TUBES System Ontology: Digitalization of building service systems

Nicolas Pauen[1], Dominik Schlütter[1], Jérôme Frisch[1] and Christoph van Treeck[1]

[1] Institute of Energy Efficiency and Sustainable Building - E3D, RWTH Aachen University, Mathieustr. 30, 52074 Aachen, Germany
pauen@e3d.rwth-aachen.de

Abstract. Building service systems are complex structures with varying relationships between different components. In the design, planning, construction, commissioning and operation of these systems, many stakeholders with different interests and information needs have to work together, which further increases the overall complexity. Building Information Modeling (BIM) was introduced to enhance the interoperability providing a machine-readable representation consisting of semantical, geometrical and alphanumerical information. Semantic web technologies enable further improvement of the interoperability by linking information on data level using a global unique identification key in a web-based decentralized data store. To contribute to these developments, a brief literature review covering representations of building service systems such as IfcOWL, BRICK, SAREF and a comparison of their scopes and core concepts is given. Based on these findings, recent developments regarding the TUBES system ontology (TSO) and their alignment to the Building Topology Ontology (BOT) are presented. TSO strives to represent interconnected building service systems and their exchange of energy, mass and data on different levels of granularity based on the general system theory. The ontology is validated using a real-life project.

Keywords: Linked Data, TUBES System Ontology, TSO, Building Information Modeling, building service systems.

1 Introduction

Building service engineering is an essential part of the Architecture, Engineering, Construction and Operation (AECO) industry and contributes to approximately 25% of the construction costs depending on the building type [1]. It is responsible for the design, planning, installation and operation of technical systems in buildings. These systems can be characterized as complex structures which consist of interconnected subsystems and components with varying relationships. Building services engineering strives to minimize the environmental impact of buildings and offers the possibility for active sustainability through intelligent planning of building service systems and their interconnections.

During the whole life cycle of these systems, many stakeholders with different interests, information needs, and specialized software products have to work together, which further increases the overall complexity [2]. Vast amounts of data are generated, exchanged and processed. To handle this, a seamless digital transfer of information is a fundamental necessity.

Building Information Modeling (BIM) is a methodology to provide structured digital information in a machine-readable way [3]. To reach level 3 in the maturity matrix proposed by Bew and Richards [4], data must be exchanged via web using open standards and decentralized model servers, which allow to link information on a data level from different domains. A research approach to cover these requirements is the adaptation of Semantic Web and Linked Data technologies [5].

Semantic web technologies (SWT) aim to create structured connections between different sources of information by using URIs as identifiers and ontologies as a structural grammar to define relationships, usually based on the Resource Description Framework (RDF). This enables the integration of heterogenous AECO datasets from different stakeholders into a web of building data.

Current representations of building services systems using SWT do not cover all concepts required for a holistic system model of the general system theory [6] and an integral description of interconnected technical systems. To fill this gap the authors present the TUBES System Ontology (TSO), which aims at explicitly defining the topology of interconnected building service systems and to link these with the spatial structure.

The remainder is structured as follows: in Section 2, a state of the art review is presented, before Section 3 deals with the recent developments of the TUBES System Ontology. A validation of TSO using a real-world project in given in Section 4 and a conclusion and outlook is presented in Section 5.

2 State of the Art

Over the recent years, the use of semantic web technologies has notably increased in the AECO industry [7]. An important contribution is the Building Topology Ontology (BOT) [8] of the W3D LBD CG [9] which aims at being the key entry point to connect the AECO sector to other domains. The following section will solely focus on ontologies describing aspects of building service systems using the aspects given in table 1 as guidelines. A detailed overview of ontologies describing building service systems is given in Esnaola-Gonzalez et. al. [10].

An early approach to integrate SWT into BIM was the IfcOWL ontology by Beetz et al. [11, 12]. The scope of IfcOWL was to implement the current IFC standard and enhance the interoperability within the AECO industry. IfcOWL features components and systems as separate classes. A system is defined as a network designed to receive, store, maintain, distribute, or control the flow of a distribution media [12]. A classification scheme for systems is provided and they can be hierarchically ordered. IfcOWL provides the means to describe topological connections, but the input and output of systems or components cannot be defined. States of systems and corresponding source or sink connections cannot be explicitly defined as well.

