A Survey on Information Modeling and Ontologies in Building Automation

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Abstract—This paper investigates research, made on semantic information models for building automation systems. It analyzes what information domains are covered to provide context, the vocabulary provided to describe building automation devices and functions, and how these models are structured. The intention is to find out good practices and try to identify trends, commonalities, differences, and possible next steps.

Index Terms—building automation, information models, ontologies, semantic description, survey, model driven development

I. Introduction

In recent years, an increasing amount of projects and research groups dealt with the semantic description of building automation (BA). In this paper, we take the opportunity to get an overview on the current state of the art, right after many of these projects have ended. The motivation to use semantic descriptions in BA or for automation systems in general are manifold. Those descriptions shall allow capturing data in a structured and machine interpretable manner, which in turn enables new solutions like the following:

- Precise discovery of information in a system of systems
- Ease of commissioning by reducing manual hard-wiring
- Compatibility check and automatic conversion of data
- Use services without specific a-priory knowledge
- Predictive maintenance and fault detection
- Interoperability on syntactic and semantic level
- Flexibility by preventing proprietary solutions
- Re-usability and portability of applications

In order to realize semantic descriptions, a common language has to be defined, including vocabulary and rules how to use vocables together. This can be done using different approaches. UML diagrams, taxonomies, or tags together with some rules might be used. However, the most formal definition of a common language would be to use ontologies. Ontologies are based on description logic; therefore machines can interpret and reason on this form of knowledge representation. In several publications, the usefulness of providing context information in a machine interpretable format has been proven. Ploennigs et al. [1] used an ontology to collect data throughout a building, to drive a physical model. The physical model is learned by an artificial neural network and is finally used for system diagnosis. Dibowski et al. [2] models both, the Building automation System (BAS) and fault detection and diagnostics (FDD) algorithms using the web ontology language (owl). The models are used to match BAS and FDD to compile a statement, if a certain FDD can be applied to a specific BAS or not. If an FDD algorithm is applicable, it will be configured accordingly. The approach is further exploited in [3] to propagate faults throughout the building and to find its root cause. The information gathered by such a system might be used to guide maintenance personnel to where it is needed. Furthermore, in [4] an ontology-based approach is used to set up virtual sensors. This allows capturing properties not directly measured by physical sensors. An easy establishment of event condition action (ECA) rules, for the technical management of buildings, using ontologies is presented in [5]. In addition, many research has been done for (semi-) automated classification of systems in BA environments. Gao et al. [6] proposes an approach to assign tags (classes) from a standard set to sensors in a semi-automated way. This enables a decentralized retrofit mechanism to introduce semantics. Schachinger et al. [7] instead proposes a centralized solution for interoperability between several protocols used in BA based on an ontology.

All these projects require a model for the data, devices, functions, and relations in a unified way. However, all these approaches created or at least modified ontologies for their purpose, which is contradictory towards a unified language. In this paper, we will have a look on the recent advances on BA ontologies and try to identify trends, commonalities, differences and possible next steps.

The paper is organized as follows. First, we will detail our goal in Sec. II. In Sec. III we will have a look at the technologies used in BAS today and how they provide meaning. Further, we will give a short overview on standards about relation and classification of building equipment and functions. Sec. IV will cover research made before 2012, as some of those developments are used by the recent research works. It is followed by an overview on the recent developments in building automation information models in Sec. V. A summary and conclusion is found in Sec. VI.

II. Goals and Research Questions

As already mentioned, most research projects use their own specialized conceptual model to provide context information.

First we want to clarify what exactly context is. Context is any information used to characterize the situation of an entity. Thus, the first question to answer is what are the entities of
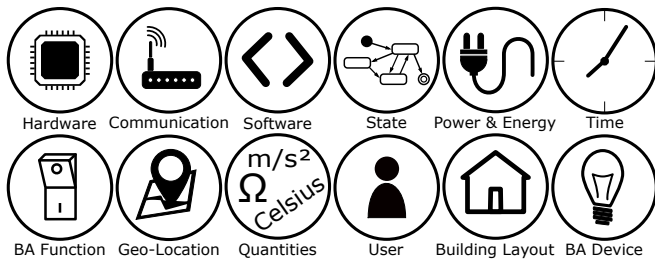
Figure 1. Context Information for Building Automation Devices

interest. In building automation, those are typically automation devices or systems. However, which information belongs to the context of a certain entity primarily depends on the application. The number of applications making use of BA data is steadily growing and thus, the required context information grows too. In Fig. 1 we have collected information domains that are used in the works we will discuss later. However, there is no single model that captures all of those perspectives, depending on the application, a subset is used instead.

