



A Modular Ontology Framework for Building Renovation Domain

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Abstract. Building renovation is a complex collaborative process requiring the interaction between planners, architects, civil engineers, energy experts, and managers of (pre-)manufacturing plants supplying building elements, components of energy supply and distribution systems “just in sequence” to densely used urban spaces – where the majority of buildings under renovation are located. Therefore, the availability of a complete, comprehensive Building Information Model, amalgamating current and future product and process models is of outstanding importance. Approaches, suggesting so-called “monolithic” building information models did not deliver the expected “value for money” since the efforts required to set up and maintain such digital models requested more resources than available. Therefore, the authors present in this paper an alternative approach to information, knowledge management, and sharing in the AECO-sector, i.e. modular ontologies. The flexible and dynamic approach to combine new and available modules of information addresses more responsively the needs of the AECO sector. Furthermore, such BIM models overcome limitations in adaptability, extensibility, etc. of current “openBIM models”. Due to this the shift towards using semantic web technologies for knowledge base and semantic interoperability has been increased in the AECO industry. The work presented in the paper introduces a recently developed linked data, an ontology-based framework that harmonizes and orchestrates ontologies recently developed for the construction domain. It studies inter-model and inter ontology relationships to address concepts that are currently absent from “building ontologies”. The developed framework can be used to support collaborative environments in the engineering and manufacturing sector supporting the efficient sharing of information between architects, engineers, manufacturing plants, and assembly crews on the construction site.

Keywords: Ontology composition · Renovation process · Information sharing/exchange · Collaborative networks · Collaborative manufacturing

1 Introduction

The building renovation process involves stakeholders throughout the life cycle. The stakeholders of the Architecture, Engineering, Construction, and Operations (AECO) industry exchange heterogeneous information among multiple stakeholders, using tools and datasets of different nature [1]. The heterogeneous information includes as-built BIM models, energy information, images, documents, plans, etc. However, the identification of critical information, its management along with the efficient collaboration, and communication between the participants in the project are some barriers in the traditional building construction process [2].

The development of Collaborative Networks (CNs) allows effective collaboration between the teams [3, 4] and there is a need to improve the data sharing and management in CNs [5]. The specifications of shared vocabulary can play an important role where knowledge-based systems are expensive to build, test, and maintain [6]. Research work by L.M. Camarinha-Matos et al. explained that ontology engineering is a potential domain that can contribute to the information/knowledge management in Collaborative Networks (CNs) [7]. Also, the usage of ontologies in CNs is supported in several research efforts [8–10]. However, the ontologies that can cover construction management data are not available on the web, and also, some existing ontologies cover limited data. There is a need to fill the gaps for entities, construction information, construction activities, stakeholders, level of details, materials, occupants, etc.

In the BIM4EEB¹ project, several ontologies (Digital Construction Ontologies² - DICon) are developed to support the renovation data modeling/sharing and act as a resource to the collaborative system called BIM management system (BIMMS³). The development of ontologies was carried out by using Web of Data (WoD) technologies. The semantic web and Linked data are two sources of WoD [11]. The semantic web technologies have Resource Description Framework (RDF⁴) model for data interchange, Web Ontology Language (OWL⁵) to represent complex knowledgebase, and Simple Protocol and RDF Query Language (SPARQL⁶) to run the queries across the data sets. Linked Data⁷ is to identify things using URIs, look up the name of things using HTTP URIs, add information to the things using semantic web technologies, and link the information to add more context or semantics to existing information.

To make the developed or existing ontologies to be useful, two objectives must be met, as per Barry Smith and Mathias Brochhausen 2008 [12]. First, it is essential to align/match existing ontologies by harmonization process. Secondly, it is necessary to find ways to evaluate ontologies transparently. In this paper, we discussed the first part and developed a framework to harmonize the ontologies by modularization approaches.

¹ <https://www.bim4eeb-project.eu/>.

² <https://digitalconstruction.github.io/v/0.5/index.html>.

³ <https://bim4eeb.oneteam.it/BIMMS/Default.aspx>.

⁴ <https://www.w3.org/RDF/>.

⁵ <https://www.w3.org/OWL/>.

