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Reno-Inst: An ontology to support renovation projects planning and renovation products installation

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ABSTRACT

While the use of semantic models has been explored in different areas of the Architecture, Engineering and Construction (AEC) industry to map and formalize knowledge and support different tasks, building renovation seems to be a neglected area in this field. Therefore, this paper presents the Renovation-Installation (Reno-Inst) ontology, which maps knowledge from the renovation domain considering different requirements, constraints, and other elements related to the installation of common renovation products such as windows, thermal insulation panels, and heat radiators. The development of the Reno-Inst ontology relies on an approach combining input from experts and knowledge from related engineering documents. The verification and validation process includes a content evaluation workshop with experts, a verification design stage, and the analysis and implementation of a real case study. The paper provides another example of the power of ontologies as a method for mapping and representing knowledge, gathering, and retrieving relevant information. Particularly, renovation projects encounter diverse challenges that lead to cost and schedule overruns, making their performance typically low. Therefore, the proposed Reno-Inst ontology provides a basis from which new applications can be developed, tested, and deployed to support improvements in the building renovation field, especially in the planning and execution of renovation activities.

1. Introduction

The rate at which buildings are renovated across Europe is expected to increase to achieve the sustainable goals set by the 2030 Agenda and other international and local agreements in Europe [1]. Since buildings account for 40% of the EU's energy consumption, 36% of its CO_2 emissions and 55% of its electricity consumption [2], the implementation of sustainability measures in this field is required. 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 [2]. To facilitate the renovation progress, information related to aspects such as planning, cost management, and operation and maintenance needs to be systematically collected [3]. Increasing renovation rates calls for dedicated tools to support stakeholders in renovation projects to enhance the performance of their activities.

Diverse tools for design, planning, and project management are usually developed for new construction and later adapted to support renovation projects. Nevertheless, renovation projects have a low degree of anticipation and effectiveness at the working site, and other complex characteristics that lead to cost and schedule overruns, making their performance typically lower than that of new construction projects [4,5]. Particularities from renovation projects such as uncertainty in the existing conditions of the building and the presence of occupants can impact certain construction activities and change their conventional logical sequence. Integrating such particularities in the planning and execution of renovation projects might be challenging due to the lack of clear workflows and dedicated tools.

Lack of shared understanding can lead to difficulties in identifying requirements for systems, procedures, and tasks from a certain domain. An approach to solving this problem is to develop formalized knowledge representations [6]. An ontology is concerned with the knowledge of engineers about physical and abstract objects, their relations, and events influencing them [7]. It includes a set of concepts/classes, relations/properties, instances/individuals, and axioms. According to Lenat & Feigenbaum [8], a great deal of real-world knowledge is a prerequisite for an intelligent program to perform complex analytical tasks accurately. A representation with machine-readable data for domains related

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to building renovation can contribute to developing tools to support information collection, processing, reuse, and retrieval in the context of renovation projects.

In general, the use of semantic web technologies in the Architecture, Engineering and Construction (AEC) industry has focused on supporting: a) interoperability, b) linking information across domains such as Building Information Modelling (BIM) – Geographic Information System (GIS), manufacturer building data, and building performance analysis; and c) logical inference to check model consistency and completeness, construction safety, and perform cost estimation and home automation [9]. Ontologies can also contribute to addressing the challenges of building renovation projects. However, most of the research efforts have been developed around the construction process of new buildings or the operational phase of existing buildings while renovation seems to be a neglected area in the AEC ontology field.

To overcome this gap, this paper presents an ontology mapping knowledge related to the installation of renovation products in existing buildings. Structuring a representation of the installation and constraints for common renovation products such as windows, external thermal insulation composite systems (ETICS), and Heating, ventilation, and air conditioning (HVAC) components can support the activity planning and execution processes in renovation projects. The knowledge capturing process implemented to develop the Renovation-Installation (Reno-Inst) ontology combines input from experts and knowledge from related engineering documents. The verification and validation process includes a content evaluation workshop with experts, a verification design stage, and the analysis of a real case study. The paper provides another example of the ability of ontologies to map and represent knowledge and gather and retrieve relevant information.

The remainder of the paper is structured as follows: Section 2 presents the background and research motivation. Section 3 summarizes the methodology implemented for the ontology development, including the specification, knowledge capturing, and verification and validation process. Section 4 introduces the Reno-Inst ontology. Section 5 presents the verification and validation process. Finally, the discussion and conclusions are synthesized in Sections 6 and 7, respectively.

2. Background and research motivation

2.1. Residential building renovation

According to the Global Building Performance Network – GBPN, different terms are used to refer to improvements in existing buildings [10]. Renovation tends to be associated mainly with the building envelope and the process of improving or modernizing a building to return it to a good state. Retrofitting is closely related to providing something with a component or feature not fitted during manufacture [11]. The related literature considered in this research covers the different aspects of renovation, retrofitting and the installation of renovation products. Nevertheless, to facilitate the reading process, the term *renovation* is used in this paper as a general term comprising building improvements in the form of renovation, refurbishment or retrofitting since a single project may gather multiple elements from one or more of them.

Renovation activities currently taking place across Europe include mainly the replacement of windows, heating, cooling, lighting systems or roof insulation [12]. While installation and commissioning procedures in new buildings may be well established, renovation projects address challenges that call for a better understanding of associated processes. Renovation encounters barriers throughout the value chain – from the initial decision to engage in renovation to the completion of the project, making it costly, difficult to organize, and lengthy to carry out [1]. A review of existing literature demonstrates that renovation projects face different challenges, especially during the construction phase and the installation of new elements when multiple limitations and constraints appear.

Renovation projects are usually affected by elements that modify conventional construction practices. Unforeseen and varying circumstances, incompleteness and inaccuracy of the information related to the existing conditions of the building can impact construction activities in renovation projects [4]. Such activities can be affected as well by deteriorated existing conditions of materials and structural elements, and additional decommissioning tasks of previous elements. The presence of occupants also affects conventional practices since it is usually necessary to include occupants' schedules in the activity planning, change egress pathways and other routes in the construction site, as well as adjust the material storage and waste management plans. Additionally, special measures should be implemented to guarantee occupants' safety and reduce pollution such as noise, dust, and debris production. For instance, approaches for envelope renovation need scaffolding on the outer facade, requiring occupants to introduce safety measures for long periods [13].

Moreover, according to Singh et al. [4], critical activities that have an impact on the final performance of renovation projects comprise preparation of plans and specifications, site investigation, preparation of site logistics plans, mobilization and demobilization, temporary construction, selective demolition, material and equipment procurement, demolition waste management, and mechanical, electrical, and plumbing (MEP) rough-ins. Notice that many of these critical activities are associated with the installation of renovation products. For instance, the installation of a window includes performing a survey of the openings in the building (site investigation by contractor), coordinating with the occupants to install the new window (preparation of site logistics plan), removing the previous window (selective demolition), disposing it (demolition waste management), and the installation of the new window (temporary construction). These and other activities can be affected by the particularities already mentioned for renovation projects, related to the uncertainty in existing conditions of the building and the presence of occupants. Moreover, constructors may often lack the technical knowledge and necessary competences [14]. There is a serious fragmentation of communication and knowledge share, creating increased cost through a disjointed approach to renovate in practice [15].

In general, planning for construction projects requires an intimate knowledge of construction methods combined with the ability to visualize discrete work elements and to establish their mutual interdependencies [16]. Reaching this intimate knowledge of methods and work elements can be challenging in renovation projects since they encounter multiple particularities, as presented previously. Moreover, since the planning and execution processes rely mostly on planners' judgement and previous experiences, those particularities could be overseen or not anticipated throughout the project. A wider view in terms of data and activities is required to avoid potential impacts of not considering the occupants, their needs and other particularities in the context of renovation activities [15]. Since an ontology is a representation that provides an explicit specification of concepts, terminologies and interdependencies that are known in a particular domain [17], an ontology could support the formalization of the knowledge from practitioners, planners, and previous experiences.

