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An ontology to represent geospatial data to support building renovation

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ABSTRACT

Energy-efficient building renovation is an inter-disciplinary task and requires investigation about the building condition in the urban, environmental, and societal context. Existing literature implicitly mentions the effect of surrounding data in different stages of building renovation. Nevertheless, no conceptual framework is available for practitioners to realize the potential of such data in specific phases of the renovation.

The main goal of this study is to understand: (1) based on what knowledge framework surrounding geospatial and environmental data can support building renovation projects, (2) if developing an ontology can help representing this knowledge framework, and (3) how experts and engineers involved in the renovation process can contribute to development of this knowledge framework. The results present an ontology that maps surrounding geospatial and environmental concepts for different renovation tasks and use cases within building renovation. The ontology is built upon knowledge captured from previous studies that implicitly mention the effect of these datasets in building renovation, as well as expert knowledge, brainstorming, and monitoring construction sites. Additionally, a semi-structured verification and validation workshop has been performed to incorporate insights from experts directly involved in different stages of building renovation process.

This paper contributes to the body of knowledge by generating a common framework for the surrounding data required in building renovation. It has an implication in practice for engineers by providing a shared knowledge framework and for software developers by providing a basis for BIM (Building Information Modeling) and GIS (Geographic Information System) data integration for renovation purposes.

1. Introduction

A ‘Climate Neutral Europe by 2050′ is one of the actions at the European level, where policies are targeted toward increasing building renovation rates and depth of energy saving in the renovation process [1]. Energy-efficient building renovation is an inter-disciplinary task. It needs to cover domains with different ontological outsets, such as contextual, environmental, and societal data [2]. Investigating the surrounding geospatial and environmental data can help to highlight the impact of some of these factors. Experts in the architecture, engineering, and construction (AEC) domain apply BIM and GIS data integration, as a common practice, to benefit from the geospatial datasets in construction projects. Sani et al. [3] and Zhu et al. [4] have carried out an extensive review of these studies. For building renovation [5], scrutinized the effect of surrounding buildings, vegetation, and parking lots in the quality of building data collection. In addition [2], generated a framework to assess the building renovation performance. The framework includes datasets from different fields, including the geospatial domain. Nevertheless, they do not explicitly mention the required surrounding geospatial data for building renovation.

Today, municipalities devote significant effort to collecting geospatial data for cities. As a result, voluminous amounts of geospatial data for different locations in several levels of detail are available. However, searching for geospatial data for a specific application from this pool of data is overwhelming and requires expertise [6]. Having a framework for managing geospatial datasets and realizing their potential in different phases of building renovation is missing in existing renovation studies. The first motivation of this paper is to fill this gap and provide an overview of the required geospatial and environmental entities to support building renovation.

Ontology is an approach for “an explicit specification of a conceptualization”, and conceptualization is the way of “thinking about a domain” [7]. There are different targets for developing ontologies. One of them is supporting engineering design requirement capture to help the experts in the domain communicate more conveniently [8]. The real-world is a broad topic and modeling and creating an ontology for such a

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system is a huge task. A common practice is to model the geospatial data for a specific application and domain that narrows it down to the required concepts. For instance, urban ontology prunes the geospatial concepts and relations and keeps those required for urban analysis. Therefore, the second goal of this research is to investigate whether ontology development helps to generate this knowledge framework. Creating such a knowledge framework is beneficial since it can be reused in different renovation cases in various locations [6].

To develop the ontology, the first step is to identify the exact renovation tasks, where geospatial data are required or beneficial, according to the knowledge retrieved from previous studies. Based on that, relevant concepts and relations are determined. The last step is to validate the ontology against the use cases and within the scope of those specific tasks with the tight involvement of experts and engineers. Hence, the final motivation of this paper is to include experts and engineers involved in the renovation process into the development of this ontology.

The paper is structured as follows: Section 2 presents the research background and motivation. Section 3 summarizes the methodology utilized for developing and evaluating the ontology. Section 4 presents the results including the ontology implementation and evaluation. Finally, the discussion and conclusions are provided in Sections 5 and 6, respectively.

2. Research background and motivation

2.1. Geospatial and environmental data in building renovation

Geographical data has been represented in the construction domain for different purposes such as urban planning, emergency response, mobility, and railway planning [9,10]. Within the context of building renovation, many studies investigate the effect of surrounding and environmental data in applications related to renovation tasks such as building energy modeling, accessibility to the renovation site, acoustic and thermal comfort analysis [11–17]. To practically integrate these concepts into building information models, [5] introduced a pre-retrofit model that performs a BIM and GIS integration strategy to combine data to provide contextual information about the building under renovation. However, this study does not enumerate the required contextual datasets. Costa et al. [18] developed a platform including an integrated ontology-based District Data Model (DDM). The DDM is a data model that semantically integrates data of building and urban scale required for retrofitting. The urban data in this ontology includes the geometry of the building envelope, and the geometric representation of urban elements such as green areas, roads, and city amenities. The authors do not explicitly mention the required or beneficial data for the application of building renovation. They believe that these datasets can have an indirect effect on the renovation process. In this study, the developed platform uses this ontology to collect data in IFC and CityGML format. However, this study highlights that CityGML cannot help in structuring all the necessary data. Therefore, other datasets were added to the platform in the form of contextual data [18].

Researchers presume that BIM and GIS data integration is the optimal solution in practice for providing the data flow between construction and urban domains. However, they usually miss an intermediate phase in which required concepts should be specified [19]. This necessities development of ontologies that can cover all essential concepts for a specific task. Applying prevalent data models such as CityGML for building renovation is not valid since it does not contain all required concepts for different applications in the building renovation workflow. In addition, expert knowledge required for renovation is missing to a great extent.

2.2. Ontologies in geospatial domain

To model geospatial data, Open Geospatial Consortium (OGC) introduced different standards. LandInfra is a conceptual model for representing infrastructure facilities such as roads and railways [20]. GML (Geography Markup Language) is an XML (Extensible Markup Language) grammar for expressing geographical features [21]. IndoorGML is a GML application schema to represent indoor spatial information [22]. CityGML is an application schema of GML for the 3D representation of data. CityGML was developed to reach a common definition and understanding of the basic entities, attributes, and relations within a 3D city model [23]. It is widely used, and recently a growing number of projects have generated CityGML models of different cities. This model is also employed frequently in integration with IFC (Industry Foundation Classes) in construction projects. IFC is an open international digital standard description of the built environment. Different parties in a construction project use it for exchanging information. This model only focuses on the individual building model and does not include surrounding information [24]. Another building information model is gbXML (Green Building XML), which aims at facilitating and enabling the interoperability between building design and engineering analysis, such as energy simulation of the building. The gbXML schema includes building information required for building energy modeling, such as thermal zones, and some surrounding information, such as vegetation [25].

