Paper submitted to the 9th International Semantic Sensor Networks Workshop – SSN 2018.
See https://ssn2018.github.io/ for the reviews, if available,
and a link to the final version if this contribution was accepted.

Integrating Building Information Modeling and Sensor Observations using Semantic Web

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Abstract. The W3C Linked Building Data on the Web community group is studying modeling approaches for the built environment using semantic web technologies. One outcome of this effort is a set of proposed ontologies together providing necessary terminology for the Architecture, Engineering, Construction and Operation (AECO) domains. In this paper, we demonstrate an integration between different datasets described using these ontologies in combination with the standard ontology for representing Sensors, Observations, Sampling, Actuation, and Sensor Networks (SSN/SOSA). In combination, the datasets cover the building's overall topology, 2D plan geometry, sensor and actuator locations and a log of their observations. We further suggest an integrated design approach that enables the designers to explicitly express the semantics of the sensors and actuators from the early stages of the project such that they can be carried on to construction and operation.

1 Introduction

The Architecture, Engineering, Construction, and Operation (AECO) industry involves numerous stakeholders. Each stakeholder generates, consumes and manipulates a shared, distributed project material on which they are all dependent. This dataset continuously evolves, and as the project undergoes different phases (programming, design, construction, operation), it is often handed over to new project participants. Handling a large distributed dataset in a fragmented, temporary organization is a challenge, and as the dataset usually consists of proprietary files, printed documents and the like, the complexity grows. It is a well-established fact that every time the project material is handed over at stage changes data is lost [2].

Building Information Modeling (BIM) is a methodology aimed at minimizing information loss by using technologies to model project data in a structured way.The buildingSMART organization is engaged in the development of industry standards to provide consensus in BIM implementations, and with the Industry Foundation Classes (IFC) schema [4] most terminology for describing a building is provided. However, where IFC is mainly aimed at file-based information exchanges, numerous research projects are focusing on how web technologies can support the dynamic nature of the projects by providing a data-based information exchange [9]. The World Wide Web Consortium Linked Building Data Community Group (W3C LBD CG) engage domain experts in the development of ontologies and modeling approaches, thereby hopefully paving the way for a near-future semantic web-based BIM.

In this work, we present an implementation between three datasets: (1) the architectural model described using the Building Topology Ontology (BOT) including simple plan geometry described using Open Geospatial Consortium (OGC) Well Known Text (WKT) formatted literals (2) containment-relationships between building spaces and sensors/actuators and (3) actual observations from a building in operation. Dataset (2) was established in post-processing by mapping datasets (1) and (3) programmatically, but the ambition is that a semantic web-based BIM can enable the designers to describe the sensor and actuator semantics as part of the design material. Section 4 illustrates an integrated design workflow that supports this goal. Lastly we discuss the potential of a semantic web-based BIM for future smart buildings.

2 Proposed LBD standards

There exists numerous ontologies aimed at the AECO industry and ifcOWL[1] by Pauwels & Terkaj, 2016 [6] is probably the widest adopted. As the name indicates, it is a Web Ontology Language (OWL) version of the IFC schema, and as pointed out by [5,8] it (1) carries on relics from the EXPRESS schema on which IFC is based and (2) covers too broad a scope of which some is already described by widely adopted ontologies (provenance data, units of measure etc.). The Building Topology Ontology (BOT[2]), on the other hand, is a simple ontology aimed solely on describing tangible and spatial elements of a building in their topological context to each other. It is included in the work by the W3C LBD CG among other initiatives such as the PRODUCT[3] ontology for describing building related products and the PROPS[4] ontology describing properties.

BOT was proposed as a central AEC ontology that provides generic terms for specifying any feature of interest in the context of its location in a building [8]. It includes the predicate bot:containsElement which has an owl:propertyChainAxiom stating the element inheritance from sub- to super zones. This property entails that a building inherits all elements contained in spaces of the building, and thereby provides a practical mechanism for establishing an overview of the subcomponents of the building. This is advantageous e.g. for cost scheduling or grouping of Heating, Ventilation and Air Conditioning (HVAC) zones.

