ifcOWL-DfMA a new ontology for the offsite construction domain

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Abstract. Architecture, Engineering and Construction (AEC) is a fragmented industry dealing with heterogeneous data formats coming from different domains. Building Information Modelling (BIM) is one of the most important efforts to manage information collaboratively within the AEC industry. The Industry Foundation Classes (IFC) can be used as a data format to achieve data exchange between diverse software applications in a BIM process. However, EXPRESS, the native IFC modelling language, is not a logic-based language and lacks formal semantics; consequently, intelligent tools cannot engage with this information directly. The advantage of using Semantic Web Technologies to overcome these challenges has been recognised by the AEC community and the ifcOWL ontology, which transforms the IFC schema to a Web Ontology Language (OWL) representation, is now a de facto standard. Even though the ifcOWL ontology is very extensive, there is a lack of detailed knowledge representation in terms of process and sub-processes explaining Design for Manufacturing and Assembly (DfMA) for offsite construction, and also a lack of knowledge on how life cycle cost and carbon emissions are incurred, which is essential for evaluation of alternative DfMA design options.

In this article we present a new ontology named ifcOWL-DfMA as a new domain specific module for ifcOWL with the aim of representing offsite construction domain terminology and relationships in a machine-interpretable format. This ontology will play the role of a core vocabulary for the DfMA design management and can be used in many scenarios such as life cycle cost estimation. To demonstrate the usage of ifcOWL-DfMA ontology a production line of wall panels is presented. We evaluate our approach by querying the wall panel production model about information on activity sequence, cost estimation per activity and also the direct material cost. This ultimately enable us to evaluate the overall product from the system.

Keywords: DfMA, IFC, Ontologies, Linked Open Data

1 Introduction

The Architecture, Engineering and Construction (AEC) sector has been criticised as low in productivity as compared with that of other sector's, e.g. the productivity of manufacturing, automotive, and aerospace sectors. One holistic approach to improve product performance is the application of Design for Manufacture and Assembly (DfMA). DfMA aims to improve products continuously through evaluating existing and developing new manufacture and assembly processes. It is, however, challenging to apply the design methodology in the AEC sector as the knowledge of offsite processes is fragmented and owned by a number of professionals - some of them (such as production engineers) are not traditionally a part of the design team. Thus, the knowledge is not readily accessible. The evaluation of DfMA design has multiple criteria and in practice relies heavily on either heuristics ("rule of thumb") or high-level estimations with little effort spent on understanding how costs are actually incurred. This is problematic as the economy of off-site manufacturing, a core element of DfMA, is process-driven. The argument that construction processes and sub-processes are premature to consider in the design stage in conventional design and construction approach does not apply if DfMA is to be adopted.

The use of Building Information Modelling (BIM) in building projects offers opportunities to extract properties and data of a building easily but there is generally a lack of attention to data collected during the construction process. Typically, process-related data in BIM are only used for scheduling purposes. The actual use of process data for informing manufacturing or off-site decision-making is limited. This paper proposes a semantic approach for linking process data with life cycle costs and carbon emissions to give an accurate production costs and carbon footprint. The estimations from the semantic knowledge-based system will an give objective measure to inform designers in evaluating DfMA options.

Semantic Technologies and Linked Open Data have been broadly used in the domains of AEC. The usage of these technologies is driven by the need to operate with heterogeneous data formats from different sources and domains, support data interoperability, flexible data exchange and distributed data management. An extensive literature review conducted by Pauwels et al. [3] has emphasised the crucial role semantic technologies and logic-based applications play in systems that require the integration of information from multiple application areas. The standard schema for the exchange of BIM data is IFC [8]. It has a strong focus on 3D geometry [8] and is modelled using EXPRESS[9]. Semantic Technologies where applied to implement a direct mapping of IFC EXPRESS schema to ifcOWL ontology [4]. IFC schema and ifcOWL ontology concepts of design differs from those used for DfMA as the latter is production led, focusing on the manufacture and assembly process. One example would be product classification in DfMA design in which products come with details of sub-assemblies, generally are under-represented in the IFC schema.

