INTEGRATED REPRESENTATION OF BUILDING SERVICE SYSTEMS: TOPOLOGY EXTRACTION AND TUBES ONTOLOGY

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ABSTRACT

This paper details parts of the work within the Energie.Digital project which aims at developing an integrated representation of building service systems consisting of technical characteristics, physical and functional semantics as well as operating states and state diagrams. This information needs to be machine-readable and linkable using a global identification key.

The focus of this paper is set on the extraction and aggregation of the semantics of service systems from an Industry Foundation Classes (IFC) file and the development of an ontology based on Semantic Web principles within the environment of the Linked Building Data Community Group of the W3C.

KURZFASSUNG

In diesem Beitrag werden die aktuellen Ergebnisse des Forschungsprojekts Energie.Digital vorgestellt. Ziel des Projekts ist eine integrale digitale Beschreibung der technischen Gebäudeausstattung. Dies umfasst Informationen zu den physikalischen und funktionalen Verknüpfungen, den technischen Eigenschaften der Komponenten, sowie zu Betriebsmodi und Ablaufdiagrammen. Diese Informationen müssen maschinenlesbar und über einen Anlagenkennzeichenschlüssel verlinkbar sein.

Im Folgenden wird zum einen die Extraktion und Vereinfachung der topologischen Beschreibung der Systeme der technischen Gebäudeausrüstung aus einem IFC Modell, anderseits die Entwicklung einer Ontologie beschrieben. Diese basiert auf den Prinzipien des Semantic Web und integriert sich in die Umgebung innerhalb der Linked Building Data Community Group des W3C.

INTRODUCTION

The building sector is one of the largest energy consumers, using vast amounts of natural resources and releasing significant amounts of greenhouse gases. Scenario based calculations by the German Energy Agency show that to achieve CO2 savings of 50 up to 75 percent in Germany by 2050, the energy demand of the building sector has to be reduced by around 40 to 55 percent compared to the present state (Hecking et al., 2017).

To implement the energy transition, the digitalisation of the construction sector is a crucial instrument. One focus is the intelligent commissioning and energetic control of the building service systems, which could significantly reduce the energy consumption up to 30% (Katipamula & Brambley, 2005). A major limitation is the absence of an integrated digital representation of the service systems, which is machine-readable and linkable at data level throughout the whole life cycle.

Vast amounts of data are generated and exchanged during the planning, construction and operating phase of building projects. Due to the fragmented structure of the industry and the unique project characteristics, the information supply chain is often established from scratch. Therefore, new data structures are used on a frequent basis, resulting in high amounts of interfaces and, thus, non-standardised processes.

Building Information Management (BIM) is a methodology to provide structured digital information in a machine-readable way. Bew and Richards (Bew & Richards, 2008) proposed a model for the maturity of the BIM implementation within the AEC industry as shown in Figure 1. The current industry maturity is set between levels 0, 1 or 2, depending on the region and the different disciplines - usually the architectural domain is more evolved in comparison to e.g. building automation. In this discipline, data is still manually exchanged with spreadsheets and PDFs and no digital representation exists in the planning phase (VDI 3814-2, 2019; VDI 3814-6, 2008).

To reach BIM Maturity Level 3, data must be exchanged web-based using open standards and decentralised model servers, which allow to link information on a data level from different domains. Currently, Common Data Environments for the web-based information exchange do not cover linking information on this level. A researched approach to cover these requirements is the adaption of Semantic Web and Linked Data technologies (Domingue et al., 2011).

