Knowledge management in PPP decision making concerning value for money assessment[1]

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[1] The knowledge management in this thesis refers to the knowledge base development and application in engineering project assessment

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Abstract

Public-private partnership (PPP) is the current procurement model used for large-scale public engineering and municipal facilities procurement and is now advocated by governments around the world. Value for money (VfM) assessment is a critical process used to evaluate whether the PPP procurement model applies to a project throughout its lifecycle. VfM assessment aligns with financial capacity assessment and feasibility assessment, providing an essential decision-making reference for project managers and associated with performance measurement (PM) in the ex-post stages, which are linked to the payment model. Therefore, the evaluation of the project through VfM determines the success of the PPP model to a great extent. Through a comprehensive literature review, the dissertation identifies the practical deficiencies for the current VfM assessment process and presents a detailed view of the content of the VfM assessment. Based on that, the dissertation determines the research motivation and formulates detailed research questions and hypotheses to establish a thorough understanding of a knowledge-based management platform to achieve automated processes that support human decision making.

By using the deductive approach, this research leverages knowledge engineering principles and developed a core VfM knowledge base to help manage knowledge in the PPP decision-making process concerning VfM assessment. The system development is based on the design science methodology. In order to integrate information about the engineering project management and VfM assessment, the standardized information exchange processes are first used to develop robust information with project versatility. The Building Information Modelling (BIM) application platform, which uses Industry Foundation Classes (IFC) as the engineering project data source, is connected with the developed information schema, thus establishing the basis for implementing automated information exchange. Second, ontology modeling is used to establish a VfM knowledge base. The various factors associated with the PPP project can be stored in a semantic environment for better identification by engineers. Furthermore, automated project assessment is achieved by developing different rules-based functions in the ontology and combining them with the data platform represented by BIM. By using case studies and action research strategies, this research demonstrates the feasibility of the constructed knowledge base.

The main outcomes of the research lie on the definition and screening of information for VfM assessment, as well as the establishment and application of a smart knowledge base. The developed components and software tools have been thoroughly tested, validated and calibrated by leveraging knowledge from experienced domain experts, software companies and other industry partners. Due to the generic development principles adopted in the research, the method, tools and framework can be further extended for other related areas where smart decision making is required.

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List of Abbreviations

AEC = Architectural Engineering and Construction

AIM = Asset Management Model

API = Application Programming Interface

BCIS = Building Cost Information Service

BIM = Building Information Model

BOO = Building-Owning-Operation

BOT = Build-Operate-Transfer

BREEAM = Building Research Establishment Environmental Assessment Method

CapEx = Capital Expenditures

CDE = Common Data Environment

CESMM4 = Civil Engineering Standard Method of Measurement

DfV = Data extraction tool for VfM

DL = Description Logics

DSR = Design Science Research

EIR = Employers' Information Requirement

ERs = Exchange requirements

FIBO = Financial Industry Business Ontology

FOL = First-Order Logic

FPs = Functional Parts

IDE = Integrated development environment

IDM = Information Delivery Manual

IFC = Industry Foundation Classes

ifcOWL = Industry Foundation Classes Web Ontology Language

ISO = International Organization for Standardization

KPI = Key Performance Indicators

LEED = Leadership in Energy and Environmental Design

LD = Linked Data

MMHW = Method of Measurement for Highway Works

MVD = Model View Definition

NPV = Net Present Value

NRM = New Rules of Measurement

OGC = Office of Government Commerce

OpEX = Operating Expenses

O&M = Operation and Management

OWL = Web Ontology Language

PEP = Project Execution Plan

PFI = Private Finance Initiative

PF2 = Private Finance 2

PI = Performance Indicator

PM = Performance Measurement

PPI = Participation in Infrastructure

PPP = Public-Private Partnership

PSC = Public Sector Comparator

RDF = Resource Description Framework

RIBA = Royal Institute of British Architects

ROT = Rehabilitate-Operate-Transfer

SPARQL = SPARQL Protocol and RDF Query Language

SPV = Special Purpose Vehicle

SW = Semantic Web

SWRL = Semantic Web Rule Language

UI = User Interface

URI = Uniform Resource Identifier

VfM = Value for Money

VfMO = Value for Money Ontology

WLCC = Whole Life Cycle Costs

W3C = WWWC = World Wide Web Consortium

Chapter 1. Introduction

1.1 Problem statement

In recent decades, the public-private partnership (PPP) have proliferated and adapted to public development. The concept of PPP was developed to support public procurement and was initially regarded as a ground-breaking approach that could relieve the pressures of local debt. The PPP model has been well implemented for project concessions in developing countries to replace the traditional procurement model. In general, PPP remains popular and continues to be implemented into infrastructure project plans (Zhang *et al.*, 2016). Holistic means are required to provide better value for money (VfM) as a fundamental part of PPP model implementation (Du *et al.*, 2016).

VfM assessment, as one of the essential components of PPP, defines the feasibility of the project procurement model and is a comprehensive assessment approach. Its performance content usually overlaps with that of other essential project factors, such as performance measurement (PM), and is used to justify the feasibility of using a PPP model. It is also a structural means to verify income based on project strategies. VfM should provide a hospitable environment within which to perform performance monitoring so that long-term targets can be achieved (Henjewele, Sun and Fewings, 2011).

The VfM assessment conducted in the initial stages of PPP plays a crucial role in financial evaluation, which informs the decision of whether a PPP model is viable or not. However, current VfM processes draw from multiple sources with second-hand data, and decisions are made without adequate information exchange between the involved parties (Farquharson *et al.*, 2011). The consequent lack of information makes it very difficult for the public to assess whether the cost is commensurate with the benefits and risks to the public sector (Shaoul, 2011). Reports (European PPP Expertise Centre [EPEC], 2015) by the EPEC have indicated that the capability and critical drivers of the consultative machinery used in a large number of PPP projects are questionable, lacking reliable information to support VfM assessment. The PPP model does not ‘bring extra money’ and has failed to meet risk transfer targets in many cases (Hall, 2014). Existing VfM assessments were made without the support of real-time engineering data (Association of Chartered Certified Accountants [ACCA], 2012). In this way, evaluating VfM in PPPs remains problematic.

Recent research that has analyzed VfM assessment requires further development, and there is a significant research gap due to the fact that very few pieces of literature consider the entire process when aiming to strengthen the assessment process and develop the methodology to specify procedures. Given concerns about the profitability of PPP, a more integrated platform is required to manage multiple performances throughout the project lifecycle.

1.2 Research motivation

1.2.1 Build-up comprehensive VfM

'The optimum combination of the whole of life cost and quality (or fitness for purpose) of the good or service to meet the user's requirements'.

– Definition of 'value for money' in 'HM Treasury's Manual'
(HM Treasury, 2006)

Due to the complexity of the definition of VfM assessment, its overall contents require comprehensive information processing and a wide range of information assembled to perform the assessment. Compared with the original definition and intention behind VfM assessment, the practice of these strategies is still relatively underdeveloped. In official publications of the government finance and construction sectors concerning the specific procurement justification strategies used in the United Kingdom (UK) and China, the justification of PPP refers to feasibility studies, and the arguments relating to public service quality efficiency usually fail to stress the specific procedure and primary coverage of delivering VfM. For example, the publications 'Value for Money Assessment Guidance', published by HM Treasury; 'PPP Value for Money Assessment Guidance', published by Ministry of Finance of China; and the 'P3-Value Evaluation Manual', published by the United States (US) Department of Transportation all stress the importance of fiscally responsible, feasibility studies and VfM assessment, but they lack the specific processes and information support necessary to achieve better performance (HM Treasury, 2006; U.S. Department of Transportation, 2013; China, 2014).

The PPP procurement model is now getting more attention in developing counties (Leigland, 2018). For instance, the PPP model was popularised within Chinese municipal works in the 1990s and early 2000s. In the process of promoting PPP, the new Chinese central government has put more emphasis on ensuring the VfM of PPP projects and on improving the efficiency of public funds since 2013. China dominates the PPP procurement projects with more than sixty percent of the total PPP contracts around the world while the VfM assessment is required to be processed at the project early-stage (Yong, 2010). Therefore, observing the VfM assessment in Chinese PPP practice will undoubtedly play an important role in guaranteeing the use of a suitable procurement model to a great extent. To achieve better VfM performance, this research aims to study and establish the VfM assessment model in the implementation of PPP projects, including measurement approach and information support, and design a new methodology for the implementation of PPP.

1.2.2 Automatic information exchange in PPPs early stage

With the acceleration of the pace of economic globalization, information technologies supporting the achievement of engineering informationisation have become an indispensable element in enterprise development (Nazarko, 2015). However, PPP infrastructure projects are often more complicated than are single building projects. The features of information management in PPP are as follows:

1) Wide range: PPP infrastructure project management is comprehensive, multi-sectoral and multi-disciplinary. It includes not only production management during the construction process but also management in terms of technology, quality, materials, plans, safety and contracts (Nathan Associates, 2017).

2) Massive workload: The formation of a building process requires a large variety of materials to be consumed and requires participation in a large number of construction activities (Demirel *et al.*, 2017). In order to formulate all these construction procedures and gather the required resources necessitates in-depth management; this level of complexity in project management is required to cover not only production and material management but also more comprehensive perspectives.

3) Strong constraints: PPP project management must conform to a step-by-step construction procedure from preparation to complete acceptance. Therefore, PPP project management must not only meet the requirements of the relevant construction regulations but also cooperate with project parties and arrange them in an orderly manner (An *et al.*, 2018).

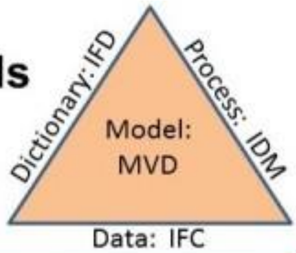
4) A large amount of information flow: Management activities in large-scale PPP engineering projects cannot be separated from the processing of certain information. The management activities of all aspects of construction projects

are not isolated, and there are interdependent and mutually restrictive links between them. Therefore, the exchange and transmission of information between management activities are inevitable, and the complexity and volume of the construction management directly determine the complexity and frequency of the information flow in the PPP management process (World Bank, 2014).

In the traditional project management model, the storage of project information is mainly file-based at project early stages, such as forms or documents; the exchange of information is mostly through the manual transfer of information between people in writing or verbally, and the retrieval of information relies on the reading and viewing of documentation. In this format, information runs at a relatively slow speed from the generation, sorting and transmission phases, which can cause errors in project management. With the continuous expansion of the scale PPP engineering construction projects, the amount of information exchanged between project departments has been expanding and the information exchange has become more frequent. Because of this, the traditional procurement currently threatens the survival and sustainable development of construction enterprises in the PPP competition environment of the market economy.

Technical Principles: Basic Standards

There are five basic methodology standards



What it does	Name	Standard
Describes Processes	IDM Information Delivery Manual	ISO 29481-1 ISO 29481-2
Transports information / Data	IFC Industry Foundation Class	ISO 16739
Change Coordination	BCF BIM Collaboration Format	buildingSMART BCF
Mapping of Terms	IFD International Framework for Dictionaries	ISO 12006-3 buildingSMART Data Dictionary
Translates processes into technical requirements	MVD Model View Definitions	buildingSMART MVD

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Figure 1 Standardized IFC for information management (*IFC Introduction - buildingSMART*, no date)

The information exchange in the procurement early-stage paly the vital roles to define the success of initial assessment such as VfM and Financial feasibility studies. Information management in large-scale PPP procurement at the early stage must be processed for efficient collection and real-time sharing and to reduce duplications as much as possible (Dewulf and Garvin, 2019). Currently, the Building Information Management (BIM) management system contributes to the automation of information exchange. It is necessary to supervise and control the timeliness of information feedback so that the automation standard can be improved. BIM-based information and data delivery standards have been the core contributions of the implemented software, and over the last few decades, the inheritance of upstream and downstream business has made the circulation of data management increasingly important in many countries. Industry Foundation Classes (IFC), developed by buildingSMART (formerly the International Alliance for Interoperability, IAI) as the standardized data model, intended to describe all the related architecture, engineering and construction (AEC) industry data (buildingSMART, 2018). With the development, IFC can be regarded now as the only standard used to share and exchange construction and facilities information globally which indicates that it may function as a panacea to improve information delivery efficiency and should be taken into consideration in this research for information exchange (Figure 1).

1.2.3 Linked data to enhance the functionality of E-commerce in PPP

'PPP procurement' not only refers to the construction engineering domain but also includes a vast branch of business and financial procedures. E-commerce in the construction sector is gradually becoming the leading business model and has a significant effect on the promotion of project collaborations (Bhutto, Thorpe and Stephenson, 2005). A few studies related to e-commerce platforms and supply chain management have shown that the combination of the two can contribute to cost control in construction and operations (Wang *et al.*, 2018). Through the use of e-commerce, information exchange in the supply chain can be made more reliable and efficient. The development of e-commerce platforms in the AEC sector is hardly disconnected from the processes of information sharing and interaction.

Furthermore, project information on the construction industry is mostly heterogeneous and distributed, which creates difficulties for information interaction. The characteristics of project information in PPP engineering that create obstacles in their integration with e-commerce can be summarised as follows:

1) Distributed: Information in different management platforms are independent of one another and independent from procurement. When the information is required for end-users, different sources of information are distinguished from each other, making it challenging to locate related information using a single query. This is mainly caused by the separation of information between different websites or databases.
2) Structurally diverse: The information structure is diverse in large-scale engineering. Different management platforms contain different types of information and have different search methods. Different business models also use different parameter attributes to describe and store product information, which includes structured information, semi-structured information and unstructured information such as multimedia information and document information.
3) Semantic heterogeneous: There are also heterogeneities in managing similar types of information for different vendors.
4) Dynamic characteristics: The information management platform is dynamically updated, and the emergence and deletion of information are dynamic as well.

Building information management (BIM) helps to achieve efficient information sharing. Because the information in BIM is managed based on open standards, the business process can be supported by the Internet so that the information can be used efficiently to cover the whole project lifecycle. BIM technology can integrate all the information throughout the entirety of the building project, facilitate the integration and allow for the required information to be searched and used. However, the massive, heterogeneous and dispersed nature of e-commerce information in PPP construction makes information integration very difficult. The information on the web and business-related information cannot be fully integrated into BIM management. Therefore, it is necessary to make information association possible.

The concept of linked data (LD), proposed by Tim Berners-Lee (2009), indicates an approach that uses a uniform resource identifier (URI) to identify information resources, that applies HTTP protocol to access resources and that uses the Resource Description Framework (RDF) information format to describe the resources (Bizer, Heath and Berners-Lee, 2009). This approach can be considered an implementation of the semantic web (SW). At present, LD applications are mainly embodied in two aspects: 1) to provide semantic elements to the 'trustable network', and 2) to implement cross-domain data fusion as a standard application programming interface (API) (Data, 2017). In library management, many countries publish library bibliographic information using a LD method, while in the enterprise application field, the LD method focusses on the retrieval of multimedia resources. Finally, in the field of e-government, the US, Australia and other countries and local governments have published government public data in the form of LD.

In the field of AEC, the use of a LD system framework was proposed by Lee et al. (2016). In this framework, the RDF format was proposed to capture and descript the related information; BIM can provide necessary information support for the engineering domain. In this approach, the LD method can theoretically solve the problem of e-commerce information integration and make up for the shortcomings of BIM in information management. The LD system can help to realize the discovery, identification and integration of commercial information in the construction industry. Its performance includes the following two aspects: First, the structure and contents of business information in PPP construction are determined by the characteristics of the construction project itself. There exists a vast number of participating units in the procurement and primary business activities throughout the project lifecycle, so e-commerce information is stored in different participating entities or platforms. LD enables association between different information sources, and the end-users can search the engine through the associated information, access other URI entities from the currently accessed URI entity and discover all relevant information based on the l–supported business correlation network. Second, the semantic association of e-commerce information can be connected with the construction industry. The RDF model is the leading information description format of Semantic Web technology, which can adequately describe the semantic relationship between project entities. Through the description of the semantic relationship between business sectors, end-users' needs can be discovered.

The LD approach combines related information from different sources, which can contribute to early-stage assessment in PPP. However, the current implementation framework and knowledge base lack development, which has, therefore, become an urgent task.

1.3 Research hypothesis

In light of the research problems and motivation identified above, this research proposes a framework and methodology to tackle the current issue concerning smart

VfM assessment, which features automatic information exchange to allow for the creation of an intelligent management system in PPP procurement. The overarching aim and hypothesis adopted in the research are as follows: *To establish a knowledge-represented approach that provides automatic information retrieval, exchange and processing that can help to support the decision-making process on ex-ante VfM assessment in PPP procurement by leveraging different data sources, such as the existing BIM system.*

1.4 Research questions

Based on the research objective of building comprehensive knowledge, the research hypothesis can be broken down into the following research questions:

Q1: *What are the contents defined in the VfM and how are the current implementation methods and tools used for assessing the VfM in the PPP procurement process worldwide?*

Q2: *What is required for VfM analysis and to what extent can the contents of VfM assessment be integrated with the BIM system?*

Q3: *How can an information exchange requirement for automatic VfM assessment be defined, and how can such BIM-based information exchange be implemented?*

Q4: *How to implement an ontological knowledge representation for all the related contents of VfM in PPP procurement, and what are the benefits of using ontology for knowledge representation considering the VfM requirements?*

Q5: *How to align the constructed knowledge base with multi-domains, such as the BIM management platform, to realize the required functionalities?*

Q6: *How reliable is a knowledge-represented system in understanding the digital engineering project model and other data resources in facilitating efficient VfM assessment? For instance, is the proposed system can support the decision-making by exchanging information and process the data accurately and automatically?*

1.5 Research innovations

This research contains work related to several theoretical and practical developments concerning VfM/PM assessment at the project level. The methodology refers to the standardized information exchange framework and existing knowledge-based reasoning approaches, and the overall system has been tested and corrected through industry projects. The main contributions of this research are listed below:

1) The related information exchange requirements in VfM assessment are defined for the first time from scratch by decomposing the legal assessment structures from the UK, China, and the US. This development is based on a comprehensive literature review and thorough comparing analysis. The defined information exchange schema takes references to the information delivery manual (IDM) development framework and can be further expanded for standardized information exchange processes. It also can be utilized in cost estimation and other performance-orientated decision-making stages.
2) A VfM knowledge base has been defined and implemented, it coverts specified rules from standardized regulations and uses them to query and fetch the required data from BIM models and environment. With such reasoning support, this study builds up the mechanism that links BIM data with ontology data (with multiple data sources combined in the ontology) and the architecture of a LD management engineering procurement system.
3) The developed knowledge base considers comprehensive performance indicators by integrating different scenarios for assessing VfM. Once these scenarios are executed with specific financial strategies, all the related information and figures can be aggregated by this ontological system. The system also links with other ontologies and rules extracted from standardized manuals/guidelines. The developed knowledge-based representation can be delivered using a machine-readable and interpretable format and it can further expand to cover more semantic web-based functions.
4) The mix-methods applied in this research is also a contribution that can be used in other domain holistic decision-making implementations. The methodology includes requirement definition; system design and development; demonstration; and evaluation using the LD approach. It focuses on rules-oriented measurement r, the integration with IFC and other data sources, and the representation of procurement guidance.

1.6 Structure of the dissertation

This dissertation is divided into several chapters corresponding to the main research questions.

The following chapter, Chapter 2, aims to answer the first and second research questions by introducing a comprehensive literature review that is relevant to the research topic. First, the concept, implementation status and related contents in VfM assessment are reviewed. By addressing the research gap, BIM-based academic papers and standards are then reviewed to strengthen the relativity between engineering-supported information management. Last, studies on the semantic approach are reviewed, which contain research related to the application of ontologies, the integration with domain knowledge and the LD approach. The main findings of the review are closely related to the research gaps and methodologies.

Chapter 3 presents the research methodology, which covers the research approaches, strategies, choices and time horizons. The conceptual framework and structure used to develop the specific LD system references or the 'Design Science' methodology.

Chapter 4 relates to the requirement definition and analysis needed to develop a VfM ontology (VfMO). The intention is that this development will answer the third research question. The information resources used to establish the requirement are based on existing knowledge, including that related to PPP procurement guidance and the related cost estimates catalogs in engineering works. Tools are also identified to create an automatic information exchange process for VfM. The entire process references the standardized IDM process, which enables automation in the early stage of the procurement. A tool is also developed in this stage to indicate the functionalities of information exchange.

Chapter 5 responds to the fourth research question. In this chapter, VfMO is developed to derive knowledge from the existing knowledge base in a semantic environment. The definition of related concepts, relations, and terms of use are connected using the World Wide Web Consortium (W3C) semantic standard. For answering the fifth research question, the developed knowledge base uses a LD approach to connect with IFC, and some of the entities within the ontology also align with external information sources while considering end-user input.

Chapter 6 addresses the testing and implementation of the VfMO system and discusses the overall research methodology in response to the sixth research question. Samples of the related reasoning rules are presented, and the details of the LD approach are explained. The adopted ontology is presented as a software demo that contains reasoning rules that align with visualization functions. The workflow of the system process is introduced in this chapter, and a case study of a BIM infrastructure model is presented with use-case scenarios. The model is used to test system operations. Moreover, the developed demos are delivered to different project experts for further validation at the project level. At the end of this chapter, a discussion is presented based on the results.

At the end of the dissertation, Chapter 7 concludes the research work presented in the previous chapters. The main research findings are highlighted to answer all the research questions. Then, the research restrictions are discussed and future work is proposed. In the end, the research contributions are summarized.

Chapter 2. Review of related works

As a vital process of project argumentation, VfM supports project sponsors in building up the original logic of whether to perform the PPP procurement model or use the traditional methods. Therefore, this chapter is presented to review all the related works which refer to VfM in PPP. Based on the relevance, BIM and ontological development in engineering procurement also are reviewed afterward. The contents are divided into three parts. Section 2.1 investigates the VfM related concept, implementation status and literature concerns. Section 2.2 reviews the BIM development that aligns with VfM contents. Section 2.3 outlines the developments around ontological processing used in the engineering procurement domain. At the end of this chapter, a research roadmap is also presented in Section 2.4 based on existed publications.

In order to produce a comprehensive review of the subject of VfM, the review has the following components:

• <u>Research Publications:</u> The papers on PPP were mainly sourced from construction and public procurement domain journals using the ScienceDirect and Scopus search engines. The information was collected via systematic literature research using keywords and content criteria. The results revealed that the assessment indicators in VfM were aligned with the other key indicators, such as key performance indicators (KPI).

• <u>Published Guidance and Documentation:</u> Due to the large-scale PPP project implementation and information accessibility, we mainly review the VfM related guidance and project documents in China. This included the status of overseas VfM-related methodology published by the World Bank Group and procurement project documents in the Chinese financial sector. The documentation explained that VfM was inadequately catered for in current project practices. More specifically, procurement documentation from the Ministry of Finance of the People's Republic of China was collected. The documents consisted of VfM reports on transportation, urban housing, education, culture, nursing, and municipal engineering from Chinese PPP demonstration projects, which heavily reflected the practical application of VfM.

• <u>Procedures and Contents:</u> Current representative legal VfM guidance was sourced from the related national and international governing bodies to express the requirements of VfM content (e.g., British VfM assessment guidance, US Federal Highway Administration Guidebook for VfM assessment, Chinese PPP VfM guidance).

