Aligning BIM and Ontology for information retrieve and reasoning in Value for money assessment

Guoqian Ren [a], Haijiang Li [b1] Song Liu [c], Jaliya Goonetillake [a], Ali Khudhair [a], Steven Arthur [a]

[a] BIM for Smart Engineering Center, Cardiff University, 52 the Parade, Cardiff, CF24 3AB, Wales, UK

[b] Cardiff School of Engineering, Cardiff University, Queen's Buildings, Cardiff, CF24 3AA, Wales, UK

[c] CCCC Second Harbor Consultants Co., Ltd., China

Abstract

Value for money (VfM) assessments often lack effective automatic processes and reasoning support in public-private partnership (PPP) projects. To automate these assessments, this paper proposes a comprehensive approach that aligns with the goals of building information modeling (BIM) as the necessary information support and ontology for the knowledge process. The main contribution of this work is the retrieval of information from the BIM environment with the ontological knowledge base to enable more efficient and persuasive methods for project and finance management that facilitate decision-making rather than an experience-based approach. The constructed ontology can also be reused and further expanded to include project needs from end-user perspectives. This work is expected to further the research on expanding semantic BIM-based decision making in different infrastructure procurement projects.

Keywords: Building information modeling; ontology; value for money; cost estimate; information retrieval; alignment approach

1. Introduction

The value for money (VfM) assessment proposed by the UK HM Treasury in 2004 acquires multiple performance-based data measurements to justify the feasibility of the procurement model for public-private partnerships (PPPs) [1]. This form of assessment would differ based on the economic infrastructure domain. The VfM concept has been defined as the performance of such assessments to calculate budget prices based on conceptual to detailed designs as well as answer questions regarding the qualitative project management. The requirements defined in the VfM can be regarded as essential methodologies for risk allocation, cost estimation, and data collection throughout the PPP life cycle and can provide a basis of reference for decision making [2]. However, current VfM assessments lack robust automatic measurement processes resulting in controversy and debate [3,4]. Therefore, it is necessary to develop detailed evaluation schemas [3,5] so that the standardized data integration and information exchange would enable automatic project assessments in the current data-rich world.

[1] Corresponding author.
E-mail address: Lih@cardiff.ac.uk

Over the past decade, building information modeling (BIM) and ontology have become popular research domains as BIM provides standardized data and information support to perform different analyses and calculations while ontology helps represent and reuse the domain concepts and reasoning rules [6]. The application of BIM, with its reasoning support, has been proven valuable in various domains [7–9]. Existing BIM applications aligned with semantic reasoning support share many development similarities. The information extracted from the BIM model should be attached with ontology to enable execution. In general, the process using BIM and ontology-based approaches for a specific domain includes the following steps: 1) definition and development of the domain ontology; 2) information extraction from the BIM model; 3) alignment between the industry foundation class (IFC) and Web Ontology Language (OWL) or transformation from IFC to Resource Description Framework (RDF); 4) reasoning and queries implemented using BIM data and rules defined in the ontology. The calculations and information index process could be automatically executed using such a BIM and ontology-based approach. Further, development of this methodology has the potential to address the requirements of the existing VfM process [4,10].

This aim of this study is to support automation and reasoning for more efficient VfM assessments. A VfM-oriented ontological knowledge base encompassing the existing ontological developments on different aspects, such as cost estimates [7] and project document management [11], is needed at this stage because the VfM requires integration of the engineering project data and documents; further, the current academic proposals for aligning BIM data are limited to using the IfcOWL, which requires appropriate transformation from the IFC files [6]. Since VfM assessments in PPPs require vast amounts of data from the infrastructure sector, using such converters is still limited by practicality.

To achieve the research goal of constructing a VfM ontological knowledge base that enables appropriate work items to be automatically processed to IFC files from the engineering database, studies regarding VfM-related automatic assessments using BIM and ontology are reviewed. The VfM ontology (VfMO) is established according to the related standards and guidance for better understanding of the domain information requirement. The semantic expressions of the assessment rules were developed using the semantic web rule language (SWRL) representation and established concepts, relationships, and numerical types in the ontology. Next, the alignment approach is presented to indicate possible solutions for mapping the SWRL rules, query functions, and IFC entities. The BIM server was used to execute and visualize the SWRL rules. The construction cost estimates and document information queries related to VfM assessments are also presented to highlight the information retrieval and reasoning functions. Lastly, validation of the semantic and syntactic correctness as well as practical functionality are presented to confirm the feasibility of the proposed method.

2. Review of related works

2.1 Literature review of VfM

As a vital process of the project argument, VfM supports project sponsors to construct the original logic on whether to use the PPP procurement models or traditional methods. The assessments include both quantitative and qualitative aspects. The public sector comparator (PSC) is proposed for the VfM assessments to specify the quantitative aspects [12]. The costs of the PSC are calculated by establishing a fictional model using a traditional public procurement strategy. The early-stage cost estimates are also significant for the quantitative assessments. For the qualitative assessments, predefined suitability criteria or questions are normally proposed to systematically forecast the assessment results [13], which requires project document support containing the relevant project information. Although different methodologies have been currently established for the assessments, more detailed measurement approaches are required to enhance the assessment levels [14].

A few reported works have considered the VfM assessment application status in public engineering. Empirical investigation–based studies on critical issues related to the costs and PSC approaches in private finance initiative (PFI) projects are available in literature [15–20]; these studies aim to demonstrate the complicated relationships between the vital elements for assessing VfM. Other studies have focused on exploring the efficiency of the VfM approach compared to traditional approaches based on project data [21–25]. There are also available research studies that propose methodologies for VfM frameworks and ownership structures [26–29]. A few other studies also focus on more specific measurement approaches by constructing simulation models and probabilistic methods [30,31].

Most of the available literature focus on enhancing the VfM framework and using data analysis for VfM performance; however, they fail to consider information support matching of the detailed work items to the VfM indicators. Owing to the inadequate performance of such methods from the beginning of the project life cycle [32], more detailed approaches are required to enhance the assessments. Quantitative methods are frequently withdrawn owing to feasibility issues for information exchange [5]. The historical data gathered from the financial sector in PPP infrastructure projects are inaccurate and manually sourced information weakens the performance of VfM [3]. The drawbacks of the current PPP practices indicate cost overruns and procurement failures, which are related to the fundamental information support from engineering projects.

2.2 Review of BIM-based approaches related to VfM

The BIM-based management system involves standardized information exchange schema that integrate information from conception to implementation [33–35]. For the quantitative aspects, BIM-based efforts for cost estimation have been stressed in serval research articles. The quantity takeoff (QTO) from BIM object geometries and properties using the IFC files for cost estimation was suggested in previous works [36–40]. Ma and Cheung [41,42] detailed the cost estimation module that enables efficient cost estimation during the early design stage and can be achieved in the BIM environment. Alzraiee [43] proposed a structured query language (SQL) system to develop a cost estimate for building projects using BIM elements. Harm et al. [44] proposed a method to evaluate the BIM staff activities by introducing a time-dependent queueing model.

Besides these academic efforts, application of BIM to cost estimation is also provided in several BIM-based software programs. Estimation software such as Autodesk Revit [45] and Bently AECOsim [46] provide core modeling and essential user cost calculation functions for component information. Cost-measurement-oriented software such as BIMestiMate [47], CostX [48], Vico Estimator [49], WinEst [50], and Innovaya Visual Estimating [51] support QTO for specific building object materials [52]. The software used in construction projects provide manual selection processes for the working items that can be matched to the related materials and cost libraries.

Since project information is managed in the form of control lists of electronic documents in the BIM system [53], recent studies have indicated that BIM could support project document management aspects that can be used for qualitative assessments of projects. Caldas et al. [54] proposed a method for controlling document information through digital BIM models; in the study, the connection between document information and BIM models was processed through the document breakdown structure based on the master format and utilization of the IFC structure. A similar approach to integrating documentation into BIM was proposed in [55], where a four-dimensional as-built model is attached to the construction process information for the owner's use after construction. Lee et al. [56] also proposed a BIM-based methodology for constructing a document information management system.

To summarize, numerous BIM-based studies are available on automation of cost estimation and documentation management. In these cases, the prominent tendency is to use BIM data to perform analyses based on specific rules outlined in the regulations or standards [6]. Thus, the possibility of constructing a VfM framework using information support from BIM and different databases aligned with ontology to automate assessments is confirmed.

2.3 Review of integration of BIM and ontology

The ontology web language (OWL) is a set of language expressions that also contains rule-based functions to query information from different knowledge bases and provide their paths for information management [57]. As one of the semantic web technologies used to represent and reuse domain concepts and relationships between concepts, ontology has already been proposed for use in the architecture, engineering, and construction (AEC) areas, and its rule-based reasoning indicates its adaptability to different information management platforms, such as BIM [6].

These ontologies can assist information exchange and sharing. For example, Yurchyshyna et al. [58] proposed an ontology implementation framework to evaluate the conformity in the construction sector. Hou et al. [59] developed an ontological system named ontology for sustainable concrete structure (OntoSCS) and SWRL rule-based reasoning mechanisms for optimized structural design solutions. Tomašević et al. [60] proposed the airport facility ontology model, which represents the general facility management knowledge related to infrastructure energy consumers. Zhang et al. [61] presented a holistic approach based on ontology to support the early design stage by considering safety, environmental impact, and cost. Lu et al. [9] proposed the construction safety checking ontology (CSCOntology), which encodes knowledge over the web using the OWL format; the safety checking constraints were extracted from the related regulation provisions and were represented in the SWRL rule. Ontology development for cost estimation have also been proposed [62–64]. A significant recommendation by most of these ontological methods is the validation process; both semantic and syntactic validations can be performed using reasoner and case studies [59,65–68].

There have been some reported efforts to integrate the ontological knowledge base with BIM, even though these have not focused on VfM. In [69], the authors researched transforming BIM data to the building knowledge model by mapping the tools simultaneously. In [70], the authors propose a framework for constructing a risk knowledge base for engineering projects and integrating BIM and ontology with separate retrieval functions to determine the potential risks. In [71], the investigators considered building evacuation scenarios by mapping the ontology and IFC to improve crowd simulation performance. Based on similar research articles published in recent years, the authors of [6] summarized and developed a BIM-based freeware application with reasoning support (BIM-R) and explained the mechanism to transform the BIM data into ontology; this research was proved to be feasible based on the IfcOWL However, this requires large quantities of information to be transformed from the IFC as a necessary step, which may cause issues when implanted in a large-scale project. Other methods to create links between ontology as the knowledge base and BIM are thus required to improve the current status of such research, which is also its starting point.

Based on the above review, the critical gap has been identified as follows: most BIM and ontology-related techniques are not integrated well with the VfM idea. The existing linked data approach cannot be readily used in large-scale engineering projects. The reasoning execution relies on conversion to obtain the IfcOWL from the initial IFC or express files limited by the production level. Software vendors should thus use a more integrated platform to develop BIM reasoning tools.

