Ontology-enabled Digital Building Logbooks for Facility Management

Martina Signorini, martina.signorini@polimi.it
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italia

Sonia Lupica Spagnolo, sonia.lupica@polimi.it
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italia

Alberto Pavan, alberto.pavan@polimi.it
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italia

Bruno Daniotti, bruno.daniotti@polimi.it
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italia

Abstract
Construction industry is characterized by highly fragmented and scarcely interoperable processes. The use of a Digital Building Logbook (DBL), as a common repository for building information, would facilitate data management for the several stakeholders involved in the construction process. However, the heterogeneity of different sources makes it fundamental to enable enhanced information exchange through interoperability management. By exploiting the potentialities of ontologies in addressing the interoperability need, the paper presents an ontology-enabled DBL. The proposed framework provides a complete building overview, describing spatial information, systems and components, maintenance, and operation as well as energy and sensing data. It is built following a federation approach, combining building existing ontologies after investigating whether they may meet similar requirements. The paper describes the methodology adopted to develop a framework as flexible as possible to accommodate various ontologies that represent specific building domains in different ways according to the case study of interest. The result is a system that can act as a gateway for connecting several areas along the building life cycle, with the main objective of enhancing data access and information extraction, to gain an interdisciplinary knowledge, and to make data-driven decisions.

Keywords: Digital Building Logbook, Interoperability, Digitalization

1 Introduction
The building industry is viewed as fragmented since many different kinds of data are generated along the whole building lifecycle (Gómez-Gil et al., 2023). This makes the process of gathering, storing, exchanging, and updating information challenging. In addition, data from the different stages of the lifecycle are acquired in a non-standardized manner by various stakeholders, who make decisions depending on data availability. Nevertheless, there are no guidelines governing data collection, organization, and accessibility by involved actors (Hartenberger & Frics, 2017). Therefore, this contributes to several issues, including data loss, inconsistencies with other stakeholders' systems, information asymmetry, lack of transparency, and increased decision-making risk (Carbonari et al., 2020, p. 2; Gómez-Gil et al., 2022). To address these problems, there is a need for a single source of information that gathers, stores, and shares data so that many stakeholders involved in the building industry can have a point of reference. A building-related database, known by different names such as Logbook, Building Logbook, Building Passport, and Digital Building Logbook (DBL), is used in several European countries to collect and organize building data. Defined as "a common repository for all relevant building data, including data

related to energy performance", it facilitates informed decision-making and information sharing among stakeholders in the construction sector (European Commission, 2021).

It is evident that without a tool for reliable sharing, the exchange of information is very limited and negatively impacts the building's efficiency and quality. This is especially true when considering the amount and variety of data in a building, as well as the various systems and aspects that are exploited when developing and managing a system. Even taking into consideration a tool such as the DBL, which gathers data on buildings, it is necessary to evaluate potential methods of exchanging different kinds of information in an interoperable manner.

Interoperability, or the ability of systems to share and act on information, is a crucial problem that emerges in the form of difficulty in accessing or interpreting data produced by other systems or in the inability to efficiently use it, and it is not only related to data exchange but also to meaning exchange (Ozturk, 2020). Traditional manual methods of information exchange are becoming bottlenecks, necessitating Information and Communication Technologies (ICT) solutions to automate interoperability. Ontologies, providing a standard vocabulary (terms or labels) as well as a semantic description of data (concepts and relationships for a given domain) (Spyns et al., 2002; Taye, 2010), are proposed as a solution to achieve semantic interoperability. They ensure a shared understanding of information, allowing for automatic processing, sharing, and reuse of knowledge .

This paper describes a strategy to manage and correlate all different types of information that can be generated along the building lifecycle, especially during the in-use phase. In this regard, it proposes a DBL as a tool to tackle information fragmentation and to improve data availability and transparency. However, since the sources to retrieve data for the DBL are various and they can be open and not open, the research considers ontologies as technologies related to the extraction, representation, storage, retrieval, and analysis of machine-readable information that can help in facilitating data integration and exchange. The attention focuses on existing ontologies that could describe the building from different contexts, representing the DBL, providing the information structure and the specific vocabulary. Specifically, given the variety of information characterizing the building sector, a federation approach is chosen to connect the disparate kinds of data originating from various systems, using them within their domain.

