Digital-Twin based data modelling for Digital Building Logbook implementation

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Abstract: Construction heavily impact on the environment , thus building management plays a central role in achieving higher sustainability objectives. In the use phase, the sustainability performance needs to be balanced with safety, health and comfort requirements, ensuring that the indoor activities can be carried out in a high-performing environment. Indoor air quality is one of the main proxies for health and safety in indoor spaces and maintaining appropriate quality levels is directly impacted by built asset condition, systems operation and other contextual factors as occupancy and weather. The Digital Building Logbook is a platform enabling the interconnection of the variety of datasets used for building management. This paper introduces a framework for implementing the Digital Building Logbook utilising semantic web technologies, in the perspective of supporting better data access and knowledge extraction for Digital Twin applications in the Facilities Management domain. The proposed framework is based on the combination of Industry Foundation Classes, the BrickSchema and a custom Digital Building Logbook ontology, needed to extend the previous two. The Digital Building Logbook ontology is based on OWL and allows to structure the information on assets, maintenance interventions associated to the different spaces and systems, while IFC and BrickSchema provide a support in representing a selection of spatial and semantic building features. The developed framework aims at enhancing the data access and knowledge extraction on the building and facilitates the digital Facilities Management applications development. A validation is carried out on the Alan Reece building at the University of Cambridge and demonstrates its effectiveness in developing users' health-based maintenance prioritisation.

1. Introduction

Building operation and maintenance (O&M) is instrumental to maintaining the buildings' regular functionality, ensuring the level of performance, efficiency and service life, and minimising unplanned failures in the connected asset (e.g. HVAC shutdown due to a lack of proper maintenance to the equipment) [1].

According to the International Energy Agency (IEA) analysis the Architecture, Engineering, Construction and Operation (AECO) sector gains attention for being responsible for about one third of energy consumption and related CO_2 emissions [2].

Especially, the investigation states that buildings' operation causes 30% of global energy consumption and 27% of total energy AECO sector emissions (part of which is due to the use of fossil fuels and production of electricity and heat) [2].

Hence, the implementation of a proper building management, that results into developing strategies for the O&M phase, becomes crucial. In fact, how a building is operated and maintained contributes to the building performance and consequently, it represents a challenge towards the environmental sustainability.

An effective management means to look into both assets conditions and spaces performance for a better users indoor comfort. On the one hand, the correct buildings management includes activities, such as monitoring the consumption and production, operating time of a system, on/off status, etc., aimed at maintaining spaces and systems of buildings in such a way to ensure a good operation. For example, organising inspections and planning maintenance to clean and replace ducts, filters, and other equipment components can help in supporting HVAC system as designed, guaranteeing to keep the energy performance at a good level during cold and warm seasons.

On the other hand, it is fundamental to pay attention to user needs looking at safety, health and comfort. Building spaces where people work, study, or live should ensure thermal, acoustic and visual comfort conditions. In this regard, temperature and humidity should be checked regularly and be acceptable for occupants' satisfaction and health.

In addition, factors such as health and comfort are directly connected to the indoor air quality, which depends on built asset conditions, systems operation, but also contingent aspects as occupancy and weather.

Therefore, it is necessary to monitor the energy consumed by the building and its parts, while maintaining and enhancing the indoor comfort conditions. The increased digital uptake in the sector can enhance efficiency and quality: devices such as sensors help to monitor temperature, humidity, as well as occupancy to guarantee that suitable levels are kept for indoor comfort conditions and avoid energy waste at the same time.

When managing the building, other issues such as the plenty and variety of data occur. Hence, a lot of information needs to be managed [3]. A large part of the building operations data is not updated, incomplete and in low interoperable formats (e.g., paper-based) [4]. This causes a lack of understanding of building systems' and components'

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performance, impacting on the effective development of operation, maintenance and refurbishment strategies [4], [5].

Focusing on these issues, this paper aims at introducing a framework for implementing the Digital Building Logbook in order to promote improved data access and information extraction for Digital Twin applications.

The Digital Building Logbook is defined as "a common repository for all relevant building data, including data related to energy performance such as energy performance certificates, renovation passports and smart readiness indicators, which facilitates informed decision making and information sharing within the construction sector, among building owners and occupants, financial institutions and public authorities" [6].