⁶ <https://www.w3.org/TR/sparql11-query/>.

⁷ <https://www.w3.org/DesignIssues/LinkedData>.

2 Ontology Modularization

Modularization of ontologies will make user easier to understand, extend, reuse, maintain and reason the ontologies [13, 14]. However, the concept of modularization is not well defined in the context of ontologies compared to software engineering. A single approach for modularization does not match every situation since people tend to have various ideas in the development of ontologies. Several various approaches appeared in the field of ontology modularization. These approaches are mainly categorized into “ontology separation” and “ontologies composition” and are shown in Fig. 1. These two main approaches are sub-categorized into ontology partition, ontology module extraction, ontologies integration, and ontologies mapping respectively [15].

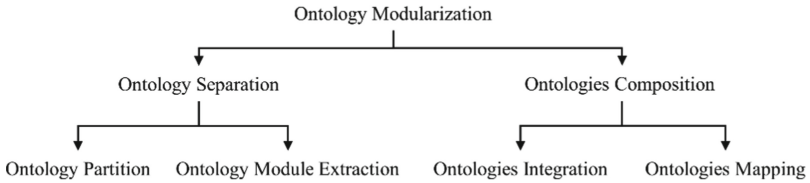


Fig. 1. Ontology modularization approaches

The ontology separation approach is mainly useful to make large-scale ontology into small-scale ontologies to use for narrower use cases. But, in the ontologies composition approach small ontologies will be integrated to make a large ontology by maintaining its modularity. The DICon ontologies cover different domain gaps (e.g. entities, occupant comfort, lifecycle, materials...etc.). To make it useful for broader domain use cases, ontologies modularization applied on DICon ontologies by using the ontologies composition approach.

2.1 Ontology Integration

Ontology integration is the process of forming a new ontology by using one or more ontologies without changing their original concepts, if possible, they are extended [16]. Integrate $(O_1, O_2, A) = O_1$, where O_1 is the target ontology into which the source ontology O_2 will be integrated and A is the alignment expressed in the same logical language as ontologies O_1 and O_2 [17]. Ontology alignment may be seen as a pre-step for detecting where the involved ontologies overlap and can be connected. This approach is especially interesting if given ontologies differ in their domain. Through integration, the new ontology can cover a bigger domain in the end.

In the integration process, two approaches are primarily considered and shown in Fig. 2. The ontologies O_1 , O_2 , and alignment O_1-O_2 are considered to discuss these approaches. The Ontology O_1 , alignment module O_1-O_2 , are imported to ontology O_2 in the first approach, few required concepts from O_1 are redefined in the ontology O_2 . In the second approach, required concepts from ontology O_1 are redefined in ontology O_2 , alignment module O_1-O_2 imports ontologies O_1, O_2 to extend the scope of usage of ontologies. In this paper, the second approach is considered to develop an ontology framework.

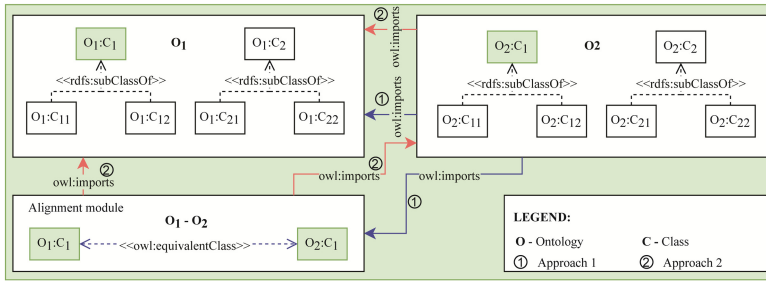


Fig. 2. Ontology integration methods

2.2 Ontology Mapping

The mapping is a set of declarative assertions specifying how the sources in the data layer relate to the ontology [18].