In the context of sensors and actuators bot:containsElement is a useful term to describe the location in relation to the building in which they operate. sosa:isFeatureOfInterestOf describes a similar relationship, but this domain specific term is hard to interpret for practitioners of other domains.

3 The datasets

The case model, Navitas, is an educational facility in Aarhus, Denmark. It was completed in 2014, has a footprint of approximately 38,000 m^2 above ground and the BIM model has a total of 1392 spaces. A data dump from the Building Management

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System (BMS) provides a dataset consisting of observations from sensors and actuators for 301 of the building's spaces. The number of observations from the different spaces varies from 7294 to 13855 and are from the period April 18, 2017 - March 4, 2018. Table 1 is illustrating an example measurement.

Table 1: An example of available observations for each space.

Item	Example	Unit
Time	2017-09-16 16:21:54	
Room status	STANDBY	STANDBY/COMFORT
Regulator status	COOLING	COOLING/HEATING
Holding time	1800	s
Air quality	-	ppm
Actual temp.	22.8	degC
Setpoint temp. (calculated)	21	degC
Setpoint temp. (comfort)	21.5	degC
Setpoint temp. (standby)	21.5	degC
Hysteresis temp. (heat)	0.3	degC
Hysteresis temp. (ventilation)	0.3	degC
User temp. (maximum)	23	degC
User temp. (minimum)	19	degC
Radiator opening	0	%
Ventilation flow	100	%
Ventilation unit	VE10	
Minimum ventilation (comfort)	10	%
Minimum ventilation (standby)	10	%
Minimum ventilation (night)	0	%
Boot ventilation	0	%
Actual LUX	450	lux
Desired LUX	300	lux
Light 1	0	%
Light 2	0	%

Besides from the BMS data, the architectural model in the proprietary format of the Revit BIM authoring tool was available. The space numbers used in the Revit model and the BMS system were assumed to match.

4 An integrated workflow

During the design of a building, the low voltage engineer must develop specifications for the BMS. The system must comply with the client's monitoring demands, the capabilities of the HVAC system and the control strategy defined by the indoor climate engineer. Further, it must be aligned with the architectural design. During the design stages these boundary conditions change occasionally, and having a clear up-to-date overview of the design is therefore crucial.

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Establishing a Linked Building Data (LBD) compliant architectural model from the proprietary BIM format was achieved by using the Revit-BOT-exporter[5] described in [7]. 2D space boundaries were exported by implementing a WKT polygon parser implemented in the visual programming environment, Dynamo for Revit. WKT is compliant with geoSPARQL [1] - a SPARQL Protocol and RDF Query Language (SPARQL) for geographic data. This allows for geospatial queries such as finding anything located within the boundaries of a polygon.

Units are described using the CDT Datatypes that leverage the Unified Code of Units of Measures UCUM [3].

Listing 1: Subset of Architect's model

```
inst:level_57d0ded0-4341-4dba-8f32-8dbdcaa9877c-0004879d a bot:Storey ;
   bot:hasSpace inst:room_4b80808e-2f04-46a0-b84d-0ad6ee9d6b1b-0012a494 .
inst:room_4b80808e-2f04-46a0-b84d-0ad6ee9d6b1b-0012a494 a bot:Space ;
   props:identityDataNumber "04.196" ;
   props:dimensionsArea "13.78 m2"^^cdt:area ;
   props:identityDataName "Gr. rum 04.196" ;
   props:spaceBoundary "POLYGON((-3319 14852, -8040 16954, -8226 17037, -8077 13710,
      -4529 12131, -3319 14852))"^^geo:wktLiteral .
```

Since the sensor data was already available (Sec. 3), establishing a SSN/SOSA compliant dataset with mappings to the architectural spaces was just a matter of writing a parser. The mapping table between Uniform Resource Identifiers (URI) of architectural spaces and their room number was created from a simple SPARQL query returning all bot:Space instances and their props:identityData-Number. Listings 2 and 3 show an example of the output. In the example, the dog:TemperatureSensor is used to specify that it is a temperature sensor. An alternative solution to determining the kind of sensor could be to use a generic property `inst:Temperature` instead of the location-specific `inst:room_04.196-Temp`.