The developed Digital Building Logbook, based on semantic web technologies, enables the link of the variety of datasets from different domains (such as building space, systems and sensors) used for building management, improving the data availability and quality, facilitating the collection and transfer of different types of building related data. Especially, it can address the need of improved maintenance decision making being a support for Facility Managers (FM) and paying attention to users' comfort needs.

Finally, a real case study, namely the Alan Reece building at the University of Cambridge, is adopted to do a demonstration of the Digital Logbook effectiveness. Especially, testing includes the assessment of assets condition and comfort condition towards a users' health maintenance prioritisation. For this purpose, some queries can be run. SPARQL queries allow to retrieve data about the building spaces indoor conditions and assets status and, then, organise and prioritise the intervention on the asset.

2. Methodology

This section describes the procedure for the realisation of the framework of a Digital Twin based data modelling for implementing the Digital Building Logbook. The working schema is illustrated in Fig. 1:

1. The first step consists in the definition of the information that should be contained within the Digital Building Logbook. The information requirements (IR) comprehends static and dynamic, geometric and non geometric information at the building and other asset levels focusing on the as-built state. This step has been realised according to the literature analysis on the Digital Logbook [7].
2. The second step is related to an analysis of the Semantic Web (SW) technologies. The study aims at identifying the existing ontologies and related data models in the built environment context that can address the selected information requirements. Given the complex built environment, each ontology has its own specific use and domain of application [8].

Following an analysis of existing ontologies and related data models, the most appropriate ontologies for the case study are chosen from this group. In an ontology-based software the Digital Building Logbook ontology is developed and enriched with classes, subclasses and relationships between them. In addition, classes and properties that could connect the existing ontologies in a federated model are generated.

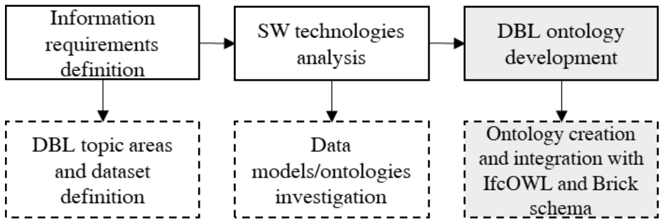

Fig. 1. *Methodology schema*

2.1. Information requirements definition

The concept of Digital Building Logbook has been introduced by the European Commission in the Renovation Wave report in 2020 [9], and the necessity of this element has been outlined in the Energy Performance of Building Directive (EPBD) the following year [6].

During the O&M phase a lot of data are generated, but there are no guidelines about how these data should be collected, organised and make accessible by stakeholders [10]. Consequently, this results in data often damaged, information asymmetry, lack of transparency and higher risk for decisions [11], [12]. A homogeneous collection and management system by harmonising the data storage process can be boosted through the use of Digital Building Logbook [11].

Starting from the State of the Art of the instrument, the analysis concentrates on the definition of information and its related structure in order to obtain a dataset as complete as possible. The definition of information requirements, namely specification for what, when, how and for whom information is to be produced, considers a great panorama of information, that have been organised within the Digital Building Logbook.

The developed Digital Building Logbook has a total of four levels of information (level 0, level 1, level 2, level 3). Level 0 corresponds to *Category* and comprises six distinctive blocks that aggregate information according to the main topic aiming to give the most complete view and description of a building. Category works as collector of more detailed information. Each category is subdivided in one or more *Typology* (level 1), which in turn has connected several *Groups* (level 2) of information. The most detailed level of information is contained in the block named by the author *Attributes* (level 3). Other information levels, if necessary, need to be defined in order to associate more detailed and precise information and data.

The dataset has been firstly developed in Excel grouping each category in a separate sheet, and in a second phase translated into a Ontology Web Language (OWL).

The different sections intend to enable information aggregation with a clear difference between the topics. The Digital Building Logbook has 6 categories, that are the following (Fig. 2):

1. General
2. Technical
3. Energy
4. Operation
5. Maintenance
6. Sensing

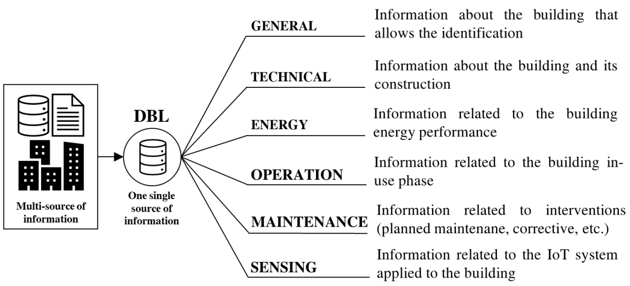

Fig. 2. *Digital Building Logbook categories and a brief description*

2.2. Semantic Web technologies analysis

The development of an integrated instrument that not only provides accurate and up-to-date information but also enables analysis, based on the needs of the various users, on how to manage, maintain, and improve the building is what is meant by moving towards a Digital Building Logbook rather than simply including files created electronically in the Building Logbooks.

