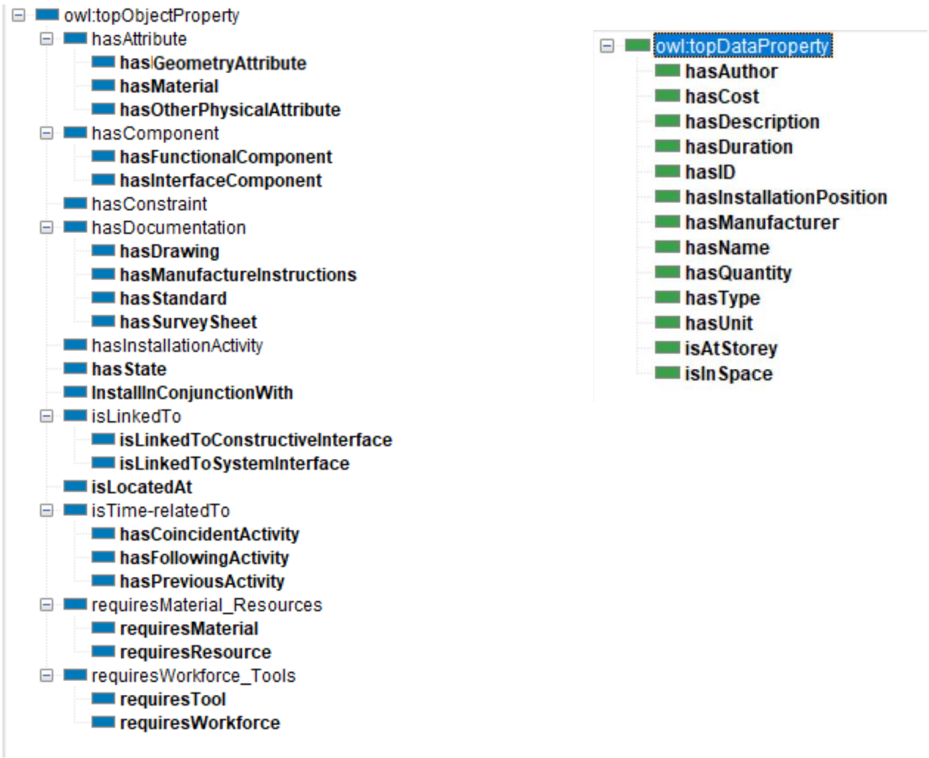
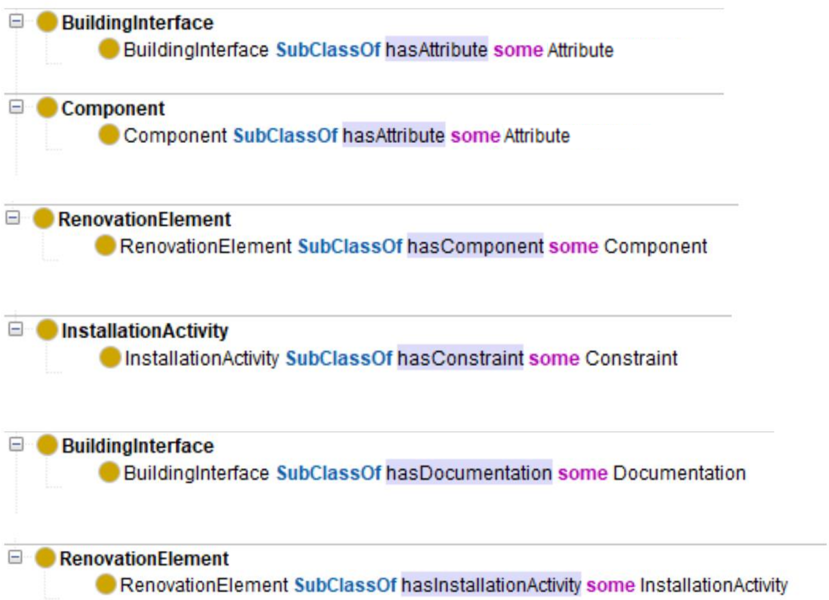


Figure 32. Object and data property hierarchies

A1.3 Object properties

The list of object properties of the Reno-Inst ontology can be summarized as follows:



RenovationElement
- RenovationElement SubClassOf hasInstallationActivity some InstallationActivity