Selection of related guidance was gathered at various conferences and events, along with the information from literature and industry reports.

The following research used the same academic sources to review BIM and semantic technologies:

• Research Publications: The intersection of BIM and project quantitative and qualitative management aspects corresponding to the contents of VfM were supplemented with transferable construction content. A combined quantitative approach was taken to classify further and analyze the literature presented. In addition, the alignment between BIM and the ontological approach was also reviewed, as a new research methodology for knowledgebase development.

• Tools and Software: The implementation of BIM for multiple project purposes corresponded to the VfM content.

2.1 Review of VfM in PPP

2.1.1 Public-private partnership

There is no unambiguous definition of the PPP model. In the broad sense, PPP is any service partnership type which offers a public product by means of both public and private sectors, and can thus be effected through operation and management (O&M), build-operate-transfer (BOT), building-owning-operation (BOO) and rehabilitate-operate-transfer (ROT) (Delmon, 2010). The model is well implemented by developing countries in project concession to replace the traditional procurement model. In the UK, the private finance initiative (PFI) approach was widely used as a method of financing through private investment projects requiring design, build, finance and operational facilities and this, nowadays, could be regarded as a form of the PPP model. There are also more narrow representations of PPP that place greater emphasis on the co-operative institution or relations which are being defined as a special purpose vehicle (SPV), shown in Figure 2, which is subsidiary co-operation with an asset. Such undertakings are often funded by a combination of equities, shared by various parties and the SPV takes charge of allocating project risk and whole life performance monitoring (Liu *et al.*, 2014).

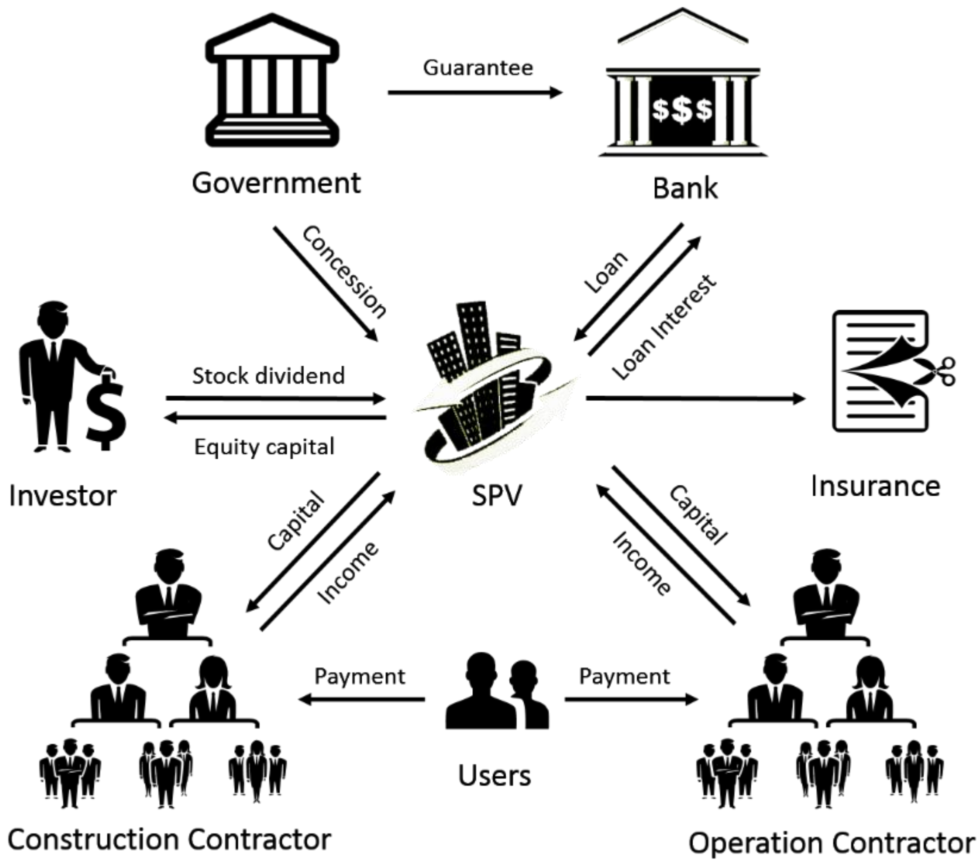


Figure 2 The party relations in PPP procurement

In general, PPP remains popular and continues to be implemented with plans for infrastructure projects stretching into the next few decades (Zhang *et al.*, 2016). Private Participation in Infrastructure (PPI) updates in 2015 showed that the total investment in PPP projects reached $111.6 billion. PPP is beginning to attain steady status in Brazil, China, and India. Projects in these historical construction heavyweights, which account for more than half of all total global deals using the current PPP model, reflect its use in thousands of construction projects (Chao and Kasper, 2015). Meanwhile, the UK Government is proposing a transition from PFI to PF2 as the new approach to PPP. PF2 having been established based on the satisfaction of major stakeholders with results of the PFI model regarding delivering long-term project information. The UK administration now seeks to address in detail problems relating to equity and debt finance, risk transfer and the efficiency of VfM procedures (HM Treasury, 2012). The data summary for the UK in 2015 shows 722 projects activated, of which 679 were operational. These represent the total capital of £57.7 billion, focusing mainly on health, national defense projects, transport, education and community development. Seven projects reached financial close in 2015, compared with nine in 2014 and 15 in 2013 (HM Treasury, 2015). In Canada, according to a report by the Canadian Council for Public-Private Partnerships, a comprehensive evaluation of PPP implementation indicates that the Canadian Government benefited from PPP to the value of $9.9 billion saved and that $7.5 billion tax revenue was generated in the last 10 years (InterVistas Consulting Inc, 2014).

Figure 3 shows the general PPP status in four countries based on the PFI data in 2017. In developing countries, as can be seen in China and India, unenforced projects account for a significant proportion of the entire PPP project release, in contrast to the developed nations such as the UK and Canada. As the ‘hot zone’ for PPP, China currently has around 13151 projects in PPP project storage which is a transparent, open PPP project database, of which 1093 are operated as national ‘demonstration projects’. The majority of PPP projects focus on transportation, municipal and social infrastructure, education, energy, water facilities and health sectors.

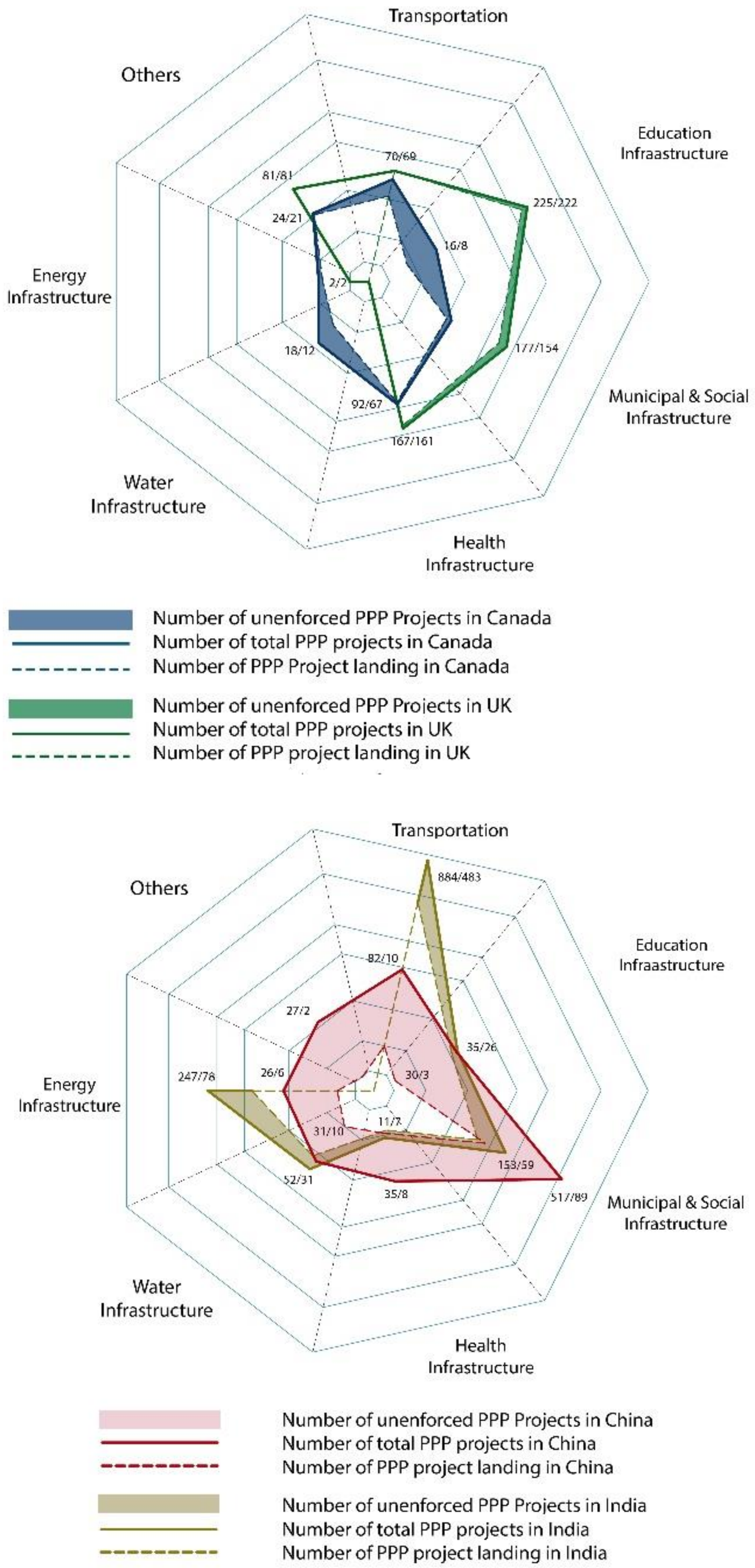


Figure 3 PPP project status in Canada, UK, China and India Source: PUBLIC-PRIVATE-PARTNERSHIP LEGAL RESOURCE CENTER

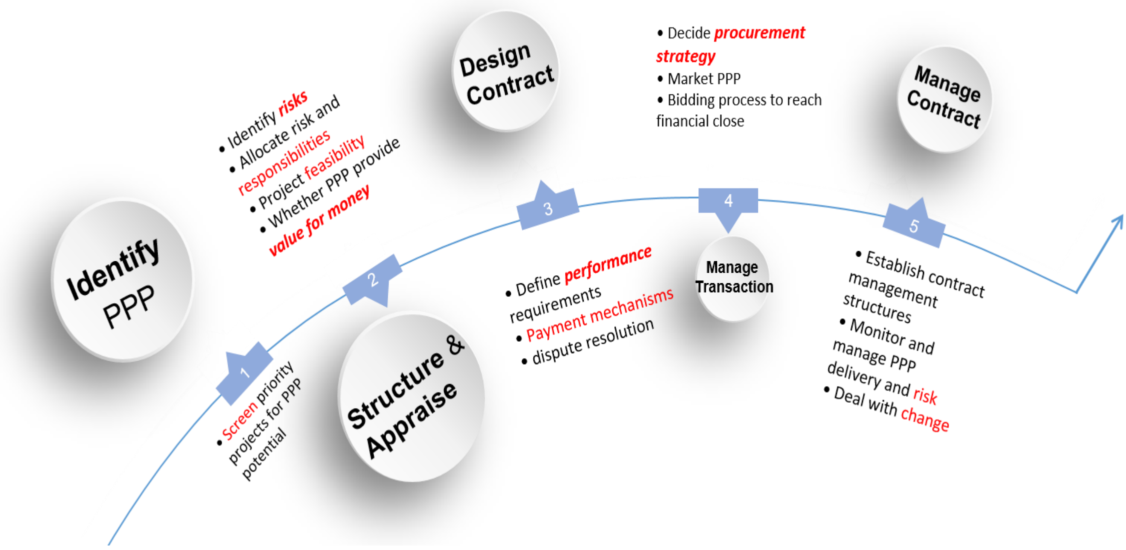


Figure 4 The typical PPP procurement process Source: World Back PPP guidance

Even though the focus is often on procurement, PPP offers a new way to manage the construction from the project's initial stages until the end of any public service it may provide. Sharing risk and responsibility provides not merely a solution to the funding problems that often face massive urbanization, but also potentially provides a new model of cooperation that facilitates highly efficient management of the financial profits in business sectors. The typical process of the PPP model is shown in Figure 4.

PPPs (Public-Private Partnerships) have been developed to offer public services designed to relieve the pressures of local debt. The aim of PPP management is to identify clear goals, shared by both the public and private sectors so that substantial capital gains can be achieved. However, despite the growing status of PPPs, there still exist a number of concerns with reference to infrastructure investment in developing regions regardless of financial uncertainties or poor quality performance (Zhang and Chen, 2013). It stresses the importance of VfM processes as VfM does not yet receive sufficient attention within project practice. Most of the financial assessments and decisions made by PPPs are formulated without considering the amount of time needed to implement the necessary engineering works (ACCA, 2012). This can result in gross inaccuracies in collaborative networks, with reference to the life cycle of the project, leading to financial crises.

2.1.2 Value for money assessment

2.1.2.1 Value for money

A PPP procurement strategy led by the public sector could stress fair cooperation with a private partner by setting up a Special Purpose Vehicle (SPV) for the targeted project. All the capital needs and financing appraisals are operated by both parties, stressing the effectiveness of financial control and lifecycle management. The definitions of VfM given by the UK Government and the World Bank Group describe the optimum combination of whole-of-life costs and quality (HM Treasury, 2006). The criteria specify that, among other factors, business incentives within the procurement process could be integrated into a performance benchmarking process, as an initial reference (Cowper and Samuels, 1997). The assessment includes both quantitative and qualitative assessments. It is regarded as an assessment process and can progress not only starting from the early stage of project demonstration but also update dynamically as the project progresses, through the bid or post-bid evaluation (Henjewele, Sun and Fewings, 2011).

Qualitative and quantitative assessments are applied during a typical workflow of the PPP process, as shown in Figure 5. During the project's decision-making phase, assessing VfM could simulate the competitiveness that can inform and prompt decision-making regarding traditional and social capital. The failure of such an assessment could lead to a change in procurement mode or cancellation. The UK Treasury's manual on assessing VfM indicates that assessment should be performed on the program, procurement, and project levels throughout the project lifecycle (World Bank, 2014). Thus, the VfM process becomes not only a decision-making tool but also a means by which project performance can be evaluated throughout its lifecycle.

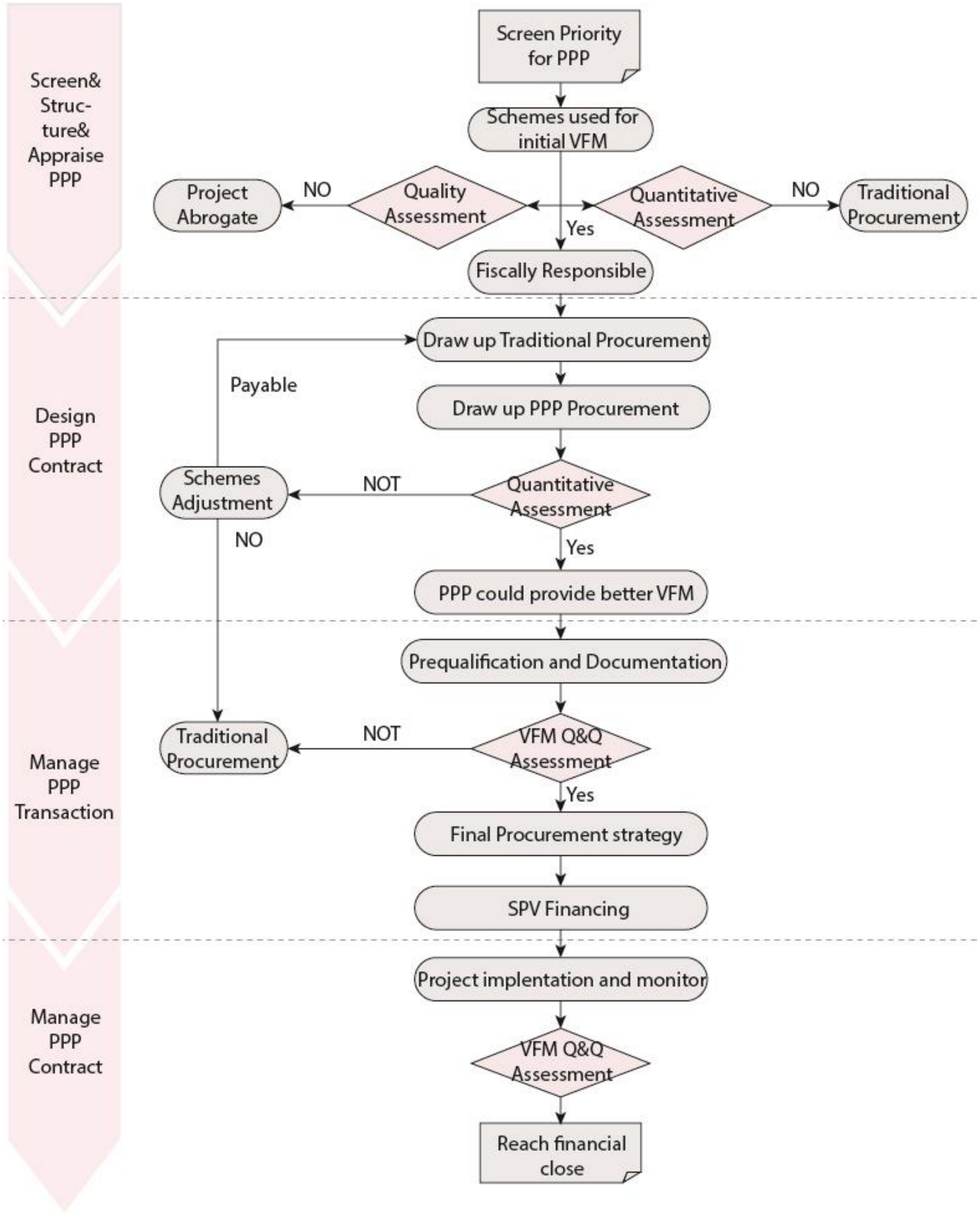


Figure 5 The VfM process through the project life-cycle (HM Treasury, 2006; US Department of Transportation, 2012)

There exist strong connections between VfM and performance measurement. The early-stage VfM stresses more on the financial aspects and the qualitative aspects in three-level: programme level, project level and procurement level. The measurement in VfM qualitative assessment is also similar to the approach used in the performance measurement. The ex-post measurement in most of the PPP cases references the initial performance requirement defined in the initial contracts and also needs to clearly specify the quality and quantity of the assets and services (World Bank, 2014). The performance measurement can be various to a great extent based on the types of build assets. Due to the fact that VfM has a more relatively clear assessment structure, this dissertation stresses the VfM and covers the aspects of its measurement requirement in technical development.

2.1.2.2 Value for money implementation status

A PPP contract usually runs 30 to 50 years or more, which is longer than traditional procurement arrangements and it can generate more project uncertainties within the lifecycle. VfM is used to determine whether a project is suitable for the PPP model, and in fact could be defined as an entire life cycle assessment (Office of Transportation Public-Private Partnerships, 2011). Using data from the World Bank Group and Public-Private Infrastructure Advisory Facility (PPIAF), Table A in the appendix shows the various VfM approaches commonly used in different regions. However, aspects of the practical operation were insufficiently considered (World Bank, 2017). Countries have begun to set up a specific methodology that concerns VfM, but they lack supporting information from engineering aspects concerning implementation(Love *et al.*, 2015).

To stress the application situation, this research also sourced the published VfM reports from the Ministry of Finance of China. The Chinese government has been embarking on an ambitious programme of investments on large urban municipal engineering projects. Until April 2018, the Ministry of Finance of China has already published four batches of demonstration projects, a total of 1093 individual projects in all.

Based on VfM performance in the engineering project domain (e.g., transportation, urban housing, education, culture, nursing, and municipal engineering) using the PPP project library of China Public-Private Partnerships Centre, the VfM reports of each project were collected and analyzed. As shown in Figure 6, a considerable number of projects did not provide an appropriate quantitative assessment. This indicates that the VfM, which is regarded as essential, still lacks completeness with respect to implementation. As for the project with the VfM report document, the author also investigated the report in detail and determined that the data processing was inaccurate. The presentation of the qualitative assessment, its content, and how managers scored related factors were also problematic in most PPP projects. More detailed explanation and measurement approaches are required to enhance the level of quantitative performance. The qualitative process was conducted in an excessively simple form, while the quantitative method was frequently abrogated or postponed, due to feasibility issues (Ministry of Finance of China, 2014).

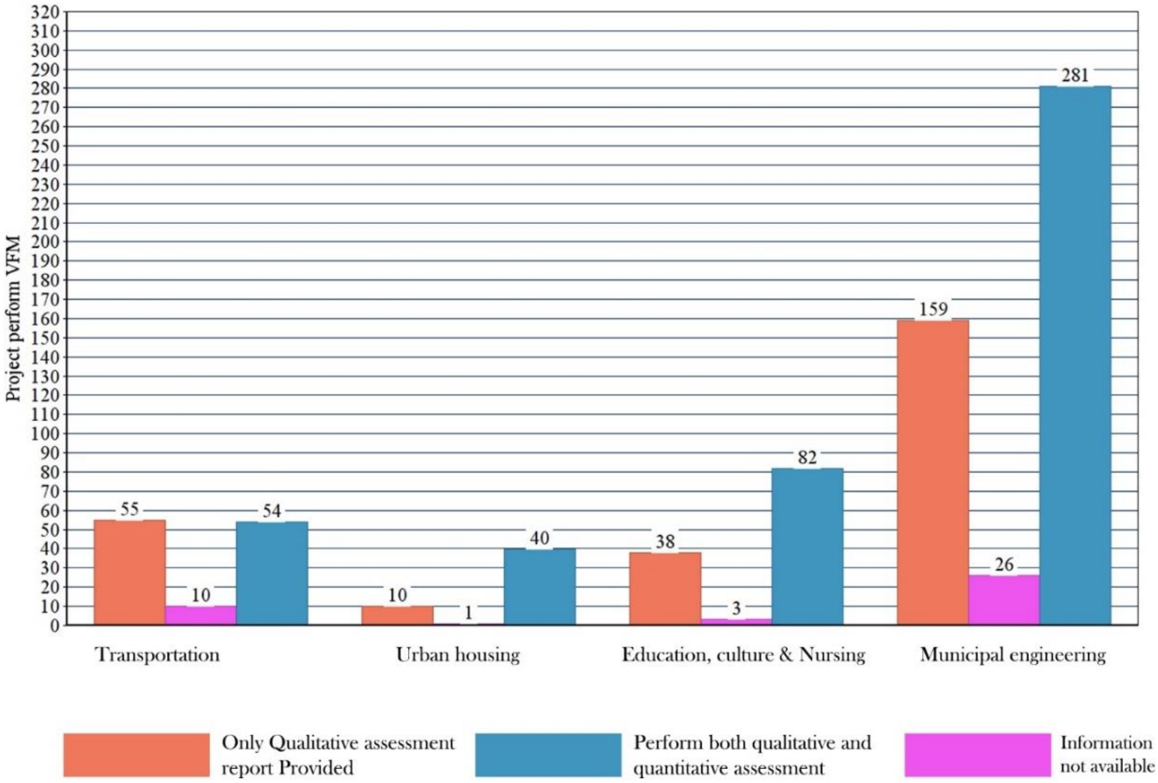


Figure 6 VfM implementation status in China. Source: Published PPP project documents from the Ministry of Finance of China.