Listing 2: Sensor and property data

```
inst:room_4b80808e-2f04-46a0-b84d-0ad6ee9d6b1b-0012a494
   bot:containsElement inst:room_04.196-Temp-Sensor .
inst:room_04.196-Temp-Sensor a sosa:Sensor , dog:TemperatureSensor ;
   sosa:observes inst:room_04.196-Temp .
inst:room_04.196-Temp a sosa:ObservableProperty .
```

Listing 3: Observation example

```
inst:room_04.196-Temp-obs0 a sosa:Observation ;
   sosa:hasFeatureOfInterest inst:room_4b80808e-2f04-46a0-b84d-0ad6ee9d6b1b-0012a494 ;
   sosa:hasResult "22.8 Cel"^^cdt:temperature ;
   sosa:madeBySensor inst:room_04.196-Temp-Sensor ;
   sosa:observedProperty inst:room_04.196-Temp ;
   sosa:resultTime "2017-09-16T16:21:54+01:00"^^xsd:dateTime .
```

In an LBD mediated integrated workflow, the mapping between the architectural spaces and the sensors and their observed properties could be part of the project delivery of the low voltage engineer. Such a workflow could look like the one illustrated in Figure 1. Based on the architectural model, the engineer defines templates for how the

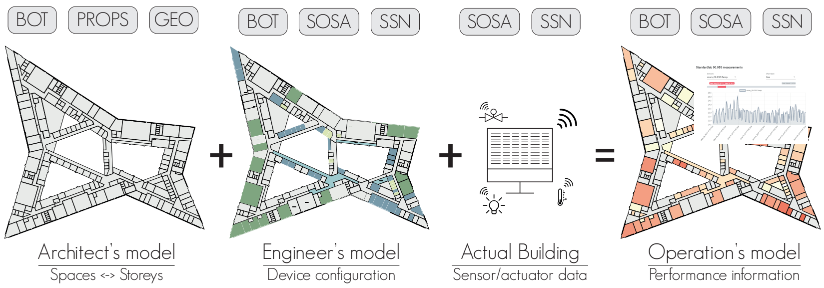

Fig. 1: Integration of the different datasets.

different space types should be equipped with sensors and actuators and potentially what control strategy to use. In a web application (Fig. 2) the engineer defines and assigns these equipment templates to each space, and the graph is extended with sensor and/or actuator instances (Lst. 2).

When following this workflow, sensor URIs exist in the building model prior to the installation phase. With correct mappings between the actual sensors and their digital twins, the semantics are already established when observation logs become available. Observations can therefore be interpreted instantly - even for third-party applications.

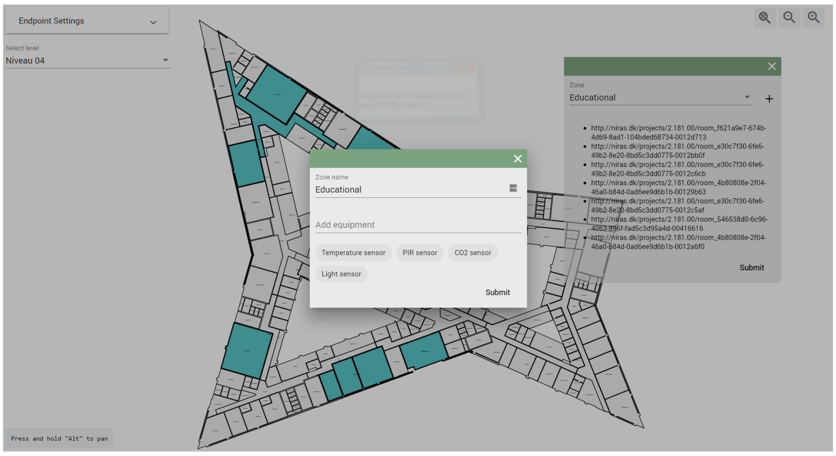

Fig. 2: Application for assigning equipment templates to architectural spaces.