The work presents the results of a study that starts from the definition of information that should be contained within the DBL, moving to outline the development of an ontologies-based framework describing the multi-domains nature of the built environment. Specifically, the analysis of existing ontologies of the built environment and their related application domains has been carried out, along with the validation process that tests the framework's effectiveness in making more informed decisions throughout the in-use phase, in another author's paper to which reference is made for further details (Signorini et al., 2023). This paper instead concentrates on the methodological development of the framework, building on the deep examination previously made. The aim is to show the framework development that enables the improvement of data sharing, use, and organization in the built environment and construction, the collection of different building-related data, and the acquisition of multidisciplinary knowledge.

The paper is structured as follows: after an introduction to describe the research background about the DBL, and the research problem that the present research will address, Section 2 shows the methodology adopted to set the ontologies-based framework, Section 3 presents the research results with an accurate representation of the ontology-based DBL framework developed and lastly, Section 4 contains a discussion and conclusions about the work.

2 Methodology

The research has been implemented starting from a preliminary literature review process analyzing the current scenario related to data and derived information, and their management in the construction sector. Specifically, it has focused on the DBL initiatives and the main issues related to it such as interoperability, for which ontologies have been largely investigated and then exploited. Referring to the development process, the proposed DBL framework has been built upon the use of ontologies following a federation approach, that allows the integration of data coming from different systems, exploiting them within their domain.

As a result, the DBL has been transformed from a static as-built asset-related data collector into a real-time gateway space to connect different domains, such as building models, systems, and maintenance-related information.

In this section, the methodology of the proposed ontology-enabled DBL is described in all its steps to make it replicable.

To realize this ontology-based DBL, it was necessary to follow the instructions to create an ontology, considering that there is not only one method to develop an ontology, but it is an iterative process that starts from the ontology context and scope definition (Noy, 2001).

The procedure for the development of the schema is outlined in Figure 1 based on the following steps:

1. Ontology domain and scope definition.

This step includes the definition of the domain the ontology is focused on, the reason why the ontology is necessary, and the information need the ontology can answer to.

2. Checking if other existing ontologies can be reused to address the same needs.

It is necessary to look on the web or in scientific literature to check if existing ontologies that cover the same domain of interest exist and if so, reuse them.

3. Classes and their properties definition.

This phase is dedicated to the development of the ontology defining the classes and their hierarchy and the connected properties. It is fundamental to pay attention to the classes that may be covered by other ontologies according to the previous analysis, and considering any properties that could link the various domains that the DBL covers.

4. Framework definition based on a federated approach.

The last step consists of connecting the various available ontologies to create the DBL based on the mentioned approach. Federation means data provision "without additional persistence or duplication of source data" (DAMA International, 2017). Data federation integrates several, often divergent, data sources into a unified perspective. As a result, federation means exposing many disparate data sources in a single view (Gu et al., 2023), allowing the reuse of data within their domain.
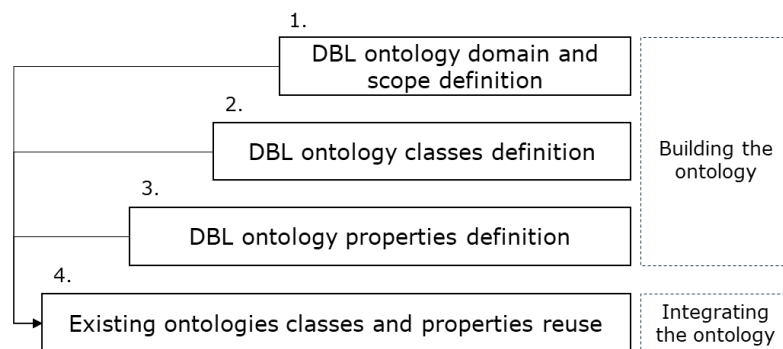
Figure 1. DBL framework development

3 Ontology-based DBL framework

In this section, the ontology-based framework is presented outlining the development process and the structure and key elements.

