2022 European Conference on Computing in Construction
Ixia, Rhodes, Greece
July 24-26, 2022

TOWARDS SEMANTIC INTEROPERABILITY FOR DEMAND-SIDE MANAGEMENT: A REVIEW OF BIM AND BAS ONTOLOGIES

Flávia de Andrade Pereira[1 2], Conor Shaw[1], Susana Martín-Toral[2],
Jose L. Hernández[2], Roberto Sanz Jimeno[2], Donal Finn[1], James O'Donnell[1]
[1]School of Mechanical & Materials Engineering and UCD Energy Institute,
University College Dublin, Ireland
[2]CARTIF Technology Centre, Energy Division, Spain

Abstract

Integration between Building Information Modelling (BIM) and Building Automation Systems (BAS) can provide valuable, accurate and real-time data and control for context-aware Demand-Side Management (DSM). Despite recent efforts to enable smart, efficient and grid-interactive buildings leveraging BIM and BAS, their interoperability remains limited. According to the literature, ontology-driven architectures provide a promising direction for enabling seamless data exchange. This review qualitatively analyses eight BIM and BAS ontologies to determine their suitability for context-aware DSM. By mitigating interoperability issues within DSM mechanisms, the use of ontologies can promote energy flexibility, environmental comfort, operational efficiency and reduced energy costs.

Introduction

The International Energy Agency (IEA) estimates that in 2040 the European Union will reduce the curtailment of renewable energy sources from 7% to 1.6% and avoid around 30 million tonnes of carbon dioxide emissions by deploying flexibility measures, such as Demand-Side Management (DSM) (Turk & Cozzi 2017). DSM refers to flexible operation strategies from the demand side that support the power grid to mitigate energy demand and generation mismatches. As the building industry accounts for 35% of the global energy demand, it points to the great potential of building-focused DSM (United Nations Environment Programme 2020). However, for DSM to be effective, building loads must be controlled in a responsive, adaptive and intelligent way, respecting local ambient conditions and occupant needs. In line with these aspects, the authors previously suggested a context-aware approach based on integrating Building Information Modeling (BIM) and Building Automation Systems (BAS) (Pereira et al. 2021). Such integration provides valuable, accurate and real-time data on building assets and energy systems, besides controlling capabilities in response to contextual conditions (e.g., grid signals, indoor temperature, occupancy status).

However, due to the heterogeneous nature of BIM and BAS data sources, their interoperability, or lack thereof, exhibits challenges for promoting context-aware DSM (Koh et al. 2017). To enable interoperability among interdisciplinary domains in the context of smart grid, the GridWise Architecture Council proposes a context-setting framework, which defines three conceptual layers: syntax, semantics, and pragmatics (GridWise Architecture Council 2008). Within the semantic layer, ontology-based architectures support shareable domain models, information exchange and logical inference, promoting data consistency, interoperability and automated reasoning capabilities (Pauwels et al. 2017). To date, due to the fragmented aspects of DSM mechanisms, there is no unified ontology solution to model contextual DSM concepts, instead there are several BIM and BAS related ontologies available.

BIM and BAS ontologies have been reviewed in previous studies for building energy applications. Quinn & McArthur (2021) proposed a qualitative and quantitative comparison between the Brick and Haystask ontologies using building datasets, accurately assessing their completeness ratio at a granular level. Pritoni et al. (2021) analysed in depth five popular ontologies, identifying their gaps and overlaps. Luo et al. (2021) investigated an alignment between standardised toolsets, including ontologies, to facilitate the exchange of information among multiple data sources. Although these studies provided detailed analysis of various ontologies, this paper proposes a first of its kind analysis of BIM and BAS related ontologies to deliver context-aware DSM.

This paper aims to provide an exploratory qualitative research method that assesses the suitability of eight BIM and BAS related ontologies for DSM from the building perspective. To achieve this, the paper is structured as follows: section 2 outlines the methodology, section 3 presents an overview of identified BIM and BAS-related ontologies, section 4 assesses each ontology, section 5 discusses the strengths and limitations of each ontology for suitability to DSM and suggests the most suitable ones, and finally, section 6 presents the concluding remarks and outlines future research directions.

Research Method

This study follows a four step methodology, including: A. Ontologies Search, B. Ontologies Assessment, C. Ontologies Comparison and D. Ontologies Selection, based on the "Data on the Web Best Practices" published by the World Wide Web Consortium (W3C) (Lóscio et al. 2017).

Ontologies Search

The search for ontologies uses the preferred reporting items for systematic reviews and meta-analysis (PRISMA) approach (Page et al. 2021) for identification, screening and selection of papers. Due to the emerging nature of ontologies in building energy applications, only publications in the last 5 years are deemed suitable for this study. The academic literature is identified in the Scopus academic database with the query string *(ontology OR (metadata AND schema) OR semantic web) AND (BAS OR smart building OR BIM) AND (interoperability AND energy))* applied to the title, abstract and keywords. The white papers are identified through expert search using the CORDIS EU research platform for the H2020 programme and the ongoing activities of the Cloud-BIM European Training Network on semantic web technologies.