It is tempting to use 3D city models such as CityGML for urban applications. However, CityGML components do not provide sufficient concepts for particular applications [9]. Currently, in the geospatial domain, there is no representation that suits all applications due to complexity of the domain [26]. Task-specific ontologies can address this issue [27]. An ontology should be developed within a specific domain and task that restrict the scope and universe of discourse. Besides, it should be developed in close collaboration with stakeholders and practitioners in the domain [28].

Spatial data modeling is investigated in different applications from different perspectives. However, to the author's knowledge, no study applied an ontology-based approach for the building renovation application. To narrow down the geospatial domain, we applied urban ontology as the starting point, as we assume the building under renovation is located in an urban context. Urban ontology categorizes the urban-related features to objects such as buildings and roads; processes such as population density; relations such as building block has buildings; and events such as traffic accidents (Fig. 1). In the ontology domain, 'object' is a term of art that is considered as things, events, and processes of all sorts [29]. In the context of this research, an *object* is a 'spatial thing' that comprehends boundaries of physical (such as building and road) or non-physical (such as district and zip code) features. Therefore, it is analogous to the '*CityObject*' concept in CityGML.

Thus, in the object view of our ontology, some concepts are inspired by the concepts introduced in *CityObject* in CityGML, such as building, vegetation, and water bodies (Fig. 1). However, sub-categories of these concepts are customized to focus on specific concepts related to renovation processes.

2.3. Identifying research gap and contribution

Based on previous studies mentioned in Sections 2.1 and 2.2, we identified three research gaps. Firstly, a knowledge framework for geospatial and environmental data is missing in building renovation studies. Such a framework would help engineers and experts in the renovation workflow comprehend the benefit and requirement of geospatial and environmental datasets. However, majority of studies implicitly mentioned it for specific applications related to building renovation. Therefore, as a first contribution, we conducted a literature review on these studies and identified the relevant concepts as basis for a knowledge framework. As a second contribution, we developed an ontology to represent this knowledge framework. Lastly, we evaluated the ontology with experts and engineers. Hence, in a bottom-up approach, we integrated the knowledge of renovation project

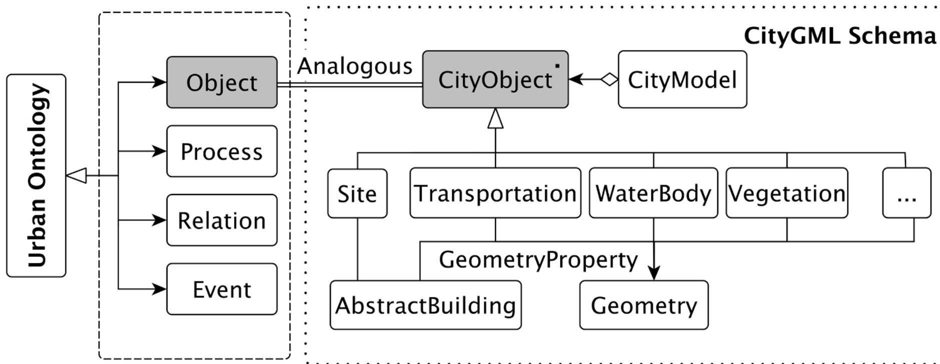


Fig. 1. Intersection of urban ontology and CityGML schema.

practitioners into the ontology development.

In the next section, we explain the methodology utilized for developing the ontology and its evaluation.

3. Methodology

This section presents the methodology utilized for developing this ontology. As depicted in Fig. 2, the process starts with a literature review on the studies which mention the utilization of geospatial data in diverse renovation tasks. We used these studies to acquire the knowledge for developing this ontology. The next step is ontology conceptualization and implementation, followed by a verification and validation step. We verified the ontology through brainstorming with experts in a workshop and consistency checking using the faCT++ reasoner available in Protégé [30]. In addition, we validated the ontology against its targeted purpose by conducting a workshop with practitioners and representing the surrounding geospatial data for a case study in GIS.

3.1. Literature review

Some studies implicitly mentioned effective parameters from the surrounding of the building in different analyses of renovation projects. Nevertheless, we realized that it is challenging for the engineers and practitioners to identify the most suitable geospatial datasets and workflows in different phases of the renovation process, for instance in the planning phase. Therefore, we conducted a survey on relevant studies and collected an explicit list of renovation tasks and the corresponding required geospatial concepts. We used this survey as a basis for capturing knowledge to develop the ontology.

Among different available approaches for literature review, we applied snowball sampling for selecting the articles. This method is recommended when it is challenging to access subjects with specific target characteristics [31]. Therefore, this approach is suitable, as it helps to access those publications which do not explicitly mention the subject of study. In summary, the procedure starts with a set of relevant papers. The next round of articles is selected based on the title, abstract, and references provided. This procedure continues until enough articles are available [32]. Most of the papers are published in journals that are focused on building in the built environment. This is expected, as the topic is in the conjunction of building and its surrounding environment. Most of the papers are from the year 2010 onward, although we did not have any constraint in selecting the papers. We surveyed mainly the articles through google scholar.

3.2. Ontology development

The research approach for developing the ontology includes ontology specification, knowledge acquisition, conceptualization and implementation [33].

3.2.1. Ontology specification

Ontology specification is done by answering questions regarding purpose, scope, intended end-users and intended use of the ontology (Table 1).

3.2.2. Knowledge acquisition

The literature review mentioned in Section 3.1 is the basis for knowledge acquisition. After defining the ontology specification, an initial list of intended uses including specific renovation tasks that can be supported by this ontology is prepared according to the literature review. For each task, a list of surrounding datasets that can be required or beneficial is assigned. These specific tasks include site planning, building energy modeling, acoustic, air quality, thermal and lighting comfort analysis.

Subsequently, brainstorming and experts' opinions as well as investigating the surrounding environment of real demonstration sites through aerial imagery, available maps, and visiting renovation sites helped authors to formalize the knowledge. After the ontology requirements are specified, the next step is to formalize and conceptualize this specification. For this purpose, a list of entities (objects) along with some attributes and processes are identified, and some relations are used to connect them.

3.2.3. Conceptualization and implementation

The ontology presented in this research aims at covering all the physical (bona fide) objects in the surrounding environment in the context of building renovation projects such as building, as well as non-physical (fiat) objects such as district [29]. The ontology also covers processes that convey information about the distribution of specific phenomena in a location, for instance, distribution of energy consumption or potential of renewable energy sources in the surrounding of a building. The ontology is developed based on the concepts in urban ontology, and in the object view it is inspired by the concepts in CityGML. Therefore, existing standards and data models are considered when developing this ontology. To this end, *objects* and *processes* associated with some attributes and properties are used as the starting point.