3.1 Development process

Following the steps outlined in the methodology section, an ontology-based DBL has been created. Firstly, it was necessary to answer some questions to understand why and how to build the new ontology as reported in Table 1. The DBL includes information about the building's envelope, systems, and other topics, as well as data on the building's use phase (such as maintenance interventions). The developed DBL connects a variety of datasets from different domains (such as building space, systems, and sensors) used for building management, increasing data availability and quality while also facilitating the collection and transfer of various types of building-related data. It can specifically address the requirement for enhanced maintenance

decision-making, as well as providing support to Facility Managers (FM). The ontology development consists of the definition of classes and properties. The classes were identified according to the main topic of interest, then two types of properties were used in the ontology creation: data properties and object properties. All the classes and properties are annotated with the prefix *dbl.* Specifically, it presents six distinct topic areas that attempt to provide the most comprehensive picture and description of a building. It is designed to be applicable to the whole building stock (both residential and non-residential), as well as new and existing structures.

Table 1. Questions that drive the ontology-based DBL development

Question	Answer
What is the domain the ontology aims to cover?	The ontology aims to cover the main areas of the built environment describing it as a whole, namely construction technologies and systems, maintenance, sensing, and energy as well as identification data
Why is it necessary to develop the DBL ontology?	The DBL ontology provides an integrated view of buildings facilitating the collection and transfer of various types of building-related data
How will the ontology be developed?	The ontology is based on OWL language and Protégé is the ontology-based software used. The whole ontology is realized based on the federation approach, relying on the use of other existing ontologies
What are the expected insights from the federation process?	Outputs would consist of improvement of building management and decision-making process such as assets status and eventual maintenance interventions with a focus that intersects different areas

Later, the authors used available published ontologies, whose online links are outlined in Table 2, to match the DBL classes as much as possible rather than developing new classes based on a federation approach. Specifically, possible alternatives of one or more existing ontologies that could describe DBL classes have been studied and shown, giving the possibility to choose the best option depending on the case study available. Finally, new properties were created to serve as links between the different topic areas. In this way, the result is a framework that is flexible enough to represent the complex building structure based on the chosen case study.

Table 2. Existing ontologies suitable for reuse in the AECO sector

| Ontology	Online link
ifcOWL	https://technical.buildingsmart.org/standards/ifc/
brick	https://brickschema.org/
bot	https://w3c-lbd-cg.github.io/bot/
SOSA/SSN	https://www.w3.org/TR/vocab-ssn/
Haystack	https://github.com/Project-Haystack/haystack-defs
SAREF	https://saref.etsi.org/saref4bldg/v1.1.2/

3.2 Structure and key elements

The DBL is made up of 6 principal classes, that are intended to facilitate information aggregation with a clear distinction between the areas. For the sake of clarity, the principal defined classes and their related subclasses are listed:

1. dbl:General
   - dbl:Building
   - dbl:Registry
   - dbl:Attachment
2. dbl:Technical
   - dbl:Envelope

- dbl:System
3. dbl:Energy
   - dbl:Certificate
4. dbl:Operation
   - dbl:EnergyPerformance
   - dbl:IndoorConditions
5. dbl:Maintenance
   - dbl:Administrative
   - dbl:WorkOrder
6. dbl:Sensing
   - dbl:SensorSystem
   - dbl:SmartMeter

