Abanda, F, Kamsu-Foguem, B and Tah, J

New Rules of Measurement ontology for construction cost estimation

Abanda, F, Kamsu-Foguem, B and Tah, J (2017) BIM - New Rules of Measurement ontology for construction cost estimation. *Engineering Science and Technology*.

Engineering Science and Technology, an International Journal xxx (2017) xxx–xxx

HOSTED BY

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

BIM – New rules of measurement ontology for construction cost estimation

F.H. Abanda [a,*], B. Kamsu-Foguem [b], J.H.M. Tah [a]

[a] Oxford Institute for Sustainable Development, School of the Built Environment, Faculty of Technology, Design and Environment, Oxford Brookes University, Oxford OX3 0BP, UK
[b] Laboratoire Génie de Production, Ecole Nationale d'Ingénieurs de Tarbes 47, Avenue Azereix, BP 1629, F-65016 Tarbes Cedex, France

ARTICLE INFO

Article history:
Received 14 September 2016
Revised 21 December 2016
Accepted 25 January 2017
Available online xxxx

Keywords:
Building Information Modelling
Construction projects
Cost estimation
New Rules of Measurement
Ontology

ABSTRACT

For generations, the process of cost estimation has been manual, time-consuming and error-prone. Emerging Building Information Modelling (BIM) can exploit standard measurement methods to automate cost estimation process and improve inaccuracies. Structuring standard measurement methods in an ontologically and machine readable format for a BIM software can greatly facilitate the process of improving inaccuracies in cost estimation. This study explores the development of an ontology based on New Rules of Measurement (NRM) for cost estimation during the tendering stages. The methodology adopted is methontology, one of the most widely used ontology engineering methodologies. To ensure the ontology is fit for purpose, cost estimation experts are employed to check the semantics, descriptive logic-based reasoners are used to syntactically check the ontology and a leading 4D BIM modelling software is used on a case study building to test/validate the proposed ontology.

1. Introduction

Emerging Building Information Modelling (BIM) is one of the leading technologies being used in different construction applications such as energy simulation [1], sustainability [3,5], facilities management [25], risk management [36,35] and cost estimation [12]. BIM has been used in cost estimation; with research revealing it is more efficient than the manual cost estimation and leads to project cost reduction [2,12]. In Finland, BIM adoption in housing projects has led to the following benefits: increased profit margins of 45%, waste reduction of 45%, on-site accident reduction of 5% [20]. In the UK, the Ministry of Justice (MoJ) adopted BIM in delivering the Cookham Wood project (value of £20 million), which yielded a 20% cost saving [49].

Detailed cost estimates consist of two parts. These are products/procurement quantities (PPQ) which are physical quantities of design components and process quantities (PQ) which are related to specific construction processes [45]. Examples of PPQ include volume of concrete columns and areas of windows. Examples of PQ include labour hours for hanging drywall and extracting quantities of earthwork. Data such as labour hours are intangible compared to volume of concrete that is obtained from a tangible geometric model. Most intangible data are non-geometric in nature. The beauty about emerging BIM is the fact that non-geometric data can be embedded into a BIM model (see Section 2). The importance of data or information embedded into a BIM model is the kernel of BIM and encapsulated in the "I" of BIM. Without loss of generality, this study will focus on PPQ. The benefits of BIM in cost estimating discussed in the preceding paragraph has been achieved partly due to the use of various BIM software packages that enabled accurate modelling of projects thus leading to precise quantity takeoffs (QTO). Some leading software in the field are Navisworks, Autodesk QTO, CostX, Innovaya, iTWO, d-profiler, Vico, ProjectWise Navigator, Bentley ConstrucSim, Balfour Technologies, etc. The process of cost estimation using these software packages can be modelled in Fig. 1.

The current cost estimating process as depicted in Fig. 1 has four major short comings.

Firstly, some of the cost estimating software do not contain a measurement standard that can be used in cost estimating. This means, potentially there could be lack of consistency in cost estimates produced with BIM software that do not contain measurement standard. A consequence of this, is the fact that two or more cost estimates cannot be easily compared. Secondly, the extraction of building components is still a manual and time consuming process. Building components and their respective quantities are generated from a BIM software, and then manually edited into a pre-prepared standard measurement template. Given, the list of components and respective quantities are not in the same order as the structured template, time is spent aligning

* Corresponding author.
E-mail address: fabanda@brookes.ac.uk (F.H. Abanda).

Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2017.01.007
2215-0986/© 2017 Karabuk University. Publishing services by Elsevier B.V.

Please cite this article in press as: F.H. Abanda et al., BIM – New rules of measurement ontology for construction cost estimation, Eng. Sci. Tech., Int. J. (2017), http://dx.doi.org/10.1016/j.jestch.2017.01.007

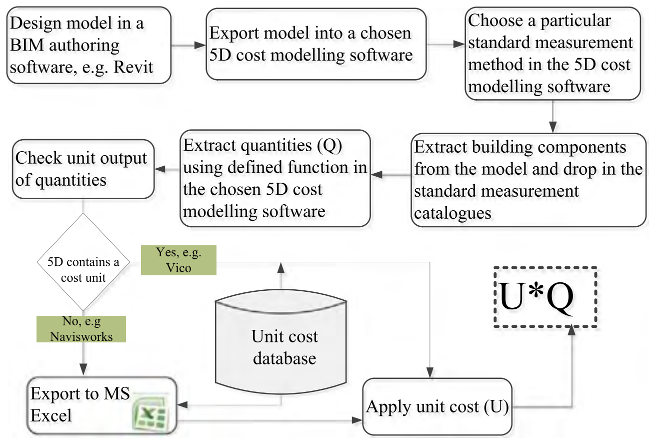

Fig. 1. Cost estimating process in a BIM-based cost estimating software.

components to the different concepts in the structured template. This is time-consuming and error-prone. Thirdly, where the software contains a measurement standard, it is likely to be that of the country where the software was manufactured. For example, most Autodesk cost estimating products generally have American and North American measurement standards and not NRM. Consequently, in countries where NRM is in common use, e.g., the UK, the need for an electronic NRM is imperative so as to be integrated in the chosen Autodesk product during cost estimation. Fourthly, for the few software that contains a standard measurement catalogue, it is embedded into the software and/or included in the installation folder, hence cannot easily be re-used by other software or professionals for any knowledge acquisition activity. An NRM ontology that is not software-dependent will be of great use to the academic as well as professional community. Previous efforts (e.g., [7,38]) aimed at addressing these challenges revealed a potential in integrating BIM and Semantic Web for improving many construction activities including cost estimation. Key to the Semantic Web, is the ontology used to formally represent knowledge and rules of a particular domain for the purposes of facilitating computer processing, reasoning, knowledge sharing and re-use.

The aim of this study is to investigate how an ontology based on NRM can be used for construction QTOs/cost estimation (In this paper, emphases will be laid on QTOs. This is because, once QTOs have been obtained, only unit cost is required to obtain the total component cost as illustrated in the formula in Fig. 1). To achieve this aim, the following objectives will be accomplished.

a. Investigate the different concepts in the NRM that can aid in (QTOs)/ and hence cost estimation;
b. Develop an ontology that model knowledge about construction QTOs/cost estimation;
c. Investigate how best to deal with constraints in NRM in the developed ontology;
d. Demonstrate the use of the ontologies in performing QTOs and hence cost estimation;
e. Evaluate the ontology whether it is fit for the intended purpose in standard BIM software systems.

To facilitate understanding the rest of this manuscript is divided into 11 sections. This study is mostly about an application of BIM for cost estimation. It falls under what is often called nD modelling. Hence, to gain insights and identify how cost estimation fits with nD modelling, the next section will be about nD modelling with focus on cost estimation (also known as 5D modelling). In Section 3, an overview of the research methods adopted for this study will be examined. An overview of BIM-based construction cost estimation is presented in Section 4. Furthermore, in Section 5, the link between BIM-based cost estimation and standard rules of measurement is examined. Section 6 is about the development of the ontology while the implementation of the developed ontology in Protégé-OWL, a popular ontology editor is discussed in Section 7. The practical applications of the ontology are illustrated in Section 8, while its validation is undertaken in Section 9. The challenges encountered during the ontology development are reported in Section 10. In Section 11, how the research aim and objectives have been attained are discussed. The study ends by a way of summary of what has been covered in this paper in the conclusion Section 12.

2. nD modelling

A model in BIM should be "a means to an end, not an end in itself". While not underminding the importance of 3D models, the information attached to a model for different applications is quite important. The importance of the "I" of BIM cannot be underestimated as strongly emphasised in Abanda et al. [3]. An nD model is an extension of a building information model that incorporates multi-aspects of design information required at each stage of the lifecycle of a building facility [30]. In other words nD modelling brings in the n^{th} number of design perspectives [10], $n \in N^+ = \{1, 2, 3,...\}$. The design perspectives varies in each phase of a construction life cycle and include scheduling, cost estimation, accessibility, crime or forensic analysis, sustainability, maintainability, acoustics, energy simulation, code reviews, conflict interference and conflict detection [10,13]. While the term nD (n-dimensions) has been used in Mathematics and Physics for generations, its usage in the construction industry is fairly recent. Although, it is unclear who and when the term was first used in construction, around 2005 researchers in the University of Salford-UK popularised the term in its Special Issue call in the Journal of Information Technology in Construction [10]. The special issue call led to the publications of six articles about nD modelling [26,15,21,50,19,24]. It is important to note the nD as used in Mathematics and Physics generally refers to the minimum number of coordinates needed to specify any point in space. In construction research and practice, 3D stands for the geometric model, 4D stands for scheduling and 5D for cost estimation. However, there is a lack of concensus about other D's where $n > 5$. The use of nD for $n > 5$ are in some cases conflicting. In Bryde et al. [16] and Kamardeen [27], 6D BIM is considered to be a facilities management information while the same 6D BIM is considered by Yung and Wang [56] to mean sustainability information. To further illustrate the degree of ambiguity, sustainability is considered as the 7D BIM in Kamardeen [27].

Although this area is still emerging, there are already few peer-reviewed literature about intelligent cost estimation techniques. Staub-French et al. [47,46] developed an ontology to support construction cost estimation. Abanda et al. [4] developed an ontology for estimating the cost of labour in construction projects. Cheung et al. [17] developed a BIM-based plug-in for SketchUp for simultaneously determining embodied energy and carbon, cost, construction waste and time. Lee et al. [31] developed a BIM and ontology-based approach for building cost estimation. Ma and Liu [33] developed a BIM-based intelligent system for cost estimation of building projects, which however did not exploit the concepts of ontologies. Lawrence et al. [29] proposed a generic approach for creating and maintaining a cost estimate using flexible mappings between a building model and a cost estimate. Wu et al. [54] examined cost estimating practice and procedure in the UK and the impact of the use of BIM. Choi et al. [18] proposed a methodology that connects BIM data (volume and area) with unit cost and developed a quantity takeoff prototype system.

From the studies cited in the preceding paragraph, Lee et al. [31] and Cheung et al. [17] considered the Chinese standard method of measurement and UK NRM respectively. However, the standard measurement methods were not translated into digital ontologies that can be re-used. Furthermore, the main focus of Cheung et al. [17] was about integrating construction waste, time, cost, embodied energy and carbon so that these variables can be determined simultaneously. A recent study funded by the Royal Institution of Chartered Surveyors investigated, albeit without developing any ontology, how BIM can support the UK New Rules of Measurement (NRM 1) [55]. Combining visual model and deep knowledge in BIM models can greatly facilitate extraction of knowledge from BIM models. Shen and Issa [45] demonstrated the effectiveness of using BIM assisted detailed estimating tools that exploit visualisations in generating detailed construction estimates. Inspite of BIM being a very rich digital model, there exists challenges extracting information from it, thereby limiting the usability of BIM for construction and other downstream processes [37]. Our approach is to combine ontologies with a 3D BIM model to facilitate information extraction from BIM models. Furthermore, another major benefit of a BIM-based ontology using NRM is the fact that it can be re-used, shared and used for other intelligent applications. Given there are 3 types of NRMs (to be reviewed in Section 4), without loss of generality, this study will focus on NRM 1.

3. Research methods

Three main methods were adopted to achieve the objectives of this study. The details of the methods are presented in Fig. 2.

Firstly, to gain a firm understanding of the domain of cost estimation, BIM and Semantic Web/ontology, a review of the literature is undertaken. As argued in Webster and Watson [53], a literature review facilitates theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed. The key knowledge gap identified through literature review is the fact that most BIM-based cost estimation techniques are not based on ontologies that can readily be re-used for other purposes. Secondly, based on the literature review, suitable types of software systems and ontology languages were identified. The systems were used to developed the proposed ontology. Thirdly, after the development of the ontology, it was evaluated for fitness. The evaluation process consists of verification for semantic and syntactic correctness and validation for the purposes for which it was developed for.

