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Ontologies for Observations and Actuations in Buildings: A Survey

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Abstract. The IoT allows connecting the physical world with virtual representations in various domains, and its rapid adoption lead to an exponential growth of the number of existing devices worldwide. Likewise, the amount of data generated is expected to grow accordingly. As a matter of fact it is estimated that in 2019, the IoT will generate more than 500 zettabytes in data. Without connecting all these data with its underlying semantics, the users of the Web of Things may end up in information silos thus hindering the exploitation of the data for better and smarter decisions. The main goal of this survey points towards ontologies involved in conceptualizations of observations and actuations, where the utility of that conceptualization arise when some features of interest need to be observed or acted upon. Spaces and elements in the buildings environment have emerged as platforms where materializations of such observations and actuations promise to be very profitable. For each of the reviewed ontology, their fundamentals are described, their potential advantages and shortcomings are highlighted, and the use cases where these ontologies have been used are indicated. Additionally, use case examples are annotated with different ontologies in order to illustrate their capabilities and showcase the differences between reviewed ontologies.

Keywords: Ontology, Ontology Design Patterns, Buildings, Energy Efficiency, Thermal Comfort

1. Introduction

The Internet of Things (IoT) [1] facilitates the monitoring of qualities of real world entities and events thanks to physical things equipped with electronic components and ubiquitous intelligence that allow them to connect, interact and exchange data. Furthermore, the expansion of IoT has lead to the massive amount of data available nowadays, which has the potential to enable new discoveries and improve decision making processes. It is estimated that in 2019, the IoT will generate more than 500 zettabytes in data [2]. This huge quantity of data not only represents observations or actuations generated by potentially billions of devices, but also describes related aspects including devices themselves, the location of these devices, and the context under which the qualities of a feature of interest are observed or acted on. Without connecting all these data with its underlying semantics, the users of the Web of Things may end up in information silos that would require different applications to access and use them. These circumstances definitely pose a challenge for transforming the raw data into business insight, thus hindering the exploitation of the data for better and smarter decisions.

The advent of the IoT paves the way to address situations that remain challenging in various domains. One of those domains is the the AEC (Architecture, Engineering and Construction) sector, where the installation of IoT systems in buildings enables understanding occupants behaviour as well as discovering the discrepancies between buildings' expected and actual performance [3]. This may in turn allow facing problems that are still unsolved in most buildings such as fulfilling occupants' thermal comfort whilst reducing energy consumption. These two aspects are equally important.

On the one hand conducted research proved that thermal comfort has a direct impact on human working efficiency [4,5], occupants morale [6], and potential health impairments [7] and on the other, the energy efficiency is one of the major concerns in buildings since they consume more than 35% of global energy in the EU [8].

Nevertheless, one of the most highlighted drawbacks of the IoT lies in the data level heterogeneity. Devices from different vendors may represent data in different formats, and even when a common format is used, the internal data model schema typically varies. Yet devices manufactured by the same vendor may use different data models, which further aggravates the data heterogeneity situation. Such a diversity derives in semantic interoperability problems, where each system can represent the same thing in different ways, hindering the integration and understanding between these systems.

Semantic Technologies can be leveraged to remedy aforementioned issues as they enable integrating data across several data sources as well as the adequate management of data semantics, data interrelationships, and knowledge representation. More specifically, ontologies, ontology-driven rules and ontology-driven data access are foreseen as the main drivers to address the aforementioned challenges. An ontology can be defined as a formal, explicit specification of a shared conceptualization [9,10]. The conceptualization specified by each ontology is usually devoted to represent a certain phenomenon, topic, or subject area, and designed with a certain purpose.

It has been proved that ontology-based approaches could contribute in achieving semantic interoperability [11], for example by annotating each data element with ontology terms thus providing them with semantics [12,13,14]. Annotating raw data with terms coming from ontologies or vocabularies allows a better representation of the data, structuring it and setting formal types, relations, properties and constraints that hold among them. In addition, it allows representing data coming from multiple sources in a uniform way, thereby supporting data integration [15]. Another benefit of the semantic annotation lies in the additional background knowledge about a domain that can be added to the set of available data. This leads to the enrichment of the dataset at hand, as well as enabling the application of indexing techniques, which are based on resource URIs and ensure the retrieval and navigation through related resources [16]. Last but not least, after a semantic annotation process, data is more domain-oriented than the original source and allows more application-independent solutions. Consequently, there is no need for the user to be aware of raw data's underlying structure.

Ontologies can be considered as part of the solution to overcome the IoT's inherent hurdles, although defining a comprehensive unified ontology for the domain of IoT may be challenging due to the existence of more than 200 ontologies available [17]. This fact may be motivated because IoT scenarios tackle a wide range of aspects such as the things used to observe or act, their configuration and capabilities, the location where they are deployed, the modalities of the context upon which they operate, data accessibility permission, or service orchestration, among others.

The central topics chosen for the presentation of this survey are observations and actuations, which can be considered variations of the more general notion of transduction. Transduction can be understood as the action or process of converting something such as energy or a signal into another form. An observation outputs a readable result from a stimulus. Likewise, an actuation transforms a signal into a change of state of a device.

The observation term is already used in different ways in different communities. The O&M (Observations and Measurements) model described in ISO 19156:2011[1] resolved this issue describing an observation as an event or activity, the result of which is an estimate of the value of a property of the feature of interest, obtained using a specific procedure. An actuation can be similarly defined as an event or activity, the result of which is a change of state of a quality of a feature of interest, achieved using a specific procedure. In order to reach a better conceptualization of these notions, a further analysis may be carried out by the 5W1H method (answering What, Who, Where, When, Which, How questions) and relating the answers with the terms of the DUL[2] (DOLCE+DnS Ultralite) upper level ontology.

For the sake of simplicity, these questions will be expressed in terms of the observation notion, but notice that they are analogous for the actuation notion. To begin with, any observation is a *dul:Event*, and the following questions can be considered:

[1] https://www.iso.org/standard/32574.html

[2] http://www.ontologydesignpatterns.org/ont/dul/DUL.owl

- What is observed? A property of a feature of interest. That notion of property is captured by the class *dul:Quality*, which is defined as: “Any aspect of an Entity (but not a part of it), which cannot exist without that Entity. For example, the way the surface of a specific PhysicalObject looks like, or the specific light of a place at a certain time, are examples of Quality". The feature of interest would be, more specifically, an individual of the class *dul:Object*, which is defined as: “Any physical, social, or mental object, or a substance. Following DOLCE Full, objects are always participating in some event (at least their own life), and are spatially located”. In the context of this survey, features of interest are elements in the domain of buildings.
- Who is the observer? A sensor, which is a particular kind of *dul:Object*.
- How is the observation made? Following a procedure, which can be considered an individual of the class *dul:Description*, which is defined as: “A Description is a SocialObject that represents a conceptualization. For example, a Plan is a Description of some actions to be executed by agents in a certain way, with certain parameters; a Diagnosis is a Description that provides an interpretation for a set of observed entities”.
- Where is the observation made? In a location, that would be represented by an individual of the class *dul:Region*, which is defined as: “Any region in a dimensional space (a dimensional space is a maximal Region), which can be used as a value for a quality of an Entity. For example, TimeInterval, SpaceRegion, PhysicalAttribute, Amount, SocialAttribute are all subclasses of Region. Regions are not data values in the ordinary knowledge representation sense; in order to get patterns for modelling data, see the properties: representsDataValue and hasDataValue”. Notice that the location of the observation is decoupled from the location of the feature of interest observed.
- When is the observation made? In a time region, represented by an individual of *dul:Region*.
- Which is the result of the observation? An encoding of a value, represented by an individual of *dul:Region*.

Figure 1 shows a diagram of the different concepts involved in the notion of an observation (and its counterpart actuation), using classes and relationships defined in the DUL ontology.

A goal of this survey points towards ontologies involved in conceptualizations of observations and actuations under the framework posed by the aforementioned 5W1H questions. Moreover, the utility of that conceptualization arise when some features of interest need to be observed or acted upon. Spaces and elements in the buildings environment have emerged as platforms where materializations of such observations and actuations promise to be very profitable. A complementary goal of this survey is to review some ontologies conceptualizing buildings topology notions.

The rest of the paper is structured as follows. Section 2 presents the scope of the survey. In Section 3 ontologies are reviewed. The outcomes of this review are discussed in Section 4. Finally the conclusions of this work are presented in Section 5.