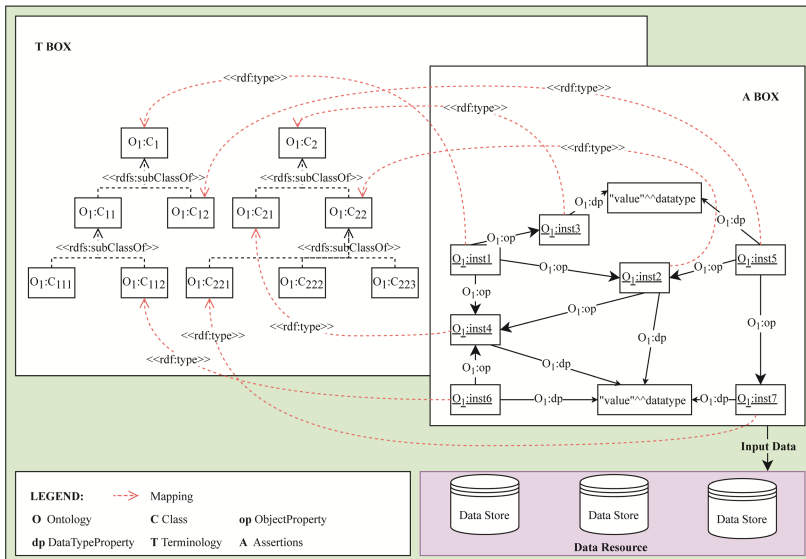


Fig. 3. Ontology mapping concept

An ontology mapping represents a function between the ontologies. The original ontologies are not changed, but the additional mapping axioms describe how to express concepts, relations, or instances in terms of the second ontology. They are stored separately from the ontologies themselves [16]. Figure 3 represents the ontology mapping concept. Three concepts called Terminology Box (T-BOX), Assertion Box (A-BOX), Data sources are considered to explain the ontology mapping process. T-BOX is an ontology with classes, properties, and A-BOX is individual data that comes from the data sources. The individual data that comes from the data sources are mapped with

T-BOX data and a knowledge base will develop. The axiom `rdf:type` is used to relate an individual for a class.

3 Collaborative BIM Environments and Knowledge Base

For several years, several research initiatives have been focused on the creation and operation of collaborative processes in the construction sector [19]. However, the lack of effective collaborative processes tools, information management of heterogeneous data, and sharing it among the actors are still barriers in AECO sector. Also, lack of tools with integrated Common Data Environments (CDE) [5, 20]. The BIMMS is a collaborative environment developed in the BIM4EEB project. BIMMS is a platform built around a common data environment (CDE) that stores all the data and information gathered through different sources and along the whole building lifecycle, acting as a single source of truth (SSOT) [21].

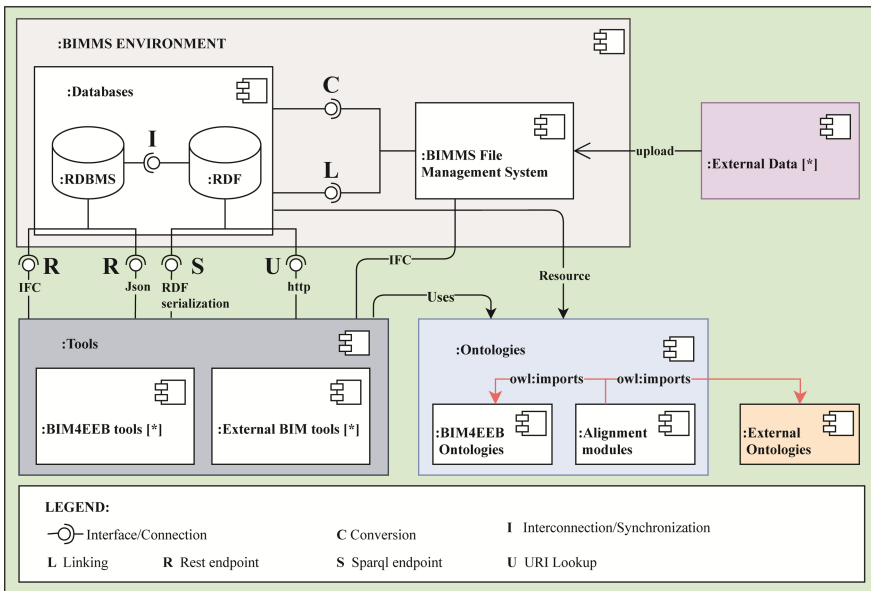


Fig. 4. Usage of modular ontologies in a collaborative environment

The aim of this BIMMS is the effective management of information produced in the renovation processes along with the establishment of efficient communication between the involved tool kits. This process supports the storage of information in various formats (ontologies, models, diagrams, etc.) and manages the information by enabling the links between them. This section intends to explore the ontology-based information management facilities within the BIMMS platform.