The proposed ifcOWL-DfMA ontology aims to provide the AEC community with a vocabulary of commonly understood concepts and relationships to represent the domain of offsite construction, as well as a means to publish linked open DfMA data. This is achieved by contributing to the development of domain knowledge that handles interdisciplinary information exchange among different participants during the life-cycle of design for manufacturing. In addition it provides a basis for future development of smart tools that will be able to provide answers for practical scenarios.

2 State of the art

2.1 Building Information Modeling

Building Information Modeling is a digital process for the representation and processing of all information relevant to the Building Life Cycle (BLC). Typically, the foundation of a BIM process will be a three-dimensional (3D) model of the architectural design, detailing the positioning and dimensions of a buildings components (walls, windows, doors etc.) and facilitating the inclusion of non-physical building features such as building cost, accessibility, safety, security and sustainability [1]. In a BIM model not only the geometric features are included but also the semantic attributes are included and the associated properties [2]. BIM is an intelligent model-based process that connects AEC professionals so they can design, build and operate buildings more efficiently. BIM is also used for creating data for infrastructure associated with physical and functional characteristics. BIM projects are implemented from the start as either closed or open models. The latter uses the Industry Foundation Classes (IFC) [8], a standardised platform-neutral schema, for data exchange. An IFC data model in practice focuses on building geometry representation in the design stage. In the work presented here, the Open BIM approach is the assumed adoption. The objective is to automatically map the BIM model to a ifcOWL-DfMA ontology with the use of a semantic parser. In the UK, BIM implementation is defined according to different levels of maturity starting from BIM Level 0 to Level 3 - a cloud-based implementation where data from different domains can be integrated seamlessly without any data loss. The Semantic Technologies and Linked Data principles proposed can also play a very important role in achieving Level 3 BIM.

2.2 IFC and ifcOWL Ontology

IFC files represent BIM components using the EXPRESS modelling language [9]. Using IFC data and instance serialization formats, BIM data can be exchanged between heterogeneous software applications. A basic overview of IFC hierarchy is given in Figure 1. However, IFC is neither an automatically machine-readable data format, nor a web-compliant one, therefore there is a requirement to use semantic standards and technologies [10] like the Web Ontology Language (OWL) for which the Linked Data standards was proposed. Initially OWL was integrated with IFC [11] to produce ifcOWL ontology. Later, a direct mapping of EXPRESS schema to OWL [4] was introduced and implemented in the current version of ifcOWL ontology. The ifcOWL is now under buildingSMART [6] International, where it eventually became a part of the ISO 16739 standard [5].

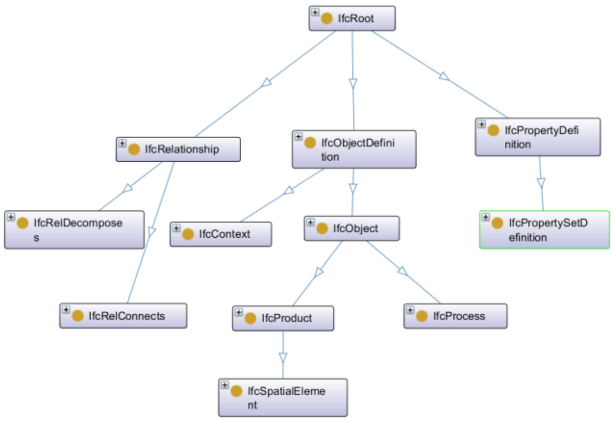

Figure 1Part of the hierarchy of classes in ifcOWL ontology.

The ifcOWL ontology is an extensive ontology. In the latest version, i.e. IFC4, consists of 1293 classes and 1572 object properties. This makes reasoning and management very hard and inefficient, and inevitability, increases the need to develop separate modules based on the core IFC modules. The proposal to implement a modular ifcOWL ontology was proposed by [15] and has started to be adopted by different authors. Even more recently the need for modularity and extensibility was explicitly from the authors a [14] when they introduced the BOT - Building Topology Ontology.