The federation process has been carried out by exploiting existing ontologies that cover specific domains, creating connections among them, and with the DBL ontology taking into consideration various domains of interest.
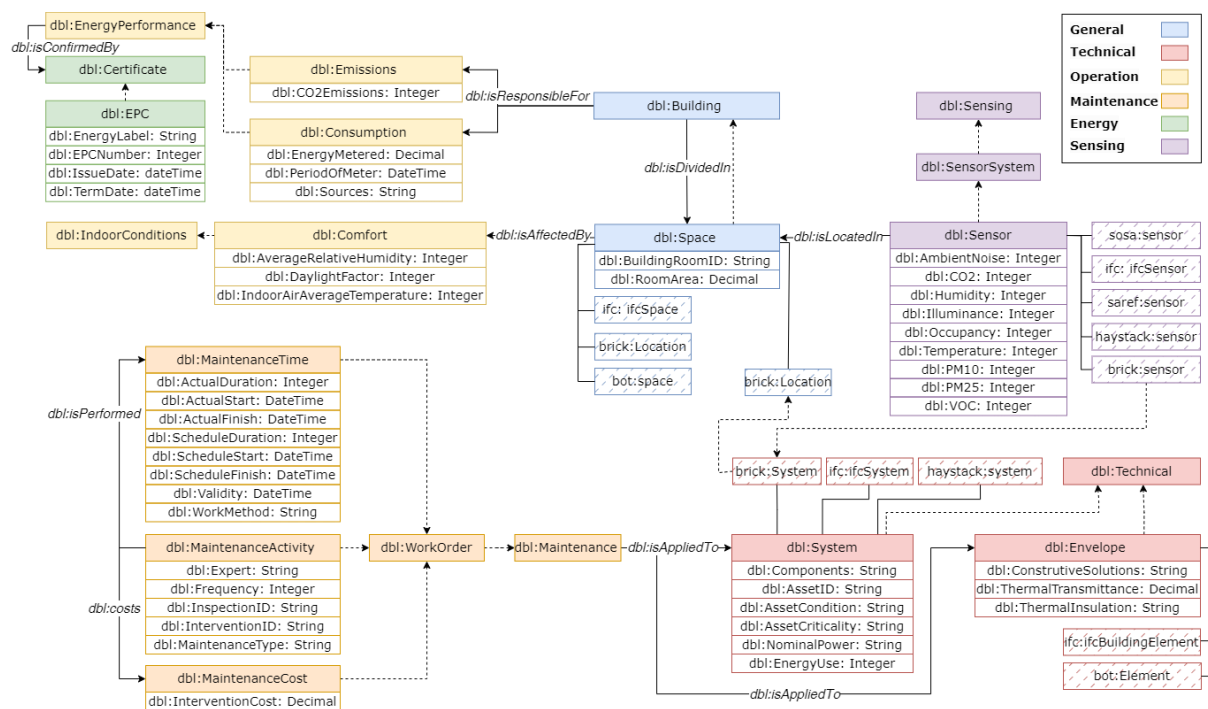
Figure 2. DBL as a gateway system and reuse of existing ontologies

As outlined in Figure 2 the different classes of DBL are represented, and space, building systems, maintenance, and sensor system, which theoretically are separate, work potentially together in the federation framework thanks to the use of object properties that underline the relationship among them. As previously outlined, in this phase of framework development, all the possible links with existing ontologies are highlighted to show the various alternatives. In fact, there is not only one ontology suitable for a specific domain, but it is only a final technical choice dictated by the selected case study and users' needs.

Particularly, the class *dbl:General* concerns all the information that allows to identify the building. Links with the operation topic, that collects the information retrieved by the in-use of buildings, can be underlined by the property *dbl:isResponsibleFor* putting in communication d*bl:Building* with *dbl:Emissions* (describing the level of CO_2 emissions) and *dbl:Consumption* (enriched with attributes related to the energy metered, the period of meter and what is the source of energy). Furthermore, the several spaces in which the building is divided (*dbl:Building isDividedIn dbl:Space*) are characterized by a level of comfort (*dbl:Space isAffectedBy dbl:Comfort*). To describe the comfort level, *dbl:AverageRelativeHumidity*, *dbl:IndoorAirAverageTemperature* and *dbl:DaylightFactor* properties have been added. Considering a general building space sensors

can be deployed. Hence, an object property (*dbl:isLocatedIn*) has been generated to link these two different domains.

Finally, the maintenance class concerns the maintenance realized on the building and its components (envelope and system). *Dbl:WorkOrder* describes maintenance tasks performed or to be performed (*dbl:MaintenanceActivity)* with details on the maintenance specialist who carried it out or will be carrying it out (*dbl:Expert*), deadlines (*dbl:MaintenanceTime*), and any associated prices (*dbl:MaintenanceCost*). Furthermore, in this section administrative documents such as maintenance contracts can be included (*dbl:MaintenanceAgreement*). The maintenance domain is connected to the building system and envelope by *dbl:isAppliedTo*.

Therefore, the derived representation should be expressive to capture geometric information like the building and its zones, spaces, visible assets, and systematic connection relationships. Some sections of the framework are worth looking into. For this reason, some modules of the framework have been described in detail separately showing the alignment with existing ontologies and their classes or properties in the next subchapters.