3.3. Ontology evaluation

The evaluation of the ontology includes investigating its quality and correctness. These perspectives are examined through consistency checking of the concepts and axioms and their relations (verification), and competency checking of the ontology for the purpose it is developed (validation) [19,34]. Fig. 3 shows the evaluation effort in summary.

3.3.1. Ontology verification

We conducted workshops with participation of five construction engineers researching ontology development in the AEC domain for verification of the concepts and relations introduced in this ontology.

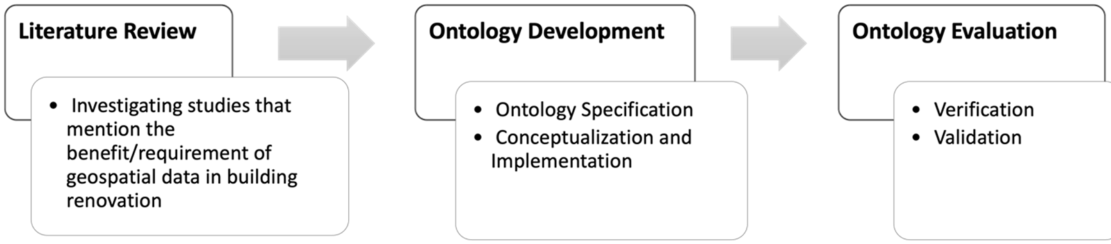


Fig. 2. Procedure of developing the ontology.

These experts help with the verification of the ontology because they have extensive general background knowledge in ontology development. Furthermore, each of them has developed ontologies for specific tasks for construction purposes in individual research. In this workshop, we did not focus on the instantiation of the ontology for a specific project. Instead, we presented a general description of the concepts and relations in the ontology. The experts discussed based on extensive scrutiny on the concepts, relations, and the hierarchy between them.

Moreover, consistency checking of the ontology helps for a correct interpretation, which can increase the quality of the ontology. In this regard, ontology reasoning helps to find the conflicts in the knowledge content [19]. We implemented the proposed ontology using OWL/RDF language in Protégé (the ontology file is available online[1]) [30]. After considering the comments from experts, we performed an automated consistency check using the faCT++ reasoner in Protégé Version 5.5.0 [35]. Reasoners perform a consistency check verifying there is no inconsistency in the concepts and relations.

3.3.2. Ontology validation

The second part of the ontology evaluation is to check the competency of the ontology for the intended uses for which it is developed. This task is more complicated than verification for two main reasons. Firstly, the evaluation requires a representation of the ontology within a specific context and for a particular purpose. Secondly, the task for which the ontology is used should be sufficiently complex [36]. One approach is implementing a prototype based on the ontology. Using the prototype, it is possible to establish a demonstration of the model to ask experts and engineers about their opinion. It is also possible to ask the experts to use the prototype to solve an engineering task within an open-ended experimental setting, without formal structuring of the process [19].

In this research, the validation of the ontology consists of a workshop conducted to check if the ontology accomplishes specific tasks, and fulfills the expectations mentioned in the intended end uses in ontology specification (Table 1). A prototype is developed to demonstrate the ontology. The experts had practical experience with the prototype to retrieve data for a specific case study. In addition, to clarify how these datasets can be helpful for the experts, we visualized the geospatial data for a case study in ArcGIS. The main activities for the validation effort include:

Table 1
Ontology Specification.

Purpose	This ontology is developed to represent surrounding geospatial and environmental data to support experts in different stages of building renovation projects.
Scope	This ontology includes real-world physical objects such as building and road, conceptual objects such as district, and urban processes related to population, environment, and energy.
Intended end-user	The intended end-users are renovation project practitioners such as site planners, data collectors, energy experts, performance and comfort analysis experts, and decision-makers
Intended use	The ontology is intended to be used as a common knowledge management framework. This framework will give a comprehensive view of all the datasets in the surrounding of a building that can support building renovation.

3.3.2.1. Preparation of the prototype. We developed a prototype based on the ontology, that serves as a repository for retrieving and storing the required geospatial data for building renovation projects. It is designed based on a service-oriented architecture (SOA) framework for retrieving the required geospatial data that adheres to the OGC standards of Web Feature Service (WFS) for retrieving vector data. The retrieved data shall be downloaded in Shapefile or GML format and visualized in a GIS software. The prototype includes a list of use cases for which the required geospatial data is suggested.

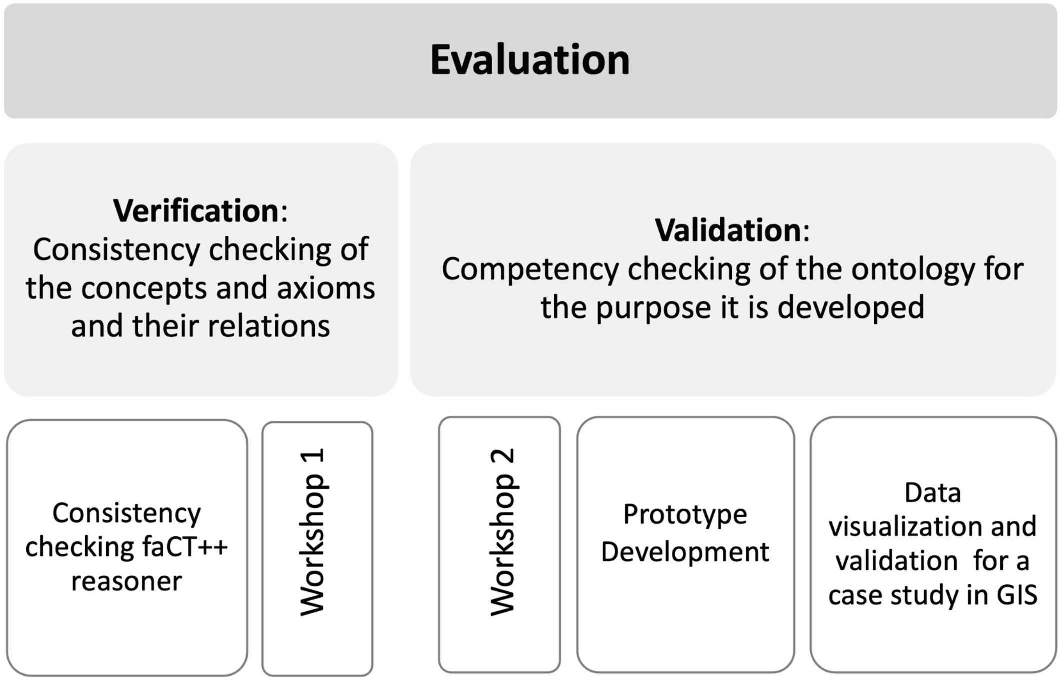
3.3.2.2. Selection of the participants for the workshop. For selecting the workshop participants, it is crucial to consider what skills are required to assess the ontology according to the intended end-users of the ontology [19]. The recipients of the invitation were chosen based on that specific expertise (Table 1) and were asked with direct invitations [37]. Based on the availability, we invited four engineers involved in building renovation. The experts work in building energy modeling, acoustic, air quality, lighting comfort analysis, research, and development in building renovation field. These experts are involved in an EU research project focused on residential building renovation (Horizon 2020 BIM-Speed project [38]). The project participants are 23 international companies and research groups working on 13 different demonstration cases across Europe. Therefore, the selected experts are directly involved in real building renovation projects and can reflect on the ontology development from an operational perspective.