Along with the existing data, it is essential to investigate how these data may be stored, used and shared, that translates into the study of interoperability. Interoperability is not only about the exchange of data but also the exchange of meaning [5].

Using semantic web technologies, namely technologies related to the extraction, representation, storage, retrieval and analysis of machine-readable information [13], is a way to improve interoperability in the AECO industries [14], facilitating data organisation, integration and exchange [15].

A key concept of semantic web is ontology, defined as “an explicit description of the concepts and entities that are assumed to exist in an area of interest and the relationships that hold among them” [16], and it can be used to address the need for semantic interoperability.

To make it possible for semantics to be encoded with the data, ontologies can be expressed using Web Ontology Language (OWL), that is a family of knowledge representation and vocabulary description languages for authoring ontologies standardised by the World Wide Web Consortium (W3C) [13].

The Digital Building Logbook contains different types of information, not only related to the building use phase, but also information related to the envelope, systems, etc. However, some of the information that the Digital Building Logbook aims at collecting are already represented by existing ontologies.

Hence, the analysis on ontologies in the built environment context was carried out in order to choose the most suitable option (Fig. 3) and a strategy to link the developed dataset was studied.

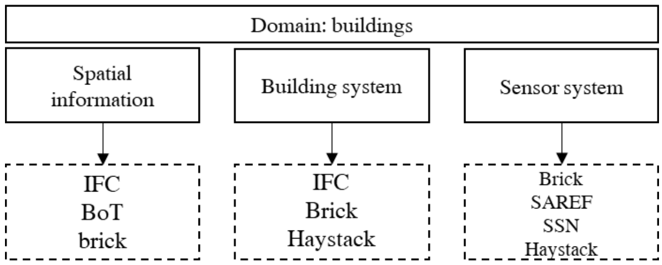

Fig. 3. Ontologies application in the built environment

For example, ifcOWL offers an Industry Foundation Classes (IFC) schema representation in Web Ontology Language [17]. The IFC was created to address every aspect of building information throughout the whole building lifecycle, from feasibility and planning to design (including analysis and simulation) and construction to occupancy and operation [18]. IFC is effective for building-related static data representation (spatial element such as site, building, facility) [19].

Brick is a schema focusing on control systems within buildings in order to provide a standardised ontology for representing locations, equipment, sensors, controls and relationships. It can be used to model semantics of the building systems, to which the real-time data relates [20]–[22].

Building Topology Ontology (BoT) is an ontology that aims to define relationships between the subcomponents of a building, It describes the topology of buildings including storeys and spaces, the building elements they contain [23], [24].

The Semantic Sensor Network (SSN) ontology is used to describe actuators, sensors and their observations in buildings, as well as the associated methods, researched aspects of interest, samples utilised in the study, and observed qualities [25].

The Smart Appliances REFerence (SAREF) is an ontology used to describe IoT devices. It does not fully represent the range of devices and sensors used in buildings, hence it may be simply included into Brick [26] .

Project Haystack is an ontology describing buildings based on collections of tags. It provides a dictionary of defined tags on its website [22], [27].

Finally, a federated data model is the used approach that allows the support of Digital Twin applications and enables the reuse of data within its own domain, preserving the capabilities of each selected data model, as opposed to physical data integration [28]. Having a Digital Twin-based data model flexible enough allows to accommodate different ontologies that represent specific building domains in a different way.

3. Results

The previous steps described in the methodology section bring to the development of the Digital Building Logbook ontology and the framework generation. This part consists in the new ontology creation and the interconnection with other existing ontologies. The generated framework connects different domains (building space, building systems and sensors system, as well as operation and maintenance) allowing a cross-domain knowledge. Especially, the Digital Building Logbook ontology based on OWL covers mainly information on assets and maintenance interventions.

The Digital Building Logbook as a standalone tool enables the organisation and storage of data and information about the building and its constituent parts. By integrating it and connecting it to other ontologies inside a federated model, as this study shows, it is possible to navigate the developed framework to address specific needs taking use of the interconnection of various domains.