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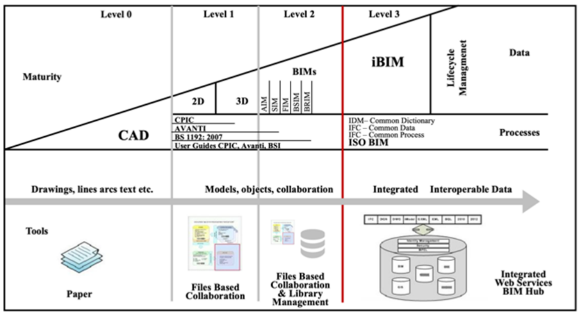

Figure 7: BIM maturity levels (Bew & Richards, 2008)

The project Energie.Digital aims at developing an integrated digital representation of building service systems for the automatic energetic control. The technical characteristics, physical and functional semantics as well as operating states and state diagrams are all linked together using Linked Data and Semantic Web principles and will be available for building managers and technicians in a reference web application. The focus of this paper is set on the extraction of the semantics of service systems from an IFC file and the development of an ontology within the environment of the Linked Building Data Community Group of the W3C (W3C, 2020).

STATE OF THE ART

Building service systems are a central part of the building design to ensure the comfort of the inhabitants as well as the efficient and functional operation of the building (van Treeck et al., 2018). In the design phase the topology and system diagrams are exchanged as planning results within schemes and 3-dimensional building models (Essig, 2017). The open standard for the exchange of building information models is IFC (ISO 16379, 2013), which is based on EXPRESS. Currently, there exists no (applied) open standard to exchange *schemes* of building service systems in a machine-readable way.

There are several attempts using linked data to interconnect the different silos in which data is stored during the process of planning, construction and the operation of a building. While the general concept was suggested as the evolution of the hypertext system of the World Wide Web (Berners-Lee et al., 2001), implementation for the AEC industry has recently gained traction in different areas (Mendes De Farias et al., 2015; Sluijsmans, 2018).

To formalize an ontology supporting the BIM process various efforts have been made, most notably IfcOWL which is an officially endorsed representation of the buildingSMART IFC (Pauwels & Terkaj, 2016; Beetz et al., 2009). IfcOWL has a very broad scope, but due to its inheritance from EXPRESS it is not an ideal base for linked data applications that combine multiple data stores and ontologies. While those try to be concise and focus on their domain of expertise, IFC defines everything internally, starting from units of measurement to people/organisations, schedules or geometric information. This makes linking items rather complicated, as they first need to define common alignments. Also, it is one of the factors that increase the resulting data sizes not only compared to other linked data graphs but also compared to the EXPRESS notation of IFC.

The Building Topology Ontology (BOT) (Rasmussen et al., 2017) is a new approach, explicitly set as a lean base ontology to define topologic concepts and dependencies within buildings. BOT serves as a central ontology for the W3C Linked Building Data Community Group and is designed to work along other ontologies from the W3C ecosystem. It is accompanied by the Building Products Ontology (BPO), describing (building) products and assembly structures and allowing for various properties (Wagner & Rüppel, 2019) as well as the Ontology for Property Management (OPM) to describe property states and their history, which allow the properties to evolve over time (Rasmussen et al., 2018).

The Semantic Sensor Network Ontology (SSN/SOSA) describing the entities, relations and activities involved in sensing, sampling and actuations in buildings gained rather widespread adoption (Haller et al., 2019). CTRLOnt is another ontology to describe control logic and state diagrams (Schneider et al., 2017). An alignment exists with the SSN/SOSA compatible SEAS ontology which primarily caters to smart energy systems (Lefrançois, 2017).

Other ontologies for semantic modelling in AEC data are using different ecosystems, e.g. SAREF for sensors, IoT and smart devices using M2M communication by the European Telecommunication Standards Institute or the Northern American Brick Schema, which is currently consolidated with the Haystack tagging system as ASHRAE Standard 223P: Building Interoperability with Bricks and Haystacks.

According to the author's research, no lightweight ontology exists to provide a high-level description of building service systems and their topology using linked data principles.

METHOD

The methodology developed for the extraction and transfer of the semantics of building service systems from IFC to a graph based on Semantic Web principles, consist of three steps and is described as follows.