In this work, we intend to get an overview on the existing models used to describe BA devices and their context. We will analyze (1) what information domains are covered, (2) the vocabulary provided to describe BA devices and functions, and (3) how these models are structured.

As already mentioned in the introduction, information models can have different representations like UML, a database schema, an ontology, or a tagging system. In this paper, we will mainly focus on ontologies, nevertheless also other representations are contained. Ontologies are based on description logic and thus allow machine readability and reasoning on data. Typically an ontology consists of concepts (terms) with properties and relations between those. In contrast to a taxonomy, which is a hierarchy of terms, ontologies set up a network. Concepts and relations are further supported by axioms (e.g. transitivity, cardinality) to ensure integrity and to allow logic reasoning. Instances of concepts are called individuals. To each individual, the axioms and relations of its concept are applied.

III. State of the Art

Today, many different technologies are used in the BA domain. The most common are BACnet, LON, KNX, ZigBee, Z-Wave and EnOcean. Others can be found as well, typically bus technologies. However, none of those is capable of sufficiently providing a description of device, function and context.

BACnet devices are described as a list of BACnet objects, which are built around data syntax. The BACnet device object properties "location" and "description" are the only possibilities to provide context information. However, those non-standardized strings result in problems regarding different schemes, as mentioned in [8]. Some guidelines have been created [9] but never became a global standard. Currently BACnet-extended data[1] is developed, which has the goal to include semantic tags from arbitrary dictionaries in the future.

A concept of profiles is used in LON[2], Z-Wave[3] and EnOcean[4]. They define a fixed set of device types, functions, and properties. On the one hand, this perfectly defines devices and a common model is set up. However, this only works as long as the device sticks to these profiles. Innovative functions or extended functionality is not possible or requires the specification of new profiles. This ends up in a large number of profiles, like in EnOcean where many profiles exist for thermometers with different measurement ranges. Another drawback is that the context is not reflected at all.

KNX provides a set of common data point types for interoperability purposes. It starts from defined data types (syntax) and assigns specific meanings in certain use cases. As example, a 2-octet float value might be a temperature in degree Celsius ("DPT_Value_Temp"). However, still context information is missing.

National and international standards exist which already specifies a set of BA functions like:

- ISO 16484-3 is specifying BA hardware and functions.
- IEC 61499 defines functional blocks for industrial measurement and control systems.
- IEC 81346 is a coding system for industrial equipment, products, and systems.
- VDI 3813 defines a structural building model and room automation functions.

Furthermore, VDI 3813, introduces the concept of templates. Templates consider several utilization modes (normal, special, out-of-order) for a single room. Each utilization has several use cases (e.g. presentation, reading, not occupied) determining the functions to be executed. A template can then be assigned to individual rooms where a rooms schedule determines what utilization/use case is active at a certain point in time.

All those standards can be used as starting point for vocabulary. However, as they are not formalized, they cannot be used as information model directly.

IV. Early Developments

This section will briefly cover the developments made until 2012. Those serving as blueprint for recent developments or are directly imported. Many developments in this period are dedicated to ontologies, modeling a certain domain. These separate models are self-contained and independent of any specific use case, which allows intense reuse. Others are first attempts to combine several of these independent models to define device systems including their context.

To express physical information, one can refer to the "Measurement Unit Ontology", the "Units of Measure" ontology or the QUDT (Quantity, Units, Dimensions, Types) ontology. They provide measurement systems where physical concepts and related engineering units are described. If there are several units measuring the same concept, often relations between those units exist, to enable automatic conversion. Time related

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[1]BACnet Addendum 135-2016bo

[2]http://lonmark.org/technical_resources/resource_files/spid_master_list
[3]z-wave.sigmadesigns.com/design-z-wave/z-wave-public-specification/
[4]http://www.enocean-alliance.org/eep/

information is also partly modeled. However, time often does not follow the same rules as other engineering units. Thus, a more suitable model is given with the W3C Time Ontology, which is also capable of handling time intervals, duration, time zones, different calendars and so on.