3. Design and development of VfM ontology

The process to construct the references for the 'Ontology Development 101' has been adopted here owing to its feasibility and specific guidance [72]. Further, the construction followed the principles defined in the W3C to create substances and rules. The established ontology consists of 1) a work item ontology consisting of the classifications defining qualitative and quantitative contents in VfM and 2) the semantic reasoning rules that specify the functions and relationships between assessment performance and information items. The software Protégé was used in this study as it is an open-source developer tool that enables both developers and end-users to construct an ontological knowledge base that is compatible with the OWL syntax [73]. Within this, Pellet is a reasoner that supports OWL and provides standard and reasoning services; SWRLTab is a plugin that provides the development environment for creating the SWRL rules and semantic query-enhanced web rule language (SQWRL) queries. The SQWRLTab is a graphical interface supported by the SWRLAPI to execute the SQWRL queries.

This developed ontology will be used in the early stage of the procurement justification phase and can provide measurement and query functions to the procurement managers, clients, and finance managers.

3.1 Definitions of the entity classes

Based on relevance, a glossary of essential work items was obtained from different sources in literature and governmental bodies, as presented in Table 1. The key concepts within these items were associated with the VfM assessment and include detailed working items for cost estimate guidance and procurement management gateways, which represent the overall scope of the VfM.

Table 1 Concept and knowledge sources used in VfMO

Concepts used	Publisher	Description
VfM assessment Guidance	HM Treasury, UK	Get assessment framework
Guidebook for VfM Assessment	Federal Highway Administration, USA	Get detailed assessment methods
PPP VfM guidance	Ministry of Finance of the PRC	Get detailed assessment methods
Guidelines for green airport planning	Civil Aviation Administration of China	Reference for performance measurement
New Rules of measurement	Royal Institution of Chartered Surveyors	For structure & items in cost estimates
SPON's cost estimates	AECOM	For obtaining unit costs among items
UniClass 2015	National Building Specification	For obtaining codes for stages and objects

PPP Reference Guide	World Bank	For listing the PPP procurement stages

A top-down approach was thus used to establish the entity classes. The general classes were added first, and the subclasses were then attached and subdivided into additional classes. Specifically, these main superclasses include the 'CostEstimatesLibrary', which contains the standardized structure for cost estimates, 'DocumentInformation' wherein the required documents are defined using BS-1992 [74] and ISO-12006 [75] for the procurement information; 'Object entity', which contains all the related objects, including 'project', and their corresponding IFC entities; and 'Material', which contains the material information related to the construction elements. 'OrganizationStructure' and 'Party' contain all the related business sectors and project or procurement roles extracted from the existing Financial Industry Business Ontology (FIBO) [76]. 'VfMProfile' includes both the qualitative and quantitative measurement approaches and detailed structures. 'Risk' is used to gather the risk-oriented costs or allocation results of the procurement. 'Stage' was added to index the procurement phases defined in the PPP guidance ‘Uniclass’ and other gateways. After defining these related concepts, the new properties should be attached to most of the general classes for further development. The class hierarchy thus developed is illustrated in Figure 1.

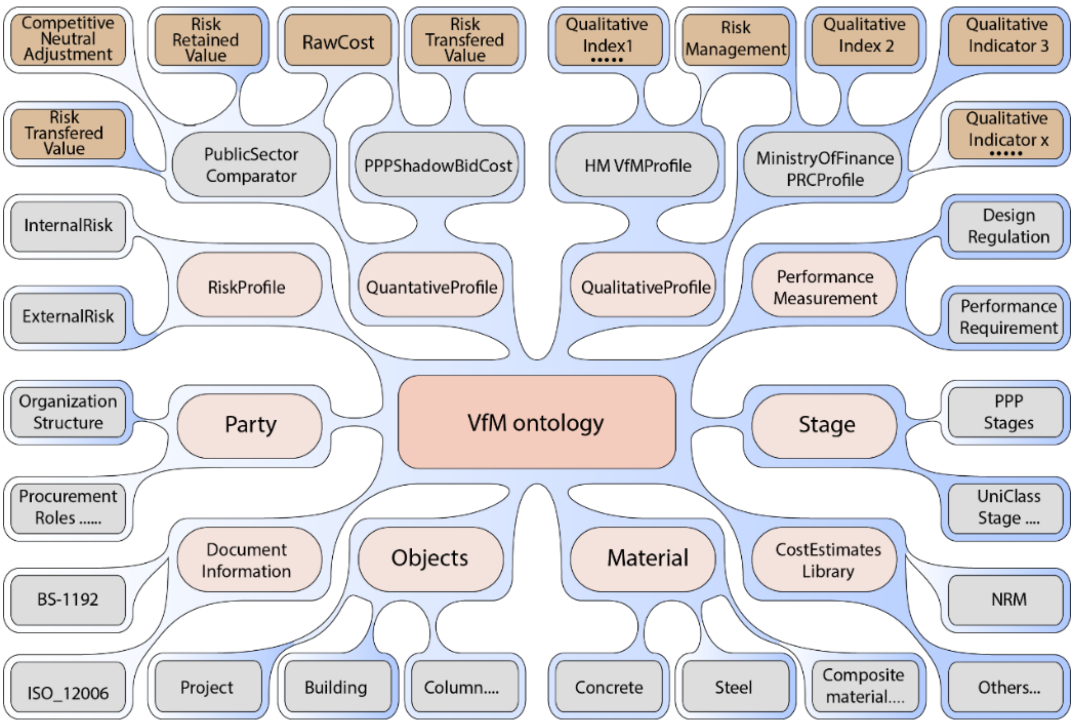

Figure 1 Class hierarchy in VfM ontology

3.2 Definition of the properties and instances

A property, as defined in OWL, consists of three parts: 'ObjectProperty', 'DataTypeProperty', and annotation properties. To create the reasoning functions, the properties necessarily incorporate class hierarchy. The object property is used to describe the relationship between the objects and instances within the class. For example, the ‘HasDocument’ property is defined to connect the entity ‘Project’ and class ‘DocumentInformation’. The object property is used to define the relationship between the different classes. The data type property can be set to construct links between object and data values both quantitatively and qualitatively. For instance, if the area of one slab is 1600 square meters, this can be represented as ‘an instance of the slab has a data property named “Area” with the value “1600”’. Different data types, such as ‘string’ or ‘int’, can also be attached with the user-defined data properties, such as thickness and width. All the properties are established based on collective knowledge to link the different classes and instances.

In the VfMO, instances referring to particular classes were added, and the following activities must be performed to build an instance: 1) instances are added by selecting a specific class, 2) instances should contain all the related data properties defined in the previous step, and 3) the basic relationship should be predefined between different instances using predefined object properties. For example, the instance 'Project' should have the 'HasDocument' property, which links to another specific instance, such as 'SiteInformation'. An example of an instance that contains several data properties is shown in Figure 2.

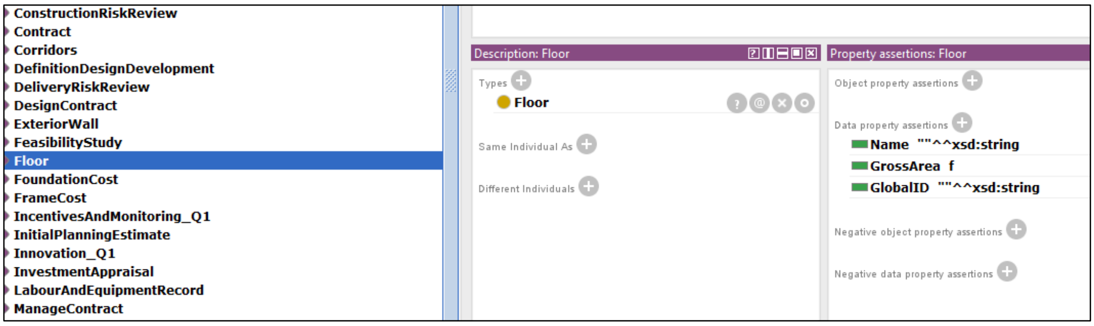

Figure 2 Instance of a floor in the VfM ontology

3.3 Define and clarify the fundamental relationships

Figures 3 and 4 indicate the basic logic defined in the qualitative assessment. The blue items represent the entity classes that contain the subclass and individuals. Each instance of the subclass inherits the fundamental relationships using the object and data properties. For example, in the qualitative assessment profile, every individual belongs to the subclass 'ObjectiveAndOutputs', representing an assessment instance that has the data property 'HasPerformanceAnswer' to conclude the evaluation feedback, while 'HasScore' represents the assessment results. Besides, the 'HasRelateDocument' properties were defined to build links between the qualitative index and standardized documentation. The instance represents the procurement document, which contains basic data such as the URI and identification details.

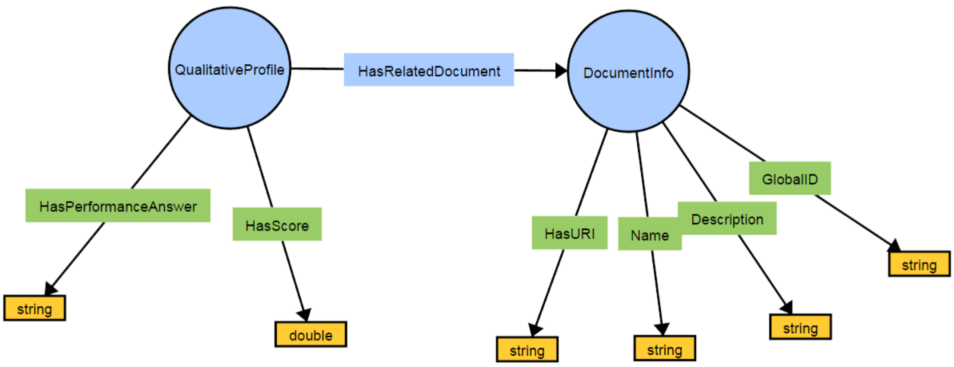

Figure 3 Main classes in the qualitative profile (a)

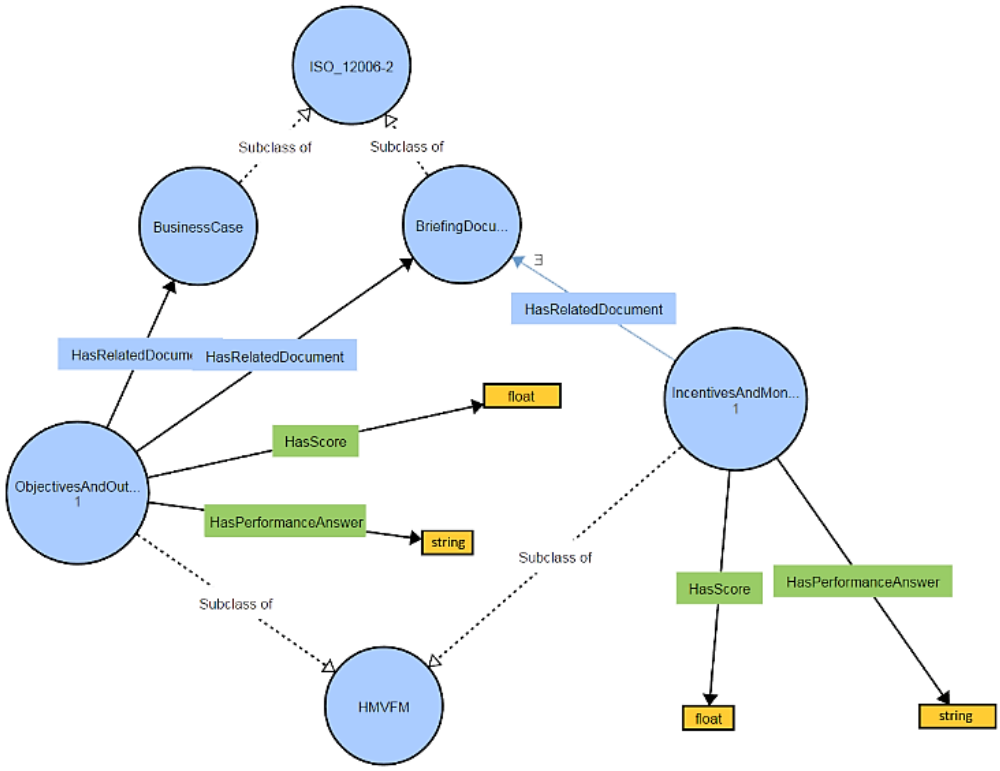

Figure 4 Main classes in the qualitative profile (b)

Following a similar logic to construct the relationship using object and data properties, as shown in Figure 5, the most characteristic upper-level entity class was defined for all the cost-related activities in the quantitative profile. 'Object' was represented virtually within the digital model and used to represent the building elements. Additionally, when considering a scenario (e.g., measuring the construction frame costs), alignment between the frame objects is used to create the functional connection. Each cost index also has a corresponding cost estimate library ('CostEstimatesLib'), which can be used to store the unit cost information. The instance in the object class represents the work items and has different datatypes attached for cost measurement. It is important to note at this point that not all subclasses in 'CapEx', which refers to capital expenditures, or 'OpEx', which refers to operational expenditures, of the quantitative profile can be related to objects. However, the cost database can still be related to those subclass elements by creating links to the project document or by manually entering values.