Part of the work presented in this paper is the development of a simple application that integrates the three datasets illustrated in Figure 1. The application first queries all the instances of bot:Storey that bot:hasSpaces which have a props:spaceBoundary assigned. These populate a drop-down list from where the user can select a specific level. When choosing a level, the WKT polygons are retrieved, parsed to geoJSON (OGC) and rendered as a 2D Scalable Vector Graphics (SVG) plan. In parallel, a query for bot:containsElement relationships to sosa:Sensor instances and their sosa:Observations grouped by bot:Space instances is executed to get the maximum temperature in each space. The results are translated to a color grade, which is appended to the 2D plan (Fig. 3).

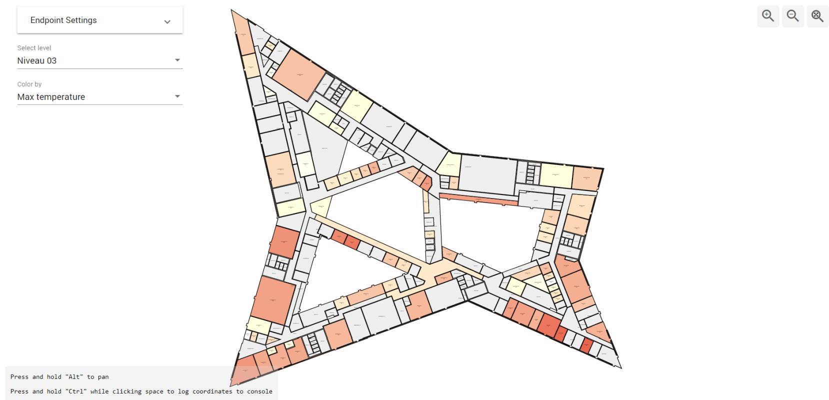

Fig. 3: Plan drawing shown in the web-app. Colors indicate max temperature.

When clicking a space, a line chart view of the sensor data is presented (Fig. 4). A drop-down list is populated with the dcterms:identifier of each sensor and when selecting from this list all the available observations are retrieved and visualized. A slider allows the user to restrict the time range of the observations.

This simple demo application serves as a proof of concept for integrating data from different sources in a web of data based viewer application and although the functionality is limited it showcases the potential.

5 Discussion

The illustrated workflow shows how a BIM model can be enriched with sensors and actuators described with SSN/SOSA. In this work, the sensors and actuators were related to the building in which they operate using BOT semantics, but they could additionally be described in the context of the systems on which they operate. These opportunities bring a new incentive for the engineer to engage in BIM, which is often mistakenly comprehended as only 3D models. Establishing a semantic model of a BMS in the design stages and relating it to the features of interest on which they operate will further provide documentation which is crucial for the overall design overview.

Having the semantics of the BMS available in an open format when the building is put into operation allows for interpreting the observations of the sensors out of the box without the need for an integrated BMS solution. This interpretation separates the devices from the software applications and marks the first step in democratizing

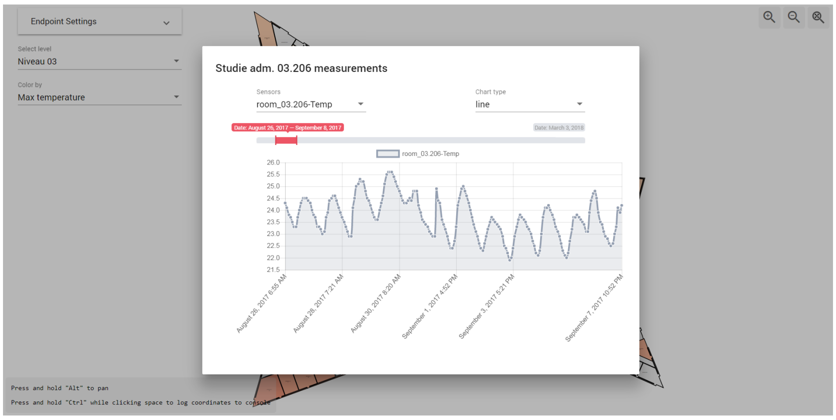

Fig. 4: Illustrate measurements for a given time range.

the market for BMS. It enables building owners to freely choose devices without being tied to one particular manufacturer for the full life cycle of the building and further makes it possible for a new industry to arise as universal, versatile software solutions can be developed.