2. Scope of the survey

IoT is a broad domain and many ontologies with different purposes and character, have been designed to address that domain. There are surveys reviewing ontologies in this domain such as the recent one presented by Bajaj et al. [18]. However, the present survey does not pretend to cover the whole IoT domain. Instead, the scope of this survey is restricted to, on the one hand, ontologies that consider as core concepts the notions exposed in the 5W1H analysis of the previous section and, on the other, ontologies that consider spaces and elements in buildings as features of interest whose qualities deserve observations and actuations.

Given the abundance of existing ontologies covering aforementioned areas of knowledge, it is necessary to make the ontology inclusion criteria of this survey explicit. Ontologies considered to be reviewed had to present a publicly available recent version, offer enough documentation to understand the ontology, have some evidences of its use, and illustrate some design principles. It is worth mentioning that very few ontologies satisfied all these requirements, therefore, ontologies that did not address all these points were also included in the survey.

The discovery of ontologies reviewed in this survey has been facilitated by the LOV[3] [19] (Linked Open Vocabularies) ontology catalogue, where vocabularies retrieved when querying terms ‘iot’, ‘observation’, ‘actuation’, ‘feature of interest’, ‘building’, ‘bim’, ‘space’

[3] http://lov.linkeddata.es

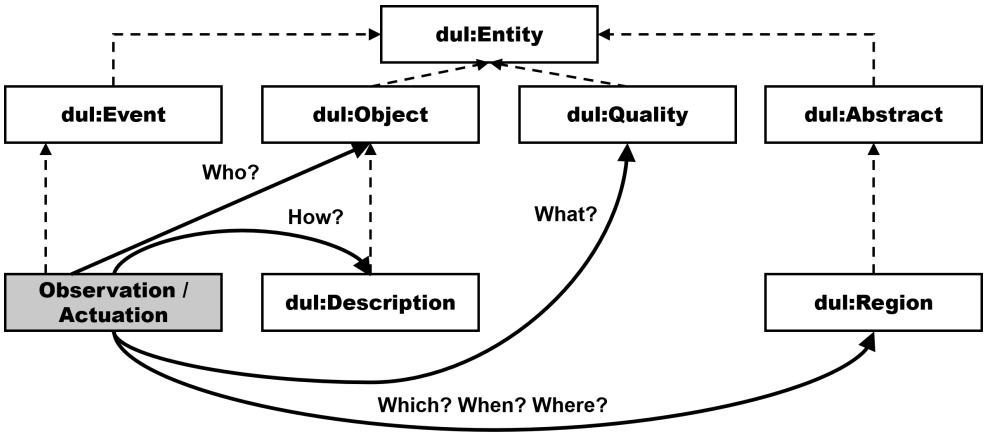

Fig. 1. Concepts from the DUL ontology involved in the notion of an observation/actuation.

and 'context' have been considered. Additionally, the ontology discovery task has also been assisted by research databases such as Google Scholar[4], IEEE Xplore[5], ScienceDirect[6].

For each of the reviewed ontology, their fundamentals are described, their potential advantages and shortcomings are highlighted, and the use cases where these ontologies have been used are indicated. For each set of ontologies categorised under the same area of interest, tables that summarize the following information are provided.

Latest available version's date. For each reviewed ontology, the latest version's date will be shown, which may hint the maintenance of the ontology.

License. As any other intellectual creation, ontologies are protected by copyright, so they cannot be used unless a license permits so. Therefore, in order to make ontologies reusable, specifying this piece of information is necessary. For each reviewed ontology, the license specified will be checked.

Documentation. When discovering an ontology, one of the first activities consists in reading its documentation to understand the ontology domain and determine whether it describes this domain appropriately or not. This is why nowadays, ontologies should have comprehensive web pages describing their theoretical backgrounds and features. For each reviewed ontology, it will be checked whether it has a documentation page or not.

[4]https://scholar.google.com
[5]https://ieeexplore.ieee.org
[6]https://www.sciencedirect.com

Metadata. W3C's Data on the Web Best Practices [20] state that providing metadata is a fundamental requirement that helps human users and computer applications to understand the data as well as other important aspects that describes a dataset. Being the guidelines described by Garijo and Poveda-Villalón [21] the most complete ones, for each reviewed ontology, it will be checked whether this guideline's recommended metadata terms are explicitly written or not.

Alignments. Setting mappings to other ontology and vocabularies alleviates integration problems [15], helps to ensure clarity in modelling and avoids errors that have unintended reasoning implications [22]. For each reviewed ontology, it will be checked whether alignments to other ontologies are provided or not.

Ontology use. According to the W3C's Data on the Web Best practices [20], the reuse of existing ontological resources is advised. The evidence of its usage can symbolize the acceptance of an ontology by the community. For each reviewed ontology, it will be checked whether there are evidences of its usage or not.

Additionally, use case examples are annotated with different ontologies in order to illustrate their capabilities and showcase the differences between ontologies.

3. Ontologies Review

This section presents the review of the ontologies selected according to the scope delimited in Section 2.

3.1. Observations and Actuations ontologies

As mentioned before, IoT devices generate a vast amount of data, specially observations of the real

world and actuations triggered to change the state of the real world. However, raw observation and actuation results do not provide the context required to adequately interpret and understand them. Without the adequate description of situation under which these observations and actuations are performed, their exploitation capabilities may be rather limited. In this regard, the semantic annotation of this data with adequate ontology terms is expected to ease the exploitation of their underlying semantics. Therefore, the review of ontologies available for this purpose is of interest.

In order to illustrate capabilities and differences between the reviewed ontologies, the following example will be considered:

"An observation of the electric consumption of a room made by a sensor.".

In addition, since there are ontologies built upon other ontologies, each ontology's parent ontology from which they inherit concepts as well as its design principles are summarized in Table 1. The design basis can be:

- ODP-based: Those based on ODPs (Ontology Design Patterns), which are modelling solutions to solve recurrent design problems that arise in ontology development processes [23].
- Model-based: Those based on existing models such as ISOs or conceptual schemas.
- Modular: Those defined as a set of modules.
- Reengineering: Those based on the reengineering of existing assets.

3.1.1. SSNx Ontology

The initial Semantic Sensor Network (SSN) ontology[7] [24] was developed by the W3C Semantic Sensor Networks Incubator Group (SSN-XG) and it proposed a conceptual schema for describing sensors, accuracy and capabilities of such sensors, their observations and methods used for sensing. Concepts for operating and survival ranges were also included, as well as sensors' performance within those ranges. Finally, a structure for field deployment was defined to describe deployment lifetime and sensing purposes. The initial SSN ontology was aligned with DUL ontology and built on top of the Stimulus-Sensor-Observation (SSO) [25] ODP describing the relationships between sensors, stimulus, and observations.

The following triples would represent the previously proposed use case example:

```
:obs01 rdf:type ssnx:Observation;
  ssnx:observedBy :sensor01;
  ssnx:observedProperty :electricCons;
  ssnx:featureOfInterest :room01.

:electricCons rdf:type ssnx:Property.
:room01 rdf:type ssnx:FeatureOfInterest.
```

3.1.2. SOSA/SSN Ontology

The W3C Spatial Data on the Web Working Group (SDWWG[8]) proposed an update of the SSN ontology [26,27] (from now on referred to as SOSA/SSN ontology) that became a W3C recommendation. This new ontology follows a horizontal and vertical modularization architecture by including a lightweight but self-contained core ontology called SOSA[9] (Sensor, Observation, Sample, and Actuator) for its elementary classes and properties. Furthermore, the SOSA/SSN ontology's scope is not limited to observations, but it is extended to cover actuations and samplings. In line with the changes implemented in the SOSA/SSN ontology, SOSA drops the direct DUL alignment although it can still be optionally achieved via the SSN-DUL alignment module[10]. Moreover, similar to the original SSO pattern, SOSA acts as a central building block for the new SOSA/SSN ontology but puts more emphasis on its lightweight expressivity and the ability to be used standalone. Then, constraint axioms are added to the vertical module extension named SSN.

A complete list of the 23 ontologies that already reuse SOSA and the 23 datasets that use SOSA classes and properties to define data in their applications can be found in the SSN Usage document[11]. Nevertheless, neither the SSNx ontology nor the new SOSA/SSN ontology describe the different qualities which can be measured by sensors or acted on by actuators. Neither are covered related concepts such as units of measurements of these qualities, hierarchies of sensor/actuator/sampler types, or spatio-temporal terms. All this knowledge has to be modelled by the user, or preferably imported from other existing vocabularies.