Table 1. Evaluated Aspects

ID	Aspect
EA1	There is a concept to describe systems
EA2	There is a concept to describe topological connections between systems.
EA3	There is a concept to describe elements of the spatial structure
EA4	Systems can be hierarchically ordered and classified based on their hierarchal level
EA5	A classification scheme, which included HVAC, MEP and electrical/data systems is provided
EA6	The input and output of systems can be defined in regard to the topological connection
EA7	Sources and sinks of systems can be defined in regard to the system
EA8	There is a concept to describe possible states of these systems

The Smart Applications REFerence (SAREF) ontology is a shared model of consensus that facilitates the matching of existing assets in the smart applications domain [13]. The scope of SAREF is to explicitly specify recurring core concepts in the smart applications domain and the relationship between those concepts. It consists of one core ontology, an ontology pattern to describe systems based on SEAS [14] and 10 extensions for e.g. the energy and building domain. SAREF features components, named devices, and systems. A system is defined as virtually isolated from the environment, whose behavior and interactions with the environment are modeled. Therefore, a system is more than just an aggregation of devices. A classification scheme for systems is not provided. A classification scheme for devices is implemented based on IFC within the SAREF4BLDG extension. SAREF provides the means to describe topological connections between systems, but a specific input and output cannot be defined. Also, for SAREF, it is not possible to describe source and sink connections and the range concept for states infers that it is connected to a device.

Another approach to describe buildings and their service systems is the BRICK ontology [15]. It has the scope to standardize semantic descriptions of the physical, logical and virtual assets in buildings and the relationships between them. BRICK features components, named equipment, and systems. A system is defined as a combination of equipment and auxiliary devices by which energy is transformed so it performs a specific function such as HVAC, service water heating, or lighting. A hierarchical classification scheme for systems is provided to some degree. BRICK provides the means to define topological connections and describe the input and output by assigning a substance to the systems or components, which is not linked to a defined connection. Describing the state of a system or source and sink connections are not possible.

The Flow System Ontology (FSO) is an approach mentioned but not detailed in Rasmussen et al. [8]. It is currently under development and not published yet. The following description is based on the unofficial draft from February, 26th 2021 [16]. The scope of FSO is to describe interconnected systems with material or energy flow connections, and their components. FSO features components and systems. A system is defined as logical collections of components, which may have attributes such as design specifications assigned to them. Systems may be divided into subsystems, and subsystems may be counted as a part of multiple supersystems. A classification scheme for systems is not provided. Systems can be hierarchically ordered and the topological connections between them can be described. Input and output can be further detailed into thermal energy, electrical charge and fluid. Source and sink connections can be defined but it is not possible to describe the state of systems. A comparison of the presented ontologies is shown in table 2.

Table 2. Comparison of ontologies describing building service systems (+: included, o: partially included)

Aspect	**IfcOWL [12]**	**SAREF [11]**	**BRICK [15]**	**FSO [16]**
EA1	+	+	+	+
EA2	+	+	+	+
EA3	+	+	+	
EA4	o	o	o	o
EA5	o		o	
EA6				
EA7				+
EA8		+		

3 TUBES System Ontology (TSO)

The scope of the TUBES System Ontology is to explicitly define the topology of interconnected building service systems and to link these with the spatial structure. The first version of TSO was published in 2020 [17]. The current development version (v0.2) of TSO [18] consists of 24 classes, 69 object properties and 1 data property. The latest version is documented and available at its Uniform Resource Identifier *https://w3id.org/tso*. The preferred prefix *tso:* is used for the namespace *https://w3id.org/tso#* in this paper.

3.1 Core Concepts

The high-level terminology of TSO is shown in Fig. 1. It has three main classes *tso:Zone*, *tso:State* and *tso:System*. A *tso:Zone* is defined as a part of the physical world or a virtual world that is inherently both located in this world and has a 3D spatial extent. The inverse object properties *tso:serves* and *tso:servedBy* define relationships linking systems and zones to describe that a zone is served by a system, respectively a system serves a zone. *tso:locatedIn* and *tso:contains* define relationships to describe that a system is located in a zone, respectively a zone contains a system. *tso:State* defines the planned internal condition of a component or abstract system. To link a state to a system, respectively a system to a state, the inverse properties *tso:stateOf* and *tso:hasState* are defined. A *tso:System* is a model of a whole which is isolated from the world or a supersystem, which may consists of interconnected components or subsystems and has attributes such as inputs, outputs and states. Within this definition there are three main concepts which are further detailed in the following sections.