Topology extraction

To exchange information about building service systems, the latest IFC release – IFC 4.1 – supports 59 classes within the Electrical, HVAC, Plumbing and Fire Protection Domain as subclasses of the abstract `IfcDistributionFlowElement` concept to model different building service components. Each class has different `IfcPropertySets` and

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predefined types. Within the Control Domain there are seven classes like `IfcSensor` or `IfcActuator` as subclasses of the abstract `IfcDistributionControlElement` class, which can be linked to `IfcDistributionFlowElements`. To describe service systems, these classes can be aggregated within `IfcSystem` and `IfcDistributionSystem`. To describe the physical connections between components, IFC supports the implicit concept of ports with the class `IfcDistributionPort` as shown in Figure 2. The concept further specifies the flow direction (source, sink, sourceandsink, notdefined), the port type (duct, pipe, cable, cablecarrier, userdefined, notdefined) and the associated system. The ports have to be manually modelled within a BIM software to be exported as an IFC class.

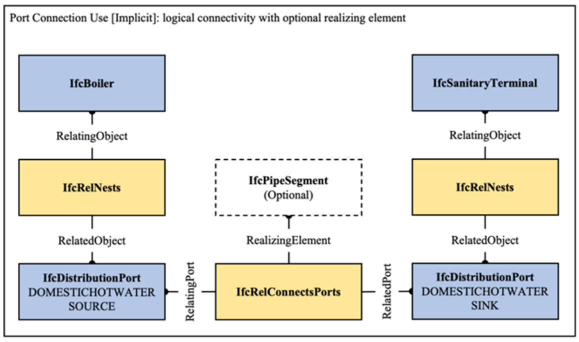

Figure 2: Concept of IfcDistributionPort (buildingSMART, 2020)

To export the information about the building service systems and their topology from the IFC model, a framework based on the python modules *ifcopenshell* (Krijnen, 2012) and *networkx* (Hagberg et al., 2008) was developed. In the first step the algorithm iterates over all `IfcDistributionFlowElements`, `IfcDistributionControlElements` and `IfcBuildingElementProxies` and saves them as well as the associated `IfcDistributionPorts`. In the second step, a new directed and undirected graph is created for every system associated with the ports and the building elements are added as nodes in these graphs. In the next step, the algorithm iterates over the ports and creates directed and undirected edges between the associated nodes in the related graph. A colour map is applied to the nodes and edges during this process to differentiate the service systems.

In order to deal with imprecisions in modelling, the geometric position of every port with no connection is analysed. These are tried to match to other free ports within a certain spatial boundary. Elements without an associated port are not further analysed.

Graph Aggregation

To lower the complexity of the exported graph while keeping the same level of information about the topology, an aggregation method was developed and applied using python and *networkx* in the second step.

For the automatic energetic control and an intelligent commissioning of buildings, the necessary Level of Geometry and Level of Information (LoG/LoI) differ between the building elements. A sensor, valve, air terminal or heat pump object needs detailed information and an accurate geometric placement, while a pipe or duct segment usually does not need e.g. precisely modelled gaskets or certain PropertySets. For an explicit description of the topology some of these segments can be aggregated as long as detailed connections are retained.

For each node in the exported graphs, the number of neighbours is computed. The computation is based on undirected graphs. If the number of neighbours is higher than two, the node is considered to be important and is not going to be aggregated. In the other case, the type of the underlying IFC class is checked. If this class belongs to a subclass within the `IfcFlowSegment` or `IfcFlowFitting` concept, the node is considered not to be relevant and can be aggregated. According to this classification, the node and the associated edges are deleted, and a new edge is created to connect the previous neighbours. This edge gets an attribute with the global identification key of the building element, which was represented by the deleted node and the global identification keys which may have been already associated to the deleted edges.

TUBES Ontology

In the last step, the aggregated graph is converted to a Resource Description Framework (RDF) file using the *rdflib* (RDFlib, 2020) python module to link information regarding other domains e.g. building automation and monitoring. Because there exists no lightweight ontology to describe service systems within the W3C environment the TUBES ontology was developed and is further described in the following section.