The screening stage analyses the title and abstract of the papers, excluding resources that: are not related to BIM and BAS domains, are tools and frameworks rather than ontologies or do not possess public repositories (e.g., the Live Web Ontology Language (OWL) documentation environment (LODE)). While performing the eligibility stage, additional ontologies named by the papers were identified and included in the study, following the snowball sampling methodology (Goodman 1961).

Overall, 12 out of 54 papers are reviewed in-depth, and eight of the analysed ontologies meet the eligibility criteria and demonstrate greater sufficiency to the proposed core concepts presented in the next section. Table 1 lists basic information about these eight ontologies. The following additional ontologies are also relevant to the scope of this paper, but they are not eligible or less suitable for the predefined concepts: real estate core, google digital buildings, smart energy aware systems and building automation and control systems.

Ontologies Assessment

For the ontologies assessment, the semantic descriptions from the identified eligible and most representative BIM and BAS ontologies are mapped against predefined core concepts to support context-aware DSM services. These core concepts have been synthesised based on previous research conducted in this area (Luo et al. 2021, Pereira et al. 2021, Li et al. 2020, Marinakis & Doukas 2018). Similar to the concept classification approach proposed by (Pritoni et al. 2021), this work proposes 6 categories:

- **Spatial information**: basis for spatial context awareness, including physical characteristics (floor area, geometry, orientation), envelope elements (types and properties), occupancy profile (number of occupants and schedule), and functional topology (storeys, spaces and zones relationship within a building).
- **Building energy systems**: basis for BAS modelling and specification, including HVAC equipment (e.g., chillers, boilers, cooling towers), lighting components (light fixture, driver, switch), appliances (plug-in office equipment and household equipment), renewable energy sources (solar thermal collector, solar photovoltaic panel), and manufacturer information (rated power, capacity and efficiency).
- **Control and topology**: basis for BAS sensing, actuation and control, including points (physical - sensor and actuator, virtual - setpoint of controllable variables), control strategies (schedule and conditional statements), operational relationships (relationship between building energy systems and building topologies), and control relationships (relationship between control, sensor and actuators, building energy systems and building topologies).
- **Measurement setup**: basis for timeseries data analysis and metering functions, measurement systems (physical quantities, units of measure and timestamp), spatial resolution (building, spaces and zones), end-use resolution (HVAC, lighting, appliances).
- **Measurable properties**: basis for energy and environmental analysis, including energy consumption/demand (electricity and natural gas), onsite power generation (solar photovoltaic), occupancy status (occupied / unoccupied state), outdoor weather conditions (temperature, humidity, solar radiation, precipitation, CO_2), indoor conditions (temperature, humidity, air velocity, illuminance level, CO_2).
- **Grid-interactivity**: basis for communication to utility providers and DSM control modelling, including utility rates (price signals), grid signals (request events) and DSM model (load control, shedding command, demand setpoint).

Ontologies Comparison

Based on the metadata quality metrics introduced by (Ochoa & Duval 2009), each ontology is compared by the degree to which they present the core concepts needed to have a semantic sufficiency to deliver context-aware DSM functionality. This *completeness ratio* is computed as the sum of the conceptual degree represented by each ontology divided by the total number of concepts needed within a category, as in the following equation (1).

$$com = \frac{\sum_{i=1}^{N} D(i)}{N} \tag{1}$$

where N is the number of concepts within a category and *D(i)* is 1 if the i-th category defines (at some level) all the aforementioned concepts, 0.5 if at least one concept is defined, and 0 otherwise. These three discrete values are assigned to each ontology to determine whether it offers full support, partial support, or no support to that category.

Ontologies Selection

After comparing the eight identified ontologies, the most suitable ones for context-aware DSM services are selected. This selection follows the semantic web best practices 15 and 16 proposed by the W3C (Lóscio et al. 2017), which

Table 1: List of the eight ontologies identified for representing BIM and BAS information

Name	Maintainer	Repository
Haystack	Project Haystack Corporation	project-haystack.org/
Brick	Brick Community Group	brickschema.org/ontology/
ifcOWL	buildingSMART alliance	standards.buildingsmart.org/IFC/DEV/IFC4$_1/OWL/$
BOT	W3C Linked Building Data Community Group	w3c-lbd-cg.github.io/bot/
SSN/SOSA	Spatial Data on the Web Working Group	w3c.github.io/sdw/ssn/
SAREF	European Telecommunications Standards Institute	saref.etsi.org/
RESPOND	Respond Project Consortium	respond-project.github.io/RESPOND-Ontology/respond/index-en
OpenADR	Delta Project Consortium	w3id.org/def/openadr#

recommend the choice of the appropriate level of formalisation for fitting data requirements, and the reuse of ontologies (preferably the standardised ones) for promoting interoperability. Thus, those ontologies with higher completeness, reuse of concepts and semantic consistency, and lower complexity, compatibility and ambiguity problems are selected. In addition, those maintained by a competent authority, such as a government agency, standards body, or recognised dedicated consortium, are prioritised.