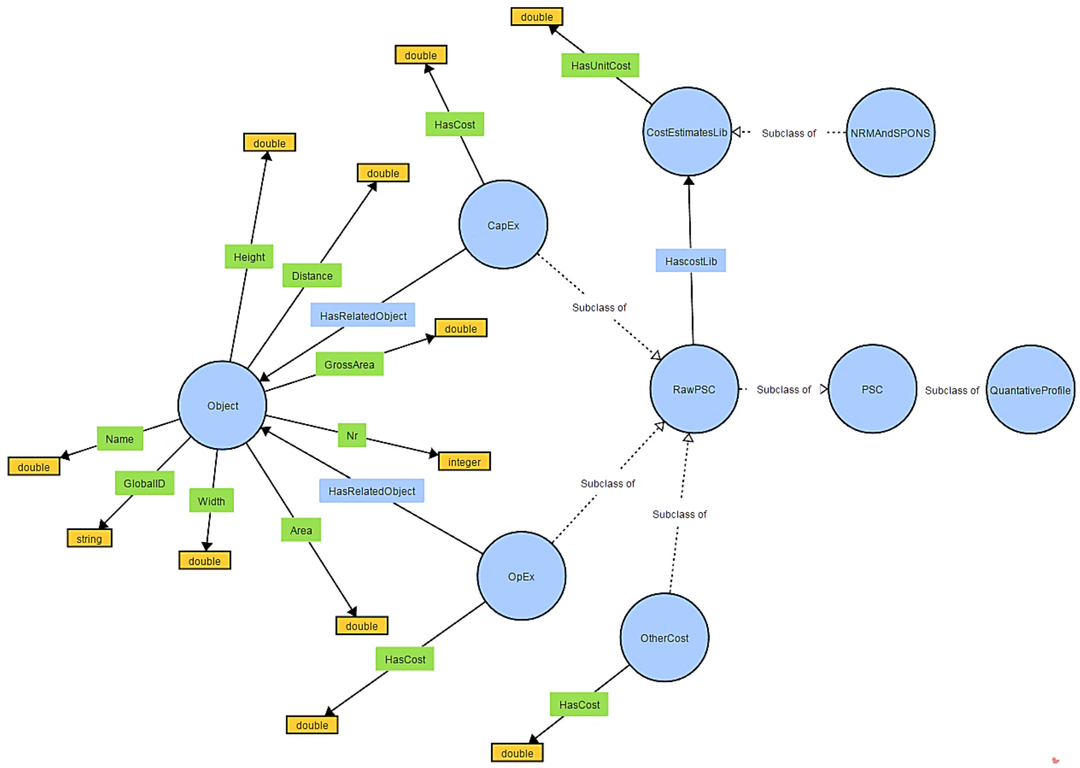

Figure 5 Main classes in the quantitative profile

3.4 Creating query and reasoning rules

To implant the semantic functions, rules should be established and integrated with the ontological items. Hence, the SWRL rule and SQWRL queries are used to create such interoperability as they provide the reasoning and contain a straightforward approach to connect different work items or scenarios. The class atom, individual property atom, and built-in atom that support several of the complex predicates in the VfMO can be connected to obtain the required information.

Table 2 SWRL rules in VfM

Rule Description	*Based on the Rules defined in the SPONS (Part 3, section 2.2): To measure the composite steel and concrete upper floors costs, the floor area needs to acquire the unit cost*
SWRL	UpperFloorCost(?U) ^ Floor(?F) ^ HasCostLib(?U, CompositeSteelAndConcrete) ^ HasUnitCost(CompositeSteelAndConcrete, ?c) ^ GrossArea(?F, ?a) ^ swrlb:multiply(?w, ?c, ?a) -> HasCost(?U, ?w)
Rule Description	*Based on the requirement defined in VfM guidance, to support the measurement of the success level of 'Incentives and Monitoring', the 'business case' document can provide relevant information*
SQWRL	IncentivesAndMonitoring(?IM) ^ Project(?P) ^ HasDocument(?P, BusinessCase) ^ BusinessCase(?b) ^ HasURI(?b, ?u) -> sqwrl:select(?b, ?u)

As seen in Table 2, an implicit symbol '∧→' is used to connect the different classes and individual atoms. Additionally, the symbol '→' is used to connect the antecedents. Variables in the atoms are represented using the interrogation identifier '?'. Based on the rules defined in the standardized references, an entity such as 'UpperFloorCost' or 'IncentivesAndMonitoring' can represent the named class that contains individuals, such as ‘(?U)’ or ‘(?IM)’, which represent the information instances. Object property atoms, such as ‘HasCostLib’ and ‘HasDocument’, were previously defined to construct the relationship in the ontology. These rules check if such a relationship exists using the symbol order ‘(?U, CompositeSteelAndConcrete)’; this indicates that the upper floor in this particular case has a specific cost library corresponding to composite steel and concrete. The data property atoms, such as ‘HasUnitCost’, ‘GrossArea’, and ‘HasURI’, display the asserted and inferred data property hierarchies within a specific instance. To identify whether an instance of the upper floor (?F) contains ‘area property(?a)’, ‘GrossArea(?F,?a)’ is used to express the existing alignment. The syntaxes ‘swrlb: multiply’ and ‘sqwrul: select’ work as built-in atoms to carry out the basic calculations and function implementations. The reasoning and query functions encompass different aspects related to VfM assessments. The defined SWRL and SQWRL rules corresponding to the measurement requirements are listed in Tables 3 and 4.

Table 3 SWRL rules for document query in qualitative assessment.

Q1	*To measure the performance ‘Incentives and Monitoring’, the Business case document’s URI is queried.* Project(?P) ^ HasDocument(?P, BusinessCase) ^ BusinessCase(?b) ^ HasURI(?b, ?u) -> sqwrl:select(?b, ?u)
Q2	*To measure the performance* ‘Innovation’, *the Technical information document’s URI is queried for measurement.* Innovation(?I) ^ Project(?P) ^ HasDocument(?P, TechnicalInformation) ^ TechnicalInformation(?T) ^ HasURI(?T, ?u) -> sqwrl:select(?T, ?u)
Q3	*To measure the performance* ‘I Objectives and output’, *the Briefing information document’s URI is queried for measurement* *ObjectivesAndOutputs(?O) ^ Project(?P) ^ HasDocument(?P, BriefingDocument) ^ BriefingDocument(?B) ^ HasURI(?B, ?u) -> sqwrl:select(?B, ?u)*

Table 4 SWRL rules for cost estimates in quantitative assessment

FrameCost1	*To measure the frame cost of a certain object, if the frame is a concrete frame, then the concrete frame cost library catalog should be used and attached to the object.* FrameCost(?FC) ^ Frame(?F) ^ HasMaterial(?F, Concrete) ^ FrameLib(ConcreteFrames) -> HascostLib(?FC, ConcreteFrames)
FrameCost2	*To measure the concrete frame cost, followed the formula C ≈ $\sum^{n} C^{k}U^{k}$, the gross area is needed to multiply the unit cost in the cost library.* FrameCost(?FC) ^ Frame(?F) ^ HascostLib(?F, ConcreteFrames) ^ HasUnitCost(ConcreteFrames, ?c) ^ GrossArea(?F, ?a) ^ Width(?F, ?w) ^ swrlb:lessThan(?w, "250.0"^^xsd:float) ^ swrlb:multiply(?s, ?w, ?a) -> HasCost(?FC, ?s)
FoundationCost1	*To measure the foundation cost of a certain object, if the foundation is column-based, then the column bases cost library catalog should be used and attached with the object.* FoundationCost(?FC) ^ Column(?C) ^ HasMaterial(?C, ColumnBases) FoundationCostLib(ColumnBases) -> HascostLib(?FC, ColumnBases)
FoundationCost2	*To measure the column bases foundation cost, followed the formula C ≈ $\sum_{k}^{n} C^{k}U^{k}$, the number of columns is needed to multiply the unit cost in the cost library.* FoundationCost(?FC) ^ Column(?C) ^ HascostLib(?FC, ColumnBases) ^ HasUnitCost(ColumnBases, ?c) ^ Nr(?C, ?n) ^ swrlb:multiply(?w, ?n, ?c) -> HasCost(?FC, ?w)
UpperFloor1	*To measure the upper floor cost of a certain object, if the floor is made of composite steel and concrete, then the cost library catalog should be used and attached to the object.* UpperFloorCost(?U) ^ Floor(?F) ^ HasMaterial(?F, CompositeSteelAndConcrete) ^ UpperFloorLib(CompositeSteelAndConcrete) -> HascostLib(?U, CompositeSteelAndConcrete)
UpperFloor2	*To measure the composite steel and concrete upper floor cost, followed the formula C ≈ $\sum_{k}^{n} C^{k}U^{k}$, the gross area of the floor is needed to multiply the unit cost in the cost library.* UpperFloorCost(?U) ^ Floor(?F) ^ HascostLib(?U, CompositeSteelAndConcrete) ^ HasUnitCost(CompositeSteelAndConcrete, ?c) ^ GrossArea(?F, ?a) ^ swrlb:multiply(?w, ?c, ?a) -> HasCost(?U, ?w)

4. Alignment with the IFC

Alignment can help software vendors identify the entity between the ontology and IFC express schema, particularly by parsing the IFC and translating the SWRL rules. Thus, the data parsing from IFC files based on previously defined information requirements [77,78] was used as the component to align the VfM ontology. Using the Eclipse IDE as the integrated development platform, the IFC model was uploaded to the BIM server platform, thereby enabling users to build their own BIM operating systems. Based on the open standard IFC, the BIM data were interpreted using codes and stored as object information in the underlying database. The functional operations, such as model-checking, authorization, merging, and logical reasoning, are available, and different plugins for IFC visualization can be merged with the server for practical purposes. The BIM server used in this research was chosen for its solid foundation to build fast and reliable niche applications for IFC data.