Engineering associations and international institutions have developed instruction material and guidelines [18–21] to support the planning process by standardizing concepts related to the installation of common products such as windows and ETICS panels. These efforts gathered technical rules and lessons learned from previous experiences to support planners, authorities, general contractors, and installers. However, many of these guidelines were developed from a general point of view, without considering the particularities of renovation projects. An ontology for the building renovation field can contribute to formalizing the knowledge related to existing conditions of the building, the installation of products, impacts due to the presence of occupants, and other elements. Since ontologies help humans and computers understand and fully utilize domain knowledge [7], an ontology can be the starting point to develop dedicated computational tools for renovation projects to support and enhance different processes. It can also trigger the development of semantic and knowledge management applications such as information retrieval, question answering, and knowledge reuse, which have been already explored in other areas of the AEC industry as presented in the following section.

2.2. Ontologies and their application in the AEC industry

In the AEC industry, ontological models and ontology-based tools have been widely studied. Some efforts have focused on the representation of general domains to map and formalize the shared understanding of their knowledge. For instance, the Industry Foundation Classes (IFC) data format established by buildingSMART International and the Building Topology Ontology (BOT) developed by Rasmussen et al. [22] modelled building-related information, while the building product ontology (BPO) [23] mapped concepts to describe building products. Construction projects information has been also mapped, enabling knowledge analysis and reuse. Torkanfar and Rezazadeh Azar [24] presented a method for measuring the similarity of construction projects based on semantic comparisons, identifying experiences gained from completed projects to improve the planning of new ones. Sigalov and König [25] applied indexing techniques to identify similar subschedules in BIM-based construction schedules to pinpoint patterns through a graph-based approach. An ontological representation of renovation projects information considering the particularities and specific constraints of such projects can prompt the development of similar dedicated approaches for this field, which can improve the way lessons are learned and reused from previous projects.

At the same time, research has focused on mapping knowledge from building construction processes to develop tools to enhance and assist management tasks. For instance, Jahr and Borrmann [26] proposed a rule-based knowledge inference system to support site equipment planners in a semi-automated fashion using data from BIM models and construction schedules. Zhong et al. [27] proposed an ontological approach to support the definition and verification of construction plans, showing its application on a deep foundation pit excavation case. Song and Fischer [28] introduced an ontology to support the analysis of the plan-do-check-act cycle and generate information items such as the actual date of work completed, products built, and quantities of materials installed. Bilal et al. [29] proposed a building materials ontology database that captures semantically diverse data of materials to establish the core of a waste analysis tool. In the context of existing buildings and renovation, Gouda Mohamed et al. [30] presented an ontological system integrating the as-is information, BIM and semantic web technology to support as-is information formalization and management for maintenance purposes. Kamari et al. [31] introduced a renovation domain model to express and capture key concepts for renovation scenarios.

2.3. Research motivation and contribution

Most of the research activities have centred on a general point of view or new construction perspectives. Knowledge from the renovation domain seems to be an unexplored area in the field of ontological representations. Even though some of the existing approaches could be extended for renovation projects, this field demands dedicated models and tools. Clearer knowledge representations in this field can improve the conventional processes, tools, and workflows to reduce re-work, cost overruns, errors, and delays in delivery times. Therefore, the specific objective underlying this study is to develop an ontology that maps knowledge from the renovation domain considering different requirements, constraints, and other elements related to the installation procedure of common renovation products. The proposed Reno-Inst ontology covers common renovation products such as windows, ETICS panels, and radiators. Nevertheless, the structure of the ontology is designed to facilitate the integration of additional renovation products.

Since activity planning usually relies on planners' judgement, previous experiences, and scattered information; restrictions and many other aspects could be overseen during these phases. Moreover, this information is usually stored throughout multiple sources, with different formats, and sometimes in an unstructured way, which makes the planning process prone to errors and loss of information. Therefore, a potential use of the Reno-Inst ontology is to assist stakeholders during the planning and execution phases of renovation projects to represent, gather and manage this kind of relevant information. On the other hand, the paper presents another example of the utility of developing ontologies to support engineering tasks within the AEC industry. In this, we provide a reproduction of previous ontology purposes explored in this area: mapping knowledge like in [22,23], gathering heterogeneous information from multiple sources like in [29], and querying and retrieving relevant information like in [32]. The proposed Reno-Inst ontology provides a basis from which previous approaches could be implemented in the renovation field and new applications can be developed, tested, and deployed to support improvements in the building renovation industry.

3. Research approach

This section presents the methodology applied to develop the Reno-Inst ontology that maps knowledge from the building renovation domain. The development of the ontology was based on the guidelines presented by Noy & Mcguinness [33] and the Methontology approach [34], documenting the motivation for the development of the ontology, its use, and purpose in natural language. The research approach presented in Fig. 1 comprises the ontology specification, knowledge acquisition and conceptualization, as well as the verification and validation process.

3.1. Ontology specification

The goal of the specification phase is to produce a general description of the ontology comprising minimum information regarding the purpose, use, users and domain covered by the ontology [34]. This section presents the specification of the Reno-Inst ontology using natural language and a set of competency questions.

3.1.1. What is the purpose?

The Reno-Inst ontology is developed to represent concepts related to requirements, constraints, and the installation of renovation products to support planning and execution tasks in building renovation projects.

3.1.2. What is the scope?

The ontology covers concepts and relations regarding the installation of windows, ETICS panels, and radiators, which are common renovation products. 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.

3.1.3. What are the intended end-users?

The final intended users are project managers, site-directors, and other stakeholders which are involved in the planning and execution of construction activities in building renovation projects.

3.1.4. What is the intended use?

The intended use of the ontology is to assist stakeholders during the planning and execution phases of renovation projects, facilitating the retrieval of installation information for different purposes. The set of competency questions presented in Table 1 was developed to identify relevant concepts.

As presented in Fig. 2, the proposed ontological model can leverage information from different sources such as general documents, communication plans, building operational schedules, etc. When as-

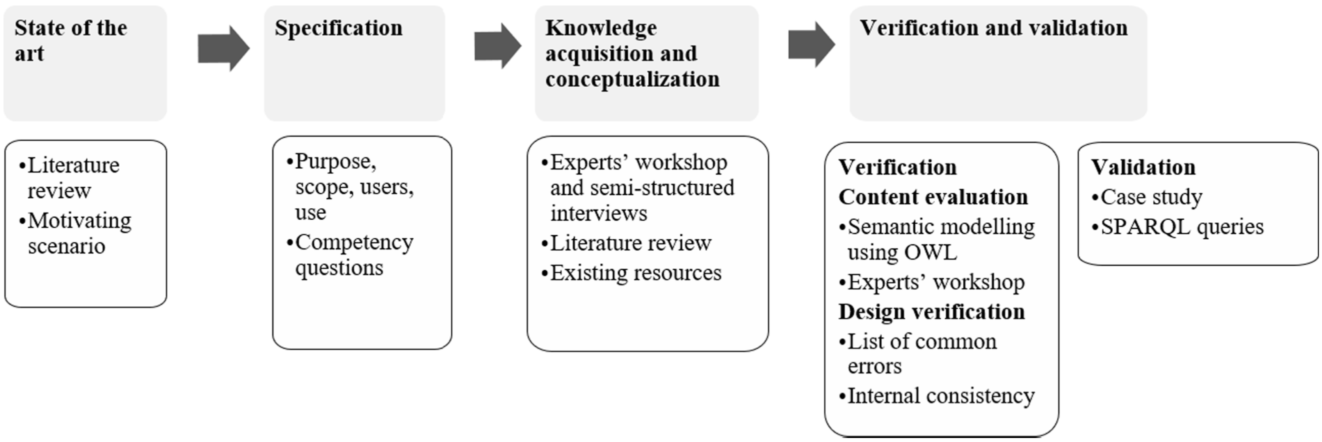

Fig. 1. Ontology development methodology.