The following triples would represent the previously proposed use case example and, additionally, two observations of another room (one of them, gas consumption and the other, electricity consumption) made by another sensor:

[7] http://www.w3.org/ns/ssn/

[8] https://www.w3.org/2015/spatial

[9] http://www.w3.org/ns/sosa/

[10] https://www.w3.org/ns/ssn/dul

[11] https://w3c.github.io/sdw/ssn-usage/

Table 1

Summary of parent ontologies and design principles of the reviewed Observation and Actuation ontologies.

Ontology	Parent Ontology	Design Principle
SSNx	SSO, DUL	ODP-based
SOSA/SSN	SSNx, SSO	ODP-based
om-lite	O&M ISO 19156	Model-based
SAREF	-	Reengineering
SEAS	SOSA, PEP, SAREF?	ODP-based
IoT-O	SSNx, SSO, SAN, AAE, MSM, hRESTS, PowerOnt, DUL	Modular
IoT-Lite	SSNx	Modular
FIESTA-IoT	IoT-Lite, SSNx, M3-lite, DUL	Modular
SmartEnv	SOSA/SSN, DUL	ODP-based

```
:sensor01 rdf:type sosa:Sensor;
  sosa:madeObservation :obs01;
  sosa:observes :electricCons.
:electricCons ssn:isPropertyOf :room01.
:obs01 rdf:type sosa:Observation;
  sosa:hasFeatureOfInterest :room01.

:sensor02 rdf:type sosa:Sensor;
  sosa:madeObservation :obs02;
  sosa:observes :electricCons.
:electricCons ssn:isPropertyOf :room02.
:obs02 rdf:type sosa:Observation;
  sosa:hasFeatureOfInterest :room02.

:sensor02 sosa:madeObservation :obs03;
  sosa:observes :gasCons.
:gasCons ssn:isPropertyOf :room02.
:obs03 rdf:type sosa:Observation;
  sosa:hasFeatureOfInterest :room02.

:electricCons, :gasCons
  rdf:type sosa:ObservableProperty.
:room01, :room02
  rdf:type sosa:FeatureOfInterest.
```

It is worth mentioning that with these triples, it is not possible to answer accurately the following question: "which is the sensor that observes the electricity consumption in *:room02*?". The rationale behind this weakness is that there is no property directly linking sensors to features of interest, and moreover, composition of properties that link them through the *sosa:Observation* class are not sufficiently constrained. The key lies in the individual *:electricCons* which does not properly satisfy the definition of a quality of *:room02* (i.e. "which cannot exist without entity *:room02*", see definition of *dul:Quality* in Section 1, which is also the definition of the class *ssn:Property* in SOSA/SSN). As a matter of fact, in this use case *:electricCons* is used, as a quality kind instead of an individual quality. An alternative codification solving this issue is possible in SOSA/SSN, but the style showed in the example is very common and the coexistence of both styles may produce mismatches in certain situations.

3.1.3. om-lite Ontology

The om-lite ontology[12] [22] is an OWL representation of the Observation Schema described in clauses 7 and 8 of ISO 19156:2011 Geographic Information - Observations and Measurements (O&M). O&M defines a conceptual schema for observations, and for features involved when observations are produced. This schema separates concerns with classes for the feature of interest, the procedure, the observed property, the result, and the act of observation itself. This allows places and times associated with each of them to be distinct. An observation is defined as an act that results in the estimation of the value of a feature property, and it involves the application of a specified procedure, such as a sensor, instrument, algorithm or process chain. Specializations of the observation class are classified by the result-type. This way, the class *oml:Observation* has subclasses such as *oml:CountObservation* for observations whose results are integer, *oml:Measurement* for scaled numbers and *oml:TruthObservation* for booleans.

The om-lite ontology allows combining data unambiguously and referring to observations made in-situ, remotely, or ex-situ with respect to the location. These observation details are also important for data discovery and for data quality estimation. Furthermore, the om-lite ontology removes dependencies with pre-

[12] http://def.seegrid.csiro.au/ontology/om/om-lite

existing ontologies and frameworks, and can therefore be used with minimal ontologies commitment beyond the O&M conceptual model. Additionally, it provides stub classes for time, geometry and measure (scaled number), which are expected to be substituted at runtime by a suitable concrete representation of the concept. Finally, the ontology is aligned with domain ontologies including the initial version of the SSN ontology as defined by the SSN-XG group.

The following triples would represent the previously proposed use case example:

```
:obs01 rdf:type oml:Observation;
  oml:observedProperty :electricCons;
  oml:procedure :sensor01;
  oml:featureOfInterest :room01.

:electricCons rdf:type owl:Thing.
:room01 rdf:type owl:Thing.
:sensor01 rdf:type oml:Process.
```

The om-lite ontology does not define any class for observed qualities or features of interest. Therefore, individuals *:room01* and *:electricCons* cannot be adequately represented.

3.1.4. SAREF Ontology

The Smart Appliances REFerence (SAREF) ontology[13] [28] is a shared model of consensus that facilitates the matching of existing assets in the smart appliances domain. The ontology provides building blocks that allow the separation and recombination of different parts of the ontology depending on specific needs. The central concept of the ontology is the *saref:Device* class, which is modelled in terms of functions, associated commands, states and provided services. The ontology describes types of devices such as sensors and actuators, white goods, HVAC (Heating, Ventilation and Air Conditioning) systems, lighting and micro renewable home solutions. A device makes an observation (which in SAREF is represented as *saref:Measurement*) which represents the value and timestamp and it is associated with a property (*saref:Property*) and a unit of measurement (*saref:UnitOfMeasure*).

The modular conception of the ontology allows the definition of any new device based on building blocks describing functions that devices perform. Furthermore, SAREF can be specialized to refine the general semantics captured in the ontology and create new concepts. The only requirement is that any extension or specialization may comply with SAREF. There are three extensions of the ontology: SAREF4BLDG for the building domain (reviewed in Section 3.3.4), SAREF4ENVI[14] for the environment domain, and SAREF4ENER[15] for the energy domain. Furthermore, at the moment of writing this survey there are three new planned extensions: SAREF4CITY for smart cities, SAREF4INMA for industry and manufacturing, and SAREF4AGRI for the agricultural domain.

The SAREF ontology terms have been used in applications that range from energy efficiency semantic models [29] to comfort management in hotels [30]. Furthermore, standards organizations and alliances, such as CENELEC[16] and the Alliance for Internet of Things Innovation (AIOTI[17]), have acknowledged and adopted SAREF in their standardization activities [31].

The following triples would represent the previously proposed use case example:

```
:sensor01 rdf:type saref:Device.
  saref:measuresProperty :electricCons;
  saref:makesMeasurement :obs01.

:electricCons rdf:type saref:Property.
:obs01 rdf:type saref:Measurement.
:room01 rdf:type owl:Thing.
```

These triples showcase SAREF ontology's device-centric modelling in contrast to the more event-centric modelling style of other ontologies such as SOSA/SSN and om-lite. Furthermore, SAREF cannot represent the relationship between an observed quality (e.g. a room's electric consumption) and the feature of interest to which it belongs (e.g. the room at hand). As a matter of fact, SAREF does not represent the notion of a feature of interest, so that in the triples above individual *:room01* cannot be adequately represented.

3.1.5. SEAS Ontology

The SEAS Ontology[18] [32] is an ontology designed as a set of simple core ODPs that can be instantiated for multiple engineering related verticals and it is planned to be consolidated with the SAREF ontology as part of ETSI's Special Task Force 556[19].

[13] http://ontology.tno.nl/saref

[14] https://w3id.org/def/saref4envi

[15] https://w3id.org/saref4ener

[16] https://www.cenelec.eu/

[17] https://aioti.eu/

[18] https://w3id.org/seas/

[19] https://portal.etsi.org/STF/STFs/STFHomePages/STF556

The SEAS ontology modules are developed based on the following three core modules: the SEAS Feature of Interest ontology[20] which defines features of interest (*seas:FeatureOfInterest*) and their qualities (*seas:Property*), the SEAS Evaluation ontology[21] describing evaluation of these qualities, and the SEAS System ontology[22] representing virtually isolated systems connected with other systems. The Procedure Execution (PEP) ontology[23], which is not strictly a SEAS ontology module but it is contained under the same SEAS project, defines procedure executors that implement procedure methods, and generate procedure execution activities. Furthermore, PEP defines an ODP as a generalization of SOSA's sensor-procedure-observation and actuator-procedure-actuation models.

On top of these core modules, several vertical SEAS ontology modules are defined, which are dependent of a specific domain. Some of these modules include the SEAS Electric Power System ontology[24] and the SEAS Building ontology (reviewed in Section 3.3.8).