To emphasize the content of the VfM, the following section contains both qualitative and quantitative features sourced mainly from VfM guidance in the UK, the USA, and China.

2.1.2.3 Value for money assessment contents break-down

As things currently stand, the VfM process is a subjective matter. There are now toolkits and measurement lists to provide guidance on PPP in comparing the actual outcomes of alternative procurement options. In the appraising and structuring stage of PPP, analysis of VfM is made under the evaluation directory, with project feasibility, commercial viability, and risk indication and allocation. Compared with other assessment processes in PPP, these drivers of VfM include most of the elements mentioned above, such as project feasibility and commercial viability. This makes the VfM process more comprehensive. VfM does not merely rely upon the whole life costs of the assets, which are regarded as an early stage quantitative assessment, but it is also viewed in terms of the project's ability to achieve a high level of performance. Thus, VfM is judged by assessing the success of every aspect and element of project quality (HM Treasury, 2006).

2.1.2.3.1 VfM qualitative assessment

The qualitative assessment seeks to establish whether the relative performance could optimise the non-financial benefits of a project, and enhance management efficiency. This contrasts with the early stage of traditional procurement processes (Morallos *et al.*, 2009). Examples of indicators used in VfM qualitative assessment toolkits published by financial institutions from both the UK and China are summarized in Table 1.

Table 1 VfM qualitative assessment indicators. Source: Value for money assessment guidance (HM Treasury, 2006; China, 2014).

Indicators	**Description**	**China**	**UK**	**Relevant Keywords**	**Function stage**
Whole project lifecycle integration	The extent of the contract that contains design-build, financing and operation demands	√		Contract acquisition; Demand;	Lifecycle
Performance outputs	Whether clear requirements and benchmarking are provided during the project monitor process	√	√	Contract acquisition; Demand;	Lifecycle
Soft Services	Facilities management related to the day-to-day supporting services required in the operation of assets.		√	Catering, Cleaning, Security	Lifecycle
Potential competition	The competitive strength between social capitals and whether to apply a proper measurement to promote.	√		Project recommend meeting; Social capitals	Project initial stage
The political and legal environment	Current policy & regulations that limit PPP application	√		Policy & Regulation	Project initial stage
Operational flexibility	Various dimensions including product flexibility, volume		√	Assets information;	Project operation stage

	flexibility, delayed differentiation				
Equity, efficiency, and accountability	The viability of Project finance equity, efficiency, and accountability		√	Accuracy; Costs accounting	Lifecycle
Risk management	The extent of Risk identification & allocation that progressed in the initial project stage	√	√	Risk identification & allocation	Project initial stage
Innovation	whether the project outputs provide social opportunities and benefits	√	√	Contract acquisition; Implementation	Project operation stage
Contract and assets Duration	The expected period of service that the assets could provide in the project lifecycle	√		Assets information;	Lifecycle
Asset classification	The amount of project asset class in PPP project	√		Assets information;	Lifecycle
Project scale	The amount of investment and asset value that fit in the PPP applications	√		Investment project; Stock project; Assets information	Project initial stage
Incentives and Monitoring	The process measures the service based on the agreed standard.		√	Contract acquirement; Output requirement;	Lifecycle
The whole Lifecycle costs	The strategy, accuracy, and requirements of integrated life-cycle cost	√	√	Accuracy; Costs accounting	Lifecycle
Market Interest	The sufficient market appetite for the projects; evidence that indicates market failure and abuse		√	Market demand;	Procurement stage
Finance feasibility	The expectation of project attraction towards credit and bond market.	√	√	Banking institution	Project initial stage
Efficient Procurement	Procurement process that sustains market interest		√	Implementation	Procurement stage
Authority Resources	The public ideology of PPP, and the evaluation based on authority abilities.	√	√	Risk management; Knowledge, Experience; Skill	Lifecycle

In the UK in 2006, the HM Treasury published a comprehensive guide to VfM assessment, written in light of substantial PFI experience. This put forward a VfM structure and related factors (HM Treasury, 2012). The UK qualitative assessment was to be applied as a continuous investigation enacted in three stages: 'program-level'. 'project level', and 'procurement level'. At each stage of the assessment, specific questions from stakeholders must be answered. The indicators thereby functioned at each project stage to maintain the accuracy of information. Relevant questioning ensured appropriate and updated information. The resulting 'viability', 'desirability', and 'achievability' were used to classify each of the indicators involved.

Notably, there is currently no well-accepted rating or weighting system applicable to all quality aspects, which leaves industry and project managers with a significant degree of freedom. The notice published by the Ministry of Finance of the People's Republic of China initially introduced general requirements of quality measurement targets in VfM processes. Expert groups working on behalf of the Ministry of Finance took responsibility for scoring assessments based on professional judgment (Figure 7). The VfM report template contained six primary evaluation indices, which accounted for 80% of the outcome. The remaining 20% involved at least six supplementary indices that covered significant elements beyond the basics (Ministry of Finance of China, 2014). As frequently seen in the literature, a five-point Likert scale method was used to identify the degree of performance of each index. The rating scale may contain various combinations of indices, according to individual project requirements.

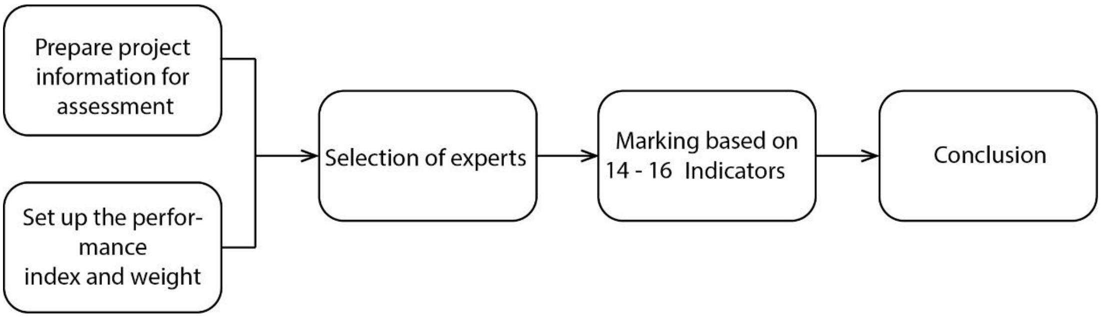


Figure 7 The qualitative assessment workflow in China. Source: Derived from Hongyue et al., (2017)

However, while the template used in qualitative assessments provided more detailed rating methods, it still lacked supporting data and any information query system that would enrich evaluations. The assessment could be supported by the project information, including historical documentation. Project management should pay serious attention to non-financial factors, such as the social and environmental impacts of the project (Mota and Moreira, 2015) or contract management (Parker and Hartley, 2003). This is now regarded as an experience-based approach to estimating the level of project competitiveness. The current index for making a qualitative assessment is broad and requires a detailed subdivision. In addition, the benchmark of qualitative evaluation has not yet been comprehensively defined. Generally, 'yes or no' scoring criteria are used in most cases, without reference to the multiple objectives related to project implementation. The detailed explanation of the assessment index indicates that the related content should be checked in different stages. For example, general information such as "incentives and monitoring" can be tracked in project briefing documentation. Although the documentation in large scale transportation projects uses typically a cloud-based platform, the position and digital label of the documentation are not connected to the assessment index. Documentation management is currently not using a standardised approach and is sperate from the physical engineering dataset.

2.1.2.3.2 VfM quantitative assessment

As the vital assessment used to reflect the economic benefits of a project, the quantitative measurement may be a central issue when processing VfM. Unlike qualitative appraisal, quantitative assessment in VfM requires the more direct computation of the PPP or PFI project's value against a public-sector comparator (PSC). The PSC is based on a fictional model or an existing reference project, created using traditional models of public sector procurement. PSC analysis is conducted from the programming level until the financial close (Grimsey and Lewis, 2005). The calculated cost value, if using PPP as the procurement model, must always be less than costs likely to be incurred in a traditional public procurement model (shown in Figure 8). This must be achieved to a specified degree so that the SPV can be assured of sufficient motivation to action the business outlined. In addition, the calculated value should be continually updated, as a clear picture of risks emerges over time (Akintoye *et al.*, 2003).

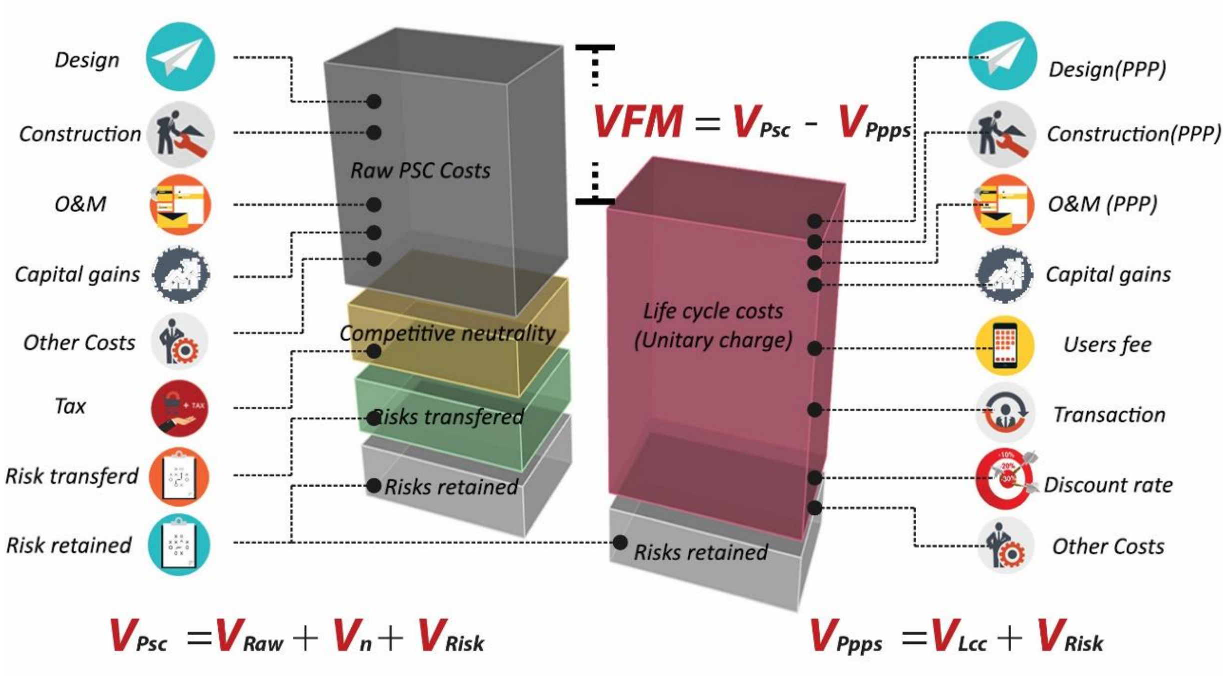


Figure 8 Structure for quantitative assessment in the VfM process (HM Treasury, 2006; US Department of Transportation, 2012; Federal Highway Administration, 2013; China, 2014).

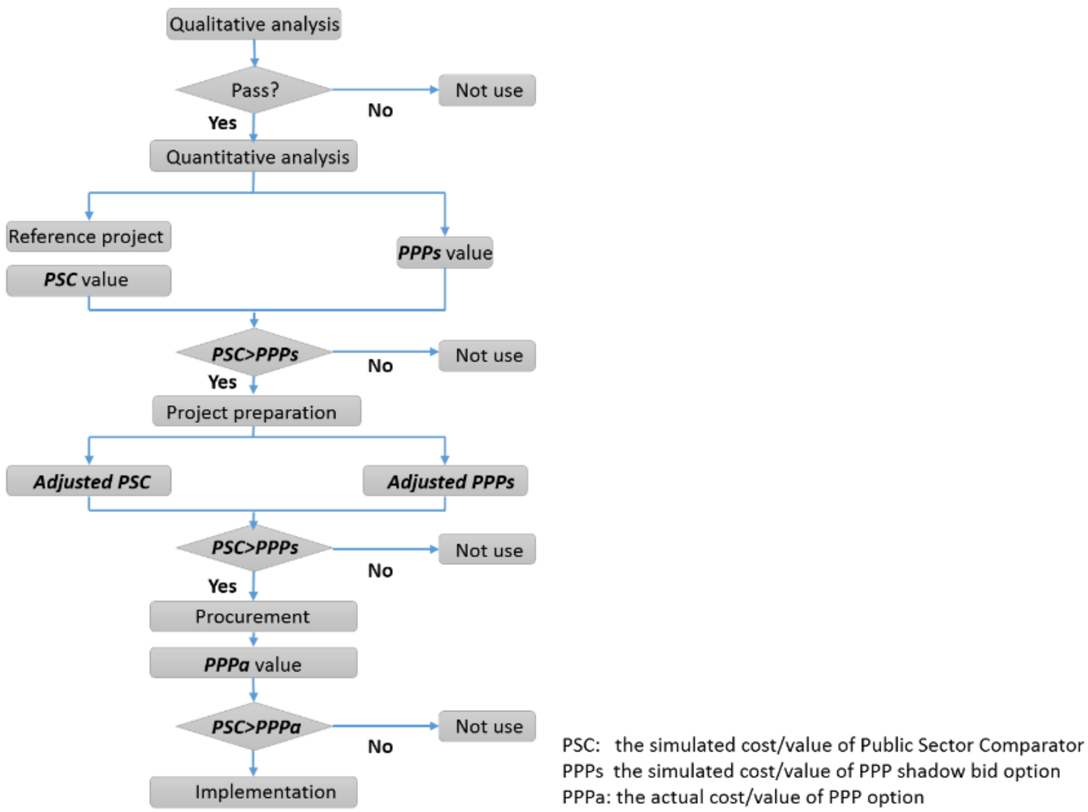


Figure 9 Typical PSC method used for quantitative assessment through the project life-cycle (HM Treasury, 2006; US Department of Transportation, 2012; Federal Highway Administration, 2013; China, 2014).

VfM assessment requires quantitative assessment in most cases. The PSC is proposed to be used for most of the VfM assessment to specify the quantitative elements. Such a strategy could be broken down effectively by using different knowledge domains from engineering finance schemes. Figure 9 indicates the workflow using the PSC method. The costs of PSC are calculated by establishing a fictional model using a traditional public procurement strategy. A reference project could be set up, which is conducted from the programming level to the financial close (Grimsey and Lewis, 2005). The calculated cost of using PPP as the procurement model should always be less than the value likely to be incurred if using a traditional public procurement model.

The calculations of VfM from the quantitative assessment were closely related to the net present value (NPV) of the entire project lifecycle. The current model in the UK used indicative present value for both PPP options and PSC value, with a traditional model providing public service assessments. Specifically, PSC represents comprehensive scenario-setting that should achieve a level sufficient to reflect the procurement strategy. It is well accepted by many countries. The UK government took the lead in standardizing PSC content as a decision process to define where, when, and how to use privately-financed infrastructure solutions (Bain, 2010). According to the UK National Audit Office, a method of computing both PSC and PPP is continually updated. The critical component of indicative present value in PSC focuses mainly on the cost of resources, transaction costs, and adjustment on tax and optimism bias. With the development of PSC accounting, the constitution of PSC now can be divided into four parts: the raw PSC value, the value of risk transfer, retention value, and competitive tax adjustment (National Audit Office, 2013).

The raw PSC value is related to resource-based costs. The cost of project design, construction, operating, and maintenance must be added to consulting service fees related to the project. The capital income as the property transfer fees or user fees should be deducted. To eliminate the advantages of public ownership, the value of competitive neutrality adjustment is used to modify the tax and responsibility cost to the public sector to achieve equality of competition (Cruz and Marques, 2013). It is worth mentioning that adaptive risk allocation and management indirectly affect the PSC value. The main advantage of the PPP/PFI model is that a considerable degree of risk may be transferred to the private sector. Therefore, the value of transferable risk is converted to a net present value using its occurrence probability, as showed in Table 2.

Table 2 Example of risk-related cost using the probabilistic method.

Risk Event	Risk Consequences	Risk Probability	Cost
Risk Event 1	Cost saving 5%	0.7	Cost overrun 5%
Risk Event 2	Cost overrun 5%	0.8	
Risk Event 3	Cost overrun 10%	0.3	
Risk Event 4	Cost overrun 15%	0.1	

The PSC-based appraisal procedure is now regarded as the most effective benchmark for measuring the quantitative aspects of VfM. However, its value has been disputed (Bidne *et al.*, 2012). The current calculation is not holistic, and the extent of its synchronization with the project lifecycle is still under development. There is no doubt that such a VfM quantitative assessment is supposed to remain its objective along the project lifecycle and has clear steps and procedures. It is anticipated that different computing methods are used at various project stages. When it comes to quantitative assessment, the process for sharing information about assets, the information required for PSC or PPP value should be attached to the VfM assessment.

2.1.2.4 Value for money assessment in the literature

There is a significant body of literature exploring the topic of PPP application. To get the important elements that can be measured to define the success of public procurement and explore the VfM related factors, the following search criterion was devised in both the Science Direct and Scopus search engines: (Public-private partnership OR PPP) AND (infrastructure OR Construction) AND (important factor OR Success factor) AND (Value for money assessment OR VfM) AND PUBYEAR AFT 2006 AND PUBYEAR BEF 2017 AND (LIMIT-TO (LANGUAGE, ‘English’)) AND (LIMIT TO (SRCTYPE, ‘j’) within (Title OR Keyword). Based on the criterion, Table 3 shows the removal of irrelevant literature types leaving only journal articles. Literature rated three to five were remained, resulting in a final literature volume of 187 papers that only concerned PPP infrastructure performance. A combined quantitative and qualitative analysis was performed to classify the literature further.

Table 3 Descriptions of rating criteria to remove irrelevant research articles.

Rating	Description of criterion to remove not related literature
5	Literature focus on the important factors in PPP infrastructure projects
4	Literature focus on investigating the PPP infrastructure status from procurement level
3	Generalized non-specific work on PPP infrastructure research
2	literature relates to public procurement on infrastructure but not specific relates to the PPP model

1	Irrelevant literature that does not concern the infrastructure type of work nor PPP procurement model

85 of selected research papers referred to multiple PPP infrastructure projects. The remaining articles were concerned with different construction types. As shown in Figure 10, over 23% of the road and tunnel work was conducted using a PPP procurement model, which was a relatively low proportion. With respect to research outcomes, literature that was focused on “investigation and analysis” produced a high volume of work; there were 72 different infrastructure subjects. There was also extensive work focusing on the most common research themes, which were project case studies, methodology development, framework, and review approach.

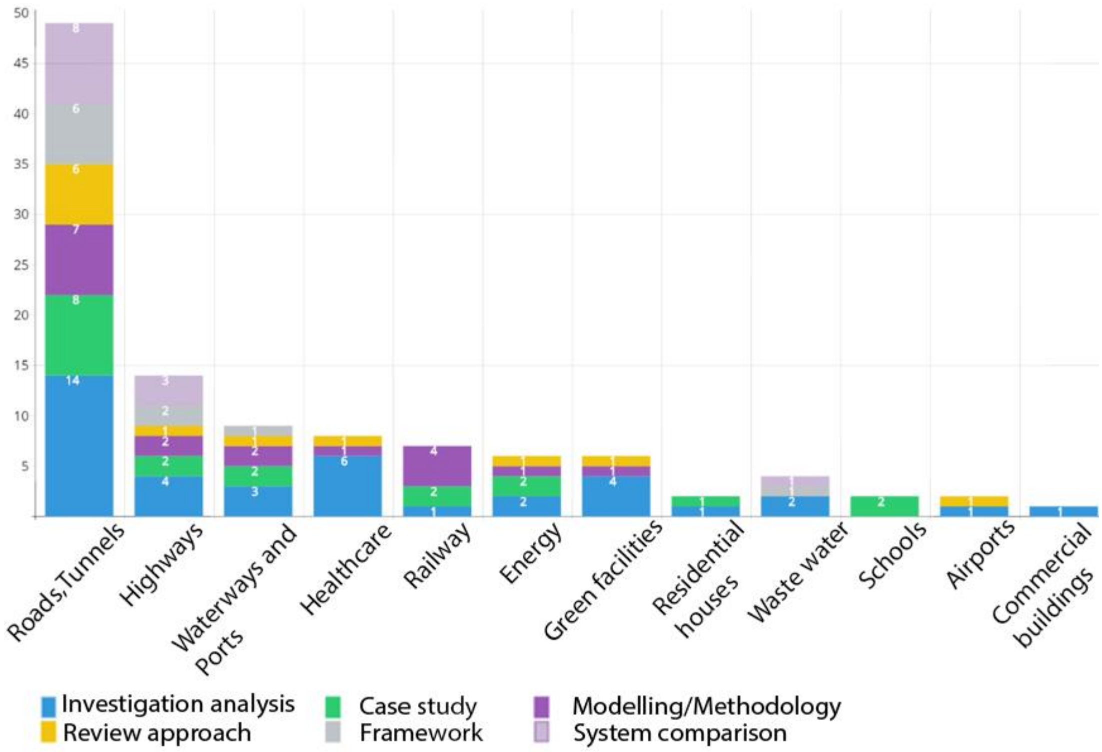


Figure 10 Distribution of PPP infrastructure publications by research outcomes & industry sector. Source: Selected literature

Figure 11 represents the distribution of the research articles that stressed different important factors or dimensions in PPP infrastructure. Literature concerning “risk factors” (35), which referred to risk indication and allocation schema, “performance factors” (32) related to project performance measurement, and “critical success factors” were found in high proportions. Other emerging areas included the leveraging of business models to stress the PPP implementation status (21) and relationship management (20). Specifically, with respect to finances, the underdevelopment of VfM assessment was indicated (4). This was due to most literature on financial management not involving the structure or official body defined in VfM nor any to links to measurement issues. The thesis refers to VfM assessment are mainly investigation

& analysis and literature review-based research. For example, Henjewele et al., (2011) proposed to use empirical studies to investigate the variations in PPP transport sectors that influence VfM assessment and find that the current assessment is often carried out with considerable uncertainty in costs estimates and requirements.

Since there were differences in the levels of detail given in the papers selected, there was some degree of overlap and ‘merging’ of indicators. There were articles in the selected papers used a five-point Likert rating scale to assess important factors from one to five. In this thesis, the papers that contained specific mean values of important factors are presented in Table 4. To classify indicators along with procurement stages, the table lists the subset of internal procurement indicators that refer to the World Bank’s typical PPP process, which goes through the contract ‘pipeline’ until final implementation (World Bank, 2014). The external indices were not included.