BIM and BAS-related Ontologies

Haystack and **Brick** are leading open-source initiatives that aim to improve interoperability between smart building applications. Due to its simplistic approach to define semantic building metadata by adding simple descriptive tags, Haystack has been widely adopted by the industry (Quinn & McArthur 2021). As **Haystack 4**, it has been elevated to a formal ontology using RDF, RDFS, and OWL statements (*docHaystack Project Haystack* 2021). Based on OWL ontology, **Brick v1.2** extends the Haystack tag-oriented approach, providing a comprehensive and extensible formalised vocabulary to represent physical, logical and virtual assets and their associated semantic relationships (Fierro et al. 2020). For representing BIM concepts, the **ifcOWL** has been introduced offering formal explicit semantics to the Industry Foundation Class (IFC) data schema (Pauwels & Terkaj 2019). Also centred on building concepts, the building topology ontology (**BOT**) acts as a core ontology that represent basic topological concepts of a building (Rasmussen et al. 2021). Dedicated to sensors and actuators concepts, the Sensor, Observation, Sample, and Actuator (**SOSA**) ontology, along with the Semantic Sensor Network (**SSN**) ontology, model observations, procedures, features of interest and samples using OWL statements (Haller et al. 2021). Focused on smart appliances, systems, meters and spaces, the smart applications reference (**SAREF**)(Daniele et al. 2020) and its extensions for building domain (SAREF4BLDG), energy domain (SAREF4ENER) and system domain (SAREF4SYST), enable interoperability among internet of things (IoT) solutions. Among the DSM-driven ontologies, there are the integrated demand response solution towards energy positive neighbourhoods (**RESPOND**) and the open automated demand response (**OpenADR**) ontologies. As a modular OWL ontology, **RESPOND** primarily reuses existing ontologies for representing building information, device concepts and properties, offering an interoperable and user-centred solution for demand response programmes (Esnaola-Gonzalez et al. 2018). Built upon the OpenADR standard, the **OpenADR** OWL ontology aligns with existing ontologies to define events, signals, schedule, resource and asset, promoting the communication of demand response signals from utilities to customers (Fernández-Izquierdo et al. 2020).

Results

Core Concepts Assessment

In this section, the scope of each ontology concerning the core concepts from section 3 is explored in depth. While each ontology has a specialty, all provide a certain level of alignment for representing BIM and BAS-related concepts, as demonstrated in Figure 1.

Spatial information

Haystack ontology models buildings, floors, rooms and logical system-oriented zones and defines their relationships using tags. Each zone can model occupancy using setpoints for the schedule, and can display their floor area. In **Brick**, a set of location classes representing buildings, storeys, zones and spaces can model their properties such as area and volume, as well as topological relationships. Besides the classification of logical system-oriented zones for heating, cooling, or lighting requirements, Brick can also define zones based on occupancy category and density. As in Haystack, Brick does not model envelope core concepts such as windows and walls. **ifcOWL** offers a rich set of classes to define the physical characteristics and envelope elements of a building, besides occupancy profiles per spatial zone. ifcOWL uses aggregation to determine spatial topology through relationships between sites, buildings, storeys and spaces. **BOT** models site, building, storeys, spaces and zones, and defines their relationship using containment, adjacency and interface attributes. Neither physical characteristics nor occupancy are defined in BOT. **SOSA/SSN** ontologies rely upon external schemas for spatial information. In **SAREF**, spatial information are modelled using the SAREF4BLDG and SAREF4SYST extensions. They include building, space and zone concepts

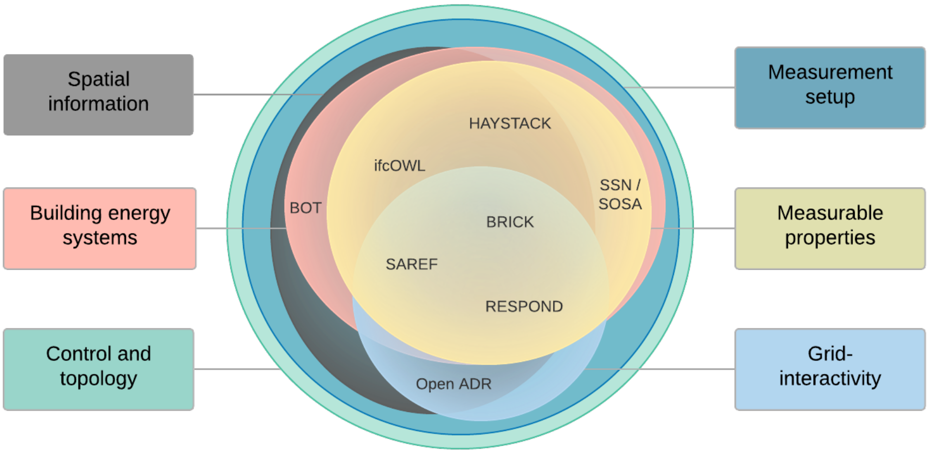


Figure 1: Conceptual overlap between the eight ontologies for modelling the DSM core concepts within the 6 proposed categories.

and model their relationship and adjacency using containment relations and system connections. As the main focus of SAREF is on device, rather than space, the remaining core spatial concepts are omitted. **RESPOND** ontology reuses BOT concepts to represent functional topology in a household and adds new concepts to determine their area and volume. RESPOND defines the usage of a space using the occupancy class, but it does not include building envelope information. **OpenADR** is limited to geospatial and geometry concepts from GeoSPARQL.