3 ifcOWL-DfMA Ontology Development

The aim of the ifcOWL-DfMA ontology is to present an ontology that defines the key terms and relationships present in the DfMA approach to building design, while simultaneously acting as an extension of the ifcOWL ontology, in order to maintain compliance with core IFC concepts. As illustrated in Figure 2, the first step taken to design ifcOWL-DfMA ontology was conducting a literature review in terms of: i) existing ontologies designed of IFC where ifcOWL was identified and analyzed; ii) existing offsite construction, DfMA and related domain; iii) general DfMA and related domains literature review in order to extract the main concepts and relation of the domain. The

literature review confirmed that there is no existing ontology that represents offsite construction and life cycle assessment with the DfMA approach.
As a second step, a set of competency questions was drafted based of the guide for developing an ontology from Stanford University [16].The competency questions have guided the discussion with the stakeholders and experts involved including architects, production engineers, structural engineers, steel supplier, client and cost consultant on one to one interviews and group discussions. An iterative approach was adopted to the ontology design process to reflect the feedback from the experts and improve the ontology.

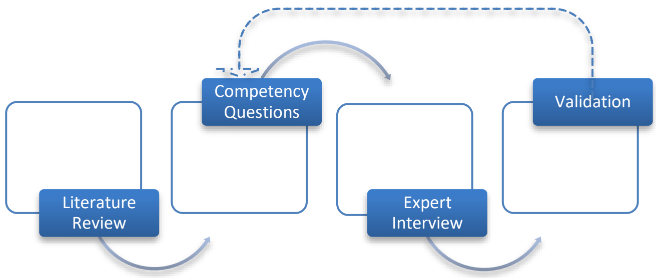

Figure 2 Methodology use to develop ifcOWL-DfMA ontology

3.1 Overview of ifcOWL-DfMA Ontology

Ontologies allow for defining concepts and relations in the domain of interest, which can be machine processable using OWL as the base language. OWL is logic based, which means the semantics of the language are explicitly defined in logic. Furthermore, OWL is rich in computational properties as it is possible to perform computations automatically using tools, called reasoners [7]. The ifcOWL-DfMA ontology is developed using OWL 2, OWL DL profile[12]. Being built upon the Description Logics (DL) language, it can be analysed as sets of first order sentences (axioms) that make statements about a knowledge domain and therefore is possible to compute what it is entailed. Formally, a DL-based ontology O= (T, R, A) consists of a set T of concept axioms (TBox), a set R of role axioms that describes relations between individuals (RBox), and a set A of assertional axioms (ABox) [15]. The asserted axioms in an ontology give rise to entailed axioms, which follow as a logical consequence of the asserted axioms. Reasoners are software systems that can be used during i) ontology design time to check consistency and infer certain desirable consequences following from what has been stated and ii) application runtime to provide query answering capabilities, which ensure queries are correctly answered using the represented knowledge. There are many reasoners, such as FaCT++ [18] and Pellet [19], that work well with OWL.

The current version of ifcOWL-DfMA ontology consists of 134 classes, 14 object properties, and 39 datatype properties.
The top-level classes of ifcOWL-DfMA ontology are illustrated in Figure 3. ifcOWL-DfMA ontology top class is dfma:Platform with subclass dfma:Building in the context of DfMA building for offsite construction. dfma:Building is designed using a dfma:OffsiteSystem that collects the current different methods of construction for a Panelized System, Pod Systems and Hybrid Systems. A DfMA house consists of a collection representing (dfma:Assembly) dmfa:Products, dfms:Components and outputs of dfma:SubAssembly-s.