4. Overview of BIM-based construction cost estimation

Based on Fig. 1, it can be inferred that BIM-based construction cost estimation requires at least a BIM authoring software and a specialised cost estimating software. The two software needs to communicate, at least unidirectionally, where the latter can read files from the former. The communication requires interoperability languages such as Industry Foundation Classes (IFC). Key to understanding construction cost estimation is the understanding of IFC and rules of measurements and how both can be related. IFC is an open and neutral data format for openBIM developed and maintained by buildingSmart International. Since the first IFC initiative was launched in 1994, different versions have been developed. The most widely used version integrated in most BIM software is IFC 2X3. Proceeding IFC2x3, the latest version IFC4 was released in March 2013 which incorporates numerous improvements and enhancements over the predecessor. However, given that IFC4 is still relatively new, and not incorporated in most software, this study will focus on IFC2x3. IFC2x3 covers nine domains in building construction, namely Building Controls, Plumbing Fire Protection, Structural Elements, Structural Analysis, heating, ventilation, and air conditioning (HVAC), Electrical, Architecture, Construction Management and Facilities Management. The NRM provides a standard set of measurement rules that are understandable by all those involved in a construction project, including the employer; thereby aiding communication between project teams and the employer [42]. Furthermore, it assists quantity surveyors/cost managers in providing effective and accurate cost advice to the employer and the project/design team. The NRM is comprised of three volumes NRM 1, NRM 2 and NRM 3 (http://www.designingbuildings.co.uk/wiki/NRM_1). The first edition of NRM was published in 2009 under the RICS New Rules of Measurement. In 2012, the second edition was published under a new name: NRM 1 (NRM Order of cost estimating and elemental cost planning). The motive for the change in name was to differentiate between capital building works and building maintenance works, and the arrangement of elements. In the same 2012, NRM 2 (Detailed Measurement for Capital Building Works) was published. NRM 2 is an enhanced update of the Standard Method of Measurement, seventh edition (SMM7) and replaced it on 1 July 2013. NRM 2 defines the detailed measurement rules that facilitates the preparation of bills of quantities, quantified schedules of works and schedules of rates in order to obtain tender prices. The NRM 2 provides guidance on the content, structure and format of bills of quantities. In March 2014, the third edition, NRM 3 was published. It is used mainly for the quantification and description of maintenance works. Also, it can be used for the initial order of cost estimates, general cost plans and asset-specific cost plans. It also provides guidance on procurement and cost control. The NRM 1 breaks building works into 15 group elements, numbered from 0 to 14. The most important group elements are 0–8 ([42], pp.24). The different group elements are Group 0: Facilitating Works; Group 1: Substructure;

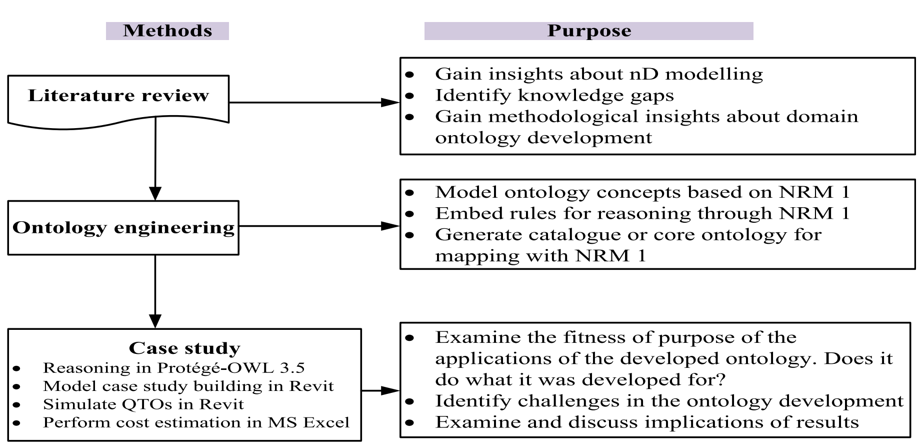

Fig. 2. Research methods and justification of choices.

Please cite this article in press as: F.H. Abanda et al., BIM – New rules of measurement ontology for construction cost estimation, Eng. Sci. Tech., Int. J. (2017), http://dx.doi.org/10.1016/j.jestch.2017.01.007

Group 2: Superstructure; Group 3: Internal Finishes; Group 4: Fittings, Furnishes and Equipment; Group 5: Services; Group 6: Prefabricated Buildings and Building Units; Group 7: Work to Existing Buildings and Group 8: External Works. Each of these groups is further broken down into elements. For example, Group 3: Internal Finishes is broken down into 3, namely, Wall Finishes, Floor Finishes and Ceiling Finishes. For purposes of this study, the ontology developed is based on the first 9 group elements (0–8) of the NRM 1.

5. Overview of BIM based cost estimation software and rules of measurement

To understand the extent to which standard rules of measurement are being used in BIM cost estimation packages, an extensive review was conducted on most popular BIM cost estimating (e.g. Vico, Sage Timberline, CostX) and QTO (e.g. Navisworks) software. Navisworks is an Autodesk product used for 4D and 5D modelling. It comes with CSI-16, CSI-48 and Uniformat catalogues for QTOs. These catalogues are in Extensible Markup Language (XML) format. Also, Autodesk QTO has the same catalogues as Navisworks. CSI-16 refers to 16 divisions of construction, as defined by the Construction Specifications Institute (CSI)'s MasterFormat. MasterFormat is a standard for organizing specifications and other written information for commercial and institutional building projects in the U. S. and Canada. Similarly, CSI-48 contains 48 divisions, although there are now up to 50 divisions. Synchro has no inbuilt work breakdown structure or standard methods of measurement, although any can be imported if developed in XML format. Vico contains a work breakdown structure based on Uniformat. CostX contains NRM 1, NRM 2, Standard Method of Measurement 7 (SMM7), Hong Kong SMM (HKSMM), Australian Standard Method of Measurement 5 (ASMM5) libraries although the author uses phaseology as its terminology referring to library or catalogue. The differences between these catalogues are related to the number of concepts and sub-concepts and the position in the hierarchy. For example, Superstructure is top or 1st level concept in NRM 1 while it is the 2nd in Uniformat. Also, Doors and Windows are considered as 1st level concepts in CSI-16 while the same are considered in NRM 1. All the concepts in CSI-16 are classified under one level while those of Uniformat and NRM 1 are broken down to at least two levels. The take-away from this review is that, as of now there is no publicly available electronic NRM catalogue that can be imported into current BIM software systems. Hence, an electronic NRM measurement systems based on ontology paradigm is proposed. This approach allows, in addition to the use of the NRM catalogue for automatic QTO and hence cost estimation, the ontology can be re-used for other purposes such as for reasoning. The proposed system achitecture will be examined in Section 6.

6. Development of the cost estimating ontology

The components of the system architecture for this study is presented in Fig. 3.

6.1. Development of ontology based on UK NRM 1

An extensive review of ontology engineering methodologies, modelling languages and software, and examples of ontologies has been examined in Gómez-Pérez et al. [22] and Iqbal et al. [32]. Recent studies have revealed the use of these methodologies in developing domain ontologies in different built environment domains [23]. Abanda et al. [9] conducted an extensive study about semantic web applications in the built environment. Grzybek et al. [23] reviewed more than 100 papers that developed domain ontologies in the construction domain. The trend in developing built environment domain ontologies seems to be on the rise with already significant publications about the same in 2015 [14,58,43,39,57]. Beach et al. [14] developed a domain ontology for automated regulatory compliance checking in the construction sector. Zhong et al. [58] proposed a novel ontological and semantic mechanism for reusing plans and their automatic verification in construction. Radulovic et al. [43] developed a set of guidelines for generating and publishing Linked Data in the context of energy consumption in buildings. One of the deliverables from Radulovic et al. [43] work is an energy consumption ontology. Niu and Issa [39] developed a domain ontology of construction contractual semantics with a case study on the American Institute of Architects (AIA) Document A201-2007. Zhang et al. [57] developed a domain ontology that can be used for organising, storing, and re-using construction safety knowledge. A recent publication by Pauwels et al. [41] provide an extensive review of Semantic Web research in the Built Environment highlighting applications in product

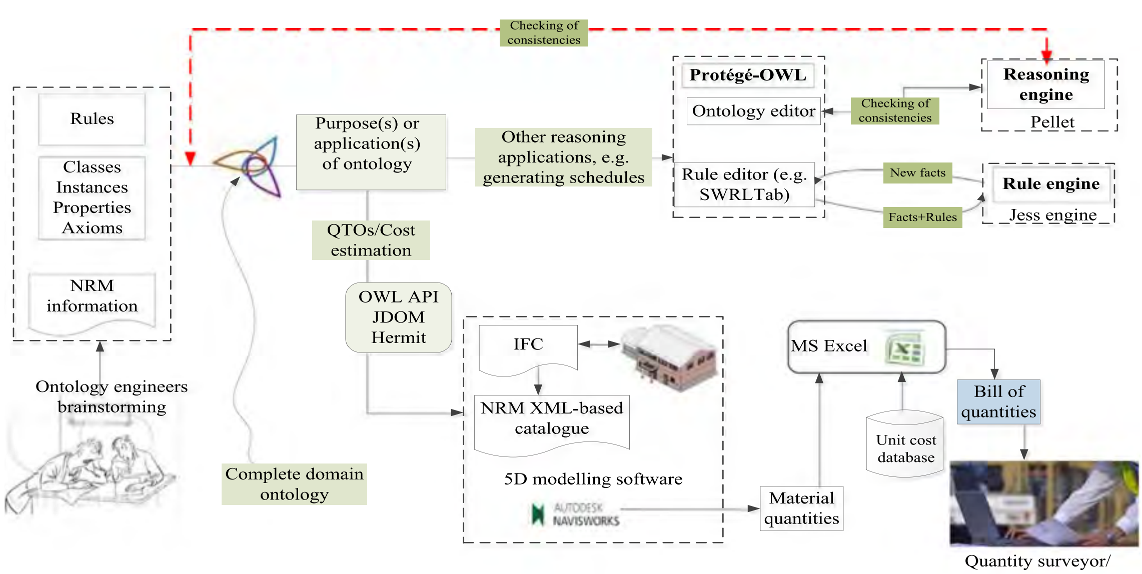

Fig. 3. The system architecture.

manufacture, building energy performance, regulation compliance checking, geographical and infrastructure. Three main conclusions can be drawn from the preceding studies. Firstly, some studies do not specify the ontology development method adopted in the development of their proposed ontology (e.g. Beach et al. [14]). Secondly, despite the numerous well-elaborated ontology development methodologies described in Gómez-Pérez et al. [22] and Iqbal et al. [32] (e.g. NeOn, Uschold and King's method, SENSUS method, Grüninger and Fox's methodology, DILIGENT, "ontology development 101", etc.) many studies often used "ontology development 101" by Noy and Mcguinness [40], yet a justification and suitability of the chosen method is hardly discussed. "Ontology development 101" is a guide that describes ontology development in an iterative manner. However, the precise nature of the iteration is unclear and this weakness has been criticised in Grzybek et al. [23]. It is not of any significant added-value to duplicate the methodological efforts well-covered in Beach et al. [14], Grzybek et al. [23], Abanda et al. [4,8] and Tah and Abanda [48] largely based on "ontology development 101" by Noy and McGuiness [40]. It has been argued in Uschold [51] that no unified methodology is suitable for all ontologies, but different approaches are required for different circumstances. We chose to adopt an established methodology called methontology, one of the leading ontology engineering methodologies. It is one of the most complete ontology engineering methodologies [11]. In fact, it can be used to build ontology from scratch as well as from reengineering or re-using existing ontologies. Furthermore, the method is so structured and uses tables for elicitating concepts instead of describing the elicitation process in essay formats common with other methodologies. It is so detailed and allows room for capturing micro-level information about concepts such as measurement units (e.g., £, $ and €) of attributes. This was very appealing and very suitable for the domain of construction cost estimation, where measurement units are key in QTO and costing. Thirdly, the domain ontology often comprise of the core domain ontology, data format ontology and the application ontology. Application here means, what the ontology is developed for. For example, in Beach et al. [14], the "regulation" ontology is the application ontology. Similarly, for this study, the core domain ontology will be concepts elicited from NRM 1. For the data format ontology, we will re-use the IFC building ontology, and the application ontology will be components cost estimation component and other related intelligent reasoning that can be performed in the ontology. To facilitate understanding, emphases will be placed on justifications of choices or decisions, lessons learned, any modelling and language issues, wider context of practical usage, experiences compared with other ontology development projects vis-à-vis methodology, tools, and languages. In the plethora of ontology methodologies, some issues are common to them. These are the needs to consider: the reasons why an ontology is to be developed for, the main concepts or classes, properties of concepts, instances or individuals of concepts, rules if reasoning is to be enhanced or conducted.