3.3.2.3. Practical experience with the prototype. In this step, we asked each of the experts to work with the prototype. We asked them to select the building location on the map, check the list of use cases, choose the use case that is most relevant to their field of work, check the data list that is suggested for the use case, and provide their ideas about the listed concepts. We asked the questions in a semi-structured manner to allow the possibility for brainstorming. Questions included but were not limited to:

- For the available list of use cases, what datasets they would recommend as required or helpful.
- For the mentioned concepts, what other attributes they consider as required or helpful.
- If the hierarchy used to present this ontology is meaningful and logical.
- What other use cases they recommend for utilizing the surrounding data in the building renovation process.

The questions have been asked in a less structured manner, as suggested by [19]. It helped to have a more open discussion which subsequently resulted in exploring new ideas to improve the quality of

[1] https://doi.org/10.14279/depositonce-12787



	Purpose	Participants' Expertise	No. of experts
Workshop 1	Verification	Ontology development in AEC domain	5
Workshop 2	Validation	Energy modeling of buildings, acoustics, air quality, lighting comfort analysis, and R&D	4

Fig. 3. Ontology evaluation effort in summary.

ontology.

3.3.2.4. Visualization of geospatial data for a case study in GIS. The benefit of having access to the surrounding data collected from the prototype can be more evident if the geospatial data are visualized on maps. For this purpose, we visualized some of these datasets on maps for a specific case study using ArcGIS software. Envisaging the building in its geospatial context can help better comprehend its limitations and possibilities. Besides, we asked the experts about their current experiences for collecting such datasets in renovation projects. Subsequently, we investigated what information can be revealed from the maps to help in a specific use case in the renovation of a particular case study.

4. Results

4.1. Knowledge capture from literature review

The studies using geospatial datasets in renovation tasks are summarized and provided online[2]. The renovation tasks are categorized into site planning, building energy modeling, thermal, acoustic, lighting, and air quality comfort analysis. We selected this list of renovation tasks from an exhaustive list of use cases for building renovation that is developed in the BIM-Speed EU research project [38]. The participants of the use case development are from construction companies and research groups and are involved in building renovation projects. From this list, the authors selected those use cases for which they expect surrounding geospatial and environmental data are required. The following provides a summary of some of the studies mentioning requirement of geospatial data in each of these use cases.

4.1.1. Site planning

It is believed that the premise for success of the future development in the renovation projects is site planning [39,40]. Different studies mention diverse aspects of surrounding datasets in site analysis and planning such as building data collection [5], primary analysis for building energy demand [11], logistics and planning for access of workforce and material, safety [40–42], regulations caused by historical preservation and interconnection within the heating network and renewable sources of energy for energy supply management of the building [12]. The surrounding geospatial datasets can provide information for planning the project in advance and understanding the limitations and facilities on the construction site.

4.1.2. Building energy modeling (BEM)

BEM is one of the critical analyses in the building renovation process. Environmental data, and particularly weather data provided from weather stations, can directly affect the energy modeling of the buildings [13,41]. The shading effect of the surrounding obstacles, such as buildings and trees, is another considerable parameter. For instance, one study which evaluated the impact of tree shades on the building's energy demand shows a considerable reduction in energy use in the summer

[2] https://doi.org/10.14279/depositonce-12787

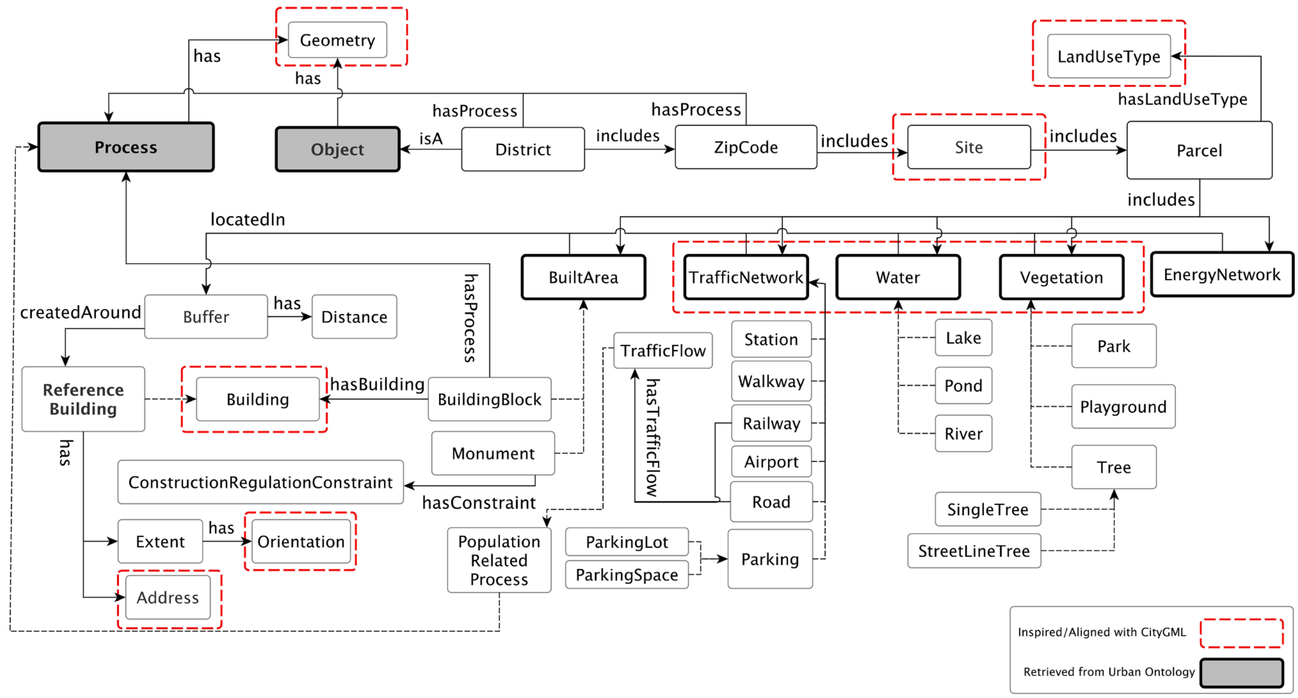


Fig. 4. Object view in the proposed ontology.

season [43]. Also, altitude, street geometries, vegetation, and water bodies that cause evaporative cooling can affect the local weather condition [44,45,46]. In addition, energy consumption in the urban context is affected by the socio-economic profile of inhabitants [44,47,48]. Consumption schedule in the building is directly affected by the consumption behavior of the occupants.