Generic spatial information is covered by a different set of models. The GeographyMarkupLanguage, iso-metadata.owl and others enable to define position, object geometry, multiple reference coordinate systems, and spatial changes.

Another aspect modeled, is the use of services in service-oriented architectures. For that purpose OWL-S and SAWSDL were developed. OWL-S for example models inputs and preconditions to be met before a service can be executed. Furthermore, the resulting output and post-condition can be modeled and thus, it is possible to determine context state changes. In order to relate descriptions to actual implementations, a service grounding using the web service description language (WSDL) can be given.

In order to describe devices, ontologies were created to model hardware capabilities such as CPU load and available memory. Furthermore, displays and communication interfaces were part of those information models. Two examples for this would be the Fipa device ontology and the TransducerML.

Towards ambient and pervasive systems, the need for extendable device descriptions including some context has emerged [10]. W3C "Composite Capabilities/Preference Profiles", SOUPA, and CoBrA were created for that purpose. They model hardware and service capabilities as well as user-preferences to enable intelligent device ensembles to satisfy user needs. Bandara et al. [10] improved those approaches by adding service descriptions based on OWL-S to enable automated service discovery and usage.

However, to plan steps to satisfy user needs it is not enough to provide preferences and device/service capabilities. To capture the environmental context, sensor descriptions were developed like SensorML or W3C Semantic Sensor Network (SSN). Those approaches bind together information on a device, its location, and the physical concept measured as well as temporal aspects. It is to note, that now several domains are put together to model a single entity and its context in a single description. Especially SSN is also nowadays often referenced to create ontologies for device descriptions.

Nevertheless, all of the former mentioned description languages model aspects on a general level. Specifics of the building automation domain are not yet covered.

The Building Information Modeling (BIM) is a framework to support planning and construction of buildings. Its main intention is the modeling of physical structure and used materials. Due to its focus on the physical setup, it is often used for structural analysis, energetic performance simulation, and 2D/3D modeling using CAD tools. The Green Building XML (gbXML) emerged to allow sharing information between BIM and energetic analysis software. To get access to the information included in the BIM model, Industry Foundation Classes (IFC)[11] are used. Those IFC classes are also available as ontology (IfcOWL). As the focus is on spatial and construction related information, this approach is promising but not satisfying for the automation domain. Technical equipment is specified, but only on a conceptual level. In particular, the functional aspects of building automation systems are not part of this approach. The IFC building location model instead might be used for BAS, which decomposes a location into site, building, storey, space, and zone. This decomposition is similar to the one proposed in VDI 3813.

Bonino et al. [12] introduced the Domotic OSGi Gateway Ontology (DogOnt). The focus of DogOnt is the smart home domain. It is based on DomoML and the EHS appliance classifications system for brown and white goods. DomoML enables the description of the environment (walls, furniture), the functionality of domotic devices and correlations between them. Devices are separated into controllable and uncontrollable, whereas controllable objects have state and functionality. Functionality is composed of building blocks containing continuous and discrete control functions for light, blinds, temperature, time, and volume. In [13] DogOnt is further extended by an ontology to model a devices energy consumption in a certain state. Next to the modeled energy consumption the current consumption is also addressed. In 2013, Grassi et al. considered DogOnt the most advanced ontology in the smart home domain [14].

Nevertheless, this solution is not suitable for larger buildings. One drawback is the location which is oriented at room types (bathroom, office, living room) rather than on spatial layout. This hampers a setup in larger buildings as it may lead to ambiguities. Furthermore, DogOnt focuses on devices users are directly interacting with (Dishwasher, TV, etc.). However, those play a minor role in commercial building automation systems. In contrast, systems that do matter in commercial BAS are not modeled, like subsystems of heating, ventilation, and air conditioning (HVAC). The functionality modeled by DogOnt is inherent functionality executed by the device itself but no functionality that can be commanded from outside.

