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PROPOSING A CENTRAL AEC ONTOLOGY THAT ALLOWS FOR DOMAIN SPECIFIC EXTENSIONS

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Abstract: In the last years, several ontologies focused on structuring domain specific information within the scope of Architecture, Engineering and Construction (AEC) have emerged. Several of these individual ontologies redefine core concepts of a building already specified in the publicly available ontology version of the ISO standardised Industry Foundation Classes (IFC) schema, thereby violating the W3C best practice rule of minimum redundancy. The voluminous IFC schema with origins in a closed world assumption is likewise violating this rule by redefining concepts about time, location, units etc. already available from other sources, and it is furthermore violating the rule of keeping ontologies simple for easy maintenance. Based on all the available ontologies, we propose a simple Building Topology Ontology (BOT) only covering the core concepts of a building, and three methods for extending this with domain specific ontologies. This approach makes it (1) possible to work with a limited set of core building classes, and (2) extend those as needed towards specific domain ontologies that are in hands of business professionals or domain-specific standardisation bodies, such as the European Telecommunications Standards Institute (ETSI), buildingSMART, the Open Geospatial Consortium (OGC), and so forth.

Keywords: Linked Data, Building Information Modelling, Web of Data, Building Topology Ontology.

1 INTRODUCTION

Design and planning of buildings is a complex and iterative process involving interaction between several stakeholders. A substantial part of the complexity originates from the amount of information to be handled, the number of parties possessing and consuming the information, and the lack of tools that can combine the distributed information, structure the data and present it in a way that is beneficial to the individual building planner (Kiviniemi, 2005). Building Information Modelling (BIM) has been introduced in the industry to overcome this problem. With this introduction, the entire industry is now shifting from an initial BIM stage with single-disciplinary silo models (maturity level 1), to a data-centric BIM stage (maturity level 3) with a purposefully interlinked network of data (Succar, 2009).

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Linked Data technologies allow for this shareable data model to be not one model, but several smaller interlinked models together forming a complete data representation. The partitioning into sub-disciplinary data models solves the issue with several stakeholders needing to specify capabilities of a single building object. It makes it furthermore easier to specify and respect legal responsibilities and intellectual property rights (IPR). Another advantage of linked data is that a vast amount of data is already available online, making it possible to integrate the building models with linked open data such as weather information, physical capabilities of materials, product datasheets, sensor readings, unit conversion and Geographic Information System (GIS).

This paper is situated in this context of interlinking building data using web technologies. Several ontologies have now been specified and proposed, aiming to capture specific knowledge related to buildings (geographical location, sensor data, domotics, construction data, and so forth). The aim of this paper is to review these publicly available ontologies and to clarify how they overlap each other (section 2). In section 3 a simple BOT ontology is suggested, to represent the overlapping building data found in section 2, and in section 4, three different approaches to extending BOT by existing ontologies (GIS and appliances in this article), by linking datasets (each following an ontology) are examined, hence clearly showing how data and ontology reuse can be done for the AEC industry. The approaches are (1) through an upper ontology (2) by defining equivalence classes and (3) by using typed links, and the latter comes out as the preferred approach.

2 Review of Existing Building Ontologies

Recent research projects suggest using web of data technologies for managing building data, thereby making it possible to link interconnected information between disciplines in the AEC domain. Figure 1 shows examples of AEC-datasets that have inter-dependencies with other AEC-datasets. Common for them is that they all consume data about the single components of the building in scope. W3C Best Practices for data on the web (Lóscio *et al.*, 2016) states that in order to increase interoperability and reduce redundancies, reuse of vocabularies should be attempted, but in research projects the same concepts of a building are contradictory redefined repeatedly.