Building energy systems

Haystack ontology defines physical assets for HVAC (e.g., air handling unit, boiler) and lighting systems, as well as logical grouping of assets such as chiller water plant. In addition, using tags Haystack models manufacturer information (cooling capacity rate). In **Brick**, the equipment and system classes model energy systems similar to Haystack, but include additional concepts for lighting (e.g., dimmer and driver), renewable energy sources and other appliances. Adopted from Haystack, Brick also defines the nominal cooling capacity. **ifcOWL** includes a comprehensive list of classes to model HVAC and lighting components including fan, pumps, lamps and switch devices, in addition to office and household appliances, and renewable energy sources (solar panels). As for manufacturer parameters, ifcOWL properties express cooling and fan capacities. Building energy systems are not evidently represented in **BOT**, but its element and sub-element classes can partially represent physical parts of equipment, such as heaters and lights. The system, subsystems and property classes of the **SOSA/SSN** ontologies can model building energy systems and represent their intrinsic aspects. In **SAREF**, building energy systems, such as HVAC, lighting and renewable solutions can be modelled combining the classes available from the core and its extension ontologies. In addition, SAREF also allow each device to capture intrinsic properties, namely model and manufacturer information (e.g., nominal efficiency, capacity and power rate). The **RESPOND** ontology reuses the device and appliance classes from SAREF to define a comprehensive set of household equipment and appliances. RESPOND also adds new concepts for renewable energy sources such as thermal solar and photovoltaic systems, but it does not include manufacturer information. The **OpenADR** ontology does not model building energy systems.

Control and topology

The entity points in **Haystack** represent the so-called hard points which refer to sensors (inputs) and actuators (outputs and commands), and soft points which refer to setpoints. Although Haystack offers to model schedules as a normal target point within the setpoint tag, it does not appear to align the schedule with control logic. Haystack also defines how points, equipment and spaces are related to one another using physical and logical containment relationships, as well as flow relationships. **Brick** includes a class for points which represents a variety of data sources such as sensors, commands, alarms, setpoints and parameters. This point class can also represent control strategies, such as schedule temperature setpoint. Brick establishes a topological relationship between controllers, equipment and devices, representing the flow of a given substance within a system. In addition, Brick can capture the relationship between equipment and spatial elements of a building (e.g., zones fed by a given HVAC system). Although **ifcOWL** is quite complete with respect to equipment definitions, points, and spatial and distributed relationships using containment attributes, it lacks the capability of modelling control strategies. Using the element class, **BOT** can model a sensor, but the definition of points such as setpoints, commands or alarms are not within its scope. Even so, the containment and adjacency attributes in BOT can represent the relationship between defined elements and zones. **SOSA/SSN** ontologies define sensors and actuators as their core concepts, defined as subclasses of a system. SOSA/SSN does not directly model setpoint and alarms, but these concepts may be defined using the property class. SOSA/SSN models procedures to define observation, sampling and actuation workflows within a system based on features of interest. SOSA/SSN classes and properties can exhibit relationships between sensors, actuators and their related systems and hosting platforms (e.g., location). The core ontology of **SAREF** defines sensors, actuators and their functions (commands) and states (e.g. on-off state, multi-level state). Using the set level command, SAREF also allows level (point) adjustments. SAREF4BLDG defines control strategies and controller concepts, but it lacks the concept of schedule. SAREF4BLDG uses the containment class to model the relation between a physical space and the objects encapsulated in that space, while SAREF4SYST models the connections of control devices using the connection point class. The alignment with SAREF and the addition of new concepts allows **RESPOND** to define sensor and actuator classes, temperature setpoint, as well as commands such as event function, state condition and level control. Using the relation *subclass of* and other properties, RESPOND can define operational and control relationships. In **OpenADR**, the concept of points is used to model load control setpoints and other demand response related setpoints, but no sensor or actuator devices are included. In terms of control strategies, OpenADR provides instructions (signals) for load controllers to operate at given levels, and schedule functions for the operation of defined targets (entities). OpenADR also defines a set of relations between targets, assets and resources, which may be used for partially modelling operational and control relationships.