O&M phase presents often issues related to an inefficient maintenance management, carrying out maintenance interventions when it is too late and causing discomfort to the building users for a lack of a service. In addition, assets within the building may be quite numerous and linked together. Occasionally, the maintenance activities are performed on a specific asset not taking into account the source of the problem and other interconnected assets, which in turn may present inefficiency.

Therefore, task that the framework aims to address is an improved maintenance decision making for Facility Managers. Demonstration of the effectiveness may be accomplished by testing the framework in a real-world case study.

The proposed framework is being tested on the Alan Reece building in Cambridge (UK). In fact, sufficient data regarding different areas are at disposal: assets and spaces, last maintenance, sensors.

After an accurate explanation of the federated data model, a description of the building case study and the assets characterising the building follow. The chapter ends with the ongoing framework validation and the partial results.

3.1. Federated data model

For the specific case study, IFC and BrickSchema have been chosen to cover respectively building spatial and semantics information. The chosen ontologies are federated to address specific information requirements.

Before creating the connection, the Digital Building Logbook dataset has been converted into OWL.

In the ontologies language the Digital Building Logbook categories, typologies and groups have been implemented as class and subclasses (describing concepts in a domain) in an ontology-based software (Fig. 4), as well as the attributes have been translated into data properties (describing relationships between instances and data values).

In addition, to describe the relationship between classes and/or subclasses object properties have been created (describing relationships between instances).

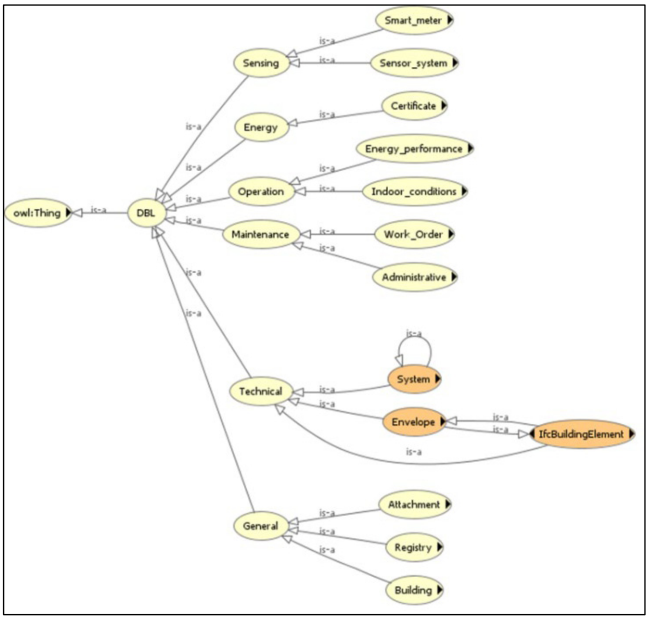

Fig. 4. *Digital Building Logbook ontology creation: class hierarchies in OWLViz visualisation.*

At this stage, the connection among the ontologies and the customised Digital Building Logbook ontology is performed taking into consideration different domains (space – building systems - maintenance – sensor).

A series of possible links between the different ontologies and the custom Digital Building Logbook ontology has been developed (Fig. 5). The outlined links should work even if other ontologies are chosen in order to have a framework as flexible as possible.

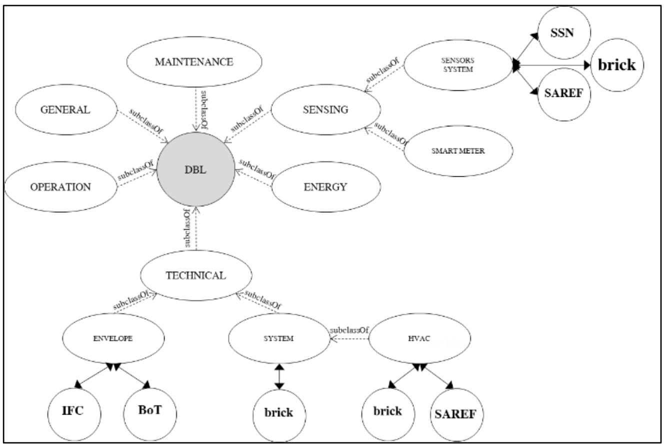

Fig. 5. *Digital Building Logbook ontology and connection with existing ontologies operating in different domains*

From one side the connection relies on the direct correspondence between one or more classes of different ontologies. Since the Digital Building Logbook aims at representing the building in all-round view it contains domains already exploited by other ontologies. Given the existence of other ontologies describing the building under determined domains, the equivalences are outlined as below.

