# Ontology-Based Spatial and System Hierarchies Federation for Fine-Grained Building Energy Analysis


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## Abstract

Building energy conservation is among the most cost-efficient paths to achieve sustainability. An in-depth understanding of the energy consumed during the operation guides more effective energy-saving actions. With the adoption of submetering systems, fine-grained building energy analysis is enabled. This allows characterising the dynamics underlying specific end-uses by associating local energy consumption patterns with relevant contextual factors. To generalise the analysis in different buildings, a interoperable data representation for spatial and system hierarchies is needed. A federation approach to integrate building ontologies is proposed. The aim is to capture hierarchical geometric, topological, and relational information, components and systems, for running canonical energy analysis. The proposed approach combines the Industry Foundation Classes (IFC) and Brick schema, complementary in representing spatial and semantic information. A case study is conducted, demonstrating the use of the federated ontologies in integrating various data. This contributes to the development of portable plug-in building energy analysis functions.



**Keywords:** Energy analysis, interoperability, building ontology, IFC, BrickSchema


## 1 Introduction

As a significant energy consumer and greenhouse gas (GHG) emission contributor, the building sector alone is responsible for over 30% of the total energy consumption worldwide, with a related emission of more than a third of total GHG (Berardi 2017). In the UK, over 20% of the GHG emissions are due to the construction and operation of buildings, with three-quarters of that arising from operational energy use (Cambridge Zero Policy Forum 2020). Improving energy efficiency is considered one of the primary strategies to reduce GHG emissions with acceptable economic costs (la et al 2017), and achieving Net Zero Carbon Building by 2050 has become a shared commitment spanning across over 80 countries.

However, if you can't measure it, you can't improve it. Measuring and understanding the underlying dynamics behind the energy consumed in each part of a building is the very first step towards energy-efficient buildings. With the advances of Internet-of-Things (IoT) devices and Building Management Systems (BMSs), buildings with ubiquitous sensing capabilities generate a vast amount of energy-related data. In exploiting energy saving potentials, a quantitative building energy analytical framework is required to support data integration across multiple building energy systems, and such an analytical approach subsequently describes the embedded interactions among buildings, occupants, and environments.

Building energy systems are hierarchically structured, and equipment is decentralised around to serve each system in a building. In practice, the measurement of energy consumption usually takes place at an aggregated level. Typically, meters and submeters are installed to measure the energy delivered to zones in a building, where equipment is located. A zone is a combination of spaces defined as indivisible volumes that provide for particular functions within a building, like a meeting room. Laying in different branch circuits, the submeters are often responsible for one specific end-use of that zone only, e.g., lighting. For example, for the building in the case study, the submeter SM15 measures the amount of energy consumed by all the lighting equipment (e.g., light bulbs, emergency lights, etc.) in the west wing zone, first floor, covering multiple private office rooms, laboratories, an open office area and a common room.

Instead of measuring the whole building's energy consumption, electrical submetering can lead to better awareness of the occupants of local electricity consumption patterns and energy use efficiency in a finer spatial granularity (Krishnanand et al 2016). Meanwhile, the driving factors that characterise a specific granulated energy consumption, including weather, building operations and occupant behaviour (Brohus et al 2012, Sun et al 2017), need to be integrated into the analysis. This allows for better interpretation of the building energy dynamics, and to drive more effective Asset Management decisions. However, the customised naming convention used by different vendors often results in irregular metadata, handled through various tools, ranging from Building Information Model (BIM), BMS, Computerised Maintenance Management System (CMMS) and so forth. This leads to inefficiency in integrating multi-source data with different models and formats.

To integrate information from different sources, a common data representation is needed to realise the semantic interoperability for building geometries, topology and system hierarchies (e.g., the hierarchy for submetering, HVAC, lighting and sensor systems). This could support the metadata interpretation and the mapping of heterogeneous data to a standard format, enabling the federation and query of diverse data sources. The federation approach allows to manage relevant information in its native data model, reducing data redundancy. Data can be accessed and used, through the definition of a set of methods and rules able to leverage the potential of each data model, in a coordinated way. This allows to enhance data availability during the lifecycle of the assets, enabling data-driven applications. More importantly, the adopted data models should be expressive enough to capture geometric and semantic information of building energy systems and the critical relationships amongst zones, equipment, occupants and environment. Based on this data modelling approach, applications can flexibly retrieve required data in a plug-in manner and portable building energy analysis can be realised for better energy efficiency.