4.1 Checking and parsing the IFC

The hierarchical structure of the IFC was based on EXPRESS, a standard data-modeling language to deliver object-oriented information. The IFC divides all the subject entities into rooted entities from ‘IfcRoot’, comprising entities organized as building elements (e.g., ‘IfcSlab’), geometry (e.g., ‘IfcExtrduedAreaSolid’), and property attributes (e.g., ‘IfcPropertySingleVlaue’). The presentation of a subject entity contains its globally unique identifier (GUID) along with attributes for names and descriptions. The string of numbers, followed by a ‘#’, was used to index the different entities. The IFC's three main abstract concepts are as follows: 1) object definitions that capture the object occurrences and types, 2) relationships that capture the relationships among the objects, and 3) property sets that capture the extensible properties of the objects. Using the Java function and following the same checking logic, the IFC at the server was parsed and checked using Java. Table 5 indicates the main functions used in this procedure, while Figure 6 presents the checking functions in Java.

Table 5 The main function used to check IFC

Name	Description
PrintHierarchy	To display and check all the IFC hierarchy uploaded in the BIM server
IFCObjData	Retrieve all IFC files according to the tree structure
objDatas	Defined function to check the IFC file, get a separated string based on functions
data.setType	Store the entity's type by return the class of the object with the simple name
data.setName	Store the entity's name
data.setPropertys	store the object's properties
GetSumByFunction	get the entities’ properties values by using summation for physical properties
GetStringByFunction	get the entities’ properties string value for entity names
GetListByFunction	get the entities’ properties List value for material and other object information
GetCountByFunction	get the entities’ number counting values
GetObjDataListByParent	get the entities’ properties secondary value for the annotation of object
GetResultBySteps	get the entities’ properties by using rules like 'lesser than' or 'more than.'

```java
public static IFCObjData PrintHierarchy(IfcObject ifcObject, IFCObjData data) throws Exception {

public WebData GetSumByFunction(Function function) {
    double rs = 0;
    results = new ArrayList<String>();
    List<ObjData> datas = new ArrayList<ObjData>();
    if (null != function.getM_Parent() && function.getM_Parent() != "")
    {
        datas= GetObjDataListByParent(function,proData,datas);
    }
    else
    {
        datas=GetObjDataListByFunction(function,proData,datas);
    }
    for(String str:results) {

        rs+=Double.valueOf(str);
    }
    WebData webData= ObjDatasToWebData(datas);
    webData.text=rs+"";
    return webData;
}
public WebData GetStringByFunction(Function function)

public WebData GetListByFunction(Function function)

public WebData GetCountByFunction(Function function)
public List<ObjData> GetObjDataListByParent(Function function,IFCObjData ifcObjData,List<ObjData> datas)
public List<ObjData> GetObjDataListByFunction(Function function,IFCObjData ifcObjData,List<ObjData> datas)
public ObjData GetResultBySteps(Function function,ObjData obj)
public WebData ObjDatasToWebData(List<ObjData> datas){
```

Figure 6 Checking functions in Java

To measure the design cost for quantitative assessments using the area method based on information exchange, the gross areas of the building slabs are required [79]. The first-order logic (FOL) is used to indicate the query logic clearly from the IFC files, and the query syntax uses the following expression to obtain the floor area:

$$\forall\alpha(\mathrm{IfcSlab}(\alpha)) \wedge \exists\alpha((\mathrm{IfcSlab}(\alpha) \wedge \mathrm{Query}(\alpha, \text{"GrossArea"})$$

Using the defined query functions to check the IFC properties, the reasoners in Java can locate the function that should be used and its return value. The XML syntax is proposed to map the predefined functions, query entities, subfunctions, and attributes with certain value types. For example, the XML syntax responding to a specific query listed above can be written as follows:

```xml
<function text="Upper floor 2" content="IfcSlab" result="Sum">
        <step type="var" attribute="GrossArea"></step>
</function>
```

The query will go through the IfcSlab entities and use the sum function listed in Table 5. It then obtains the value within the attribute entities that store the gross area. The ‘text’ field represents the query name. The ‘content’ field represents the required IFC entity corresponding to the information exchange requirements; the ‘result’ field indicates the returned value type, which can vary and included such possibilities as ‘Sum’, ‘String’, ‘List’, or ‘Count’. The ‘type’ field connects to the specific mathematical method defined in the exchange functions. The ‘attribute’ field locates the patent corresponding to the required information items. Corresponding to the previous SWRL rules, this syntax is used to represent the rule functions in structured XML format, which can be parsed to decide the specific functions used and results that should be stored. Based on the rules corresponding to the IFC entities, the returned value can be stored for further knowledge reasoning rules to execute more complicated functions and mapped with SWRL rules from the developed ontology. The examples used in this study are shown in Table 6.

Table 6 The description of the XML representation of information query

Quantitative assessment – Work estimates – Substructure- FoundationCost2	
XML representation	<function text=*"substructure-Colum bases"* content=*"IfcColumn"* parent=*"IfcBuildingStorey"* pcontent=*"01 - Entry Level"* result=*"Count"*> </function>
Description	To measure the column-based foundation cost in substructure, the entry-level IfcColumn entities are required and its counting number should be returned.
Quantitative assessment – Work estimates– Superstructure- UpperFloor2	
XML representation	<function text=*"UpperFloor"* content=*"IfcSlab"* parent=*"IfcBuildingStorey"* pcontent=*"01 - Entry Level|02 - Floor|03 - Floor"* result=*"Sum"*> <step type=*"var"* attribute=*"GrossArea|Area"*></step> </function>
Description	To measure the upper floor cost in the superstructure, all the IFC entities(excluded the roof slab) are required and their gross area should be added.
Quantitative assessment – Work estimates– Superstructure- FrameCost2	
XML representation	<function text=*"FrameCost"* content=*"IfcSlab"* result=*"Sum"*> <step type=*"lessThan"* attribute=*"Thickness"*>250</step> <step type=*"var"* attribute=*"Area"*></step> </function>
Description	For measuring the frame cost, the IfcSlab entities with thickness less than 250 are checked and get the sum of the area.
Qualitative assessment – Objectives And Outputs – Q3	
XML representation	<function text=*"*ObjectivesAndOutputs*"* content=*"IfcProject"* result=*"String"*> <step type=*"var"* attribute=*"BriefingDocument"*></step> </function>
Description	For measuring the objective and outputs indicator, the briefing document attached in the IfcProject entity should be retrieved to get the string value.

4.2 Translate and map the SWRL rules into Java

Because the SWRL rules in the VfMO play a vital role in rationalizing the assessment approach, it is necessary to align the SWRL rules with other data sources to process the complicated rules. The scheme and architecture for mapping the ontology reasoned using SWRL rules are as presented in Figure 7.

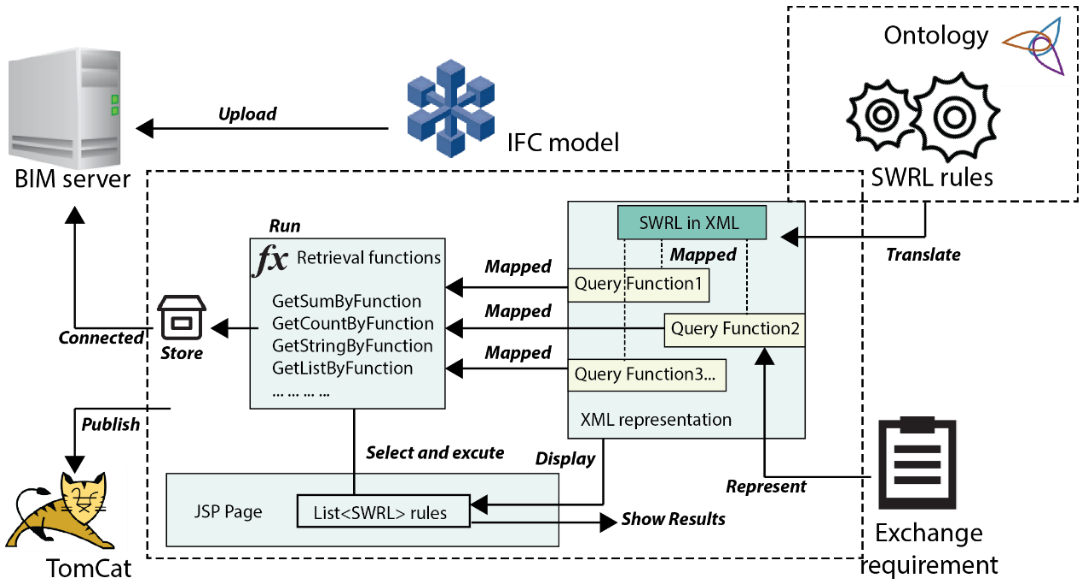

Figure 7 Architecture to align SWRL rules with IFC

The SWRL written in Protégé can be represented as a DL safe rule in OWL/XML. However, SWRL writing, either as a human-readable syntax or as a DL safe rule, is difficult to parse and execute in a compatible software environment. Thus, the SWRL rules are represented in XML syntax, which can be easily identified by development engines. Figure 8 shows the mapping translation pertaining to a single rule.

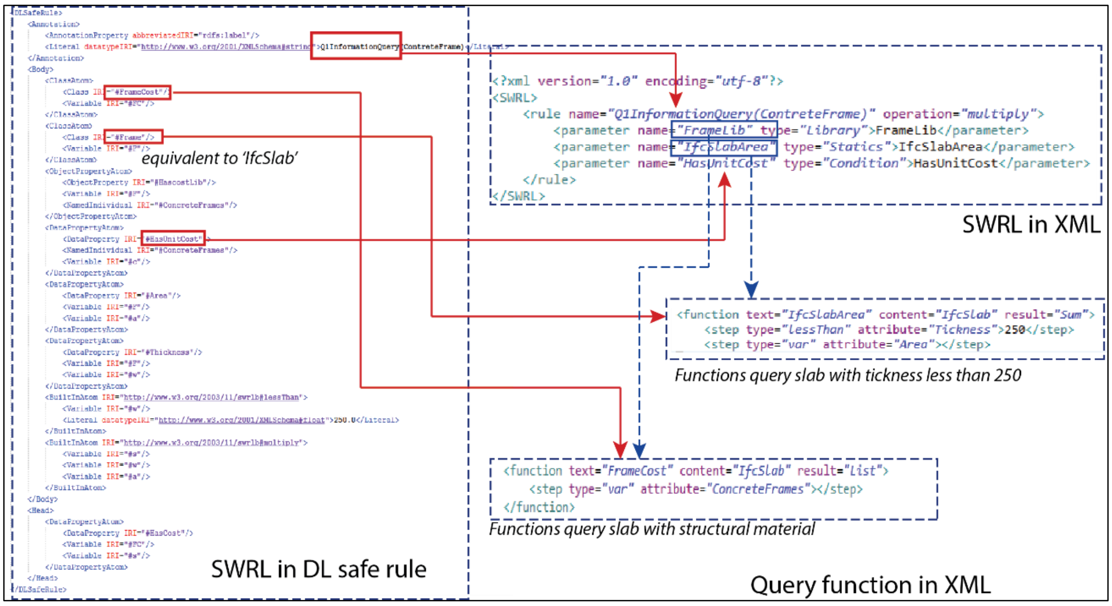

Figure 8 Integrated connections between the SWRL and query functions

A knowledge base within the SWRL rules can contain several query functions; for example, the SWRL rule named 'Q1InformationQuery (ConcreteFrame)' is used to query the related information and calculate the frame cost in the quantitative assessment. In the DL safe rule syntax, the rule names stored in the 'rdf: label' and the ruling body contain different classes and property atoms, and the head contains the output property. In the translated SWRL/XML, this parameter was used to align the query functions, such as 'FrameCost', which is used to check all the 'IfcSlab' with concrete attributes, and 'IfcSlabArea', which is used to obtain the property area with constraints. Each 'parameter' corresponds to a user interface (UI) name on the webpage. The element in 'type' connects to the function text defined in the query functions, as presented in Table 7.