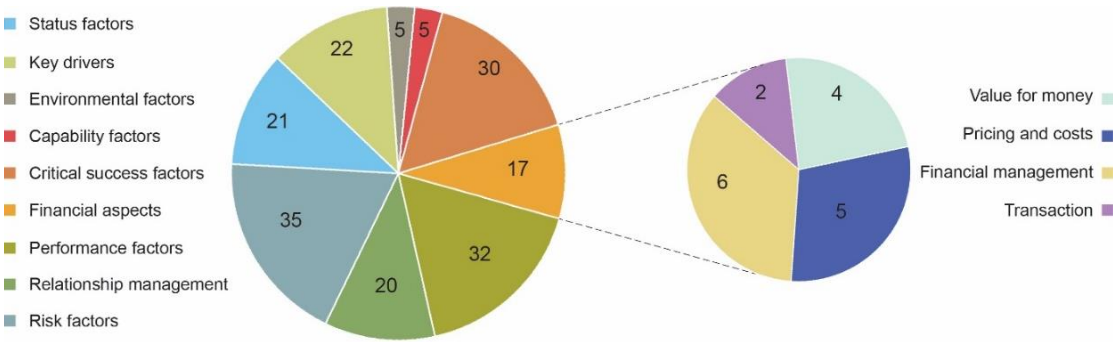


Figure 11 Distribution of important factors/dimensions addressed in PPP infrastructure publications. Source: Selected literature

Through the average of the mean values in procurement workflow, it can be seen that in PPP project stages, ‘risk and responsibility allocation’ and ‘procurement assessment of cost and benefits’ in the pre-construction phase are regarded as very important and are focused upon in the literature. These two aspects are vital constituents of the early stage VfM process which indicates that the VfM influences the success of a PPP project to a great extent (Sobhiyah, Bemanian and Kashtiban, 2009). The performance ‘technical innovation’, ‘brief and contract documents’ and ‘market interest’ are also overlapped with the performance indicators in VfM qualitative assessment. Moreover, in the project implementation phase, the literature reveals the crucial nature of construction management, especially ‘the management of material and available resources’ and of cost-related factors during the procurement phase. Based on the definition of quantitative assessment in different nations, these costs related aspects also can be regarded as the fundamental constitution of VfM; these contents are discussed in the following quantitative assessment section.

VfM is currently defined as a comprehensive assessment approach. Its performance contents usually overlap with other essential project factors. VfM is even used to justify the feasibility of using a PPP model. It is also a structural means to verify income based on project strategies. VfM should provide a hospitable environment within which to perform performance monitoring so that long-term targets can be achieved (Henjewele, Sun and Fewings, 2011). However, the current research articles that stress assessment lack further development. Very few pieces of literature consider the entire process when aiming to strengthen the assessment and develop the methodology to specify procedures.

Table 4 Overview of PPP project internal indicators in recent research articles with mean values of importance. Source: Selected literature. The classification catalogue is based on the World Bank Group PPP reports.

Internal Indicators	(Chou and Pramudawardhani, 2015)	(Chou and Pramudawardhani, 2015)	(Hwang, Zhao and Gay, 2013)	(Liu, Wang and Wilkinson, 2016)	(Thomas Ng, Tang and Palaneeswaran, 2009)	(Tang and Shen, 2013)	(Toor and Ogunlana, 2008)	(Wibowo and Mohamed, 2010)	(Wibowo and Mohamed, 2010)	(Xu *et al.*, 2010)	(Zhao, Hwang and Gao, 2016)	**Average Value**
Screen as PPP												
The methodology of project selection			3.40		3.10	4.06	4.33			3.69	3.97	3.76
Project plan/programming				3.16	4.24		4.42					3.94
Structure PPP												
Risk/Responsibility allocation	4.34	3.89	3.77			3.98	3.99					4.00
Appraise PPP												
Cost/benefits assessment	3.79	3.61		4.25	4.51		4.00			3.57	4.81	4.08
Finance/resources availability			4.25		2.90		4.37					3.84
Finance closure			3.02					3.69	4.00	3.74		3.61
Technical innovation	3.62	3.72			4.40		3.88	3.38	4.25		4.06	3.90
Delay in approval and payment			3.65		4.07					3.40	4.35	3.87
Design and Manage PPP												
Tender and competition	3.81	3.70		3.06				4.17	3.82	3.35		3.65
Requirements of stakeholders	4.04		3.33	3.66	2.92	3.70	4.33	3.15	4.00		4.55	3.74
Brief and contract documents		3.75		3.63		3.91	4.34			3.48	4.61	3.95
Transparent procurement process	4.00	3.98					4.00			3.69		3.92
Building a team/Competent team					3.07	4.06	4.30				4.35	3.95
Change in contract			3.38		3.06		4.24	3.54	4.13	3.40	4.29	3.72

Design & Construction & Completion												
Site construction safety			4.08		3.13						4.65	3.95
Site availability			2.50					3.92	4.00	3.43		3.46
Design deficiency/Buildability			3.17								4.74	3.96
Workmanship/Complexity			3.15				4.17					3.66
Completion/Time delay			4.21		4.57	3.04		3.54	4.44	3.49		3.88
Material/Labour/Equipment			3.28		4.36		3.64	4.23	4.47	3.41	4.74	4.02
Construction cost overrun			4.08					4.15	4.29		4.65	4.29
Operation and Market Risk												
Market interest	4.15	3.54	3.42	3.00	4.07					3.60		3.63
Operation cost			3.29		4.43			4.15	3.94	3.54		3.87
Operation performance			3.23					3.73	4.27			3.74
Residual assets			2.48							2.70		2.59
Operation strategy change			2.40		4.22			3.38	3.76	3.49		3.45

2.2 The review of BIM and related Ontology Modelling Technologies

2.2.1 Building information management

According to Eastman (2011), the benefits of BIM should influence a project's pre-construction phase, driven by the owner. The phases of design, construction, and fabrication which are primarily driven by contractors, as well as the post-construction period, driven by operators will also be affected (Eastman *et al.*, 2011). The use of BIM as the foundation for building engineering projects dates back to the early 1990s (van Nederveen and Tolman, 1992). The term 'building information management,' is now used to describe a process whereby the digital approach guides project construction and operation. This approach, and more precisely the enhanced information-sharing properties within it, could be beneficial to the public sector and political behavior. BIM technologies serve to build a low-cost integrated working system into infrastructure projects (Bradley *et al.*, 2016). The finalized digital model has tremendous potential, not only to help contractors for inspection purposes but also to aid in intelligent management at a municipal level (Hartmann *et al.*, 2012).

BIM-related research has gradually covered both quantitative and qualitative aspects of projects. To stress this possibility, a BIM-based literature review is presented in this section. 97 research articles related to BIM cost functions and 118 research articles related to project quality management over the last ten years were collected and analyzed. A set of keywords was identified for classification using Science Direct and Scopus. The main keywords were "BIM", "building information management", "cost", "procurement", "documentation", "contract", "risk", and "quality.".

As shown in Table 5, for the qualitative aspect, many research papers are presenting how BIM helps to improve project quality or building performance. The literature volume also consisted of papers that concern about the BIM functions on project internal quality control. The result also reveals that the prevailing of BIM in construction is spreading out to the procurement level. Based on this, there is research comes down to documentation and contract management. Abdirad (2015) stated that BIM contracting provision could be stressed in the future to add more industry requirements to the existing contracts. However, there are few numbers of research that focus on quality information management on the procurement level. Ramanayaka and Venkatachalam (2015) pointed out in the research that the BIM stimuli set by developers do not have close attention towards integrating qualitative features and project externalities. This is likely due to the information used in BIM mainly focus on object level and the data standard is not ready to cover the project management field.

Table 5 The distribution of BIM research articles on both qualitative and quantitative aspects.

BIM-related research article on the qualitative aspects	Number
Documentation management	4
Quality control in facility management	13
Quality performance improvement	35
Contract and process management	5
Quality control in construction	24
Quality control in procurement strategy	7
Risk management	30
BIM-related research article on the cost-based quantitative aspects	
Data analysis for cost estimation	11
Integration with the design stage for cost efficiency	14
The relation between cost and other performance	16
The 5d cost management scheme	17
Cost for lifecycle assessment	15
Construction cost estimation	24

In the field of cost management, except the cost estimation and 3D technology, some papers focus on cost estimation. This thesis including applying BIM for construction cost estimating (Ma, Wei and Zhang, 2013; Niknam and Karshenas, 2014; Abanda, Kamsu-Foguem and Tah, 2017), construction quantity take-off scheme (Shen and Issa, 2010; Choi, Kim and Kim, 2015; Olsen and Taylor, 2017) , and project scheduling (Liu, Al-Hussein and Lu, 2015; Wang *et al.*, 2016; Sigalov and König, 2017). A few research stresses the integration using BIM to facilitate the cost-based construction management and life cycle assessment. There also exist several studies that propose to combine BIM-based cost function and other domain knowledge for the improvement of project management efficiency. As for the deliverable data level, Ma (2011) suggested to use industry foundation class standard and establish the IFC-based information model for project tendering in China while Kehily (2013) use BIM that incorporated with Whole Life Cycle Costs (WLCC) data to progress calculations.

2.2.2 BIM and PPP performance

Information management using BIM can connect quantitative and qualitative fields within VfM assessment, but lacks a specific scheme to influence PPP project justification.

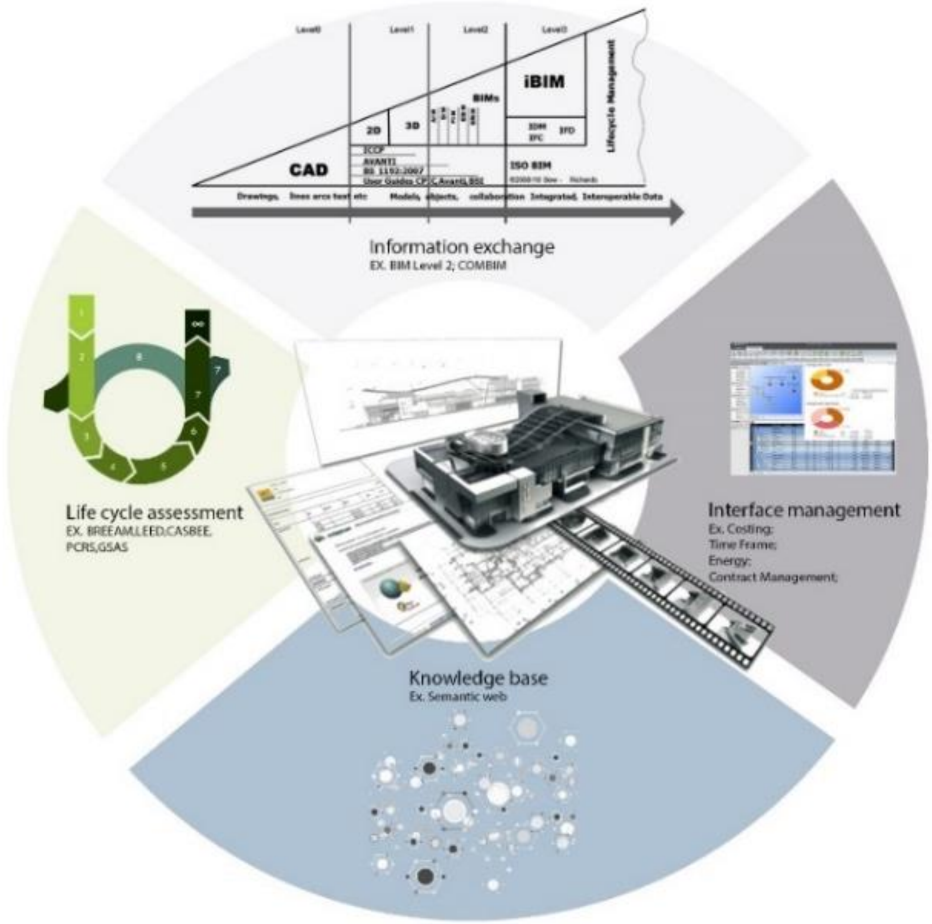


Figure 12 The Concept of building information management (BIM).

From an engineering performance perspective, the benefits of BIM are the provision of an environment which refers to management framework, tools, standards, and assessment methods through the whole project lifecycle (as shown in Figure 12). PPP, however, is extensively concerned with more holistic and sustainable business targets. This thesis suggests that PPP could be an ideal platform for BIM, as it facilitates whole lifecycle measurement and information editing and sharing with digital plans. The lack of supporting data and unstable framework in current VfM processes demand a holistic information system that contains lifecycle functionalities that can respond to change.

The important indicators that align with the contract agreement in the PPP process are frequently subject to regulations and requirements to periodically monitor project performance. In most PPPs, the key project targets are written into the contract for performance measurement, while some of the indicators may be taken into consideration for lifecycle evaluation. The actions and outcomes of public service functions in major infrastructure projects should be strictly supervised by the government, which assesses the project operation status, including its adaptability and impact in social and environmental terms (Guo *et al.*, 2014). The important indicators in PPP procurement vary at different stages according to the project's flow and available data. Currently, information management often ignores those dynamic evaluations (Love *et al.*, 2015). Table D in the appendix provides all related lifecycle indicators with the corresponding available BIM functions and associated tools and carriers. This article has referenced the PPP process based on the World Bank's recommendations, and the construction project flow is according to the Royal Institute of British Architects (RIBA) Information Exchanges. The index follows the common project flow and stresses the role of VfM. The use of BIM within its supported resources could potentially maximize benefits along the entire project lifecycle.

The initial stage of a PPP project is screening, which commonly involves investment planning and should be formally approved. Unsolicited proposals and initial outputs of the project in this phase could benefit from a digital plan of work (dPOW) that uses simple, plain-language questions (PLQs) to capture clients' initial needs and generate initial information exchange requirements (BSI, 2014). In this phase, information is transmitted to an initial asset management inquiry that covers clients' needs. SPV or a related client-based organization could take on updating further asset and employee information, which is used in project monitoring and assessment. Other factors related to project planning are the physical scale of the project and the constraints of probable sites. Space and site analysis capabilities within BIM software can be advantageous here, in providing visualization for use in early decision-making. Furthermore, VfM assessment has the potential to construct a library of supporting information for reference in the PSC project. Although currently the information available in the earlier stage of a project is not productive enough to generate a convincing VfM output, with BIM support for integration it would be possible to create favorable premises for further information delivery.

The structuring and appraisal phases of PPP involve, to a greater extent, the core information that determines the substance of the project, including risk identification and allocation, project feasibility, and viability, which could be added to the project execution plan (PEP). Risk management is directly connected with the VfM assessment and could be represented explicitly by using domain-related indicators to define project risk. A semantic approach is proposed for use at this stage. The interaction of ontological structure and IFC data in the risk management field provides a list used by this model specifically for risk events in PPP. Information could be gathered into a semantic environment of ‘knowledge blocks’ and displayed through domain-based taxonomy. Since this stage occurs close to the final procurement, rich data should provide the required scope to commence VfM. The information exchange generated in the BIM environment could help parties to extract relevant data for the employers’ information requirement (EIR) and initial design or existing models for NPV measurement. A 5D representation, which may include a digital design, should have sufficiently detailed asset information. The current cost-related tools align with BIM and, thus, could provide favorable measurements to make it possible to structure value more holistically. At this point, the quantitative assessment will not depend on non-transparent historical data, because the information contained in the BIM has real-time properties (Love *et al.*, 2015).

The ‘manage PPP’ designation refers to the final procurement strategy and business agreement. The results of VfM, especially the quantitative output, should be expressed through the final contract award. The EIR will address contractors and handover to different sectors. The distinctive project goals and asset information could be delivered using the construction operations building information exchange (COBie). The COBie-UK-2012 is a useful application for non-graphical information exchange, as it initializes the critical project information in a manner that strictly follows the standard. Such information delivery and sharing have crucial roles in a common data environment (CDE), which is defined as a single source of information and frequently as the extranet source of information used to import, manage, and disseminate data connected with all potential requirements (Royal Institute of British Architects, 2015). Thus, applications, such as BIM 360TM and Viewpoint, with cloud-based capacity could conveniently deliver actual, real-time information to stakeholders.

The PPP project implementation stage is likely to be the point at which the benefits of BIM functions become fully evident. The costs of construction currently account for a significant proportion of the NPV of quantitative results in VfM. Theoretically, the cost results should meet the previous value in quantitative assessment, while BIM now has the potential to address change in real-time. There are plenty of resources amenable to BIM application in project design and construction. In most cases, contractors should take responsibility for integrating processes ‘‘as-built’’, while BIM maximizes profits. An application in the earlier design stage could be 3D parametric design, which differs from traditional design approaches. It offers software tools allowing the design team to visualize the architecture, structure, mechanical electrical and plumbing, and support facilities plan. Similarly, 4D and 5D BIM used at the pre-construction stage could eventually output a federated model for construction specifications. Any insufficiency occurring at earlier design stages could be visualized within the bounds of known parameters, using software to minimize any need for later rework. The quantitative value of VfM could also be generated by using the federated model and continually applying it to project implementation. The scheduling and costing in the BIM model not only support construction on site but also directly connect to the expenses incurred in real-time. Asset management is a vital element of the PPP operation stage. Regarding BIM application in facility management, radio frequency identification (RFID) and quick response (QR) codes on devices or structural components could be used to track the information needed by operators and could be connected to the asset information model (AIM), which is the output of the project information model. The AIM is managed in CDE and provides graphical and non-graphical data related to multiple assets. More detailed information could be provided on operation attributes. The tracking system in a BIM environment adds convenience to the 'future-proofing' of VfM by enhancing the efficiency of asset maintenance.

The following is a summary of BIM functionality for PPP construction and operation:

- Model Checking: Automatic checking has two scopes: object-oriented and rules-based regulation checking. Software functions, such as clash detection, could help a project team to resolve conflicts before construction starts. The traditional 2D and 3D approaches were poor at minimizing design faults, and this has been a particular challenge in large-scale projects and complex structures. Performance monitoring during the construction stage must satisfy the industry standard(s) or a sustainability benchmark system. In an ideal situation, automated checking should progress before the federated model. As for information extraction, IFC data could be used according to authoritative standards, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), and a rules engine could be attached to a digital model. The analysis of results will establish if part of the digital model meets the requirements in LEED or BREEAM.

- Model Analysis: The availability and diversity of automatic analysis in BIM are becoming more adaptable and practical. Current data are oriented mainly to focus on cost and workload. The cost of construction is a vital part of the WLCC, as there are often multiple changes and cost directly influences asset operation. Real-time data imported into the analysis system are used to receive valuable outputs in project CDE.

The cost of construction is a large proportion of the NPV of quantitative results in VfM. Theoretically, the cost results should meet the previous value in actual PPP (PPPa), while the CDE addresses change.

- Model Comparison: While the construction-based use of point cloud 3D scanning technologies are still limited, intricate issues such as the structural renovation of existing infrastructures (which are regarded as ‘stock assets’ in PPP projects) could be rendered more efficiently by using the same. The process of generating a model from point clouds to mesh geometries is present in a BIM environment. Thus, the 3D scan has access to BIM-based data for further asset management (Bosché *et al.*, 2015).

2.3 The Semantic Web and Linked Data in related works

This review chapter discussed BIM-related research and indicated the possibility that the information and process in a BIM system could be applied to the PPP knowledge domain. The IFC-based data structures and related information exchange standards have the potential to provide support to both qualitative and quantitative aspects of VfM. However, there is a need for knowledge development of VfM in PPP projects, which requires a method of sharing, exchanging, and reusing domain knowledge. This thesis discusses how a semantic BIM could facilitate the integration of information in PPP, due to its focus on the project scale, type, and domain-related knowledge. In addition, it would help to manage risk using clear taxonomy and could eventually provide better deliverables for VfM purposes.

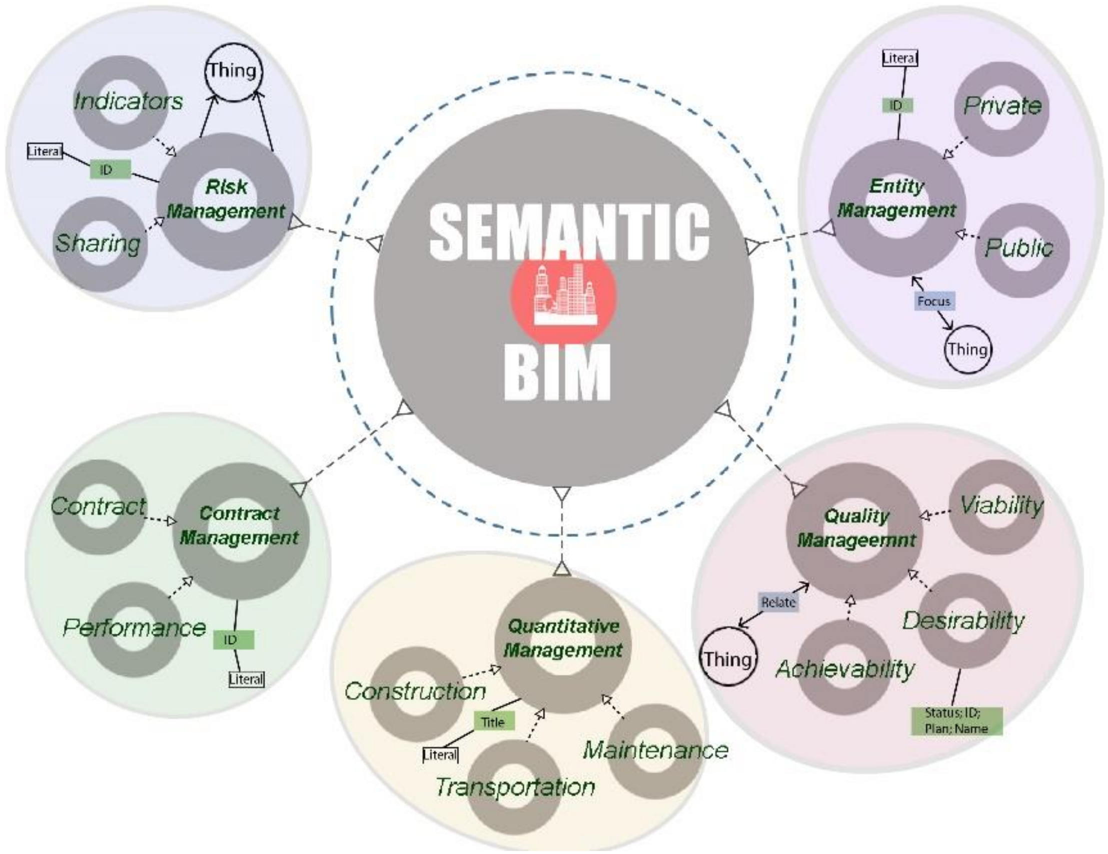


Figure 13 BIM aligns with semantic function.

The SW represents explicit domain knowledge that could be related to the built environment. That information is initialised by human knowledge-oriented language and linked to multiple domain knowledge bases (Abanda, Tah and Keivani, 2013). As an integral component of the SW, ontology plays a significant role, since it structures the implementation framework that could be made readable by computer language applications. Ontology web language (OWL), the language of expression, has been given rules-based functions to query information from a different knowledge base, and then provide the path for data management (Golbreich, 2004). An ontological representation allows sophisticated knowledge to be incorporated into a project system that is implemented logically (Hitzler, Krotzsch and Rudolph, 2009). Unlike general object-oriented programming models in software development that enable the model's transformation into software artifacts, a model in an ontological environment contains semantic relationships, domain knowledge annotation, and rich rules for information management (Karan and Irizarry, 2015).