The remainder of the paper is organised as follows. Section 2 overviews the state-of-the-art of the submetering strategy and the data schemas for building and system architecture. Section 3 describes the proposed federated ontology integrating IFC and BrickSchema. Section 4 gives a real-life case, demonstrating the capability of the federated ontology in representing geometries, topologies and systematic connections. Section 5 concludes the paper.

## 2 State of the art

In this section, a brief literature review on building energy submetering and digital modelling is presented to support the development of the building energy analytical framework.

## 2.1 Submetering building energy consumption

Submetering strategy has been verified to be effective in identifying energy efficiency opportunities through few case studies (Zhai et al 2020). The U.S. Department of Energy estimated that implementing a submetering system contributes up to 20% reduction in energy use (Parker et al 2015). However, due to the costs associated with installing submeters and potential modifications of the existing mechanical systems, the depth of submetering in energy analytics implementations needs to be determined wisely for a trade-off between costs and benefits. Usually, submetering to the second level from the top is appropriate, consisting of four primary submeters and several representative secondary submeters, as shown in Figure 1 (Ji et al 2015).

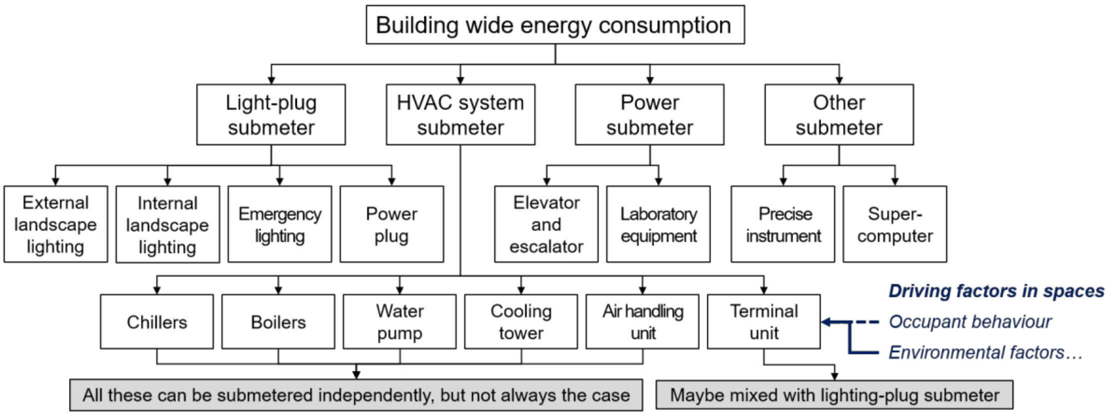


**Figure 1.** Submetering structure at primary and secondary levels

Based on the submetering readings, Building Energy Simulation Models (BESMs) at the system level can be constructed to evaluate the dynamics between specific end-use and associated parameters. Effective hierarchical representation of the building zones and systems is needed to identify and extract all possible driving factors that influence the end-use until the simulated end-use matches the corresponding submetering reading.

## 2.2 Data modelling of building and system architecture

Geometric and contextual information throughout the building's life cycle can be better managed by establishing an appropriate digital model for the building and its systems. Geometric information includes but not limits to the 3D models of space and asset components, and contextual information ranges from materials and costs of components to the architecture of building energy systems. This information needs to be correctly represented to support various computer-based architectural and engineering analyses (Eastman et al 2011). Relevant data sources tend to be heterogeneous, and great efforts have been devoted to addressing interoperability challenges (Gallaher et al 2004). On the one hand, exchanging information throughout design, construction, operation and maintenance (O&M) phases eliminates the need to reinput or even recollect critical information in later stages of the building's life cycle (Lu et al 2019). On the other hand, describing interdependent building systems using common machine-readable representation enables efficient cross-referencing of metadata for diverse analytical purposes. Therefore, a federated ontology for building equipment, locations, sensors, and actuators and more importantly, the relationships between these entities need to be defined, based on standardised vocabulary and taxonomy across different domains (Leal et al 2020).