The scope of the TUBES ontology is to explicitly define the topology of interconnected building service system and their components. As a lightweight ontology it has a strong alignment to other ontologies within the W3C community and aims to provide the means to link information at data level within the AEC industry.

The TUBES ontology consists of 5 classes and 12 object properties. The terms defined in TUBES are identified by Uniform Resource Identifiers (URIs) and use the prefix tso:, which is not registered yet.

The ontology consists of the three main classes tso:Element, tso:System and tso:Zone. A tso:Zone is a part of the world with a 3D spatial boundary (e.g. space, segment, building) and has an alignment to the bot:Zone class. A tso:Element is a component with some kind of technical characteristics. It can be any object (e.g. pipe, air terminal, sensor) within the world and has an alignment to the bot:Element class. A tso:System is an aggregation of tso:Elements and defines building service systems (e.g. domestic water, air supply, exhaust air), respective a sub-part or super-part of those, a tso:System can have multiple subsystems or supersystems. The structure of the main classes is shown in Figure 3.

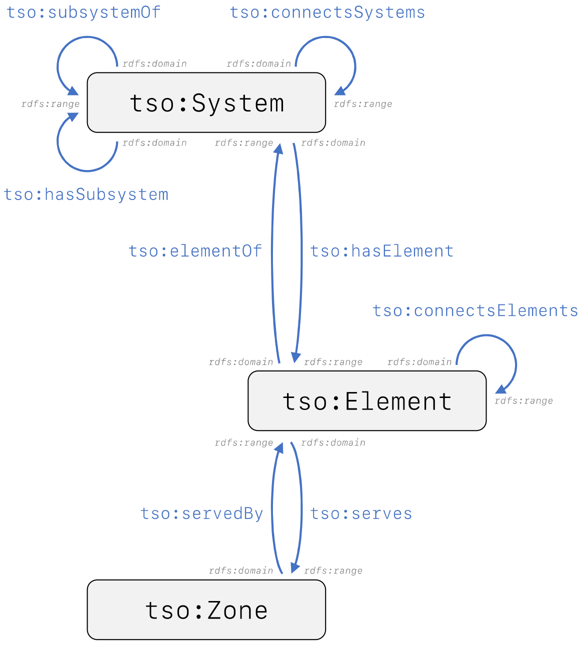

Figure 3: TUBES main class structure

A tso:Element has two sub classes, which are defined as tso:FlowElement and tso:ControlElement. While tso:FlowElement describes all elements that contribute to the flow within a system (e.g. pipes, valves, pumps), tso:ControlElement defines the components that form a part of the control (e.g. sensor, actuator) and do not contribute to the flow. There are five relationships defined between tso:Elements. The tso:connectsElements relationship is symmetric and links two tso:Elements together. The relationship shall not be used explicitly but is to be inferred from the sub-properties tso:exchangeFlow and tso:exchangeControl. The properties tso:supplyFlow and tso:flowSuppliedBy are inverse and define the directed flow between two tso:FlowElements as sub-properties of tso:exchangeFlow – as illustrated in Figure 4. These relationships shall solely be used if the direction of the flow between two tso:FlowElement can be defined explicit. If the direction may vary the connection shall be defined on the level of tso:exchangeFlow.

The tso:Zone class is connected to tso:Element by the inverse relationship tso:serves and tso:servedBy to define the spatial connection between those two concepts.

The class tso:System is linked to tso:Element by the inverse relationship tso:hasElement and tso:elementOf. These properties define the affiliation of components to building service systems, where one component can be linked to more than one system. To take the hierarchical order of systems into consideration, tso:System can be linked as a subsystem to another tso:System, which can have multiple supersystems as well. This is applied by the use of the inverse relationship tso:hasSubsystem and tso:subsystemOf. The symmetric relationship tso:connectsSystems defines the interaction between different systems.