Designing systems for building automation typically undergoes several stages. Initially, an Indoor Climate and Energy (ICE) engineer simulates the spaces - often only the critical ones regarding internal and solar heat gains, but in some cases also the whole building. When doing such simulations, a control strategy for heating, cooling, and ventilation is applied, and this should be reflected in the actual systems of the building. The capacity of the systems used in the simulation should match the ones described by the HVAC engineer, and the control strategy should be reflected in the description of the low voltage engineer. Installed systems in the building must further be programmed in order to comply with these specifications. The physical design of the spaces often change during the design stages, and this might influence the technical systems. It is therefore crucial that changes are carried on all the way from the ICE engineer to the contractor. Being able to specify the control strategy in an explicit format could significantly reduce the risks in this supply chain.

6 Conclusion

With this work, we present an integration between a building dataset described using proposed Linked Building Data (LBD) ontologies and an SSN/SOSA compliant dataset with sensor and actuator observations. Sensors and actuators are typically not part of the BIM model as it provides only little profit for the overall project. With the showcased integration between the BIM model and the observations, however, there is an incentive for the engineer to model sensors and actuators conceptually. Dedicated tools for assisting in modeling the sensors and actuators in their context of the building, the control strategies, thermal simulations etc. is an future research topic of interest.

The implementation consisted of a 20M triples graph of which the observations were the primary component. Some of the more resource intensive queries like getting the maximum temperature of all spaces at a storey took up to 3.5 seconds, thereby devoting the user experience slightly. This could be solved by doing some pre-processing on the server to infer hourly, daily, weekly, monthly and annual maximum temperatures explicitly. Most queries, however, like getting all observations (5000) from a server ordered by time can be accomplished in less than 500 ms.

Acknowledgements

Special thanks to the NIRAS ALECTIA Foundation and Innovation Fund Denmark for funding and to Michael K. Therkildsen, Aarhus University, for providing the Navitas dataset.

Notes

[1]http://www.buildingsmart-tech.org/ifcOWL/IFC4#
[2]https://w3id.org/bot#
[3]https://github.com/w3c-lbd-cg/product
[4]https://github.com/w3c-lbd-cg/props
[5]https://github.com/MadsHolten/revit-bot-exporter

References

1. Battle, R., Kolas, D.: Enabling the geospatial semantic web with parliament and geosparql. Semantic Web **3**(4), 355–370 (2012)
2. Eastman, C.M., Eastman, C., Teicholz, P., Sacks, R.: BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons (2011)
3. Lefrançois, M., Zimmermann, A.: The unified code for units of measure in RDF: cdt:ucum and other UCUM datatypes. In: Extended Semantic Web Conference (2018), demonstration paper
4. Liebich, T., Wix, J.: Highlights of the development process of industry foundation classes. In: Proceedings of the 1999 CIB W78 Conference (1999)
5. Pauwels, P., Roxin, A.: SimpleBIM : From full ifcOWL graphs to simplified building graphs. In: ECPPM2016. No. October (2016)
6. Pauwels, P., Terkaj, W.: EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology. Automation in Construction **63**, 100–133 (2016). https://doi.org/10.1016/j.autcon.2015.12.003
7. Rasmussen, M.H., Hviid, C.A., Karlshø, J.: Web-based topology queries on a bim model. In: LDAC2017–5th Linked Data in Architecture and Construction Workshop (2017)
8. Rasmussen, M.H., Pauwels, P., Hviid, C.A., Karlshoj, J.: Proposing a central aec ontology that allows for domain specific extensions. In: Joint Conference on Computing in Construction. vol. 1, pp. 237–244 (2017)
9. Redmond, A., Hore, A., Alshawi, M., West, R.: Exploring how information exchanges can be enhanced through cloud bim. Automation in construction **24**, 175–183 (2012)