Specifically, the geometric and semantic architectures of the building and its components can be represented in different ways, according to the type of classification system and the adopted data model. For example, the objects composing a physical entity can be classified either according to their compositional properties (e.g., geometry and construction materials, etc.) or according to their functional properties (e.g., heating, cooling, load-bearing, etc.) (Afsari & Eastman 2016). From the perspective of modelled objects, the conceptualisation of the space includes defining the geometry and topology (hierarchically connect stories, zones, spaces) of spaces and the building components they contain, while the conceptualisation of the system aims to describe a set of interacting building components, and how they function collectively and collaboratively to provide specific services. For the spatial elements, the focus is concentrated on creating, sharing, exchanging, and managing the information throughout their lifecycle. For system architecture, capturing essential dependencies and connections within and between different systems (e.g., lighting, electric power, water, and heating, ventilation and air conditioning, etc.) becomes more crucial.

Many metadata schemas and ontologies spanning across different phases of the building life cycle have been proposed. Schemas like Industry Foundation Classes (IFC) and Green Building XML (gbXML) sufficiently capture geometry-related information for buildings, stories, zones, spaces and embedded mechanical components of building systems, supporting the exchange of information between different phases of the building (Ramaji et al 2020). Meanwhile, ifcOWL is developed to improve data interoperability and flexible data exchange of the IFC model, and an OWL representation of the original EXPRESS language is used to describe the IFC model. However, these schemas lack much of the vocabulary needed to explain the building operation, such as the Building Management System (BMS) and metering system (Pritoni et al 2021). Mainly, outdated and unreliable (i.e., inaccurate and incomplete) building information exists extensively in practice, and IFC or gbXML alone cannot easily represent complex non-geometric building operation metadata.

On the other hand, several schemes were developed to provide a standard set of domain vocabulary and taxonomy used in commercial building BMSs, including Project Haystack, BrickSchema (Balaji et al 2016) and Google Digital Building Ontology. Project Haystack uses tags to annotate metadata to heterogeneous data points in a flexible and scalable manner. It defines a vocabulary of tags describing automation, control, energy, HVAC (heating, ventilation and air conditioning), lighting, etc., but is not expressive enough to represent the topological hierarchy. Similarly, BrickSchema and Google Digital Building Ontology create an open-source schema and toolset for representing structured information, designed for both building topology and building-installed equipment. Particularly, the BrickSchema has been verified to be capable of mapping almost all BMS metadata and relationships from existing buildings to the schema and meeting the requirements of eight representative categories of building energy applications. Table 1 gives an overall comparison of these data schemas.

**Table 1.** Comparison between different metadata schemas

| Schemas | Geometry | Topology | Metering Systems | Sensor system | Operational Relationships |
|---|---|---|---|---|---|
| **IFC** | Yes | Yes | No | Generic | Generic |
| **gbXML** | Yes | Yes | No | Generic | Generic |
| **Haystack** | No | No | Partial | Yes | No |
| **Brick** | No | Yes | Yes | Yes | Yes |
| **Google** | No | Yes | Yes | Yes | Yes |

Given that a single model cannot describe everything, ontologies allowing sufficient flexibility in the aggregation and query of data should be federated. Each data schema has its specific capabilities in representing the object's geometric and contextual properties. For supporting the quantitative building energy analytical framework, the ISO 12006 (ISO 2015), which leads to the IFC model, and the Brick (Balaji et al 2016) schemas are federated, offering the ability to map common concepts across different resources used in building energy analysis.

## 3 Methods

The hierarchical building energy analysis is enabled by an ontology federation approach that integrates building spatial and systematic architectures and incorporate available submetering data. The derived representation should be expressive to capture geometric information like building, stories, zones, spaces and visible assets (e.g., radiators, return air ducts), topological hierarchical relationship (e.g., a specific HVAC zone is a combination of few interconnected spaces) and systematic connection relationship (e.g., mechanical/electrical components connect without explicitly modelled pipelines/cables). Provided the IFC and BrickSchema capabilities, building geometry, topology, visible assets and sensors distributed in each different space are modelled with IFC, while the relationships among submeters and decentralised equipment, as well as non-geometric or even hidden assets and their connections, are represented using BrickSchema. As shown in Figure 2, portable and fast querying capacity is enabled to retrieve relevant information from both IFC and Brick, supporting applications under the hierarchical building energy analysis framework.