1. In this research, the Digital Building Logbook ontology contains the class *Space* (namely an area or volume that performs certain functions within a building). This element can be represented in the

same way by *IfcSpace* in ifcOWL ontology (Space EquivalentTo IfcSpace).

2. The building construction elements are described by the class *Envelope* (representing the building enclosure, comprising elements that constitute the construction of a building, such as wall, window, roof, etc.) in the Digital Building Ontology. This element is equivalent to *IfcBuildingElement* in ifcOWL ontology (Envelope EquivalentTo IfcBuildingElement).
3. Another element characterising the building construction element is represented by the class *System* (a combination of equipment and auxiliary devices such as controls, accessories, interconnecting means, and terminal elements by which energy is transformed so it performs a specific function such as HVAC [29]. This class can be associated to the class *System*, available in Brick ontology (System EquivalentTo System).
4. The Digital Building Logbook ontology has a class describing the IoT devices applied to the building, namely *Sensor* (an input point that represents the value of a device or instrument designed to detect and measure a variable [29]). There is an equivalent class Sensor in Brick ontology (Sensor is EquivalentTo Sensor).

From the other side, in order to connect other type of domains, such as maintenance, targeted object properties have been created. They describe the relationship that exist between one or more class.

1. The maintenance interventions are applied to each system characterising the building. A new object property has been created named *isAppliedTo* and relationship between *Maintenance* class and *System* class has been generated (*Maintenance isAppliedTo System*).
2. If the maintenance is applied to each system, vice versa each system is subjected to maintenance. Hence, a new object property has been created, named *isSubjectedTo*, and relationship between *System* class and *Maintenance* class has been generated (*System SubjectedTo Maintenance*).
3. Sensors monitoring the building performance are represented by the class *Sensor* and they are placed in different spaces of the building. Then, a new object property has been created named *isLocatedIn* and relationship between *Sensor* class and *Space* class has been generated (*Sensor isLocatedIn Space*).
4. As stated before, the Digital Building Logbook ontology contains information on maintenance interventions that are associated to the several system characterising the building. To outline when the maintenance intervention occurs, the object property *isPerformed* has been created and the relationship between the *Maintenance_Activity* class and the *Maintenance_Time* has been generated (*Maintenance_Activity isPerformed Maintenance_Time*).
5. In the same way, to outline the cost of each maintenance intervention, the object property *Costs* has been created and the relationship between the *Maintenance_Activity* class and *Maintenance_cost* class has been established (*Maintenance_Activity* costs *Maintenance_cost*).