The SEAS ontology and its modules have a thorough documentation and complete metadata, which eases its understanding and their potential reuse. One of the few examples of its usage is EROSO [33], a framework that is aimed at ensuring thermal comfort in workplaces and extends the SEAS Forecasting ontology[25]. Additionally, the SEAS ontology offers a set of alignments to other domain ontologies such as SOSA/SSN.

The following triples would represent the previously proposed use case example, as well as the two additional observations and the sensor proposed for the example in SOSA/SSN ontology. Namespace *pep* belongs to the PEP ontology.

```
:obs01 rdf:type pep:ProcedureExecution;
  pep:madeBy :sensor01;
  seas:observesProperty :room01electricCons.

:room01electricCons rdf:type seas:Property;
  seas:isPropertyOf :room01.

:obs02 rdf:type pep:ProcedureExecution;
  pep:madeBy :sensor02;
  seas:observesProperty :room02electricCons.

:room02electricCons rdf:type seas:Property;
  seas:isPropertyOf :room02.

:obs03 rdf:type pep:ProcedureExecution;
  pep:madeBy :sensor02;
  seas:observesProperty :room02gasCons.

:room02gasCons rdf:type seas:Property;
  seas:isPropertyOf :room02.

:sensor01 rdf:type pep:ProcedureExecutor.
:sensor02 rdf:type pep:ProcedureExecutor.
:room01 rdf:type seas:FeatureOfInterest.
:room02 rdf:type seas:FeatureOfInterest.
```

The aforementioned three observations on two rooms are appropriately codified in SEAS for adequately anwer the question: "which is the sensor that observes the electricity consumption in *:room02*?". This is due to the constraint of functional object property added to the definition of *seas:isPropertyOf*. Therefore, SEAS ontology supports the notion that a quality is intrinsic to the feature of interest to which it belongs.

3.1.6. IoT-O Ontology

The IoT-O ontology[26] [34] is an IoT domain modular ontology describing connected devices and their relation with the environment. It is intended to model knowledge about IoT systems and to be extended with application specific knowledge. It has been designed in five separated modules to facilitate its reuse and/or extension:

1. A sensing module, based on the SSNx ontology and particularly on the SSO pattern.
2. An acting module, based on the SAN (Semantic Actuator Network) ontology[27], and particularly on the AAE (the Actuation-Actuator-Effect) pattern, which intends to model the relationship between an actuator and the effect it has on its environment through actuations.
3. A service module, based on MSM[28] (Minimal Service Model) and hRESTS ontology[29].

[20] https://w3id.org/seas/FeatureOfInterestOntology
[21] https://w3id.org/seas/EvaluationOntology
[22] https://w3id.org/seas/SystemOntology
[23] https://w3id.org/pep/
[24] https://w3id.org/seas/ElectricPowerSystemOntology
[25] https://w3id.org/seas/ForecastingOntology
[26] https://www.irit.fr/recherches/MELODI/ontologies/IoT-O
[27] https://www.irit.fr/recherches/MELODI/ontologies/SAN
[28] http://iserve.kmi.open.ac.uk/ns/msm
[29] http://www.wsmo.org/ns/hrests/

4. A lifecycle module[30], based on a lifecycle vocabulary (a lightweight vocabulary defining state machines) and an IoT-specific extension.
5. An energy module, based on PowerOnt[31].

Furthermore, to maximize its reusability and extensibility, IoT-O imports DUL and aligns all its concepts and imported modules with it.

The ontology as a whole has been used by an application aimed at distributing semantic data processing in the Fog [35] as well as an ontology to represent interactions between an entity and an IoT system [36]. Likewise, IoT-O's SAN ontology module has been reused by the BCI (Brain-Computer Interaction) ontology[32] [37].

Being based on SSNx, the previously proposed use case example would be represented with the same triples proposed in Section 3.1.1.

3.1.7. IoT-Lite Ontology

The IoT-Lite Ontology[33] [38] is a lightweight ontology planned to be used by other independent platforms in the open calls of H2020 project FIESTA-IoT[34]. It is an specialization of the SSNx ontology designed with a clear purpose of defining only the most used terms when searching for IoT concepts in the context of data analytics such as sensory data, location and type. The ontology's lightweight allows the representation and use of IoT platforms without consuming excessive processing time when querying the ontology. However, it is also an ontology that can be extended in order to represent IoT concepts in a more detailed way in different domains. The ontology is aimed to be simple, as it is considered as one of its requirements, and it is aligned with other well-known and widely used ontologies such as SWEET[35] (Semantic Web for Earth and Environmental Terminology) and the SSNx ontology.

IoT-Lite is built around the main three concepts which, according to IoT-Lite authors, are necessary in any ontology describing IoT: objects/entities, resources/devices, and services. However, the coverage of the ontology is limited to upper-level concepts, rather than representing types of devices as subclasses of *ssnx:SensingDevice* (e.g. thermometer) or units of measurements as subclasses of *qu:Unit* (e.g. degrees celsius). Although the vocabularies used in IoT-Lite are aligned with their generalized counterparts, the representation of the key concepts in sensor-related environments (e.g. sensor, action and observation) is limited.

As mentioned before, the IoT-Lite ontology is developed aimed at being used by platforms in the open calls of the Fiesta-IoT Project. To the extent of knowledge of authors, the ontology has been reused by the Fiesta-IoT ontology reviewed next.

Being based on SSNx, the previously proposed use case example would be represented with the same triples proposed in Section 3.1.1.

3.1.8. FIESTA-IoT Ontology

The FIESTA-IoT Ontology[36] [39] aims at creating a lightweight ontology that achieves semantic interoperability among heterogeneous testbeds. The ontology is focused on the description of the underlying testbeds' resource descriptions and the observations gathered from their physical devices. Furthermore, the design of the ontology is guided by the methodologies of ontology reuse and alignment. Some of the reused ontologies and taxonomies include the SSNx ontology, IoT-Lite and DUL ontology.

The SSNx ontology has a strong influence in FIESTA-IoT when describing sensors and observations. The central class is *ssnx:Observation*, which is related with the *ssnx:Sensor* which generates it, the property it observes (*qu:QuantityKind*) and the temporal and location context.

The M3-lite taxonomy[37] is a light version of the M3 ontology [40], designed to meet FIESTA-IoT ontology's requirements. M3-lite follows a modular design and provides links with other IoT-related ontologies to facilitate interoperability. These links are represented with the *rdfs:seeAlso* utility property. The main purpose of the M3-lite taxonomy is to extend the representation of concepts that are not covered by the SSNx ontology in a rather detailed way. In fact, M3-lite defines over 30 types of actuators (as subclasses of *iot-lite:ActuatingDevice*), over 100 types of sensors (as subclasses of *ssnx:SensingDevice*), over 170 types of quantities (as subclasses of *qu:QuantityKind*) and

[30] https://www.irit.fr/recherches/MELODI/ontologies/IoT-Lifecycle
[31] ttp://elite.polito.it/ontologies/poweront.owl
[32] https://w3id.org/BCI-ontology
[33] http://purl.oclc.org/NET/UNIS/fiware/iot-lite
[34] http://fiesta-iot.eu/
[35] https://sweet.jpl.nasa.gov/
[36] http://ontology.fiesta-iot.eu/ontologyDocs/fiesta-iot/doc
[37] http://purl.org/iot/vocab/m3-lite

over 90 classes of units of measure (as subclasses of *qu:Unit*). Furthermore, the scope of the taxonomy is not limited to a single domain. As a matter of fact, it covers 12 different IoT application domains.

The FIESTA-IoT ontology has been used to federate eleven IoT deployment testbeds from heterogeneous application domains including smart cities, maritime and smart grids [41]. Furthermore, the M3-lite taxonomy, which is part of FIESTA-IoT, has been used in an outlier detection framework in Wireless Sensor Networks (WSN) [42]. However, even though the ontology has a complete documentation and metadata, not having an explicit license may hinder its reuse.

Being based on SSNx, the previously proposed use case example would be represented with the same triples proposed in Section 3.1.1.

3.1.9. SmartEnv Ontology

The SmartEnv ontology[38] [43] proposes an ontology for sensorized environments. The ontology is a network of 8 different ontology modules. Each module is represented in the form of a pattern to modularize the proposed solution, and it is represented as general as possible avoiding strong dependencies between the modules to manage the representational complexity of the ontology. Furthermore, the modularization allows the update of concepts with the minimum change propagation on the entire ontology, and individual patterns can also be used in isolation for some specific reasoning tasks (e.g., in order to avoid issues with reasoning complexity or clashes in the relations to foundational ontologies). The basis of these ontology modules are extracted from the SOSA/SSN ontology and DUL ontology, a number of specializations are defined, either in the form of extension of class hierarchies or updating links between concepts.