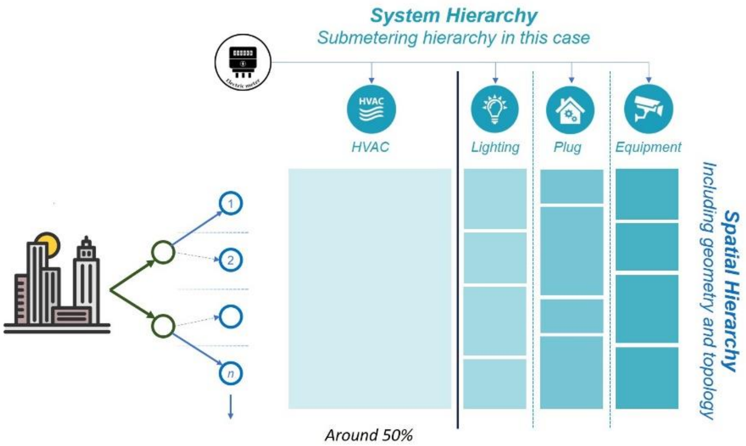


**Figure 2.** Hierarchical building energy analytical framework

### 3.1 Industry Foundation Classes (IFC) for geometry

The Industry Foundation Classes (IFC) is a widely used scheme for interoperability in the Architecture, Engineering, Constructions and Operations (AECO) sector. This standard allows addressing, mainly at the building level, the representation of the building components both geometrically and semantically. The latest official version of the IFC schema is version 4 ADD2 TC1 (ISO 2018), though many efforts are ongoing for extending the schema to infrastructural and built environment elements (e.g., the Room Activities). The IFC schema is compliant with the ISO 12006 ontology (ISO 2015) and has the capability of representing not only the physical elements composing the building with the related properties, but also other non-geometric entities as processes and controls as, for example, action requests, cost items and work orders. This makes the schema semantically rich, despite not all these objects can be easily accessed and leveraged for improved information management. In fact, IFC data exported from the design and construction phases are often insufficient, due to unclear data modelling and interoperability procedures. Many BIM editing software allows controlling the IFC export procedure through mapping the building component types to the corresponding IFC elements. However, this is not always planned enough, resulting in the underutilisation of the large variety of classes offered by the schema. Moreover, it is not always possible to develop or map process-related domain classes (e.g. the *IfcAsset* in the *IfcSharedFacilitiesElements*) directly through the most common BIM authoring software, making it impossible to leverage the related information. An example of how to access programmatically access and use some of these non-geometric and semantic intensive classes is presented in Moretti et al (2020).

In this paper, we leverage the geometric representation and topological capabilities of the IFC schema to represent the spatial, product and representation hierarchies of the building and its parts, as shown in Figure 3.

### 3.2 Brick for submetering hierarchy

The BrickSchema is an emerging data schema, which aims at providing a standardised ontology for representing different locations, equipment, sensors, controls, and relationships used in buildings during their operations. The design of Brick is based on more than 17,700 data points supplied by BMSs from six different vendors, concerning vastly varying systems and sensors in buildings. It is verified to be valid for not only lighting, electric power, water, heating, ventilation