The semantic approach or as called ontology, interacting with BIM technology, has in recent years led to a significant shift in research and development in the AEC (Figure

13). SW technologies added value to BIM by permitting data integration and complex search queries across several data sources (Pauwels, Zhang and Lee, 2015). Concerned with domain use, recent outlook and review articles have considered the latest semantic methods. Research by Mignard and Nicolle (2014) proposes the ontologies' application by merging BIM and geographic information system (GIS) data for urban scale facility management. Wetzel and Thabet (2015) proposed a BIM-based ontology framework to support safe maintenance and repair practices for the construction facility management phase. Hou (2015) created OntoSCS, an ontology for sustainable concrete structures using semantic web rule language (SWRL) to optimize structural design solutions. Zhang et al. (2015) developed an ontology-based job hazard analysis for construction safety management, while Tomašević et al. (2015) applied facility ontology to energy management. In the field of cost-related ontology, Cheung et al. (2012) proposed schematic BIM models using a low impact design explorer, which was a knowledge-based tool to define and estimate the early stage costs. Lee et al. (2014) proposed an ontological inference process for building costs; this translated IFC XML, extracted from BIM to a resource description framework (RDF) format that contained the information required for semantic reasoning. The process takes into consideration working conditions and work items to help estimators decide on an efficiently automated method. Abanda (2017) developed new rules of measurement ontology for cost estimation during the tendering stage. In the field of construction risk management, Tserng et al. (2009) developed an ontology-based framework of risk management that addressed risk identification and analysis concerning the project flow of design and construction. Ding et al. (2016) constructed a comprehensive ontological prototype to manage construction risk. The data drawn from the BIM could be extracted or mapped to a risk knowledge base–a semantic environment providing reasoning and retrieval to corresponding objects. These studies were all performed within a single field; however, all failed to contribute to a structural procurement and had limited potential for use in a PPP model.

2.4 The review findings

To summarise, VfM assessment issues include:

• Qualitative assessment lacks an information query system, i.e., one able to support information queries and position.

• The project data currently used for quantitative financial accounting are historical and may generate unreliable results. The information that could be acquired from multiple sources and resources is neither sourced nor represented, which brings about issues with the information exchange necessary for calculating present values.

Parties to PPP projects face multiple barriers because the provision of accurate VfM assessment cannot be guaranteed. A substantial proportion of VfM indicators are challenging to measure using standard means, yet this situation could be improved through technological innovation. The technology applied in a PPP project should be appraised on its ability to enhance performance. The prevalence of PPPs in infrastructure projects also creates significant issues at various stages. From a project management point of view, well-organized data management at the initial stage is required. The following section suggests that the application of BIM could more effectively and fully express VfM. In addition, the semantic structure that aligns with BIM could also help PPP parties to achieve better knowledge in order to support both qualitative and quantitative assessment.

The assessment of VfM is a long-term process, seeking to guarantee profits throughout the program, project, and procurement levels. This thesis presents a comprehensive review of the method used in the VfM contents and related information support. The fundamentals of VfM are still under development, and a more holistic workflow is required to optimise both qualitative and quantitative assessment processes. The literature related to PPP infrastructure was insufficient in terms of the structure of VfM. The procedures applied in VfM toolkits still use traditional measures, which are limited regarding both automation and accuracy of decision-making. Thus, it is necessary to build a VfM strategy that can provide more valuable deliverables.

Currently, the application of BIM techniques to PPP projects is still limited and has had minimal impact on lifecycle information management. BIM technology is expanding into different types of infrastructure engineering projects. However, the current practice only stresses functionality on the project level and rarely addresses the programme and procurement level. The BIM run by construction industries, design institutions, consulting firms, and research institutions can implement BIM in a certain perspective. However, these implementations fail to stress the lifecycle aspects, especially from the initial appraisal stage. By matching the BIM function to the essential element of VfM, as well as the review of knowledge-oriented BIM approaches, the VfM assurance process could be supported by both qualitative and quantitative assessment. The application of elements of BIM to VfM processes could also be used to identify and organise the relationships between and attributes of risk factors and events, thereby producing more holistic VfM results.

Through a review concerning VfM, BIM and SW technology. this thesis has identified the scope for a partnership between these two concepts. As a lifecycle project management strategy, PPP focuses mainly on procurement benefits; but to achieve these, the PPP approach requires a lifecycle information exchange and management platform, where BIM can play a significant role. The VfM process could, throughout the entire PPP workflow, determine whether the provided value is sufficient. The data would be attained as a result of using the PPP procurement model, rather than a traditional approach. The current BIM approach implemented within the engineering project area of measurement and evaluation has not yet been able to connect to the VfM. To explore whether the BIM has the comprehensive ability to facilitate VfM assessment, this thesis addressed these gaps presented in current knowledge. A BIM-based decision-making roadmap in the VfM was proposed. Future work should cover the comprehensive semantic development of this knowledge base, along with an automatic information exchange scheme.

From the identified gaps, it can be seen that:

1) Information exchange scheme development for VfM which is missing at this stage.
2) The current VfM assessment lacks knowledge base support to cover comprehensive concepts defined in different engineering procurement domains
3) There is no reliable database that includes project externalities to support VfM and financial assessment.

Chapter 3. Research methodology

Based on the previous review findings, this chapter will firstly introduce the general methodology through which this research was carried out. It helps clarify the principles, approaches used in this design-based research. Following this, a more detailed approach for each research question will be provided including the specific research strategies based on the chosen methodology framework.

3.1 Research philosophies

For illustrating the related methodology applied in this research, the epistemology is the core research philosophy theory of knowledge in this study. The ‘Research Onion’ model of research methodology is presented in the following Figure 14. Following the research logic and way of thinking, the research methodology is explained from the outer layers to the inner layers.

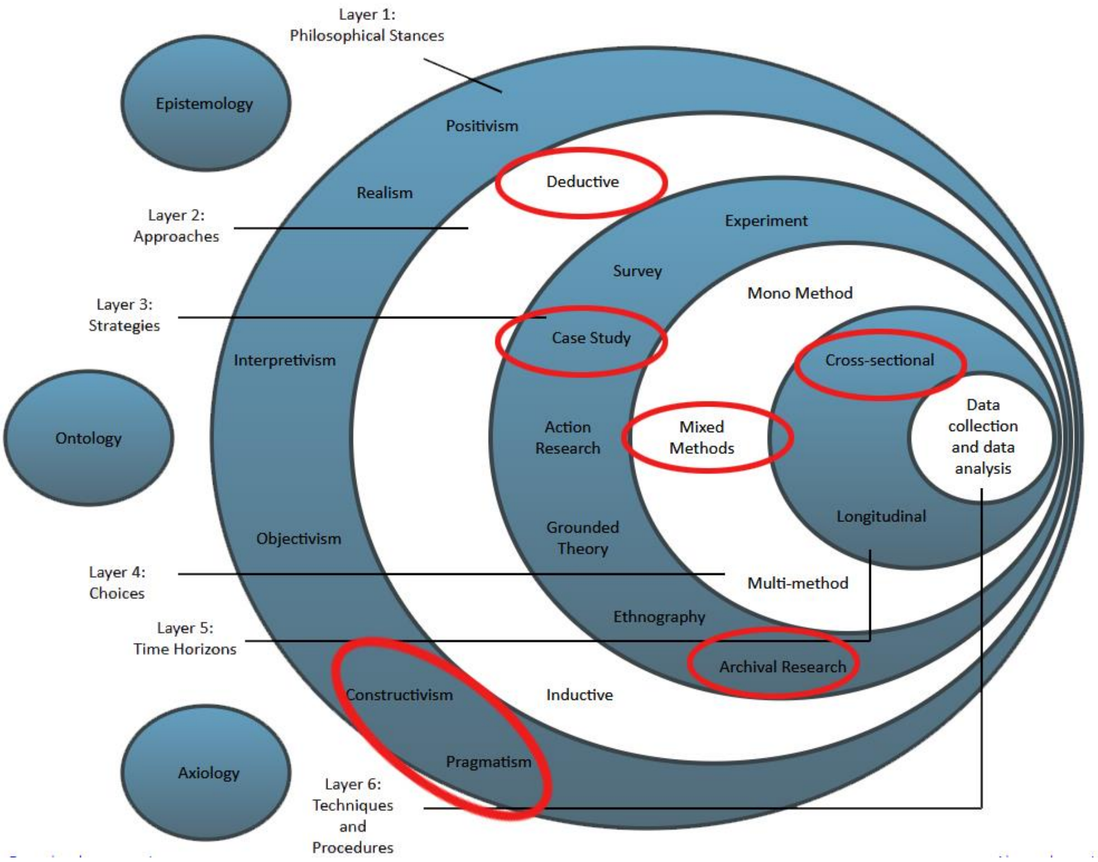


Figure 14 The research onion(Catterall, 2000).

There exist a few philosophical stances. Positivism refers to the hypotheses that can provide an explanation based on common understanding knowledge. It includes clear research questions that can be tested and validated through quantifiable and credible data. Based on certain natural phenomena and relations, it aims to observe and summarize the acquired knowledge (Craib, 1997). Similar to the positivism process and belief, realism stress that social reality and Research are independent of each other. However, it did not recognize the scientific approach as the total perfect solution and it believes the created theory can be revised base on the variation of reality. All the believes and independence in human value will be respected in realism to a great extent. In contrast to both positivism and realism, the interpretative approach emphasizes the meaningful nature of human participation in social science. It plays an important role in the information systems research domain(Walsham, 1995). The next pragmatism rejects the previous philosophical thoughts that the function of thought is to describe and represent reality(James, 1909). It argues that a researcher would not use a single methodology to conclude the actual reality. It pointed out that mixed research should be combined to achieve the predicted phenomena, as opposed to how accurately it describes objective reality. The constructivism and objectivism are the ideal ways to conduct the research based on the views of pragmatism. The objectivism helps research to learn different meanings which social phenomena may have on the social actors while constructivism stands in the opposite position which believes social phenomena are constructed by social actors. Constructivism-founded research nowadays brings together the paradigmatic perspectives such as constructivist epistemologies (Avenier, 2010). It is a standpoint that proposes social phenomena are constructed by social actors. From this perspective, every new product or solution be done by certain parties and they also needs to be managed and maintained by the same parties as well.

Whilst the research carried out in this dissertation contains certain elements of both positivism and interpretivism, through the testing of different research questions, the pragmatist research philosophy has aligned with the research project throughout its lifecycle. More specifically, taking more specific methods enables the entire workflow to be flexibly represented. Followed the deductive approaches, the case study and grounded theory Methodological strategies are deployed in this research.

3.2 Research approach

The deductive approach and inductive approaches are the two different types of research approaches. In the deduction, it seeks the answers to the question from the very beginning. In this process, researchers can gather data or knowledge to answer by statements or informed speculations about the research topic (Bryman, 2015).

Induction refers to the theory development from the collected data. Base on the observations, the created theories will be tested an retested using the research hypothesis (Bernard, 2013).

In this Research, the deductive approach is associated with the contents in the review chapters to provide the fundamentals for VfM assessment knowledge built up as well as to fulfill the Research objectives.

3.3 Research design

Due to the fact this research is implemented in the information technology research domain while design science Research methodology (DSR) offers the specific guidelines on the development and performance artifacts. In opposition to explanatory science research, DSR respects more on the pragmatic nature and is typically applied to categories of artifacts referring to engineering and computer science disciplines and aims to solve a generic problem experienced in practice (Kuechler, Petter, and Esearch, 2012). As shown in the following Figure 15 which indicates the nominal process of DSR. There are several procedures which are: i) identify the problem & motivation; ii) define the objective the requirement for solutions; iii) design & development artefacts; iv) demonstration; v) evaluation; vi) communication. To achieve the comprehensive VfM assessment, this study follows the principles of the design science research (DSR) to build up the research framework.

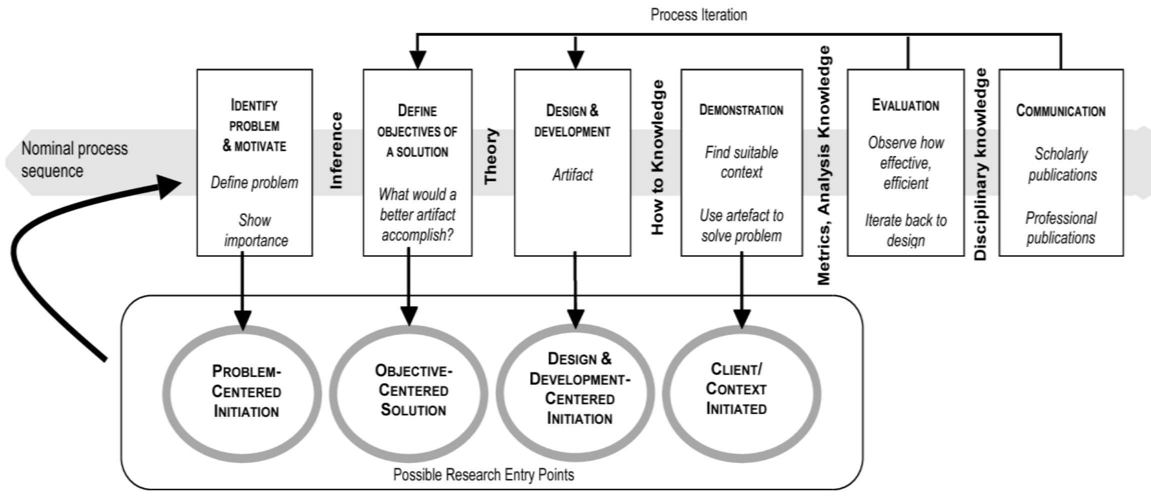


Figure 15 Design Science Research Methodology (DSRM) Process Model (Peffers *et al.*, 2007)

In this thesis, the artifact relates to the VfM and other project performance knowledge bases, addressing the need to have an automated assessment method. Figure 16 indicates the research framework.

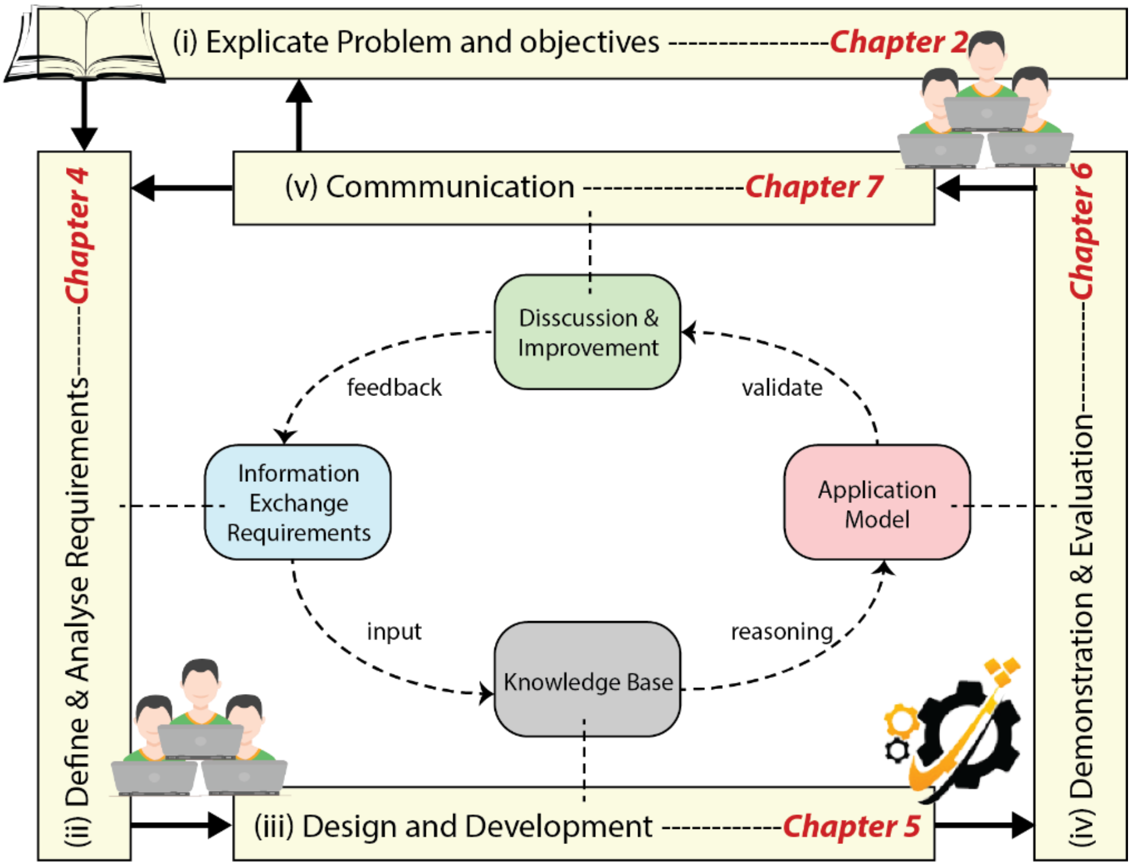


Figure 16 The research framework based on DSR.

The goal of the proposed methodology is to evaluate and automate VfM processes. It suggests a series approach to create the following information exchange requirements that function on assessment (Peffers *et al.*, 2007):

(i) Problem explication: The related problem has been stressed in the introduction and literature review section, demonstrating that PPP engineering projects, as a complex procurement model, require the presence of real-time information exchange from different parties to progress the early-stage assessment. The index in VfM assessment can be connected with existing published knowledge. The contents of Chapter 2 responded to Q1 and Q2, which are as follows:

Q1: *What are the contents defined in VfM and how are the current implementation methods and tools used for assessing the VfM and other design performance features in the PPP procurement worldwide?*

Q2: *What is required for VfM analysis and to what extent can the contents of VfM assessment be integrated with the BIM system?*

(ii) Requirement definition: To define the required information within the mentioned context, this thesis breaks down the structure of VfM assessment and describes the relationships apart from its constituent parts. The requirement definition was presented to answer Q3:

Q3*: How can an information exchange requirement for automatic VfM measurement be built up, and how can such BIM-based information exchange be implemented?*

The requirement definition is particularly focused on construction quantity measurement rules for cost estimates and qualitative assessment performance, thus paving the way to create a conceptual template for an IDM for VfM based on the required contents. There is a standardized inventory model that supports information exchange across different project domains. In this thesis, the information exchange scheme references the involved measurement standards in the New Rules of Measurement (NRM), Civil Engineering Standard Method of Measurement (CESMM4), Method of Measurement for Highway Works (MMHW) and Building Cost Information Service (BCIS) Building Maintenance Price Book for its quantitative aspects, which collectively contain 65 classes of cost items that relate to buildings, civil engineering works and highways. For the project's qualitative aspects, the project documents were also used to meet the need for representative guidance. There is also existing knowledge and guidance on other performance-based measurements such as green design regulations, which can be merged into the knowledge base. This research relied heavily on the available resources because of its time limits.

The methods used in this chapter reference the standardized IDM method, which supports BIM, business process and software solutions (International Organization for Standardization [ISO] 29481-1 , 2017; BSI Standards Publication Building Information Models – IDM, 2017). As shown in Figure 17 with reference to the assessment guidance, the process map and exchange requirements are proposed and discussed in Chapter 4. The content of VfM assessment is also discussed to support the information exchange requirement, which is represented using the ontology-based approach; the requirement can be divided into specifications that link to IFC entities.

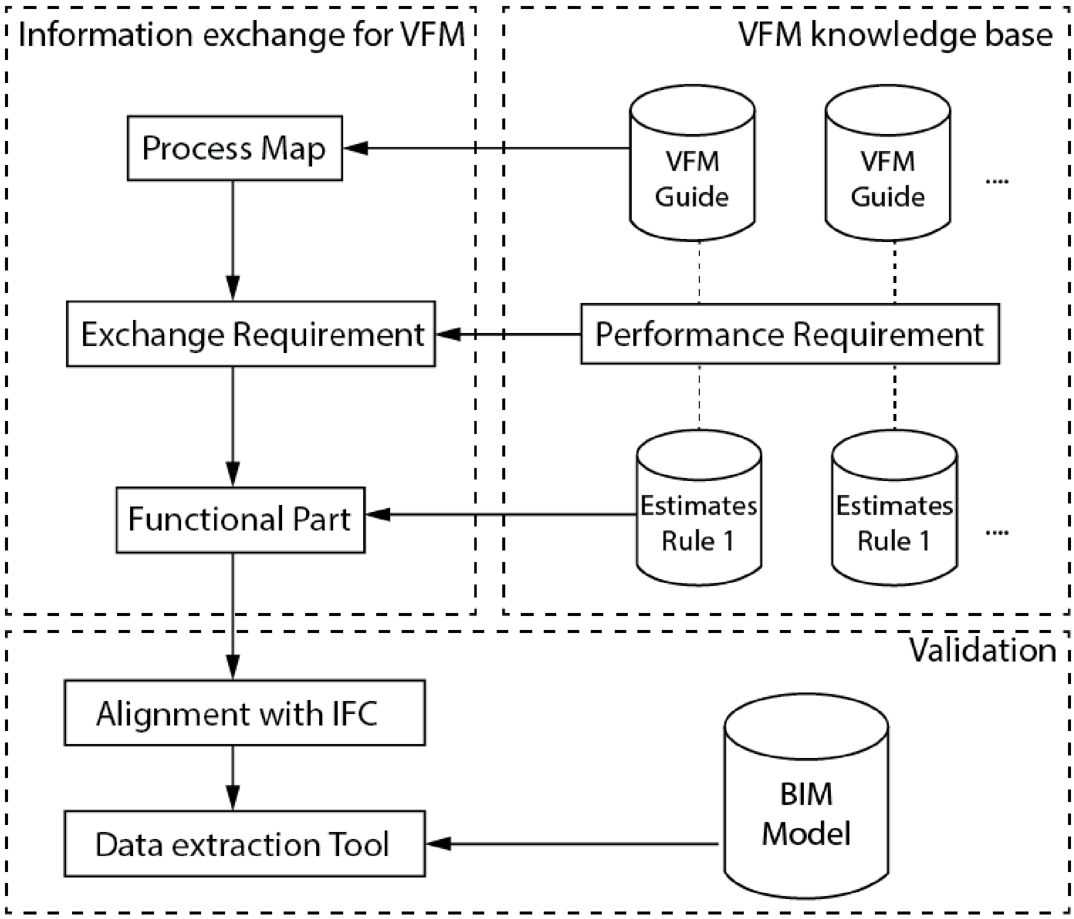


Figure 17 Framework for implementing VfM information exchange scheme using BIM

(iii) Design and development: This stage was targeted at the knowledge construction concerning all the related domain knowledge. The development, presented in Chapter 5, involved an ontology engineering approach and proposed to answer Q4:

Q4: Is it possible to build up an ontological knowledge representation of all the related contents of VfM in PPP procurement, and what are the benefits of using ontology for knowledge representation considering the VfM requirements?

The VfM assessment ontology and other domain-related ontologies were developed and integrated as VfMO. The procurement internal data sources were designed to be integrated with VfMO, and the additional ontologies were used to draw the external data resources. In this research, the language used to develop ontology was W3C Web Ontology Language (OWL) / Extensible Markup Language (XML). OWL can present the concepts expressively enough. All the developed ontologies were tested and went through system validation. The knowledge representation was constructed dynamically and always updated along with the information change and user feedback in a standardized process.

The integration challenges in a fully functional knowledge base are presented in an attempt to align multiple knowledge domains by answering Q5:

Q5: Is it possible that the constructed knowledgebase can align with other domains, such as the BIM management platform, and actualize the functions defined previously?