BuildingInterface
- BuildingInterface SubClassOf hasState some InterfaceState

RenovationElement
- RenovationElement SubClassOf InstallInConjunctionWith some RenovationElement

RenovationElement
- RenovationElement SubClassOf isLinkedTo some BuildingInterface

BuildingInterface
- BuildingInterface SubClassOf isLocatedAt some BuildingElement

InstallationActivity
- InstallationActivity SubClassOf requiresMaterial_Resources some MaterialsAndResources

InstallationActivity
- InstallationActivity SubClassOf requiresWorkforce_Tools some WorkforceAndTools

InstallationActivity
- InstallationActivity SubClassOf isTime-relatedTo some InstallationActivity

7.1 Data properties

The list of data properties of the Reno-Inst ontology can be summarized as follows:

Documentation
- Documentation SubClassOf hasAuthor some xsd:string

MaterialsAndResources
- MaterialsAndResources SubClassOf hasCost some xsd:double

WorkforceAndTools
- WorkforceAndTools SubClassOf hasCost some xsd:double

BuildingInterface
- BuildingInterface SubClassOf hasDescription some xsd:string

Constraint
- Constraint SubClassOf hasDescription some xsd:string

Documentation
- Documentation SubClassOf hasDescription some xsd:string

InstallationActivity
- InstallationActivity SubClassOf hasDescription some xsd:string

InterfaceState
- InterfaceState SubClassOf hasDescription some xsd:string

InstallationActivity
- InstallationActivity SubClassOf hasDuration some xsd:double

- **BuildingElement**
  - BuildingElement **SubClassOf** hasID **some** xsd:string
- **BuildingInterface**
  - BuildingInterface **SubClassOf** hasID **some** xsd:string
- **Documentation**
  - Documentation **SubClassOf** hasID **some** xsd:string
- **RenovationElement**
  - RenovationElement **SubClassOf** hasInstallationPosition **some** xsd:string
- **RenovationElement**
  - RenovationElement **SubClassOf** hasManufacturer **some** xsd:string
- **WorkforceAndTools**
  - WorkforceAndTools **SubClassOf** hasName **some** xsd:string
- **MaterialsAndResources**
  - MaterialsAndResources **SubClassOf** hasQuantity **some** xsd:double
- **WorkforceAndTools**
  - WorkforceAndTools **SubClassOf** hasQuantity **some** xsd:double
- **RenovationElement**
  - RenovationElement **SubClassOf** hasType **some** xsd:string
- **MaterialsAndResources**
  - MaterialsAndResources **SubClassOf** hasUnit **some** xsd:string
- **PhysicalAttribute**
  - PhysicalAttribute **SubClassOf** hasUnit **some** xsd:string
- **WorkforceAndTools**
  - WorkforceAndTools **SubClassOf** hasUnit **some** xsd:string
- **InnerElement**
  - InnerElement **SubClassOf** isAtStorey **some** xsd:integer
- **InnerElement**
  - InnerElement **SubClassOf** isInSpace **some** xsd:string

A2. LCA-C ontology

A2.1 Reno-Inst ontology hierarchy

Figure 33 and Figure 34 present the complete hierarchy of the LCA-C ontology. The environmental indicators and parameters are not shown to facilitate the representation.

Figure 33. LCA-C ontology hierarchy (a)

Figure 34. LCA-C ontology hierarchy (b)

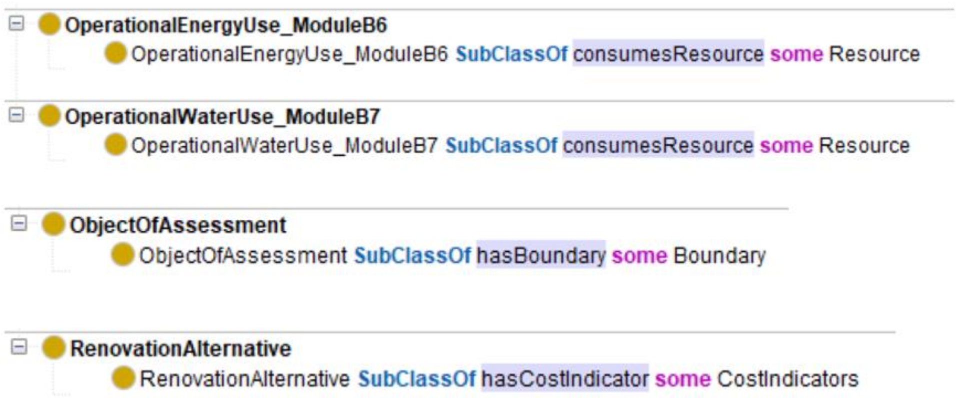
A2.2 Property hierarchies

Figure 35 depicts the object and data hierarchies of the LCA-C ontology.