4.1.3. Comfort analysis

It is essential to find effective factors in studying the occupants' comfort from different aspects, as it is connected to the health issues and well-being of the building occupants [49]. Different studies address the effect of the surrounding built area, roads, walkways, playgrounds, running water, and pools in the acoustic comfort of the building [44,47]. Different urban objects can affect the urban soundscape in the built environment, such as playground zones because of children's voices, trees, vegetated areas, and pools, due to running water, footsteps, roads, and walkways on account of traffic, and human voices [50–54]. Collecting this information in the early stages of a building renovation from geospatial data sources provides valuable information for understanding the possible sound sources in the built environment. These datasets deserve great attention in renovation projects since correct insulation of facades or replacement of windows can considerably improve indoor acoustic comfort [53]. Other issues such as air quality, outdoor temperature, wind speed, and wind direction are also affecting the comfort of the residents and they are all considered as external features. Building's height to road's width ratio is used as an indicator to find the density of the urban area. Dense areas (indicated through high ratio values) can weaken the wind circulation that reduces the air dispersion capability, which leads to less indoor air comfort [53–56]. Decrease in indoor daylight availability due to the external obstructions may increase building heating and lighting energy demand [57].

It is also important to mention that understanding the availabilities of the heat supply at the district level, and taking advantage of utilizing these sources, along with reducing heat loss through a careful design of the building envelope, leads to thermal comfort of the occupants [53–55,58]. Surrounding building height and the façade material that cause shading effects impact the interior lighting of the building and the visual comfort of the occupants [52,53,57]. The next section provides a detailed description of the concepts and relations in the ontology.

4.2. An ontology to represent surrounding environment of a building

As mentioned before, urban ontology is used as a basis for developing the ontology in this research. *Object* and *Process* are the concepts retrieved from urban domain and expanded in the direction which is required for renovation task. On the other hand, to account for the urban context, for the *Object* concept, a top-down bird's-eye view is applied to categorize the entities. The bird's-eye view is the view which is used to represent geographical features on the maps and aerial images [59]. Some components in CityGML are also the source of inspiration to define the objects in the urban domain (these components are highlighted in red in Fig. 4).

Any object on the surface of the earth *hasGeometry* to define the representation of the feature. *Geometry* is an important aspect of geospatial data as geographic objects are tied to space [60]. We did not add further details of geometry, with the purpose of keeping the ontology at the conceptual level. The first view from the top is the *District* which includes *ZipCode*. On the lower scale, a *Site* i.e., an area with a specific radius around the building under renovation is presented. A *Site* includes different *Parcels*. Each *Parcel* is related to *LandUseType* with the object property *hasLandUseType* (Fig. 4). Each *Parcel* may include five main categories. These categories are the *BuiltArea*, *Vegetation*, *Water*, *EnergyNetwork*, and *TrafficNetwork*. Each of the categories contains different sub-categories and different attributes are assigned to them. *BuildingBlock* and *Monument* are considered as *BuiltArea*. *BuildingBlock* has an object property *hasBuilding* which connects it to the *Building*. *Monument* has an object property *hasConstraint* which connects it to *ConstructionRegulationConstraint*. It is important to know the construction regulation of monuments and historical places since it can affect renovation workflow. Sub-categories of *BuiltArea* have object property *hasAttribute* which relates them to some specific attributes such as *Area* and *Name*. Attributes such as *Height*, *FacadeMaterial*, *RoofMaterial* and *NumberOfFloor* and *Area* are assigned to *Building*.

The *ReferenceBuilding* corresponds to the building under renovation. This concept is included in the context of *Site* as a sub-category of *Building*. A *Buffer* should be created around the *ReferenceBuilding* to select the desired surrounding concepts. The *Buffer has* a *Distance* to define in which radius the objects are required to be collected. All the sub-categories under *Parcel* such as *BuiltArea* and *Vegetation* are connected to *Buffer* with *locatedIn* object property.

Vegetation category contains *Park*, *PlayGround*, and *Tree*. *Park* and *PlayGround* have *Area* and *Name* attributes, while Tree including *SingleTree* and *StreetLineTree* has *Height*, *CrownSize*, and *TreeSpecies* attributes. Water category includes *River*, *Pond* and *Lake* with *Name* and *Width* attributes. The *EnergyNetwork* distinguishes between different energy sources such as gas and district heating by *EnergyType* attribute. The *TrafficNetwork* category comprises *Airport*, *Road*, *Railway, Walkway and Station* with *Width*, *Type* and *Name* attributes, and *Parking* consisting of *ParkingLot* and *ParkingSpace* with *Name* and *Area* attributes. Some attributes such as *Height* and *Area* are extended with two data properties namely *hasValue* and *hasUnit* for more description. Although, same approach is not used for multivalued attributes such as *FacadeMaterial* and *EnergyType*, as the information related to them is not in the scope of this study.

Fig. 5 shows the categorization of different *Processes*. The main processes which can be helpful in renovation projects are *PopulationRelated*, *EnergyRelated* and *EnvironmentRelated* processes. The *PopulationRelated* process includes those processes which are relevant to the people living in the urban context such as *PopulationAge*, *PopulationDensity* and *PopulationEducation. TrafficFlow* is also considered as *PopulationRelated* process, as it is defined as the interaction of pedestrians and travelers (i.e., people) in the traffic network. Therefore, it is also connected to some entities in *TrafficNetwork* object. *EnvironmentRelated* process includes particulate matter distribution (*PMDistribution*), *CO2Emission*, *UndergroundTemperature, NoiseLevel*, *ClimateZone* and *WeatherData*. The appropriate weather data for building energy modeling requires to include at least six parameters namely dry bulb temperature, relative humidity, wind speed, wind direction, direct and diffuse solar radiation.

EnergyRelated processes include *EnergyConsumption* and *RenewableEnergySource*. *RenewableEnergySource* includes *WindEnergy, BiomassEnergy, GeothermalEnergy* and *SolarEnergy*. *Photovoltaic* and *SolarThermal* are sub-categories of *SolarEnergy*. The *hasFeed* relation is used to connect different renewable energy sources to *ElectricityFeed* and *HeatFeed,* which are two entities used to define the potential of the renewable energy sources. In addition, *GeothermalEnergy* is related to *Depth* with *hasDepth* object property, to define in which depth, the *HeatFeed* is provided. Information about all the processes mentioned can be provided in *District* and *ZipCode* or even *BuildingBlock* and *Building* level.

4.3. Ontology verification

We documented the discussion of the participants of the workshop for verifying the ontology. Based on that, we recognized a list of deficiencies and recommendations (Table 2), and modified the ontology based on that.