A component diagram represented in Fig. 4 comprehensively illustrating the adopted BIM4EEB framework. The involved components in this framework are 1) Ontologies,

2) BIMMS environment, 3) BIM4EEB tools, and finally, 4) external data (images, files, models, sensor data, etc.). As shown in the figure, the ontology component describes a set of developed ontologies as part of the BIM4EEB project and their alignments to external ontologies in terms of alignment modules. This ontology component is further integrated into BIMMS environment and supports the representation of the BIM model information and other resource information. In specific, the BIMMS system enables this representation by converting the resource data in the File management system into Linked data (RDF data) and Relational Database (RDBMS). It also provides the linkage between these data models or data formats to synchronize the updates or changes effectively. The use of ontologies and linked data in the tools is a promising solution to explore dynamic and heterogeneous data [22].

The last component in the framework is the tool-set, which is used for the progressive and successful implementation of the renovation process. This tool component is equipped either with BIM4EEB tools and/or external tools. The data stored in BIMMS system is effectively shared to these tools based on the required interface connections. In general, there are many interface connections but their application is only dependent on the available data formats and compatibility with the developed tools. In the BIM4EEB framework, APIs like Rest endpoint, SPARQL endpoint, and URI Lookup is used in the data sharing process between the tools and BIMMS system.

4 Modular Ontology Framework

In the BIM4EEB project, modular ontologies set called Digital Construction Ontologies (DICon⁸) are developed to achieve semantic interoperability and enhance the information sharing and representation of renovation data in the building renovation life cycle process. To expand the scope of ontologies usage, relations are established between the DICon⁸ and external ontologies by using ontology modularization. The developed modular ontology framework consists of two parts. One is ontology integration and the second one is ontology mapping as shown in Fig. 5.

The ontology integration process is explained by considering BIM4EEB ontologies, External ontologies, Alignment Modules. The O_1 and O_2 conceptually represent BIM4EEB ontologies and O_3 represents external ontology, O_1 - O_3 and O_2 - O_3 are the alignment modules. To establish a connection between the ontologies three-step approach is followed. In the initial step, removed the overlapping concepts between the BIM4EEB ontologies and imported one ontology to the other. For example, $O_1:C_1$ is a class in O_1 and the same class is defined in the ontology O_2 with the URI of O_1 . This approach helps to avoid redundancy and the ontology merging process will be easier. In the second step, alignment modules are developed between the BIM4EEB ontologies and external ontologies and kept as separate files. In the last step, aligned ontologies are imported into its alignment module, which extends the scope of the ontologies. The modular ontologies developed using this integration process are published on the GitHub page <https://digitalconstruction.github.io/v/0.5/index.html>.

In the second part ontology mapping developed using the concept of ‘‘Ontology-Based Data Access (OBDA) [23]’’. The idea behind OBDA is to use a DL ontology as

⁸ <https://digitalconstruction.github.io/v/0.5/index.html>.

a means to access a set of data sources, to mask the user from all application-dependent aspects of data, and to extract useful information from the sources based on a conceptual representation of the domain, expressed as a T-Box in a suitable DL [24]. The ontologies O_1 , O_2 , and O_3 are ontology T Box data, `inst:Individual1`, `inst:Individual2`, `inst:Individual3`, `inst:Individual4` are the assertions (A Box data) or data stored in the data resource layer or from the tool. The T-Box data and A-Box data are mapped together using the axioms to form a complete Knowledge Base (KB).