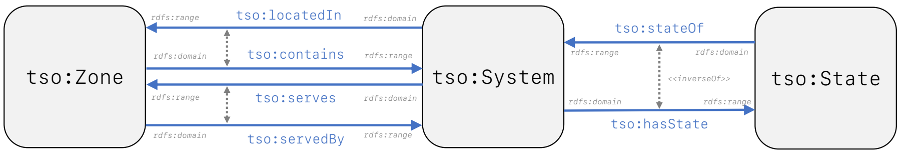

Fig. 1. High-level terminology of TSO

Hierarchical Concept. The hierarchical concept describes a system as a model of a whole which is isolated from the world or a supersystem. To fulfill this concept and describe the hierarchy, *tso:subSystemOf* defines a relationship linking a system to its supersystem. *tso:hasSubSystem* is defined as the inverse of *tso:subSystemOf* and describes a relationship linking a system to its subsystem. Both object properties have their range and domain defined as *tso:System*. The hierarchical concept is shown in Fig. 2.

Structural Concept. The structural concept describes a system as a model of a whole which may consist of interconnected components and subsystems. To fulfill this concept, systems and components need to be distinguished and their interconnections need to be defined, whereas the hierarchical structure is already defined in the hierarchical concept. A *tso:Component* is defined as a model of a whole which is isolated from the world or a supersystem, which may consists of interconnected components or sub-systems and has attributes such as inputs, outputs and states. The boundary which isolates the component from the world or a supersystem is defined by the manufacturer with regards to the product aspect. Therefore, *tso:Component* is defined as a sub-class of *tso:System*. To further classify different components, concepts from ontologies like IFCOWL [12] or BRICK [15] need to be implemented.

tso:connects is a symmetric property defined as a relationship linking systems to describe their topological connection. Domain and range of *tso:connects* is defined as *tso:System*. The structural concept is shown in Fig. 2.

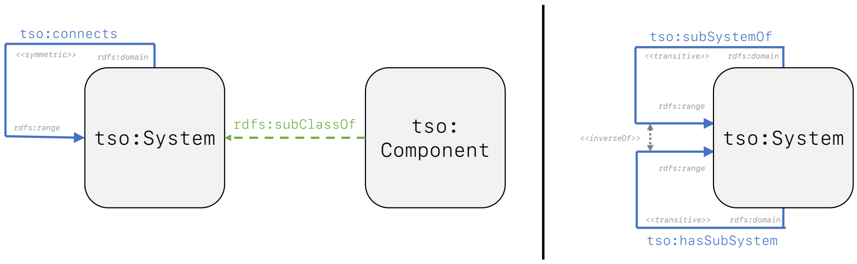

Fig. 2. Structural and Hierarchical concept of TSO

Functional Concept. The functional concept describes a system as a model of a whole which has attributes such as inputs, outputs and states. *tso:State* defines the planned internal condition of a component or abstract system. Multiple states can be defined for one system. This includes specific aspects as on, off, open or closed as well as general aspects such as outdoor-air-operation, mixed-air-operation or heating-operation. Hence, *tso:State* adds another layer of abstraction to describe building service systems which can be operated in more than one manner. To describe the hierarchy of states, the inverse object properties *tso:hasSubState* and *tso:subStateOf* are defined linking a state to its substate or superstate. The domain and range of these object properties are defined as *tso:State*. To further detail different states, their characteristics, control strategies and changes over time, the ontologies described in Schneider et. al. [19] or SAREF can be used.