Figure 35. LCA-C object and data property hierarchies

A2.3 Object properties

The list of object properties of the Reno-Inst ontology can be summarized as follows:



Material

Material SubClassOf hasCostParameter some CostParameter

RenovationProduct

RenovationProduct SubClassOf hasCostParameter some CostParameter

Resource

Resource SubClassOf hasCostParameter some CostParameter

CostIndicators

CostIndicators SubClassOf hasCostType some CostType

LCC_Assessment

LCC_Assessment SubClassOf hasCostVariable some CostVariable

CostParameter

CostParameter SubClassOf hasDataSource some DataSource

EnvironmentalParameter

EnvironmentalParameter SubClassOf hasDataSource some DataSource

InformationRequirements

InformationRequirements SubClassOf hasDataSource some DataSource

RenovationAlternative

RenovationAlternative SubClassOf hasEnvironmentalIndicator some EnvironmentalIndicator

Material

Material SubClassOf hasEnvironmentalParameter some EnvironmentalParameter

RenovationProduct

RenovationProduct SubClassOf hasEnvironmentalParameter some EnvironmentalParameter

Resource

Resource SubClassOf hasEnvironmentalParameter some EnvironmentalParameter

EPD

EPD SubClassOf hasEPDdata some EPDData

LCA_Assessment

LCA_Assessment SubClassOf hasGeneralInformation some LCA_AssessmentGeneralInformation

LCC_Assessment

LCC_Assessment SubClassOf hasGeneralInformation some LCC_AssessmentGeneralInformation

ObjectOfAssessment

ObjectOfAssessment SubClassOf hasGeneralInformation some ObjectOfAssessmentGeneralInformation

Scenario

Scenario SubClassOf hasGeneralInformation some Scenario_GeneralInformation

LCA_Assessment

LCA_Assessment SubClassOf hasObject some ObjectOfAssessment

LCC_Assessment

LCC_Assessment SubClassOf hasObject some ObjectOfAssessment

- **DataSource**
  - DataSource **SubClassOf** hasQuality **some** QualityofData

- **ObjectOfAssessment**
  - ObjectOfAssessment **SubClassOf** hasRenovationAlternative **some** RenovationAlternative

- **Boundary**
  - Boundary **SubClassOf** hasScenario **some** Scenario

- **RenovationAlternative**
  - RenovationAlternative **SubClassOf** includes **some** RenovationProduct
  - RenovationAlternative **SubClassOf** includes **some** Material

- **EnvironmentalIndicator**
  - EnvironmentalIndicator **SubClassOf** isAssociatedTo **some** Scenario

A2.4 Data properties

The list of data properties of the LCA-C ontology can be summarized as follows:

- **ObjectOfAssessment**
  - ObjectOfAssessment **SubClassOf** hasBIMModel **some** xsd:string

- **Boundary**
  - Boundary **SubClassOf** hasDescription **some** xsd:string

- **DataSource**
  - DataSource **SubClassOf** hasDescription **some** xsd:string

- **Goal**
  - Goal **SubClassOf** hasDescription **some** xsd:string

- **DataSource**
  - DataSource **SubClassOf** hasName **some** xsd:string

- **RenovationProduct**
  - RenovationProduct **SubClassOf** hasNumberOfReplacements **some** xsd:integer

- **Material**
  - Material **SubClassOf** hasQuantity **some** xsd:double

- **RenovationProduct**
  - RenovationProduct **SubClassOf** hasQuantity **some** xsd:double

- **RenovationProduct**
  - RenovationProduct **SubClassOf** hasReferenceServiceLife **some** xsd:integer