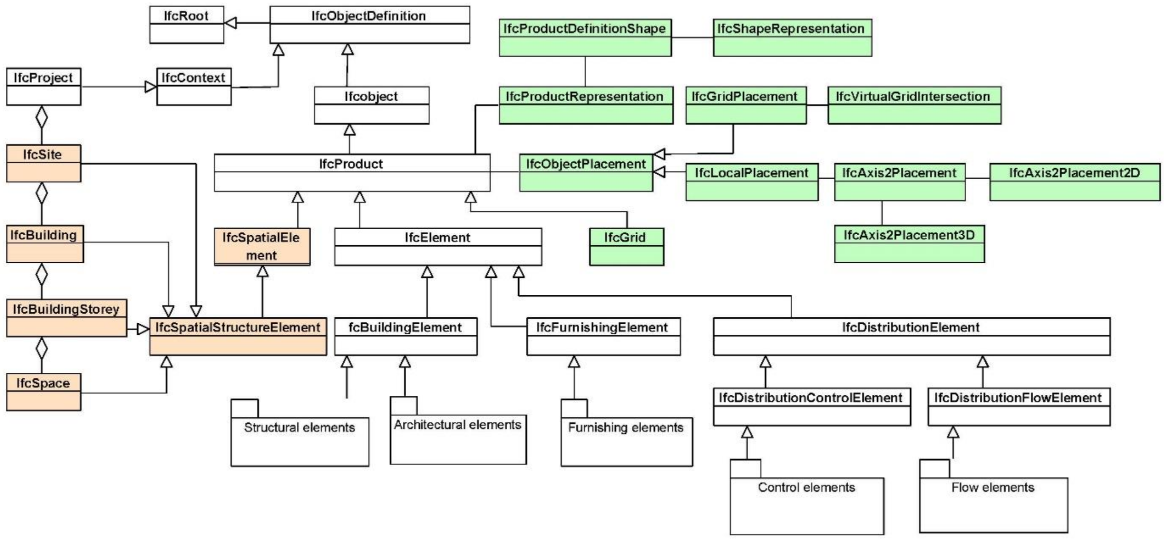

**Figure 3:** UML conceptualisation of the spatial (orange), product (white) and representation (green) hierarchies in IFC ADD2 TC1.

and air conditioning (HVAC) systems, but also the submetering system illustrated in this paper. Due to the domain vocabulary and canonical relationships devised to capture dependencies and connections in and between building systems, BrickSchema outperforms IFC concerning the flexibility to deal with complicated hierarchies and relationships (i.e., taxonomy, indirect location, equipment connection, equipment composition, point connection, monitoring) as well as the extensibility to further sets of assets or relationships.

Adhering to the Resource Description Framework (RDF) data model, the BrickSchema represents knowledge as a graph expressed as tuples of subject-predicate-object. Several high levels concepts are defined as the scaffolding for Brick's class hierarchies, centred on Point, surrounded by Equipment, Location and Resources, as shown in Figure 4. Point class, designed to represent points in BMS, indicates physical or virtual entities that generate time-series data. The relationships between these specific BMS points and relevant equipment the point belongs to or areas with various granularities the point is located or a part of, help characterise the way the buildings systems and embedded equipment works and their impacts on different areas in the building. In terms of the submetering hierarchy, the utility meter and its connection with primary and secondary submeters can be modelled using BrickSchema. Further, the topological and systematic hierarchies and their dependencies with each meter/submeter can be represented as well, assisting the interpretation of energy usage dynamics and corresponding influencing factors (e.g., occupancy).

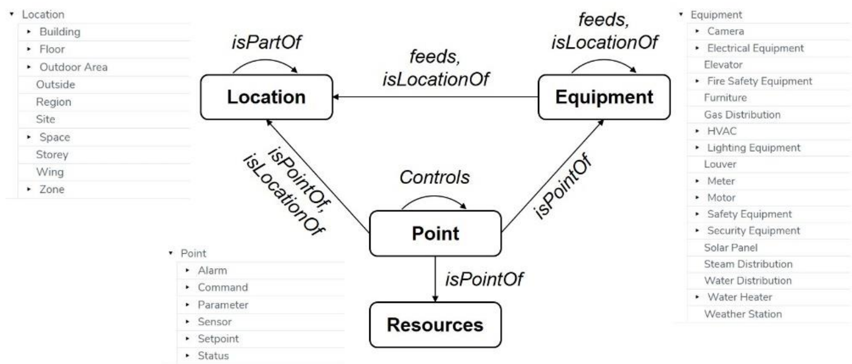

**Figure 4.** Class hierarchies defined in BrickSchema

## 3.3 Querying knowledge from data schemas

The spatial hierarchy of the building and its components can be accessed through the IFC schema. The minimum level of spatial representation is allowed by the *IfcSpace*. The *IfcSpace* contributes to the definition of the geometry and topological structure of the building spaces, composed of the following sequence: *IfcSpace*/*IfcBuildingStorey*/*IfcBuilding*/*IfcSite*/*IfcProject* in IFC4 ADD2 TC1. The hierarchy can be accessed through the inverse relationships *Decomposes* and *is DecomposedBy* that allow respectively to access the spatial elements with an increasing level of details (from *IfcProject* to *IfcSpace*) and the reverse. To access the location of the spaces, the direct attribute *Representation* can be used. This attribute allows accessing the data need to locate and represent the space in the local Coordinates Reference System (CRS). The objects contained in the spaces of the building can be accessed by adopting the same approach. The IfcOpenShell Python software library (https://github.com/IfcOpenShell) offer useful tools for querying and processing the IFC schema.