Although the SmartEnv ontology and its modules were developed under the E-care@home project[39], it remains unclear whether they have been really used in real applications or not. To the extent of knowledge of authors, neither the SmartEnv Ontology neither its modules have been used in other use cases, which might be motivated by the lack of an ontology license.

Being based on SOSA/SSN, the previously proposed use case example would be represented with the same triples proposed in Section 3.1.2.

[38] https://w3id.org/smartenvironment/smartenv.owl

[39] http://ecareathome.se

3.1.10. Summary

The representation of the notion of an observation is the central element in most reviewed ontologies, although its counterpart actuation is also addressed by certain ontologies. The main ontology in this regard is the SOSA/SSN ontology, which is based on the SSNx ontology. There are also other ontologies based on the SSNx (e.g. FIESTA-IoT and IoT-O) and the SOSA/SSN can be considered more as an evolution of SSNx. Likewise, there are ontologies based on the new SOSA/SSN (e.g. SmartEnv). However, thanks to the alignment between the initial SSNx and the new SOSA/SSN versions, interoperability issues may be alleviated.

Furthermore, there are ontologies that differ from SOSA's event-centric modelling and take a more device-centric modelling (e.g. SAREF) or try to make a more faithful representation of an ISO schema model (e.g. om-lite).

Most ontologies offer explicit classes for representing the notions of Observation, Actuation, Sensor, Actuator, Feature of Interest, and Quality, but some of them misses Feature of Interest (i.e. om-lite, and SAREF) or Quality (i.e. om-lite), and SAREF does not relate a quality to its feature of interest.

The SOSA/SSN ontology allows different ways of modelling observable properties, although this flexibility means that different stakeholders may adopt different modelling options that can derive in interoperability problems. In this regard, there are ontologies such as SEAS that renounce to this flexibility and propose the notion that a quality is functionally related to its feature of interest, being therefore more aligned with DUL's conceptualization.

Table 2 summarizes the reviewed Observation and Actuation ontologies.

3.2. Context ontologies

Observations and actuations are the central elements of the problem tackled in this survey, and their values and result representation play an important role. Spatial, temporal, and units of measurements aspects of these values are a context information that may differ in nature and granularity levels. They respond to the When, Where, Which questions of the 5W1H analysis of Section 1. Next, ontologies representing such context of observations and actuations are reviewed.

Table 2
Summary of the reviewed Observation and Actuation ontologies.

Ontology	Latest Version	License	Documentation	Metadata	Alignments	Use
SSN	2017-04	W3C	Yes	Yes	Yes	Yes
om-lite	2016-10	CC BY 3.0	Yes	Yes	Yes	No
SAREF	2018-05	CC BY 4.0	Yes	Yes	No	Yes
SEAS	2017-08	Apache 2.0	Yes	Yes	Yes	Yes
IoT-O	2016-02	CC BY 4.0	Yes	Yes	No	Yes
Fiesta-IoT	2017-11	EU H2020 Fiesta-IoT	Yes	Yes	No	Yes
IoT-Lite	2017-06	CC BY 3.0	Yes	No	No	Yes
SmartEnv	2017-10	No	No	Yes	No	No

3.2.1. Time

Since nearly everything is liable to undergo change, the notion of time features in the discourse about any subject. Many ontologies defining temporal context exist [44,45,46,47,48], even though the most commonly used ontology is the Time Ontology in OWL[40] [49] (OWL-Time).

OWL-Time is a W3C recommendation representing temporal concepts for describing the temporal properties of resources. The vocabulary expresses facts about topological relations among instants and intervals, together with information about durations and temporal position including date-time information. Time positions and durations may be expressed using either the conventional (Gregorian) calendar and clock, or using another temporal reference system such as Unix-time, geologic time, or different calendars.

The following triples would represent an observation generated on 15th December 2018 at 19:00. Namespace *xsd* belongs to the XML Schema Datatypes.

```
:obs01time rdf:type time:Instant;
  time:inXSDDateTimeStamp
    "2018-12-15T19:00:00+08:00"
    ^^xsd:dateTimeStamp.
```

3.2.2. Location

Together with time, spatial location is the other primary aspect that may help specifying a context. The WGS84 Geo Position[41] is a vocabulary for representing latitude, longitude and altitude information in the WGS84 geodetic reference datum.

The following triples would represent the location of a building with WGS84 Geo Position terms:

```
:building01Location rdf:type geo:Point;
  geo:lat "40.74";
  geo:long "-73.98"
```

Another approach proposes a more detailed ontology to describe the location of device-based services that occur in ubiquitous computing environments [50]. GeoSPARQL [51] is the OGC (Open Geospatial Consortium) standard that not only defines an extension to the SPARQL query language, but also defines a vocabulary for representing geospatial data in RDF.

3.2.3. Units of measurements

Units of measurement play a key role in many engineering and scientific applications, and the correct handling of the scale is of utmost importance in most fields. Therefore, nowadays there are numerous ontologies describing units of measurement and their relations. Keil et al. [52] evaluate and compare different ontologies for modelling units of measurements and one of the main findings is that reviewed ontologies use different terms to refer to the same concepts. For example, the concept "kind of quantity", is denoted as "physical quality" by MUO[42] (Measurement Units Ontology), and as "quantity kind" by QU[43] (Ontology for Quantity Kinds and Units) and QUDT[44] (Quantities, Units, Dimensions and Data Types Ontologies). OBOE[45] (Extensible Observation Ontology), OM[46] (Ontology of Units of Measure) and SWEET do not provide an explicit class for this concept, but they model the respective notions as subclasses of "physical

[40] https://www.w3.org/TR/owl-time/
[41] https://www.w3.org/2003/01/geo/
[42] http://idi.fundacionctic.org/muo/
[43] https://www.w3.org/2005/Incubator/ssn/ssnx/qu/qu.owl
[44] http://www.qudt.org/
[45] https://code.ecoinformatics.org/code/semtools/trunk/dev/oboe/
[46] http://www.ontology-of-units-of-measure.org/page/om-2

characteristic" (OBOE), "quantity" (OM), and "property" (SWEET).

The use of any of the aforementioned ontologies for representing observation results, means that quantity values are usually represented as OWL individuals linked to numeric values and a unit of measure. Next, QUDT and another approach (which is not covered in the aforementioned survey) are reviewed.

QUDT. QUDT[47] is an initiative sponsored by the NASA to formalize Quantities, Units of Measure, Dimensions and Types using ontologies. QUDT is organized as a catalogue of quantity kinds and units of different disciplines (e.g. acoustics or climatology). A quantity (*qudt:Quantity*) is the central element which represents a measurement of an observable property of a particular object, event or physical system. The quantity is related with the context of the measurement, and the underlying quantity kind remains independent of any particular measurement. A quantity kind is distinguished from a quantity in that the former is a type specifier, while the latter carries a value.

The dimensional approach of QUDT relates each unit to a system of base units using numeric factors and a vector of exponents defined over a set of fundamental dimensions. By this means, each base unit's role is precisely defined in the derived unit. Furthermore, this allows reasoning over quantities as well as units.

Although at the moment of writing this survey there are efforts towards the development of a second version of QUDT, these ontologies have only been partly published.

The following triples would represent a 29°C quantity value in QUDT:

```
:temp01 rdf:type qudt:QuantityValue;
  qudt:unit unit:DegreeCelsius;
  qudt:numericValue "29"^^xsd:double.
```

UCUM Datatypes. The work presented by Lefrançois et al. [53] leverages UCUM (Unified Code of Units of Measure), a code system which aims at including units of measures currently used in international sciences, engineering, and business.

This proposal is different to the rest of the aforementioned ontologies representing units of measurements and related concepts. The proposed lexical space is the concatenation of a *xsd:decimal* value, at least one space, and a unit chosen from the case sensitive version of the UCUM code system. The value space corresponds to the set of measures, or quantity values as defined by the International Systems of Quantities. Using the UCUM datatypes requires only one triple to link a quantity to a fully qualified value, which is a reduction from the at least three triples needed in the aforementioned proposals.

```
:temp01 sosa:hasSimpleResult
    "29 Cel"^^cdt:temperature.
```

Furthermore, custom mechanisms to canonicalize literals based on external descriptions of units of measurements are not required. Therefore, one of the main advantages of the use of UCUM Datatypes lies in the lighter datasets and simpler queries achieved. However, although the specification is stable, at the time of writing this survey authors acknowledged that this work has not yet been implemented in the main RDF stores.