CostIndicators
CostIndicators SubClassOf hasUnit some xsd:string

CostParameter
CostParameter SubClassOf hasUnit some xsd:string

CostVariable
CostVariable SubClassOf hasUnit some xsd:string

EnvironmentalIndicator
EnvironmentalIndicator SubClassOf hasUnit some xsd:string

EnvironmentalParameter
EnvironmentalParameter SubClassOf hasUnit some xsd:string

Material
Material SubClassOf hasUnit some xsd:string

RenovationProduct
RenovationProduct SubClassOf hasUnit some xsd:string

Resource
Resource SubClassOf hasUnit some xsd:string

CostIndicators
CostIndicators SubClassOf hasValue some xsd:double

CostParameter
CostParameter SubClassOf hasValue some xsd:double

CostVariable
CostVariable SubClassOf hasValue some xsd:double

EnvironmentalIndicator
EnvironmentalIndicator SubClassOf hasValue some xsd:double

EnvironmentalParameter
EnvironmentalParameter SubClassOf hasValue some xsd:double

Resource
Resource SubClassOf hasValue some xsd:double

RenovationProduct
RenovationProduct SubClassOf hasYearOfReplacement some xsd:integer

A3. BEM-Reno ontology

A3.1 BEM-Reno ontology hierarchy

Figure 36 and Figure 37 present the complete hierarchy of the BEM-Reno ontology, it was extracted from the model developed in Protégé.

Figure 36. BEM-Reno ontology hierarchy (a)

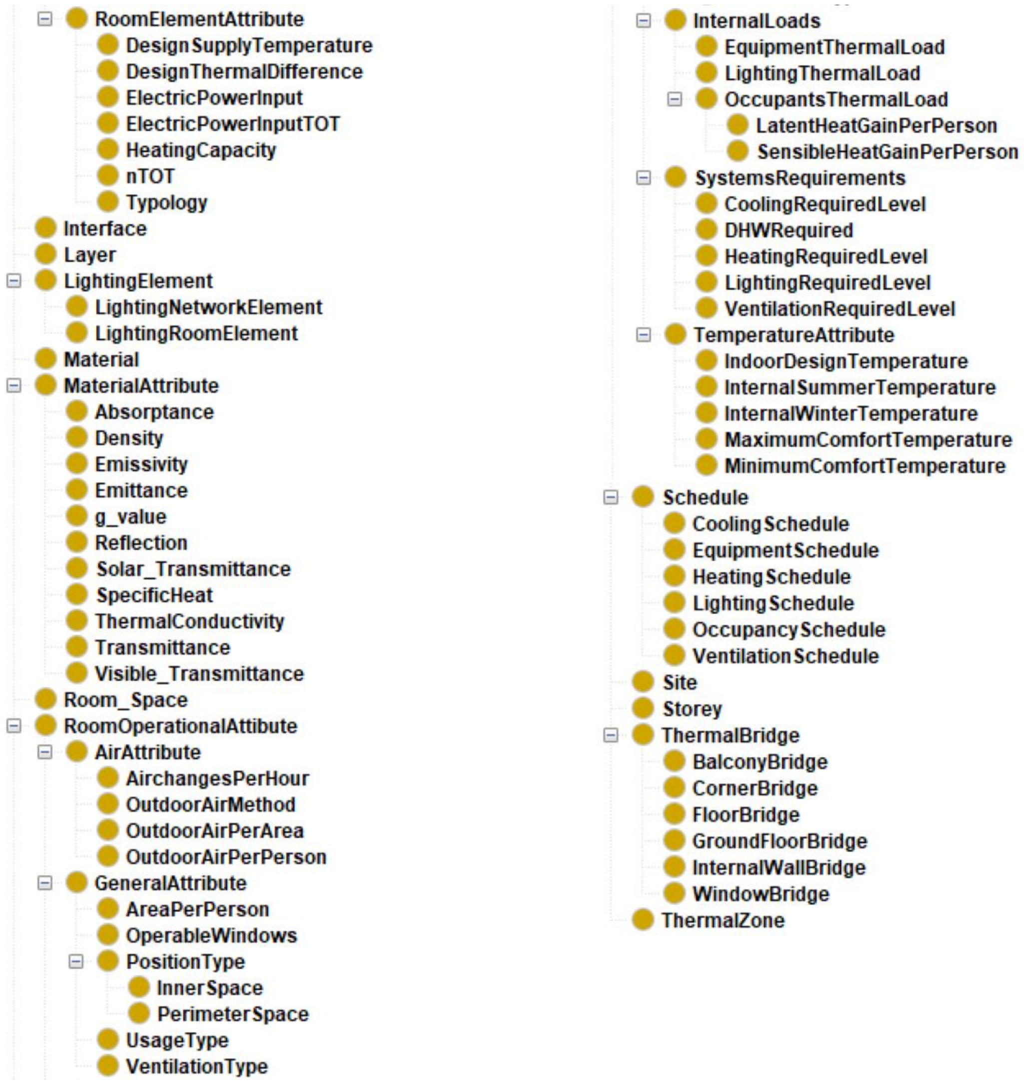


Figure 37. BEM-Reno ontology hierarchy (b)

A3.2 Property hierarchies

Figure 38 depicts the object and data hierarchies from the BEM-Reno ontology.

