ifcOWL-DfMA a new ontology for the offsite construction domain

Edlira Vakaj Kalemi[1], Franco Cheung[1], Abdel-Rahman Tawil[1], Panagiotis Patlakas[1]
Kudirat Alyania[2]

[1] Birmingham City University, United Kingdom
[2] University of East London, United Kingdom
edlira.vakaj@bcu.ac.uk

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. 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 product and productivity measurement such as production costs and durations 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 such as activity sequence, cost estimation per activity and also the direct material cost. This ultimately enable users to evaluate the overall product from the system.

Keywords: Offsite Construction, 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 productivity is the application of Design for Manufacture and Assembly (DfMA). DfMA, first developed for product design, aims to improve production so that products produced are consumed by the manufacturing process as quickly as possible with the least amount of waste and redundant works. In practice, it involves a continuous evaluation of the manufacture and assembly processes by designers. It is now widely accepted within the AEC that one major direction to improve productivity is to move the production activities offsite [1]. The application of DfMA thus enable designers to consider alternative offsite production approaches with automation in mind.

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 give an 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 inter-disciplinary 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 Domain Knowledge and State of the art

2.1 Design for Manufacturing and Assembly

Traditionally, design and construction are separated with the relevant responsibilities assigned to different parties. The role of a contractor is mainly an integrator that focuses on the delivery of buildings with little attention to the potential benefits of factory production. The call for improvement of the AEC sector in terms of productivity and product performance has led to a change in some market segments of the sector to consider alternative approaches to design and construct buildings. DfMA is a design approach that is composed of two parts: design for manufacture (DfM) and design for assembly (DfA). Through engineering a building design – often, a standardised design, the goal of DfMA is to minimise waste and redundant operations. Examples of specific targets for DfM are the selection of materials that minimise wastage and handling, optimising processes and sub-processes, optimising parts and systems fulfill tolerance requirements, and those for DfA are minimising number of modules for assembly and optimizing assembly. In practice, it is a continuous task of reviewing, evaluating, rationalising, standardising and optimising the functionality, producibility, handling and fixing of design.

The task is very knowledge intense and complex, and requires input from experts of various disciplines - some of them such as production engineers are not traditionally a part of the building design team. As the knowledge is not readily accessible, there is a need to systemise the knowledge to enable the evaluation of building design by individual discipline owners. The current approach for evaluation relies heavily on either heuristic ("rule of thumb") or high-level estimations with little effort spent on understanding how processes and sub-processes are related and interacted. For instance, an estimated cost – as a measure for rationalizing or optimizing - is calculated based largely on historical high level per unit cost without taking into account on how cost actually incurred. This is problematic as the economy of off-site manufacturing, a core element of DfMA, is process-driven and can only be evaluated properly if the estimate reflects the cost implications of processes. For instance, the cost for a static production process, i.e. the use of mainly labour for production would be different from an automated production, i.e. the use of mainly machine or robot for production. The knowledge however is not typically kept in the system of the current status quo. The argument that construction processes and sub-processes are premature to consider in the design stage in traditional approach does not apply if DfMA is to be adopted as building design is based on standardised design. Standardised design makes product, production and assembly data to be kept and reuse in a more efficient manner. Systemising knowledge of product, production and assembly for DfMA through creating an accurate representation of the relationships of the process and sub-processes can automatically generate estimates of productivity and performance matrics such as production cost, life cycle cost, duration or CO2 emissions.

2.2 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.

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 [2]. The Semantic Technologies and Linked Data principles proposed can also play a very important role in achieving Level 3 BIM.

2.3 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 not 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].

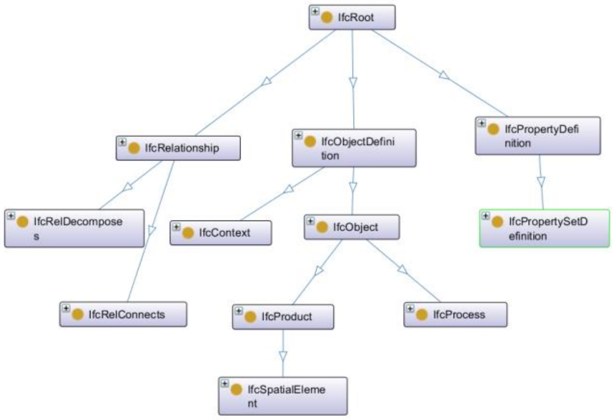

Figure 1Part of the hierarchy of classes in ifcOWL ontology.

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.

3.1 Ontology Development Methodology

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 ontologies for 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.