3.3. Building domain ontologies

BIM (Building Information Modeling) is a process used by different stakeholders involved in the construction process of a building, and deals with the digital representation of functional and physical characteristics of a building [54]. Each of these stakeholders adds domain knowledge to a common model which keeps information of the whole building life cycle. As a consequence, the model serves as a valuable source of information.

A BIM model may contain static information of a building element. For example, in the case of a window, data about its location, the material it is made of, and even when it was installed is available in the BIM model and can be queried. Nevertheless, BIM models are not aimed at containing more dynamic information such as data stemming from IoT sources because otherwise, they would be too big to manage and exchange[48]. As a matter of fact, the integration of static building information and IoT data becomes a prime challenge [55]. Therefore, it can be stated that more often than not, easy and intuitive ways to rapidly browse, query and use BIM information combined with IoT data are not available [56].

[47] http://www.qudt.org/

[48] IoT data, which is characterized by its abundance, is recommended to be stored in suitable storage systems such as Time Series Databases which are able to manage such an amount of data while ensuring a high performance.

Semantic Technologies can be leveraged to remedy these issues, as they allow a more dynamic manipulation of the building information in RDF graphs via query and rule languages [56]. Furthermore, the ontology modelling paradigm for providing and implementing a BIM model of a target building increases its value [57] and supports a variety of advantages such as reusability and automated reasoning upon the modelled entities. There are a variety of technologies that offer conceptual modelling capabilities to describe a domain of interest, but only ontologies combine this feature with Web compliance, formality and reasoning capabilities [58].

There are many building domain ontologies, each designed to fulfil the specific information requirements of a certain use case within the AEC domain. However, the lack of a common building model for representing data prevents interoperability and limits the scalability of applications. Next, a set of the most relevant ontologies for modelling buildings are reviewed.

Ontologies that do not cover building topology representation but instead they cover areas that are indirectly related to buildings are out of the scope of this survey. For example, the HBC (Human Comfort in Building) ontology[49] [59] focusing on occupants comfort. Furthermore, ontologies such as EEOnt [60] (Energy Efficiency Ontology) and BIMSO [61] (BIM Shared Ontology) that are not available online at the moment of writing this survey, are also left out of the review.

In order to illustrate capabilities and differences between the reviewed ontologies, the following example will be considered:

"The location of a room in a given floor of a building".

3.3.1. ifcOWL Ontology

The ifcOWL ontology[50] [62] provides an OWL representation of the EXPRESS schemas of the ISO 16739:2013[51] IFC (Industry Foundation Classes), which is the open standard developed by buildingSMART[52] for representing building and construction data. Using the ifcOWL ontology, IFC-based building models can be represented as directed labelled graphs. Furthermore, resulting RDF graphs can be linked to related data including material data, GIS (Geographic Information Systems) data or product manufacturer data. At the moment of writing this survey, the latest ifcOWL ontology is based on the IFC4 Addendum 2[53] and developed with the ExpressToOwl tool[54].

The ifcOWL ontology aims at supporting the conversion of IFC instance files into equivalent RDF files. This means that it is of secondary importance that an instance RDF file can be modelled from scratch using the ifcOWL ontology and an RDF editor. Furthermore, ifcOWL defines a faithful mapping of the IFC EXPRESS schema, replicating its conceptualization which has been found inconvenient for some practical engineering use cases [56]. For example, the ifcOWL conceptualization of some relationships and properties as instances of classes (i.e. *ifc:IfcRelationship*, *ifc:IfcProperty*) is counterintuitive to Semantic Web modelling principles that would expect OWL properties to represent them. In this regard, a systematic transformation of this modelling issue has been proposed in the IfcWoD (IFC Web of Data) ontology[55] [63], which claims to simplify query writing, optimize execution of queries and maximize inference capabilities. There are also other initiatives which focus on addressing ifcOWL ontology weaknesses such as making IFC-based exchanged data more semantically robust [64] or making the ontology more flexible in terms of its capability to deal with the real-world scenarios [65].

The ifcOWL ontology is a necessary tool to incorporate IFC models to the Semantic Web infrastructure but resulting graphs will be at least as large and complex as the original IFC models, which may be too complicated and even inconvenient for some scenarios. In this regard, efforts were made to split the ontology into modules representing different domains [66], but it is still closer to the concepts introduced within EXPRESS and IFC than to those of the Semantic Web modelling style [67]. The lack of such a modular approach may be one of the reasons behind the lack of evidence of usage of the ontology. However, it is worth mentioning that, since it follows the EXPRESS schema of IFC in order to allow bidirectional conversion, many ontologies from the building domain offer a set of mappings to the ifcOWL.

[49] https://w3id.org/ibp/hbc
[50] http://ifcowl.openbimstandards.org/IFC4_ADD2.owl
[51] https://www.iso.org/standard/51622.html
[52] https://www.buildingsmart.org/
[53] http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html/
[54] http://www.terkaj.com/tools.html#ExpressToOwl
[55] At the moment of writing this survey, the ontology is not publicly available.

The following triples would represent the previously proposed use case example:

```
:building01 rdf:type ifc:IfcBuilding;
  ifc:isDecomposedBy_IfcObjectDefinition
    :ifcRelAggregates_01.

:ifcRelAggregates_01
  rdf:type ifc:IfcRelAggregates;
  ifc:relatedObjects_IfcRelAggregates
    :floor01.

:floor01 rdf:type ifc:IfcBuildingStorey;
  ifc:isDecomposedBy_IfcObjectDefinition
    :ifcRelAggregates_02.

:ifcRelAggregates_02
  rdf:type ifc:IfcObjectDefinition;
  ifc:relatedObjects_IfcRelAggregates
        :room01.

:room01 rdf:type ifc:IfcSpace.
```

In the IFC standard, the relationship between buildings, storeys and spaces are represented using intermediate IfcRelAggregates instances. However, these instances are unnecessary in most of the applications and services that may use or query this information. Therefore, their presence in the RDF graph raises its complexity unnecessarily.

3.3.2. BOT

The Building Topology Ontology[56] [68] (BOT) is a minimal OWL DL ontology developed by the W3C LBD (Linked Building Data) Community Group[57] for covering core concepts of a building and for defining relationships between their subcomponents. Following general W3C guidelines, a first design principle for BOT has been to keep a light schema that could promote its reuse as a central ontology in the AEC domain.

BOT describes sites comprising buildings, composed of storeys, which have spaces that can contain and be bounded by building elements. Sites, buildings, storeys and spaces are all non-physical objects defining a spatial zone [69]. These basic concepts and properties make the schema no more complex than necessary and this design makes the ontology a baseline extensible with concepts and properties from more domain specific ontologies. Therefore, BOT serves as an ontology to be shared.

Moreover, the W3C LBD is aimed at producing more ontologies addressing geometry, products and other requirements across the life cycle of buildings that will extend from BOT concepts. The Building Product Ontology (PRODUCT[58]) is aimed at describing building elements (e.g. doors and windows), furnishings (e.g. chairs and tables), and MEP (Mechanical, Electrical and Plumbing) elements (e.g. humidifiers and energy meters) by means of different ontology modules. Furthermore, the iterative nature of a building design entails that information which is valid at one point in time might no longer be valid in the future. In order to manage that value variability and to keep track of property evolution history, the OPM (Ontology for Property Management) ontology[59] [70] is proposed. Finally, the emergence of a need for a standardized approach towards building-related properties derives in the future creation of the PROPS ontology[60]. It is worth mentioning that the W3C LBD group is working on IFCtoLBD[61] to transform IFC files into RDF triples that follow the aforementioned ontologies.

BOT has been reused by other ontologies leveraged for different use cases that range from Building Automation and Control Systems (BACS) [71] to applications that support the design decisions related to thermal comfort and indoor climate [72], as well as the management of Demand Response actions in the H2020 RESPOND project[62]. Likewise, the ontology is aligned with other related domain ontologies including ifcOWL [73].

The following triples would represent the previously proposed use case example:

```
:building01 rdf:type bot:Building;
  bot:hasStorey :floor01.

:floor01 rdf:type bot:Storey;
  bot:hasSpace :room01.

:room01 rdf:type bot:Space.
```

[56] https://w3id.org/bot
[57] https://www.w3.org/community/lbd/
[58] https://github.com/w3c-lbd-cg/product
[59] https://github.com/w3c-lbd-cg/opm/blob/master/opm.ttl
[60] https://github.com/w3c-lbd-cg/props
[61] https://github.com/jyrkioraskari/IFCtoLBD
[62] http://project-respond.eu/

3.3.3. DogOnt

The DogOnt ontology[63] [74] formalizes IDE (Intelligent Domotic Environment) aspects and it is designed with a particular focus on interoperation between domotic systems. Although primarily models devices, states and functionalities, it also supports the description of residential environments where devices are located.