Finally, with the help of faCT + reasoner, we discovered no inconsistency in the concepts and their hierarchy in the ontology (Fig. 6). There are different purposes for using a reasoner including consistency checking, classification, and realization of an ontology [61]. In this research, we did not use the reasoner for classification and instantiation, but only for checking if there are any contradictory factors in the model.

4.4. Ontology validation

4.4.1. Exploring the prototype

In the validation workshop, the experts worked with the prototype. Each expert selected a use case that was most relevant to their field of work and explored the concepts suggested for that (Fig. 7). Then, they provided their suggestions related to missing concepts, relations, or any other consideration.

Based on the comments from the participants, the validation of the ontology resulted in the inclusion of some new concepts and relations, that were missing. The experts did not have suggestions for adding new use cases or specific renovation tasks, and the hierarchy of the concepts and their relations seemed logical to them. Regarding the necessity of having such an ontology, surprisingly, some experts believed there is no requirement for such an ontology in building renovation projects, although most of the others admitted that this ontology is beneficial. They pointed out that the ontology is concise and provides an overarching framework for required geospatial data while it is not

Table 2
Recommendations and modifications from verification workshop.

Recommendations	Modification
Include concepts related to the buffer around the reference building	New concepts were added: *Site, ReferenceBuilding, Buffer, Distance.* New relation was added: *locatedIn*
Relate concepts to their attributes via object property rather than data property	In the first version, attributes were assigned as data properties to entities. In the updated version a new concept has been created named *Attribute*. An object property namely *hasAttribute* is utilized to connect each concept to different attributes.

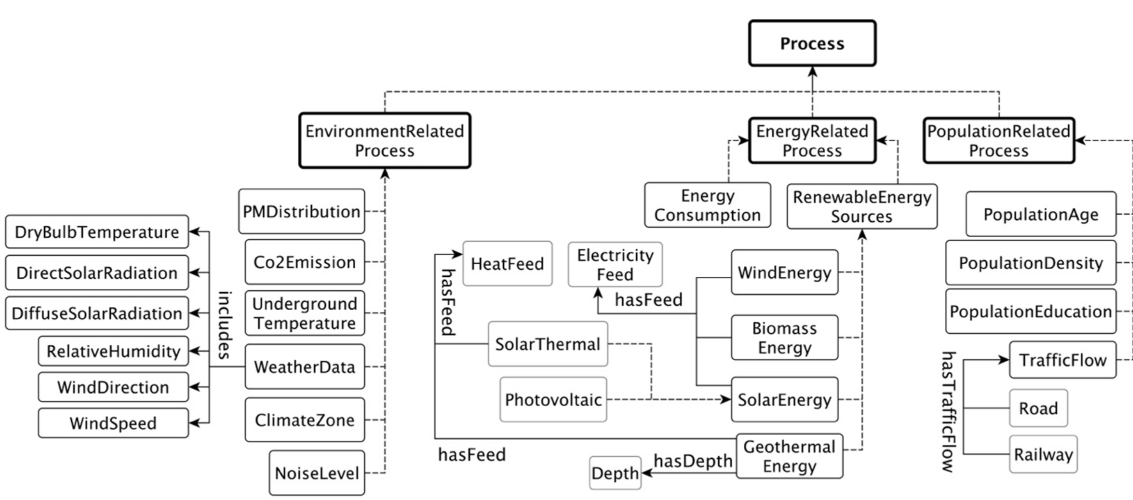


Fig. 5. Process view in the Ontology.

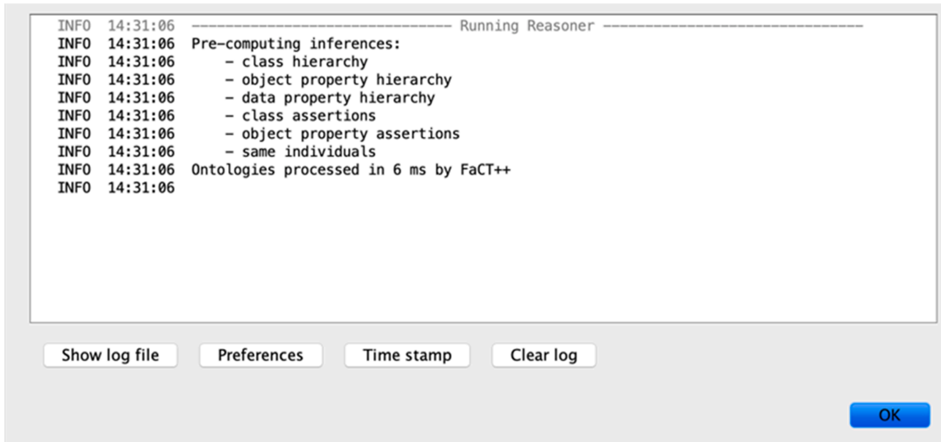


Fig. 6. Result of the faCT++ reasoner.

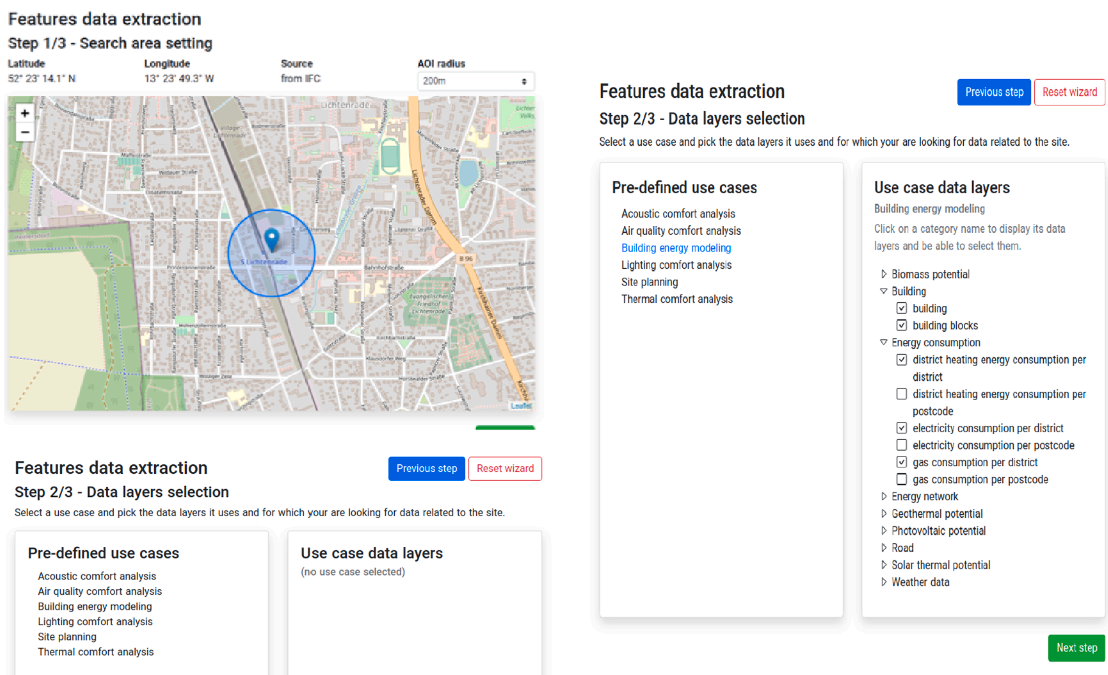


Fig. 7. The prototype implemented based on the ontology.

superfluous. The main points mentioned for each of the use cases are summarized in the Table 3.