Firstly, the purpose of the NRM 1 ontology is to facilitate and automate construction cost estimation in the UK. Hence, the ontology should capture concepts relevant and understandable to professionals in the UK, although it can still be re-used by other professionals who are familiar or interested in using UK NRM 1 measurement standards. Secondly, the ontology concepts were developed from the work breakdown structure from the NRM 1 book. They work breakdown structure includes Group 1: Substructure; Group 2: Superstructure; Group 3: Internal Finishes; Group 4: Fittings, Furnishes and Equipment; Group 5: Services; Group 6: Prefabricated Buildings and Building Units; Group 7: Work to Existing Buildings and Group 8: External Works. In all, concepts were categorised into five levels. The top (first) level concepts adopted are Substructure; Superstructure; Internal Finishes; Fittings, Furnishes and Equipment; Services; Prefabricated Buildings and Building Units; Work to Existing Buildings and External Works. The second level concepts were obtained from the immediate breakdown of first level concepts as in the NRM. The third, fourth and fifth concepts were obtained from the first and second column respectively from the tables under each second level concept.

6.2. Conceptualisation

The methontology technique divides the ontology building process into small understandable tasks. All the tasks are briefly presented in the ensuing paragraphs.

- **Task 1:** In this task, a glossary of terms including relevant terms of the domain of construction cost estimating is developed. This includes concepts, instances, attributes and relationships, their natural language description, their synonyms and acronyms. The terms were all abstracted from the UK NRM 1. Top concepts were easy to spot, as these have already been well-structured in the book. As recommended in Gómez-Pérez et al. [22], synonyms should be identified and dealt with.

A screenshot showing the different concepts, using Superstructure as an example has been presented in Fig. 4. To facilitate understanding, instead of using different concepts to illustrate different aspects of the ontology, only the Superstructure will be used as in Figs. 6, 7, 10, 11 and 12. Given that the concepts that reached the fifth levels were not many, only an excerpt of the first four is presented in Fig. 4.

One other aspect not straightforwardly captured in NRM are the model measurements concepts. In this regards, we explored the way Navisworks and Autodesk QTO work and with practical experiences in using Navisworks shared by Mullin [34], 9 concepts were captured and included as part of the ontology. These are the ModelLenghth, ModelWidth, ModelThickness, ModelHeight, ModelPerimeter, ModelArea, ModelVolume, ModelWeight and the Count concepts (see Fig. 7).

- **Task 2:** Based on the list of glossary terms, concept taxonomies are built. To facilitate identification, top-down approach proposed by Uschold and Grüninger [52] is adopted. In building taxonomies, Methontology proposes that four taxonomic relations, *SubClass-Of*, *Disjoint-Decomposition*, *Exhaustive-Decomposition* and *Partition* should be used. We will define these taxonomic relations using mathematical formulations.

A concept C_1 is a SubClass-Of a concept C_2 if and only if every instance of C_1 is an instance of C_2. This is mathematically represented as:

$$\forall x \ \text{instance}, x \in C_1 \rightarrow x \in C_2$$

A *Disjoint-Decomposition* of a concept C is a set of subclasses of C that do not have common instances and do not cover C, i.e., there can be instances of the concept C that are not instances of any of the concepts in the decomposition. The mathematical modelling of this is as follows:

A family of sets $F = \{1 \leqslant i \leqslant n$, where i and n are integers, $C_i \subset C\}$ is a Disjoint-Decomposition of a concept C if and only if all of the following conditions hold:

(1) $\forall i \ 1 \leqslant i \leqslant n \ C_i, \forall i \ 1 \leqslant i \leqslant n$ with $i \neq j$ and $C_i \neq C_j$ then $C_i \cap C_j = \varnothing$
(2) $C \not\subset \cup C_{i, 1 \leqslant i \leqslant n}$

An *Exhaustive-Decomposition* of a concept C is a set of subclasses of C that cover C and may have common instances and subclasses,

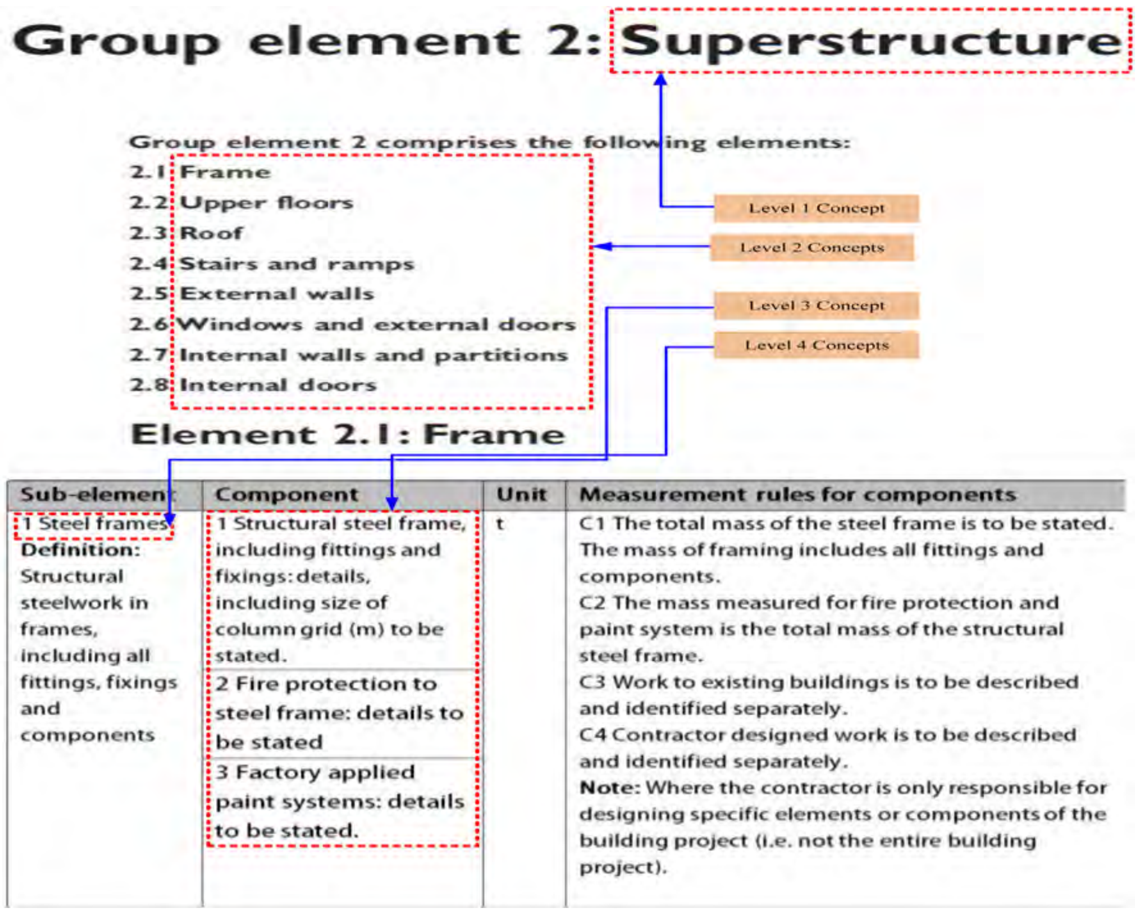

Fig. 4. Abstraction of concepts from NRM.

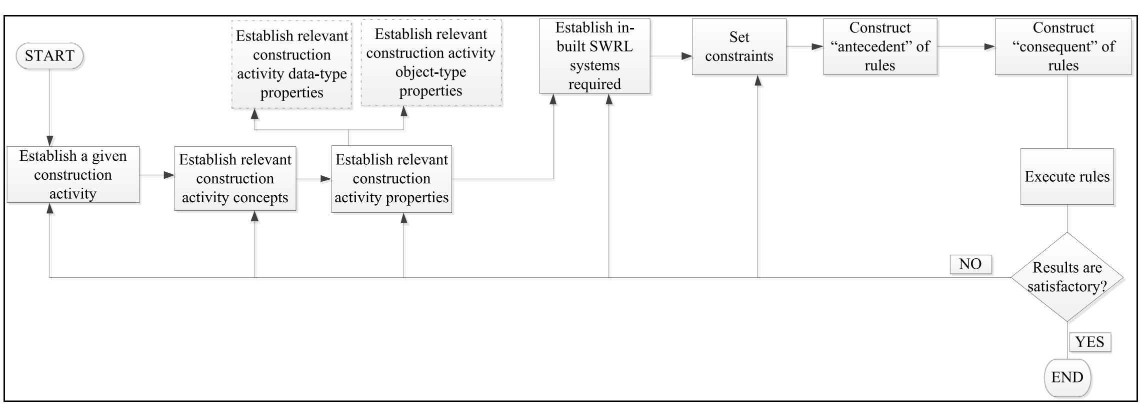

Fig. 5. SWRL rule construction and verification process.

i.e., there cannot be instances of the concept C that are not at least one of the concepts in the decomposition. This can be modelled mathematically as:

A family of sets $F = \{1 \leqslant i \leqslant n$, where i and n are integers, $C_i \subseteq C\}$ is an exhaustive-decomposition of a concept C if and only if the following condition holds:

(1) $\forall$ x instance, $x \in C \Rightarrow \exists\, C_i$, $C_i \in F$ and $x \in C_i$

A *Partition* of a concept C is a set of subclasses of C that does not share common instances but that covers C, i.e., there are no instances of C that are not instances of one of the concepts in the partition. This can be modelled mathematically as:

A family of sets $F=\{C_i, 1 \leqslant i \leqslant n$, where i and n are integers$\}$ is a *Partition* of a concept C if and only if all of the following conditions hold:

(1) $\varnothing \notin F$
(2) $\forall i\ 1 \leqslant i \leqslant n\ C_i$, $\forall i\ 1 \leqslant i \leqslant n$ with $i \neq j$ and $C_i \neq C_j$ then $C_i \cap C_j = \varnothing$
(3) $\cup C_{i,1 \leqslant i \leqslant n} = C$

- **Task 3:** In this task, ad hoc binary relation diagrams are built to identify the ad hoc relationships between concepts of the same ontology (or different) ontologies.
- **Task 4:** This task consists of building a concept dictionary which includes concept instances, instance and class attributes and their ad hoc relations.