Concerning the BrickSchema, applications may query the graph for entities like zones, spaces, or equipment, which are measured by a specific submeter. This enables a zoomed-in view for a granulated part of the studied building, helps to clarify the dynamics behind the energy use within that part and further supports decision making in energy-saving. In this case, the SPARQL tool can be used to specify constraints and patterns of triples, returning entities and relationships that match the specification.

## 4 Case study

The proposed data modelling approach is applied to the Alan Reece building at the University of Cambridge, demonstrating its role in supporting the designed hierarchical building energy analytical framework. The Alan Reece building (Figure 5) is a three-story building sitting at the West Cambridge site of the University and it stands over a 40,000 square foot comprehensive area. It includes spaces with different uses, including study, office, research, laboratory, canteen, etc. The Building Management System (BMS) is deployed in the building, which accumulatively collects building-scale data from the mechanical and electrical systems (Lu et al 2020). To implement the designed submetering strategy in the Alan Reece building, the LV panel and associated distribution boards are provided with intelligent Modbus electricity meters. These gather the meter information in its most accurate form as the data is being read directly from the meter. A total number of 28 electricity meters are deployed, with 3 of them left as spares. The utility meter is used to quantify the total income energy from the grid, and the other submeters measure the energy hierarchically delivered to lighting, power and plug panels, and HVAC equipment, respectively. This provides an opportunity to interpret the effect of particular factors on dedicated energy usage, such as the influence of occupancy on power and plug consumption.

The spatial hierarchy of the building can be accessed through the IFC data, according to the approach explained in the methodological section. To support BIM-based energy analysis, the metered zones have been modelled as *IfcZone*, grouping multiple *IfcSpaces.* Figure 5a represents one submetered zone (2D and 3D view), while Figure 5b shows the 3D view of one of the spaces

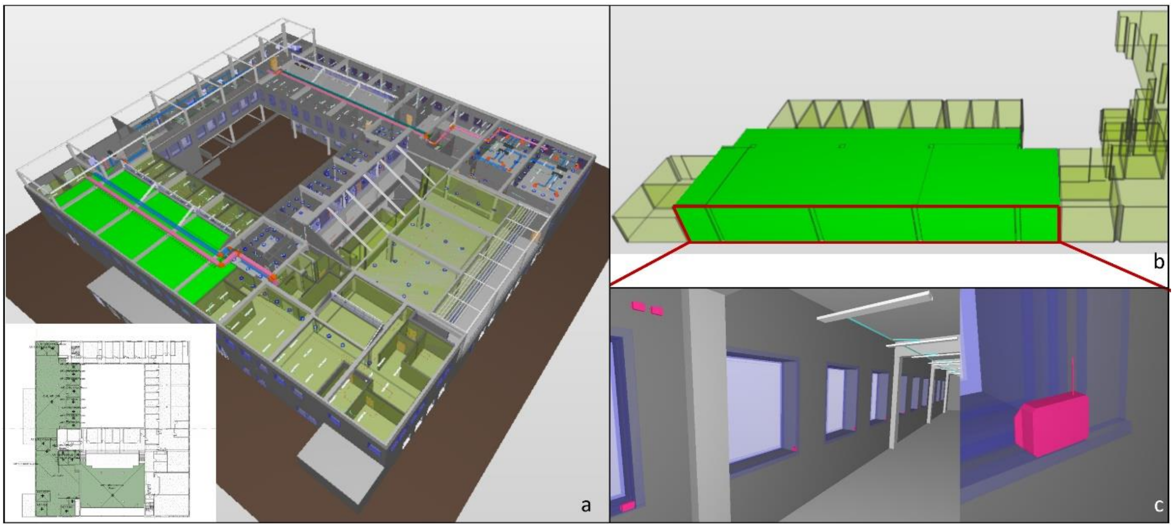


**Figure 5.** IFC model of the case study building. (a) 2D and 3D view of the submetered zone; (b) 3D view of the sample space; (c) Modelled sensor within the sample space.

(solid fill) among those composing the zone (transparent fill). The *IfcSpace* is the minimum spatial entity that can be modelled, and is the class that relates the IFC data model and hierarchies to the Brick ontology. The *IfcSpace*, in fact, is not only directly related to the *IfcZone* measured through the sub-metering strategy, but also allows to locate, represent and query the metadata of the sensing points used for collecting the real-time contextual data (e.g. indoor comfort parameters) and the performance of the systems (e.g., room temperature, operation status of some components, light intensity, etc.). Figure 5c represents the sensors, modelled in IFC as *IfcSensor* in one of the spaces of the sample zone. Spaces and sensors are both inheriting attributes from the *IfcProduct*, that allow to locate and represent the objects in the space. The location of the *IfcSensor* can be accessed through its ObjectPlacement direct attribute.