3.2.1 General

General is one of the most information-rich classes and it is represented in Figure 3. One of its subclass is *dbl:Building*, that provides the identity card of the building, subdividing it into *dbl:Identification*, *dbl:Use*, *dbl:Lifecycle*, *dbl:Space*. The first helps in identifying the building itself, providing a codification, name, and the location where it is (e.g. *dbl:BuildingID*). To represent and describe the several spaces characterizing the building, *dbl:Space* has the goal of containing information about the area and the code associated with the specific room. In addition, the building can be described by *dbl:Use*: in detail, with destination – such as residential, commercial, industrial, etc. – and with building category – such as single-family detached, hotel, office, warehouse, etc. Other necessary information is those related to the *dbl:Lifecycle*: when the building was constructed, its service life, and its conservation status. The subclass *dbl:Registry* regards actors involved in the building life cycle with their related names and contacts. Lastly, a subclass with several attachments can be found. Here significant documentation about the building is collected.

Finally, it is crucial to check if there are available existing ontologies that can cover the DBL classes created. Ontologies such as ifcOWL, Building topology ontologies, and brickSchema contain classes describing the space, in which the building is divided (*dbl:isDividedIn*). IfcOWL is well suited for geometric representation (ifcSpace), Brick ontology contains a class that lends itself to representing space (brick:Location), and Bot ontology also includes a class for spatial distribution, namely bot:Space representing a section of the real or virtual environment with a bounded 3D spatial extent and a specific purpose. In addition, PROV, which is an ontology used to communicate and represent provenance data, could be suited for representing the DBL Registry class.
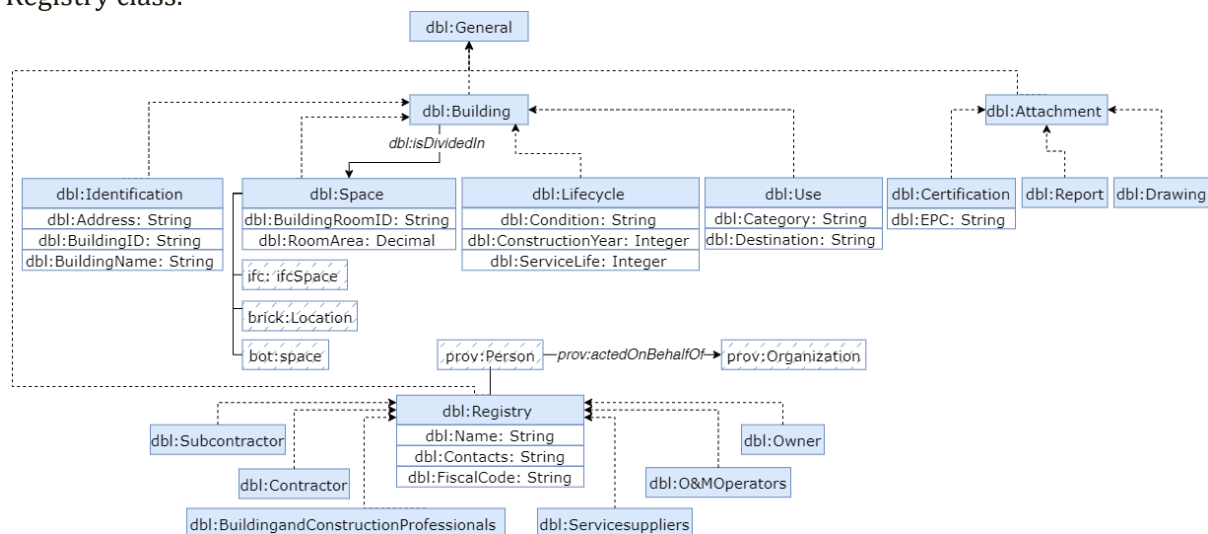

Figure 3. Building identification and relationships

3.2.2 Technical

This class, illustrated in Figure 4, wants to outline information about the building envelope (*dbl:Envelope*) from one side, namely the integrated elements of a building that separate its interior from the outdoor environment, classified by its function such as walls, roofs, floors, and windows with data about each layer, and information about the systems (*dbl:System*) from the other side, such as HVAC, Domestic hot water system, Electrical system, etc. and the equipment that constitutes the system, and their main features as well.