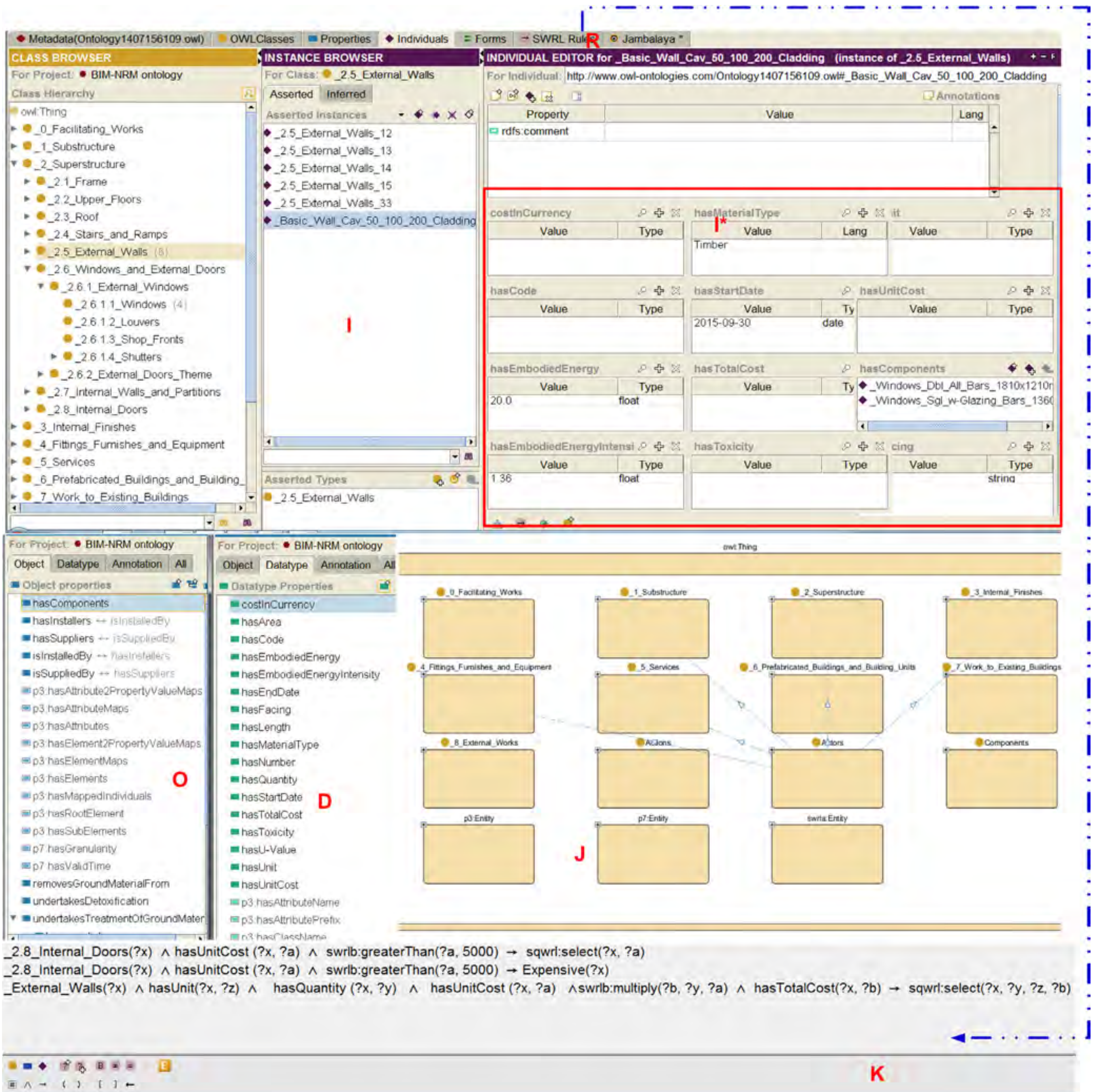

Fig. 6. Proposed ontology for cost estimation.

- **Task 5:** In this task, all ad hoc binary relations in the ad hoc binary relation diagram and concept dictionary are described.
- **Task 6:** In this task, all the instance attributes in the concept dictionary are described.
- **Task 7:** In this task, the details of the class attributes in the concept dictionary are described.
- **Task 8:** In this task, all the constants listed in the glossary of terms are described.
- **Task 9: Describe formal axioms:** In this task the formal axioms in the ontology are described.
- **Task 10:** In this task, rules in the ontology are identified, formulated and then described.
- **Task 11:** Once the conceptual model of the ontology has been developed, relevant instances in the concept dictionary are defined.

Upon execution of tasks 1–11, the excerpts of the outcome of the different tasks are summarised Table 1.

It is important to clarify how IFC was re-used in this study. In Protégé-OWL, instances can be generated automatically or manually edited. The former assumes names that may not be consistent with other ontological concepts. For example, instances generated automatically from Protégé-OWL assumes its parent class' name, which can be confusing. Partly for the preceding reason, we opted for manual creation of instances.To facilitate understanding, it is recommended and logical to use same names of the building components as in the BIM model. This could be the IFC nomenclature or native BIM software file name. Although, in this case study house, most IFC nomenclature were similar to the Revit native nomenclature. For example, a cavity wall in the Revit is named as ***Basic Wall Cav 50 100 200 Cladding*** while the IFC equivalent is ***Basic Wall:***

```
<ItemGroup Name="Superstructure" WBS="2">
    <ItemGroup Name="Frame" WBS="1">
      <ItemGroup Name="Steel Frames" WBS="1">
        <ItemGroup Name="Structural Steel Frame" WBS="1">
          <Item Name="Structural Steel Frame" WBS="1" Description="Structural Steel Frame" Transparency=".4" Color="5526869">
            <VariableCollection>
              <Variable Name="Length" Formula="=ModelLength" />
              <Variable Name="Width" Formula="=ModelWidth" />
              <Variable Name="Thickness" Formula="=ModelThickness" />
              <Variable Name="Height" Formula="=ModelHeight" />
              <Variable Name="Perimeter" Formula="=ModelPerimeter" />
              <Variable Name="Area" Formula="=ModelArea" />
              <Variable Name="Volume" Formula="=ModelVolume" />
              <Variable Name="Weight" Formula="=ModelWeight" />
              <Variable Name="Count" Formula="=1" />
              <Variable Name="PrimaryQuantity" Units="Count" />
            </VariableCollection>
          </Item>
        </ItemGroup>
        <ItemGroup Name="Fire Protection to Steel Frame" WBS="2">
          <Item Name="Fire Protection to Steel Frame" WBS="1" Description="Fire Protection to Steel Frame" Transparency=".4" Color="5526869">
            <VariableCollection>
              <Variable Name="Length" Formula="=ModelLength" />
              <Variable Name="Width" Formula="=ModelWidth" />
              <Variable Name="Thickness" Formula="=ModelThickness" />
              <Variable Name="Height" Formula="=ModelHeight" />
              <Variable Name="Perimeter" Formula="=ModelPerimeter" />
              <Variable Name="Area" Formula="=ModelArea" />
              <Variable Name="Volume" Formula="=ModelVolume" />
              <Variable Name="Weight" Formula="=ModelWeight" />
              <Variable Name="Count" Formula="=1" />
              <Variable Name="PrimaryQuantity" Units="Count" />
            </VariableCollection>
          </Item>
        </ItemGroup>
        <ItemGroup Name="Factory Applied Paint Systems" WBS="3">
          <Item Name="Factory Applied Paint Systems" WBS="1" Description="Factory Applied Paint Systems" Transparency=".4" Color="5526869">
            <VariableCollection>
              <Variable Name="Length" Formula="=ModelLength" />
              <Variable Name="Width" Formula="=ModelWidth" />
              <Variable Name="Thickness" Formula="=ModelThickness" />
              <Variable Name="Height" Formula="=ModelHeight" />
              <Variable Name="Perimeter" Formula="=ModelPerimeter" />
              <Variable Name="Area" Formula="=ModelArea" />
              <Variable Name="Volume" Formula="=ModelVolume" />
```


Fig. 7. An excerpt of the ontology used for QTO/cost estimation.

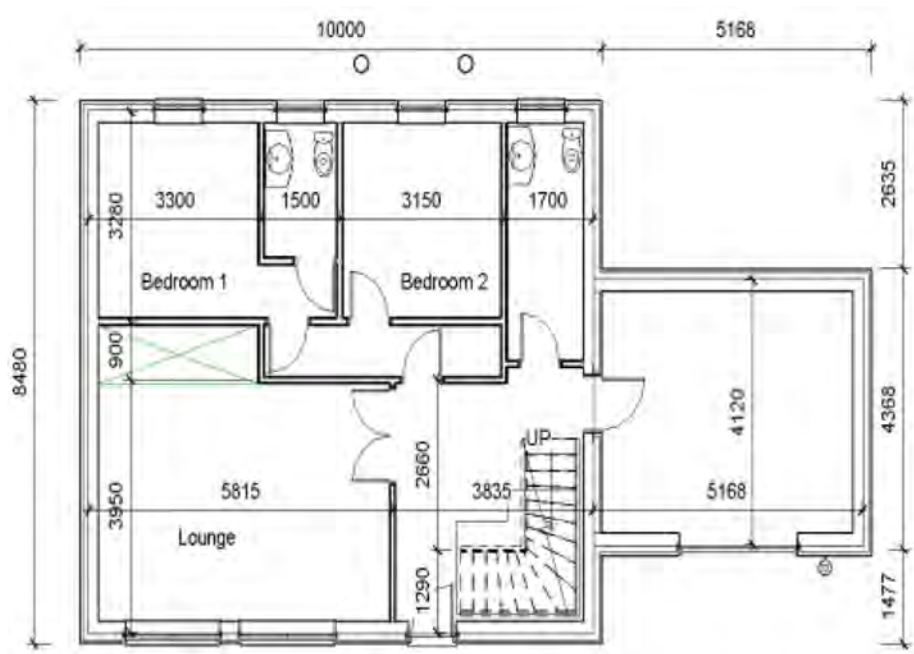

Fig. 8. Floor plan of case study.

Cav 50 100 200 Cladding:219191. We re-used IFC nomenclature, although in editing in Protégé-OWL, underscore were used between strings as spaces and double colon are not allowed in Protégé-OWL (see pane I of Fig. 6). However, automatic generated instances such as _2.5_External_Walls_12 have been allowed in the pane I just to illustrate the difference. It can be edited to conform with IFC nomenclature. Once an instance is created, it assumes properties that had been defined or attributed to its parent concept or class. These properties are like placeholders (see I∗ on Fig. 6), and corresponding data values can be edited. The last 10 rows of Table 1 are examples of IFC instances edited in the ontology.

So far, the development of concepts (see Fig. 4), object properties, datatype properties, instances and constraints (see Table 1) has been examined. The next task is to elaborate on development of rules for reasoning over the ontology especially in the context of cost estimation. The Semantic Web Rule Language (SWRL), well-documented on the W3C website (http://www.w3.org/Submission/SWRL/) will be used. SWRL is based on first-order logic implications (Horn clauses). A rule is generally in the form:

$$\text{Body} \rightarrow \text{Head} \qquad \text{(Rule1)}$$

The body is also known as the Antecedent while the Head is known as the Consequent.

Alternatively Rule 1 can be written as:

$$A_1, A_2, \ldots, A_n \rightarrow B \qquad \text{(Rule2)}$$

where A_i and B are the atomic formulas, ∀i belonging to the set of natural numbers. The rule reads as thus: If the conditions A_1,

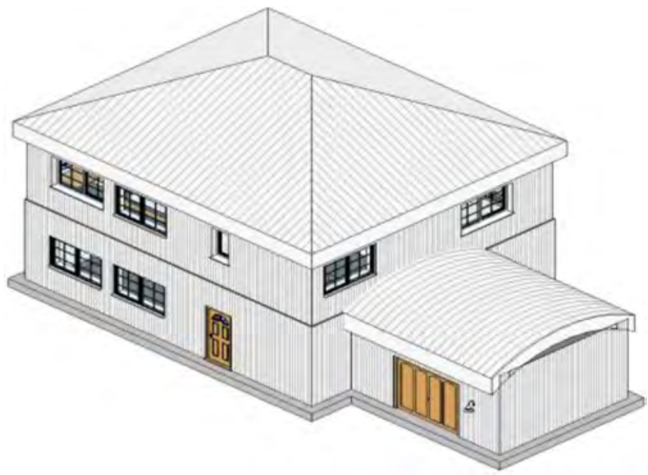

Fig. 9. 3D model of case study house.

$A_2, \ldots, A_n$ or the Body are true, then carry out the action B or execute the Head. The rules 1 or 2 are generic in nature and therefore the SWRL language syntax will need to be used in constructing the rules that will be edited in SWRLTab. SWRLTab is a protégé-OWL plug-in and editor that facilitates the writing of SWRL rules. The SWRL language syntax used are the conjunction symbol, the implication symbol, the rule variables, the individual syntax, class atomic syntax, individual property atoms syntax, data valued property atoms. The conjunction syntax is denoted as Λ and the implication symbol as→. The rule variables are represented by the interrogation identifier?, e.g. ?x. The class atoms are constructed from an OWL named "class", followed by one variable or individual name in parenthesis, e.g. 2.5 External_Walls(?x). The individual property atoms are constructed from an OWL object property name followed by two arguments in the parenthesis, e.g. hasMaterialType (?z, ?a). Similarly, the data valued property atoms are represented in the same way as individual property atoms. With regards to the application of the proposed ontology, some selected atoms for cost estimation and scheduling of components are:_2.5 External_Walls(?x) lists all the external walls x; hasUnitCost(?x, ?a) lists all the unit cost of the components x; hasQuantity(?x, ?y) lists all the quantities of the components x.

Similarly, all the syntax meanings for SWRL can be found on the link (https://github.com/protegeproject/swrlapi/wiki/SQWRL#SQWRL_Language_Features).

Based on our experience from previous research works (e.g. [6,4,8,48,44], the process map for developing SWRL rules is proposed in Fig. 5.

The proposed process map facilitates the understanding of the construction of SWRL rules, ensures nothing is missed during rule construction and optimises the chances of the rules to be syntactically and semantically correct.