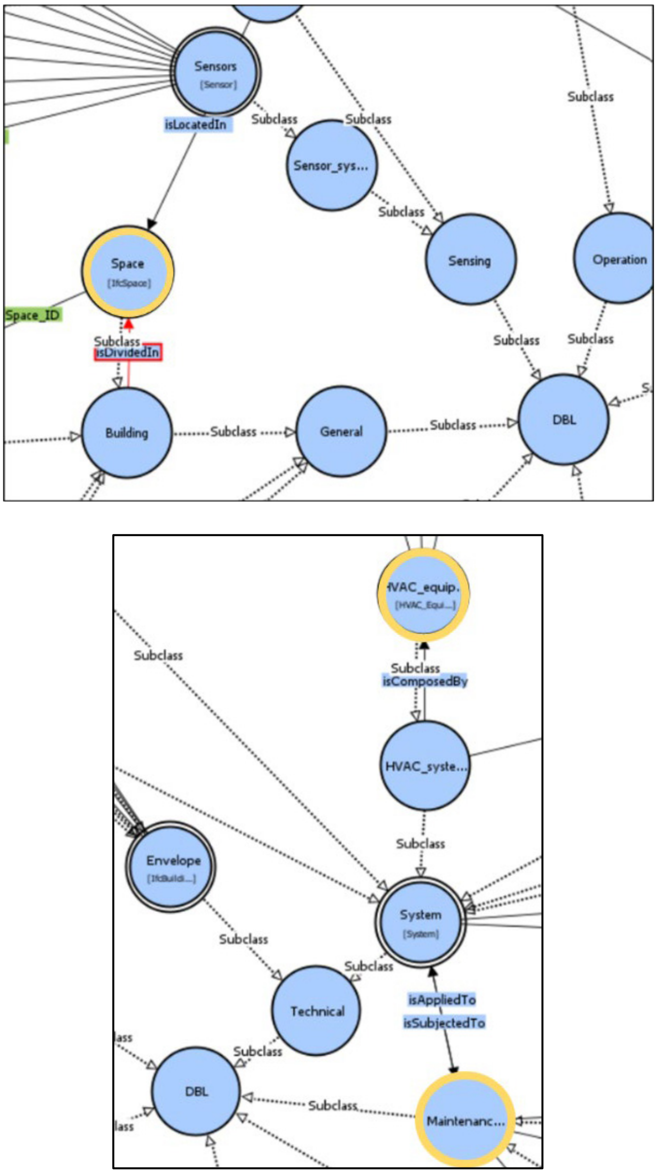

Fig. 6. *Example of classes (circles), individuals (sections in the circles) and property relations (connecting lines and arrows) in a graphical visualisation VOWL.* ***(a)*** Link between different domains: space and sensor system, *(b)* Link between different domains: maintenance and system.

3.2. The case study building

The Alan Reece building, the seat of the Institute for Manufacturing (IfM), was used for validating the Digital Twin-based framework. It is a three-story building with a total floor area of 3000 m^2 and it is located at the University of Cambridge - West Cambridge campus. The building contains offices, research space, laboratory, canteen, etc.

Given the building extension and variety of systems contained within it, the validation of the framework focused only on a part of the building, namely the HVAC system of the IfM building.

Data in possession concern the assets related to the IfM building HVAC system. Especially, a list of all the assets present inside the building is available as well as their position in space, such as thermostatic radiator valves, biomass boiler, air handling units, etc.

Furthermore, data about asset condition and criticality are provided.

3.3. *Federated data model validation*

After analysing several ontologies in the built environment and investigate how they can collaborate, given the specific case study and the analysis context the ontologies and related data models are chosen.

IFC and BrickSchema have been selected for the case study in question. Spatial data are modelled with IFC, while the system and equipment are mapped with BrickSchema. The customised Digital Building Logbook ontology instead meets the need of collecting maintenance and other information related to the operation phase.

Firstly, available data regarding the IfM building are mapped in the ontology editor enriching the developed framework with information related to the real case study. In Fig. 7 an extract from the IfM HVAC assets is provided. The position in the space, condition, criticality, codification have been associated to each asset.

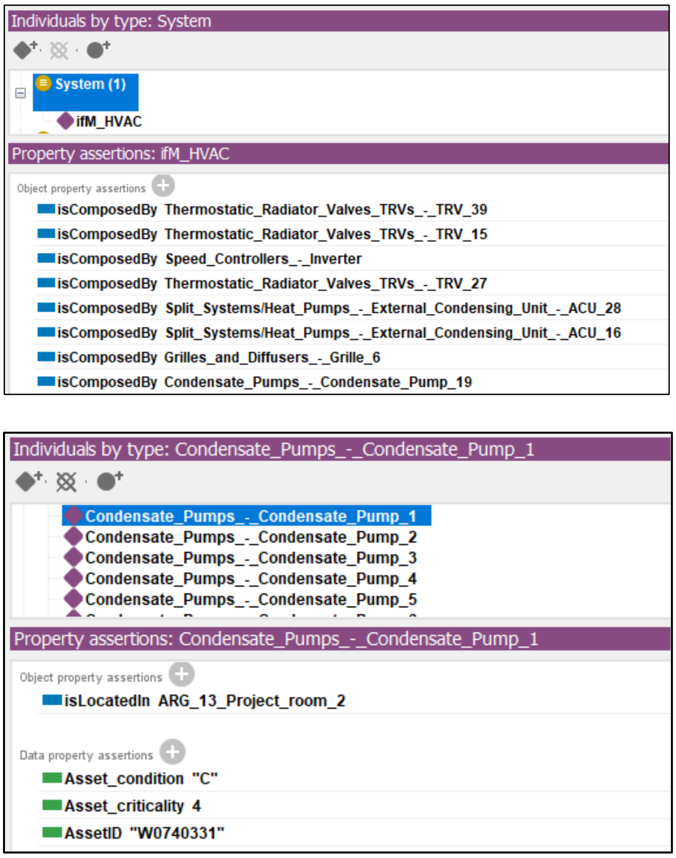

Fig. 7. *Ontology-based software frontend filled with IfM building related data.* ***(a)*** List of HVAC system assets, ***(b)*** Properties associated to each asset.