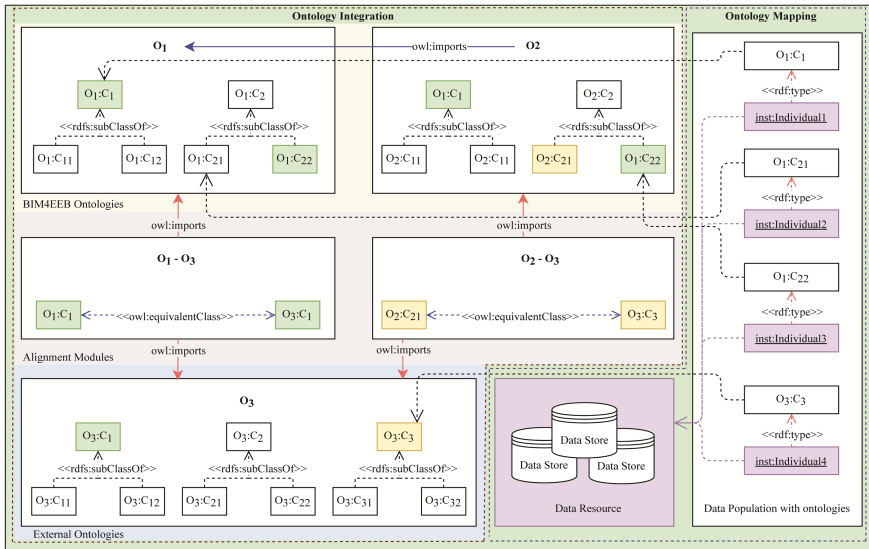


Fig. 5. Modular ontology framework using ontologies composition approach

5 Proof of Concept and Result

The developed use case is based on the BIMEaser (BIM Early Stage Energy Scenario tool) tool. The BIMEaser was developed for the early phase evaluation of residential building refurbishment designs. This tool able to download BIM models from the BIMMS and Renovation scenarios are defined for simulation, computes the indicators of building energy performance. These indicators are then compared with reference requirements, the Owner’s Project Requirements (OPRs). However, the modular ontologies framework is used to establish a relation between the ontologies used to store BIMEaser OPRs. Finally, OPRs calculated with BIMEaser are uploaded into BIMMS in the triple store. Ontologies have been developed and integrated, mapped with the BIMEaser OPRs to develop complete KB. In this process, BIM4EEB ontologies entities (DICI), Contexts (DICC), Variable (DICV), Information (DICI), Materials (DICM), and Energy (DICES) are used. Also, the vocabulary Units (DICU) used. The external ontologies Building Topology Ontology (BOT), Quantities, Units, Dimensions and Types (QUDT⁹), QUDT

⁹ <http://www.qudt.org/pages/QUDToverviewPage.html>.

UNITS (see footnote 9), Data Catalog Vocabulary (DACT¹⁰), PROV Ontology (PROV-O¹¹), QUDT Quantity Kind (see footnote 9). The ontologies are aligned and imported to their respective align modules as shown in Fig. 6. Therefore, BIMeaser provides an effective collaboration tool for experts with different backgrounds in the design team and can speed up decision-making in building refurbishment projects [25].