The envelope dataset in the DBL could be covered by the class bot:Element of bot ontology, identified as a constituent of a construction entity with a characteristic technical function, form, or position. Also, ifcOWL can be exploited: in fact, each different construction element finds its representation (IfcBuilding element > IfcWall, IfcRoof, IfcWindow, etc.). Systems (HVAC system, Electrical system, etc.) and each element connected to them can be accessed through BrickSchema since the ontology describes systems but also hidden assets, and it contains the relationships that exist among them. Similarly, this class could be partially covered by ifcOWL, which, nonetheless, is strictly connected to the geometry of the object. Also, Haystack ontology contains a class system that groups equipment such as boiler, chiller, etc. but, relying on the use of tags not following guidelines, brings to customized modeling practices.
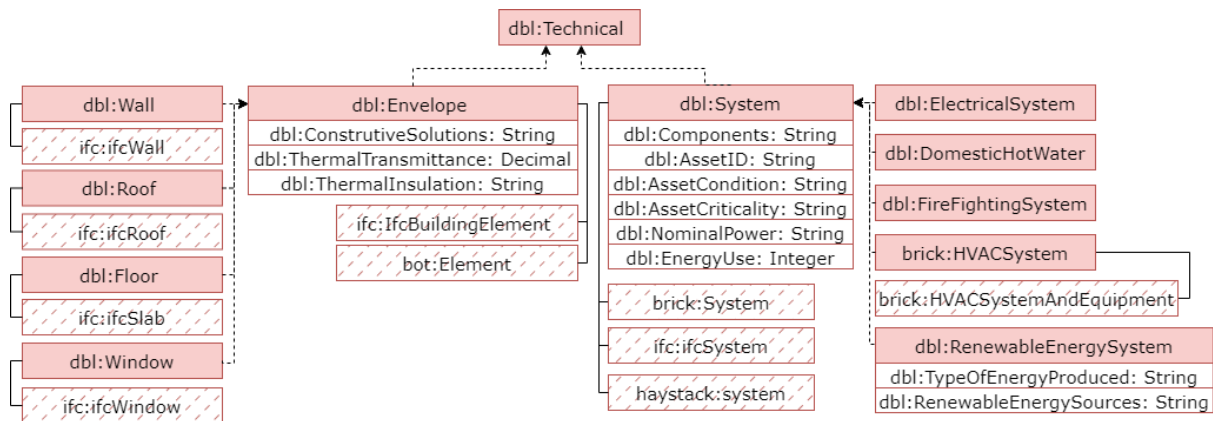
Figure 4. Building technical representation

3.2.3 Sensing

Dbl:Sensing describes the IoT system applied into the building as represented in Figure 5.