Furthermore, sensors have been applied to some of IfM HVAC assets to monitor their operation status. Sensors have been applied to monitor temperature and humidity in the room a well. They are mapped in the federated model and associated to assets and then related spaces.

To demonstrate the capabilities of the developed framework, SPARQL queries can be exploited. It allows to investigate the ontology and to retrieve data stored in .rdf format.

It will be attempted to demonstrate the effectiveness of the Digital Building Logbook in maintenance decision-making by taking into account the various assets present in the building, their interconnection, and potential failures, considering the problem of managing an efficient maintenance plan.

Sensors provide data every 15 minutes on the operation of certain assets. Thanks to the use of applied sensors, assets operation and related anomalies can be detected by analysing the time series of sensors streaming (for instance, value equal to zero in the historic series translates into an anomaly). After anomalies detection, the developed federated ontology can be exploited. Investigating the ontology allows to understand which are the connected assets, if any, and the spaces that could be affected by the failures. Taking into account the link with maintenance information, it is possible to retrieve automatically the information about the last maintenance intervention as well.

Consequently, a support to FM can be offered for a maintenance prioritisation, registering the assets failure profile and then, assessing the asset that needs more maintenance interventions, repair, replacement, or upgrade.

User comfort should be taken into consideration while evaluating a maintenance intervention as well. In the same way, by analysing temperature sensor time series, it is possible to track when there is an anomaly (understanding if it is a sensor anomaly or an asset failure that brings automatically a change in the room temperature), check the involved spaces and make an assessment if an intervention is needed immediately or can be planned for the future.

An example can be provided by the biomass boiler that is located in the plant room. It is subjected often to failures that cause its shut down and a consequent lack of heating. This issue seriously affects users' condition, whose health and comfort are put at risk.

4. Discussion and conclusions

This paper presents a Digital Twin-enabled Digital Building Logbook implementation. It proposes the methodology adopted in order to develop a framework as flexible as possible to accommodate different scenarios and address various service requirements. The main objective is to enhance data access and information extraction for Digital Twin applications.

Given the interoperability issue and the complexity of the built environment, different ontologies have been studied relying on a federation approach to connect several contexts.

IFC, BrickSchema and a custom Digital Building Logbook ontology that is connected and extend the previous two, characterise the framework operating complementarily. It is possible to enable better accessibility and multi-services data interoperability through the established framework. The final framework acts as a gateway space to connect different domains: in this case, spatial information are given by IFC, semantic by BrickSchema, building maintenance/renovation/identification by the Digital Building Logbook.

The Digital Twin-based data model developed, that has as fundamental element the Digital Building Logbook, can be used for an improved maintenance decision-making as support for FM. It provides an interdisciplinary knowledge connecting different areas such as space, assets, sensors system and maintenance.

The presented approach is being testing on a case study to verify the effectiveness of the Digital Building Logbook implementation, as a collector of buildings model, systems, maintenance related information.

Running SPARQL queries on the developed framework allows to address service requirements and help in decision making accordingly.

The testing, that is ongoing, consists in a verification of assets anomalies to detect the source of the problem and if other assets are involved, and collect information about their failure profile to prioritise the intervention on the asset.

Analysing the time series of sensors data streaming it allows to finds peaks and associate an anomaly to them. At this point, the federated model can be used to evaluate the other connected assets and space potentially affected. This can be a guide to FM in evaluating what and why a failure occurred and manage a proper maintenance intervention.

Although the presented approach is not complete because the study is still in progress, another challenge results in a users' health-based maintenance prioritisation. Given temperature data streaming from the sensors applied to the building from one side, assets and their location, potential anomalies detected, it is possible to offer a support for planning maintenance that focus primarily on users health and comfort.

However, when dealing with Digital Twin, issues related to data granularity and quality can emerge. Sensors streaming time should be sufficiently low to have a real-time view of the building and to achieve the main function of Digital Twin, namely being a realistic digital representation of assets, processes or systems in the built or natural environment [30]. Data quality is another aspect to analyse. Data in the Digital Twin can be used for various application, decision making and prediction. Nonetheless, data may degrade, causing them to be inappropriate for specific uses. For instance, data streaming interruption due to internal technical problems could affect data collection success and quality.

In future work, data collection from real-time sensors and investigation exploiting the federated model will continue.

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