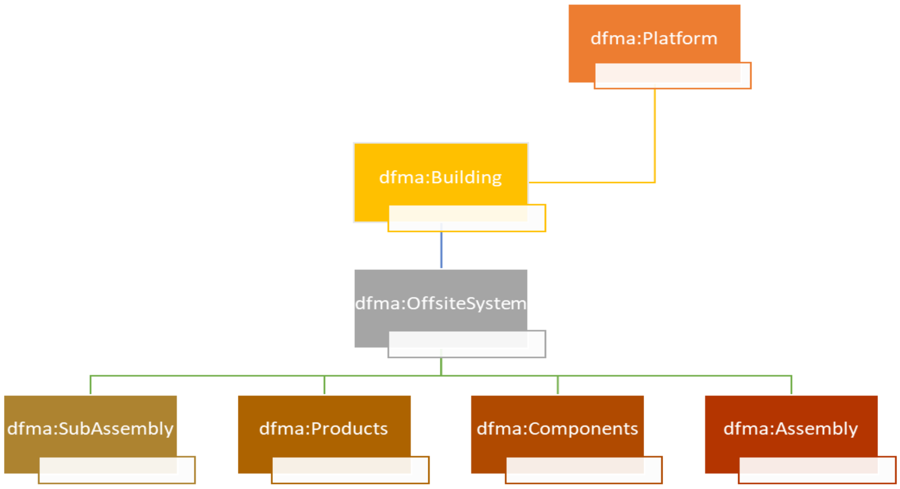

Figure 3 Top level hierarchy of the ifcOWL-DfMA ontology

Table 1 lists some of the object properties that represent the relationships between concepts in the ifcOWL-DfMA ontology. The class dfma:SubAssembly captures the knowledge of the production line where sub-assembled components are manufactured, the activities that are carried, the cost and also the time each of these activities takes. A dfma:Production line is mapped from the methods used as part of off-site production. Professionals are currently working on different methods of production but currently three main categories are consolidated dfma:PanelMethod, dfma:PodMethod and dfma:Hybrid method. Figure 4 illustrates the subclasses of dfma:PanelMethod for automated production lines of wall panels.

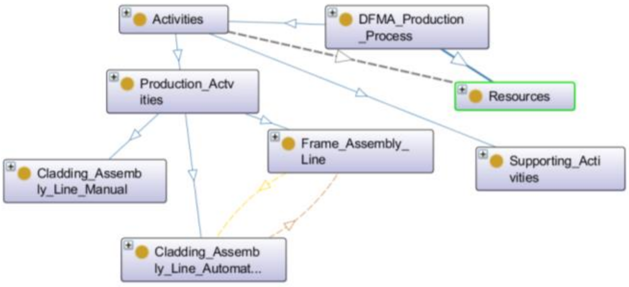

Figure 4 Wall Panel production main activities

Dfma:Transportation from factory to site and related information like distance, fuel type etc. that can support the designer of DfMA buildings are also represented.

Table 1. Examples of the ifcOWL-DfMA ontology object and data properties

Name	Domain	Range	Type
consumerResources	Activities	Resources	Object Property
hasComponentPart	Product	MaterialComponent	Object Property
hasActivity	SubAssembly	Activities	Object Property
consumesPlant	Activity	Plant	Object Property
hasDimentions			Data Property
hasDistance			Data Property
hasThickness			Data Property
hasArea			Data Property

3.2 Alignments with ifcOWL ontology

As mentioned in previous sections ifcOWL-DfMA ontology is developed independently from the ifcOWL ontology but is aligned with it such that every dfma:Building is an IfcBuilding and every dfma:Product is an IfcProduct.

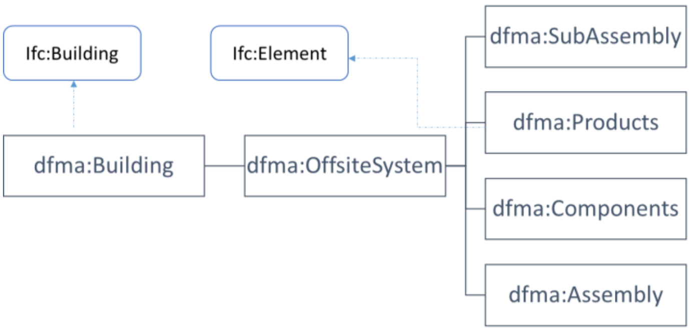

Figure 5 Alignment between ifcOWL-DfMA ontology and ifcOWL ontology.

Developing ifcOWL-DfMA as a separate domain of the existing ifcOWL ontology was a conscious choice. Naturally, many aspects of a completed DfMA project, such as the building geometry or the material properties, fit ifcOWL concepts and can be represented accordingly. However, as a process with roots in industrial engineering, DfMA engages more with procedural and optimisation aspects, and introduces concepts, such as “assembly” or “sub-assembly”, with different semantics from current BIM and construction technology practice. As such, a separate ontological domain was considered necessary in order to avoid semantic and ontological conflicts, as well as to implement DfMA concepts appropriately. Ideally, ifcOWL-DfMA will be able to facilitate a two-way conversation: enable AEC practitioners to apply DfMA design concepts in a BIM workflow, while simultaneously acting as an introduction to the DfMA concept to BIM-literate AEC practitioners.