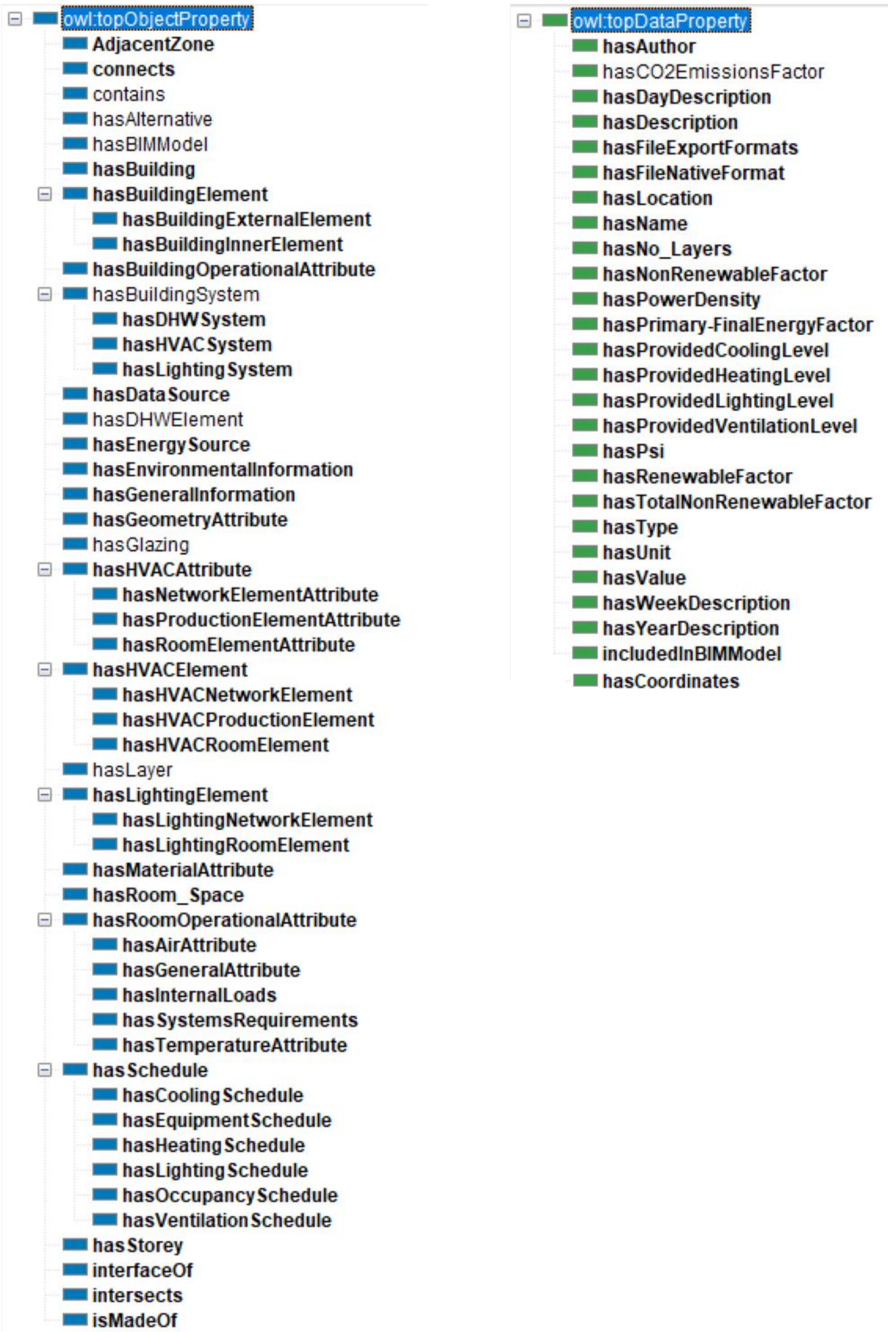


Figure 38. Object and data property hierarchies

A3.3 Object properties

The list of object properties of the BEM-Reno ontology can be summarized as follows:

ThermalZone
- ThermalZone SubClassOf AdjacentZone some ThermalZone

Connection
- Connection SubClassOf connects some LightingElement
- Connection SubClassOf connects some HVACElement

Room_Space
- Room_Space SubClassOf contains some HVACRoomElement
- Room_Space SubClassOf contains some LightingRoomElement

ThermalZone
- ThermalZone SubClassOf contains some Room_Space
- ThermalZone SubClassOf contains some Storey
- ThermalZone SubClassOf contains some Building

Material
- Material SubClassOf hasAlternative some Material

Building
- Building SubClassOf hasBIMModel some BIMModel

Site
- Site SubClassOf hasBuilding some Building

Room_Space
- Room_Space SubClassOf hasBuildingElement some BuildingElement

Building
- Building SubClassOf hasBuildingOperationalAttribute some BuildingOperationalAttribute

Building
- Building SubClassOf hasBuildingSystem some BuildingSystem

BuildingOperationalAttribute
- BuildingOperationalAttribute SubClassOf hasDataSource some DataSource

EnvironmentalInformation
- EnvironmentalInformation SubClassOf hasDataSource some DataSource

GeometryAttribute
- GeometryAttribute SubClassOf hasDataSource some DataSource

HVACElementAttribute
- HVACElementAttribute SubClassOf hasDataSource some DataSource

MaterialAttribute
- MaterialAttribute SubClassOf hasDataSource some DataSource

RoomOperationalAttibute
- RoomOperationalAttibute SubClassOf hasDataSource some DataSource

Schedule
- Schedule SubClassOf hasDataSource some DataSource

DHWSystem
- DHWSystem SubClassOf hasDHWElement some DHWProductionElement

Site
- Site SubClassOf hasEnergySource some EnergySources

Site
- Site SubClassOf hasEnvironmentalInformation some EnvironmentalInformation

Building
- Building SubClassOf hasGeneralInformation some BuildingGeneralInformation

BuildingElement
- BuildingElement SubClassOf hasGeometryAttribute some GeometryAttribute

Glazing
- Glazing SubClassOf hasGeometryAttribute some GeometryAttribute

Layer
- Layer SubClassOf hasGeometryAttribute some GeometryAttribute

Room_Space
- Room_Space SubClassOf hasGeometryAttribute some GeometryAttribute

ExternalWindow
- ExternalWindow SubClassOf hasGlazing some Glazing

InternalWindow
- InternalWindow SubClassOf hasGlazing some Glazing

DHWProductionElement
- DHWProductionElement SubClassOf hasHVACAttribute some HVACElementAttribute

HVACElement
- HVACElement SubClassOf hasHVACAttribute some HVACElementAttribute

HVACSystem
- HVACSystem SubClassOf hasHVACElement some HVACElement

BuildingElement
- BuildingElement SubClassOf hasLayer some Layer

LightingSystem
- LightingSystem SubClassOf hasLightingElement some LightingElement

Material
- Material SubClassOf hasMaterialAttribute some MaterialAttribute

Storey
- Storey SubClassOf hasRoom_Space some Room_Space

Room_Space
- Room_Space SubClassOf hasRoomOperationalAttribute some RoomOperationalAttibute

InternalLoads
- InternalLoads SubClassOf hasSchedule some Schedule

Room_Space
- Room_Space SubClassOf hasSchedule some Schedule

Building
- Building SubClassOf hasStorey some Storey

- **Interface**
  - Interface SubClassOf interfaceOf some BuildingElement
  - Interface SubClassOf interfaceOf some ThermalZone

- **ThermalBridge**
  - ThermalBridge SubClassOf intersects some BuildingElement
  - ThermalBridge SubClassOf intersects some Room_Space

- **BuildingElement**
  - BuildingElement SubClassOf isMadeOf some Material

- **Glazing**
  - Glazing SubClassOf isMadeOf some Material

- **Layer**
  - Layer SubClassOf isMadeOf some Material

A3.4 Data properties

The list of data properties of the BEM-Reno ontology can be summarized as follows:

- **BIMModel**
  - BIMModel SubClassOf hasAuthor some xsd:string

- **EnergySources**
  - EnergySources SubClassOf hasCO2EmissionsFactor some xsd:double