To describe inputs and outputs of systems, multiple sub-properties of *tso:connects* are defined. On the first level, the three object properties *tso:exchangeData, tso:exchangeEnergy* and *tso:exchangeMass* are distinguished, which are symmetric properties. *tso:exchangeData* defines a relationship linking systems to describe that the systems exchange data. It can be further detailed by the inverse sub-properties *tso:suppiesData* and *tso:dataSuppliedBy*, which define a directed flow of data.

tso:exchangeMass defines a relationship linking systems to describe that the systems exchange mass. *tso:suppliesMass* and *tso:massSuppliedBy* are inverse sub-properties of *tso:exchangeMass* to define a directed flow of mass between interconnected systems. To describe which kind of mass is exchanged, 12 sub-properties are defined, differentiating between a solid mass and a fluid mass. The fluid mass can be further detailed into a liquid mass and a gaseous mass. For each classification of mass (*[]*), a symmetric *tso:exchange[]* property and its inverse sub-properties *tso:supplies[]* and *tso:[]SuppliedBy* are defined. For example, *tso:suppliesFluid* and *tso:fluidSuppliedBy* are the inverse sub-properties of *tso:exchangeFluid*.

To describe a relationship linking systems which exchange energy, the symmetric object property *tso:exchangeEnergy* is defined. It can be further detailed by its inverse sub-properties *tso:suppliesEnergy* and *tso:energySuppliedBy*, which define a directed flow of energy between interconnected systems. Energy is further classified into thermal energy, electrical energy and mechanical energy. For each of these energy classifications (*[]*) a symmetric *tso:exchange[]* property and its inverse sub-properties *tso:supplies[]* and *tso:[]SuppliedBy* are defined.

Connections between Systems which are capable of a bi-directional flow can be described using the *tso:exchange[]* properties on the level of components. Depending on the use of functional and technical systems a bi-directional flow may not affect the definition of directed flows of energy, mass or data between them.

The data property *tso:hasDataPointKey* defines a relationship which assigns a reference designation to a system. The domain is defined as *tso:System.* The functional concept is shown in Fig. 3.

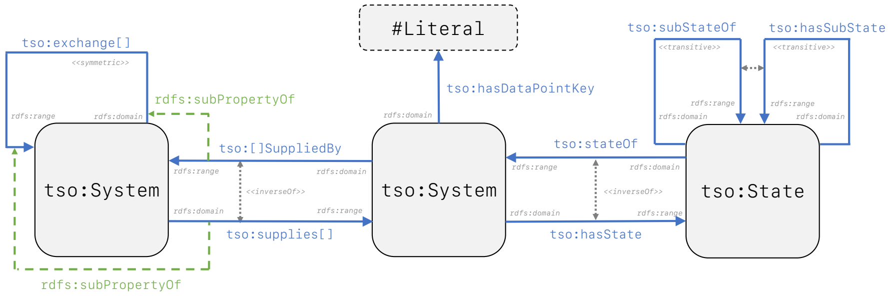

Fig. 3. Functional concept of TSO

Sources and Sinks. Systems can be defined as a source or a sink. Since this classification is depending on the perspective, e.g. a heat exchange or a tank can be a sink for a downstream component and a source for an upstream component, it needs to be defined with regard to the considered system. Hence, the object properties *tso:hasSource* and *tso:hasSink* define relationships identifying the source, respectively the sink of a system. *tso:sourceOf* and *tso:sinkOf* are defined as their inverse properties identifying the corresponding system of a source or a sink. All of these object properties have their domain and range defined as *tso:System.*

Linking systems and zones. As shown in Fig. 1, *tso:Zone* and *tso:System* can be linked via *tso:serves* and *tso:servedBy.* To further detail what is served by a system, 10 sub-properties are defined for *tso:serves* and *tso:servedBy,* respectively. The same classification scheme as for the sub-properties of *tso:connects* is implemented. *tso:serves* is distinguished into serving mass, solid, fluid, gas, liquid, energy, thermal energy, mechanical energy, electrical energy or data. The domain is defined as *tso:System* and the range as *tso:Zone.* The corresponding inverse property *tso:servedBy* is detailed into mass, solid, fluid, gas, liquid, energy, thermal energy, mechanical energy, electrical energy or data. The domain is defined as *tso:Zone* and the range as *tso:System.*

Classification of systems. Systems can be either classified by their overall function (*tso:FunctionalSystem*) or the technical solution by which the function is fulfilled (*tso:TechnicalSystem*) [20]. The technical solution can be specified by taking the Input (X), the Output (Y) as well as the time and space of the input (TX/SX) and output

(TY/SY) into consideration [6]. If X = Y, SX = SY and TX ≠ TY it is a *tso:StorageSystem. tso:DistributionSystem* is defined by X = Y, TX = TY and SX ≠ SY. It can be further detailed into a *tso:SupplySystem* and a *tso:ReturnSystem.* If X ≠ Y it is a *tso:ConversionSystem.* A conversion system can be further detailed into a *tso:EnergyConversionSystem* and a *tso:MassConversionSystem*. An overview of the technical systems and the defined functional systems is shown in Table 3.