Measurement setup

Haystack models units of measure, real-time values and historical records of timestamp/value pairs. Haystack also defines meters, submeters and their relationships, including equipment, point loads, space and end-use references. **Brick** includes timeseries storage properties and a measurable class which represents quantity as an observable property and substance. To represent specific instance units, Brick is aligned by default with the Quantities, Units, Dimensions, and Types (QUDT) ontology. Brick uses the *regulates* relationship to determine the metric of usage by equipment domain. **ifcOWL** models timeseries data types, including physical quantity and units of measure, but it does not seem to include metering resolution with respect to space or end-use. Metering concepts can be represented in **BOT** using the interface property which defines the relationship between elements and zones. BOT does not represent measurement concepts, requiring another ontology for the purpose. **SOSA/SSN** includes classes to represent timeseries data in the form of observations, actuations and samplings from devices. For defining units of measurement, SOSA/SSN should be aligned with another ontology. SOSA/SSN ontologies do not cover metering concepts for both spatial and end-use resolutions. **SAREF** models measurement concepts to describe a physical quantity including the value, timestamp properties and *unit of measure*. SAREF also includes a metering function used to measure a given property, which may be related to an end-use and a space. **RESPOND** also reuses the SAREF and QUDT ontologies to define property quantities, units of measurement and timestamps. Based on the *relation* subclass of and given *properties* relationships, RESPOND seems to be able to relate metering functions with particular spaces. In addition, the RESPOND ontology has a *function related* class which allows group measurements by end-use systems. **OpenADR** includes temporal entities and reuses the unit of measure classes from the Ontology of units of Measure (OM) to model data measurement, but it does not offer spatial and end-use resolution from the building perspective.

Measurable properties

Haystack offers a vast array of measured quantities, from electrical and thermal flows, occupation state, weather station observation points, and indoor temperature and illuminance levels. **Brick** can represent measured energy consumption and generation and electrical power. Brick also includes a class dedicated to a weather measurement station, and has a variety of sensors to detect temperature, humidity, airflow, illuminance and CO_2 measures. **ifcOWL** classes define energy and gas consumption, power generation, occupancy status, outdoor and indoor conditions. **BOT** does not model measurable concepts, and needs to be used in conjunction with another ontology. The *result* class of **SOSA/SSN** stores an observation, sampling and actuation value associated with an observed property, such as energy, temperature and humidity. In the core ontology of **SAREF**, the *property* class can characterise measurement values and sensed data for energy, power, occupancy, temperature, humidity and light. **RESPOND** ontology is used together with SAREF and Smart Energy Aware Systems (SEAS) to represent properties such as energy consumption and production, power, occupancy and temperature. **OpenADR** does not model energy and environmental-related measurable qualities.

Grid-interactivity

The **Haystack**, **ifcOWL**, **BOT** and **SOSA/SSN** ontologies do not include concepts to support grid interactivity commands and services. **Brick** defines classes that can be leveraged for DSM control modelling and customer preferences, including demand, deadband and load shed setpoint, as well as load shedding commands. **SAREF** extension for energy (SAREF4ENER) can model smart energy management to schedule appliances in certain modes, preferred periods and associated prices, using power profiles that can optimise energy use and cost and accommodate customer preferences. SAREF4ENER also includes load control and event classes that can model actions to be performed under grid requests based on incentives, prices or emergency scenarios. The **RESPOND** ontology is aligned with some of the SAREF4ENER entities for modelling demand response scenario. Nevertheless, at the time of writing this paper, RESPOND does not include classes to model the interaction between the utility grid (or aggregators) and the end-user. Finally, the **OpenADR** ontology defines concepts to support energy curtailment request events, utility price signals, load control signals (e.g., controller setpoints, levels and capacity), state of resources reports, registration of parties involved in the interaction, and availability schedule.

Completeness Comparison

From the in-depth analysis of the scope of each ontology, its degree of support for the core concepts proposed is evaluated using the metric of the completeness ratio. The maximum value of this metric is 1, in the case of full support where all the concepts are defined by the ontology, the minimum value is 0, in the case of no support from the ontology to define needed concepts, and a value of 0.5 is applied in the case of partial support where at least one concept is defined by the ontology (Figure 2). It is important to note that the level of completeness does not represent the level of granularity but rather the ability of the ontology to broadly represent a given concept.

According to the levels of support established for the required concepts, Figure 3 displays the resulting weighted-completeness ratio for each ontology in relation to the 6 categories. The greater the completeness ratio, the larger the number of semantic concepts being represented by the ontology and the lower the need for custom semantics definitions to accurately model a DSM mechanism. The results indicate the most comprehensive ontologies as being SAREF, ifcOWL, Brick and RESPOND, respectively. The ifcOWL ontology is the most complete for representing spatial information and measurable properties, sharing this result with Brick for the latter category. SAREF offered greater semantics for building energy systems and metering setup. The Brick and SAREF ontologies had the best results for control and topology. Finally, openADR is the best suited for grid-interactivity representation.