At the same time, the need for a separate domain suggests that there are some limitations to the current ifcOWL ontology. Attempting to capture *all* possible aspects of a building in a single hierarchical ontology, mapped to a super-schema, has innate limitations and lacks the flexibility to accommodate different design concepts. DfMA is a characteristic case study on that: future innovative philosophies and practices are likely to face similar challenges in BIM implementation.

4 Using ifcOWL-DfMA ontology in practice

On the cost life cycle estimation problem, construction cost models is a very important aspect of construction project design [1]. Most of the existing standard measurement methods are text based therefore the authors propose the development of an ontology based on New Rules of Measurement [20]which is commonly used in the UK. Therefore different proposals of ontology-based approaches that mainly operate on the New Rule of Measurement are in place. Considering the fact that DfMA design is relatively new, the NRM that primarily breakdown buildings by defined elements or conventional work packages (focusing on costs of end products rather than how costs actually incurred in the production) cannot be applied. For production, the conventional approach to estimate construction cost does not enable the designers to identify areas for improvement. Often the estimated overall construction costs are broken down into cost targets for building elements in order to create a 2nd-tier cost control references in the design stage. While this method is useful for traditional constructions in which design and construction activities are mostly separated and most of the construction works are carried out on-site, the benefit of elemental costing for off-site construction is limited as the method does not take processes into account. To overcome the limitations of elemental and resource-based approach for costing design and construction, the ifcOWL-DfMA ontology adopts a manufacturing costing approach, namely Activity-Based Costing (ABC).

The ABC method is built on the idea that product development requires certain activities and these activities consumes some resources in order to be completed. It measures the cost and performance of cost objects (manufactured products) attempting to give accurate and traceable cost information. This presents the opportunity for classifying activities as either value-adding (dfma:ValueAdded) or non-value(dfma:NonValueAdded) adding so that there is possibility of eliminating or reducing the non-value adding activities that consumes resources. Decision makers are thus presented with more in-depth information that encourages corrective actions. For instance, it does not allow users to identify cost drivers of an off-site production such as factory rent and production volume. ABC provides a process view that the traditional costing method cannot provide, which could be advantageous in terms of making informed decisions on production flow, and techniques and understanding how best to improve the performance of individual cost drivers. A separate process mapping exercise for DfMA production is carried out and a process map for proposed off-site production line for DfMA house wall panels has been produced. The wall panels are modeled by describing their attributes such as the components that compose a wall panel but also the production line detailed in terms of activities carried to produce a wall panel as illustrated in Figure 6. All activities are connected with each other by keeping track of which activity should perform first(*hasStartingActivity*) and which activity takes place next(*hasNextActivity*) or in parallel. Further on, the knowledge represented in the ontology is used to estimate cost (*hasDirectCost, hasMaterialCost, hasActivityCost* etc.) per each activity and overall cost of producing one product in this case a wall panel. By estimating the cost per each activity the designer can get insights in which activity are occurring overhead costs and optimize their design if possible.