Table 1
Competency questions and answer examples.

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?	Installation of air-thigh 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 the ref_123 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

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.

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.

3.2. Knowledge capture and conceptualization

The knowledge acquisition aims at identifying relevant concepts for the ontology, defining requirements, constraints, and information essential for the installation of each renovation product and how these diverse concepts can be gathered in a knowledge network including different classes, relationships, and properties. Capturing and

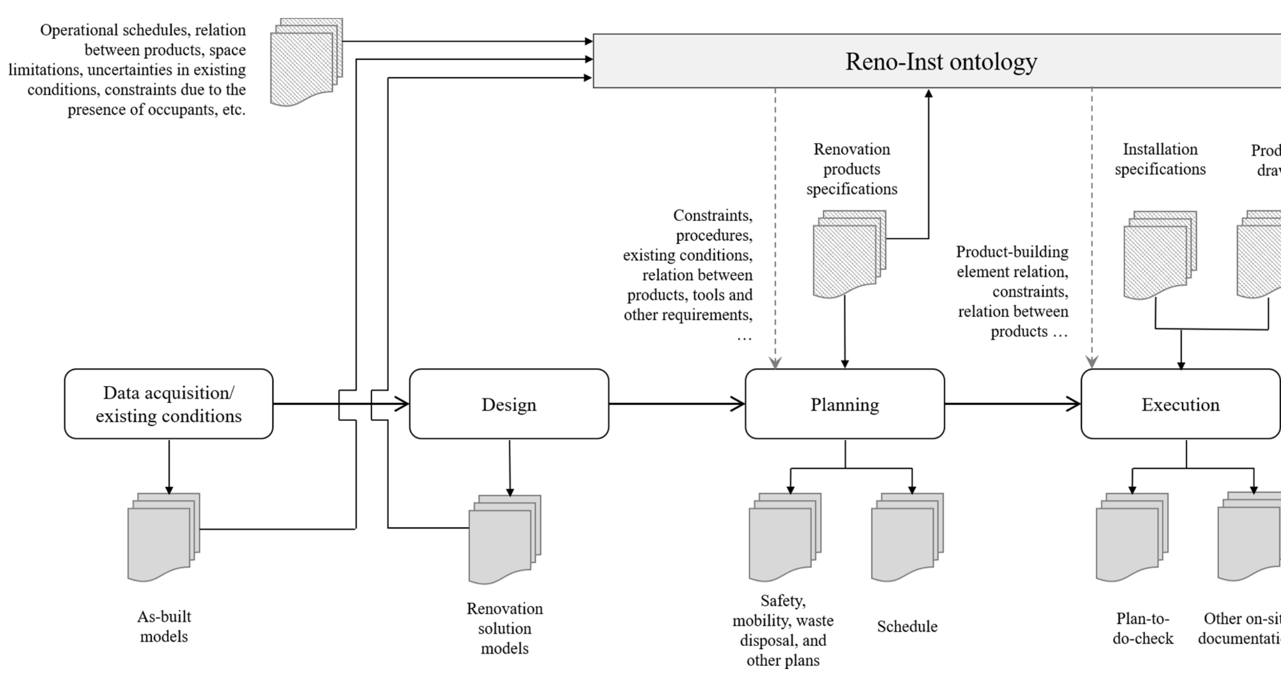

Fig. 2. Potential use of the proposed Reno-Inst ontology.

representing engineering knowledge is one of the main tasks in the Advanced Engineering Informatics field. Common engineering knowledge elicitation approaches are based on social science methods or the analysis of engineering documents and models [7]. Social science-based methods rely on interviews, workshops, and additional empirical approaches. While other methods include the structured analysis of documents and advance text mining techniques.

The capturing of knowledge implemented for the Reno-Inst ontology combined input from experts in the field and knowledge from sources such as related literature, manufactures' catalogues, and guidelines from regional engineering associations as summarized in Table 2. The specification and competency questions presented in the previous section were used to guide the identification of relevant terms. The input from experts was collected through a workshop and semi-structured interviews. Experts from four companies in Europe were involved, comprising an architect with experience in windows design and installation, a second architect and a BIM coordinator with experience in management and execution of renovation projects, and an R&D director with experience in the design and installation of multiple types of facades and heating systems. During the workshop, the experts described the installation procedure of a particular renovation product at a time (e.g. a window). Questions such as *Could you describe how to install a window? Which are common challenges during the installation?* were used throughout the discussion to encourage the experts to provide more details. Experts were also asked to provide information required to install the renovation product being analysed. Special attention was given to information related to physical features of the renovation product and the building interface where it will be installed, and constraints imposed by the presence of occupants, space limitations, and other aspects.

A class hierarchy was created with the main concepts identified during the knowledge capturing activities. Class properties between the concepts were established to represent their relationships. The nomenclature and terms that represent the concepts correspond to the terms used by the experts and related literature. When different terms were used to refer to the same concept, the terms were contrasted with classification systems for the construction industry to model the information according to standard vocabulary, facilitating semantic interpretation and unambiguous communication among users in the renovation field.

3.3. Verification and validation

The Reno-Inst ontology was implemented using Web Ontology Language (OWL) and the Resource Description Framework (RDF) in the Protégé environment [36]. This language enables a machine-readable representation to support and make information collection, processing, reuse, and retrieval easier. Evaluating whether a certain knowledge formulation is appropriate and useful is one of the main tasks in the field of Advanced Engineering Informatics. It requires that the proposed knowledge representation is systematically verified and validated [7]. Verification is the process of ensuring that the axioms of the ontology reflect the intentions of the author [37]. Validation is the process of evaluating whether the knowledge representation is fit to the engineering purpose at hand [7]. To verify the Reno-Inst ontology the authors performed a workshop with experts to evaluate the content of the model and a design verification stage to search for potential mistakes in the development of the ontology. Once the ontology was instantiated with the information from a case study, a reasoner was used to verify the internal consistency of the model. The validation stage included the analysis and implementation of a case study, illustrating how the ontology can support the planning in renovation projects.

Table 2
Sources for ontology knowledge.

Main Concepts	Terms Examples	Source
Renovation products	Functional component, interface component, material	[18,20,21]
Installation procedure	Main installation activity, tools, construction material, activity description	[19,20], and experts' input
Existing conditions, Occupants, and Constraints	Building interface, opening, pollution constraint, activities coordination	[4,35], and experts' input

3.3.1. Content evaluation

For the content evaluation of the model, the ontology implemented in Protégé was presented to experts in a workshop to evaluate whether the model and its content were coherent with the studied domain. The experts' group comprised two architects and an R&D director from three different companies. The 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 real-world interactions?

During the workshop, we presented the ontology specification to the experts, in conjunction with the general model and details of each concept. After the experts discussed each of the concepts and their relationships, we modified the model according to the issues and recommendations pointed out by them. We also presented a fictional case to the experts, including the replacement of 12 main windows and 4 general windows of a four-story residential building, with eight apartment units. The experts discussed the activities and information required to plan and implement the task while we verified whether the information required by the experts was represented in the ontology.