Table 7 The parameter description in swrl.xml

Type in Swrl.xml	**Description**
type="Statistics"	Connect to the text in a query function, which is a statistic. Ex. 'sum'
type="Text"	Connect to the text in a query function, which is a filter. Ex. 'URI'
type="Library"	Connect to the text in a query function, which is a class library. Ex. 'material'
type="Condition"	The general operation of the input by the user. Ex. the unit cost value

The rules in the SWRL/XML 'operation' contain elements such as 'multiply', 'lists', and 'show' for the progression of the logic algorithm. Thus, the SWRL can be efficiently translated as XML syntax while connecting with the predefined query functions in XML. This is unlike the previous approach for converting IFC to OWL; such a mapping method transforms the OWL rules to the machine-readable environment, which is an automatic process. Moreover, the integrated development process can be operated on the BIM server and publish using a private container-based server based on TomCat to assemble the functions with visualization. The developed VfMO interface is presented in Figure 9.

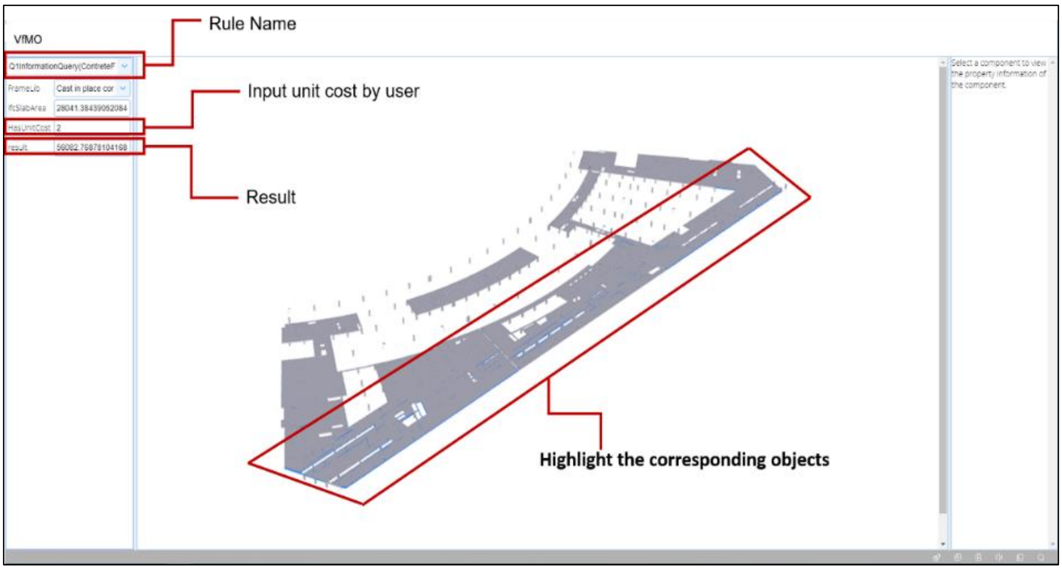

Figure 9 VfMO interface

4.3 Workflow of the developed VfMO

The developed VfMO contains functional rules that can improve the VfM practice while creating the decision-making workflow within procurement management. Figure 10 represents the VfM information exchange defined in a previous work [78]; this process includes the concepts/elements/parts regarding the project objective identification and preparation phases in the PPP model. Horizontal swim lanes are used for the major tasks in the assessment corresponding to the stage activities. The proposed VfMO can thus be used for qualitative and quantitative assessments and measurements.

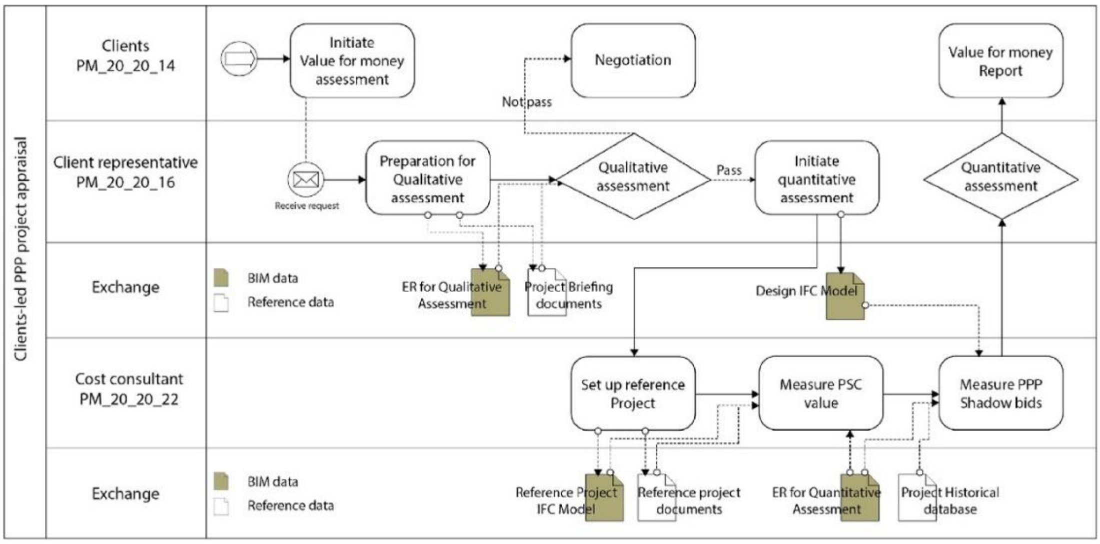

Figure 10 Process map for VfM information exchange [78]

As presented in the VfMO framework (Figure 11), the relevant domain ontologies can be combined into one that contains the project information, such as cost, documentation, and evaluation indicators. The management gateway, such as the project procurement stage, can also be included to identify the process. Under the client authorization, the end user (i.e., expert team or decision-maker) can use the software platform to edit and conduct VfM requirements as domain-related rules in semantic forms. The knowledge base at the center is connected to different information exchange requirements, which are presented in a computer-editable format. The knowledge engineer can modify and update these rules in a timely manner with the procurement consultant’s guidance. By integrating the ontologies, rules, and query functions, the framework can be used for automatic assessments.

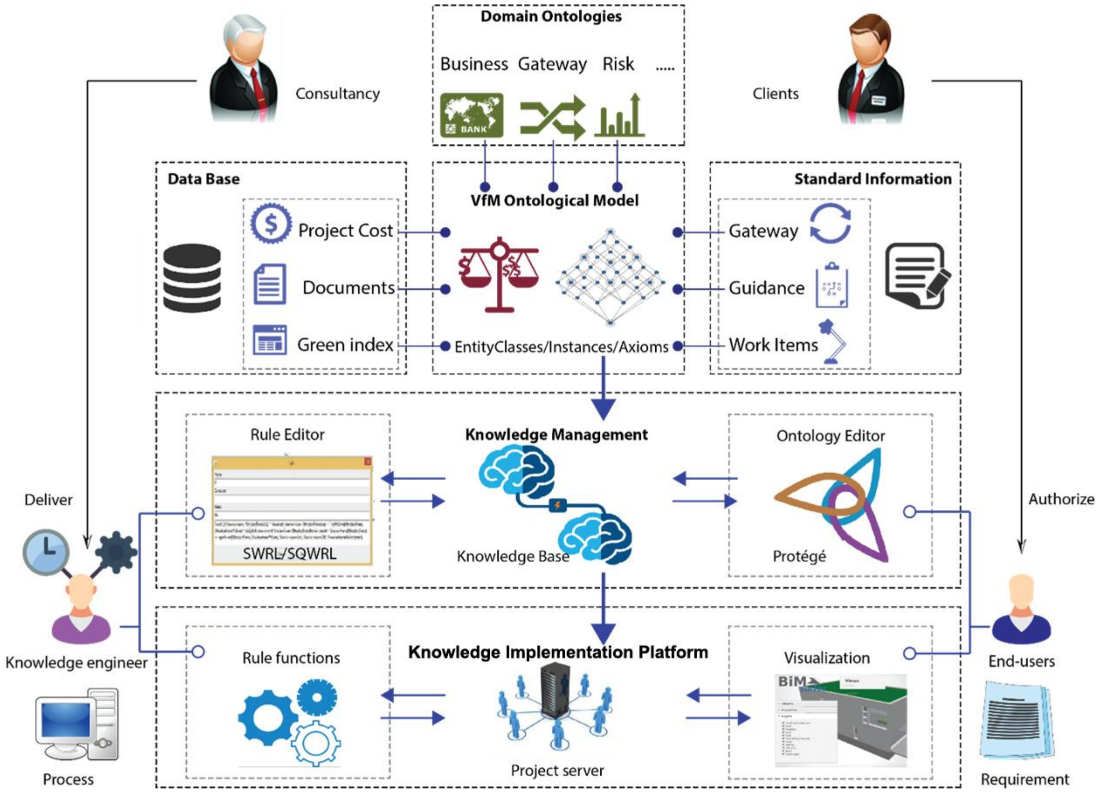

Figure 11 Workflow of the VfMO framework.

An online platform such as the BIM server can aggregate engineering information into a cloud platform that can store and visualize information to facilitate operations. The information exchange applies a standardized process, while the data is filtered using standardized data carriers. In this manner, the established framework was merged with different decision-making phases during infrastructure procurement.

5. Validation

An integrated platform containing the reasoning and functions was formulated and proposed to validate the infrastructure project. A software demo was constructed at this stage for the assessment functions. The semantic and syntactic validation processes of the developed ontology were presented and functional validations were carried out to prove the feasibility of assessing practical perspectives.

5.1 Semantic and syntactical validations

The ontology in the present study uses semantic validation for the alignment, and comparison techniques were used for the semantic validation [80]. The concepts incorporated in the VfMO were extracted from standardized guidance and were identified and proven to be practical and correct by the domain experts. It is imperative to validate the knowledge base syntactically. The subsumptions, equivalence, instantiation, and consistencies should be checked accordingly [81]. The ontology reasoner Pellet, a functional plugin in Protégé, was used for the automatic checking process. Pellet allows the user to check and eliminate errors following the syntax defined in the ontology; Figure 12 displays this applicable reasoner. Based on the messages, anomalies can be identified and presented to the user. In the present study, both semantic and syntactical validations were conducted.