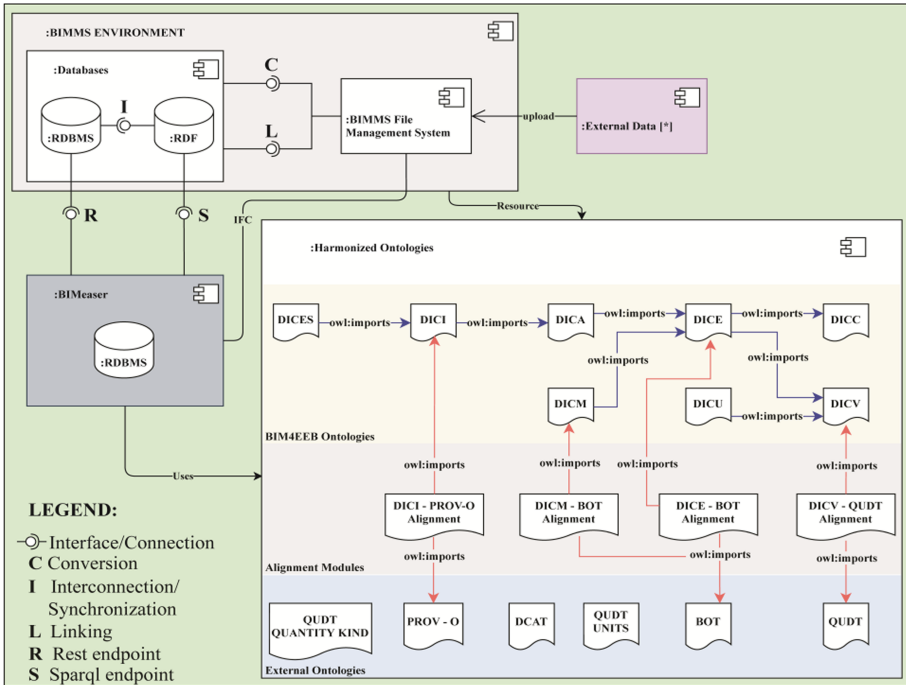


Fig. 6. Usage of modular ontologies in BIMeaser tool

The OPRs for the baseline (no investment cost) and different scenarios are considered and listed in the table below. Each renovation scenario is specified by renovation measures to change building structures or technical systems. The impact of these measures is presented in the terms of Owners Project Requirements (OPR) indicators. The OPR's -e.g. operational energy cost, the payback time of renovation, and summer thermal comfort are an important part of the performance-based building design process, which assumes that design selections are validated against the OPR's in each design stage before moving to the following design stage. The design team will handle the detailed technical energy selections affecting the OPR's using the tool as part of the collaborative work. OPR indicators are computed after detailed building energy simulations based on localized data (e.g. energy and investment cost data). After all, OPRs have been prepared the scenarios can be compared. In a conclusion, BIMeaser presents the impact of each

¹⁰ <https://www.w3.org/TR/vocab-dcat-2/>.

¹¹ <https://www.w3.org/TR/prov-o/>.

renovation scenario and also baseline results in terms of Owners Project Requirements (OPR). The most important OPR values are calculated to support the performance-based building design process and validation of design decisions.

Table 1. An example of scenario and OPR results presented in BIMeaser tool

Scenario	Operational energy cost €/floor-m ² , a	Investment €/floor-m ²	RES share %	Heating kWh/m ² , a	Cooling kWh/m ² , a	Electricity kWh/m ² , a	Summer thermal h/year, zone (Tindoor > 27 °C)
S1	14.87	0.00	0.01	123	0.0	35	1763
S2	13.39	46.41	0.01	97	0.0	35	2045
S3	12.89	11.25	5.55	123	0.0	26	1763
S4	13.88	16.00	0.01	106	0.0	35	1763
S5	13.60	72.18	0.01	101	0.0	35	1875
S5	9.55	145.84	8.89	64	0.0	26	2284

The OPR results are enriched with the classes of the ontologies in BIMeaser tool. These results are converted into an RDF file for data sharing. An example of the OPR data with the ontologies shown in Fig. 7.

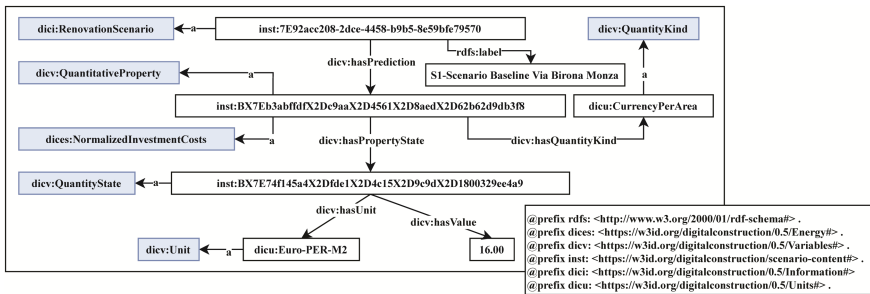


Fig. 7. An example of OPR data in RDF notation

These RDF will be stored in the BIMMS containing links to the IFC model used in the simulation. The linking of OPR's and the BIM model in the BIMMS enables tracking of the building energy performance during the evolution of the renovation design, which is an important part of the performance-based design approach. Also, BIMMS system allows the stakeholder to query and get the required information using the SPARQL Endpoint. For example, the OPR data of heating energy consumption for all renovation scenarios can get from the BIMMS by using the SPARQL query.