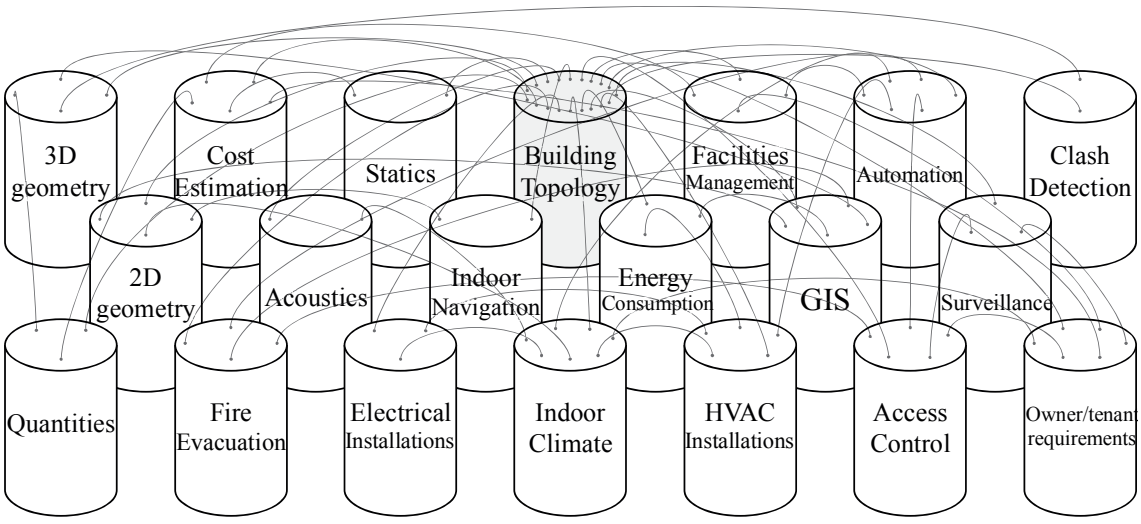

Figure 1: Example of interdependencies between datasets.

In this section a selection of ontologies are examined, specifically aiming to retrieve concepts and classes about buildings. We distinguish between generic ontologies (broad scope) and domain-specific ontologies (narrow scope). The considered ontologies are listed in Table 1 where it is also stated which domain they seek to cover, whether they are accessible online and the name of the building related classes if these are part of the ontology. The offline ontologies are mentioned in the literature, but as they are not publicly available, they are of very limited use in a linked data environment.

2.1 Generic ontologies

Generic ontologies encompass a wide span of concepts to represent knowledge about the world as we know it. One of the largest knowledge bases on the web of data is *DBpedia* which is a community effort to extract structured information from Wikipedia and make it available on the web (Auer *et al.*, 2007). The DBpedia ontology contains classes to describe a *place* and a *building*, but the main purpose of the schema is to define simple facts such as floor area, building type and number of floors, and hence no further details of the building components and their relationships and context to the building can be described. The same accounts for *schema.org*, a joint effort between Bing, Google and Yahoo (Ronallo, 2012), which can only hold information about where a building is located and mainly sees it as a location of a certain service of importance to people. Another widely used example is the *Suggested Upper Merged Ontology* (*SUMO*), a so-called upper ontology or superstructure for information that is true in lots of domains (Pease, no date). Concepts already defined in *SUMO* have been diligently used in some of the domain ontologies described in section 2.2.

The most general schema for describing buildings is IFC (Liebich and Wix, 1999). Several research projects have dealt with the conversion of this schema into an ontology. Pauwels and Terkaj (2016) suggested the *ifcOWL*, and T. M. De Farias, Roxin and Nicolle (2015) suggested the *ifcWOD*, which further simplifies querying. The *ifcOWL* ontology contains 1313 classes and 1580 object properties and besides from defining information about a building, it can also hold data related to time planning, costs, physical units, etc. An ongoing initiative aims at extending the schema to also hold information about roads (Lee and Kim, 2011) and bridges (Yabuki *et al.*, 2006). For the purpose of a simple building representation one may argue that the IFC schema is too extensive, and for the same reason (Pauwels and Roxin, 2016) suggested *SimpleBIM*, which cuts away elements like geometric data and intermediate relation instances between objects. *SimpleBIM* is not an individual ontology, but rather an approach to post-process an *ifcOWL*-compliant RDF graph with a simplified building representation.

A core ontology initiated by the Dutch civil engineering industry called *Cbim* consists of a minimal schema containing class definitions for objects, their properties and their relations (van Nederveen, Beheshti and Willems, 2010). The ontology functions as an upper ontology with the capability of checking that relationship constraints are not violated, and the minimal extent of it means that it should be extended depending on demand. Another general building ontology is the *BIM Shared Ontology* (*BIMSO*), which can likewise serve as a core for domain specific ontologies. It uses the UNIFORMAT II classification system for declaring the classes and is therefore not a minimal schema as *Cbim*, but rather an alternative to IFC (Karshenas and Niknam, 2013).

2.2 Domain-specific ontologies

Domain-specific ontologies limit to very specific domains, in contrast to the earlier mentioned generic ontologies. In a sense, building ontologies such as *ifcOWL*, *BIMSO*, and *Cbim* could be considered ontologies specific to the building domain as well, but they cover a wider domain as they point to ontologies outside the building domain as well (units, geometry, location, etc.). This also happens with, for example, *Geographical Information Systems* (*GIS*) and smart cities ontologies, which typically have a geographical basis that heavily points to buildings. *cityGML*, *DAREED* and *SEMANCO* are examples of ontologies in the smart city domain that include the concept of a building. *cityGML* and *SEMANCO* are the only ones that were available online at the time of writing. *cityGML* has its own definition of a building. *SEMANCO* includes *SUMO* for describing overall concepts like *Building* and *Floor* but defines its own classes for what is not contained in *SUMO* (Madrazo, Sicilia and Gamboa, 2012).

Table 1: Building topology information in domain specific ontologies.