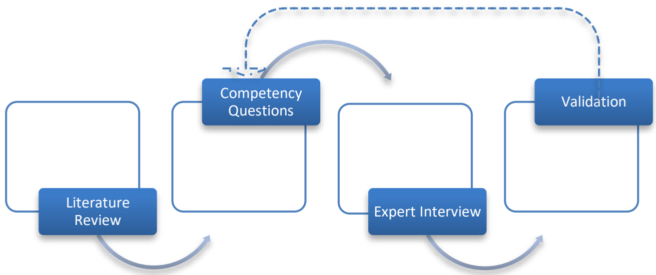

Figure 2 Methodology used to develop ifcOWL-DfMA ontology

3.2 Overview of ifcOWL-DfMA Ontology

ifcOWL-DfMA define a model of categories within the offsite manufacturing Universe of Discourse (UoD), plus sufficient knowledge about those categories to allow for them to be reasoned upon and classified automatically. Our aim is to use ifcOWL-DfMA as a COmmon REference, or CORE model for offsite manufacturing. The proposed ontological model is language independent, using the broader term 'terminology' for a semantic model linked to the offsite manufacturing domain.

A high level schema (upper ifcOWL-DfMA ontology) is a prerequisite for categorisation and integration, as illustrated in Figure 3:

- Fits closely with building standards especially in applications for design and manufacturing assembly or in the retrieval and classification of ifcOWL-DfMA concepts.
- Sufficiently general to be used in different applications for decision support and interoperability.
- Formally defined in OWL Description Logic (DL) and can be considered a general-purpose modelling language for offsite manufacturing.
- Supports OWL-DL reasoners to allow for core ifcOWL-DfM concepts to be combined to create new descriptions of classes and instances constructed according to constraints implemented within the ontology.
- Support intuitive and practical collaboration between different groups, being easily understood and application independent.

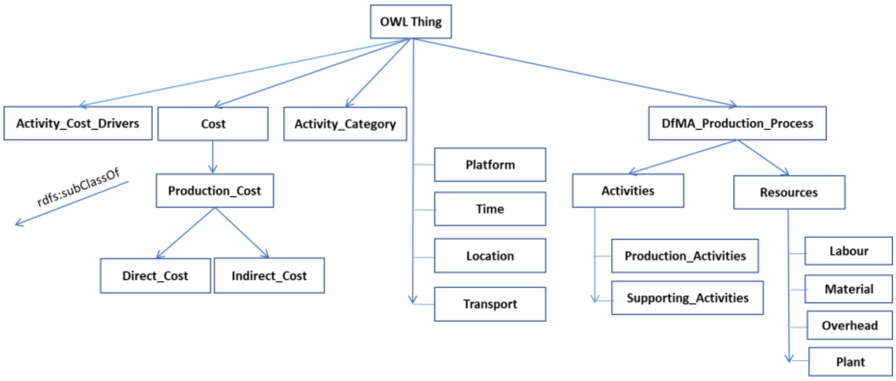

Figure 3 A high level schema of ifcOWL-DfMA ontology

In ifcOWL-DfMA, the primary breakdown is into:

- DfMA_Production_Process, defines both production and supporting activities
- Resources, defines labour, material overhead and plant
- Activities, defines production activities (e.g., gladding assembly line automation, frame assembly line) and resources (e.g., labour, material and component, overhead etc.)
- Modality, defines platform, time, location and transport, representing a heterogeneous grouping for usage in associations with production processes and activities.

A secondary structure is superimposed over the primary, aiming to capture DfMA production process, activities and resources. Table 1 shows ifcOWL-DfMA taxonomy of major elementary categories associated with the production process. The category labelled DfMA_Production_Process represents the disjunction of two main categories, activities and resources which can be observed.

As an ontology for offsite design and manufacturing, ifcOWL-DfMA further divides production processes into production activities e.g., Cladding_Asssembly_Line, Frame_Assembly_Line and supporting activities such as loading, packaging and transporting. For example, a cladding assembly line is an automated activity that is defined as a production activity which begins only after frame assembly line is completed and consumes some labour.

Cladding_Assembly_Line_Automated and beginsAfter only Frame_Assembly_Line
Cladding_Assembly_Line_Automated and consumeLabour some Labour
Loading isSubClassOf Suppoting_Activity and consumeLabour some Labour

Resources are further divided into MaterialandComponents (e.g., Direct_Matrial and Packaging_Material), Overhead (e.g., Cleaning, Security) and plant (e.g., Movable_Tools, Static_Tools). MaterialandComponents is used to group Direct_Material together including external wall cladding, internal wall cladding, wall finishing, wall fixing and wall framing.