For further reading on ontologies in the smart home, the survey of Grassi et al. [14] goes into more detail.

Ploennigs et al. [15] introduced a layered ontology architecture for BAS. The most abstract and generic level contains conceptual interactions generally known and accepted. On the next level, domain specific components are added, such as automation devices. The next layer adds vendor specific information models. On the most concrete level, information unique to devices is captured. Entities on more concrete layers are subclasses of concepts on the abstract layers. This approach allows mapping several technologies to a unified model. The paper focuses on the approach instead of the vocabulary, so it needs further elaboration for use.

V. RECENT RESEARCH

As seen in the previous section until 2012 no satisfying solution existed to model commercial BAS. However, from 2012 on a number of research initiatives started, working on new models for home- and commercial-BAS, which shall be discussed in the following.

The ThinkHome Ontology[5][16] is dedicated to smart home environments with focus on energy supply and consumption. It contains models for comfort, actor (user), process, energy, resource (devices), external influences (weather), and building structure. Compared to other ontologies the categorization of some classes differs, which makes the learning curve quite high. However, in advance this approach not only focuses on vocabulary for data-, and device-types but also on processes, algorithms and applications.

BOnSAI [17] "Smart Building Ontology for Ambient Intelligence" focuses on service orientation and web services in smart home environments. The main entities designed are either very abstract or specific to web services. Building specific vocabulary is only minimally covered. Altogether, the set of available devices, functions, locations, and environmental parameters is way too limited for commercial building automation systems. Devices may be extended, however, other relevant concept are also not deeply covered.

BASont [18] uses IFC for building location and the Device Description Ontology (DDO)[19]. The approach enables room templates conform to VDI 3813 and is using the concept of function blocks with input output relations. The templates allow for easy reuse, and efficient scaling to large buildings. The solution follows a layered approach, with technology independent concepts on the upper layer, and manufacturer and device specific information on the lowest layer. The device functionality is grounded on web services.

Project Haystack provides tags for BA equipment and a REST API to retrieve them. Those tags comprise Markers to model device types, References, as well as Numbers, Booleans and Strings to be used as properties. The tagging system is easy to use, but it also has some drawbacks. Most important, is is not formally defined how tags have to be used together. Additionally, the majority of tags are for heating, ventilation and air-conditioning (HVAC) systems only. Finally, it is not yet specified how those tags are to be used with established technologies. However, there are plans to integrate them with BACnet XD (extended data). To overcome the drawback of implicit relations in Haystack, the Haystack Tagging Ontology (HTO)[6][20] was created. Based on this approach, also patents are pending in Europe[7], US and China. The openBAS project [21] has created an automatic transformation from primitive metadata to haystack tags.

[22] analyzes IFC, Haystack and SSN regarding completeness, ability to capture relationships and flexibility. The authors conclude, that requirements are only partly covered. Haystack is quite complete regarding HVAC systems and can capture relations in that domain but not in other domains. Further, it is considered less flexible as it can only be extended through the community. SSN is concluded as too superficial regarding completeness, and allows no relationships between assets. However, flexibility of SSN is high and it is the only approach capable of dealing with uncertainty. IFC has a good pareto performance regarding its completeness, however relationships are only done via the spatial model and it is as inflexible as Haystack.

[23] developed a domain model for sense-compute-control applications. The general model is based on an entity of interest, which is observed by sensors, affected by actors, and stored in storage. Sensors, actors, and storage are resources which are provided by devices. A device is further described by a location and a set of software components. A software component is either a computational server, or a driver for a sensor, actor, or storage. The model is on a high level of abstraction, thus domain specific vocabulary is needed (but not provided) for a specific purpose. Nevertheless, systems of systems are not supported in this model.

In [24] and [25] an ontological approach is used for integration in Ambient Assisted Living (AAL) scenarios. Thus, the ontology had to cover medical and home domain. Inspired by the "Integrating the Healthcare Enterprise-Initiative" (IHE) they created profiles based on the SSN-ontology. However, the ontology itself is not available for further investigation.