2.8 Internal_Doors (?x) ∧ hasUnitCost(?x, ?a) ∧ swrlb:greaterThan(?a, 5000) →sqwrl:select(?x, ?a) q-1

The first atoms of the antecedent of the SWRL q-1 list internal doors (i.e. 2.8 Internal_Doors (?x)) and their respective unit costs (i.e. hasUnitCost(?x, ?a)) and then a constraint on the unit costs to be greater than 5000 (units in £ as this will be defined in the ontology editor Protégé-OWL) (i.e. swrlb:greaterThan(?a, 5000)) is imposed. The consequent of the query q-1 then list only those internal doors with unit cost greater than £5000.

2.8 Internal_Doors (?x) ∧ hasUnitCost(?x, ?a) ∧ swrlb:greaterThan(?a, 5000)

→ Expensive(?x) (Rule3)

Rule 3 classifies all doors with cost greater than £5000 as Expensive.

2.5 External_Walls(?x)∧hasUnit(?x, ?z)∧hasQuantity(?x, ?y) ∧hasUnitCost(?x, ?a) ∧swrlb:multiply(?b, ?y, ?a)∧hasTotalCost(?x, ?b)→sqwrl:select(?x, ?y, ?z, ?b) q-2

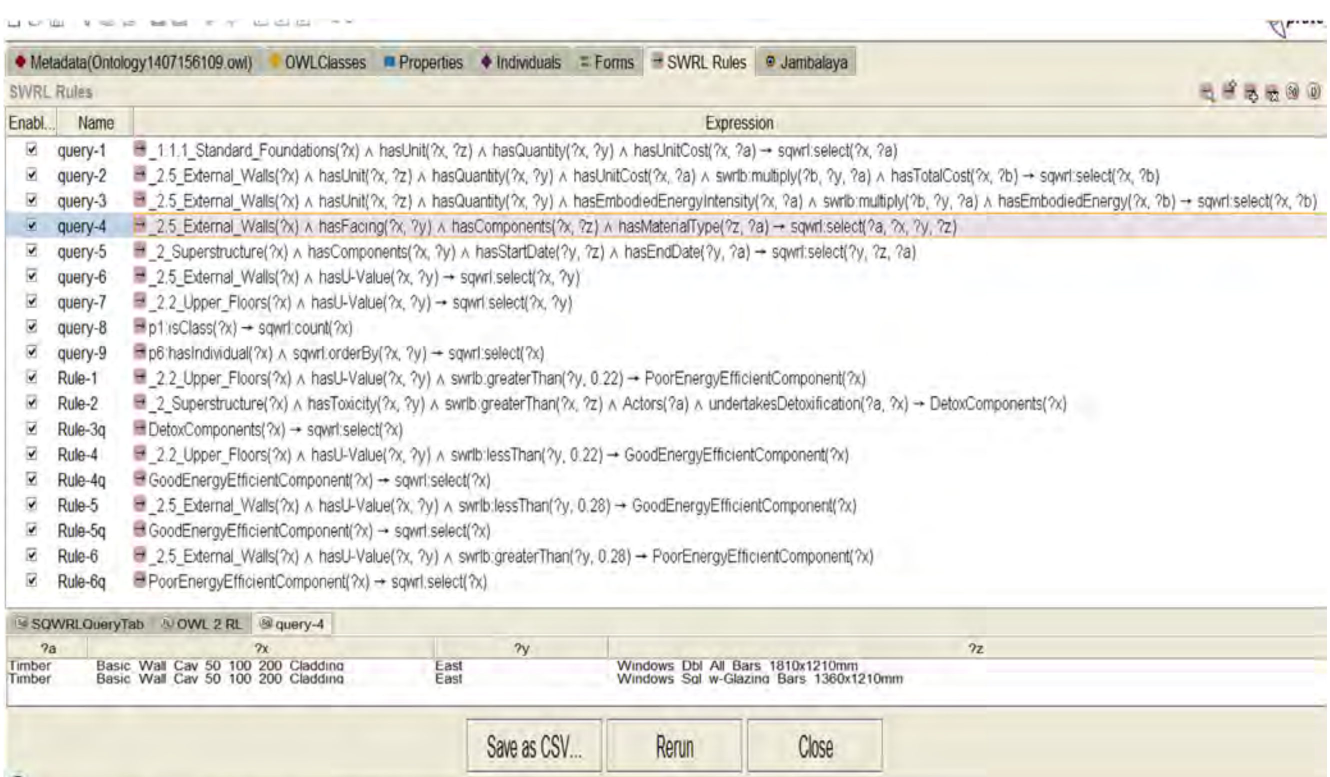

Fig. 10. Querying and reasoning in the cost estimation ontology.

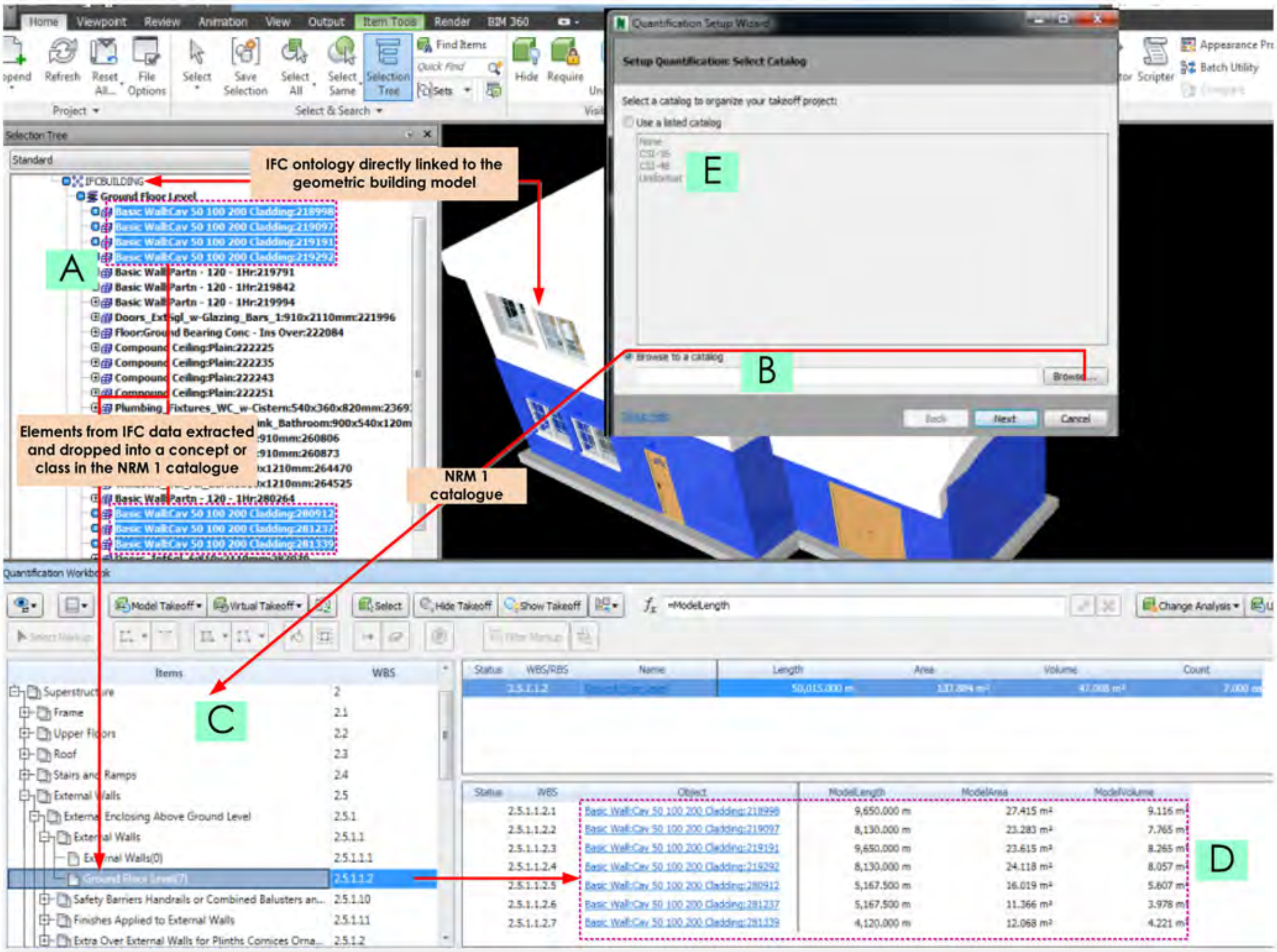

Fig. 11. BIM-based quantity take-offs in Navisworks.

Sub-element	Component	Unit
2 Specialist foundations **Definition** -Load bearing foundation piles and caissons -Inserting additional foundation support under and around existing foundations	**Piled foundations:** 1 Piling mats/platforms : details, including thickness of mat/platform (mm) to be stated	m^2
	2: Piling plant: details to be stated. **Underpinning:** 14 Underpinning: details to be stated	Item m

Fig. 12. Illustration of lack of consistency in concept headings/levels.

In q-2, in the antecedent, the measurement units (i.e. hasUnit(?x, ?z)), quantities (i.e. hasQuantity(?x, ?y)) and respective unit costs (hasUnitCost(?x, ?a)) of the external walls are determined. Then an SWRL built-in function (i.e., swrlb:multiply(?b, ?y, ?a)) is used to determine the total cost (i.e., hasTotalCost(?x, ?b)) of the external walls. In the consequent, the external walls with their respective measurement units, quantities and total costs (?b) are determined and listed.

The Rule 3 and queries q-1 and q-2 are just some of the examples of applications of the proposed ontology. So many others such as for project scheduling, energy efficiency (e.g. determine the most energy efficient rooms), eco-materials (i.e. determining the most eco-friendly materials) and embodied energy assessment can be conducted using the proposed ontology.

7. Implementation in an ontology engineering editor

Based on the review of the different ontology editors (e.g. Gómez-Pérez et al., [22]), Protégé-OWL 3.5 was adopted. One major reason is its stability and popularity in the ontology and Semantic Web community. Another reason is its compatibility with other plug-ins required for other purposes. For example, in the case of this study, Jambalaya, SWRLTab and JessTab were required. Jambalaya is a plug-in for visualising the ontology in

Please cite this article in press as: F.H. Abanda et al., BIM – New rules of measurement ontology for construction cost estimation, Eng. Sci. Tech., Int. J. (2017), http://dx.doi.org/10.1016/j.jestch.2017.01.007

Table 1
Output of the different tasks.

An excerpt of glossary of terms

Name	Synonyms	Acronyms	Description	Type
Basement excavation	//	//	Bulk excavation required for construction of floors below ground floor	Concept
Steel frames	//	//	Structural steelwork in frames, including all fittings, fixings and components	Concept
Component	Sub-element		Measured item that forms part of an element	Concept

Concept taxonomies

Concept name	Class attributes	Instance attributes	Relations
Space frames/deck		Gross internal floor area	hasArea
Column		Linear length between top of the slab and the soffit of the beam attached to the next floor level	hasLength
Steel frame		Total mass of steel	hasMass
Concrete casing		The linear length is the distance between the top of the slab/bed and the soffit of the beam attached to the next floor level	hasLength
External wall		The area measured is the area of the external wall, measured on the centre line of the external wall. No deductions of windows or external walls	hasArea
External soffit		The area measured for each type of external soffit is the surface area of the soffit to which the finish is to be applied.	hasArea
Roof covering		This is the surface area of the roof covering the extremities of the eaves or to the internal face of the parapet wall, whichever is applicable	hasArea
External doors		Where components are to be enumerated, the number of components is to be stated	hasNumber
Structural screed		Area to which screed is applied	hasArea

An excerpt of the ad hoc binary relation table

Relation name	Source concept	Source card. (Max)	Target concept	Mathematical properties	Inverse relation
hasArea	Structural screed	1			
hasLength	Column	1			
undertakesDetoxfication	Actors			Symmetrical	
hasUnit	Superstructure	1			

An excerpt of the instance attributes

Instance attribute name	Concept name	Value type	Measurement unit	Precision	Range of values	Cardinality
hasArea	Earthwork support	float	m^2	...	...	>0
hasLength	Guide walls	float	m	...	...	>0
hasVolume	Disposal of excavated	float	m^3	...	...	>0

(*continued on next page*)

Please cite this article in press as: F.H. Abanda et al., BIM – New rules of measurement ontology for construction cost estimation, Eng. Sci. Tech., Int. J. (2017), http://dx.doi.org/10.1016/j.jestch.2017.01.007

Table 1 (*continued*)