Table 3. Overview of system classifications

Technical System	Functional System
Storage System	Heating System
Distribution System	Cooling System
Supply System	Ventilation System
Return System	Sanitary System
Conversion System	Fluid System
Energy Conversion System	Drainage System
Mass Conversion System	Safety System
	Electrical System
	Data System
	Automation System

3.2 Alignments

TSO is designed to work as a central ontology describing the topology of interconnected building service systems and to link these with the spatial structure. The aim is to integrate with existing ontologies, which further specify certain concepts. As an example, the alignment to BOT is presented in this paper. Further alignments, which are provided as separate ontologies, can be found in the documentation [18].

The scope of BOT is to describe the core spatial topology concepts of buildings. *tso:Zone* is equivalent to the *bot:Zone* concept, as it is defined to be an *owl:equivalentClass*. Furthermore, *tso:Component* can be specialized from *bot:Element*, since *tso:Component* covers product and devices which are described in the context of a building as well. To describe the hierarchy between different systems, *tso:hasSubSystem* can be specialized from *bot:hasSubElement* and, to describe spatial relationships, *tso:contains* can be specialized from *bot:contains*.

4 Validation

TSO is implemented and validated using a real-world testbed for potable hot water (PWH) and potable cold water (PWC) systems, which consists of over 1,500 components. The corresponding BIM model and a schematic view on a subset of this testbed is shown in Fig. 4.

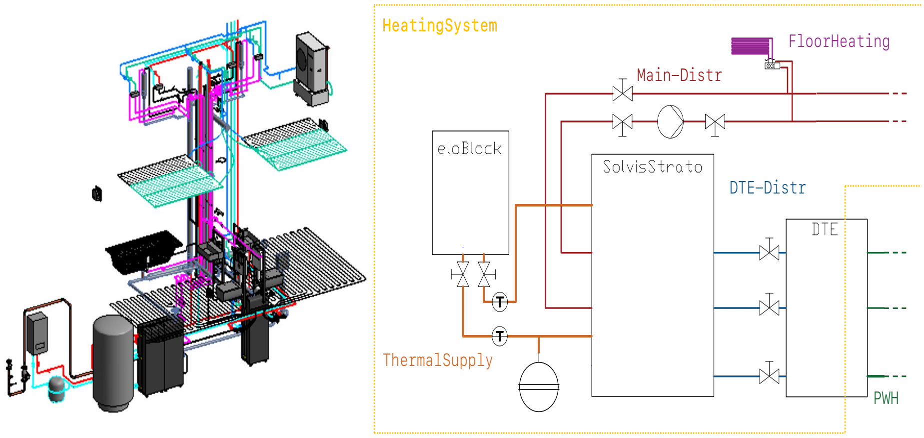

Fig. 4. Application example

The testbed contains a heating system using various components and subsystems. A stratified tank (Solvis Strato) is used to buffer the heat generated by the electric heater (eloBlock) in the Thermal Supply system and make it available to the DTE-Distr and Main-Distr systems. The tank can be defined as a *tso:Component.* It has a label Solvis Strato linked via *rdfs:label* and a reference designation key linked via *tso:hasDataPointKey*. It is hierarchically structured as part of the ThermalSupply, DTE-Distr and Main-Distr systems using the *tso:subSystemOf* relation. Each of these systems can be further characterized as *tso:EnergyConversionSystem* for the Thermal Supply system or *tso:DistributionSystem* for the DTE-Distr, Main-Distr and FloorHeating systems as well as *tso:subSystemOf* of the HeatingSystem. The tank is defined as *tso:sinkOf* of the ThermalSupply system and *tso:sourceOf* the Main-Distr and DTE-Distr systems. It exchanges a liquid to the connected components described by the relationships *tso:exchangeLiquid*. The pump can be defined as a *tso:Component* as well and is linked to the upstream pipe segment (*tso:Component*) by *tso:suppliesLiquid* and to the downstream pipe segment (*tso:Component*) via *tso:liquidSuppliedBy.* To describe the supply of mechanical energy by the pump, it can be linked to the Main-Distr system via *tso:suppliesMechanicalEnergy*. The supply of thermal energy between the components and systems is represented via the *tso:suppliesThermalEnergy* relationship. It links for example the ThermalSupply system to the DTE-Distr system and subsequently to the PWH system, which is defined as a *tso:SanitarySystem*. The PWH system is serving a zone in which some of the components are located. A brief representation of the application example using the TSO is presented in Fig. 5. The whole representation of the testbed in the turtle syntax and the following SPARQL queries can be found in the documentation of TSO [18].