3.3.2. Design verification

Structuring ontologies is an error-prone activity. To verify the design of the Reno-Inst ontology, the final model implemented in Protégé was examined to check the concepts description, their hierarchy, object and data properties, and the relations between them. The ontology was reviewed extensively, the hierarchy was revisited and the relations of each class and sub-class were checked. The following list of common errors from the ontological development process was used as a guideline to check and restructured the ontology [38]:

- A class defined as a sub-class and super-class at the same time
- An excessive use of the isA property
- Incomplete existing classes
- Non-disjoint classes
- Concepts are not modelled exhaustively
- Concepts or terms represented multiple times
- Lack of specification and limitation of the properties

Moreover, once the ontology was instantiated with the information of a real case study, the Pellet reasoner [39] was used to evaluate the internal consistency of the ontology and search for contradictory facts in the model. The reasoner supports analysis on individuals, restrictions, datatypes, sub-property axioms, symmetric properties, and disjoint properties.

3.3.3. Validation

At the validation stage, the ontology, already instantiated with the information from the case study, was used to demonstrate the practical application of the proposed Reno-Inst model. The plan of a previous renovation project (in the form of a Gantt diagram) and complementary documentation were the main data sources. The collected data were contrasted with the information requirements included in the ontology, evaluating to which extend the proposed model covered the information contained in a real practical case. Using Protocol and RDF Query Language (SPARQL), a set of queries was executed on the ontology in response to typical questions that can be relevant during the planning of renovation activities. The task-based evaluation demonstrated the use of the ontology in satisfying its purpose and objectives. In the next section, we describe the proposed Reno-Inst ontology. Then, in Section 5, we summarize the results of the verification and validation process.

4. Ontology for renovation products installation

Even though the starting point for the development of the Reno-Inst ontology focuses on windows, ETICS panels, and radiators, the main classes of the ontology aim at representing a general view of diverse aspects related to the domain of renovation projects, requirements, constraints, and the installation of renovation products. As presented in Fig. 3, each *RenovationProduct* has *Component* and *InstallationActivity*, and it is linked to a *BuildingInterface*. The installation activities for each renovation product require specific *MaterialsAndResources*, *Workforce,* and *ToolsAndEquipment*. Moreover, activities are subjected to a set of constraints related to aspects such as existing conditions, coordination, and safety, which are gathered in the class *Constraint*. On the other hand, the *BuildingInterface* where a *RenovationProduct* will be installed is located at a *BuildingElement* such as a wall, ceiling, or other. Different concepts such as *RenovationProduct*, *BuildingInterface*, and *BuildingElement* can be described by the concept *Attribute*. These attributes correspond to features such as dimensions (e.g. height, width), materials, colour and weight. Notice that existing ontological resources such as the datatype property schema:value of schema.org, and unit definitions of the Quantities, Units, Dimensions and Data Types Ontologies (QUDT) catalogue can be used to complement the representation of the concept *Attribute*.

4.1. Building interface and renovation products

In a deeper level of abstraction, as presented in Fig. 4, each *RenovationProduct* will be linked to a *BuildingInterface*, which can be a *ConstructiveInterface* or a *SystemInterface*. Architectural elements where a *RenovationProduct* will be installed such as a specific point in a wall, an opening, or an area on a floor correspond to *ConstructiveInterface*. In contrast, the class *SystemInterface* gathers building elements that link one of the building systems to a *RenovationProduct*, e.g. an existing hot water pipeline that will be connected to a new radiator.

As mentioned previously, the existing conditions of the building can impact the way the construction activities are performed in renovation projects. Hence, the class *InterfaceState* is included to represent the current state of the *BuildingInterface*. The explicit classification of the building interfaces and the representation of their state allow modelling the linking points between the new renovation products and the existing building, as well as the identification of potential requirements that should be fulfilled to guarantee the proper integration of them.

As presented in Fig. 5, specific knowledge related to different renovation products can be added to the model as blocks of concepts. A window, a radiator and other products can be represented as subclasses of the concept *RenovationProduct*. Since certain pairs of renovation products such as window/solar protection system and radiator/pipe require close coordination between their installation activities, the symmetric property *InstalledInConjunctionWith* was created to represent this relationship. The Reno-Inst ontology classifies the components of a certain *RenovationProduct* in two classes *FunctionalComponent* and *InterfaceComponent*. The concept *FunctionalComponent* represents the main components of a renovation product, which perform the main function of it, e.g. the core of a radiator. In contrast, *InterfaceComponent* represents the components that are directly linked to the building interfaces, 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 product can be added to the model.

The existing BPO ontology [23] was a potential candidate to model the renovation products, nevertheless, it does not categorize their components. The alternative modelling approach implemented in the Reno-Inst ontology enables representing explicitly the components that will be directly linked to the *BuildingInterface*, facilitating the retrieval of specific details of these components to analyse the compatibility of materials and technologies between the *RenovationProduct* and the *BuildingInterface*. For instance, information regarding the fixing mechanism of a window can be easily retrieved to check compatibility between its material and the material and state of the opening where the window will be installed.

4.2. Installation activities and constraints

Each renovation product has a particular installation procedure, a window requires different steps than an ETICS panel to be integrated into the existing building. Developing an ontology to represent each of these procedures separately could derive in a complex, large, and probably unpractical approach. To deal with this complexity, the main class *InstallationActivity* in Fig. 6 includes general tasks such as *RemovalActivity*, *WorkAreaPreparationActivity*, *InsituTransportActivity* and *InstallationVerificationActivity* which are shared by different renovation products. A block with a concept *WindowMainInstallationActivity* and the associated activities *FixingActivity*, *AirtightClosureActivity*,

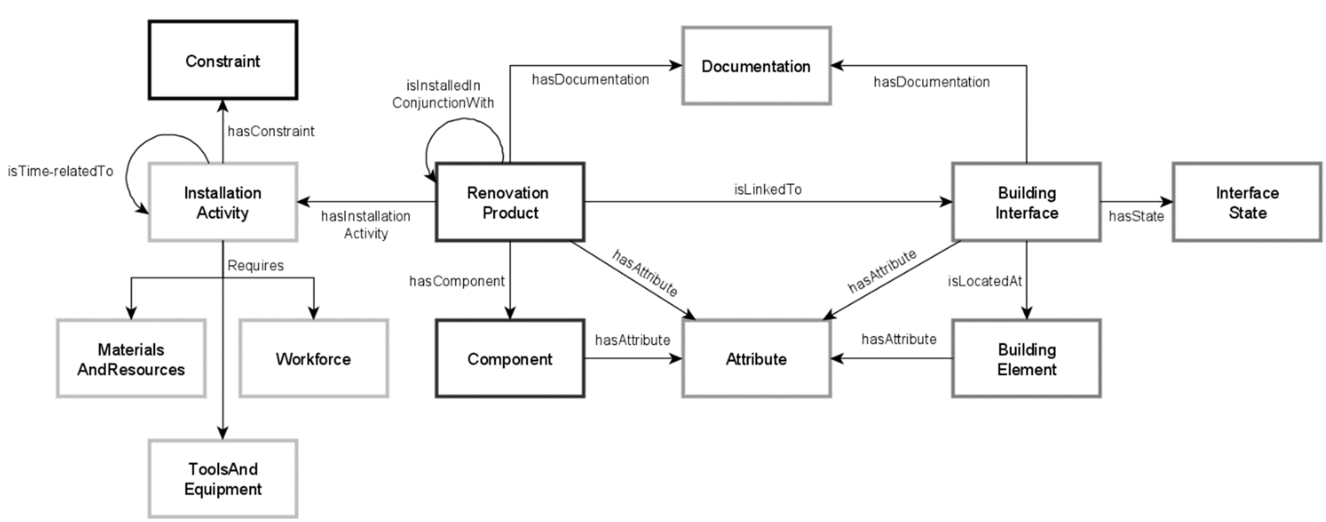

Fig. 3. Reno-Inst ontology overview.