SPARQL Query

```

prefix dicv: <https://w3id.org/digitalconstruction/0.5/Variables#>
prefix dices: <https://w3id.org/digitalconstruction/0.5/Energy#>
prefix dicu: https://w3id.org/digitalconstruction/0.5/Units#
prefix inst: <https://w3id.org/digitalconstruction/scenario-content#>
SELECT ?scenarioName ?Property ?PState ?Value ?Unit
FROM <https://w3id.org/digitalconstruction/scenario-content-opr>
WHERE { ?scenario dicv:hasPrediction ?Property .
?scenario rdfs:label ?scenarioName .
?Property dicv:isPropertyFor dices:hasNormalizedHeatingEnergyConsumption .
?Property dicv:hasPropertyState ?PState .
?PState dicv:hasValue ?Value .
?PState dicv:hasUnit ?Unit . }
    
```

SPARQL Query Results

Figure 8 shows the query results which are shown by the SPARQL Endpoint in BIMMS. These results are validated with the OPR data (Table 1) presented in BIMEaser tool.

scenarioName	Property	PState	Value	Unit
"S2-Scenario Insulation-211a3c72-67df-4f5d-ae45-11c3ae8e6c73"	inst:BX7E02748d58X2Dfa92X2D4f02X2Daad9X2D4dc5cd3522ea	inst:BX7Eee4a6369X2D0ea4X2D45ccX2D999aX2D97ef026943bf	97.0	dicu:KiloW-HR-PER-M2-YR
"S1-Scenario Baseline Via Birona Monza"	inst:BX7Ea0a2d9fcX2D3888X2D4595X2D9bd9X2Dd30d0e51a55c	inst:BX7E0fa86f9X2D73dfX2D46dcX2Db614X2D7e13c65c0b9d	123.0	dicu:KiloW-HR-PER-M2-YR
"S5-Scenario Replacing the windows-6438eaf-578b-4d3f-9934-68705cdadbe9"	inst:BX7E60b57d94X2D2d96X2D4fd2X2Dab7dX2De4e9e50f7b9f	inst:BX7E89a150a7X2D1743X2D42e6X2Da2d9X2De174ca256935	101.0	dicu:KiloW-HR-PER-M2-YR
"S3-Scenario Solar PV panels-4aee83d0-5df5-4edb-a3ee-1a93b0a75477"	inst:BX7Efd2acff9X2Ded7bX2D4274X2D9730X2D3179481bbb80	inst:BX7E71b4ccfbX2D86dfX2D4393X2D99b8X2D6a31bef47748	123.0	dicu:KiloW-HR-PER-M2-YR
"S6-Scenario-7634d9d3-0a94-4c7a-a2cd-f08ea2890a70"	inst:BX7Eb939fb70X2D4771X2D4072X2D8653X2D7b397ccffbaa	inst:BX7E7ae930edX2D5b6eX2D4ab3X2D9f0dX2D581190637c06	64.0	dicu:KiloW-HR-PER-M2-YR
"S4-Scenario New condensing gas boiler-92acc208-2dce-4458-b9b5-8e59bfe79570"	inst:BX7Efc2ac50dX2D3826X2D49aaX2Da837X2De67e0c07c3fd	inst:BX7E98d48f7eX2D8735X2D42e9X2Da971X2D084824999ca9	106.0	dicu:KiloW-HR-PER-M2-YR

Fig. 8. SPARQL query results for scenario and OPR data

6 Conclusion

The building renovation is a complex process, requires the intervention of stakeholders throughout the renovation. The efficient Collaboration Networks (CNs) equipped with Common Data Environments (CDE) can play a crucial role in the collaboration between the stakeholders in the project. The developed framework will enhance the interoperability between the stakeholders and tools. Ontologies composition approaches have been used to develop the framework. The developed harmonized shared vocabulary will be a

resource to the collaboration system and it can be used in the renovation tools for data mapping and representation. A small use case of BIMeaser tool is considered to apply the ontology framework and discussed.

In the future more detailed demonstration of ontologies mapping, data transfer of the other tools using the ontologies, and validation is carried out.

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