The European Telecommunications Standards Institute has created the Smart Appliances Reference (SAREF)[8] ontology [26]. The goal of SAREF is to capture the fundamental concepts in the domain of smart appliances. It includes three main sections about (1) devices and their functions, (2) power consumption/production and (3) buildings. To determine the capability of a device, it contains lists of functions (e.g. light switch, temperature sensor). Each function in turn, has associated commands like toggle or get sensing data. This allows more flexible capability modeling but the set of available functions and commands is very limited.

In [5] each data point is addressed according to a "Property-Entity-Location" system. Each data point can then be used in event condition action (ECA) rules as event, condition, and action with the corresponding values. When a "Property-Entity-Location" point is used as action a post-fix for the desired high-level goal is added. As example one point may be "Temperature-Air-Kitchen", an attached ".raise()" would specify the goal to raise the air temperature in the kitchen. However a precise ontology is not given.

Corry et al. [27] created an ontology based on IfcOWL and SSN. This ontology only focuses on concepts to classify measurements of building performance indicators and adds no further concepts regarding building automation.

BRICK [28] was developed based on Haystack and SAREF. It covers sensors and subsystems of typical building automation systems as well as relationships among them. The domains covered by BRICK comprise HVAC, lighting, spatial and power infrastructure and thus is currently the most sophisticated ontology for building automation[9]. The approach follows a pragmatic approach. Instead of providing many different modeling capabilities, the model is kept as simple

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as possible. Data is annotated along four different dimensions: (Data)Point, Equipment, Location and Measurement. The possible relations are limited to seven different kinds of relations to model spatial relationships, composition/aggregation and input- output relationships. This setup makes it easy to model systems without huge learning efforts. However, the authors have shown that the information provided is sufficient to model approx. 98% of building equipment in office- and university buildings needed for the use cases defined in [22]. Technically the BRICK ontology is split into four parts, where: 1) BRICKFrame defines abstract high level classes and relations, 2) BRICK delivers concrete BA equipment classes and their subclass-relations, 3) BRICKTag defines tags and assigns them to the BRICK classes, and 4) BRICKUse defines relationships between concrete classes.

Fernbach et al. [29] created the Secure and Semantic Web of Automation (SeWoA)[10] ontology. It is based on ThinkHome and added security related concepts. Furthermore, it uses the IEC 81346 coding system implemented as ontology for device categorization. This approach intends to enable communication among several protocols like KNX, Lon and BACnet.

A centralized approach to enable technology overarching data exchange is presented in [7]. The authors propose to collect and provide all information on a central instance via a single interface. Technology specific connectors are used to implement this API for different protocols. For this purpose, an Ontology[11] was created based on the results of ThinkHome, DogOnt, BASont and BOnSAI. The result was extended by smart grid related concepts in [30] and integrated in the Colibri building energy management system.

The solution in [31] resides in the Internet of Things (IoT) domain. A similar separation by person, space, appliance, and device is done as in the AAL ontology [24], [25]. Functions are modeled using function blocks containing input and output but also effects on the context. In advance to others also response times and reliability of functions are modeled.

The Building as a Service (BaaS) Project[32] describes data with meta information such as quantity (e.g. Temperature) and engineering unit using QUDT. Data is used by "Features" to describe building automation functions. "Data Points" in turn consist of features, to describe the functionality of a certain device. Furthermore,"Data Points" provide the context called "Building Automation Function" (BAF). The BAF comprises information about the usage domain, spatial information, and type of the building automation function. "Data Points" also model relations as SPARQL queries, utilizing information of features and BAF. "Service types" give information on the implementation details of services.

The Smart Energy Aware Systems (SEAS) Project [33] focuses on energy production, storage, delivery, and consumption. Thus, the developed ontology[12] comprises many related concepts. However, also concepts for the domains of smart

meter, lighting, devices, and building location are contained. SEAS separated its ontologies into one upper ontology and 34 independent ontologies for several sub domains such as architecture, batteries, communication, device, etc.

As rooms and segments are often very similar in buildings with regards to their use, size, and BA-equipment, in [34] a template driven tool is designed, to model and simulate BAS. The templates are based on the shell model and building automation functions of VDI 3813. A template consists of a name and the required building automation functions to be applied. In order to apply the template it is just instantiated multiple times to meet the situation in the building. The templates itself are stored as AutomationML files.