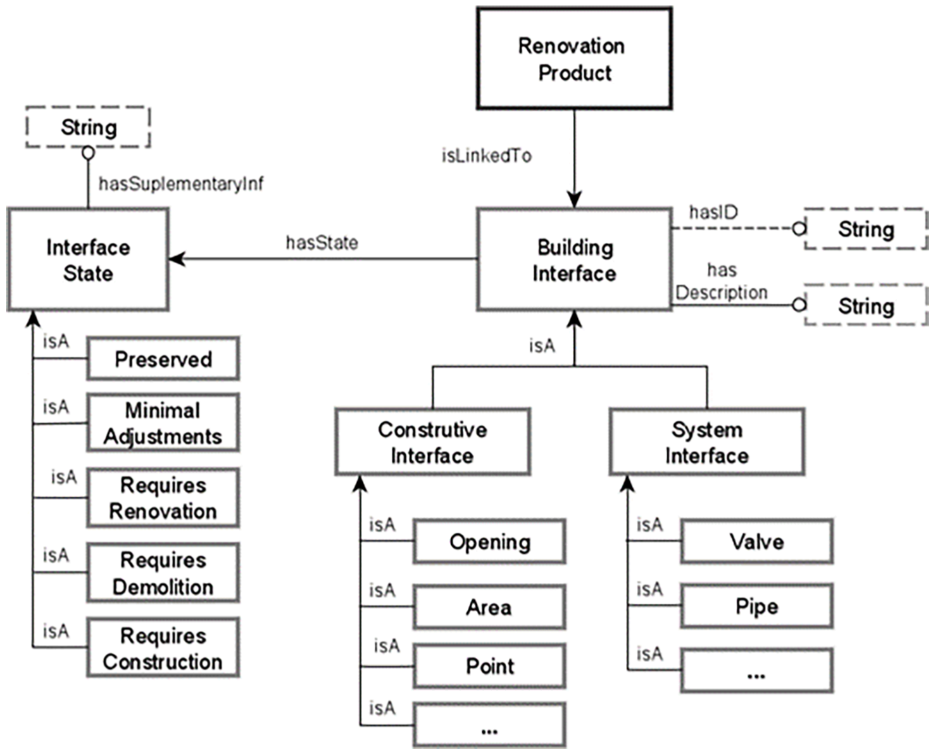

Fig. 4. Building interface representation.

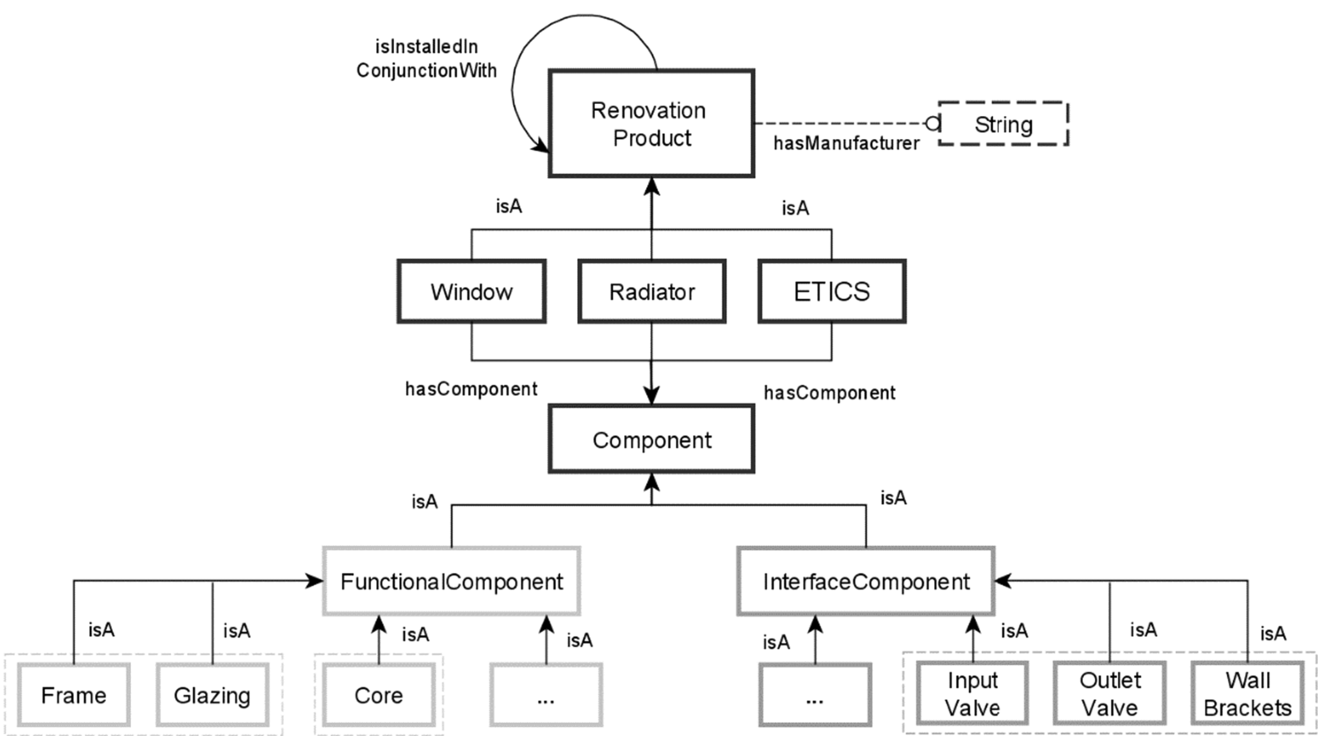

Fig. 5. Renovation product representation.

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 facilitates the integration of new renovation products, contributing to extend Reno-Inst for future 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*, and hasFollowingActivity *AirthightClosureActivity*. Each activity has associated data properties to specify its description, ratio, and duration.

Multiple particularities can cause certain differences when installing

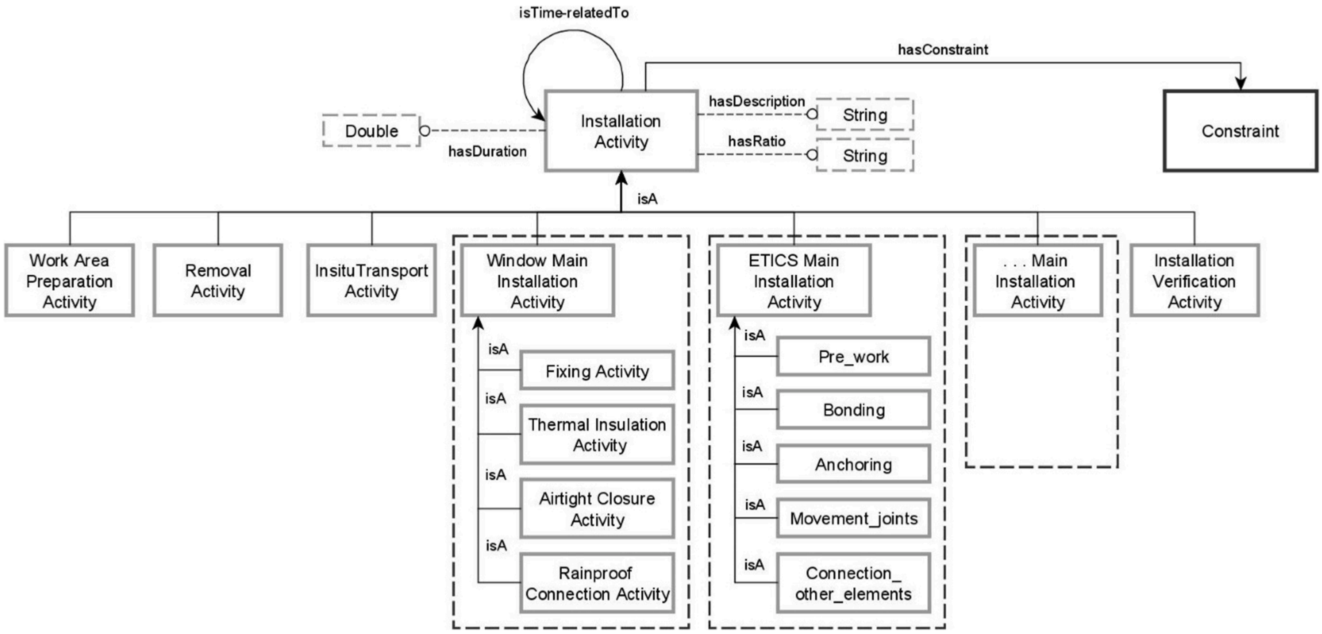

Fig. 6. Installation activities for renovation products.