Environment modelling in DogOnt is rather abstract and mainly aimed at locating indoor devices at room granularity. Reflecting this general design goal the available concepts permit to represent: (a) buildings, (b) storeys, as part of multi-storey buildings, (c) flats, either located on single or multiple storeys, (d) rooms inside flats and other indoor locations located outside flats (e.g. garages), (e) walls, ceilings, floors, partitions, doors and windows composing both rooms and building boundaries, and (f) objects contained in an indoor environment including furniture (e.g. chairs and desks) [75].

DogOnt influenced the design principles of other ontologies such as EEOnt [60] and it has been used in research projects that encompass different domains such as the smart grid domain in the case of the JEERP (Java Energy-Aware ERP) project [76]. Moreover, authors claim that such common origin of its ontology enables DogOnt to be reused as a foundation towards a shared and unified schema for AEC ontologies interoperability. However, the latest DogOnt version available at the moment of writing this survey (version 4.0.1) counts with over 1,000 classes and over 70 properties, which may be rather large to reuse it in some cases. Moreover, the scarce ontology metadata and the lack of mappings to other related ontologies may hinder DogOnt's usage as a unified schema.

The following triples would represent the previously proposed use case example:

```
:building01 rdf:type dogont:Building;
  dogont:contains :floor01.

:floor01 rdf:type dogont:Storey;
  dogont:contains :room01.

:room01 rdf:type dogont:Room.
```

[63] http://elite.polito.it/ontologies/dogont.owl

3.3.4. SAREF4BLDG

SAREF4BLDG[64] [77] is an extension of the SAREF ontology (reviewed in Section 3.1.4) based on the IFC standard. This extension is limited to the annotation of smart devices and appliances, focusing on the devices themselves and their location within buildings. Therefore, unlike in ifcOWL where the whole IFC is translated, only the corresponding part of the standard is transformed. In fact, it includes definitions from the IFC4 Addendum 1[65] to enable the representation of such devices and other physical objects in building spaces.

According to its representation, a building may have different spaces, which may also have other sub spaces within themselves. These classes alongside with the class representing physical objects, are declared as subclasses of *geo:SpatialThing* in order to reuse the conceptualization for locations already proposed by the Basic Geo vocabulary (also known as WGS84 Geo Position vocabulary). Moreover, SAREF4BLDG's current list of building devices should not be considered exhaustive, and it might be needed to extend this hierarchy if needed by a particular use case. At the moment of writing this survey there are no evidences of the usage of this ontology, but it has a rich documentation and ontology metadata, apart from setting mappings to the ifcOWL ontology (IFC4 Addendum 1) using the property *rdfs:seeAlso*.

The following triples would represent the previously proposed use case example:

```
:building01 rdf:type s4bldg:Building;
  s4bldg:hasSpace :floor01.

:floor01 rdf:type s4bdlg:BuildingSpace;
  s4bldg:hasSpace :room01.

:room01 rdf:type s4bldg:BuildingSpace.
```

SAREF4BLDG does not define a class for storeys, so they may be represented with class *s4bldg:BuildingSpace*

3.3.5. ThinkHome Ontology

The ThinkHome ontology[66] [78] formalizes all relevant concepts needed to realize energy analysis in residential buildings. The knowledge captured in the on-

[64] https://w3id.org/def/saref4bldg

[65] http://www.buildingsmart-tech.org/ifc/IFC4/Add1/html/

[66] https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/

tology spans different domains, and it is logically segmented in different modules such as WeatherOntology[67] and EnergyResourceOntology[68].

The building information module (BuildingOntology[69]) describes knowledge that supports optimized control strategies striving for energy-efficient operation of smart homes. It consists of a set of basic classes, properties and customized datatypes that have been generated through XSLTs (Extensible Stylesheet Language Transformation) from gbXML (Green Building XML) Schema version 5.10[70]. gbXML was chosen over IFC because it focuses on the exchange of information for energy simulation and calculation, which is ThinkHome system's focal point.

There are enough concepts to model whole buildings including wall layers, window sizes and types, door sizes and positions, room areas and volumes as well as room purposes and orientation of buildings. Although the M3 framework [40] reused terms designed by ThinkHome for the weather domain, there is no evidence of usage of the reviewed building information module. This fact may be influenced by the lack of ontology documentation page, ontology metadata and especially, the lack of an ontology license.

The following triples would represent the previously proposed use case example:

```
:building01 rdf:type bo:Building;
  bo:containsBuildingStorey :floor01.

:floor01 rdf:type bo:BuildingStorey;
:room01 rdf:type bo:Space.
```

The BuildingOntology does not define a relationship between a storey and a room within that storey, therefore, this connection cannot be represented.

3.3.6. FIEMSER Ontology

The FIEMSER ontology[71] describes an energy-focused BIM model and WSN (Wireless Sensor Network) related data for residential buildings. With regards to the building-related concepts, it takes into account other approaches such as IFC. The ontology describes buildings which consist of some building spaces representing flats or common areas. Likewise, these spaces consist of some other physical spaces. Furthermore, a building zone defines a functional area in the building that will be controlled as a unique zone and which can be an aggregation of one or more building spaces. The source used to create the FIEMSER ontology is a secured PDF file from which the information could not be automatically copied. As a consequence, comments that could better explain the ontology may be missing.

The FIEMSER data model represents one of the main trends identified in the context of the Smart Appliances study of the SAREF ontology and it is therefore linked to it. However, no license is specified, which may explain the lack of FIEMSER ontology's usage evidence.

The following triples would represent the previously proposed use case example:

```
:building01 rdf:type fi:Building;
  fi:consistOf :floor01;

:floor01 rdf:type fi:BuildingPartition;
  fi:consistsOf :room01.

:room01 rdf:type fi:Space.
```

Although the FIEMSER ontology does not contain the notion of a storey, this may be represented with the class *fi:BuildingPartition*.

3.3.7. Brick Ontology

Brick[72] [79] is a uniform schema for representing metadata in buildings and defines a concrete ontology for sensors, their subsystems and relationships among them. While other ontologies focus on BIM which is more oriented towards design and construction efforts, Brick has a specific emphasis on BMS (Building Management Systems) focused on building operation. The ontology captures hierarchies, relationships and properties for describing building metadata and has a clear focus on commercial buildings.

The design of Brick follows a methodology that combines tagging (like in the Project Haystack[73]) and semantic models. The resulting terminology allows describing real buildings but at the cost of a counterin-

[67] https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/WeatherOntology.owl
[68] https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/EnergyResourceOntology.owl
[69] https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/BuildingOntology.owl
[70] http://www.gbxml.org/schema/5-10/GreenBuildingXML_Ver5.10.xsd
[71] https://sites.google.com/site/smartappliancesproject/ontologies/fiemser-ontology
[72] https://brickschema.org/
[73] http://project-haystack.org/

tuitive hierarchy of classes and a biased set of properties. Moreover, explanatory annotations accompanying term definitions are very scarce. Authors of Brick ontology showcase the effectiveness of their schema by converting six buildings with a wide range of BMS, metadata formats and building infrastructure.

The following triples would represent the previously proposed use case example. Namespace *bf* belongs to BrickFrame, an ontology module imported by Brick ontology.

```
:building01 rdf:type brick:Building;
  bf:contains :floor01.

:floor01 rdf:type brick:Floor;
  bf:contains :room01.

:room01 rdf:type brick:Room.
```

3.3.8. SEAS Building Ontology

The SEAS Building ontology[74] is a module of the SEAS ontology (reviewed in Section 3.1.5) which describes a taxonomy for defining the structure of buildings or more general facilities (e.g. rooms and spaces) and zones related to measurement and control actions. It offers a hierarchy of types of spaces and buildings including offices, educational buildings and buildings categorized based on their energy efficiency such as passive houses and ZEB (Zero Energy Buildings). It leverages the SEAS Zone ontology[75] to describe the relationship between different parts of buildings.

Likewise the rest of the SEAS ontology modules, it has a rich documentation page and ontology metadata which eases its understanding. However, at the moment of writing this survey, the SEAS Building Ontology is not used in any project or known use case.

The following triples would represent the previously proposed use case example:

```
:room01 rdf:type seas:BuildingSpace;
  seas:subZoneOf :floor01.

:floor01 rdf:type seas:BuildingStorey;
  seas:subZoneOf :building01.

:building01 rdf:type seas:Building.
```

The *seas:subZoneOf* object property links a zone to another it is contained in, which may be the inverse to the relationship defined in other reviewed ontologies (e.g. *bot:containsZone*).