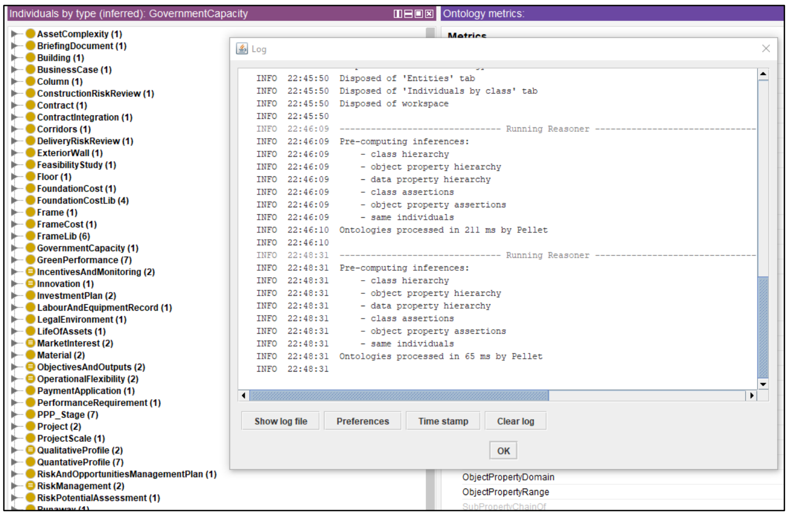

Figure 12 Reasoning process in VfMO

5.2 Case study and functionality validation

Next, a case study and feedback analysis from the engineering industry were performed to validate the VfMO. The case study uses the airport BIM model from an infrastructure project in China. The VfMO features were demonstrated by considering particular groups of scenarios covering the VfM assessment contents. The feedback was collected by delivering the demo to the domain experts. The objective of using the case study was to test if the developed VfMO could cover specific content, such as cost estimates and documentation queries, regarding VfM assessments and provide functional abilities for procurement decision making.

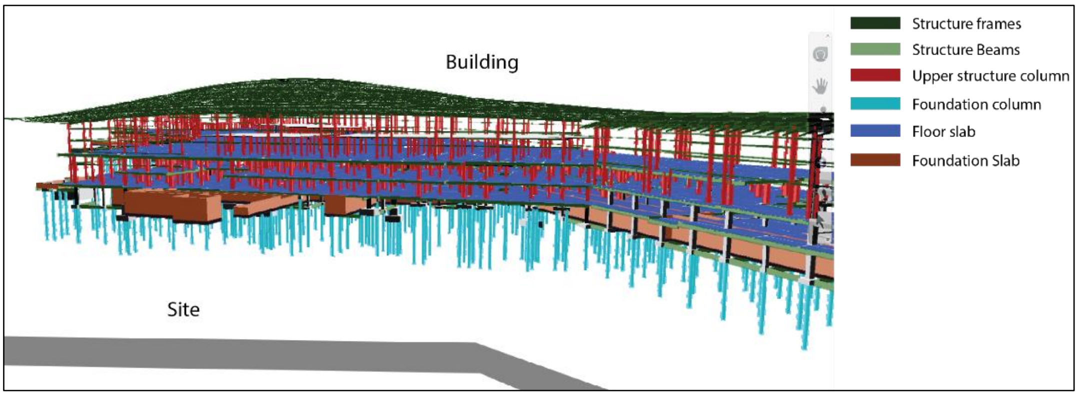

Figure 13 Object elements in the case study model.

An airport IFC model was uploaded to the server as seen in Figure 13. Using Java code aligned with the BIM Server, the developed engine was able to integrate multiple BIM objects and render them accessible. The model contained several construction and architecture elements: two-level floor slabs, structure beams, concrete frameworks, substructure and superstructure columns, and foundation slabs. Several documentation URI addresses and project-level information were also used in the IFC model for document queries. To identify the available information for testing, the model elements were divided into several categories. The VfMO checked the item information and output query results. Taking the cost estimates as an example, unlike previous ontology applications where the required data had to be input to measure the cost manually, the floor area was obtained automatically from the BIM server. Based on the new rule of measurement (NRM) and SPONS to obtain the unit cost data, the cost estimates were processed after constructing the SWRL rules. In the model, 112191 IFC entities were retrieved, containing attribute information sets and building elements. The project information was also included in the Revit BIM model and was stored in the IFC instances, such as 'IfcProject', 'IfcSite' and 'IfcBuilding'. Scenarios were created to cover both the VfMO qualitative and quantitative assessments. In the defined scenarios, the case study model contained 10 IFC files, which were uploaded to the BIM server. Based on all the available information in this model, the scenarios are outlined in Table 8. To assess the defined scenarios, reasoning SWRL rules were created in the ontology with specific query functions. Tables 9 and 10 list the details of the rules used, along with the entities checked in the scenarios as well as the results.

Table 8 Scenarios used in the case study

No.	Scenario Questions relates to quantitative assessment
Q1	For the CapEX costs referred to in the quantitative assessment, using this model, what is the cost estimate on the substructure?
Q2	For the CapEX costs referred to in the quantitative assessment, using this model, what is the cost estimate on the superstructure?
Q3	For the CapEX costs referred to in the quantitative assessment, using this model, what is the cost estimate on the upper floor structure?
Q4	For the CapEX costs referred to in the quantitative assessment, using this model, what is the cost estimate on the internal walls?
No.	**Scenario Questions relates to qualitative assessment**
Q5	For measuring the indicator 'Incentives and Monitoring' in qualitative assessment, what is the related document URI address?
Q6	For measuring the indicator 'Objectives and Output' in qualitative assessment, what is the related document URI address?
Q7	For measuring the indicator 'Risk Management' in qualitative assessment, what is the related document URI address?
Q8	For measuring the indicator 'Operational Flexibility' in qualitative assessment, what is the related document URI address?

For quantitative assessments, the SWRL rules were written to contain all the required IFC elements to be executed. In general, a single SWRL rule corresponded to several query functions, which separately checked the material information and the elements' attributes. After the screening, the value of the unit cost was manually input into the ontology system by referring to a cost book, and the total cost was calculated.

Table 9 The main features and results in Scenario 1-4

Scenario	Num of rules	Num of query functions	Num of Entity checked	Checked IFC Entity	Required Quantity	Material	Unit cost (£)	Cost (£)
Q1	3	6	15678	Slab;	27500 .5	Concrete	84	2,310,042
				Column	1302.0	Concrete	180	234,432
				Beam	31131.5	Concrete	85	2,646,177.5
Total								5190651.5
Q2	3	5	14563	Beam	11376.0	Concrete	120	1364400
				Beam	11170.8	Steel	145	1619766
				Column	13066.2	Concrete	71	927700.2
Total								3911866.2
Q3	1	2	11341	Slab	110779	Concrete	69	7,643,751
Total								7,643,751
Q4	1	2	548	Wall	56115.2	Concrete	130	7,294,976

Total	7,294,976

Qualitative assessments often require documentation support rather than a single form of information. Based on the project documents and file, the URI information can be retrieved in the upper IFC instance.

Table 10 The main features and results in Scenario 5-8

Scenario	Num of rules	Num of query functions	Num of Entity checked	Entity checked	Results (Supported documents)
Q1	3	6	71	Project; Building; Site	www.briefingdocument.org
Q2	3	5	71	Project; Building; Site	www.briefingdocument.org; www.businesscase.org
Q3	1	2	71	Project; Building; Site	www.riskandopportunitiesplan.org www.deliveryriskreview.org www.riskpotentialassessment.org
Q4	1	2	71	Project; Building; Site	www.feasibilitystudy.org

Owing to the limitations of the current software, the URI of the file was not set to be stored in the appropriate IFC entities, but the majority of the information was placed under the IFC instance for extraction. According to the evaluation requirements, the user can choose when the evaluating rules (SWRL rules) can be developed and select the relevant documents. It is worth mentioning that all the documents contained the required codes, such as UniClass. The query functions used in these scenarios could also use the UniClass code rather than the keyword to retrieve the documents.

The developed VfMO and guidance were delivered to engineering procurement constancy companies, namely ASEAIR Co. Ltd., Zhixing Co. Ltd., and Jianlu Zhihua Co. Ltd. in China, which participated in the PPP engineering project. The demonstration videos and case study models were attached to explain the logic and functional application of the VfMO to the end users, who can select the measurement rules to check or query the existing data stored in the BIM platform. Meanwhile, the BIM viewer functions attached to the BIM server were used to visualize the digital model and highlight the objects corresponding to specific query functions. The external data such as unit cost, which are not stored in the IFC or knowledge base, can also be input at this stage. Questionnaire forms (212 delivered, 114 returned, including 24 financial managers, 33 civil engineers, 25 procurement/project managers, and 32 project consultants) were used to survey the company staff on whether the VfMO methods were accurate and efficient compared with the traditional methods (Figure 14). Most of the respondents indicated that the use of BIM data to assist assessments provided reliable results. This automated evaluation method has thus been consistently recognized by the project management and engineering design departments. Compared with real-time information requirements, the BIM can provide reliable IFC data. In terms of the efficiency of the VfMO in comparison with the traditional approach, most respondents agreed that the proposed approach could improve the efficiency of project assessments. A few respondents also considered that this approach was not very different from the traditional evaluation method. This may be because, in the field of financial computing, different mature financial algorithms and software are already used and have multiple financial models. Additionally, the current VfMO has limitations to cover all the applicable rules. The BIM model sometimes cannot store all the project information; however, the BIM advantage lies in its ability to be combined with real-time engineering data. Further, the BIM data schema is rapidly developing to include more domain elements; consequently, information exchange can be enhanced between different parties.

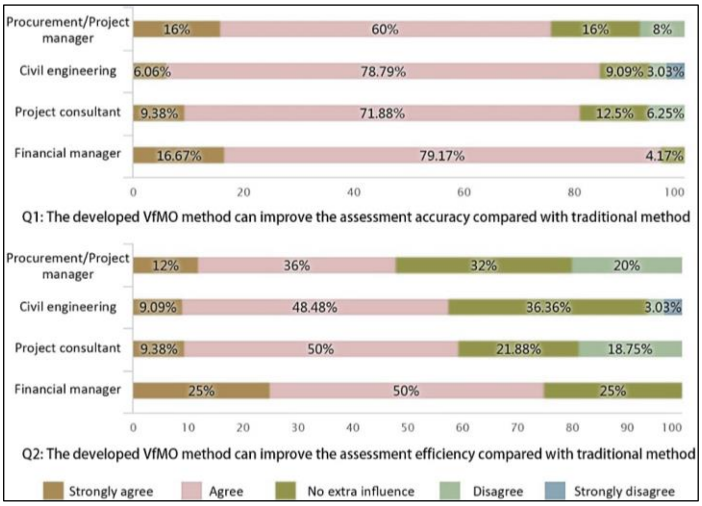

Figure 14 Distribution of agreement on accuracy and efficiency improvements of VfMO

6. Conclusion

VfM requirements are prone to vast variations and not all the information can be extracted from the BIM and project documents because multiple sources of heterogeneous data exist and need to be efficiently collected. The high-level procurement information can be extracted from clients and other project participants. Owing to time constraints, the resources extracted from a broad range of PPP project models are limited. However, the developed VfMO can be used to evaluate the specific subelements of the corresponding assessments according to the supporting regulations. The scope of these studies mainly lies in the automation process from the existing standardized environment, which is a BIM-based system. Cost estimates and document queries constitute the majority of the VfM elements, and these elements can be associated with the BIM environment. It is worth noting that such IFC-based expansibility for a wider operational domain can be upgraded to cover more assessment contents in the future. Besides, database or information items from human-oriented finance strategies can be embedded in the knowledge base. This process can be performed by either computer-based alignment, big data processing, or manual inputs by decision makers.