a product in a renovation project in comparison to the conventional procedure. The *Constraint* class depicted in Fig. 7 represents potential constraints associated with the execution of the installation activities in the context of renovation projects. These constraints can be produced by *Physical, Uncertainty, Coordination, Pollution*, and *Safety* aspects. The subclasses *PhysicalConstraint* and *UncertaintyConstraint* represent restrictions due to physical limitations and lack of information from the existing building. The sub-class *CoordinationConstraint* includes limitations imposed by the building operational schedule and coordination required with the occupants. For instance, *OwnerOperationalConstraint* can include constraints imposed by the owner/manager of the building regarding the working period to execute noisy installation activities, e.g. only between 9:00–12:00 and 15:00–18:00 and other regular activities between 8:00–18:00. *OccupantsCoordinationConstraint* describes constraints such as the coordination required with occupants to execute construction activities inside the dwelling units.

On the other hand, *PollutionConstraint* is related to situations such as large dust production, handling of building materials containing contaminants, or high noise production during long periods, which can affect occupants. These constraints require the constructor to implement strategies to mitigate the 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 can have a high or medium *SafetyConstraint.* The occupants' transit through the staircase should be completely or partially restricted while performing this task to avoid potential accidents. Modelling these constraints contributes to getting a better understanding of the particularities of construction processes in renovation projects, enabling stakeholders to have a more comprehensive view of the aspects that should be considered while planning the renovation

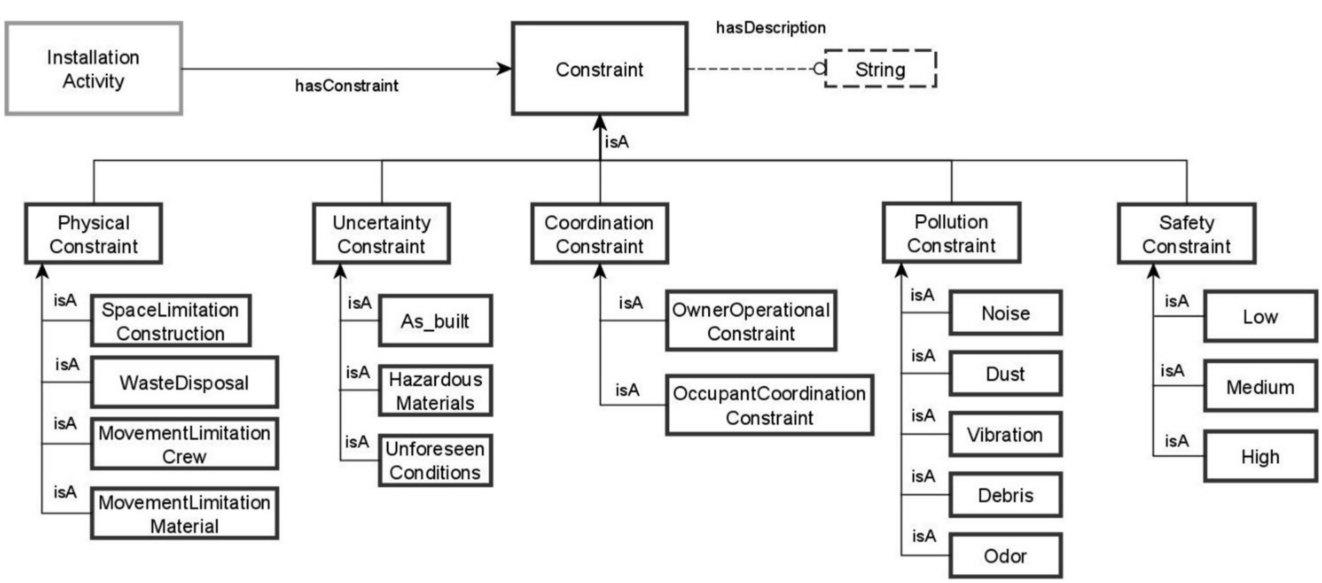

Fig. 7. Constraints associated with the installation activities of renovation products.

activities.

4.3. Practical overview

Fig. 8 depicts a simplified example of how the information can be mapped into the proposed ontological model. For the window *window_pvc_123* the mapped information includes attributes, installation activities and their constraints. For the sake of clarity, not all the relations and instances are shown in the figure. An occupants' coordination constraint is associated with the activity *work_area_preparation_window*. During the planning, the fact that inhabitants should be informed one day in advance about the installation of the window should be included, so they can re-allocate any furniture or elements around the opening to facilitate the work.

The information associated with the building interface *opening_678* on the right of the diagram is relevant to characterize its existing conditions. Additional attributes regarding material and other aspects can be included. Mapping this knowledge from different concepts in the context of renovation projects allows anticipating any requirement from the existing conditions of the building interface, constraints and particularities that can impact the renovation activities, and other relevant information.

5. Verification and validation

5.1. Verification

5.1.1. Content evaluation

During the content evaluation workshop experts reviewed the concepts included in the Reno-Inst ontology as described in Section 3.3.1. They checked the different terms and relationships in the model, discussed alternative knowledge structures, and identified missing information. The ontological model was adjusted according to experts' recommendations as summarized in Table 3. Experts suggested representing the resource requirements of installation activities. The initial ontology included a single class for tools, materials, and workforce requirements. Therefore, dedicated classes were created to model each of those requirements individually, combining materials and resources in a single class *MaterialsAndResources*. Experts indicated that waste management requires a high level of attention during renovation activities due to the lack of space and the presence of occupants. This concern motivated the representation of waste management constraints explicitly in the ontology. Moreover, experts indicated that certain activities need to be coordinated frequently with the occupants. For instance, occupants should often adapt the space around the work area in advance, re-allocating furniture and other elements when construction activities will be performed inside the dwelling units. Hence, experts suggested including a constraint to represent these situations.

Table 3
Ontology adjustments according to experts' feedback.

Recommendation or issue to be addressed	Adjustment
To include resources requirements for *InstallationActivities*.	The class *Workforce, ToolsAndMaterials* was split into three main classes *Workforce, ToolAndEquipment* and *MaterialsAndResources.* The latter includes materials, but also resources such as water, electricity, and compressed air.
To include a concept to represent the waste disposal constraints.	The subclass *WasteDisposalConstraint* was created as part of the class *PhysicalConstraint.*
To include other attributes of the *BuildingInterface* and *RenovationProducts* such as shape, position, load capacity.	Additional subclasses were created as part of the class *Attributes.*
Some activities should be coordinated with the inhabitants.	To represent this requirement an additional subclass *OccupantCoordinationConstraint* was created as part of the class *CoordinationConstraint.*
It is often required to perform some demolition activities on the *BuildingInterface* where a *RenovationProduct* will be installed (e.g. enlargement of window openings).	A subclass was created as part of the class *InterfaceState* to indicate if the building interface requires demolition work.
Certain *RenovationProducts* 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 products.