The presence of sensors within the building is described (*dbl:Sensor*) as well as the corresponding monitoring for different purposes (such as *dbl:Temperature*, *dbl:Occupancy*, etc.). Information can be retrieved also by smart meters (*dbl:Meter*), devices to collect data on energy consumption and generation. Physical sensors deployed in the building and its spaces could be covered by ifc:IfcSensor entity. Also, SSN/SOSA ontology can be exploited to model the interaction between sensors, actuators involved in the observation and actuation, but it is a concise general-purpose specification. SAREF ontology can describe IoT devices as well, but it does not capture the whole set of equipment and sensors that exist in buildings. In addition, Haystack ontology contains class point, that could suit for sensors, actuators, setpoints. Finally, BrickSchema helps modeling not only the geometric parts of sensors and their relations, but also hidden parts not visible.
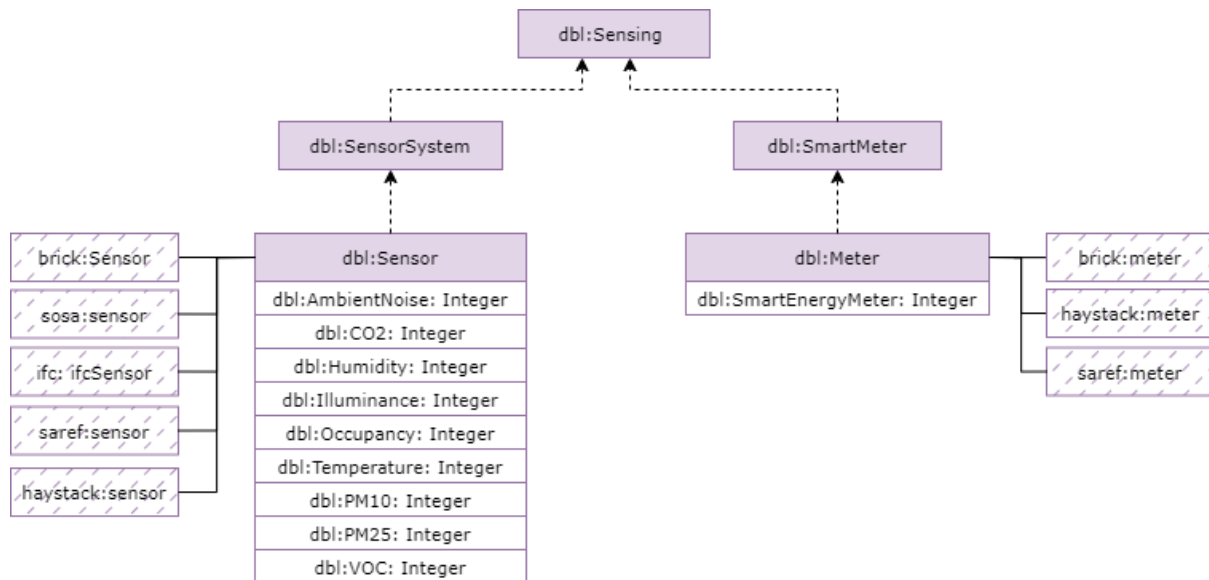
Figure 5. IoT system application

4 Discussion and conclusions

This paper presents the development of a Digital Building Logbook (DBL), the dissemination of which is supported primarily by the European Union as a tool not only for data collection but also as a means to enhance building knowledge and to support more informed maintenance and renovation, characterized by indicators studied according to specific built asset requirements that cover mostly the building complex system. Specifically, the paper introduces the methodology adopted, and related results, to build a DBL by the use of Web Ontology Language, relying on a federation approach and reusing existing ontologies. This study presents an approach that is well-suitable in the case of building management during the in-use phase due to the intersection of space-systems-sensors-maintenance, but it could be suitable and reusable also in other contexts, regardless of the DBL implementation. The number of federated data models could increase, investigating other possible relationships in the representation of the built environment, or decrease, concentrating on the interconnection of just two areas. The choice of ontologies that will characterize the framework is a technical decision driven by the case study and the related requirements. This translates into an overview of available data about the building (or the object of analysis), the considered domain of interest, and the aim of the analysis. The outlined links should work even if other ontologies are chosen to have a framework as flexible as possible. By implementing the DBL by ontologies exploitation, covering not only a specific area of interest, but embracing and interconnecting different aspects (general information, technical features, maintenance interventions, etc.), the study wants to address the need for interoperability.

Since each ontology has been created to address specific needs, even if the DBL includes a variety of data, it was not considered appropriate to rely only on the use of this in the form of ontology. Thus, following the federation approach and the intention of not imposing one model on others, the reusing of existing ontologies proved necessary to interact with systems that have already committed to certain ontologies, and to maintain information in their restricted vocabularies. The interconnection of ontologies, each capable of representing the building from different perspectives, forms the basis of the DBL. This interconnection is developed using identified links and properties that facilitate communication between different ontologies. As a result, by identifying these components, semantic interoperability is made possible, allowing for the linking of various data models. Especially, connections among 6 different domains (1. Building general information, 2. Technical, 3. Energy, 4. Operation, 5. Maintenance, 6. Sensing) are generated: the general information about the building and its spaces are put in communication with the emissions produced and the level of comfort that characterize it. In addition, building spaces are connected with sensors that can be deployed within them. Buildings are also

characterized by systems and envelopes to which maintenance activities are applied. Regarding available ontologies, BrickSchema is commonly used to depict interactions between sensor points and decentralized equipment, as well as non-geometric or even hidden assets and their linkages. Building geometry, topology, and visible assets in each area could be better represented instead of using Industry Foundation Classes (IFC). With this approach, building spatial and systematic architecture could be blended and accessible Building Management System data could be incorporated towards better knowledge extraction for the Facility Management domain, such as improved maintenance decision-making process.