IFC is not sufficient to exhaustively describe many electrical or mechanical building components, especially those without explicit reference to the geometry. The electrical meters in the submetering system, typical components under this category, are represented using BrickSchema in this case study. The submetering architecture consists of a utility meter, 19 submeters at the primary level and 7 submeters at the secondary level. It requires the following relationships to be represented in the Brick graph: utility meter *feeds* primary submeters, primary submeters *feeds* secondary submeters, *Energy_Zone* and *Lighting_Zone isLocationOf* primary and secondary submeters, *Space isPartOf Energy_Zone* or *Lighting_Zone*, *Energy_Zone* and *Lighting_Zone isPartOf Storey*. As shown in Figure 6, Brick simplifies the integration between the submetering system and various types of zones in the building and makes it easy to retrieve necessary information for the analytical framework in a few simple queries.

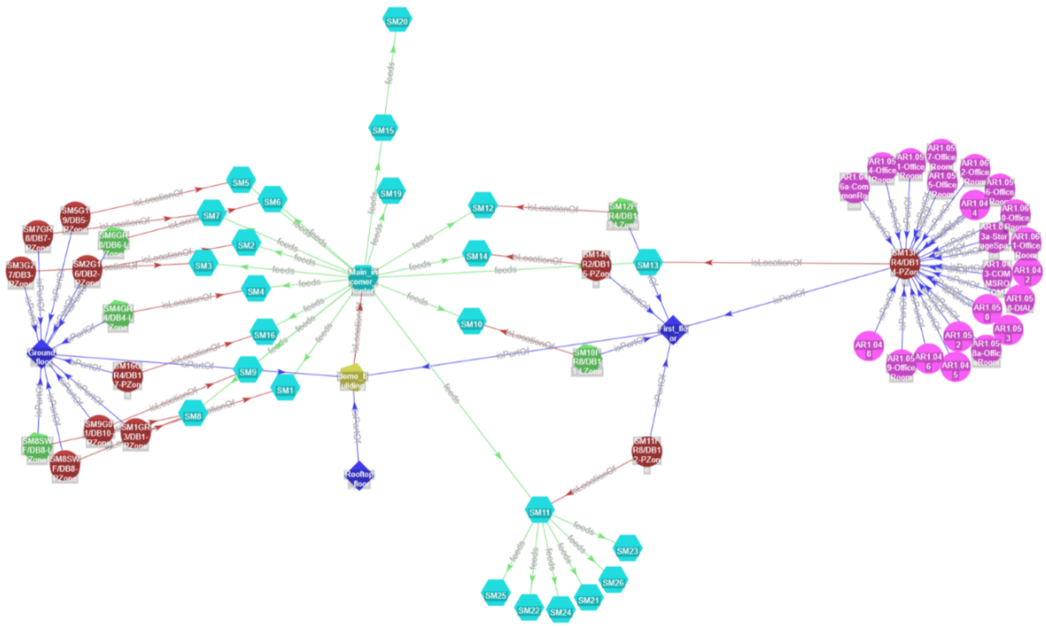

**Figure 6.** Brick model of the submetering strategy in the case study building

A simple example is made to show the role the complementary models play in supporting the hierarchical building energy analytical framework. To investigate the energy consumed by the general power and plug usage in the studied building, the submeters measuring the power and plug loads are searched through the Brick model. Figure 7a gives the Brick query retrieving all the submeters relevant to any power and plug panel. The query returns a total number of 11 submeters, help to splitting the entire building into 11 non-overlapping energy zones. Taking one of the submeters/zones ("*SM13*"/ "*SM13FR4/DB14-PZone*") as an example, Figure 7b shows the Brick query result for all the spaces included in the energy zone with the label "*SM13FR4/DB14-PZone*", and Figure 7c illustrates the query request through IfcOpenShell for all the sensors located in an open office space "*AR1.058-DIAL*" within this zone.