Ontology	Domain	Online	Building	Storey	Room	Elements
DBpedia	World	X	Building	-	-	-
Schema.org	World	X	Civic-Structure	-	-	-
ifcOWL	AEC	X	IfcBuilding	IfcBuildingStorey	IfcSpace	IfcElement
ifcWOD	AEC	-	X	X	X	X
BIMSO	AEC	-	?	?	?	?
CBIM	AEC	X	-	-	-	Object
SEMANCO	Smart cities	X	SUMO: Building	SUMO: Floor	Space	subclasses
cityGML	Smart cities	X	Building	-	-	-
DAREED	Smart cities	-	?	?	?	?
SEAS	Systems	X	Building	Building-Storey	Room	Building-Space-Connection
SAREF	Smart homes	X	-	-	Building-Space	Building-Object
DogOnt	Smart homes	X	Building	Storey	Room	Building-Thing
ThinkHome	Smart homes	X	Building	Building-Storey	Space	Opening, Equipment

With the prevalence of Internet of Things (IoT) technologies, sensors, actuators, meters and home appliances need a common way of communicating with a building to create

so-called *Smart Homes. Smart Appliances REFerence* (*SAREF*) is an example of an ontology in this domain which includes the definition of a building (Daniele, 2015). *DogOnt* is also concerned with home automation, and it defines both controllable and architectural building elements as well as building spaces (Corno and Bonino, 2008). Another ontology, *ThinkHome*, which consists of several smaller domain-specific ontologies, that together shape the *Smart Home Ontology*, is a refinement of the *DogOnt* ontology, extending it with representations for energy information (Kofler, Reinisch and Kastner, 2012). Part of *ThinkHome* is the *Architecture and Building Physics Information* ontology, which represents building information for the scope of Smart Home Systems. It retrieves its classes from gbXML - an XML schema for representing buildings for indoor climate and energy simulations. *OntoFM* is an ontology for sensor-based building monitoring relying on the IFC specification for representing the building, but also inheriting key concepts from *SUMO* (Dibley et al., 2012).

Smart Energy Aware Systems (*SEAS*) consists of several smaller ontologies together forming a whole infrastructure for storing data about systems that consume energy. Part of this infrastructure is the Building ontology, which defines spatial elements of a building, but only the building elements which act as a connection between building spaces. The device ontology further defines controllable devices and sensors. The ontology uses terms defined in *ifcOWL, gbXML* and *SAREF*, but does not extend these ontologies as they are only referred to by *rdfs:seeAlso*.

3 Building Topology Ontology (BOT)

From Section 2, it can be concluded that several ontologies violate the principle of reuse, which might be due to the fact that several ontologies cover the whole AEC domain. Another W3C principle is to keep schemas light for easy reuse. This might be a second key reason why so little ontology reuse is present in the AEC domain. Although a domain-specific and standardised building ontology is available (*ifcOWL*), it is far from simple / reusable. Therefore, we suggest creating a simple *Building Topology Ontology* for easy reuse across the considered domain ontologies. This ontology is made available at (Rasmussen, 2016), and it is a simple ontology only defining the core topology of a building should include the physical and conceptual objects and their relationships. This can be limited to the following concepts:

- A *building* is subdivided into *storeys* and *spaces*
- A space can be bounded by *building elements*
- A space can contain *building elements*

According to these definitions, there is a direct relationship between a space and its adjacent or contained building elements, but relationships to the storey and the building can be inferred by an owl:propertyChainAxiom. The following First Order Logic (FOL) rules or subsets of these can infer *has element*-relationships:

$$\forall b,s,r,e : hasStorey(b,s) \wedge hasSpace(s,r) \wedge adjacentElement(r,e) \rightarrow hasElement(b,e)$$

where b=Building, s=Storey, r=Space, e=Element

Limiting the ontology to 4 key classes and 5 object properties, results in a very simple ontology that can easily be extended by anyone (see Figure 2). Even the ontologies listed in Table 1 are compatible with this ontology, so also they can reuse these key concepts. Such ontology reuse can appropriately stimulate a networked data exchange as explained in the introduction of this paper.

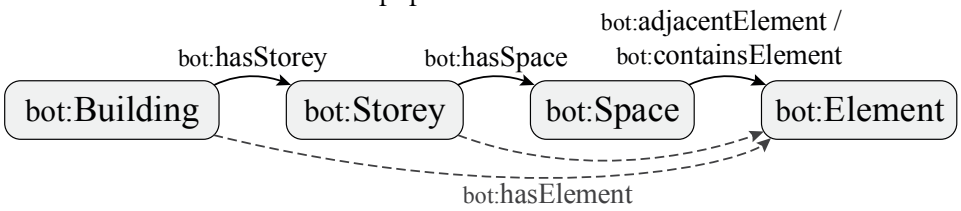

Figure 2: Simple Building Topology Ontology (BOT)

4 LINKING ONTOLOGIES

Several strategies exist for linking separate datasets that represent distinct ontologies. As we now have a situation with a central *BOT* ontology that is to be reused by several of the ontologies from section 2, we need to be specific in how this reuse should ideally take place. Overall, three approaches can be specified for linking data from different ontologies. These approaches are all visualised in the example shown in Figure 3, where a *BOT*-compliant dataset is extended with geographical and appliance data. The same approaches can be used for further extension with *SAREF*, *DogOnt* etc.