3.3.9. SBIM ontology

The Semantic BMS (SBMS) ontology[76] [80] aims to provide a semantic description of the building automation systems and the data available for operation analysis. It contains a simplified model of selected elements from BIM models in the SBIM ontology[77] which is imported by the main SBMS ontology.

The SBIM ontology contains concepts describing locations and parts of facilities adapted from the IFC 4 specification. The representation of BIM individuals are modelled as subclasses of classes defined in BOT (reviewed in Section 3.3.2) using *rdfs:subClassOf* axioms. Authors of this ontology state that BOT serves for SBIM ontology's identical purposes but lacks the representation of site, universal transitive *isPartOf* property and the representation of device types. The first two issues are covered in BOT's version 0.2 by means of the class *bot:Site* and the transitive object property *bot:containsZone* respectively. Therefore, the SBIM ontology could be updated to be defined as an extension of devices that are out of the scope of BOT.

Regarding the ontology's usage, the SBIM ontology (as part of the SBMS ontology) is used to evaluate the environment of a room and an energy efficiency use case at the University Campus of Masaryk University (Czech Republic). Nevertheless, not having a license, the future reuse of the ontology may be hurdled.

The following triples would represent the previously proposed use case example:

```
:building01 rdf:type sbim:Building;
  sbim:hasFloor :floor01.

:floor01 rdf:type sbim:Floor;
  sbim:hasRoom :room01.

:room01 rdf:type sbim:Room.
```

3.3.10. Summary

Ontologies like ifcOWL are necessary to convey data registered in standard formats (like IFC files) to the semantic realm (like RDF files). These ontologies enable the automatic conversion of big quantities of data to leverage capabilities offered by the Semantic

[74] https://w3id.org/seas/BuildingOntology
[75] https://w3id.org/seas/ZoneOntology
[76] https://is.muni.cz/www/akucera/sbms/v1_0/SemanticBMS.owl
[77] https://is.muni.cz/www/akucera/sbms/v1_0/SemanticBIM.owl

Technologies. However, such ontologies may be inadequate for a direct use in some scenarios due to their inconvenient, complex and often counterintuitive conceptualization of data for the task at hand. This aspect has been demonstrated by the triples annotated with ifcOWL to represent the use case example.

In this section, focus is placed in a rather limited scope of the building domain, namely in building topology. However, this did not prevent from finding ontologies re-defining overlapping concepts over and over again.

It is remarkable that many of the reviewed ontologies have the IFC specification as a reference, although the influence on some of them is bigger (e.g. ifcOWL) than on others (e.g. SAREF4BLDG or SBIM). However, there are also ontologies that follow other standards that are more suitable for their use cases, such as ThinkHome's Building Ontology which is based on gbXML or Brick Ontology which follows Haystack project's foundation.

Some ontologies such as DogOnt, ThinkHome and FIEMSER are more focused on the residential sector, while others are more independent from the type of building. Furthermore, there are ontologies that do not represent the notion of a storey (e.g. FIEMSER and SAREF4BLDG) or the relationship between storeys and rooms (e.g. BuildingOntology), which may be rather recurrent concepts when describing the topology of a building.

The number of ontologies that show evidences of their usage in a variety of real-world use cases is rather limited (e.g. BOT and DogOnt), although the rich documentation and metadata puts some of these ontologies in a good position to be reused (e.g. SAREF4BLDG and SEAS Building Ontology). Obviously, ontologies without a license (e.g. ThinkHome, FIEMSER and SBIM) are not in such a good position to be reused in the future.

Table 3 summarizes the reviewed Building domain ontologies.

4. Discussion

A trend towards a pattern-based design tends to produce modular ontologies that are more understandable and more easily extended or reengineered when necessary. The SSNx ontology may be an example of this pattern-based design, and IoT-O and FIESTA-IoT ontologies may be considered extensions of such SSNx. Moreover, when some undesirable design decisions on the SSNx were spotted, its reengineering to the new SOSA/SSN ontology was clearly affordable. ODPs promote the conceptualization of concise and simple ideas that may ease the usage, reuse and extension of ontologies. For example, SmartEnv was developed as SOSA/SSN extensions. SEAS and BOT are other representative ontologies of this pattern-based design.

Potential ontology users may be tempted to design their own ontologies rather than reusing/reengineering an existing one when doubts about the meaning of terms arise. A good documentation increases the understandability and potential usability of ontologies, both by experts in semantics and by people who are not necessarily experts in semantics and languages like OWL or RDF [81]. This documentation can be addressed with the increase of tools for the automatic generation of HTML documentation from ontologies. These tools minimize the efforts of writing proper documentation, and enable the interactive exploration of the ontology with the use of hyperlinks and/or Javascript mechanisms. A clear example of ontologies offering a nice documentation are SOSA/SSN, SEAS, and BOT.

Apart from offering an ontology documentation page, it is of utmost importance to provide proper descriptions of the ontology itself (e.g. authors or version dates) as well as of the classes and properties (e.g. labels and textual definitions) defined in the ontology if its reuse is aimed. Specially in ontologies with a high number of classes and/or properties a lack of careful documentation with explanatory descriptions of the intended meanings of their terms becomes a hurdle to their usage. This situation may be present in ontologies such as DogOnt, ThinkHome, ifcOWL and Brick. Moreover, ontologies that lack of an explicit license that specifies the terms under which they can be used, or worse still, the lack of public access to them, makes ontologies impossible to analize or reuse.

Sometimes vocabularies play a similar role to catalogues. In such cases, a clear definition of the desired scope, a well explained criteria for the term hierarchy and classification, and a comprehensive coverage of the needed concepts makes a difference. The M3-lite taxonomy can be considered an example of these vocabularies.

Finally, the explicit alignment of terms from different ontologies as well as the mapping to upper-level ontologies promotes interoperability. More comprehensive alignments are favoured between clearly conceptualized and well documented ontologies. BOT offers a set of mappings to other domain ontologies

Table 3
Summary of the reviewed Building domain ontologies.

Ontology	Latest Version	License	Documentation	Metadata	Alignments	Use
ifcOWL	2016-12	CC BY 3.0	Yes	No	No	No
BOT	2018-06	CC BY 1.0	Yes	Yes	Yes	Yes
DogOnt	2017-11	Apache 2.0	Yes	No	No	Yes
SAREF4BLDG	2017-01	CC BY 4.0	Yes	Yes	No	No
BuildingOntology (ThinkHome)	2014-03	No	No	No	No	No
FIEMSER	2014-01	No	Yes	No	No	No
Brick	2016-04	Brick license	Yes	No	No	Yes
SEAS Building	2016-05	Apache 2.0	Yes	Yes	No	No
SBIM	2017-05	No	No	No	No	Yes

such as ifcOWL, Brick, and DogOnt. Both SOSA/SSN and SEAS publish collections of precise mapping files to other related ontologies. Unfortunately, few ontologies follow this practice, which may further impede the achievement of an interoperable ontology space. There are even cases such as SAREF, which is claimed to be aligned with other ontologies, even though these alignments are a set of concept pairings in an Excel sheet without an explicit indication of the precise relationship between each pair of concepts.

Summarizing, a concise representation of appropriate concepts, covering an adequately limited scope, accompanied by a well explained documentation, and augmented with the proper and most complete alignment with other related and upper level ontologies, definitely contribute to the reuse of an ontology.

5. Conclusions

This survey focuses on the review of ontologies involved in conceptualizations of observations and actuations. Furthermore, it reviews ontologies describing the building environment as a particular kind of features of interest, and the context of those observations and actuations.

After the review, the following can be concluded:

- The significance of concise representation of concepts covering a limited scope to serve as shared concepts among different ontologies covering the same domain, may ease the communication of actors within the same domain.
- There is a disordered proliferation of ontologies with a poor foundation and covering the same concepts of already existing ontologies. This is definitely an inappropriate tendency that may exponentially difficult the ontology reuse task.
- The importance of an explicit license, and a complete documentation and metadata for ontologies to ease their understanding and subsequent potential reuse is still underestimated. Furthermore, the alignment of ontologies with related ontologies as well as upper-level ontologies to contribute to the interoperability of the solution is yet to be considered essential by design.

Bearing these learnt lessons, this survey aims at supporting novice users to discover IoT domain ontologies to avoid the development of "Yet-Another-Ontology" and to show examples that follow the ontology community best practices when new ontology developments are necessary.

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