Based on the participants' feedback, the authors scrutinized the missing concepts and relations and included them in the ontology.

4.4.2. Validating the ontology for a case study

The ontology developed in this research aims at providing a knowledge framework for geospatial information retrieval to support building renovation. To validate the ontology, we tested it against a case study. To clarify if the ontology can fulfill the specific goals that it is intended to accomplish, we focused on employing the ontology for one of the tasks, i.e., information retrieval for site planning. Using the prototype, we downloaded some of the geospatial datasets suggested for site planning for a specific case study in Berlin, Germany. Then we created some maps in ArcGIS software to present them to the experts. We assume it is an appropriate case study for this research, since (1) the building location represents a real case scenario for building renovation, (2) the site includes urban features such as surrounding buildings, road and railway that can make building renovation a challenging task, (3) the site is located in an active urban area, where the exterior situation of the building can affect the building renovation from different perspectives.

Before exploring the maps with the workshop participants, we asked them about the conventional approaches they use to examine the renovation site before starting the project. One participant mentioned that collecting information for investigating the construction site is based on the data availability. A general practice before building renovation is to examine existing 2-dimensional drawings, which may not represent all the data layers of the building context. Another option is using the 'site plan' of the area, which shows the existing and proposed conditions of a given area. They usually include information about transportation, utilities, vegetation, etc. Based on the available datasets, the expert decides about the actions required before the renovation. Another participant of the workshop mentioned that depending on the size of the building under renovation, they may investigate the construction site and possibilities for the equipment, accessibility of water and electricity, etc. The first step to collecting such information is always visiting the site. Although, the expertise and knowledge of the engineer determine the topics to consider in the site survey. The procedure

Table 3
Comments from the experts in validation workshop.

Renovation task	Missing concepts	Concerns
Site planning	Orientation of the building, climate zone	District level information are more beneficial in planning stage.
Building energy modeling	Underground temperature	Information about energy sources is useful in connection with information about culture and population age (societal data).
Lighting comfort analysis	Radius of the buffer around the building, height, façade material and roof material of surrounding buildings	A simple extrusion of building can be enough (required), but information about façade materials in buildings can improve analysis (beneficial), the radius of the buffer for data collection is important when studying the surrounding lighting effect.
Acoustic comfort analysis	Traffic flow, tree, buildings	Some of the experts think ontology is not required for acoustic analysis as they believe each software requirement determines the necessary concepts.

mentioned by both participants suggests that the knowledge and expertise of the engineers involved in a renovation project have a key role in selecting the required contextual data. Therefore, a standard procedure is not available to realize the concerns for site analysis and planning of the area and to have the knowledge framework to collect the required datasets.

By developing this ontology, we introduced a knowledge framework that helps engineers investigate the urban context of the building. How to interpret these datasets is beyond the scope of the ontology. The ontology only provides the knowledge framework for interpretation for the experts. Based on the information retrieved from these datasets, the experts can interpret and decide on better site analysis and planning.

As mentioned, to clarify the impact of the suggested geospatial concepts by the ontology, we visualized some of the surrounding data on maps and presented them to the experts. Some of the maps for this specific case study are shown in Fig. 8.

The experts believe that the maps show that the building is located in an area covered by historical objects. Therefore, it is essential to consider possible limitations for the construction. Furthermore, the building is surrounded by major and minor roads as well as a railway. Therefore, acoustic analysis of the building is an essential task. Also, information about the roads in the surrounding area can help for performing activities such as logistic analysis, construction material and work force accessibility. Moreover, solar thermal potential in the zip code level and solar photovoltaic locations in the building surrounding provides information about alternative energy sources for the building. The experts believe that the suggested concepts by the ontology provide the possibility for improving the site analysis. They mention that the ontology fulfills the purposes, namely information retrieval and providing a knowledge framework for the specific task of site planning in the building renovation.

5. Discussion

The main questions that motivate this study are: (1) based on what knowledge framework surrounding geospatial and environmental data can support building renovation, (2) If developing an ontology is helpful