One of the main contributions of this research is that it proposes to align the developed knowledge base with the BIM Server so that the functional rules can run with information supported by the engineering project management side. The alignment was done via using matching concepts based on their similarities (Euzenat and Valtchev, 2004), or in some cases, with the use of knowledge rules, where datasets were too large for manual methods. In this way, the VfMO can be more functional with integrated information sources, which is run by project parties using the open-source BIM collective. Based on the proposed methods, links are made to the BIM Server, which represents the information assembled in the BIM. The alignment method is further discussed in Chapter 5 (Section 5.2).

(iv) Demonstration: The proposed VfMO schema was delivered to the software process to demonstrate its application. After creating the complicated knowledge operator types and fit in use scenarios (Chapter 5), it was necessary to integrate the developed knowledge. Due to the nature of the knowledge base (i.e., being reliant on several distributed resources), complexity was introduced. Therefore, this research attempted to implement different rules and functions that were separately involved in different scenarios, which can represent some crucial aspects of VfM assessment. This practical approach was also discussed in pursuit of insight into the research topic.

To tackle this, some primary research blueprints have already been drawn for future development. First, the construction of a VfM knowledge base was based on a semantic approach, and ontology was used to encompass the formal naming and definition of related concepts, properties and relations. Protégé was used due to its popularity in the academic area and its capability to integrate different ontology-based functions into its environment. Second, the BIM server was used to integrate the IFC data, as it is a developed open-source environment that enables users to store and manage construction information or any other building-related projects. It is worth mentioning that the BIM server also can be used to retrieve IFC based on the pre-developed functions outlined in Chapter 4 using IfcEnging.dll. The development environment for linking semantic knowledge and IFC was Eclipse. A Java integrated development environment (IDE) supported the development that also supported C/C++ and could easily combine different languages within different features into default packages.

Due to the reasoning rule, the attached VfM knowledge base was based on SWRL rules, which is represented as a Description Logics (DL) safe rule in XML syntax. Each variable defined in SWRL can occur and can be restricted to known individuals, as SWRL is expressive and decidable enough. In this way, the VfMO application is demonstrated to users by aligning IFC data from the BIM server with the defined OWL/XML exported from Protégé; in this process, server alignment approaches are made for the check, IFC and OWL syntax are phrased and the rule functions are translated into Java appliance.

(v) Evaluation: Finally, the proposed platform and methodology for VfMO were tested on a case study of an existing airport project BIM model to see if the tool meets the requirements defined in this thesis and as the next step to their delivery to the domain experts for validation. This approach aligns with Q6:

Q6: How reliable is a knowledge-represented system in understanding the digital engineering project model and other data resources in facilitating efficient VfM assessment?

The methodology—presented using the digital model of a real airport project to simulate its operation-related data, documentation address and some general information from the project level were gathered and integrated with the BIM model, which was used to make a design scenario. The testing and evaluation can be specified in the following stages:

Stage I – Semantic and syntactical validation: to check the developed VfMO as a knowledge base of its semantic and syntactic correctness.

Stage II – Case study scenario presentation: Based on the defined information exchange requirement and assessment performance guidance rules, a scenario was created to process the automatic function. This was done to check if the developed system could actually interpret the ontology resources defined in Chapter 5. On the basis of the evaluation and reasoning rules concerning object geometry data, text data and the location of procurement documentation, it is essential to mention that the VfMO was not targeted at validating the entire process but at validating the pre-defined functional rules and at the alignment process. The input and output were captured to support the results in this case study. The VfMO demo was also delivered to a domain expert in the construction sectors, to get feedback about its ability to be used in large-scale scenario models. The different scenarios were attached in an introduction file with a detailed explanation of their performance. The feedback provided by experts included 1) a detailed answer regarding the different performances using VfMO and 2) specific text feedback written by the expert to help to improve its applicability.

3.4 Strategies and Methodological choices

In common methodological choices, both quantitative and qualitative methods can contribute to pragmatical research to a great extent. There is no necessity to define a specific method to achieve research goals (Mackenzie and Knipe, 2006). The mixed methods in most of the cases can make well-constructed research design to a great extent. To be more specific in this research, a variety of strategies that refer to the approach undertaken to achieve objectives are used in the research process. Based on the fact that the gap found in this research be involved a certain amount of existing knowledge, therefore, this research project uses two different strategies: archival research and case study.

The archival research approach is proceeded by using the existing information and archived documents. It allows the researcher to explore and explain the changes tracked over a long period of time. This related information may be held either in collecting institutions such as libraries or in the custody of the organizational bodies (Welch, 2000). Regarding this research, there are a certain amount of standards and official guidance relating to VfM assessment. The validation is also intended to use the existing project documents and data to make a more clear description. Therefore the archival research approach suits the research topic at this stage.

The case study is also an important method that refers to the research scenarios to which researchers have applied their proposed methods and techniques (Oates, 2006). The implementation of the case study can reveal the in-depth explorations from multiple perspectives of the research project in a ‘real-life’ context (Bassey, 2003). For this research, the case study can focus either one instance of BIM related projects being investigated or multiple cases and it suited to the deductive approaches and align with the archival research approach to a great extent. On the basis of information integration and validation design, the case studies scenarios are set up within a BIM project model. The software demon is developed to run the case study in a more efficient way. There is also a survey concluded at the end of the case study to cover the feedback of achieved software functionalities.

3.5 Research Time Horizon

There exist two-time horizon methods. Frist is cross-sectional studies that refer to the conduction of short-time study (Catterall, 2000) while longitudinal is defined to cover the more repeated measurements of the same sample over a period of time(Churchill, 1999).

In this research, cross-sectional studies are time horizon methods. The collection of information regarding VfM assessment is processed through different samples and the proposed knowledge foundation also took part at particular times and not over a specific period of time.

3.6 Techniques and data collections

As described in the archival research approach, the information and data sourced from both quantitative and qualitative perspectives. The data are obtained from the published guidance books or standards by the UK and China and international authoritative regarding the certain knowledge concerning the VfM assessment.

Besides, To conclude the description of the methods used in this study, the developed framework currently uses secondary Linked Data approaches and reliable scenarios extracted from assessment guidance and a real procurement case. This was done to indicate that this methodology is able to draw real-time data from procurement platforms.

Based on the principles of knowledge representation and mining, the tool developed in this thesis for representing VfM assessment knowledge is created using ontologies. VfMO is a form of knowledge representation in this research. Using the principles of knowledge representation and mining (Kaufman and Michalski, 2005), Table 6 specifies the main contents of the tool, which includes databases, knowledge bases and process operators.

Table 6 The main components used in VfMO development

VfMO components	Main contents	Descriptions
Databases	IFC data source	The data present engineering project data supported by BIM
	Project internal/external data	The data present various sources of information
Knowledgebase	VfM ontology	The representation of VfM related ontologies and also cover some contents relates to other design performance
	Other financial ontologies	The representation of other related financial knowledge concerning project parties and processes.
Process operators	Demo of data extraction	Information exchange tools which extract related data from BIM
	Demo of knowledge reasoning	logical expressions which are used to supplement VfM knowledge from existing knowledge bases

Aligning with the knowledge base, the data analysis and codes are built to cover the comprehensive assessment rules and processes. The collected data also aligned with the new-created ontology in a meaningful way using statistical functions in IFC schemas. The data filtering functions are suitable for the extraction of related information in BIM models and the linked data approach is the main functional alignment for both ontology and IFC schemas. Finally, the integration of these different methods and strategies is made for the feasibility of validation.

Chapter 4. Requirement analysis

This chapter provides the initial technological information requirements for delivering a functional VfM system for practical deployment, following the proposed conceptual framework. The logic to build information requirement references the standardized information exchange process defined in ISO 29481-1 which is defined as Information delivery manual (IDM)

IDM is the documentation that captures the business process and gives detailed specifications of the information that a user fulfilling a particular role would need to provide at a particular point within a project.

------ *ISO 29481-1 : 2017 BSI Standards Publication Building information models – Information delivery manual*, 2017

An Information Delivery Manual (IDM) is defined at project levels to capture the business processes and provide a user information exchange requirements specification between the different actors. The domain-specific Model View Definition (MVD) is a programming as a technical solution for formalizing special-purpose knowledge which can be used to deliver the technical representation to the soft vendors. Its functional parts (FPs) refer to objects or document attributes that have been recognized as the critical feature in IFC data structures. The IDM-MVD method provides the basic framework for information delivery and exchange requirement on different project tasks. However, based on the review of existing information exchange research (Kim *et al.*, 2010; Ole Berard and Karlshoej, 2011; Obergriesser and Borrmann, 2012; Lee, Park and Ham, 2013; Liu *et al.*, 2013; Lee *et al.*, 2016; Petrova *et al.*, 2017), only a few have been developed so far to concern about the early-stage project justification. Although digital costs estimation, quantity take-off, data management and reporting tools are become more widely used, the secondary component and raw material auctions or automated reporting to authorities relate to assessment are not fully covered by BIM-based approach (Volk, Stengel and Schultmann, 2014). Currently, the IDM framework is the only standardized information exchange framework in BIM oriented engineering projects that referring to information items and processes (*ISO 29481-1 : 2017 BSI Standards Publication Building information models – Information delivery manual*, 2017). It is a reliable information exchange approach to obtain better quality information through the project lifecycle which is an important element in this research. As shown in Figure 18, to define an information exchange scheme, the following process based on the IDM framework is helpful to clarify the process:

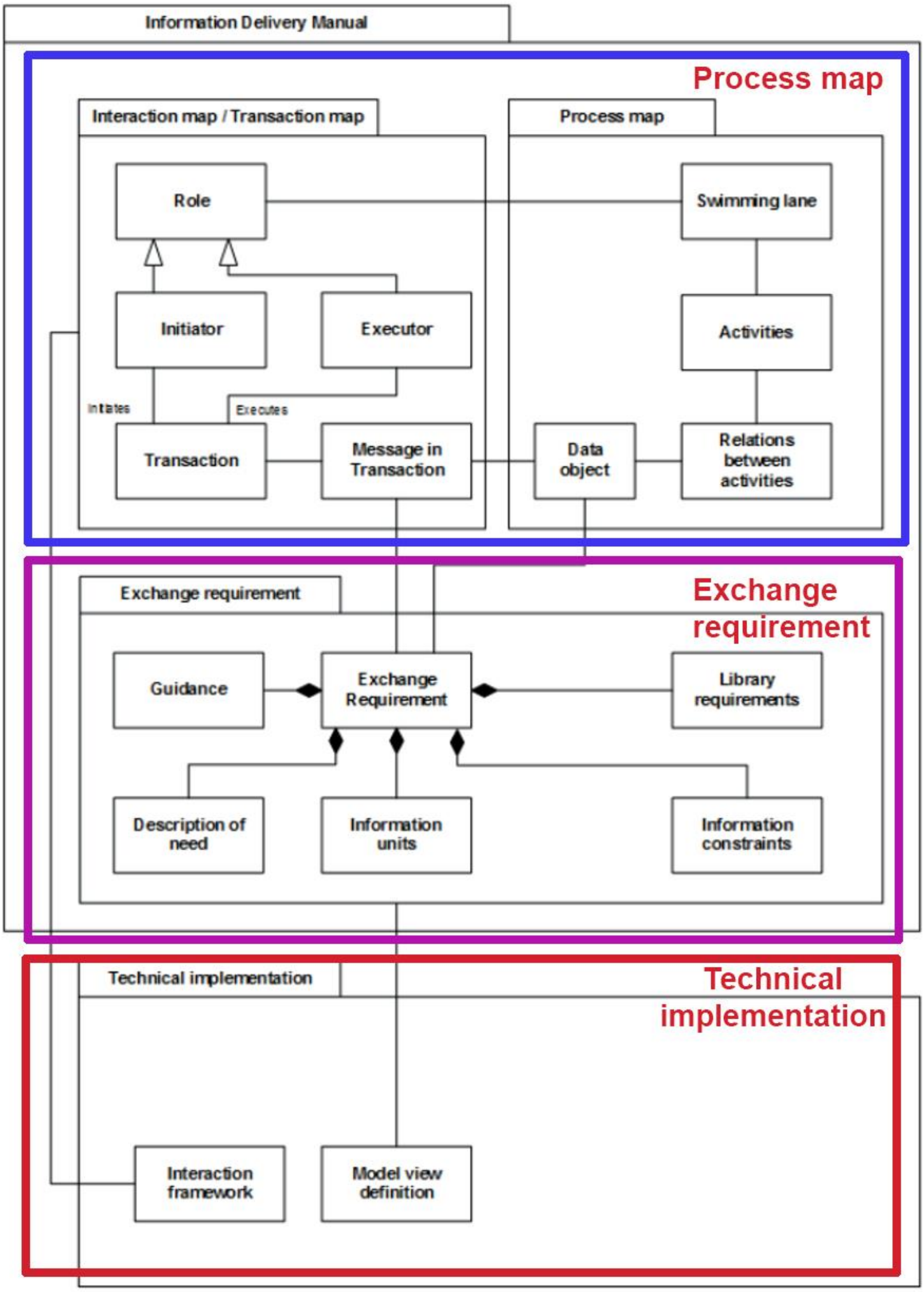


*Figure 18 The basic framework in IDM (*ISO 29481-1 : 2017 BSI Standards Publication Building information models – Information delivery manual*, 2017)*

1) A process map that describes the flow of work activities within the boundary of a business process, and also states the roles played by the actors involved with the information required.
2) Exchange requirements define the information that should be exchanged to support a particular business process at a particular stage of a project. The presentation of exchange requirements should be described by using non-technical terms and should be understandable to all the related end-users.
3) The technical implementation that concerned with the technical representation and application of the information requirements of business processes. The carrier of the technical model can be used as the basis for automated processes involving the use of software applications.

Based on the process defined in IDM, the chapter is divided into sections that align with the structure of IDM intending to answer Q3.

4.1 The process map definition for VfM

Based on the VfM assessment guidance and requirement, the proposed exchange models identified in the process maps are shown in Figure 19 below. Horizontal swim lanes are used for the major tasks in the assessment corresponding to Uniclass2 (ISO, 2012) project stage activities. The workflow uses the existing contents defined in the Value for Money Assessment Guidance (HM Treasury, 2006; Office of Transportation Public-Private Partnerships, 2011; US Department of Transportation, 2012; China, 2014). This process map currently only includes the concepts/elements/parts regarding the project objective identification and preparation phases, which contribute to developing the PPP model. This is expected to be extended to future stages.

For the involved parties, the value for money assessment is driven by project clients, which in most cases in PPP procurement are represented by governments. The client representatives will delegate/employ experts to perform an assessment based on the available project information, to which the first exchange of information is delivered. A cost consultant may take responsibility for the cost estimates mainly for the quantitative assessment where a second exchange requirement is needed.

The assessment is proposed to progress at least once at the initial stage of procurement by many countries (World Bank, 2014). According to the guidance and the real PPP project cases, the process can be concluded as follows: firstly, the clients initiate the assessment on the proposed project whether it is an existing or a new project. Then, the related information should get prepared for qualitative assessment. The exchange requirement for qualitative assessment needs to provide meta-data support such as keywords or storing databases that relate to project documentation. The project related information such as owner information, project scope and description can be retrieved from the BIM model. Documentation concerning project briefings, proposals, historical materials, feasibility studies can be linked to IFC-based datatypes. If the qualitative assessment passes, then by setting up the IFC model, the reference project should be chosen to measure the value of PSC – a value that represents the method using the traditional procurement approach. The exchange requirement for quantitative assessment functions on both reference IFC models and project design IFC models to acquire the information needed for PSC and PPP shadow bids. The historical project database is built by governments to calculate the external values such as risk cost and confirm the discount rate. The exchange requirement covers from brief strategic preparation to the technical design development along with the update of information. (Table 7)

Table 7 The VfM information exchange function on project stages (China, 2014; HM Treasury, 2006; Office of Transportation Public-Private Partnerships, 2011; World Bank, 2014)

Project Stage	**Unicalss code**	**Exchange Requirement for qualitative assessment**	**Exchange Requirement for quantitative assessment**
Strategic brief preparation	Ac_05_00_80	√	
Preliminary design preparation	Ac_05_10_61	√	√
Concept design preparation	Ac_05_20_21	√	√
Definition design development	Ac_05_30_25	√	√
Technical design development	Ac_05_40_87	√	√
Build and commission	Ac_05_50	√	
Handover and close-out	Ac_05_60		
Operation and end of life	Ac_05_70		

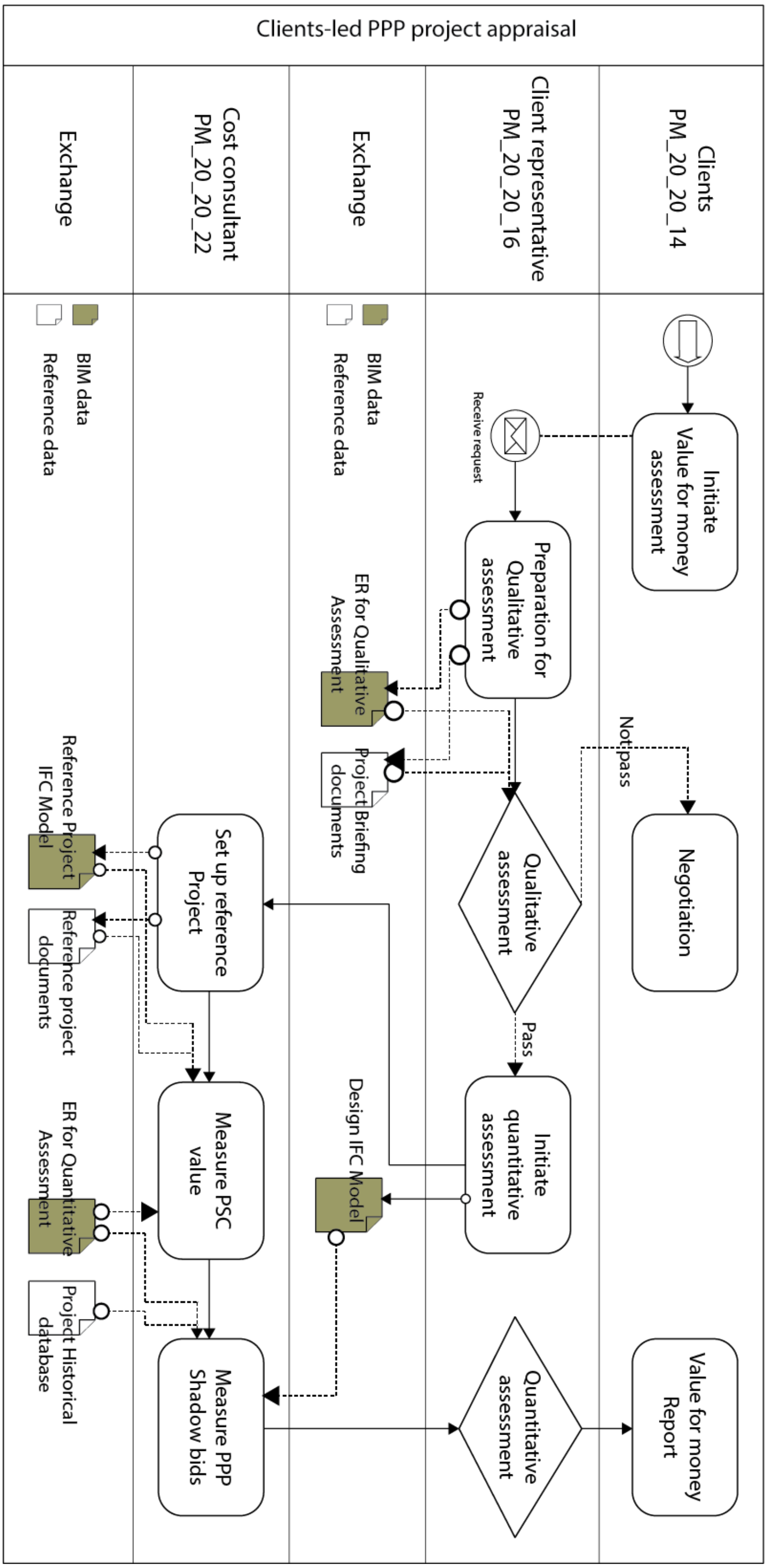


Figure 19 *The Process map of VfM information exchange based on related VfM guidance* (HM Treasury, 2006; Office of Transportation Public-Private Partnerships, 2011; China, 2014; World Bank, 2014)

4.2 Define the exchange requirements from scratch

To define the basic information exchange concerning VfM, the contents of VfM is analysed in 4.2.1 Section. By extracting the related information items in both quantitative and qualitative requirements, it can be concluded that the qualitative assessment requires support from procurement documentation and related project and asset information. The quantitative assessment is more cost - orientated measurement meanwhile considering the whole life cycle performance.

4.2.1 Decomposing /Analysing of quantitative VfM assessment

This section outlines a general composition of value for money assessment with its related indicators. The structure is shown in Figure 20, the constituents of both quantitative and qualitative assessment can be related to cost estimates standard and qualitative assessment guidance.

As a vital assessment used to reflect on the economic benefits of a project directly, a quantitative measurement requires more direct measurement of a procurement strategy (Bain, 2010; Davies and Harty, 2013). The PSC method, originally used in the UK, is now widely regarded as an effective means in quantitative assessment around the world (Ismail, Takim and Nawawi, 2012). Figure 21 illustrates the various cost estimating stages in the context of the PPP procurement, RIBA Work Stages (Royal Institute of British Architects, 2015) and OGC Gateways (*Office of Government Commerce OGC*, 2018). The cost estimating workflow is referenced by the documentation of the Royal Institution of Chartered Surveyors (RICS). In the cost structure, the initial cost estimate provides a preliminary estimate based on the initial project proposal, financial consultancy and engineering data. This is the vital element part of PPP quantitative assessment. Because the assessment has its whole life cycle feature which is supposed to apply in different project stages, it should be updated along with the cost estimate through a formal cost plan, bills of tender and post tender estimates. In this thesis, it proposed the information exchange requirement of value for money assessment that includes the initial cost estimate and documentation management in the different type of building and infrastructure properties.