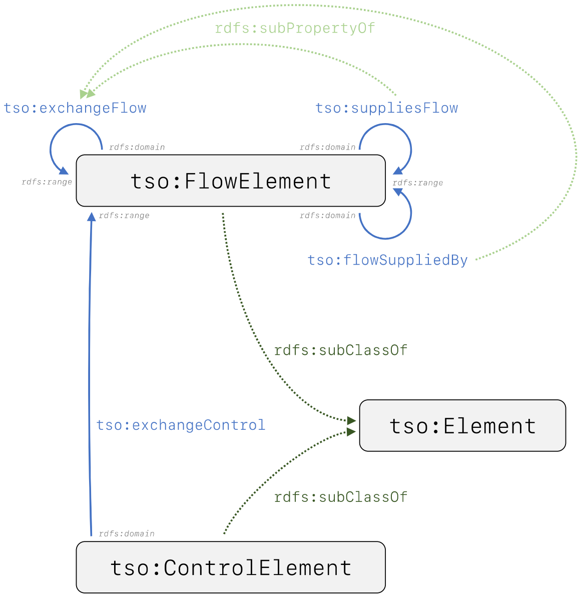

Figure 4: TUBES flow system

TUBES has a strong alignment to other ontologies like BOT or IfcOWL for the classification of different building elements. The concepts bot:Element and ifc:IfcElement can be directly linked to the tso:Element class, as well as ifc:IfcDistributionFlowElement and ifc:IfcDistributionControlElement from tso:FlowElement and tso:ControlElement. This also applies to the bot:Zone concept, which can be linked to the tso:Zone class accordingly.

APPLICATION EXAMPLE

The described methodology is tested on a part of the ventilation system of a laboratory building at Fraunhofer ISE in Freiburg. Based on the existing scheme, a geometric representation was modelled using Revit. The model includes an air handling unit, the necessary pipe and duct components as well as the sensors and their alphanumeric information. As stated in the previous section, a high LoG/LoI was required. For the unique identification of the components, a global identification key was applied in a semi-automatic process. The ventilation system is shown in Figure 5.

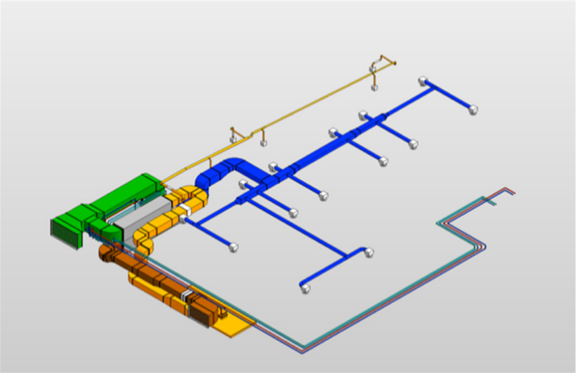

Figure 5: 3D view of the ventilation system

Furthermore, the model was exported using the build-in export function in Revit 2019 to an IFC model using the IFC4.1 Design Transfer View definition. It consists of 422 building elements, which are represented by different IFC classes detailed in Table 1. The air handling unit was exported as an `IfcBuildingElementProxy`, because there exists no associated classification within the IFC scheme.

Table 1: Building elements in the IFC model

Amount	IfcClass
100	IfcPipeSegment
80	IfcPipeFitting
96	IfcDuctSegment
87	IfcDuctFitting
5	IfcValve
1	IfcPump
2	IfcFlowMeter
22	IfcAirTerminal
13	IfcSensor
16	IfcBuildingElementProxy
422	Total

RESULTS

The graph resulting from the topology extraction consists of 422 nodes and 393 edges. All building elements given in Table and their connections were correctly exported. Five of those elements within the class `IfcBuildingElementProxy` have no port. Therefore, they are not connected to any other element and do not have a system associated. The other 417 components which are represented by the nodes can be classified into eight different systems. The graph is illustrated in Figure 5.