Table 1. ifcOWL-DfMA taxonomy of major elementary categories

Entity **DfMA_Production_Process**	Example
Activity	
Production_Actvity	
Cladding_Assembly_Line	
Adhesive_Station	T31_Feed_Adhesive, T32_Dispense_Adhesive
Briquette_Apply_Station	T35_Place_Briquettes
Briquette_Load_Station	T34_Feeding_Briquettes
…	
Frame_Assembly_Line	
Conveying_Station	T13_Return_Conveyor
Frame_Riveting_Station	T5_Rivet_Joints, T6_Move_Frame_to_Lift, T7_Lift_Frame
Frame_Transfer_Station	T9_Transfer_Frame
FrameBeam_Load_Station	T1_Deliver_Pallets, T2_Select_and_Load_Beam, T3_Clamp_Beam
…	
Supporting_Activity	
…	
Resource	
Labour	
Direct_Labour	
Casual_Labour	hasLabourHrRate "9.0"^^xsd:double
Semi-Skilled_Operative	hasLabourHrRate "13.0"^^xsd:double workingOnActivity T1_Deliver_Pallets workingOnActivity T2_Select_and_Load_Beam
MaterialandComponent	
Direct_Material	
EXT_Wall_Cladding	
INT_Wall_Cladding	
Wall_Finishing	
Overhead	
Plant	

Subcategories share common characteristic from which a single constraint may be inherited, but are otherwise disjoint and heterogeneous. In addition, ifcOWL-DfMA recognises, UnitsOfMeasures such as miles, kilometres, metre, kilogram, minute, currency etc. which are used as part of quantities.

ifcOWL-DfMA Attribute Hierarchy

The taxonomy of ‘attributes’ (or ‘semantic link types’) is influenced by and supports the outlined category taxonomy. The primary distinction here is between object and data properties. While data properties (e.g., hasUnitRate, hasLabourHrRate, hasCount) describe what kind of values a triple with the property should have by relating individuals to literal values (e.g., strings, numbers, datetimes, etc.), object properties (e.g., beginsBefore, beginsAfter, isComponentPartOf) relates concepts together to define relationships across concepts.

Rules in the form of the Semantic Web Rules Language (SWRL) are used to provide more powerful deductive reasoning capabilities than OWL alone. For example, the rule below determined the cost of labour for an activity by multiplying the processing time with the labour hourly rate.

Activities(?a), Labour(?s), hasLabourHrRate(?s, ?r), hasProcessTime(?a, ?p), workingOnActivity(?s, ?a), multiply(?result, ?p, ?r) -> hasActivityCost(?a, ?result)

3.3 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.

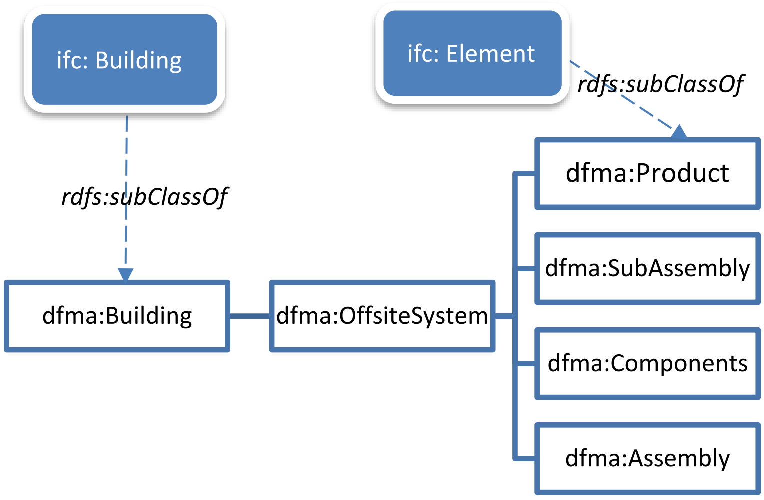

Figure 4 Alignment between ifcOWL-DfMA ontology and ifcOWL ontology.

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

The ifcOWL-DfMA ontology is applied on the production of a wall panel system for a house design using DfMA. The application captures its production process and adopts a manufacturing costing approach, namely Activity-Based Costing (ABC) to classify cost data. The process-based costing method measures the activity costs of cost objects (i.e. various cost centres for wall panels) attempting to give accurate and traceable cost information. Decision makers are thus presented with more in-depth information that encourages corrective actions. For instance, it allows users to identify cost drivers of an off-site wall panel production such as factory rent and production volume. 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 5.

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 optimise their design if possible.