An excerpt of glossary of terms

Name	Synonyms	Acronyms	Description	Type
	material arising from piling			

An excerpt of the class attribute table

Attribute name	Defined at concept	Value type	Measurement unit	Precision	Cardinality	Values
hasCode	All	string	. . .	. . .		
hasUnitCost	All	float	£, $, €	. . .	>0	
hasTotalCost	All	float	£, $, €	. . .	>0	

Description of constants

Name	Value type	Value	Measurement unit
Allowance for subcontractor's preliminaries	float	. . .	£, $, €
Allowance for design fees	float	. . .	£, $, €
Allowance for overheads	float	. . .	£, $, €
Risk allowances	float	. . .	£, $, €

An excerpt of the formal axiom table

Axiom name	Hazardous parts of building fabric
Description	Every toxic part of the building fabric contains hazardous materials.
Expression	∀ (?x, ?y, ?z) such that: Building fabric (?x) and Chemical (?y) and contains (?x, ?y) and Actor (?z) and owns(?x, ?z) then undertakesDetoxification (?z, ?y)
Concepts	Building Elements, Action
Adhoc binary relations	detoxify, undertakesDetoxification
Variables	?x, ?y, ?z

An excerpt of the rule table

Axiom name	Hazardous parts of building fabric
Description	Every toxic part of the building fabric must be detoxified.
Expression	∀ (?x, ?y, ?z) such that: Building fabric (?x) and Chemical (?y) and contains (?x, ?y) and Actor (?z) and owns(?x, ?z) then undertakesDetoxification (?z, ?y)
Concepts	Building Elements, Action
Adhoc binary relations	detoxify, undertakesDetoxification
Variables	?x, ?y, ?z

An excerpt of the instance table

Instance name	Concept name	Attribute	Values
Windows_Sgl_Plain:1810x1210 mm:299503	Windows	hasArea	
Windows_Sgl_Plain:910x910 mm:299282	Windows	hasArea	
Doors_ExtSgl_Flush:1010x2110 mm:303335	External doors	hasArea	
Doors_IntSgl:910x2110 mm:296738	Internal Doors	hasArea	
Doors_IntSgl:910x2110 mm:297610	Internal Doors	hasArea	
Basic Wall:Wall-Ext_215Bwk:300258	External Walls	hasArea	
Basic Wall:Wall-Ext_215Bwk:295727	External Walls	hasArea	
Wall Foundation:Standard:300533	Standard Foundations	hasModelLength	
Basic Wall: Cav 50 100 200 Cladding:219191.	Internal Walls	hasInsulationThickness	100
Basic Roof:Roof_Pitched-50 SS-220Ins-20 MPan-225Purl:300386	Roof Structure Pitched Roofs	hasModelHeight	

graphical format. SWRLTab is used in modelling rules in the ontology. JessTab is a plug-in for Protégé that allows ontology developers to use Jess and Protégé together. Rule-based reasoners, like Jess, allow for more general reasoning than the OWL-based reasoners often incorporated in Protégé-OWL editors.

7.1. The complete ontology

The complete ontology is made up of classes, properties, instances and rules. The different components of the ontology are presented in Fig. 6.

Please cite this article in press as: F.H. Abanda et al., BIM – New rules of measurement ontology for construction cost estimation, Eng. Sci. Tech., Int. J. (2017), http://dx.doi.org/10.1016/j.jestch.2017.01.007

The top extreme left of Fig. 6 are made up of classes that represent different work breakdown structure of NRM 1. For example _2_Superstructure is a top class directly under the overall "Thing" concept used to represent tangible and non-tangible things in ontology development. Some examples of the subclasses of the _2_Superstructure are _2.1._ Frame, _2.2_Upper Floor, and _2.3_Roof. The pane **O** denotes the different object properties captured in the ontology. This indicates relations between concepts. The pane **D** represents the data type properties. Some examples include hasArea, hasLength, hasVolume, hasU-Value, etc. The pane **I**, are ontological instances. Generic instances are generated directly in Protégé-OWL and property values assigned to them. To facilitate understanding, it is recommended and logical to use same names of the building components as in the BIM model. This could be the IFC nomenclature or native BIM software file name. Although, in this case study house, most IFC nomenclature were similar to the Revit native nomenclature; it might not be the case with other BIM software. For example, a cavity wall in the Revit is named as ***Basic Wall Cav 50 100 200 Cladding*** while the IFC equivalent is ***Basic Wall: Cav 50 100 200 Cladding:219191.*** with the term IFCBUILDING being at the top concept as earlier explained in Table 1. We opted for IFC nomenclature, although in editing in Protégé-OWL, underscore were used between strings as spaces and double colon are not allowed in Protégé-OWL (see pane I of Fig. 6). However, automatic generated instances such as _2.5_External_Walls_12 have been allowed in the pane I just to illustrate the difference. It can be edited to conform with IFC nomenclature. Once an instance is created, it assumes properties that had been defined or attributed to its parent concept or class. These properties are like placeholders (see I* on Fig. 6), and corresponding data values can be edited. To facilitate reasoning, rules have been embedded in the ontology as indicated in the pane **R**, an expansion of the pane is the pane K with some queries and rules. The details of the rules and how they are executed have been discussed in Section 8.1. To facilitate understanding, Jambalaya-a visualisation tool was used to generate the graph form of the ontology as indicated in the pane **J**.

7.2. Editing the ontology into a BIM software

In order to use the developed ontology in a BIM software, a programme was written to translate the OWL ontology of Fig. 6 to an XML-based ontology. This was done because most BIM software can only read XML based files. The transformation is achieved by using the OWL API to manipulate the OWL ontology file; JDOM to manipulate and create the content of XML and Hermit to reason over the file. To provide more clarity, the specific contributions of OWL API, JDOM and Hermit will be examined in the ensuing paragraphs. The purpose of the OWL API in this transformation process is to parse the OWL file (i.e. the developed ontology) in order to extract the name of each class and transform it to a corresponding String that will be used in the building of the XML file. This is achieved by redefining the ***visit*** method of the interface **OWLAnnotationObjectVisitor** in the class **LabelExtractor** of the project as shown in code 1.

Code 1: Parsing of the OWL file

```
public void visit(OWLAnnotation annotation)
{
        // TODO Auto-generated method stub
        if(annotation.getProperty().isLabel())
        {
                OWLLiteral c = (OWLLiteral) annotation.getValue();
                result = c.getLiteral();

        }
}
```

The JDOM API is used for building an XML file based on the input OWL file. Although it is possible to convert the OWL file into RDF/XML format within the Protégé software, the resulted XML file will have a ".rdf" extension and not an ".xml" extension. The ".rdf" extension is not supported in Navisworks. This is corroborated by findings from Karan et al. [28], that stated that the results of Semantic Web queries are not supported by BIM authoring tools. That is why it is necessary to convert the OWL file into an XML file with the extension ".xml". The produced XML file must respect a particular structure (which can be read by Navisworks) depicted in Fig. 7. Before building the entire XML, a String containing XML elements is built incrementally by the method printHierarchy(**OWLReasoner reasoner, OWLClass clazz, int level**) according to the hierarchy in the OWL file. At the end of the OWL file the resulted String is transformed into an XML document as depicted in code 2.

Code 2: Building an XML file from the OWL ontology

```
public void printHierarchy(OWLReasoner reasoner, OWLClass clazz, int level) {
    //System.out.print("level ="+level);
    if (reasoner.isSatisfiable(clazz)) {
        String className = labelFor(clazz).substring(labelFor(clazz).lastIndexOf("#") + 1, labelFor(clazz).length());
        HierarchyNumberAndName hiera = new HierarchyNumberAndName(className);
        hiera.GetHierarchyNumber();
        if (hiera.getName() != null) {
            Set<OWLClass> set = reasoner.getSubClasses(clazz, true).getFlattened();
            String numberId = "WbSn" + "\"" + hiera.getNumber().substring(hiera.getNumber().lastIndexOf(".") + 1) + "\"";
            String debutItemGroup = "<ItemGroup " + "Name=" + "\"" + hiera.getName() + "\" " + numberId + ">";
            if (set.size() == 1) {
                for (OWLClass child : set) {
                    if (child.isOWLNothing()) {
                        String additionalAttribut = "Description=" + "\"" + hiera.getName() + "\" Transparency=\".4\" Color=\"5526809\"";
                        String debutItem = "<Item " + "Name=" + "\"" + hiera.getName() + "\" " + "WBS=\"1\"" + " " + additionalAttribut + ">";
                        xmlString = xmlString + debutItemGroup;
                        xmlString = xmlString + debutItem;
                        xmlString = xmlString + varialbleCollection;
                        xmlString = xmlString + "</Item>";
                    } else {
                        xmlString = xmlString + debutItemGroup;
                    }
                }
            } else {
                xmlString = xmlString + debutItemGroup;
            }
        }
        try {
            Thread.sleep(1);
        } catch (InterruptedException e) {
            // TODO Auto-generated catch block
            e.printStackTrace();
        }
        for (OWLClass child : reasoner.getSubClasses(clazz, true).getFlattened()) {
            if (!child.isOWLNothing()) {
                if (!child.equals(clazz)) {
                    printHierarchy(reasoner, child, level + 1);
                }
            }
        }
        if (hiera.getName() != null) {
            xmlString = xmlString + "</ItemGroup>";
        }
    }
}
```

Please cite this article in press as: F.H. Abanda et al., BIM – New rules of measurement ontology for construction cost estimation, Eng. Sci. Tech., Int. J. (2017), http://dx.doi.org/10.1016/j.jestch.2017.01.007

Based on code 2, it is the variable xmlString that will be transformed into an XML document. The XML file supported by the BIM is structured as follows:

- o *ItemGroup* with attributes name and work breakdown structure (WBS), required for building the hierarchy in the XML file. It can contain several ItemGroup elements.
- o *Item* with a WBS required attribute and some optional attributes like name, description, and transparency. *Item* cannot contain an element ItemGroup. The only element that *Item* can contain is *VariableCollection*.
- o *VariableCollection* contains *variable* elements, which are quantitative elements such as length, width, perimeter, thickness, etc.

In code 2:

- It is checked if the current variable contains one element and when scanning the child set:
  - o If the child is an OWL nothing element (a "nothing" element in OWL paradigm means a parent concept with no children), it means that the current element is an Item, then a String "*<Item* "+"*Name=*"+"\""+*hiera.getName()*+"\" "+"*WBS=*\"*1*\"" +" "+*additionalAttribut*+">" and its sub-elements are added to the variable xmlString. The element "</*Item*>" is added to the resulted xmlString.
  - o Else it means that the current element is an ItemGroup element, then "*<ItemGroup* "+"*Name=*"+"\""+*hiera.getName()*+" \" "+*numberId*+">" is added to xmlString.
- Otherwise, it means that the current element is an ItemGroup element, then "*<ItemGroup* "+"*Name=*"+"\""+*hiera.getName()*+" \" "+*numberId*+">" is added to xmlString
- The method (printHierarchy(**OWLReasoner reasoner, OWLClass clazz, int level**) is called in a recursive manner for the higher level. When exiting a level it is checked if the name of the current element (class) is not null. If yes, the String "</Item Group>" is added to xmlString.
- The method in code 3 facilitates the creation of an XML document with a String as parameter

Code 3: Creation of an XML document with a String parameter

```
/**
 * Convert a string in an xml format
 * @param xmlString
 * @return {@link Document}
 */
public Document convertStringToXML(String xmlString)
{
        SAXBuilder sxb = new SAXBuilder();
        Document doc = null;
        try
        {
                doc = sxb.build(new ByteArrayInputStream(xmlString.getBytes()));
        }
        catch(Exception e)
        {
                e.printStackTrace();
        }
        return doc;
}
```

The Hermit reasoner is an API, which facilitates reasoning on ontologies. With regards to this transformation process, it was used to create an OWLReasonerFactory, which was later on used to create an OWLReasoner for parsing the OWL file (refer to the method **printHierarchy(OWLReasoner reasoner, OWLClass clazz, int level**) in code 3.

Based on the transformation details described in codes 1, 2 and 3, an XML NRM 1 catalogue that can be processed by Navisworks is generated. An excerpt of the transformed ontology is presented in Fig. 7.

8. Application of the ontology

The main purposes of the proposed ontology are twofold. The first is to facilitate reasoning over the building items for different purposes. For example, the ontology can be queried to list a schedule of windows that can be used for procurement. For this first purpose, the ontology was allowed as it was created with complete ontological concepts. This corresponds to the branch denoted as "*Other reasoning application(s) of ontology*" of Fig. 3. The intention is to make the complete ontology publicly available for users to be able to transform or adapt to meet their various needs. The second purpose was to use the developed ontology for QTO that will subsequently be used for cost estimation. Such an ontology will allow consistency among measurement concepts that can facilitate comparison of cost of components or efficient cost control. For this purpose, a code was written to transform the developed ontology into a suitable format that can be read by BIM authoring software systems. This component corresponds to branch captioned "*QTOs/Cost estimation*" in Fig. 3 and made up of only classes for mapping quantities obtained from the geometric model or IFC building ontology.