- **Schedule**
  - Schedule SubClassOf hasDayDescription some xsd:string

- **DataSource**
  - DataSource SubClassOf hasDescription some xsd:string

- **BIMModel**
  - BIMModel SubClassOf hasFileExportFormats some xsd:string

- **BIMModel**
  - BIMModel SubClassOf hasFileNativeFormat some xsd:string

- **Building**
  - Building SubClassOf hasLocation some xsd:string

- **Site**
  - Site SubClassOf hasLocation some xsd:string

- **BIMModel**
  - BIMModel SubClassOf hasName some xsd:string

- **BuildingElement**
  - BuildingElement SubClassOf hasName some xsd:string

- **DataSource**
  - DataSource SubClassOf hasName some xsd:string

HVACElement
- HVACElement SubClassOf hasName some xsd:string

Layer
- Layer SubClassOf hasName some xsd:string

LightingElement
- LightingElement SubClassOf hasName some xsd:string

Material
- Material SubClassOf hasName some xsd:double

Room_Space
- Room_Space SubClassOf hasName some xsd:string

Schedule
- Schedule SubClassOf hasName some xsd:string

ThermalZone
- ThermalZone SubClassOf hasName some xsd:string

Glazing
- Glazing SubClassOf hasNo_Layers some xsd:integer

EnergySources
- EnergySources SubClassOf hasNonRenewableFactor some xsd:double

LightingRoomElement
- LightingRoomElement SubClassOf hasPowerDensity some xsd:double

EnergySources
- EnergySources SubClassOf hasPrimary-FinalEnergyFactor some xsd:double

CoolingRoomElement
- CoolingRoomElement SubClassOf hasProvidedCoolingLevel some xsd:double

HeatingRoomElement
- HeatingRoomElement SubClassOf hasProvidedHeatingLevel some xsd:double

LightingRoomElement
- LightingRoomElement SubClassOf hasProvidedLightingLevel some xsd:double

VentilationRoomElement
- VentilationRoomElement SubClassOf hasProvidedVentilationLevel some xsd:double

ThermalBridge
- ThermalBridge SubClassOf hasPsi some xsd:double

EnergySources
- EnergySources SubClassOf hasRenewableFactor some xsd:double

EnergySources
EnergySources SubClassOf hasTotalNonRenewableFactor some xsd:double

Glazing
Glazing SubClassOf hasType some xsd:string

BuildingOperationalAttribute
BuildingOperationalAttribute SubClassOf hasUnit some xsd:string

GeometryAttribute
GeometryAttribute SubClassOf hasUnit some xsd:string

HVACElementAttribute
HVACElementAttribute SubClassOf hasUnit some xsd:string

MaterialAttribute
MaterialAttribute SubClassOf hasUnit some xsd:string

RoomOperationalAttibute
RoomOperationalAttibute SubClassOf hasUnit some xsd:string

Schedule
Schedule SubClassOf hasUnit some xsd:string

BuildingOperationalAttribute
BuildingOperationalAttribute SubClassOf hasValue some xsd:double

GeometryAttribute
GeometryAttribute SubClassOf hasValue some xsd:double

HVACElementAttribute
HVACElementAttribute SubClassOf hasValue some xsd:double

MaterialAttribute
MaterialAttribute SubClassOf hasValue some xsd:double

RoomOperationalAttibute
RoomOperationalAttibute SubClassOf hasValue some xsd:double

Schedule
Schedule SubClassOf hasWeekDescription some xsd:string

Schedule
Schedule SubClassOf hasYearDescription some xsd:string

BuildingOperationalAttribute
BuildingOperationalAttribute SubClassOf includedInBIMModel some xsd:boolean

EnvironmentalInformation
EnvironmentalInformation SubClassOf includedInBIMModel some xsd:boolean

GeometryAttribute
GeometryAttribute SubClassOf includedInBIMModel some xsd:boolean

HVACElementAttribute
HVACElementAttribute SubClassOf includedInBIMModel some xsd:boolean

- MaterialAttribute
  - MaterialAttribute **SubClassOf** includedInBIMModel **some** xsd:boolean
- RoomOperationalAttibute
  - RoomOperationalAttibute **SubClassOf** includedInBIMModel **some** xsd:boolean
- Schedule
  - Schedule **SubClassOf** includedInBIMModel **some** xsd:boolean