This approach can also be replaced with other methods to achieve the same results, such as implementing the mapping logic without using the SWRL rules and ontology. However, for the combination of rules and ontology, end-user knowledge engineering allow efficient writing of the rules and ontology use to depict relationships and vocabulary. Besides, as noted in the literature review, the current link data approach by mapping ontological rules and building information modeling depends on the IFC to owl/rdf conversion, which increases the information flow in the semantic and syntactical levels. Most importantly, it is difficult to handle large amounts of BIM data, so the ontological knowledge base has to be expanded to interact with other database platforms and software development environments. Therefore, the alignment approach in the present study has value from a practical perspective.

It is also worth mentioning that the nature of the decisions cannot intuitively be defined by indicators from a set of criteria. Computer-aid technology has been increasingly used in various decision-making processes; nevertheless, for the highly complex decision-making problems, computerized decision making cannot completely replace human decision making. The ‘value’ within the assessment is decided by various factors extracted from the human-based decision-making process. As a result, giving full play to the advantages of humans and computers, building a human-computer cooperative decision-making model, and improving people's trust in the computer system will significantly affect and improve the overall decision-making efficiency. The current research proposes the reasoning support that aligns with BIM and represents the engineering information management system. The decision makers or experts can benefit from having such automatic support. Although this study mainly presents the perspective of VfM, the established system can be applied to other computer-aided human decision-making scenarios in large-scale engineering projects.

In the case of available resources to fill the research gaps, the proposed VfMO addressed reasoning support. Combined with an efficient database, such as the IFC, the established knowledge for integrating project information should be further developed to align with various data sources to enrich their practical application. Moreover, computer-aided human decision making should be further refined to develop an finely integrated decision framework.

Acknowledgments

The authors wish to express the appreciation to the Cardiff University for information support and the Elsevier Webshop Group for helping the language check.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] HM Treasury, Value for Money Assessment Guidance, 2006. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/252858/vfm_assessmentguidance061006opt.pdf (accessed January 7, 2021).

[2] P. Wei, J. Chen, Q. Cui, S. Mu, Comparative analysis of value for money assessment in public-private partnership projects, Soft Science 28(5), 2014, pp. 28–42. https://doi.org/10.13956/j.ss.2014.05.006.

[3] World Bank Institute, Public-Private Infrastructure Advisory Facility, Value-for-Money Analysis--Practices and Challenges: How Governments Choose When to Use PPP to Deliver Public Infrastructure and Services, 2013. http://hdl.handle.net/10986/17622 (accessed January 7, 2021).

[4] G. Ren, H. Li, BIM based value for money assessment in public-private partnership BT - collaboration in a data-rich world, In: Proceedings of the 18th IFIP WG 5.5 Working Conference on Virtual Enterprises, PRO-VE 2017, Vicenza, Italy, September 18-20, 2017, L.M. Camarinha-Matos, H. Afsarmanesh, R. Fornasiero (Eds.), Springer International Publishing, Cham, 2017, pp. 51–62. https://doi.org/10.1007/978-3-319-65151-4_5.

[5] W. Hongyue, Y. Jingfeng, D. Jing, Qualitative evaluation of value for money of international PPP project and enlightenment to China, Construction Economy 38, 2017, pp. 38–42. https://doi.org/10.14181/j.cnki.1002-851x.201703038.

[6] Z. Ma, Z. Liu, Ontology- and freeware-based platform for rapid development of BIM applications with reasoning support, Automation in Construction 90, 2018, pp. 1–8. https://doi.org/10.1016/j.autcon.2018.02.004.

[7] S.K. Lee, K.R. Kim, J.H. Yu, BIM and ontology-based approach for building cost estimation, Automation in Construction 41, 2014, pp. 96–105. https://doi.org/10.1016/j.autcon.2013.10.020.

[8] H.P. Tserng, S.Y.L. Yin, R.J. Dzeng, B. Wou, M.D. Tsai, W.Y. Chen, A study of ontology-based risk management framework of construction projects through project life cycle, Automation in Construction 18, 2009, pp. 994–1008. https://doi.org/10.1016/j.autcon.2009.05.005.

[9] Y. Lu, Q. Li, Z. Zhou, Y. Deng, Ontology-based knowledge modeling for automated construction safety checking, Safety Science 79, 2015, pp. 11–18. https://doi.org/10.1016/j.ssci.2015.05.008.

[10] P.E.D. Love, J. Liu, J. Matthews, C.P. Sing, J. Smith, Future proofing PPPs: Life-cycle performance measurement and building information modelling, Automation in Construction 56, 2015, pp. 26–35. https://doi.org/10.1016/j.autcon.2015.04.008.

[11] A. Hegazy, M. Sakre, E. Khater, Arabic ontology model for financial accounting, Procedia Computer Science 62, 2015, pp. 513–520. https://doi.org/10.1016/j.procs.2015.08.524.

[12] E. Hromada, Utilization of dynamic simulation for design and optimization of PPP/PFI projects, Procedia Engineering 196, 2017, pp. 399–406. https://doi.org/10.1016/j.proeng.2017.07.216.

[13] European PPP Expertise Centre, A Guide to the Qualitative and Quantitative Assessment of Value for Money in PPPs, 2018. https://wbif.eu/storage/app/media/Library/8.%20Public%20Private%20Partnership/WBIF-Value-for-Money-Assessment-Guide-Serbian-Latin-FINAL.pdf (accessed January 7, 2021).

[14] P. Vullo, A. Passera, R. Lollini, A. Prada, A. Gasparella, Implementation of a multi-criteria and performance-based procurement procedure for energy retrofitting of facades during early design, Sustainable Cities and Society 36, 2018, pp. 363–377. https://doi.org/10.1016/j.scs.2017.09.029.

[15] R. Bain, Public sector comparators for UK PFI roads: Inside the black box, Transportation (Amst) 37, 2010, pp. 447–471. https://doi.org/10.1007/s11116-010-9261-5.

[16] S. Newberry, Financial black holes: Accounting for privately financed roads in the UK, European Accounting Review 20, 2011, pp. 196–198. https://doi.org/10.1080/09638180.2011.566679.

[17] S. Zwalf, Competitive neutrality in public-private partnership evaluations: a non-neutral interpretation in comparative perspective, Asia Pacific Journal of Public Administration 39, 2017, pp. 225–237. https://doi.org/10.1080/23276665.2017.1391454.

[18] S. Zwalf, G. Hodge, Q. Alam, Choose your own adventure: Finding a suitable discount rate for evaluating value for money in public-private partnership proposals, Australian Journal of Public Administration 76, 2017, pp. 301–315. https://doi.org/10.1111/1467-8500.12242.

[19] E. Nizkorodov, Evaluating risk allocation and project impacts of sustainability-oriented water public–private partnerships in Southern California: A comparative case analysis, World Development, 2020, 105232. https://doi.org/10.1016/j.worlddev.2020.105232.

[20] G. Abatecola, M. Mari, S. Poggesi, How can virtuous real estate public-private partnerships be developed? Towards a co-evolutionary perspective, Cities 107, 2020, 102896. https://doi.org/10.1016/j.cities.2020.102896.

[21] C. Ameyaw, T. Adjei-Kumi, D.-G. Owusu-Manu, Exploring value for money (VfM) assessment methods of public-private partnership projects in Ghana, Journal of Financial Management of Property and Construction 20, 2015, pp. 268–285. https://doi.org/10.1108/JFMPC-01-2015-0003.

[22] J.Y. Kweun, P.K. Wheeler, J.L. Gifford, Evaluating highway public-private partnerships: Evidence from U.S. value for money studies, Transportation Policy 62, 2018, pp. 12–20. https://doi.org/10.1016/j.tranpol.2017.03.009.

[23] L. Jasiukevičius, A. Vasiliauskaitė, The assessment of public-private partnership's possibilities to optimize investments in public infrastructure, Engineering Economics 29, 2018, pp. 32–45. https://doi.org/10.5755/j01.ee.29.1.19101.

[24] M. Djuric, D. Milosevic, J. Filipovic, S. Ristic, Benchmarking as a quality management tool in public administration, Engineering Economics 24, 2013, pp. 364–372. https://doi.org/10.5755/j01.ee.24.4.2785.

[25] C. Peterson, G. Skolits, Value for money: A utilization-focused approach to extending the foundation and contribution of economic evaluation, Evaluation and Program Planning 80, 2020, 101799. https://doi.org/10.1016/j.evalprogplan.2020.101799.

[26] G. Romano, M. Molinos-Senante, A. Guerrini, Water utility efficiency assessment in Italy by accounting for service quality: An empirical investigation, Utilities Policy 45, 2017, pp. 97–108. https://doi.org/10.1016/j.jup.2017.02.006.

[27] D. Tsamboulas, A. Verma, P. Moraiti, Transport infrastructure provision and operations: Why should governments choose private–public partnership?, Research in Transportation Economics 38, 2013, pp. 122–127. https://doi.org/10.1016/j.retrec.2012.05.004.

[28] P. Jílek, H. Černá Silovská, P. Kolařík, M. Lukavec, Selection of quantitative and qualitative methods for comprehensive evaluation of PPP projects focusing on the Czech Republic, Transylvanian Review of Administrative Sciences, 2018, pp. 38–54, ISSN 1842-2845. https://doi.org/10.24193/tras.54E.3.

[29] Z. Jianfeng, H.J. Liu, M.C.P. Sing, X. Jin, K. Ginige, Delivery of transport infrastructure assets: Decision-making model to ensure value for money, Journal of Infrastructure Systems 27, 2021, 5020008. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000584.

[30] C.O. Cruz, R.C. Marques, Using probabilistic methods to estimate the public sector comparator, Computer-Aided Civil and Infrastructure Engineering 27, 2012, pp. 782–800. https://doi.org/10.1111/j.1467-8667.2012.00771.x.

[31] F. Liu, J. Liu, X. Yan, Quantifying the decision-making of PPPs in China by the entropy-weighted pareto front: A URT case from Guizhou, Sustainability 10, 2018, 1753. https://doi.org/10.3390/su10061753.

[32] National Audit Office, Review of the VFM assessment process for PFI, HM Treasury, London, 2013. https://www.nao.org.uk/report/review-vfm-assessment-process-pfi (accessed January 7, 2021).

[33] L. Ding, Y. Zhou, B. Akinci, Building information modeling (BIM) application framework: The process of expanding from 3D to computable nD, Automation in Construction 46, 2014, pp. 82–93. https://doi.org/10.1016/j.autcon.2014.04.009.

[34] S. Tang, D.R. Shelden, C.M. Eastman, P. Pishdad-Bozorgi, X. Gao, BIM assisted building automation system information exchange using BACnet and IFC, Automation in Construction 110, 2020, 103049. https://doi.org/10.1016/j.autcon.2019.103049.

[35] D. Utkucu, H. Sözer, Interoperability and data exchange within BIM platform to evaluate building energy performance and indoor comfort, Automation in Construction 116, 2020, 103225. https://doi.org/10.1016/j.autcon.2020.103225.