In summary, using this data integration approach, the studied building can be hierarchically classified into several zones and the corresponding submeters that reflect the energy usage patterns in fine spatial granularity. Sensors and other data points located within the spaces

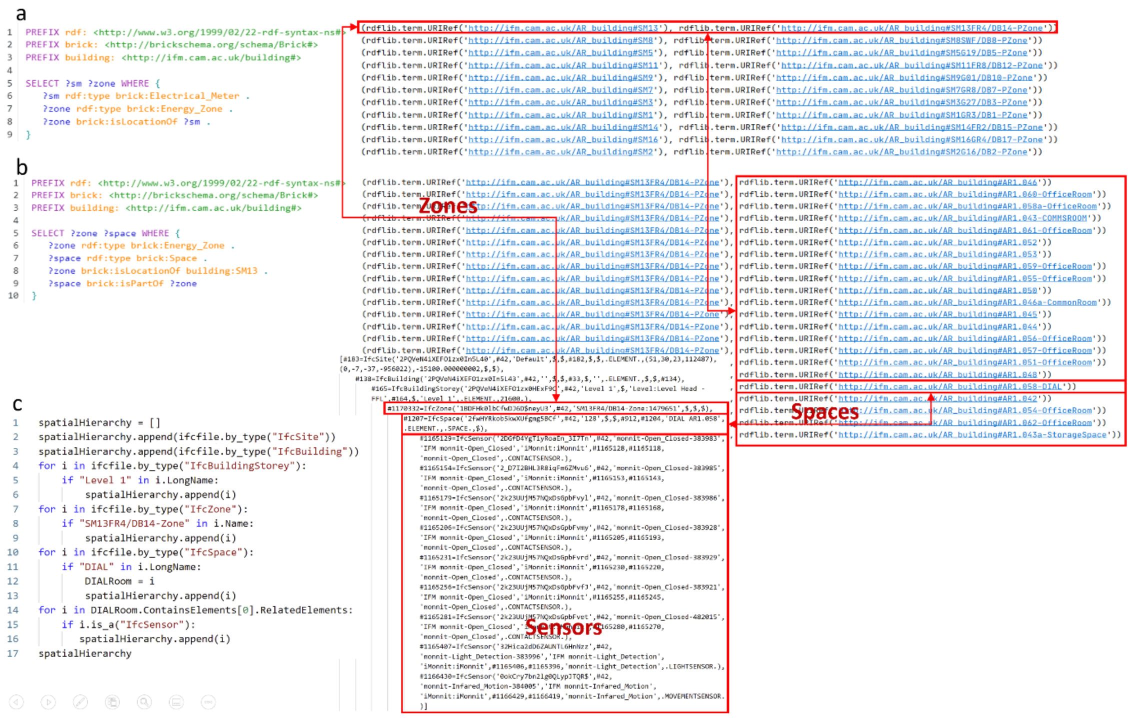


**Figure 7.** Knowledge extraction for supporting the hierarchical building energy analysis

included in the zone can be associated with the submetering readings for the building energy analysis, providing a better interpretation of the energy dynamics, and supporting better-informed decision-making under the defined framework.

## 5 Discussion and conclusion

Refined and hierarchical building energy analysis contributes to a better understanding of the complicated energy flow in buildings. Particularly, the adoption of the submetering strategy helps characterise fine-grained energy consumption in partitioned zones and for specific end-uses. In this process, IFC and BrickSchema work in a complementary manner, allowing the federation of spatial and semantic information. Both geometries, topological hierarchical and systematic connection relationships can be represented at diverse levels of abstraction, compatible for incomplete as-built data and supporting updates up to the availability of inspections. Through achieving effective hierarchical representation of buildings and easier query of the metadata, further insights into the building energy dynamics are gained, guiding the building energy conservation. Different approaches for achieving similar objectives exist in the literature. For example, the IFC dataset could have been converted to ifcOWL. However, this could prevent the federation capabilities of the adopted data modelling approach, reducing the flexibility, and the extensive representation of IFC and Bricks in their own domains.

The proposed approach is expected to bring substantial change to the current information management process. Participants involved in different stages along the building lifecycle could follow a coherent way to produce and manage spatial and semantic information, which lays a solid foundation for the development of Digital Twin (DT). Further evidences are needed to verify the capability of the federated ontology in representing diverse information in buildings. And more case studies and energy-related applications will be conducted, to validate the interoperability, robustness, and applicability of the proposed approach.

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