In [35], the authors describe a more general approach to information modeling using ontologies. A "Data Asset" describes exchanged data comprising context, classification, and provenance. The context contains "spatial, temporal, and socio-economical coordinates" based on several ontologies like W3C Time Ontology or NeoGeo. The data is classified according to domain-ontologies, which are not defined by [35]. The "Data Service" describes operations on a certain "Data Assets" including input, output, and fault parameters. A "Data Endpoint" (communication endpoint) is consuming or providing "Data Asset" representations. Their description comprises usage policies, pricing, and provenance. For use in BAS, the classification-, and location-ontology needs to be selected accordingly.

The Web of Things project[13] (WoT), is still in progress and tries to describe devices in the IoT. At its current stage there is no vocabulary defined. On the conceptual layer it is reflected that mainly the technological perspective is covered providing classes for interaction patterns, security, and data schemes.

IPSO smart objects[14] is grounded on RESTful Webservices. The approach is reusing the OMA LWM2M object model, for the creation of these objects a building block approach is taken. Each information is labeled using Object Type ID, Object Instance ID and Resource Type ID. Object Type ID and Resource Type ID are defined in a registry, but can be extended by the community[15]. The approach is very generic, thus no BA specific types and resources are contained.

VI. SUMMARY AND CONCLUSION

To summarize this survey, most of the technologies used in practice today, mainly specify data on the syntax level. The semantic level often only covers a classification of input, output, or configuration parameters. Functional profiles are often either too narrow (no freedom, many similar profiles with minor differences) or too vague (large freedom, low interoperability, ambiguity).

Most of the recent research activities resulted in very similar solutions on the abstract conceptual level compared to each other, even when targeted at smart home. However, sometimes the way of modeling it as an ontology differs as shown in Table

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[10]https://github.com/afernbach/openKB4BMS

[11]https://github.com/dschachinger/colibri/tree/master/colibri-commons

[12]http://ci.emse.fr/seas/

[13]https://www.w3.org/WoT

[14]http://www.ipso-alliance.org/wp-content/uploads/2016/01/ipso-paper.pdf

[15]https://github.com/IPSO-Alliance/pub/tree/master/reg

Table I
ONTOLOGY METRICS (ONLY PROJECTS PROVIDING AN ONTOLOGY)

Ontology	Expressivity	Classes	Object Prop.	Data Prop.	Indivi- duals
Colibri	SROIQ(D)	197	62	22	37
ThinkHomeActor	SROIN(D)	62	50	31	21
ThinkHomeBuilding	ALCIQ(D)	263	237	207	0
ThinkHomeShared	ALCQ	31	5	0	0
ThinkHomeEnergy	SROIQ(D)	549	108	65	31
ThinkHomeProcess	SROIQ(D)	182	68	34	21
ThinkHomeWeather	SROIQ(D)	133	55	41	26
SeWoA	SROIQ(D)	554	117	66	31
SAREF	SROIQ(D)	138	66	36	100
SEAS all combined	SROIN(D)	529	355	83	112
BRICKFrame	ALERI+	12	30	0	0
BRICK	AL	2042	0	0	0
BRICKTag	AL	2347	0	0	0
BRICKUse	AL	2042	0	0	0
BOnSAI	ALCHIN(D)	99	76	41	1
DogOnt	ALCHOIQ(D)	1036	37	72	369
HTO	ALCRIQ(D)	110	64	1	62
IFC	SHIQ(D)	1313	1580	5	1158

I. Sometimes the context is not explicitly modeled, however some projects provide generic classes that can be used to attach any kind of context. This enables flexibility, but lacks certainty required to accomplish interoperability. Thus in these cases further ontologies need to be used. As shown on the left part of Table II, the coverage of the context domains depicted in Fig. 1 slightly varies, depending on their goal and focus. The vocabulary on the lower layers shows even more specialization in one or another direction (see right hand side of Table II). Those differences are mainly caused by the different aspects covered in those projects. Some projects doesn't even provide specialized vocabulary as they focus on very abstract modeling purposes. Following the principle of specialized, reusable sub ontologies the vocabulary and concepts defined in all of the ontologies might be separated into sub-domains and merged between the projects. A goal should be, not to reinvent the vocabulary repeatedly.