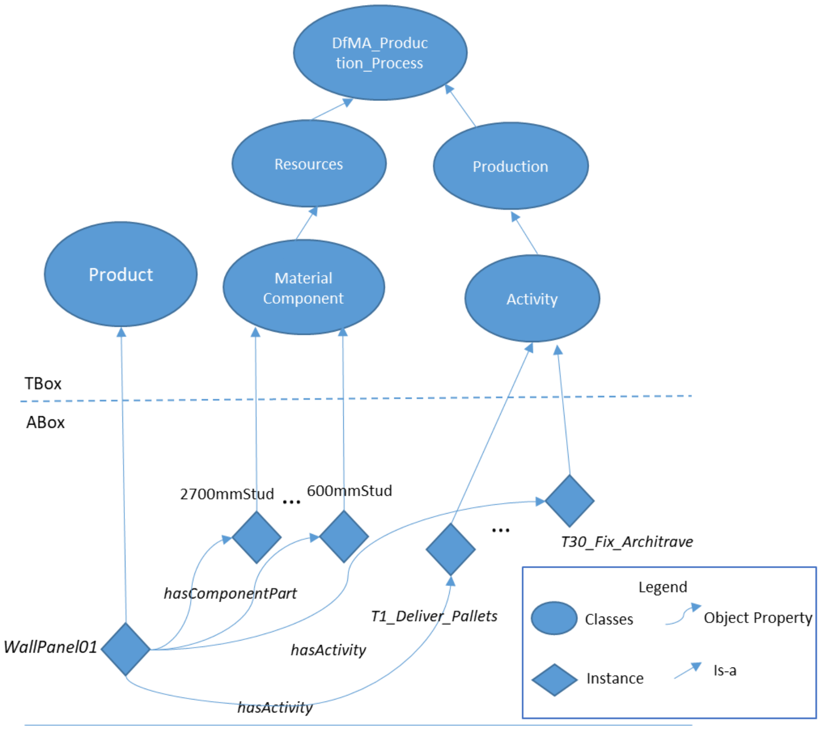

Figure 5 Modeling wall panel instantiation

Apart from costing, 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, which are the estimates of potential productivity and performance matrices. The queries are expressed in SWRL or SQWRL and the reasoning is made by Pellet reasoner.

Table 2. Example queries in SWRL/SQWRL and respected results.

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) -> sqwrl:select(LSF_3BED_01_LHS) ^ sqwrl:sum(?m)	"3075.81918"	This result aggregates the cost of each components/materials used in building up the 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 mmSS mmStud mmHT mmHT mmBT mmCS 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_SelectandLoadBeam	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 World Wide Web Consortium (W3C) Linked Building Data Community Group 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.

Acknowledgments

This research was supported by an Innovate UK funded project “Collaborative Knowledge- Based DfMA approach to build cost efficient, low impact and high performance houses”. The authors would like to thank the participating industrial partners of the research project, particularly Walsall Housing Group and Northmill Associates for their contribution in this study.

6 References

1. Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., Sridhar, M., Parsons, M., Bertram, N. and Brown, S., 2017. Reinventing construction through a productivity revolution. McKinsey Global Institute,(https://goo. gl/1Nqqf8)(Feb. 06, 2017).
2. British Standard Institute (2013) PAS 1192-2: Specification for Information Management for the Capital/Delivery Phase of Construction Projects Using Building Information Modelling, British Standard Institute.

3. 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)
4. 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
5. Pauwels, P., Zhang, S., & Lee, Y. C. (2017). Semantic web technologies in AEC industry: A literature overview. Automation in Construction, 73, 145–165.
6. 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.
7. 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
8. BuildingSMART, https://www.buildingsmart.org/, Accessed: February 2020
9. 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
10. ISO 16739, Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, 2013, International Standardisation Organisation, Geneva, Switzerland.
11. 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.
12. J. Domingue, D. Fensel and J.A. Hendler, Handbook of semantic web technologies, Springer, 2011.
13. 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.
14. P. Hitzler, M. Krötzsch, B. Parsia, P.F. Patel-Schneider, S. Rudolph
15. 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)
16. M. H. Rasmussen, M. Lefrancois, G. F. Schneider, P. Pauwels, BOT: the Building Topology Ontology of the W3C Linked Building Data Group, Semantic Web (2020) 1–21Accepted, Last accessed: 27 March 2020. URL http://www.semantic-web-journal.net/system/files/swj2279.pdf
17. Terkaj, W., & Pauwels, P. (2017). A method to generate a modular ifcOWL ontology. CEUR Workshop Proceedings.
18. Krötzsch, M., Simanˇ, F., & Horrocks, I. (2013). A Description Logic Primer ∗ arXiv : 1201 . 4089v3 [cs . AI] 3 Jun 2013.
19. N. F. Noy, D. L. McGuinness, Ontology Development 101: A Guide to Creating Your First Ontology, Tech. Rep. SMI-2001-0880, Stanford University, Stanford, USA, last accessed: 27 March 2020 (2001). URL https://protege.stanford.edu/publications/ontology_development/ontology101.pdf
20. 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.

21. 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.