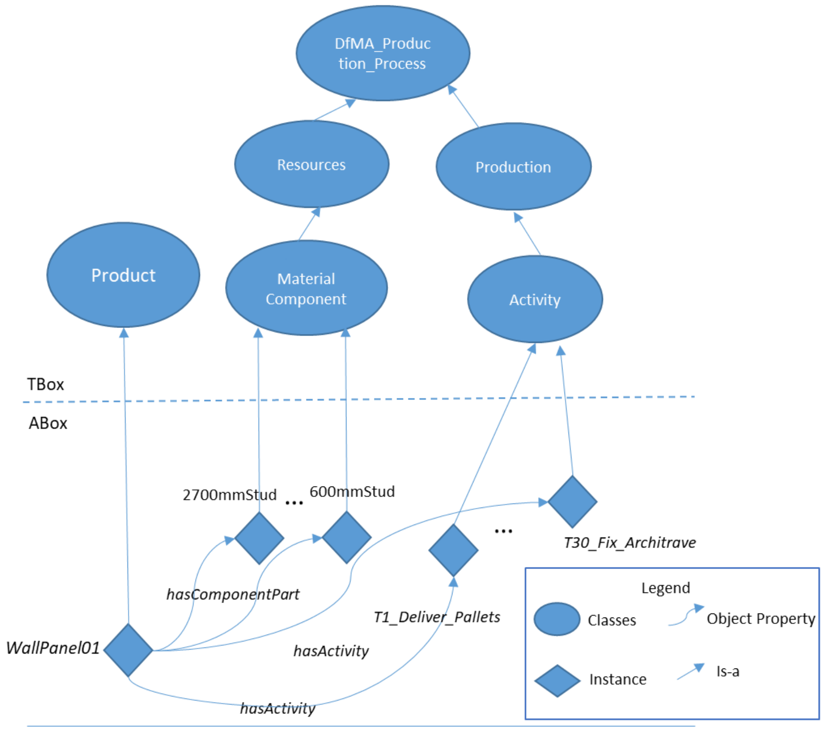

Figure 6 Modeling wall panel instantiation

Table 2 gives some example queries that a designer might possibly ask regarding the DfMA house composed of 32 wall panels to the instantiated ontology. The queries are expressed in SWRL or SQWRL and the reasoning is made by Pellet reasoner.

Table 2. Table captions should be placed above the tables.

Question	Query(SWRL/SQWRL)	Result in Protégé	Comment
Q1. What is labor cost for each semi-skilled operative working on each activity of the wall panel production?	Semi-Skilled_Operative(?s) ^ Activities(?a) ^ workingOnActivity(?s, ?a) ^ hasProcessTime(?a, ?p) ^ hasLabourHrRate(?s, ?r) ^ swrlb:multiply(?result, ?p, ?r) -> sqwrl:sum(?result) ^ sqwrl:select(?s)	"1.17"^:SSO_1 "2.6" ^:SSO_4 "5.85"^:SSO_6 "1.4689"^:SSO_3 "3.237"^:SSO_5	The result displayed shows the labour cost of building a single wall panel automatically on the production line with five operatives supporting different activities done by the robots to form the panel.
Q2. What is total direct material cost for producing panel?	Product(LSF_3BED_01_LHS)^hasDirectMaterialCost(LSF_3BED_01_LHS, ?m) ->	"3075.81918"	This result aggregates the cost of each components/materials used in building up the

	sqwrl:select(LSF_3BED_01_LHS) ^ sqwrl:sum(?m)		panel of a semi-detached house (with identity 01)
Q3. What are the components of WallPanel01?	Product(?p) ^ hasComponentPart(?p, ?Component) -> sqwrl:select(?Component)	mmS mmStud mmHT mmHT mmBT mmCS mmSS mmStud mmBT mmBT mmBT mmFS mmStud	This results show the components used in building the wall panel 01 which includes Studs, Head Track, Base Track, Cripple studs of different sizes.
Q4. What is the starting and upcoming activity for producing LSF_3BED_01_LHS wall panel?	Product(LSF_3BED_01_LHS) ^hasStartingActivity(LSF_3BED_01_LHS, ?StartActivity) ^ hasNextActivity(?StartActivity, ?NextActivity)->sqwrl:select(LSF_3BED_01_LHS, ?StartActivity, ?NextActivity,)	LSF_3BED_01_LHS, T1_Deliver_Pallets, T2_Select_and_Load_Beam ,	This result displays the sequence of activities carried out by operatives in building the wall panel with identity 01

5 Conclusion and Discussions

This article proposes a new domain specific ontology ifcOWL-DfMA ontology which expands ifcOWL ontology as a separate module deriving from core element of IFC. The ifcOWL-DfMA ontology is however on the early versions of development and further improvements can be done. In order to ensure interoperability this ontology is rooted in the de-facto standard ontology for IFC (ifcOWL) and follows the Linked Data principles. To address the complexities that ifcOWL has, the Linked Open Data on the Web community is standardizing the Building Topology Ontology (BOT) [14] that will interlink different domain specific ontologies more efficiently and when this is needed. BOT uses Linked Data approach to describe the buildings by only using the fundamental properties and if more detailing are required the linking with other relevant ontologies is enabled. This is the direction that ifcOWL-DfMA is planning to take after wider evaluation with the community of interest.