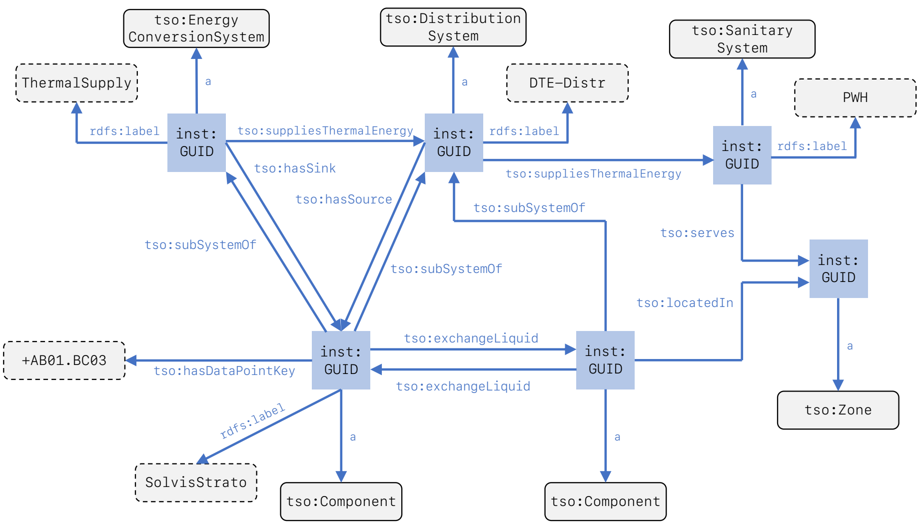

Fig. 5. Application example using the TSO

Example SPARQL queries which were implemented are described below. To select the planned states of a system, the following query can be used:

```
SELECT ?state WHERE {inst:GUID tso:hasState ?state}
```

The location of the first valve, which is located downstream of the component serving thermal energy to a zone can be selected by this query:

```
SELECT ?z WHERE {inst:GUID tso:thermalEnergyServedBy ?c .
                 ?c tso:liquidSuppliedBy+ ?c2 .
                 ?c2 a ifc:IfcValve .
                 ?c2 tso:locatedIn ?z .
                 ?z a tso:Zone }
                 LIMIT 1
```

The following query to be used to select the location of the source of the electrical system, which supplies electrical energy to this valve:

```
SELECT ?z WHERE {inst:GUID tso:subSystemOf ?s .
                 ?s a tso:ElectricalSystem .
                 ?s tso:hasSource ?c .
                 ?c tso:locatedIn ?z .
                 ?z a tso:Zone}
```

This shows that TSO is capable of describing complex interconnected building service systems and to link these with the spatial structure. The SPARQL queries visualize the accessibility of this information, which can be used to gain a deeper understanding of the underlying system.

5 Conclusion

This paper presented a brief literature review covering representations of building service systems using SWT. Based on these findings, developments leading to the current version 0.2 of the TUBES System Ontology are shown. It is designed to work as a central ontology which aligns with existing developments like IfcOWL, BOT or SAREF to further specify concepts, e.g. classification schemes for components, spatial structures and states. To validate the concepts of TSO, an application example based on a real-world project is presented. It is shown that TSO provides the means to describe hierarchically structured building service systems and their interconnections as well as the flow of mass, energy and data. It is capable of defining sinks and sources and can be used to connect this functional knowledge to the corresponding spatial structure. It can be used in the AECO industry to structure building service systems throughout their whole life cycle starting in the design phase by introducing multiple levels of granularity. This allows for a better handover of knowledge and an integral understanding of how different systems are interconnected and exchange matter, data and energy on different levels. Moving down the hierarchy gives a more detailed explanation of the system, while moving up the hierarchy gives a deeper understanding of its meaning.