However, as the number of federated data models grows, mapping across multiple ontologies becomes increasingly complex. The research is limited as it only explores federation among a limited number of ontologies, without investigating other potential relationships in representing the built environment. In addition, a testing process should be involved to demonstrate the framework validity: to test the effectiveness of the ontologies-based framework, the RDF query language, namely SPARQL, should be used to run some queries. SPARQL queries allow the retrieval of data about the building spaces' indoor conditions and assets status and, then, organize and prioritize the intervention on the asset.

Future developments can expand the mapping of the DBL to involve other ontologies. Moreover, the framework can be extended by considering other topics and then investigating the relationship between other domains, such as, for example, sustainability and construction sites. Along with it, a deeper testing process can be carried out in the future to demonstrate the capabilities of the framework in enhancing data access and knowledge extraction in the building.

References

Carbonari, G., Ricci, M., Dourlens-Quaranta, S., Calderoni, M., Loureiro, T., Sterling, R., Glicker, J., Toth, Z., Volt, J., De Groote, M., Borragán, G., Paduart, A., & De Regel, S. (2020). *Building logbook—Report 2 of the study on the development of a European Union framework for buildings' digital logbook.* Publications Office. https://data.europa.eu/doi/10.2826/519144

DAMA International. (2017). *DAMA-DMBOK Data Management Body of Knowledge*. Technics Publications, Basking Ridge.

European Commission. (2021). *Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings (Recast)*. https://eur-lex.europa.eu/resource.html?uri=cellar:c51fe6d1-5da2-11ec-9c6c-01aa75ed71a1.0001.02/DOC_1&format=PDF.

Gómez-Gil, M., Espinosa-Fernández, A., & López-Mesa, B. (2022). Review and Analysis of Models for a European Digital Building Logbook. *Energies*, *15*(6). https://doi.org/10.3390/en15061994

Gómez-Gil, M., Sesana, M. M., Salvalai, G., Espinosa-Fernández, A., & López-Mesa, B. (2023). The Digital Building Logbook as a gateway linked to existing national data sources: The cases of Spain and Italy. *Journal of Building Engineering*, *63*. https://doi.org/10.1016/j.jobe.2022.105461

Gu, Z., Lanti, D., Mosca, A., Xiao, G., Xiong, J., & Calvanese, D. (2023). Ontology-Based Data Federation. *Proceedings of the 11th International Joint Conference on Knowledge Graphs*, 10–19. https://doi.org/10.1145/3579051.3579070

Hartenberger, U., & Frics, D. L. (2017). *Global Trends in Data Capture and Management in Real Estate and Construction—RICS*.

Noy, N. (2001). *Ontology Development 101: A Guide to Creating Your First Ontology*. https://api.semanticscholar.org/CorpusID:500106

Ozturk, G. B. (2020). Interoperability in building information modeling for AECO/FM industry. *Automation in Construction*, *113*(January), 103122. https://doi.org/10.1016/j.autcon.2020.103122

Saeed, M. R., Chelmis, C., & Prasanna, V. K. (2017). Chapter 9—Automatic Integration and Querying of Semantic Rich Heterogeneous Data: Laying the Foundations for Semantic Web of Things. In Q. Z. Sheng, Y. Qin, L. Yao, & B. Benatallah (Eds.), *Managing the Web of Things* (pp. 251–273). Morgan Kaufmann. https://doi.org/10.1016/B978-0-12-809764-9.00012-3

Signorini, M., Moretti, N., Merino, J., Daniotti, B., & Parlikad, A. (2023). Digital-twin based data modelling for digital building Logbook implementation. *Low-Cost Digital Solutions for Industrial Automation (LoDiSA 2023)*, 130–137. https://doi.org/10.1049/icp.2023.1744

Spyns, P., Meersman, R., & Jarrar, M. (2002). Data modelling versus Ontology engineering. *SIGMOD Record*, *31*(4), 12–17.

Taye, M. M. (2010). Understanding Semantic Web and Ontologies: Theory and Applications. *ArXiv*, *abs/1006.4567*. https://api.semanticscholar.org/CorpusID:17720879