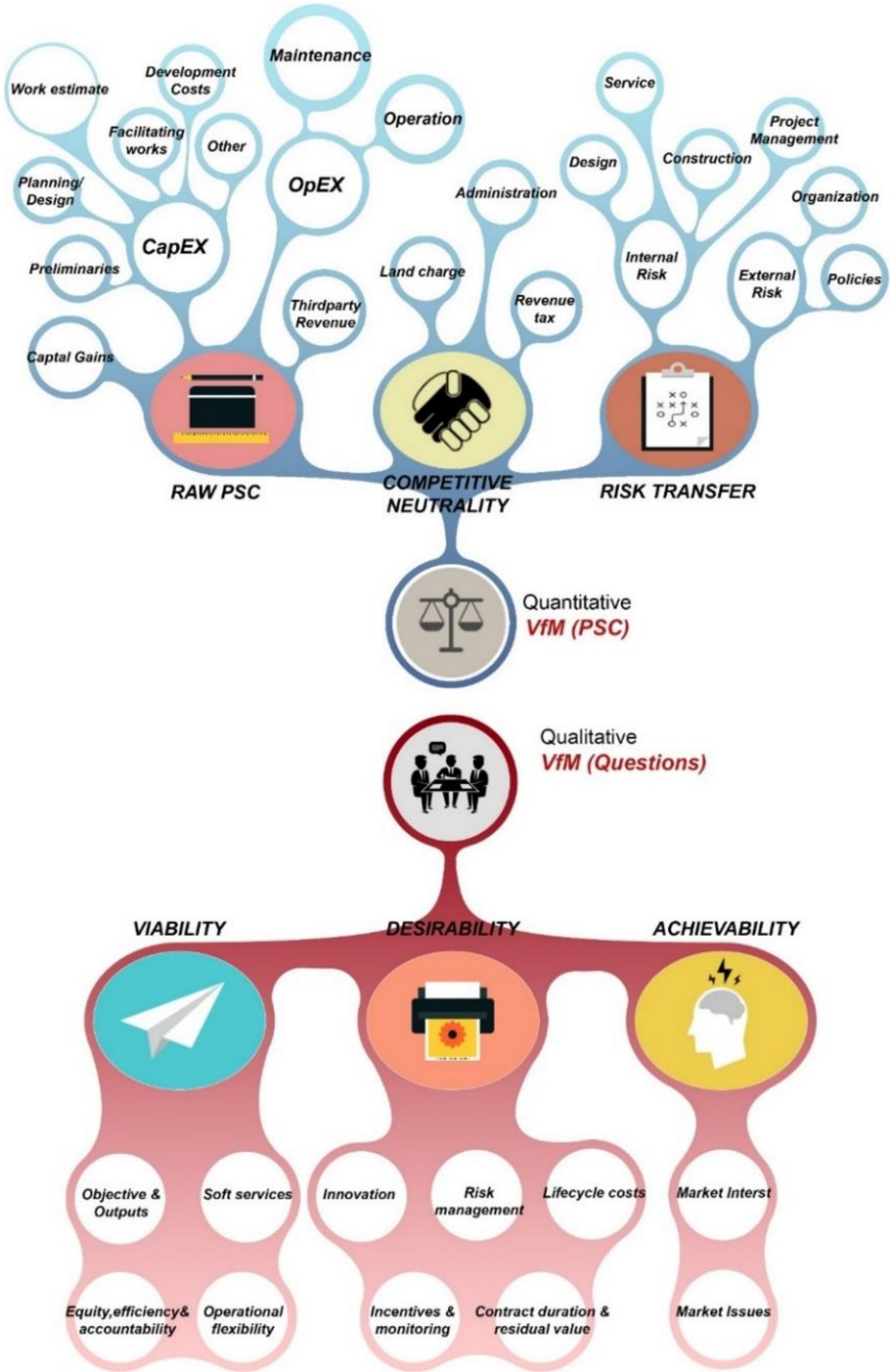


Figure 20 The constituents in quantitative and qualitative assessment (HM Treasury, 2006; Morallos *et al.*, 2009; Office of Transportation Public-Private Partnerships, 2011; Ismail, Takim and Nawawi, 2012; China, 2014)

The calculation of the PSC-related formula is shown below:

$$V_{psc} = V_{raw} + V_{cn} + V_r \quad (1)$$

$$V_{ppps} = V_{lcc} + V'_r \quad (2)$$

where V_{psc} (value of PSC) is composed of mainly three parts. V_{raw} represents the resource costs through the entire lifecycle, V_{cn} represents the value of competitive neutrality, which is based on beneficial factor adjustments, such as differences in state tax rates and interest rates and differences in regulatory costs. V_{cn} is used to guarantee that the government provision of goods or services has no advantage over the public sector. V_r represents the quantitative value of risk-related costs that contain external and internal project aspects. In PPP, the procurement strategy proposed is shadow prices (V_{ppps}), where V_{lcc} is given by the subsidy based on the lifecycle costs of using social capitals, V'_r is the risk costs remaining in the public sector.

$$V_{lcc} = C_{ca} + V'_{raw}(1+r) + C_o \quad (3)$$

V_{lcc} can be decomposed as shown in equation (3), where C_{ca} stands for the public investment allowance during the project design to the construction stage, V'_{raw} represents the resource costs of authorizing private sectors, r is the respected profit margin and C_o is the other costs of the public sector. These can be further evaluated using the formulas below:

$$V_{raw} = C_{CapEX} + C_{OpEX} + C_o \quad (4)$$

$$C_{CapEX} \approx \sum_{k}^{n} C^k U^k \quad (5)$$

C_{CapEX}	the capitalized cost of project design and construction, excluding capital gains
C_{OpEX}	the cost of project operation and maintenance, excluding third-party income
k	the particular item of the project work breakdown structure
C	the corresponding quantities of engineering work item
U	the overall unit price that contains the costs of labor, materials and equipment
N	the total amount of working items types in PPP project

All the equations above are based on the quantitative assessment methods defined in the VfM structure bodies (HM Treasury, 2006; Ball, Heafey and King, 2007; U.S. Department of Transportation, 2013; China, 2014). The cost calculation in both capitalized costs and operation costs referenced the NRM serious (RICS, 2009).

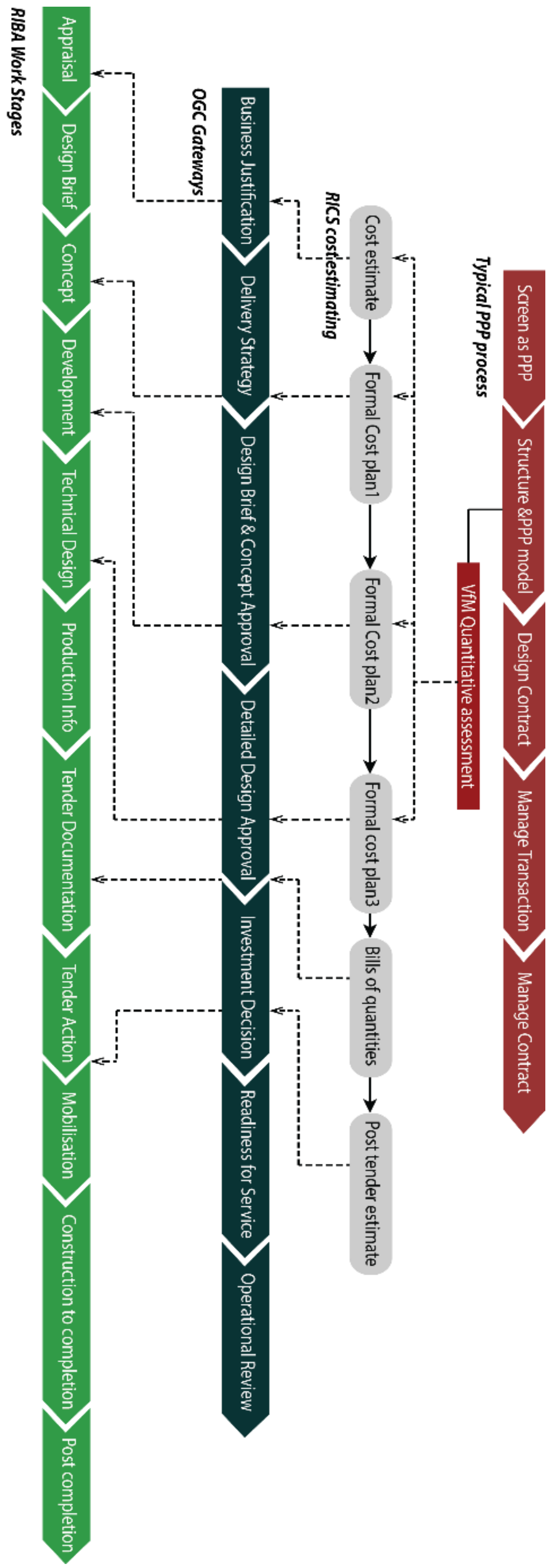


Figure 21 VfM quantitative assessment in the different standardized workflow ((Royal Institute of British Architects, 2015),(Office of Government Commerce, 2007),(Abanda, Kamsu-Foguem and Tah, 2017),(World Bank, 2014)*)*

The resource costs are an essential element based on both calculation schemes. Due to project type differences, the schema used to forecast the operation and maintenance expenditure may vary along the project lifecycle (World Bank, 2014). Based on this fact, the cost institution still lacks information support to cover most public facilities, such as railways and highways. The information in the project's early stage plays a vital role in estimating the capitalized cost, and it could provide fundamental support for estimating the O&M expenditure (Kehily and Woods, 2013).

More content relating to evaluating quantitative assessment is in Appendix A.

4.2.2 Decomposing/Analysing of qualitative VfM assessment

For the qualitative assessment, the notice published by the Ministry of Finance of the People's Republic of China initially introduced general requirements of quality measurement targets. It is one of the few VfM assessments which implements the detailed requirement relating to whole life cycle procurement which is helpful for the analysis of qualitative VfM assessment. Special expert groups working on behalf of China's Ministry of Finance take responsibility for scoring assessments. As was frequently encountered in the literature, a five-point rating scale is used to identify the degree of performance of each index. The rating scale may contain various combinations of indices, according to individual project requirements. While the template used in Chinese qualitative assessments is beginning to provide more detailed rating methods, it still lacks supporting data and information query systems that would enrich evaluations.

The following Table 8 shows the performance list used for evaluating qualitative aspects in VfM assessment toolkits published by fiscal institutions from both the UK and China that are currently used as guidance. The qualitative assessment aims to judge whether such a public procurement model has the potential to optimize benefits and to provide a valid scheme for the whole life cycle information management. The flow process of qualitative assessment requires experts to evaluate the performance index and make a qualitative assessment report. The foundation information support such as project information or documentation could help experts to refine the evaluation process. This can happen in an ideal situation, while BIM is formally used in project management. The IFC data can be used to store all the project information and documentation through different standardized data types. A detailed explanation of the assessment index indicates that related content should be checked at different stages. To clarify, the indicators in qualitative assessment do not point to the physical information within the digital model; the evaluation acquires the information at the project level, which is normally collected from clients' requirements, surveys, and financial reports. Based on current knowledge, the information relating to qualitative indicators contains:

1) Documentation information with encoding system. The traditional file management will inevitably produce certain deficiencies in the process of project information creation and delivery. The main reason is that documentation management is separated from the engineering project model information, and the spatial requirements for information management will be significantly improved. Different management systems bring great difficulties to information retrieval and inquiry. BIM can generate information about the various participants of the project, which can be centralized to display and store. The system of document coding can be used as the underlying support of the BIM system. In this process, the application classifies documents based on the original data-based document organization, which provides users with a tree-structured, hierarchical directory interface. For example, general information such as 'incentives and monitoring' can be tracked in project briefing documentation with code. The BIM-based information management can make up the lack of space requirements in traditional information management, and guarantee the efficiency of information retrieval.

2) Assets information in the model. The BIM software provides functionalities to store critical information in the entities. These entities can be projects, civil elements, building elements, and facility elements. The indicators relating to asset information can be extracted from these relevant entities by using keywords queries. BIM data integration is efficiently supplemented along with the development of procurement. The design change information, purchase information, or rental information for equipment can be updated in the IFC based database.

Table 8 Example of the current qualitative assessment index in both China and the UK

Assessment Index	Description	China	UK	Related Information
Objects and outputs	Requirement and benchmarking are provided during the initial project stage	√	√	Project brief documentation
Soft Services	Facilities management related to the day-to-day supporting services required in the operation		√	FM information and documentation; Project brief documentation
Operational flexibility	Product flexibility, volume flexibility, delayed differentiation		√	Assets information;

Risk management	The extent of risk identification & allocation that progressed in the initial project stage	√	√	Risk identification documentation
Contract and assets Duration	The expected period of service that the assets could provide in the project lifecycle	√		Project brief documentation
Asset classification	The information based on various project types	√		Assets information; Project brief documentation

A more performance-related list used for evaluating qualitative assessment is in Appendix A.

4.2.3 Define the information units and constraints

There exists the standardized inventory model that supports information extraction and sharing across different project domains. In this thesis, the information exchange scheme references the involved measurement standards (NRM, CESMM4, MMHW, BICS) for quantitative assessment and use the UK and China PPP value for money guidance for the qualitative assessment. The cost measurement method is defined in different ways. Quantities for construction, maintenance and renewal works can be determined using the value of the total gross floor area of the built assets or by projecting the value of functional units. In certain circumstances, for either newly built or existing assets, an elemental method is applied to measuring the estimated capital building and maintenance costs. The elemental method takes the significant elements of the building works and provides element-by-element estimates. By using the rules of this method, the content related to specific elements can be defined to satisfy the exchange requirements. Figure 22 indicates the example used in NRM for quantitative assessment. The information groups can be broken down, followed the structure defined in elemental methods. The examples in Table E show the specification of the information hierarchy. The layered structure clearly shows all the information items and indicates how their attributes are related. For example, to provide information support for calculating work cost estimates of the upper floors, there are specific attributes of building slab systems that need to be collected. The gross area is the attribute that provides the basic unit for pricing the structural type, material type, level and other property sets while matching the specific cost items when it comes to calculation. More table lists on the information items are shown in Appendix B.

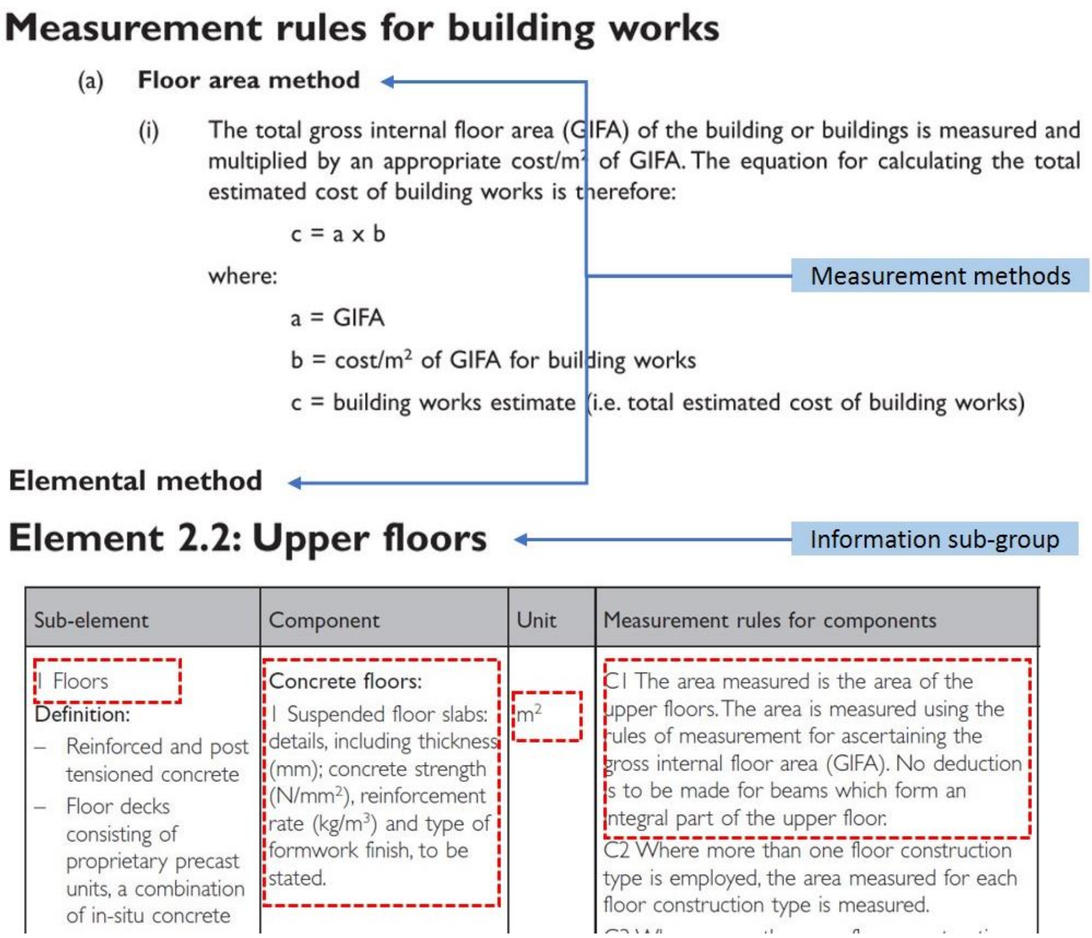


Figure 22 The abstraction of related concepts from RICS new rules of measurement (RICS, 2009)

The manually developed information exchange requirement is often not either manageable nor efficient enough to update and share, especially when software vendors are developing on the IFC schema. The reason is mainly that the developed scheme did not provide the semantic structure in an open file format. Such table-based data sets cannot indicate the semantic relationships between entities and attributes which can cause binding problems when software companies use their methods linking to IFC schema. Most importantly, unstructured specification and implementation rules impede functional information extraction.

4.3 System development and implementation

4.3.1 Ontology representation

Ontology Web Language (OWL), a set of makeup language of expression, has now been given rules-based functions to query information from a different knowledge base, and then provide the path for data management (Golbreich, 2004) and regulation-compliance checking for buildings (Kamsu-Foguem *et al.*, 2019). Semantic

Web Rule Language (SWRL) and OWL help define a schema of rules and SPARQL (SPARQL Protocol and RDF Query Language) query based on the predefined ontological model. Such capabilities that represent semantic relationships of domain knowledge can play an essential role in defining an information exchange requirement and creating a robust link between a manually defined IDM and functional model views. The outputs of IDM can be delivered as OWL/XML which is the computer-readable format and can further link to MVD documentation and other programming environments. The reason for using Ontology to represent information exchange contents is based on the previous contribution of related research: Lee, et al, (2013) proposed a new extended process to create a tight connection between ERs and FPs to improve the reusability which use XML as document files to replace separate table documents. Lee et al. (2016) then proposed to use an ontology to create IDM and develop a tool that aligns with ontology software to translate OWL/XML IDM files into .mvd/.xml and proved it can be formally documented as MVD documents. Therefore, to define the scope and business rules for VfM assessment and stress the semantic relations, ontology is used to represent information exchange requirements.

Figure 23 shows the structure of the exchange requirement in the ontology and the corresponding functional part which is used to map the requirement information concepts to IFC. The structure of the FP ontology follows the semantic structure of IFC4 due to its standardized definition of all the related taxonomies and hierarchy structure. The ontology model of the VfM exchange requirement is created based on the information exchange specifications and is proposed to function as a template that can be updated for various types of PPP projects in the future. The correlations between entities and attributes can be expressed clearly from ontology models and presented as OWL/XML format.

Figure 24 shows the ontology of the exchange requirement, where the functional part can be separately made and aligned in ontology software. The basic ER ontology is made to cover the index of indicators and the FP ontology is made to cover the object specifications. The built ontology can also be integrated with other building domain ontologies, such as BOT (building topology) ontology. The nomination and structure to define objects relationship (used in the ER ontology) respect the previous structure defined in BOT ontology. The object properties in the ontology are used to define the relationship between various concepts. For example, *HasFP* and *HasInformationItems* are used to build connections between different ontology and information objects. Moreover, the property *HasDescription* or *HasProperties* is created to link the corresponding objects and attributes. In this way, it is using ontology as a central connector, which facilitates the ERs and functional schemes. This benefits information sharing and reuse. The developed ontological IDM is computer-readable, which can be simply set up. The XML-representation can also be mapped to different programming software, thus benefiting data extraction. The ontology represented format can be translated to mvdXML in the future, which contains the definitions of data exchanges that can be shared and reused for developing standardized MVD documents.

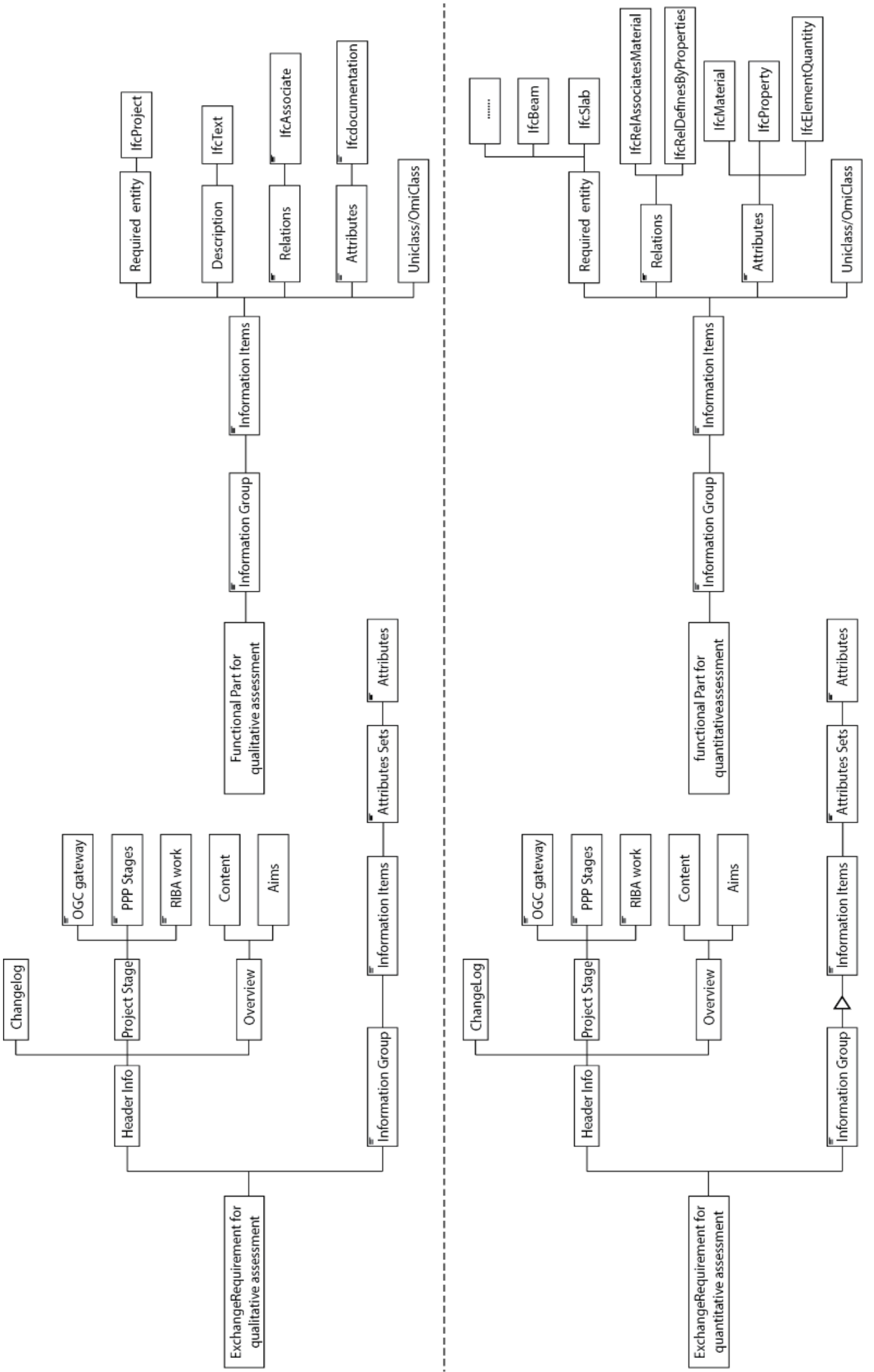


Figure 23 Structure of VfM exchange requirements in the ontology

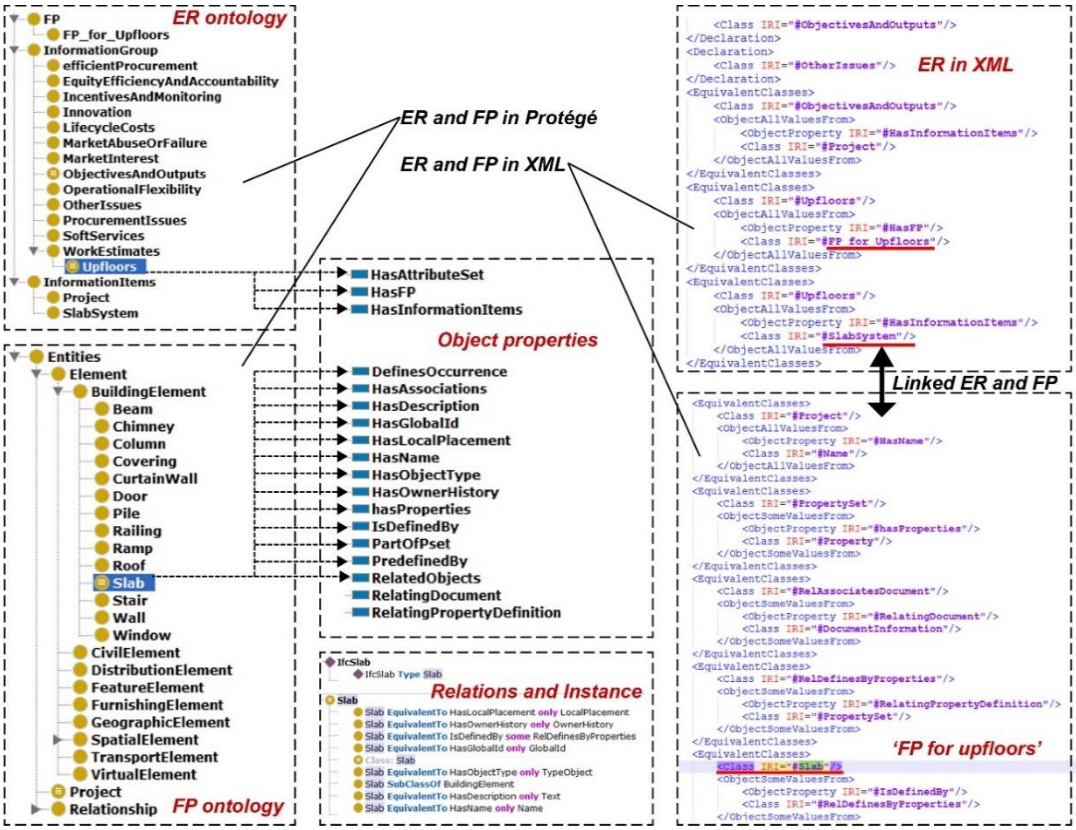


Figure 24 VfM exchanges in Protégé and OWL/XML

4.3.2 Developing the functional part by linking to IFC

A technical representation is required to deliver the information exchange scheme to software vendors. Specifically, the FPs should be set up to describe the information regarding the required capabilities of a standard information model. The FPs represents the software requirement specification for the implementation of an IFC interface to satisfy the exchange requirements. Based on the proposed ERs, the FPs are specified using elements in IFC 4.