8.1. Description of the case study house

The case study house chosen for this work is a house with well-known information. This house was designed by one of our undergraduate students on Quantity Surveying and Commercial Management programmes in the School of the Built Environment in Oxford Brookes University. The house is a typical UK detached domestic dwelling consisting of the ground floor and first floor. On the ground floor, there are 2 bedrooms, 1 lounge and 2 bathrooms. On the first floor, there are 3 bedrooms, 1 ensuite and 1 bathroom. The total ground floor area (GFA) is 192.2m^2. To facilitate understanding, the floor plan of the ground floor and the 3D model of the house are presented in Figs. 8 and 9 respectively.

Application 1: General reasoning in the ontology

An excerpt of rules for querying and generating knowledge about different concepts of the house edited in Protégé-OWL is presented in Fig. 10.

For example the schedule of different house components is modelled in query-4, where:

- _2.5 External_Walls(?x) lists all the external walls x;
- hasFacing (?x, ?y) reveals the facing (y: East, West, South, or North) of the external walls x
- hasComponents (?x, ?z) lists each component z located on each external wall x
- hasMaterialType (?z, ?a) lists the material type a of each component z located on each external wall x
- sqwrl:select(?a, ?x, ?y, ?z) lists the different external walls (x) and their facings (y), the components or house elements (z) on them, the material (a) from which the component is made from. See query-4 results at the bottom of Fig. 10.

An example illustrating the determination of energy performance of house components has been modelled rule-6 and rule-6q where:

- 2.5 External_Walls(?x) lists all the external walls x;
- hasU-Value(?x, ?y) reveals the U-values (y) of all the external walls x;
- swrlb:lessThan(?y, 0.28) is an in-built function that sorts out all U-values less than 0.28
- PoorEnergyEfficientComponent(x) is where all the external walls with U-values less than 0.28 are classified
- The consequent "PoorEnergyEfficientComponent(x)" is now use as an antecedent of rule-6q and the sqwrl:select(?x) lists all the poor energy efficient components.

Protégé-OWL offers the possibility of performing many other types of queries and rule-based reasoning such as cost estimation (e.g. query-2), embodied energy computation (query-3), generating schedules (query-9) and basic project sequencing (query-5).

8.2. Application 2: QTO and cost estimation

To facilitate understanding, an illustration of QTO in Navisworks is presented in Fig. 11.

The user imports the house model into Navisworks and the model data is presented in the palette **A**. The quantification function is selected and the standard measurement catalogues are displayed as shown in **E** for the user to choose. As earlier argued, there is no NRM for quantification, hence our proposed solution. All that are visible in **E** are CSI-16, CSI-48 and Uniformat. To import our proposed ontology, the user can browse (see "Browse to a catalogue") below **B** to select the catalogue stored anywhere on the computer system. This is where the major contribution of this paper is. Once a template is selected in **B**, the catalogue opens in **C**, and house elements can be selected from **A** and dropped into the respective concepts in **C**. The quantities are generated in **D**.

To compare the accuracy of the computation, we manually computed the quantities of the house components and compared the results to that automatically generated. Without loss of generality, the results of ModelLength, ModelArea and ModelVolume for the external walls yielded similar results with very insignificant differences. In fact, the automatic computation yielded 50.014 m, 217.42 m^2 and 74.749 m^3 while the manual computation yielded 51.664 m, 219.5 m^2, 76.825 m^3 for the ModelLength, ModelArea and ModelVolume respectively. Although, these differences are insignificant we sought to investigate why there were variations. A detailed investigation revealed that Revit default setting for walls was *Wall Centerline*, meaning measurements were from centreline to centreline, while manual computation was based on exterior finish. We then set the measurement on *Wall Centerline*, for both the manual computation and the automatic generated methods and the results were the same with no differences. Furthermore, we tested both methods using *Core Centerline, Finish Face: Exterior, Finish Face: Interior, Core Face: Exterior and Core Face: Interrior* and results from both methods were the same.

9. Evaluation of the developed ontology

Evaluation of ontology is a mandatory activity [22]. The evaluation of an ontology consists of three activities. The first two activities are verifying the ontology for semantic and syntactic correctness. The last consists of validating the ontology for the purpose it was developed for.

With regards to semantic verification, the concept elicitation exploited the structured format of the NRM 1. Concepts were manually extracted and edited into Protégé-OWL 3.5. Through a focused group discussion with 6 experts, the ontology was revised and the final version deemed to reflect practice was semantically correct. The experts consisted of 2 Senior Lecturers in quantity surveying, and 4 practicing quantity surveyors working in the construction industry. The focus of the group's discussion was whether the abstracted concepts were accurate and reflected concepts use in the bill of quantities templates for cost estimation.

For syntactic verification, it is important to ensure the ontology is technically consistent and complies with OWL syntax, the intended developed language. For technical consistencies, Pellet 1.5.2, an OWL-based reasoners in Protégé-OWL was used. For OWL syntax compliance, the Manchester OWL syntax validator was used. The OWL validator accepts ontologies written in RDF/XML, OWL/XML, OWL Functional Syntax and Manchester OWL Syntax.

After the ontology has been semantically and syntactically verified, it was now validated against what it was intended for. In other words does the ontology do what it was intended for? This is achieved through the employment of a case study. It is important to recall the two main purposes of the developed ontology are an ontology that allows reasoning to be performed and also for QTO to be undertaken for cost estimation. As can be seen in Fig. 10, reasoning can be conducted on the full ontology. The transformed ontology was imported into one of the leading BIM software-Navisworks. The importation was successful and the imported ontology was used in performing QTO. The work breakdown structure generated in the 5D software (see C on Fig. 11) conforms with what is generally common in practice. Furthermore, the model lengths generated (see D on Fig. 11) are exact values of the model prior to being imported into Navisworks. The results from the 5D software was also validated by the same 6 experts through focus group discussion discussed in the second paragraph of this section.

10. Challenges and lessons learned in the modelling process

In the development of this ontology, three major challenges were encountered. Firstly, given spaces are not allowed in concepts or names in Protégé_OWL, it was not possible capturing names of concepts as they appear exactly in NRM 1. For example, in practice the concept "Fittings, Furnishes and Equipment" will appear as it is but in protégé-OWL, commas(,) and spaces are not allowed. Underscore (_) was therefore used to separate words, such that this

Table 2
Attainment of research objectives.

Investigate the different concepts in the NRM that can aid in (QTOs)/ and hence cost estimation;
• Manually elicited different NRM concepts from the NRM 1 book
Develop an ontology that model knowledge about construction QTOs/cost estimation;
• Identified and employed appropriate ontology engineering methodologies (e.g. Methontology) and tools (e.g. Protégé-OWL 3.5) in modelling the NRM 1 concepts
• The main outcome is a rich ontology that can be re-used for other purposes
• A code is written to transform the rich ontology to a NRM 1-based catalogue for QTO/cost estimation
Investigate how best to deal with constraints in NRM in the developed ontology;
• Identified constraints in the NRM 1
• Model the constraints using axioms and rules
Demonstrate the use of the ontologies in reasoning and performing QTOs/cost estimation;
• Used queries and rules to infer knowledge from the rich ontology
• Used the transformed ontology in QTOs by mapping the generated quantities from Navisworks
Evaluate the ontology whether it is fit for the intended purpose in standard BIM software systems.
• Queries from the ontology in Protégé-OWL 3.5 were compared to those from schedules manually counted in the model and the results were the same
• The quantities generated from the ontology in Navisworks was compared to those generated from manual computation and the results were the same with very insignificant differences;
• Six experts were also used in validating the structure of the electronic NRM 1 and the QTOs from the system.

concept now becomes "Fittings_ Furnishes_ and_ Equipment". Also, hyhens (-) were used to add additional meanings, when required to avoid confusion. Secondly, some concepts names were too long to be edited into Protégé-OWL. Although there is no restriction on length of names in Protégé-OWL, the first few words of the concepts were used as names of concepts and the remaining parts were captured as part of annotation properties. Thirdly, in some cases, there were repetitions in some concepts appearing in different hierarchies. For example, 1 Substructure and 1.1 Substructure appearing as level 1 and 2 concepts respectively. Fourthly, in some cases, some terms were included as major components before types of components included. For example, in Fig. 12, Piled Foundations and Underpinning have been stated before sub-components or activities are listed. In order to be consistent with the solution of the preceding fourth challenge, these concepts, Piled Foundations and Underpinning were included as they appear without change.

11. How the research aim and objectives were achieved

To facilitate understanding, a recapitulation of how the research objectives were achieved is presented in Table 2.

In addition to achieving the afore-mentioned objectives, some outputs of the research process could be of use to the professional and academic community. Some key outputs include the proposed BIM-cost estimating process (see Fig. 1), the system architecture (see Fig. 3) that integrate BIM and Semantic Web concepts, the abstraction techniques of NRM 1 concepts to translating to ontological concepts (Fig. 4), the SWRL construction and verification process map (Fig. 5), and how the constraints in NRM 1 were translated rules.

12. Conclusion

This study commenced with an extensive literature review which led to a gain in insights of the domain of 5D modelling. Furthermore, challenges facing construction cost estimators were identified and discussed. One main challenge was the lack of an ontology that could be used in reasoning and undertaking QTOs/cost estimation compliant to the UK New Rules of Measurement. To address these challenges, an ontology-based approach has been proposed. The approach is divided into three main actvities. Firstly, appropriate knowledge engineering/tools and BIM software systems were identified. Secondly, based on the chosen knowledge/ontology engineering technique/tools, the modelling of an ontology based on NRM concepts was undertaken. Specifically, methontology, one of the leading knowledge/ontology engineering methodologies was used. Also, the re-use of existing ontologies is crucial in the development of ontologies. To this end, the IFC domain ontology, one of the most important ontology in the construction domain was used. The use of IFC facilitated the abstraction of house components for QTOs and hence cost estimation. Thirdly, the developed ontology was implemented in Protégé-OWL 3.5, as this tool is one of the leading open source ontology editing tool widely used in the academic community. The fourth activity consisted of checking for consistencies in the ontology using reasoners. It is important to recall that the purposes of the ontology are for performing reasoning for other applications in construction and cost estimation. So after the complete ontology was checked or validated for consistencies and compliance, in the fifth task a code was written and used in transforming the complete ontology for purposes of cost estimation. In effect two ontologies were obtained-one complete rich ontology that included all ontology concepts and core ontology or catalogue of classes that consisted mostly of NRM 1 concepts. The sixth activity consisted of illustrating examples of reasoning task that can be performed in the complete ontology and QTOs in the core ontology. The reasoning examples were performed in the Protégé-OWL 3.5 environment while for QTOs and cost estimation the core ontology was exported to Navisworks for QTOs and later on to MS Excel for cost estimation. After these stages both results were validated whether both ontologies met the purposes for which they were developed for. For the reasoning component, the queries from protégé-OWL 3.5 were compared to the schedules generated from the Revit software and found to be the same. For the QTOs, the automatic results QTO from Navisworks were compared with real manual computation of quantities using real dimension of the case study house. Both results yielded similar results with very minor insignificant differences. Furthermore, 6 experts were used to validate the core ontology for QTOs. Given we have tested the core ontology on only Navisworks, as part of future study, this ontology will be tested on other BIM software systems such as Autodesk QTO. Also, it is expected that other end-users can adapt or transform the complete ontology in this study to meet their various needs.

Acknowledgements

This work was jointly funded by the Ecole Nationale d'Ingénieurs de Tarbes through the "Projet Soutien á la Mobilité Internationale (SMI) 2014" programme and the Oxford Brookes University through the Central Research Fund. Encouraging interdisciplinary research is amongst the top strategies of the two institutions. The authors gratefully acknowledge the financial support received.

Also, this work was conducted using the Protégé resource, which is supported by grant GM10331601 from the National Institute of General Medical Sciences of the United States National Institutes of Health.

The last but not the least, we thank Mr. George Swann for producing the model used as a case study in this manuscript. At the time of submission of this article George was a student on the Quantity Surveying and Commercial Management degree programme in the School of the Built Environment, Oxford Brookes University. He is also an Assistant Quantity Survey at Ridge and Partners LLP, UK.