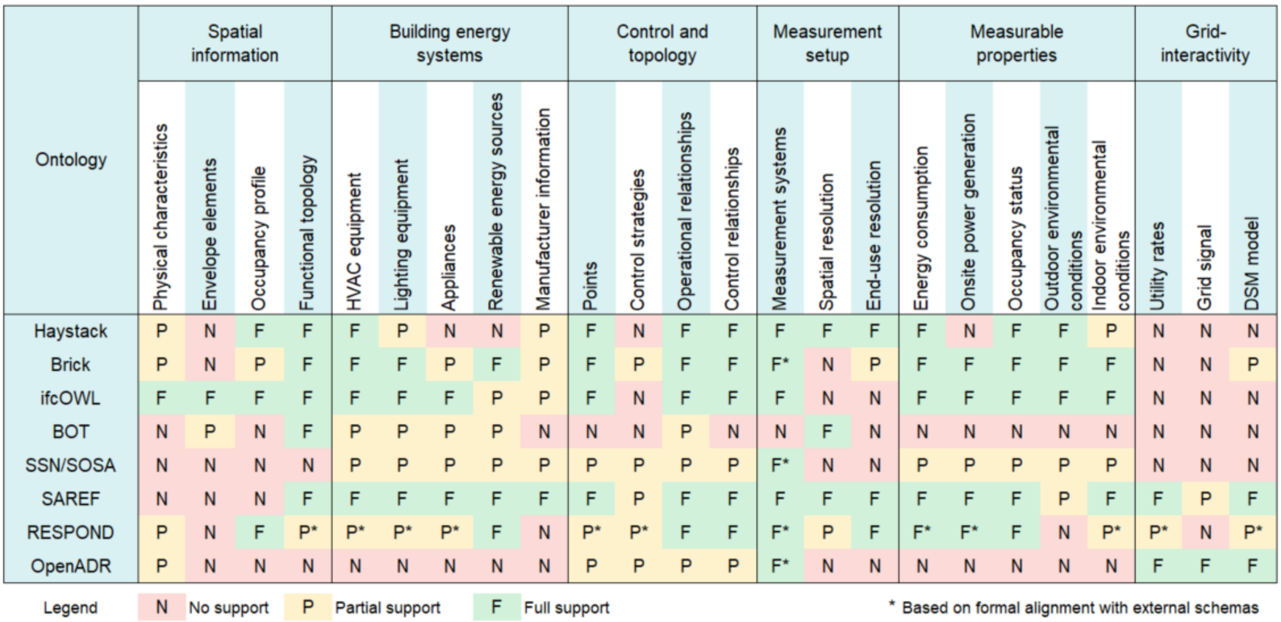
Discussion

Overall, this review shows that each ontology has different levels of completeness depending on its main purpose and that all ontologies share overlapping concepts having a certain degree of built-in interoperability. This study also reveals that there is no one ontology that can model all concepts required by context-aware DSM services. Therefore, and because a modular ontology approach is advised, it may be necessary to integrate suitable existing ontologies. However, since maintenance and updating vary by ontology in terms of rate and procedures, as noted by (Pritoni et al. 2021), it can be challenging to sustain a model that combines multiple ontologies. Taking into account that DSM is applied to meet critical grid needs (Potter et al. 2018), integrating cross-domain stakeholders and affecting power and thermal grid reliability and stability, a trade-off is desired to define the most appropriate ontologies. One should select a minimum number of ontologies while increasing their combined level of completeness. Other aspects must also be considered in this selection, such as the reuse of concepts, semantic coherence, compatibility, complexity and ambiguity issues, and the support of the competent authority against initiatives of fixed duration.

Dedicated to DSM concepts, the RESPOND and OpenADR ontologies can be seen best suited to represent DSM building energy dispatch and enable automated demand response events, respectively. However, although the European Commission finances both the RESPOND and OpenADR projects, the consortia that maintain them have a contractual project life cycle whose continuity is uncertain. This fact differs from other ontologies with a dedicated consortium community to support them, which are prioritized in this study.

While Haystack is capable of modelling most of the concepts required in this study, its ontological descriptive aspects are still in the early stages, limiting its inferential potential and interoperability. In addition, its excessive level of flexibility and non-standardised use of semantic concepts by instantiated schemas leads to compatibility issues even between different Haystack models (Luo et al. 2021, Quinn & McArthur 2021). ifcOWL, on the other hand, although a standard-based one, brings other issues into place. Due to its large set of incomplete and ambiguous concepts and adopted top-down approach, which covers the entire structure of a building, ifcOWL is considerably complex to handle (Bonduel et al. 2018). To address this, while leveraging the information offered by IFC, the ifcOWL schema can be converted into modular ontologies such as BOT. BOT provides a rich functional building topology but neglects critical BAS-related concepts lacking completeness. Although the industry extensively uses SSN/SOSA to represent observation, sampling, and actuation concepts, other ontologies, as Brick and SAREF, support these concepts. Thus, the use of SSN/SOSA may not be necessary.

Compared to the other ontologies, Brick offers a more comprehensive formal structure, providing more consistent semantics needed to capture operational aspects, especially for HVAC applications (a critical asset for DSM from the building viewpoint). In addition, Brick can comprehensively model crucial spatial awareness concepts for DSM. These modelling capabilities from Brick, combined with those from the SAREF ontology, can significantly contribute to achieving semantic interoperability for DSM services. SAREF has proven a reference ontology to promote interoperability between several standards within the DSM domain (Strabbing et al. 2019) and has shown in this study the highest degree of support between the eight analysed ontologies. Nevertheless, SAREF only captures high-level aspects of building energy systems and BAS controls; as such, Brick would strengthen the ability of