5.1.2. Design verification

At the second stage of the verification process, the Reno-Inst ontology was reviewed according to the list of common errors presented in Section 3.3.2. The properties and axioms associated with each class in the hierarchy were checked to identify mistakes made during the development of the ontology. Most of the pitfalls identified through this process were related to the lack of specification and limitation of

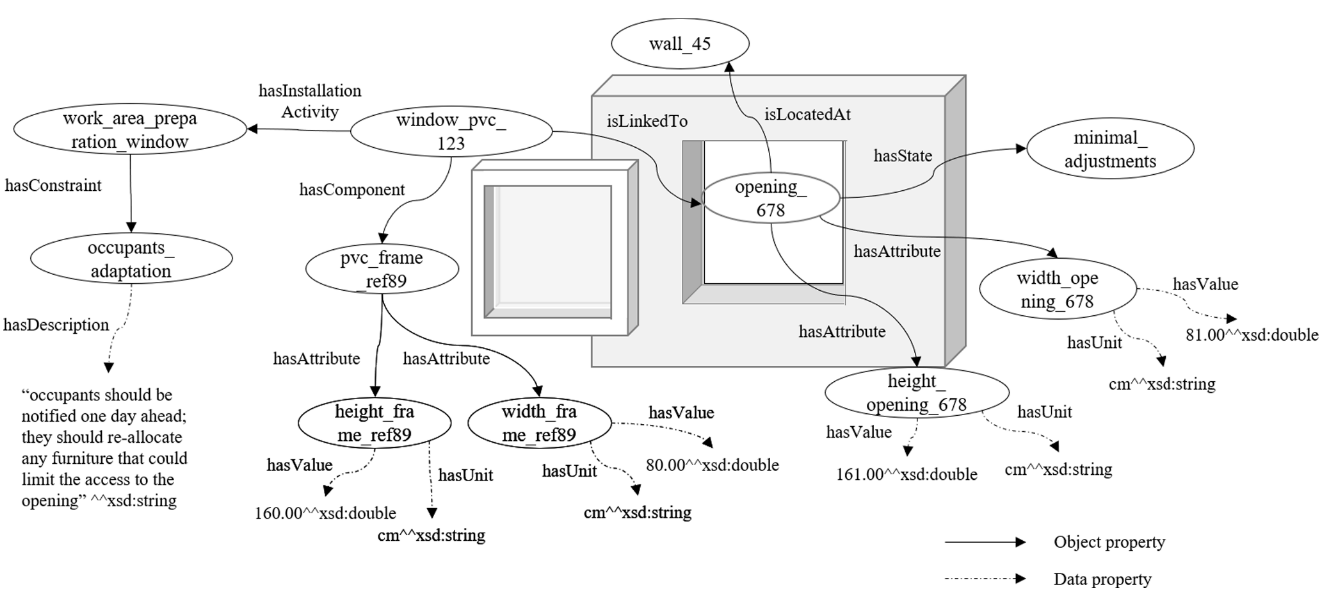

Fig. 8. Example for describing the overview of the proposed model.

properties. Object properties such as requiresMaterial_Resource were not specific enough. Sub-properties requiresMaterial and requiresResource were created to clarify this relationship and facilitate inference over the model. Additionally, for specific classes such as *FunctionalComponent* and *InterfaceComponent* it was necessary to add a disjoint axiom to guarantee that an instance of one class cannot belong to the other one. A few axioms related to object and data properties were missing, e.g. *BuildingInterface* hasState some *InterfaceState* and *RenovationProduct* hasType some *string*.

5.2. Validation

To validate, the Reno-Inst ontology was implemented using OWL/RDF language in Protégé. A previous renovation project was selected as a case study to analyse the application of the ontology. The renovation project included the installation of thermal insulation panels in the facade, new thermal insulation of the roof, replacement of a set of windows and complementary activities in a five-floor residential building with eight dwelling units. The renovation activities were performed while the building was occupied. The Gantt diagram of the renovation activities and complementary documentation were used as the main source of data.

At the initial stage, the available information was contrasted with the data model proposed by the Reno-Inst ontology. Even though during the content evaluation workshop most of the experts stated that waste management encounters multiple restrictions and difficulties in renovation projects, neither the plan of the activities nor the waste management report of the case study included explicit information regarding the on-site space limitations or the special measures that should be applied to deal with aspects such as the presence of occupants (if any is required). The explicit representation of this information can create a more comprehensive understanding of the management of construction activities on-site. Another element missing in the planning information material from the case study was related to the coordination with the occupants. In the communication protocol of the project, it is mentioned that occupants must be notified 48 h in advance about any activity affecting them directly. For instance, as part of the installation of the thermal insulation panels, the existing pipelines installed on the facade had to be removed. Since this task led to the interruption of the gas supply, the constructor had to inform the occupants 48 h in advance before starting the activity. Nevertheless, this information was not explicitly included in the Gantt diagram from the case study. Missing this relevant constraint during the execution of the construction activities can lead to effects on the occupants and legal claims against the constructor. The representation of this constraint in the Reno-Inst ontology showed to be relevant. The ontology facilitates the consideration of this and other constraints throughout the planning process, preventing the loss of information in the chain of decisions.

Moreover, according to the project records, multiple incidences appeared during the execution of the construction activities due to unforeseen elements from the existing conditions of the building. These situations were related to defects of columns and beams, and adherence problems of the thermal insulation panels to the existing mortar that required the contractor to execute additional activities, including the partial removal of the existing facade and application of a new layer of mortar. During this activity, structural elements got exposed and additional activities were necessary to repair them. Capturing these incidences in the constraint concept of the Reno-Inst ontology can enable the reuse of knowledge in future renovation projects. Stakeholders can exploit these previous experiences to foresee potential constraints related to the existing conditions of the building to plan the project accordingly and avoid schedule delays.

At the second stage of the validation, the plan for the renovation activities of the case study was used to instantiate the ontology and create a knowledge base. A set of construction activities from the case study was included in the knowledge base to illustrate the application of the ontology. This evaluation aimed at assessing how the ontology can support the stakeholders involved in the planning process. In the case study, three scenarios were demonstrated using SPARQL queries as presented in Fig. 9. These scenarios included a query for the installation activities of a certain renovation product (Fig. 9a), additional renovation products that require close coordination with the studied product (Fig. 9b), and constraints associated with its installation (Fig. 9c). The first query allowed retrieving information related to the installation activities of a thermal insulation panel, including the workforce and productivity ratio. This information is required during the planning phase to structure the extent of work and its requirements. The second query allowed identifying which of the additional renovation products require close coordination with the installation of the thermal insulation panel being analysed. In this case, the ventilation dampers and external clothes hangers will be replaced as well. While planning the installation of the thermal insulation panels, the installation activities of those two products should be reviewed to identify coordination requirements between the different tasks to be performed. Finally, the third query allowed identifying a constraint associated with one of the activities. The removal of the existing gas pipes on the facade requires the constructor to interrupt the gas supply to the dwelling units. This should be notified to the occupants 48 h in advance. Having access to information regarding this and other constraints during the early stages of the activity planning can help the stakeholders to structure the extent of work better, preventing impacts on the construction activities and the occupants.

6. Discussion

As its main contribution, this paper introduced an ontology that maps knowledge from the renovation domain considering different requirements, constraints, and other elements related to the installation of common renovation products. The proposed Reno-Inst ontology comprises the description of renovation products and the building interface where they will be installed. It also covers the installation activities and their constraints. Mapping these concepts can support stakeholders to check critical aspects of the existing building, constraints or limitations that can affect the construction activities in the context of renovation projects. Disregarding some of these aspects can impact the performance of the renovation project and lead to cost and schedule overruns. On the other hand, since the information in renovation projects is usually stored in diverse sources and formats such as spreadsheets, writing reports, and drawings, it is difficult to link information. The stakeholders should usually deal with this diversity, which makes the planning process prone to errors and loss of information. Gathering renovation projects data in a knowledge base relying on the Reno-Inst ontology can help users to manage information consistently and increase the reuse of knowledge in future projects.