Especially device vocabulary is usually repeated, just leaving out some, not of interest for the particular project.

To define functionality, building blocks seem to provide a good tradeoff between flexibility and interoperability. As long as they capture only a single specific function, they can be freely combined to provide flexibility and are still specific enough to be used for interoperability. Inputs and outputs are used in any case when functional blocks are used to model functionality. Some applied a more detailed approach, also incorporating pre- and post-conditions, which is advantageous when machines shall reason what action to take.

Spatial and temporal aspects are considered in almost all ontologies. However, often the spatial dimension focuses on the location of a device. In some cases, also a functional space is assigned (e.g. a zone served by an HVAC System).

Systems are mostly modeled via specific relationships among its individuals (e.g. "AirHandlingUnitOf"). Models using a dedicated concept like "heating circuit" are rare. Brick takes a more generalized approach by modeling flows between entities, as a more flexible way modeling system relationships.

Most difference is seen on the lowest, technology depen-

dent, layer. Some tried to connect the approach of semantics to existing technologies (Web-Services through WSDL or RESTful Services e.g. by bindings to CoAP). Others resulted in a fixed set of commands, or do not even cover this aspect at all. A layered approach as in [15] is the most promising to connect abstract concepts with concrete implementations. Instead of focusing on a single technology, the goal should be, to map all technologies to the conceptual model.

For future research activities, the conceptual layer might be compared in more detail, to see if a mapping or merging on this level is possible. This might be used to form an overarching ontology meeting the needs of all provided use cases. Furthermore, a bottom-up approach can be used to incorporate the vocabulary of all solutions to provide a unified, merged, and thus, more complete set. Vocabulary for transportation and security related devices like elevators, escalators, door locks, or keypads are underrepresented at all, so those might be added. As this merging does not take place at the conceptual level, it will not increase the mental complexity of the ontology. Instead, it provides an increased detail in modeling capabilities. It should be targeted to separate the vocabulary from the conceptual layer. Last, in order to gain significant traction in automation it is not enough to provide a single technology binding. Instead, the formed ontology should be able to be mapped to many technologies, in order to enable true integration capabilities.

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Table II
BA CONTEXT DOMAINS, AND DEVICE-FUNCTIONALITY VOCABULARY COVERED. "O" = LIMITED

Name	BA Device Context Domains										Device-Functionality Vocabulary							
	HW	Comm.	SW	State	Power	Time	Function	Spatial	Quantity	User	HVAC	Light	Elec.	Water	Gas	Transport	Safety	Security
Colibri	-	+	-	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-
ThinkHome	-	-	-	+	-	+	+	+	o	+	o	+	+	+	+	-	+	-
SeWoA	-	+	-	+	+	+	+	+	+	-	o	+	+	+	+	-	+	+
SAREF	-	-	-	o	+	+	o	+	+	-	-	-	-	-	-	-	-	-
SEAS	-	-	-	-	o	+	o	+	o	o	-	+	+	o	o	-	-	-
BRICK	-	-	-	o	-	-	+	+	o	-	+	o	o	+	-	o	o	-
BaaS	-	+	-	-	-	+	+	+	+	-	-	-	-	-	-	-	-	-
BOnSAI	+	+	+	o	+	o	o	o	+	o	o	o	o	-	-	-	-	-
BASont	+	+	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-
DogOnt	-	+	-	+	o	+	+	o	+	o	o	+	o	o	o	-	o	o
Haystack	-	-	-	+	-	-	o	+	-	-	+	o	o	o	o	-	-	-
IFC	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	-
[23]	-	+	-	-	-	+	o	+	+	-	-	-	-	-	-	-	-	-
[27]	-	-	-	-	+	+	o	+	+	-	+	-	-	-	-	-	-	-
[31]	+	-	-	+	+	+	+	+	+	+	-	o	-	-	-	-	-	-
[35]	-	-	-	-	-	+	+	+	-	-	+	-	-	-	-	-	-	-
WoT	-	o	-	o	-	o	-	o	-	-	+	-	-	-	-	-	-	-
IPSO	-	-	-	o	+	+	o	+	+	-	-	o	-	-	-	-	-	-

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