Ontology	Spatial information				Building energy systems					Control and topology				Measurement setup			Measurable properties					Grid-interactivity		
	Physical characteristics	Envelope elements	Occupancy profile	Functional topology	HVAC equipment	Lighting equipment	Appliances	Renewable energy sources	Manufacturer information	Points	Control strategies	Operational relationships	Control relationships	Measurement systems	Spatial resolution	End-use resolution	Energy consumption	Onsite power generation	Occupancy status	Outdoor environmental conditions	Indoor environmental conditions	Utility rates	Grid signal	DSM model
Haystack	P	N	F	F	F	P	N	N	P	F	N	F	F	F	F	F	F	N	F	F	P	N	N	N
Brick	P	N	P	F	F	F	P	F	P	F	P	F	F	F*	N	P	F	F	F	F	F	N	N	P
ifcOWL	F	F	F	F	F	F	F	P	P	F	N	F	F	F	N	N	F	F	F	F	F	N	N	N
BOT	N	P	N	F	P	P	P	P	N	N	N	P	N	N	F	N	N	N	N	N	N	N	N	N
SSN/SOSA	N	N	N	N	P	P	P	P	P	P	P	P	P	F*	N	N	P	P	P	P	P	N	N	N
SAREF	N	N	N	F	F	F	F	F	F	F	P	F	F	F	F	F	F	F	F	P	F	F	P	F
RESPOND	P	N	F	P*	P*	P*	P*	F	N	P*	P*	F	F	F*	P	F	F*	F*	F	N	P*	P*	N	P*
OpenADR	P	N	N	N	N	N	N	N	N	P	P	P	P	F*	N	N	N	N	N	N	N	F	F	F

Legend N No support P Partial support F Full support * Based on formal alignment with external schemas

Figure 2: Comparative analysis on the completeness of the scope for each ontology disregarding their level of granularity.

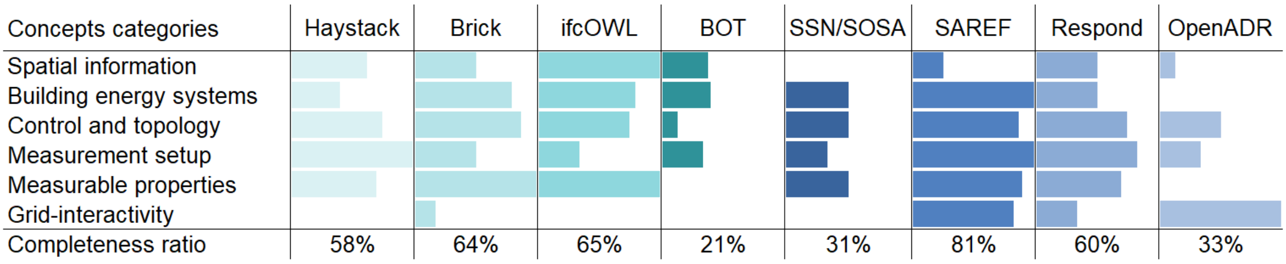


Figure 3: Completeness results of each ontology against the core concepts categories disregarding their level of granularity.

SAREF to optimise and manage HVAC related assets for DSM. Therefore, based on the strengths and limitations of each ontology, their combined level of completeness and the proposed ontology selection criteria, out of the eight ontologies: Brick and SAREF ontologies have aspects that are most suitable for context-aware DSM services.

A limitation in this proposed set of ontologies is that the completeness ratio used as one of the selection criteria depends on the predefined core concepts. While the results of this study provide a comprehensive view of DSM concepts, specific applications may require particular semantic and conceptual requirements, affecting the suggested selection. Consequently, there may be exceptions to the proposed ontologies, and their suitability must be validated by implementing them for different use cases.

Conclusions

Context-aware approaches can drive the adoption and performance of DSM services on the client-side, improving energy flexibility, efficiency, operating costs, and environmental comfort with intelligent, adaptive, and responsive control strategies. The integration of BIM and BAS has the potential to enable these strategies, providing relevant information about building assets and allowing buildings to operate in response to contextual conditions. Achieving seamless interoperability among these domains can be significantly supported by using ontology-driven architectures. This study reviews in-depth eight ontologies demonstrating that a modular ontology approach based on the Brick and SAREF ontologies would be the most suitable solution to deliver context-aware DSM. This outcome provides a practical direction for future research, including the specification of well-defined conceptual requirements to capture given use cases, harmonisation of the selected set of ontologies to support such requirements, and exploration of standards-centric approaches that can ensure scalability of context-aware DSM applications.

Acknowledgments

This work was supported by the CBIM-ETN funded by the European Unions Horizon 2020 research and innovation programme under the Marie Skodowska-Curie grant agreement No 860555.

References

Bonduel, M., Oraskari, J., Pauwels, P., Vergauwen, M. & Klein, R. (2018), 'The IFC to Linked Building Data Converter - Current Status', *6th Linked Data in Architecture and Construction Workshop* p. 10.

Daniele, L., Garcia-Castro, R., Lefrançois, M. & Poveda-Villalon, M. (2020), 'SAREF: the Smart Applications REFerence ontology'.
URL: *https://saref.etsi.org/core/v3.1.1/*

docHaystack Project Haystack (2021).
URL: *https://project-haystack.org/doc*

Esnaola-Gonzalez, I., Díez, F. J., Berbakov, L., Tomasevic, N., torek, P., Cruz, M. & Kirketerp, P. (2018), Semantic Interoperability for Demand-Response programs: RESPOND projects use case, *in* '2018 Global Internet of Things Summit (GIoTS)', pp. 1–6.