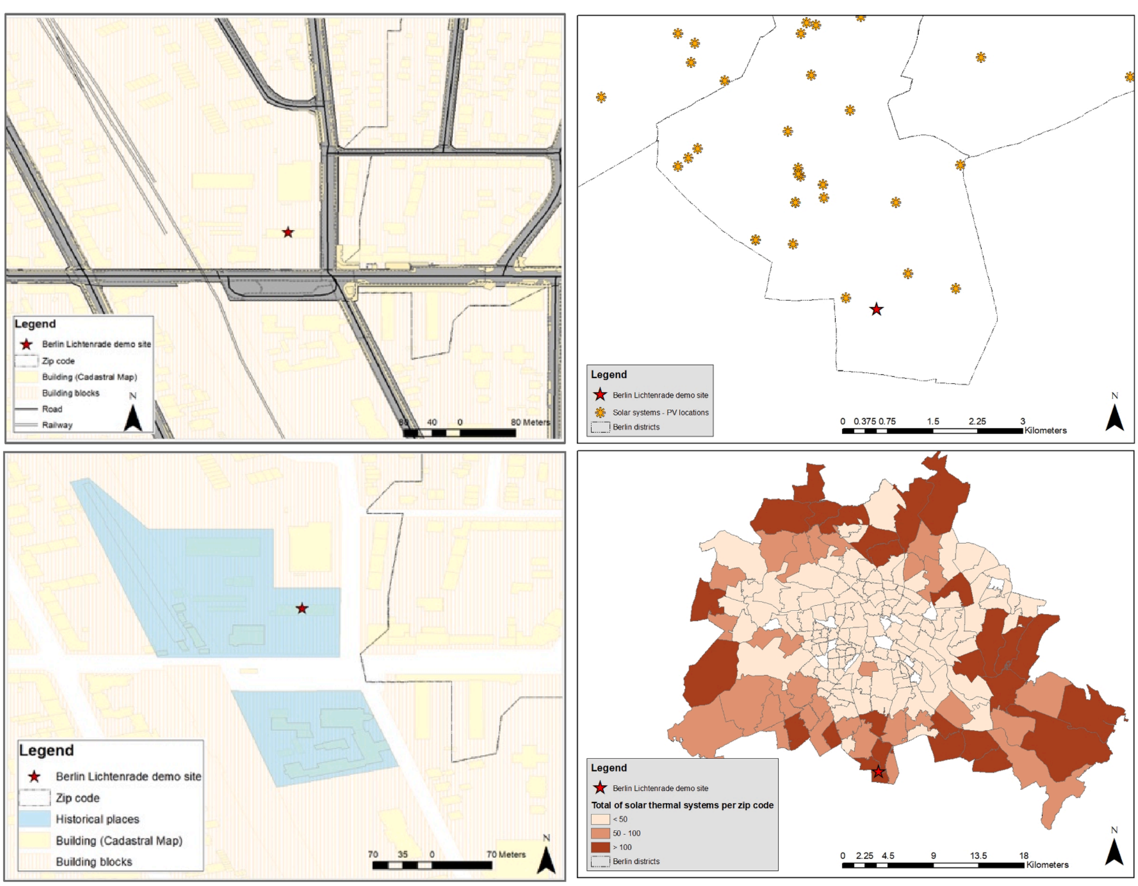


Fig. 8. Maps of the surrounding data for Berlin renovation case study.

to generate this knowledge framework, (3) How experts and engineers involved in the renovation process can contribute to development of this knowledge framework.

Researchers focusing on BIM and GIS integration promote it as an optimal solution for providing the data flow between construction and urban domain [62]. However, the expert's knowledge is crucial in this stage to determine the required concepts for specific applications of a particular task. When this is clear, the entities and relations can be represented in an ontology. There are different data models to represent geospatial data such as CityGML which represents 3D features in cities such as buildings, road, river, and vegetation. There are also some models within the AEC domain which include surrounding data. For instance, gbXML is a building data model to facilitate building energy modeling. In addition to the building information, gbXML includes surrounding data such as buildings and vegetation, as they can affect the building energy modeling [63]. Even though CityGML in urban domain and gbXML in energy modeling field are the focus of attention, none of them fit suitably for the building renovation task. Therefore, this study narrowed down the concepts and relations in the surroundings of a building to a finite number of concepts and relations required for the specific task of building renovation as suggested by [64].

To this end, the main contribution of this research is an ontology that represents a comprehensive view of surrounding geospatial and environmental data that can support building renovation in different phases. The ontology comprises surrounding physical and conceptual objects, processes i.e., the geospatial distribution of specific phenomena, attributes assigned to these concepts, and relations used to connect these concepts. The development of the ontology started by identifying a list of renovation tasks and use cases from an available list of use cases from an EU research project and in the light of existing literature. After developing the ontology, we performed a verification and validation workshop to analyze the ontology against those use cases. We also suggested a tight involvement of practitioners and engineers in ontology development, as proposed by [19]. Therefore, several practitioners who are experts in building renovation participated in the workshops, thereby forming, and expanding the knowledge framework. The experts who participated in the validation workshop have acknowledged that the proposed ontology can work as a common knowledge framework to help engineers and decision-makers in the building renovation projects control cost and quality.

One of the limitations of the study is the limited number of experts in the validation workshop. Some outlook for future research includes involving more experts from more diverse fields within the renovation workflow to expand the perspective on this topic. Moreover, applying different approaches in the workshop, such as gaming to have more task-oriented and in-depth discussions are some of the activities foreseen for future research. New ideas from other experts as well as adding new articles to the literature review resources may lead to some alteration in the concepts and relations of the ontology. Therefore, the proposed ontology is an evolving knowledge framework, and it has potential for expansion in the use cases, concepts, and relations.

Another future research topic is extending existing ontologies and data models from the geospatial domain such as CityGML. We utilized the concepts in CityGML in this research as a basis for developing the ontology. Nevertheless, implementing a CityGML ADE (Application Domain Extension) is a future research task. CityGML ADE is a mechanism of CityGML that extends the data model with additional concepts for particular use cases [65]. Using an acknowledged model such as CityGML makes the BIM and GIS data integration more straightforward in a potential next stage.

This paper suggests utilizing this ontology for the building renovation application, but one of its limitations is that it does not demonstrate all aspects of using the ontology and its application in any practical project. A future task can focus on the instantiation of this ontology for particular use cases. As mentioned before, reasoner has different applications including consistency checking, classification, and instantiation, while we only employed it for consistency checking [61]. A future research topic includes using the reasoner for instantiation. In addition, the scope of the ontology is limited to the surrounding concepts. Therefore, another limitation of this ontology is the partial information about the building under renovation and possibilities for including concepts related to sensors connected to the building. Moreover, there is no extended information about some properties of some concepts such as façade material, roof material, energy types, road type. Lastly, different design choices for relating concepts and their attributes may lead to different acceptable alternatives for the ontology.

The topic of ontology is inaccessible, particularly to the practitioners and engineers for whom it can be most helpful. For this reason, many practitioners believe ontologies are not beneficial in practice. This study claims that developing a knowledge framework in the form of ontology provides an opportunity to bring a more holistic view of the requirement of geospatial data in the renovation workflow in practice as well as in current and future research. Furthermore, the proposed ontology helps integrating practitioners' knowledge from the engineering domains to the conceptual field of engineering informatics.

The ontology has implications in practice for engineers involved in building renovation and software development. For the former group, as a tool for a common understanding about a particular domain, while for the latter, as a basis for BIM and GIS integration. It also has an implication for research by demonstrating that ontology can be used to map knowledge from the geospatial domain for the building renovation tasks.

6. Conclusion

Building renovation is a multi-disciplinary task involving experts from different fields, where most of them are not aware of the accessibility and benefit of surrounding geospatial and environmental data. As a result, most of the time, analysis is performed, excluding the impact of context. This necessitates developing an overarching knowledge framework that includes several renovation stages in a holistic manner and reflects on the significance of surrounding features in the renovation workflow. This paper presents this knowledge framework and contributes to the body of knowledge by developing an ontology that serves as a common reference for different expert groups in renovation projects. It helps practitioners in the construction domain to understand how they can benefit from the data which describes the surrounding to improve their analysis.

For developing the ontology, knowledge is acquired from previous studies that implicitly mention the effect of surrounding data in different stages of renovation process. It also includes brainstorming, obtaining expert knowledge, investigating maps of real demonstration sites, and visiting construction sites. To evaluate the ontology, we conducted a workshop attended by expert participants involved in building renovation projects, those supposed to be the end-users of this ontology. Their comments and concerns have been integrated into the development of the ontology. Nevertheless, ontology development is an evolving task. Therefore, this ontology has potential for expansion by investigating the concepts suggested by other experts or redeveloped using available data models from the geospatial domain such as CityGML.

Declaration of Competing Interest

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