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6 References

1. Taylor, J., Bernstein, P.: Paradigm Trajectories of Building Information Modeling Practice in Project Networks. Journal of Management in Engineering - J MANAGEENG 25(2009). https://doi.org/10.1061/(ASCE)0742-597X(2009)25:2(69)
2. Li, N., Li, Q., Liu, Y.-S., Lu, W., & Wang, W. (2020). BIMSeek++: Retrieving BIM components using similarity measurement of attributes. Computers in Industry, 116, 103186. https://doi.org/10.1016/J.COMPIND.2020.103186
3. Pauwels, P., Zhang, S., & Lee, Y. C. (2017). Semantic web technologies in AEC industry: A literature overview. Automation in Construction, 73, 145–165.
4. Pieter Pauwels, Walter Terkaj, EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology, Automation in Construction, Volume 63, 2016, Pages 100-133, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2015.12.003.
5. Pauwels, P., Krijnen, T., Terkaj, W., & Beetz, J. (2017). Enhancing the ifcOWL ontology with an alternative representation for geometric data. Automation in Construction, 80, 77–94. https://doi.org/10.1016/j.autcon.2017.03.001
6. BuildingSMART, https://www.buildingsmart.org/, Accessed: February 2020
7. Horridge, M., Brandt, S., Parsia, B. and Rector, A. L.,2014, A Domain Specific Ontology Authoring Environment for a Clinical Documentation System, IEEE 27th International Symposium on Computer-Based Medical Systems, New York, NY, pp. 329-334.doi: 10.1109/CBMS.2014.84
8. ISO 16739, Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, 2013, International Standardisation Organisation, Geneva, Switzerland.
9. ISO 10303-11, Industrial automation systems and integration – Product data representation and exchange – Part 11: Description methods: The EXPRESS language reference manual, 2004, International Standardisation Organisation, Geneva, Switzerland.
10. J. Domingue, D. Fensel and J.A. Hendler, Handbook of semantic web technologies, Springer, 2011.
11. J. Beetz, J. van Leeuwen and B. de Vries, IfcOWL: A case of transforming EXPRESS schemas into ontologies, Artificial Intelligence for Engineering Design, Analysis and Manufacturing 23(01) (2008), 89.
12. P. Hitzler, M. Krötzsch, B. Parsia, P.F. Patel-Schneider, S. Rudolph
13. OWL 2 web ontology language primer (second edition) — W3C recommendation 11 December 2012, W3C recommendation, available online: http://www.w3.org/TR/2012/REC-owl2-primer-20121211/ (Last accessed on February 2020)
14. Rasmussen, M. H., Lefrançois, M., Schneider, G. F., & Pauwels, P. (2019). BOT: the Building Topology Ontology of the W3C Linked Building Data Group. Semantic Web Journal, 0(0). http://www.semantic-web-journal.net/content/bot-building-topology-ontology-w3c-linked-building-data-group-0
15. Terkaj, W., & Pauwels, P. (2017). A method to generate a modular ifcOWL ontology. CEUR Workshop Proceedings.

16. Krötzsch, M., Simanˇ, F., & Horrocks, I. (2013). A Description Logic Primer ∗ arXiv : 1201 . 4089v3 [cs . AI] 3 Jun 2013.
17. https://protege.stanford.edu/publications/ontology_development/ontology101.pdf
18. Tsarkov, D., & Horrocks, I. (2006). FaCT++ Description Logic Reasoner: System Description. In U. Furbach & N. Shankar (Eds.), Automated Reasoning (pp. 292–297). Springer Berlin Heidelberg.
19. Sirin, E., Parsia, B., Grau, B. C., Kalyanpur, A., & Katz, Y. (2007). Pellet: {A} practical {OWL-DL} reasoner. J. Web Semant., 5(2), 51–53.
20. RICS. (2012). RICS new rules of measurement - Order of cost estimating and cost planning for capital building works (2nd ed.). Royal Institution of Chartered Surveyors (RICS).