References

[1] F.H. Abanda, L. Byers, An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling), J. Energy 97 (2016) 517–527.

[2] F.H. Abanda, B. Kamsu-Foguem, J.H.M. Tah, Towards an intelligent ontology construction cost estimation system: Using BIM and New Rules of Measurement techniques, Int. J. Comput., Control Quantum Inf. Eng. 9 (1) (2015) 294–299.

[3] F.H. Abanda, M.B. Manjia, C. Pettang, J.H.M. Tah, G.E. Nkeng, "Building Information Modelling in Cameroon: Overcoming existing challenges", Int. J. 3-D Inf. Model. (IJ3DIM) 3 (4) (2014) 1–25.

[4] F.H. Abanda, A. Ng'ombe, J.H.M. Tah, R. Keivani, An ontology-driven decision support system for land delivery in Zambia, Expert Syst. Appl. 38 (9) (2011) 10896–10905.

[5] F.H. Abanda, G.E. Nkeng, J.H.M. Tah, E.N.F. Ohandja, M.B. Manjia, Embodied energy and CO_2 analyses of mud-brick and cement-block houses, AIMS Energy J. 2 (1) (2014) 18–40.

[6] H. Abanda, J.H.M. Tah, C. Pettang, M.B. Manjia, K. Sambo, An ontology-driven approach to labour cost estimation: The case of house-building projects in Cameroon, in: The Proceedings of the International Conference on Computing in Civil and Building Engineering 2010, June 30-July 2, The University of Nottingham, UK, 2010, pp. 225–231.

[7] F.H. Abanda, W. Zhou, J.H.M. Tah, F. Cheung, Exploring the relationships between Linked Open Data and Building Information Modelling, The Proceedings of the Sustainable Building Conference, Coventry University, UK, 2013.

[8] F.H. Abanda, J.H.M. Tah, M. Manjia, C. Pettang, An ontology-driven house-building labour cost estimation in Cameroon, J. Inf. Technol. Constr. 16 (2011) 617–634.

Please cite this article in press as: F.H. Abanda et al., BIM – New rules of measurement ontology for construction cost estimation, Eng. Sci. Tech., Int. J. (2017), http://dx.doi.org/10.1016/j.jestch.2017.01.007

[9] F.H. Abanda, J.H.M. Tah, R. Keivani, Trends in built environment Semantic Web applications: Where are we today?, Expert Syst Appl. 40 (14) (2013) 5563–5577.
[10] G. Aouad, A. Lee, S. Wu, From 3D to nD modelling, ITcon 10 (2005) 15–16.
[11] A. Ayimdji, S. Koussoube, L.P. Fotso, B.O. Konfé, Using Methontology to build a deep ontology for African traditional medicine: First steps. [Online] http://www.cari-info.org/cari-2012/session%203/3B3.pdf [19/11/2016], 2012.
[12] S. Azhar, Building Information Modeling (BIM): Trends, benefits, risks and challenges for the AEC industry, Leadersh. Manage. Eng. 11 (3) (2011) 241–252.
[13] S. Azhar, A. Nadeem, J.Y.N. Mok, B.H.Y. Leung, Building Information Modeling (BIM): A new paradigm for visual interative modeling and simulation for construction projects, the proceedings of the First International Conference on Construction in Developing Countries (ICCIDC-I), dvancing and Integrating Construction Education, Research & Practice , August 4–5, 2008, Karachi, Pakistan, 2008.
[14] T.H. Beach, Y. Rezgui, H. Li, T. Kasim, A rule-based semantic approach for automated regulatory compliance in the construction sector, Expert Syst. Appl. 42 (2015) 5219–5231.
[15] N.B. Bouchlaghem, M. Holmes, D. Loveday, A. Bennadji, The engineering dimension of nD modelling 10 (2005) 17–25. Special Issue From 3D to nD modelling.
[16] D. Bryde, M. Broquetas, J.M. Volm, The project benefits of Building Information Modelling (BIM), Int. J. Project Manage. 31 (7) (2013) 971–980.
[17] F.K.T. Cheung, J. Rihan, J. Tah, D. Duce, E. Kurul, Early stage multi-level cost estimation for schematic BIM models, Autom. Constr. 27 (2012) 67–77.
[18] J. Choi, H. Kim, I. Kim, Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage, J. Comput. Des. Eng. 2 (1) (2015) 16–25.
[19] N. Dawood, D. Scott, E. Sriprasert, Z. Mallasi, The virtual construction site (VIRCON) tools: an industrial evaluation, ITcon 10 (2005) 43–54. Special Issue From 3D to nD modelling.
[20] B. Delcambre, Mission Numérique Bâtiment.[Online] http://www.territoires.gouv.fr/IMG/pdf/rapport_mission_numerique_batiment.pdf [02 June 2015], 2014.
[21] A.A. Ganah, N.B. Bouchlaghem, C.J. Anumba, VISCON: Computer visualisation support for constructability, ITcon 10 (2005) 69–83. Special Issue From 3D to nD modelling.
[22] A. Gómez-Pérez, M. Fernández-López, O. Corcho, Ontological Engineering With Examples From the Areas of Knowledge Management, E-Commerce and the Semantic Web, Springer-Verlag, London Limited, UK, 2011.
[23] H. Grzybek, S. Xu, S. Gulliver, V. Fillingham, Considering the feasibility of semantic model design in the Built-Environment, Buildings 4 (2014) 849–879.
[24] A. Hamilton, H. Wang, A.M. Tanyer, Y. Arayici, X. Zhang, Y. Song, Urban information model for city planning, ITcon 10 (2005) 55–67. Special Issue From 3D to nD modelling.
[25] K.F. Ibrahim, FH Abanda, C. Vidalakis, G. Woods, BIM for FM: input versus output data, Proc. of the 33rd CIB W78 Conference 2016, Oct. 31st - Nov. 2nd 2016, Brisbane, Australia, 2016.
[26] R. Jongeling, M. Emborg, T. Olofsson, nD modelling in the development of cast in place concrete structures, ITcon 10 (2005) 27–41. Special Issue From 3D to nD modelling.
[27] I. Kamardeen, 8D BIM modelling tool for accident prevention through design, in: C. Egbu (Ed.), Procs 26th Annual ARCOM Conference, 6–8 September 2010, Association of Researchers in Construction Management, Leeds, UK, 2010, pp. 281–289.
[28] E. Karan, J. Irizarry, J. Haymaker, "Generating IFC models from heterogeneous data using Semantic Web", Constr. Innovation 15 (2) (2015) 219–235.
[29] M. Lawrence, R. Pottinger, S. Staub-French, M.P. Nepal, Creating flexible mappings between building information models and cost information, Autom. Constr. 45 (2014) 107–118.
[30] A. Lee, S. Wu, A. Marshall-Ponting, G. Aouad, J. Tah, R. Cooper, C. Fu, nD modelling - a driver or enabler for construction improvement? RICS Research, 2005.
[31] S.-K. Lee, K.-R. Kim, J.-H. Yu, BIM and ontology-based approach for building cost estimation, Autom. Constr. 41 (2014) 96–105.
[32] R. Iqbal, M.A.A. Murah, A. Mustapha, N.M. Sharef, An analysis of ontology engineering methodologies: a literature review, Res. J. Appl. Sci. Eng. Technol. 6 (16) (2013) 2993–3000.
[33] Z. Ma, Z. Liu, BIM-based intelligent acquisition of construction information for cost estimation of building projects, Procedia Eng. 85 (2014) 358–367.
[34] L. Mullin, Using catalogues in Navisworks quantification. [Online] http://beyonddesign.typepad.com/posts/2013/08/using-catalogues-in-navisworks-quantification.html [21 September 2015], 2013.
[35] A.M. Musa, F.H. Abanda, A.H. Oti, J.H.M. Tah, C. Boton, The potential of 4D modelling software systems for risk management in construction projects, 20th CIB World Building Congress 2016, May 30 - June 3, Tampere, Finland, 2016.
[36] A.M. Musa, H. Abanda, H. Oti, Assessment of BIM for managing scheduling risks in construction project management, CIB W78 conference, 27-29 October, 2015, Eindhoven, The Netherlands, 2015.
[37] M.P. Nepal, S. Staub-French, R. Pottinger, J. Zhang, Ontology-based feature modeling for construction information extraction from a building information model, J. Comput. Civil Eng. 27 (5) (2013) 555–569.
[38] M. Niknam, S. Karshenas, Integrating distributed sources of information for construction cost estimation using Semantic Web and Semantic Web Service technologies, Autom. Constr. (2015).
[39] J. Niu, R.R.A. Issa, Developing taxonomy for the domain ontology of construction contractual semantics: A case study on the AIA A201 document, Adv. Eng. Inform. 29 (3) (2015) 472–482.
[40] N.F. Noy, D.L. Mcguinness, Ontology Development 101: A Guide to Creating Your First Ontology, Knowledge System Laboratory, Stanford, CA, 2001.
[41] P. Pauwels, S. Zhang, Y.-C. Lee, Semantic web technologies in AEC industry: A literature overview, Autom. Constr. (2016). in press.
[42] RICS, NRM1: Order of Cost Estimating and Cost Planning for Capital Building Works, The Royal Institution of Chartered Surveyors, UK, 2012.
[43] F. Radulovic, M. Poveda-Villalón, D. Vila-Suero, V. Rodríguez-Doncel, R. García-Castro, A. Gómez-Pérez, Guidelines for Linked Data generation and publication: An example in building energy consumption, Autom. Constr. 57 (2015) 178–187.
[44] D. Saba, F.Z. Laallam, H. Belmili, F.H. Abanda, A. Bouraiou, Development of an ontology-based generic optimization tool for the design of hybrid energy systems, Int. J. Comput. Appl. Technol. (2016) (In press).
[45] Z. Shen, R.A.A. Issa, Quantitative evaluation of BIM-assisted construction detailed cost estimates, ITcon 15 (2010) 234–257.
[46] S. Staub-French, M. Fischer, J. Kunz, K. Ishii, B. Paulson, A feature ontology to support construction cost estimating, Artif. Intell. Eng. Des. Anal. Manuf. 17 (2003) 133–154.
[47] S. Staub-French, M. Fischer, J. Kunz, B. Paulson, K. Ishii, An ontology for relating features of building product models with construction activities to support cost estimating (Working paper #70): Centre for Integrated Facility Engineering. Stanford University, 2002.
[48] J.H.M. Tah, F.H. Abanda, Sustainable building technology knowledge representation: using semantic web techniques, J. Adv. Eng. Inf. 25 (3) (2011) 547–558.
[49] The HM Government, Procurement trial case study: Cookham Wood Prison [Online] https://www.gov.uk/government/publications/procurement-trial-case-study-cookham-wood-prison [03 June 2015], 2013.
[50] TK. Tse, K.A. Wong, K.F. Wong, The utilisation of building information models in nD modelling: A study of data interfacing and adoption barriers, ITcon 10 (2005) 85–110. Special Issue From 3D to nD modelling.
[51] M. Uschold, Building Ontologies, Towards a Unified Methodology, In 16th Annual Conference of the British Computer Society Specialist Group on Expert Systems, 1996. pp. 16-18.
[52] M. Uschold, M. Grüninger, Ontologies: Principles, methods and applications, Knowl. Eng. Rev. 11 (2) (1996) 93–155.
[53] J. Webster, R.T. Watson, Analyzing the past to prepare for the future: writing a literature review, MIS Q. 26 (2) (2002) xiii–xxiii.
[54] Song. Wu, K. Ginige, G. Wood, S.W. Jong, How Can BIM Support the New Rules of Measurement (NRM1)? Research Report, RICS, London, UK, 2014.
[55] S. Wu, G. Wood, K. Ginige, S.W. Jong, A technical review of BIM based cost estimating in UK quantity surveying practice, standards and tools, ITcon 19 (2014) 529–562.
[56] P. Yung, X. Wang, A 6D CAD Model for the automatic assessment of building sustainability, Int. J. Adv. Rob. Syst. 11 (131) (2014).
[57] S. Zhang, F. Boukamp, J. Teizer, Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA), Autom. Constr. 52 (2015) 29–41.
[58] B.T. Zhong, L.Y. Ding, P.E.D. Love, H.B. Luo, An ontological approach for technical plan definition and verification in construction, Autom. Constr. 55 (2015) 47–57.

Please cite this article in press as: F.H. Abanda et al., BIM – New rules of measurement ontology for construction cost estimation, Eng. Sci. Tech., Int. J. (2017), http://dx.doi.org/10.1016/j.jestch.2017.01.007