[36] S. Staub-French, M. Fischer, J. Kunz, B. Paulson, A generic feature-driven activity-based cost estimation process, Advanced Engineering Informatics 17, 2003, pp. 23–39. https://doi.org/https://doi.org/10.1016/S1474-0346(03)00017-X.

[37] J. Choi, H. Kim, I. Kim, Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage, Journal of Computational Design and Engineering 2, 2015, pp. 16–25. https://doi.org/10.1016/j.jcde.2014.11.002.

[38] C. Chen, L. Tang, BIM-based integrated management workflow design for schedule and cost planning of building fabric maintenance, Automation in Construction 107, 2019, 102944. https://doi.org/10.1016/j.autcon.2019.102944.

[39] E.L. Isatto, An IFC representation for process-based cost modeling BT, In: Proceedings of the 18th International Conference on Computing in Civil and Building Engineering, E. Toledo Santos, S. Scheer (Eds.), Springer International Publishing, Cham, 2021, pp. 519–528. https://doi.org/10.1007/978-3-030-51295-8_37.

[40] C. Khosakitchalert, N. Yabuki, T. Fukuda, Automated modification of compound elements for accurate BIM-based quantity takeoff, Automation in Construction 113, 2020, 103142. https://doi.org/10.1016/j.autcon.2020.103142.

[41] Z. Ma, Z. Wei, X. Zhang, Semi-automatic and specification-compliant cost estimation for tendering of building projects based on IFC data of design model, Automation in Construction 30, 2013, pp. 126–135. https://doi.org/10.1016/j.autcon.2012.11.020.

[42] F.K.T. Cheung, J. Rihan, J. Tah, D. Duce, E. Kurul, Early stage multi-level cost estimation for schematic BIM models, Automation in Construction 27, 2012, pp. 67–77. https://doi.org/10.1016/j.autcon.2012.05.008.

[43] H. Alzraiee, Cost estimate system using structured query language in BIM, International Journal of Construction Management, 2020, pp. 1–13. https://doi.org/10.1080/15623599.2020.1823061.

[44] N. Ham, S. Moon, J.-H. Kim, J.-J. Kim, Optimal BIM staffing in construction projects using a queueing model, Automation in Construction 113, 2020, 103123. https://doi.org/10.1016/j.autcon.2020.103123.

[45] AUTODESK, Revit, BIM Software, Autodesk, 2019. https://www.autodesk.co.uk/products/revit/overview (accessed January 7, 2021).

[46] Bentley, OpenBuildings - BIM Information Modeling Software, 2019. https://www.bentley.com/en/products/brands/openbuildings (accessed January 7, 2021).

[47] Innovative Solutions, BIMestiMate4, 2019. https://www.advanceduninstaller.com/BIMestiMate4-633f422b724f4fc2f2aa0d238db6d15e-application.htm%0D (accessed January 7, 2021).

[48] Exactal, The complete 3D/BIM and 2D estimating solution, (n.d.). https://www.exactal.com/en/costx/products/costx/ (accessed January 7, 2021).

[49] Trimble, Vico Office for Cost, 2020. https://gc.trimble.com/product-categories/vico-office-cost (accessed January 7, 2021).

[50] Trimble, WinEst, 2020. https://gc.trimble.com/product/winest%0D (accessed January 7, 2021).

[51] Innovaya, Innovaya Visual Estimating, 2014. http://www.innovaya.com/ (accessed January 7, 2021).

[52] Construction Project Management Software - Price Comparison & Reviews - Capterra UK, (n.d.). https://www.capterra.co.uk/directory/30057/construction-management/software?account_campaign_id=6727011822&account_adgroup_id=83074231327&target=building quantity estimation software&ad_id=388383714657&matchtype=b&gclsrc=aw.ds&&utm_source=ps-google&gclid=CjwKCAiAy9jyBRA6EiwAeclQhII2tK8Lhd9PFIKneoSeq__a-Sx4ltb8cJGP36UwoOTGyjeF1nhE5BoC6uUQAvD_BwE (accessed February 26, 2020).

[53] Autodesk, What is Document Management?, 2019. https://knowledge.autodesk.com/support/bim-360/learn-explore/caas/CloudHelp/cloudhelp/ENU/BIM360D-Document-Management/files/GUID-1E2C1BF0-A1D6-495D-8044-B0C74050D04D-html.html (accessed January 7, 2021).

[54] C.H. Caldas, L. Soibelman, Automating hierarchical document classification for construction management information systems, Automation in Construction 12, 2003, pp. 395–406. https://doi.org/https://doi.org/10.1016/S0926-5805(03)00004-9.

[55] J.D. Goedert, P. Meadati, Integrating construction process documentation into building information modeling, Construction Engineering and Management 134, 2008, pp. 509–517. https://doi.org/10.1002/9780470432846.

[56] D.G. Lee, H.S. Cha, Exploratory study on BIM-based information breakdown structure for construction document management, Journal of Construction Engineering and Project Management 5, 2015, pp. 32–39. https://doi.org/10.6106/JCEPM.2015.5.1.032.

[57] C. Golbreich, Combining rule and ontology reasoners for the semantic web BT - Rules and rule markup languages for the semantic web, In: Proceedings of the 3rd International Workshop on RuleML 2004, Hiroshima, Japan, November 8, 2004, G. Antoniou, H. Boley (Eds.), Springer Berlin Heidelberg, Berlin, Heidelberg, 2004, pp. 6–22. https://doi.org/10.1007/978-3-540-30504-0_2.

[58] A. Yurchyshyna, A. Zarli, An ontology-based approach for formalisation and semantic organisation of conformance requirements in construction, Automation in Construction 18, 2009, pp. 1084–1098. https://doi.org/https://doi.org/10.1016/j.autcon.2009.07.008.

[59] S. Hou, H. Li, Y. Rezgui, Ontology-based approach for structural design considering low embodied energy and carbon, Energy Buildings 102, 2015, pp. 75–90. https://doi.org/10.1016/j.enbuild.2015.04.051.

[60] N.M. Tomašević, M. Batić, L.M. Blanes, M.M. Keane, S. Vraneš, Ontology-based facility data model for energy management, Advanced Engineering Informatics 29, 2015, pp. 971–984. https://doi.org/10.1016/j.aei.2015.09.003.

[61] J. Zhang, H. Li, Y. Zhao, G. Ren, An ontology-based approach supporting holistic structural design with the consideration of safety, environmental impact and cost, Advanced Engineering Software 115, 2018, pp. 26–39. https://doi.org/10.1016/j.advengsoft.2017.08.010.

[62] Z. Liu, Z. Ma, Establishing formalized representation of standards for construction cost estimation by using ontology learning, Procedia Engineering 123, 2015, pp. 291–299. https://doi.org/10.1016/j.proeng.2015.10.093.

[63] E. Simperl, T. Bürger, S. Hangl, S. Wörgl, I. Popov, ONTOCOM: A reliable cost estimation method for ontology development projects, Journal of Web Semantics 16, 2012, pp. 1–16. https://doi.org/10.1016/j.websem.2012.07.001.

[64] Z. Ma, Z. Liu, Z. Wei, Formalized representation of specifications for construction cost estimation by using ontology, Computer-Aided Civil and Infrastructure Engineering 31, 2016, pp. 4–17. https://doi.org/10.1111/mice.12175.

[65] K. Kim, Y.K. Cho, Construction-specific spatial information reasoning in building information models, Advanced Engineering Informatics 29, 2015, pp. 1013–1027. https://doi.org/10.1016/j.aei.2015.08.004.

[66] F.H. Abanda, B. Kamsu-Foguem, J.H.M. Tah, BIM - new rules of measurement ontology for construction cost estimation, Engineering Science and Technology, an International Journal 20, 2017, pp. 443–459. https://doi.org/10.1016/j.jestch.2017.01.007.

[67] C. Golbreich, Combining rule and ontology reasoners for the semantic web, In: 2004 International Workshop on Rules and Rule Markup Languages for the Semantic Web, Antoniou G., Boley H. (eds), Springer, Berlin, Heidelberg, 2004, pp. 6–22. https://doi.org/10.1007/978-3-540-30504-0_2.

[68] P. Salvaneschi, M. Cadei, G.M. Calvi, P. Rossi, Towards a knowledge-based system for seismic assessment of buildings, Computer-Aided Civil and Infrastructure Engineering 5, 1990, pp. 29–41. https://doi.org/10.1111/j.1467-8667.1990.tb00039.x.

[69] R. Fruchter, T. Schrotenboer, G.P. Luth, From building information model to building knowledge model, In: 2009 International Workshop on Computing in Civil Engineering, American Society of Civil Engineers, Reston, VA, USA, 2009, pp. 380–389. https://doi.org/10.1061/41052(346)38.

[70] L.Y. Ding, B.T. Zhong, S. Wu, H.B. Luo, Construction risk knowledge management in BIM using ontology and semantic web technology, Safety Science 87, 2016, pp. 202–213. https://doi.org/10.1016/j.ssci.2016.04.008.

[71] C. Boje, H. Li, Crowd simulation-based knowledge mining supporting building evacuation design, Advanced Engineering Informatics 37, 2018, pp. 103–118. https://doi.org/10.1016/j.aei.2018.05.002.

[72] N.F. Noy and D.L. McGuinness, Ontology Development 101: A Guide to Creating Your Ontology, 2000, pp. 1 ‒ 25. http://protege.stanford.edu/publications/ontology_development/ontology101.pdf (accessed January 7, 2021).

[73] Protégé, A free, open-source ontology editor and framework for building intelligent systems, Stanford University, 2013. https://protege.stanford.edu/ (accessed January 7, 2021).

[74] British Standard Institute, Specification for information management for the capital/delivery phase of construction projects using building information modelling: PAS 1192-2:2013, BSI Standards Publishing, 2013, pp. 1–68. British Standard Limited, ISSN 9780580781360.

[75] ISO 12006-2:2015, 2015. https://www.iso.org/standard/61753.html%0D (accessed January 7, 2021).

[76] E.D.M. Council, FIBO Primer, 2018. https://spec.edmcouncil.org/fibo/OWL(accessed March 21, 2019).

[77] G. Ren, H. Li, Y. Jiao, W. Zhang, Data exchange requirement analysis for value for money assessment in public-private partnerships, In: 2018 Workshop of the European Group for Intelligent Computing in Engineering, Smith I., Domer B. (eds), Springer, Cham, 2018, pp. 429–446. https://doi.org/10.1007/978-3-319-91638-5_24.

[78] G. Ren, H. Li, R. Ding, J. Zhang, C. Boje, W. Zhang, Developing an information exchange scheme concerning value for money assessment in public-private partnerships, Journal of Building Engineering 25, 2019, 100828. https://doi.org/10.1016/j.jobe.2019.100828.

[79] RICS, RICS new rules of measurement, 2009, 306. https://www.rics.org/uk/upholding-professional-standards/sector-standards/construction/rics-nrm-new-rules-of-measurement/ (accessed January 7, 2021)

[80] N.F. Noy, M.A. Musen, The PROMPT suite: Interactive tools for ontology merging and mapping, International Journal of Human-Computer Studies 59, 2003, pp. 983–1024. https://doi.org/10.1016/j.ijhcs.2003.08.002.

[81] G. Antoniou, P. Groth, F. van Harmelen, R. Hoekstra, A Semantic Web Primer, The MIT Press, 2012.