The ontology layer, also called the terminological component (TBox) is above the dashed line and the data layer also called the assertion component (ABox) is below.
To the left in Figure 3 the separate ontology abbreviated by a *h* for *heater ontology* has a class h:Heater, which is specified as a subclass of bot:Element. Thereby it inherits the properties of its superclass; in this case the OWL property chain rule defining that the heater is related to the building in which it belongs, given that it is contained in a space of that building (not shown in the figure). This automatically infers the bot:hasElement link from the building. When linking to an upper ontology this approach is used.

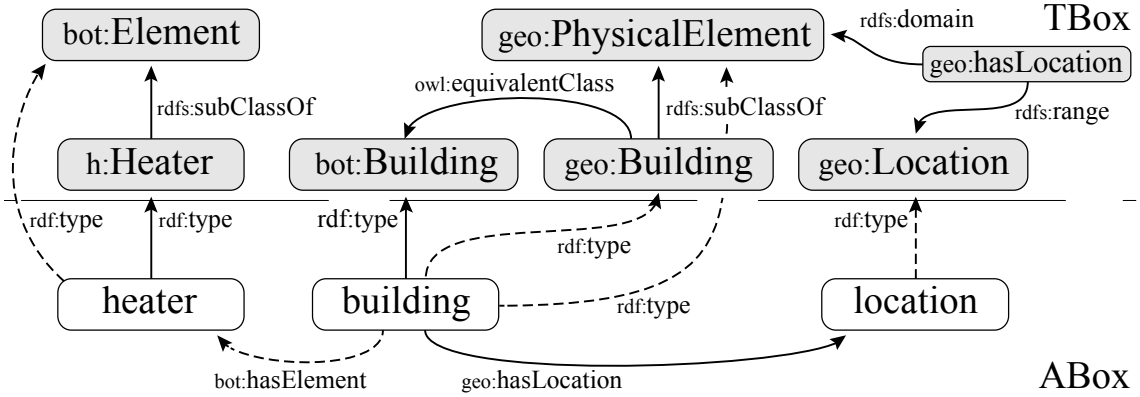

Figure 3: Extending a BOT-compliant dataset with geographical and appliance data.

owl:equivalentClass in the middle of Figure 3 specifies that a class defined in one ontology has an equivalent class in another ontology. The geo:Building class of the *geography ontology* is specified to be equal to the bot:Building class. This statement is

defined in the TBox, hence extending the *BOT* ontology, and it infers the fact that the building instance is of type geo:Building and its superclass geo:PhysicalElement.

Establishing typed links between individuals in the data layer is another approach to combining ontologies. If the GEO ontology specifies the domain and range of the geo:hasLocation property as illustrated, it is inferred that the building instance is a geo:PhysicalElement and the location instance is a geo:Location. The redundant geo:Building class is unnecessary with this approach. One advantage of the typed links approach is that the links are visible at the data layer, giving a better transparency to what is defined.

5 Conclusion

By examining domain specific ontologies in the scope of AEC it was found that they all redefine similar concepts of a building, hence creating overlaps. The suggested simple extendable BOT ontology will help overcome the observed redundancy issues currently violating W3C best practice rules, and it will allow for an easily accessible, extendable base to connect with existing and future domain ontologies, hopefully leading to a wider distribution and a more rapid development of the technology.

Distributed ontologies have several advantages over a one-size fits all, as it makes it possible for domain specialists to develop and maintain ontologies meeting the specific demands, and use of web technologies in addition makes it possible for experts in other industries to have a better interface to the AEC industry. In section 2 specific domain ontologies were investigated, but it would not be hard to imagine new ones in other domains emerging in near future.

Three different approaches to linking ontologies were explained. When extending an existing ontology with new classes, defining them as subclasses of a more general class is applicable as it allows for inheritance of properties. The suggested BOT ontology might benefit from having more specific classes for building related elements in the future as the bot:Element class is tending toward an upper ontology definition, which was not the intention. A starting point could be to define subclasses defined in IFC, and for further detailing more subclasses of bot:Element could be generated in domain ontologies. Establishing typed links was found to be the better linking approach as it provides transparency and omits the redundancy of ie. owl:equivalentClass. It also allows for a direct link between for example sensor data and a bot:Space instance, which can easily be defined by the end user.

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