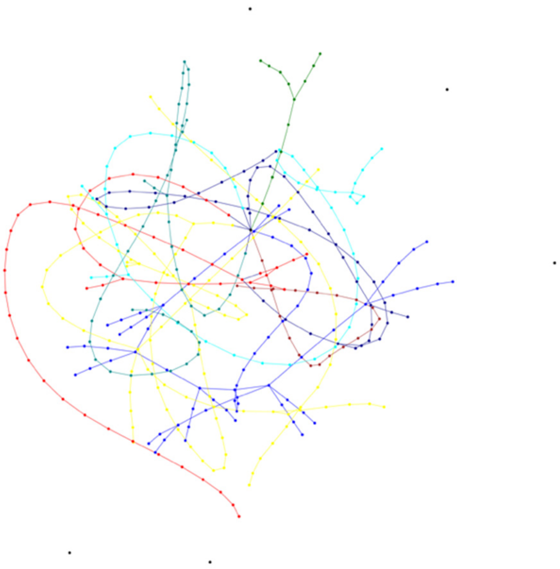

Figure 6: Exported Graph

In the second step the graph was aggregated. The total amount of nodes could be reduced from 422 to 83. The amount of edges was reduced from 393 to 76, while keeping the same level of topological information. This corresponds to a reduction of the complexity by approximately 80%. The resulting graph is illustrated in Figure 6. The differences between the computed graph and the aggregation are further detailed in Table 2.

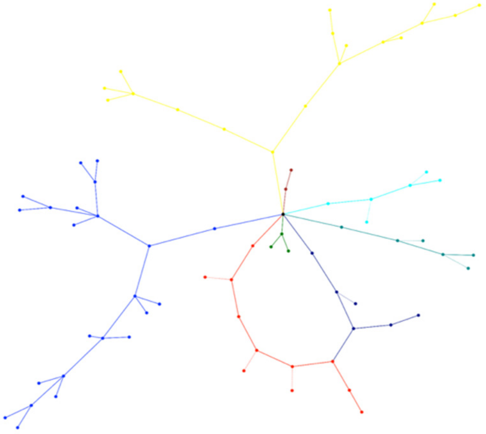

Figure 7: Aggregated Graph

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Table 2: Results of the aggregation

IfcClass	Graph	agg. Graph
IfcPipeSegment	100	4
IfcPipeFitting	80	9
IfcDuctSegment	96	12
IfcDuctFitting	87	6
IfcValve	5	5
IfcPump	1	1
IfcFlowMeter	2	2
IfcAirTerminal	22	22
IfcSensor	13	13
IfcBuildingElementProxy	16	11
Total nodes	422	85
Total edges	393	76

CONCLUSION AND OUTLOOK

This paper presented a methodology to extract the semantics of building service systems out of an IFC4.1 model into a graph based on semantic web principles. To facilitate this, a lightweight ontology was designed, aligned within the W3C Linked Building Data Community Group for an integrated digital representation of those systems.

The methodology consists of three steps. At first the topology is extracted and saved as a graph. In the second step the graph is aggregated, while keeping the same level of topological information and the different systems are visualized. In the third step the aggregated graph is converted into an RDF file, which is compliant with the presented ontology. Within the Energie.Digital project this representation will be further developed by linking real life monitoring data as well as state diagrams and functions, which are modelled using an IEC 61131-3 (IEC 61131-3, 2012) standardized programming language for an automatic energic control of buildings. The real benefit of this methodology will be further evaluated on a building project, which is already in construction in Germany.

Areas for further extensions and improvements include the detailed analysis of geometric connections in IFC, which are modelled without the use of distribution ports, and possible spatial algorithms to extract these. Another area is the extension of the presented ontology by a classification scheme based on the VDI 2552-9 (VDI 2552-9, 2020) and the analysis of different types of systems as well as the application of the methodology on a larger scale project. Furthermore, the ontology needs to be revised and further researched.

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