One of the limitations of the proposed ontology is related to the renovation products covered during the knowledge acquisition. The structure of the Reno-Inst ontology was based on the information captured for three common renovation products. However, there are multiple components, activities and constraints that can be considered during a renovation project. Some of them may not fit into the proposed representation. Another limitation is associated with the fact that two of the experts that took part in the content evaluation workshop during the verification stage participated in the knowledge capturing process as well. However, it is important to notice that the knowledge acquisition stage relied also on other sources such as related literature, manufactures' catalogues, and guidelines from regional engineering associations. Therefore, during the content evaluation workshop, experts analysed and discussed a larger set of knowledge than the one they had provided at the first stage of the ontology development.

An important aspect in the development of ontological models is the re-use of existing ontologies. However, the renovation domain seems to be an unexplored area in the field of ontological representations, making

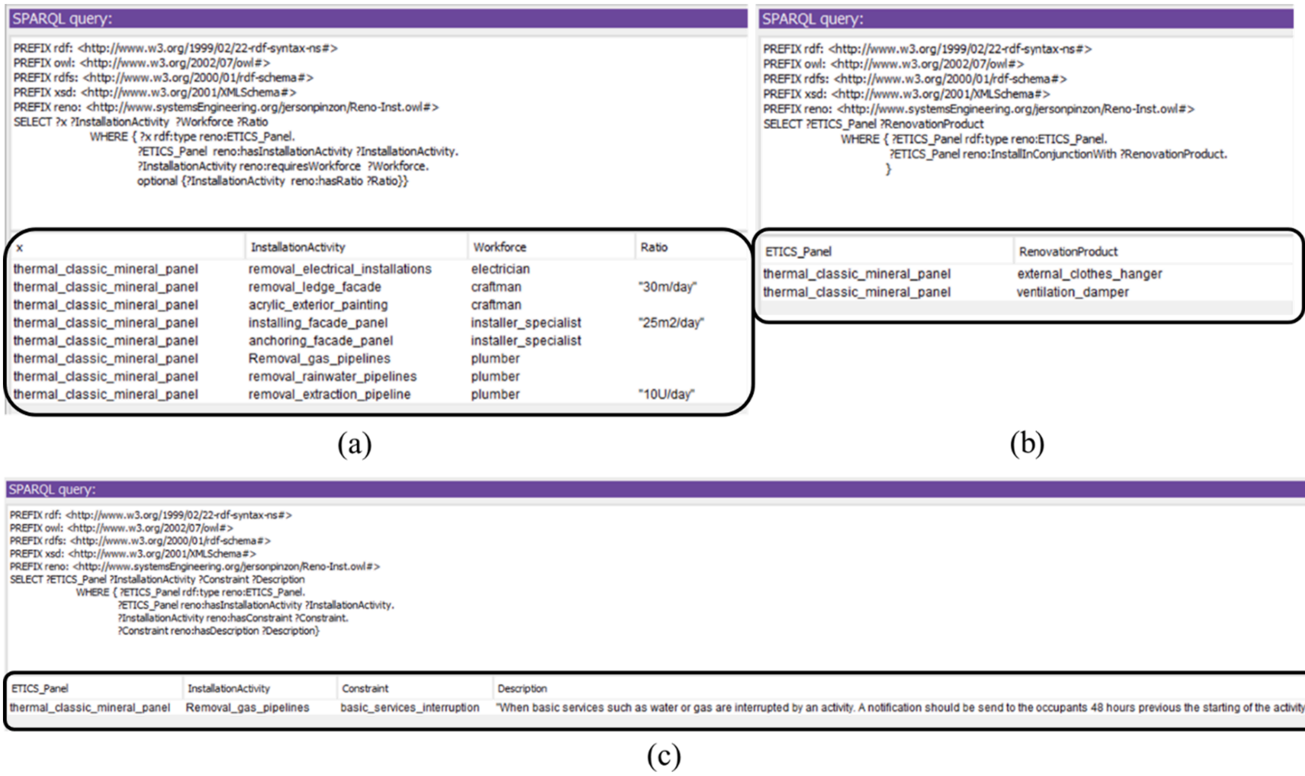

Fig. 9. SPARQL queries and results based on the case study.

the re-use of existing resources a challenging task. Even though some of the existing approaches for new construction could be partially adapted for renovation projects, the particularities presented in Section 2.1 motivated the development of a dedicated ontological model for this field. The possibility to re-use the existing BPO Ontology [23] to describe the *RenovationProduct* was considered, nevertheless, it was noticed that an alternative approach would be more suitable to represent separately the components by *FunctionalComponent* and *InterfaceComponent* classes. This approach facilitates the retrieval of specific details of the *InterfaceComponent* that would be linked to the *BuildingInterface* where the *RenovationProduct* is installed to analyze the compatibility of materials and technologies between them.

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 [22], 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 by Rasmussen et al. [22]. 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. Moreover, in case the renovation project includes construction or structural activities such as the redistribution of internal spaces or reinforcement of columns and beams, a link or alignment with the model proposed by Zhong et al. [27] could support the planning of more complex activities in conjunction with the installation activities of the renovation products covered by the Reno-Inst ontology.

Future research activities should include an additional knowledge capturing process to map information about other renovation products. Moreover, an observation group exercise or a knowledge-intensive case study can analyse how the ontology supports the stakeholders to address the challenges of real renovation practices. Another potential extension of our research is to formalize explicit and implicit if/then rules from renovation projects through the Semantic Web Rule Language (SWRL). Rule languages have been conceived as partners for ontologies, allowing for reasoning especially in problem domains that have to deal with default knowledge [40]. These rules can cover more specific and complex relationships such as associating constraints to the activities based on their particularities. For instance, if a certain activity *requires* a tool such as a *driller*, it should get associated with a *PollutionConstraint* (e.g. Noise) and an *OwnerOperationalConstraint* (it should not be performed between 12:00–14:00). Finally, other potential uses of the Reno-Inst ontology can be explored. For instance, by combining the Reno-Inst ontology with recognition patterns approaches such as the ones presented in [24,25], the knowledge from previous renovation activities can be exploited in future projects.

7. Conclusion

While construction workflows and supporting tools in new construction projects may be well established, renovation projects address specific challenges that call for specialized supporting tools and procedures. The use of semantic models has been explored in other areas of the AEC industry, however, building renovation seems to be a neglected area in this field. The development of an ontology covering this domain is a starting point in renovation projects to apply approaches that have been explored in other areas. This paper introduced the Reno-Inst ontology, which represents the main concepts and relationships covering knowledge from the renovation domain considering different requirements, constraints, and other elements related to the installation of renovation products such as windows, thermal insulation panels, and heat radiators. This formal representation of knowledge provides an integrated view of the information that can support the planning and execution processes in the context of renovation projects.

This paper provided another clear example of the power of ontologies as a method for mapping knowledge, gathering heterogeneous data from multiple sources, and retrieving relevant information. The proposed model can leverage information from different sources such as general documents, communication plans, building operational schedules, etc. While planning and executing renovation activities, constraints related to the operational schedule of the building, occupants' considerations, space limitations, the state of existing building elements, and tools and material requirements information can be retrieved in a structured way. This information is relevant to establish process outputs such as the schedule of renovation activities, safety, mobility, waste disposal, and other plans. The proposed ontological model could benefit from an additional knowledge capturing process to map information about other renovation products and the formalization of explicit and implicit if/then rules from renovation projects.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [This research project is funded under the European Union's program H2020-NMBP-EEB-2018, under Grant Agreement no 820553.].

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