Fernández-Izquierdo, A., Cimmino, A., Patsonakis, C., Tsolakis, A. C., García-Castro, R., Ioannidis, D. & Tzovaras, D. (2020), OpenADR Ontology: Semantic Enrichment of Demand Response Strategies in Smart Grids, *in* 'International Conference on Smart Energy Systems and Technologies', pp. 1–6.

Fierro, G., Prakash, A. K., Mosiman, C., Pritoni, M., Raftery, P., Wetter, M. & Culler, D. E. (2020), 'Shepherding Metadata Through the Building Lifecycle', *BuildSys 20 Conference* p. 10.

Goodman, L. A. (1961), 'Snowball Sampling', *The Annals of Mathematical Statistics 32(1),* pp. 148–170.

GridWise Architecture Council (2008), 'GridWise Interoperability Context-Setting Framework'.
URL: *https://www.gridwiseac.org/pdfs/interopframework_v1_1.pdf*

Haller, A., Janowicz, K., Cox, S., Phuoc, D. L., Taylor, K. & Lefrançois, M. (2021), 'Semantic Sensor Network Ontology W3C Editor's Draft'.
URL: *https://w3c.github.io/sdw/ssn/*

Koh, J., Ray, S. & Hodges, J. (2017), Information Mediator for Demand Response in Electrical Grids and Buildings, *in* '2017 IEEE 11th International Conference on Semantic Computing (ICSC)', pp. 73–76.

Li, Y., Rezgui, Y. & Kubicki, S. (2020), 'An intelligent semantic system for real-time demand response management of a thermal grid', *Sustainable Cities and Society 52,* p. 101857.

Luo, N., Pritoni, M. & Hong, T. (2021), 'An overview of data tools for representing and managing building information and performance data', *Renewable and Sustainable Energy Reviews 147,* p. 111224.

Lóscio, B. F., Burle, C. & Calegari, N. (2017), 'Data on the Web Best Practices'.
URL: *https://www.w3.org/TR/dwbp/*

Marinakis, V. & Doukas, H. (2018), 'An Advanced IoT-based System for Intelligent Energy Management in Buildings', *Sensors 18,* p. 610.

Ochoa, X. & Duval, E. (2009), 'Automatic evaluation of metadata quality in digital libraries', *Int. J. on Digital Libraries 10,* pp. 67–91.

Page, M. J., McKenzie, J. E., Bossuyt, P. M. et al. (2021), 'The PRISMA 2020 statement: an updated guideline for reporting systematic reviews', *British Medical Journal Publishing Group 372,* p. n71.

Pauwels, P. & Terkaj, W. (2019), 'ifcOWL ontology (IFC4x1)'.
URL: *https://standards.buildingsmart.org/IFC/DEV/IFC4_1/OWL/index.html*

Pauwels, P., Zhang, S. & Lee, Y.-C. (2017), 'Semantic web technologies in AEC industry: A literature overview', *Automation in Construction* **73**, 145–165.

Pereira, F. d. A., Shaw, C., Martín-Toral, S., Jimeno, R. S., Finn, D. & ODonnell, J. (2021), 'Building Automation System Exchange Requirements to support BIM-based Demand Side Management', *European Council on Computing in Construction* p. 8.

Potter, J., Stuart, E. & Cappers, P. (2018), 'Barriers and Opportunities to Broader Adoption of Integrated Demand Side Management at Electric Utilities: A Scoping Study', *Lawrence Berkeley National Laboratory* .

Pritoni, M., Paine, D., Fierro, G., Mosiman, C., Poplawski, M., Saha, A., Bender, J. & Granderson, J. (2021), 'Metadata Schemas and Ontologies for Building Energy Applications: A Critical Review and Use Case Analysis', *Energies 14(7)* .

Quinn, C. & McArthur, J. J. (2021), 'A case study comparing the completeness and expressiveness of two industry recognized ontologies', *Advanced Engineering Informatics 47* .

Rasmussen, M. H., Pauwels, P., Lefrançois, M., Schneider, G. F., Hviid, C. A. & Karlshøj, J. (2021), 'Building Topology Ontology: Draft Community Group Report'.
URL: *https://w3c-lbd-cg.github.io/bot/*

Strabbing, W., Stapersma, P., Roelofsen, B., Daniele, L. & Aalberts, A. (2019), *Study on ensuring interoperability for enabling Demand Side Flexibility*, European Commission and Directorate-General for Communications Networks, Content and Technology: Publications Office.

Turk, D. & Cozzi, L. (2017), *Digitalization Energy*, Organization for Economic Co-Operation and Development International Energy Agency (OECD/IEA).

United Nations Environment Programme (2020), '2020 Global Status Report for Buildings and Construction: towards a zero-emission, efficient and resilient buildings and construction sector'.
URL: *https://wedocs.unep.org/20.500.11822/34572*