Currently, the focus of TSO is set and only validated for HVAC, mechanical and plumbing systems. Electrical and data systems can be defined as well, but the concepts need to be validated on the corresponding structures which is part of future work. Furthermore, TSO shall be implemented on a large-scale project with over 60,000 components to identify possible enhancements for simplifying the representation of the hierarchical structure. Another field of future work is to revise the pipeline to convert information from IFC to TSO shown in [17] to support the presented developments.

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References

1. Orth, D.L., Maines, C.: A need for expansion: Mechanical and electrical courses. In: Proceedings of the Associated Schools of Construction, pp. 1-8, Gainesville (2009).
2. Bertelsen, S.: Construction as a complex system. In: Proceedings of the 11th Annual Conference of the International Group for Lean Construction, pp. 143-168 (2003).
3. Sacks, R., et al.: BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers. 3rd edn. John Wiley & Sons, Inc. Hoboken, USA (2018).

4. Bew, M., and Richards, M.: Bew-Richards BIM maturity model. In: BuildingSMART Construct IT Autumn Members Meeting, Brighton, UK (2008).
5. Berners-Lee, T., Hendler, J., Lassila, O.: The semantic web. Scientific American 284(5), 34-43 (2001).
6. Ropohl, G.: Allgemeine Systemtheorie – Eine Systemtheorie der Technik. 3rd edn. Universitätsverlag Karlsruhe, Karlsruhe, Germany (2009).
7. Pauwels, P., Zhang, S., Lee, Y. C.: Semantic web technologies in AEC industry: A literature overview. Automation in Construction 73, 145-165 (2017).
8. Rasmussen, M. H., et al.: BOT: the Building Topology Ontology of the W3C Linked Building Data Group, Semantic Web 12(1), 143–161 (2020).
9. W3C Linked Building Data Community Group, https://w3c-lbd-cg.github.io/lbd/, last accessed 2021/04/13.
10. Esnaola-Gonzalez, I., Bermúdez, J., Fernandez, I., Arnaiz, A.: Ontologies for observations and actuations in buildings: A survey. Semantic Web 11, 593-621 (2020).
11. Beetz, J., van Leeuwen, J., de Vries, B.: IfcOWL: A case of transforming EXPRESS schemas into ontologies. Artifical Intelligence for Engineering Design, Analysis and Manufacturing 23(01) (2008).
12. Industry Foundation Classes 4 ADD2 TC1, https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL, last accessed 2021/06/22.
13. Daniele, L., den Hartog, F., Roas, J.: Created in Close Interaction with the Industry: The Smart Appliances REFerence (SAREF) ontology. In: 7th International Workshop Formal Ontologies Meet Industries, pp. 100-112, Springer International Publishing, Berlin, Germany (2015).
14. Lefrançois, M.: Planned ETSI SAREF Extensions based on the W3C&OGC SOSA/SSN-compatible SEAS Ontology Patterns. In: Proceedings of Workshop on Semantic Interoperability and Standardization in the IoT (2017).
15. Balaji, B., et al.: Brick: Towards a Unified Metadata Schema For Buildings. In: Proceedings of the 3rd ACM International Conference on Systems for Energy-Efficient Built Environments, pp. 41-50, New York, USA (2016).
16. Flow System Ontology, https://alikucukavci.github.io/FSO/, last accessed 2021/06/22.
17. Pauen, N., et al.: Integrated representation of building service systems: topology extraction and TUBES ontology. Bauphysik 42(6), 299-305 (2020).
18. TUBES System Ontology, https://rwth-e3d.github.io/tso/index.html, last accessed 2021/06/22.
19. Schneider, G., Pauwels, P., Steiger, S.: Ontology-Based Modeling of Control Logic in Building Automation Systems. IEEE Transactions on Industrial Informatics 13, 3350-3360 (2017).
20. International Organization for Standardization: ISO 81346 – 12: Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations – Part 12: Construction works and building services. International Organization for Standardization (2018).