Table 9 shows an example of the IFC 4 entities corresponding to the work items covering the capital expenditures (CapEx), operating expenses (OpEX) and quality assessment aspects. The classification in the left column represents the quantities for different engineering work items. The layered classification of quantitative assessment references the NRM series for buildings, CESMM and MMHW. The related unit linking to cost value can be obtained from pricing books for construction and building maintenance. The specific requirement of qualitative assessment was sourced from HM Treasury quality assessment guidance that indicates the content of the quality performance. As shown in Table 9, in the project-planning phase, the information can be connected/retrieved by the *IfcSite* which is an IFC schema object so that the planning-related attributes or documentation can be stored and located easily within the model. The attributes relating to the performance of ‘temporary road,’ ‘cleaning area’ or the ‘building pad’ can also be traced to different IFC data types. Likewise, the information in the early building design stage can be extracted from concepts like *IfcBuilding*, *IfcBuildingStorey* or *IfcSlab*. The detailed design afterward is supposed to contribute to the formal cost plan, which includes the estimates of the basic site, building, indoor space and structure design. The maintenance works could also be measured using the physical model attributes that are similar to those used to build cost estimates. IFC entities, such as *IfcSlab* and *IfcWall* that respond to various cost items in a ‘superstructure’ and ‘internal finishes’ class. *IfcSpace* as a particular entity to represent an area or volume within a building can be decomposed in areas where the functionalities of building spaces, such as ‘office’ or ‘meeting room’, can be located. By setting up constraints, these spaces with their related objects and attributes could be extracted to measure the construction and maintenance cost items based on NRM and BCIS. For the stock PPP projects or the projects that have already established a planning and design scheme, these data could be captured systematically follow the same methods.

Table 9 IFC data type corresponding to the VfM Exchange requirement

VfM content	Information group	Unit	IFC entity	IFC attribute datatype
Preliminaries (NRM)	Labour	Weeks	IfcLaborResource	
	Site huts/Formworks	weeks/nr	IfcConstructionProductResource	IfcQuantityCount
	General equipment	weeks/nr	IfcConstructionEquipmentResource	IfcQuantityTime
Planning /Design	Planning costs	m2/km2	IfcSite	IfcQuantityArea
	Design costs	m2	IfcBuildingStorey;IfcSlab	IfcQuantityArea
Work estimates (NRM)	Facilitating works	item/m2/m3	IfcSite;IfcSlab;IfcBuildingStorey;IfcWall;IfcColumn;IfcConstructionProductResource;IfcSpace	IfcQuantityArea; IfcQuantityCount
	Substructure	nr/m/m2/m3	IfcSlab;IfcWall;IfcColumn;IfcPile;IfcBeam	IfcQuantityArea; IfcQuantityCount;IfcQuantityLength;IfcQuantityVolume
	Superstructure	m2/nr	IfcSlab;IfcCloumn;IfcBeam;IfcRoof;IfcStair;IfcRamp;IfcWall;IfcDoor;IfcWindow	IfcQuantityArea;IfcQuantityLength;IfcQuantityCount
	Internal finishes	m2	IfcWall;IfcSlab;IfcCovering	IfcQuantityArea
	Fittings/furnishings	Nr	IfcFurnishing	IfcQuantityCount
	Services	m2/nr	IfcBuilding;IfcBuildingStorey;IfcSpace;IfcTransportElement	IfcQuantityArea
	External works	m2	IfcSlab;IfcWall;IfcSite;IfcBuildingStorey;IfcBeam	IfcQuantityArea
	Scaffolding	m2/ nr	IfcWall	IfcQuantityArea
	Demolitions/ Alterations	m2/m/nr	IfcWall;IfcChimney;IfcBoiler;IfcWindow;IfcDoor	IfcQuantityArea;IfcQuantityCount
	Excavations	m3/m2	IfcSpace	IfcQuantityArea;IfcQuantityVolume
	Concrete work	m3/m2/nr	IfcBeam;IfcColumn;IfcSlab	IfcQuantityArea;IfcQuantityVolume;IfcQuantityCount
	Underpinning/Stone-work	m2/nr	IfcWall;IfcBeam;IfcSpace;IfcSlab	IfcQuantityArea;IfcQuantityVolume
	Reroofing	m2/nr/m	IfcRoof;IfcChimney	IfcQuantityArea;IfcQuantityCount;IfcQuantityLength

Building Maintenance (BICS)	Woodwork	m2/nr/m	IfcWall;IfcCovering;IfcSlab;IfcFloor;IfcWindow;IfcStairs;IfcFurniture;IfcPipeSegment	IfcQuantityArea;IfcQuantityCount;IfcQuantityLength
	Plumbing	m/nr	IfcPipeSegment;IfcSanitaryTerminal;IfcFurniture;IfcTank;IfcFlowStorageDevice;IfcSpaceHeater;IfcBoiler	IfcQuantityCount;IfcQuantityLength
	Internal/External Finishes	m2/nr	IfcSlab;IfcCovering;IfcWall	IfcQuantityCount;IfcQuantityArea
	Glazing Repairs	m/nr/m2	IfcWindows	IfcQuantityArea;IfcQuantityLength
	Painting/Decorating	m2/m	IfcWall;IfcSlab;IfcWindows;IfcPipeSegment;IfcDoor;IfcRailing	IfcQuantityArea;IfcQuantityLength
Qualitative assessment (partially from HM)	Contract outputs	Metadata; document	IfcProject;IfcAsset	IfcDocumentInformation;IfcLable;IfcText
	Soft services	Metadata; document	IfcSystem;IfcConstructionResource	IfcDocumentInformation;IfcLable;IfcText

The quantities extracted from BIM could significantly improve the measurement of the work estimates process. The cost constituent outlined in this section references the NRM standard specifically for building types; the related data can be found in the IFC quantity sets or the property sets depending on different BIM software. In cases that refer to the detailed measurement conditions, other information references should also be identified to set up constraints. For example, to get the particular property value of office space, the keyword ‘office’ should be searched out from IFC property sets so that the entity *IfcSpace* with ‘office’ property can be identified.

This hierarchy of the embedded data types in IFC 4 can cover the contents of both quantitative and qualitative assessment concepts/elements particularly on quantitative assessment at the movement. Although there are limited IFC data types that can relate to the current performance index of qualitative aspects, all the related documentation or contracts from reference projects could be sourced by getting their URI reference or metadata which is stored in related IFC data types. It is worth to mention that these datatypes could be valuable to store the key outputs and objectives which should be retained from project briefing documents. Additionally, a PPP project involves multiple assets. The set of projects or objects that refer to certain procurement resources or services can also be captured and visualized for better understanding. Table 10 shows a sample of the functional part using IFC data types. It is described within the exchange requirements to find the necessary IFC subset that corresponds to the specific element.

Table 10 An example of a functional part linking to IFC

Information Sub-group	IFC Entity	Related Attribute	Data type	IFC check (FOL expression)
		Structural Type	String	∀α(IfcSlab(α)) ∧ ∃α((IfcSlab(α) ∧ Query(α, IfcPropertySingleValue.Name)) ∧ Query(IfcPropertySingleValue.Name, "Type"))
		Material Type	String	∀α(IfcSlab(α)) ∧ ∃α((IfcSlab(α) ∧ Query(α,IfcMaterial))

Upper floor	IfcSlab	Gross Area	Real	∀α(IfcSlab(α)) ∧ ∃α((IfcSlab(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "GrossArea"))
		Function	String	∀α(IfcSlab(α)) ∧ ∃α((IfcSlab(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "Function"))
		Nominal thickness	Real	∀α(IfcSlab(α)) ∧ ∃α((IfcSlab(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "Thickness"))
		Structural Material	String	∀α(IfcSlab(α)) ∧ ∃α((IfcSlab(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "Structural Material"))
		Reference level	String	∀α(IfcSlab(α)) ∧ ∃α((IfcSlab(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "Level"))
Scaffolding	IfcWall	Structural Type	String	∀α(IfcWall(α)) ∧ ∃α((IfcWall(α) ∧ Query(α, IfcPropertySingleValue.Name)) ∧ Query(IfcPropertySingleValue.Name, "Type"))
		Material type	String	∀α(IfcWall(α)) ∧ ∃α((IfcWall(α) ∧ Query(α,IfcMaterial))
		GrossSideArea	Real	∀α(IfcWall(α)) ∧ ∃α((IfcWall(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "GrossArea"))
		Height	Real	∀α(IfcWall(α)) ∧ ∃α((IfcWall(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "Height"))
		Function	String	∀α(IfcWall(α)) ∧ ∃α((IfcWall(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "Function"))
		Structural Material	String	∀α(IfcWall(α)) ∧ ∃α((IfcWall(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "Structural Material"))
		Reference level	String	∀α(IfcWall(α)) ∧ ∃α((IfcWall(α) ∧ Query(α, IfcPropertySingleValue.Name) ∧ Query(IfcPropertySingleValue.Name, "Level"))
Project information	IfcProject	Name	String	∃α((IfcProject(α) ∧ Query(α, IfcProject.Name))
		Scope	String	∃α((IfcProject(α) ∧ Query(α, IfcProject.LongName, "Scope"))
		Description	String	∃α((IfcProject(α) ∧ Query(α, IfcProject.Description))
		Client Information	String	∃α((IfcProject(α) ∧ Query(α, IfcProject.LongName, "Client information"))
		Briefing document	String	∃α((IfcProject(α) ∧ Query(α,IfcDocumentation.Name) Query(IfcDocumentation.Name, "Briefing document"))

First-Order Logic (FOL) has been used to explain the method for IFC data extraction. The associative laws of logic in the expression are used to indicate the logical meanings(Solihin and Eastman, 2015). For instance, a checking rule states that “for measuring the upper floor cost, the gross floor area of floor slabs and the material information are checked.” The representation in FOL can be expressed as the following:

∀α(IfcSlab(α)) ∧ ∃α((IfcSlab(α) ∧ Query(α, IfcProperty) ∧ Query (IfcProperty, IfcPropertySingleValue.Name) ∧ Query (IfcPropertySingleValue.Name, "area"))∧ ∃α((IfcSlab(α) ∧ Query(α,IfcMaterial))

This rule shows an example to check the existence of properties and material information for related constraints. ∀α represents the variable structured by universal quantifier and ∃α represents the variable structured by existential quantifier. The query functions are applied to check the existence of an IFC entity or properties and also was discussed in section 5. The related IFC entity is *IfcSlab* which contains related attributes information. Followed the hierarchy structure defined in the IFC, the rule checks the existence of IFC entity *IfcProperty* and checks the existence of *IfcPropertySingleValue.Name* and checks the contents of the related string "area" within in *IfcPropertySingleValue.Name* and then checks the existence of *IfcMaterial* using the query function. The *IfcProperty and IfcPropertySingleValue* are the IFC entities that contain property information, *IfcMaterial* is the IFC entity contains material information relates to the building element.

By using ontology to represent the information exchange schema as the technical representation enables MVD developers and software vendors to manage the information and data in a single knowledge map. In Section 4.3.3, the OWL/XML represented ERs and FPs are used and delivered to software applications.

4.3.3 Automatic data extraction

To validate the developed schema, a Data extraction tool for VfM (DfV) was developed to stress the technical feasibility by using the proposed information exchange schema. The developed schema represented as OWL/XML format is used to clear the hierarchy of information items for practical implementation. The concept templates of the FPs are used to control the valid mapping between related objects and IFC structure. The mapping rules are edited in a .NET C# program. Figure 25 indicates the process implemented for checking the required data type corresponding to the functional part defined in VfM requirements. To query and implement rules for checking IFC structure, IFC engine DLL, a set of open read/write toolbox is used to check responding IFC datatype and help develop the software interface. This testing process functioning on BIM model later shows that such an information exchange scheme simplifies the process of obtaining related data from BIM.

The attributes in IFC (related to the cost estimates) are the physical quantities linking with the related projects or objects. Based on certain circumstances, the rules for checking related datatypes state that the target object will be checked first and then the acquired attributes are located, as shown in Figure 26. For example, to measure the cost of wall finishes, the ‘gross side area’—as the defined physical quantity in the *IfcWall*—was used to capture the value directly. Moreover, ‘name’ and *IfcMaterial* were also located so that programming could obtain the cost specification. *IfcPropertySet* is used to store additional data annotations, which are not written into *IfcElementQuantity*. The requirement of getting the ‘gross area’ of floor slab could reference the related IFC property sets, such as *IfcPropertySet*, or *IfcElementQuantity* and go a step further to check whether the required data type is connected with *IfcSlab*. Based on the method defined in the IFC engine, the categorized rule sets were coded and implemented for checking the required IFC data type corresponding to the functional part. As Figure 27 illustrates the accessibility of checking IFC entities including different information sets, users can select the following options to activate:

- Functions that select the assessment structure—to get the related assessment index in the quantitative or qualitative contents, this development references the NRM and VfM assessment structures for the elements in cost estimates. ‘Work estimates’ is the most relevant to cover most aspects of building works. The main contractors’ preliminaries and the contractors’ overheads, profits prepared using prices, and the other external costs elements in PSC are also included in the structure and can link to different databases based on project circumstances.
- Functions that select the measurement methods—based on different cost estimate scenarios, the floor area method, functional unit method, and the elemental method are used to capture cost estimate units in IFC. In the developed scheme, these methods should all be stressed to benefit the assessment.
- Functions that select the functional part linking to the IFC—at the initial stage of this development process, the research followed IFC4 conceptual data schema. Because the required properties or quantities might sometimes have various locations in IFC structures, this scheme should be able to retrieve the related entities, attributes, properties, and relations in different model scenes.

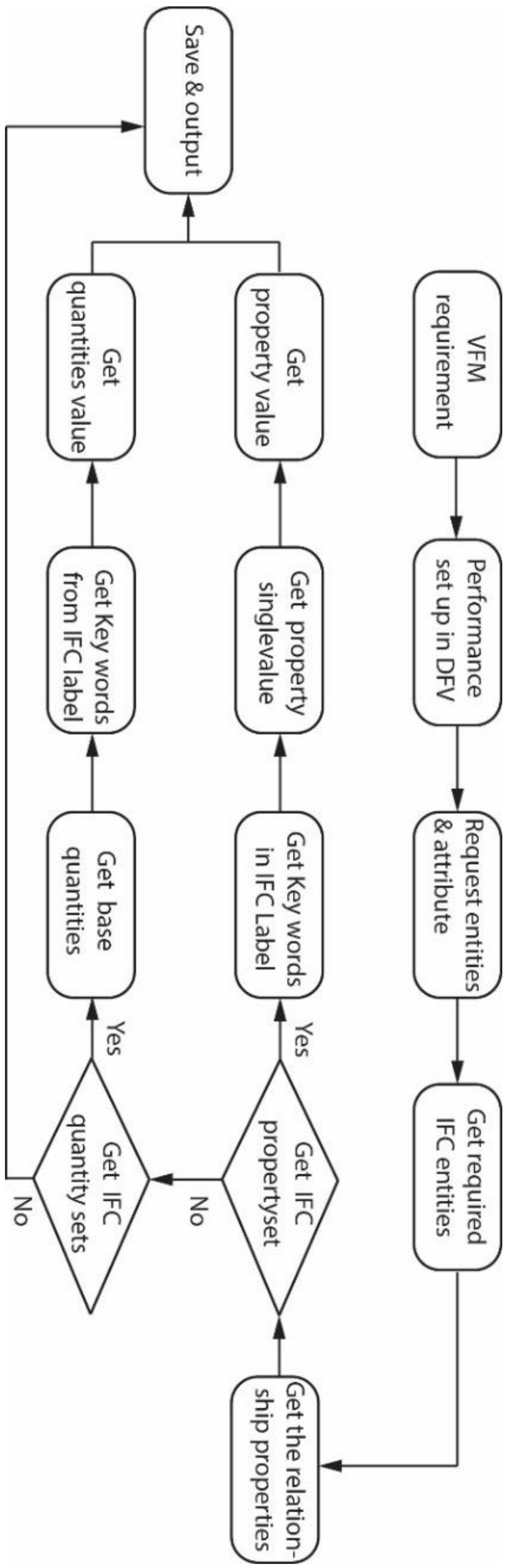


Figure 25 Data extraction process using IFC 4

Figure 26 An excerpt of constraints checking using IFC Engine

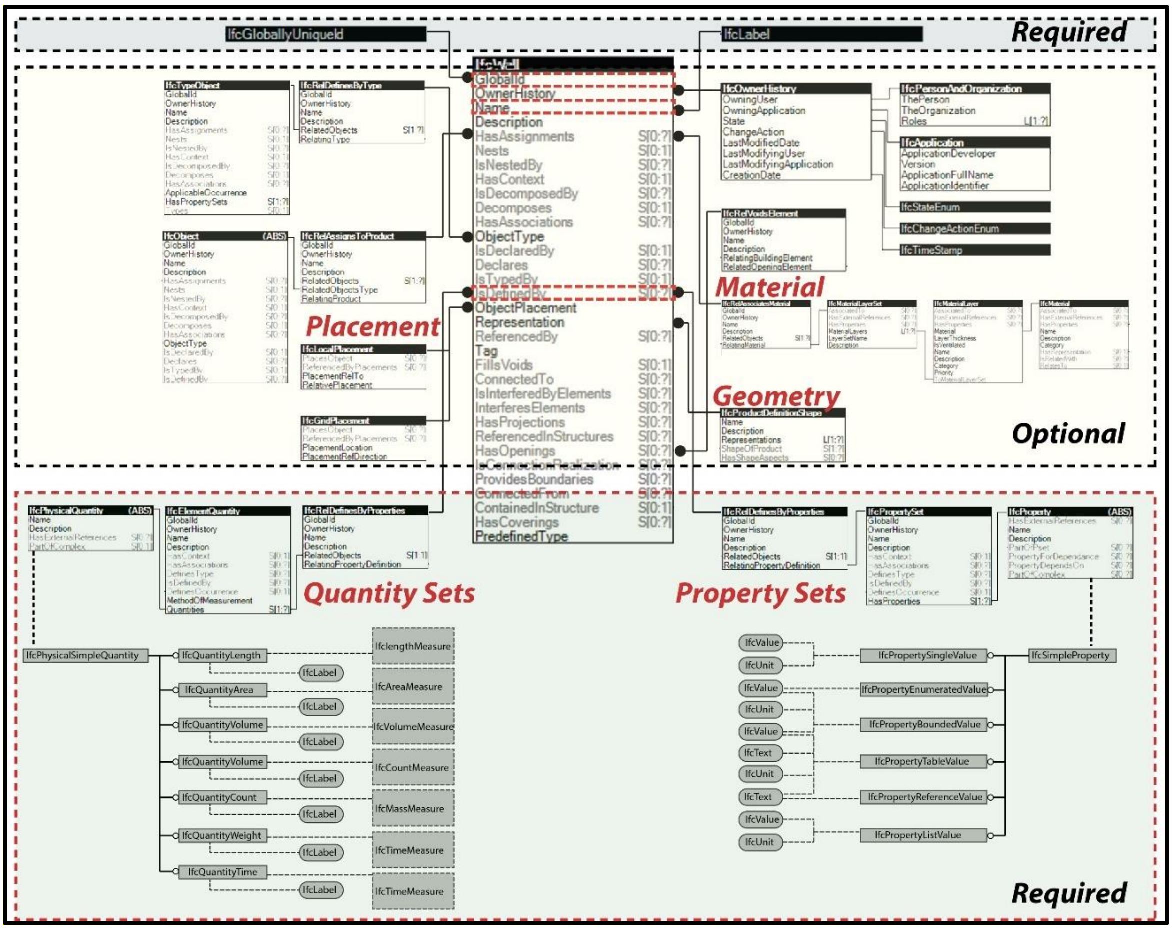


Figure 27 Data extraction based on IFC 4 data structure

More specifically, in the developed DfV, the ERs by defining the functional rules in different information catalogs can be selected and edited. Both the information group (on the left-hand side of Figure 28) and FPs (on the right-hand side of Figure 28) can be viewed. For instance, the information group 'Substructure' option provides a convenient channel that includes all the information sub-groups and FPs can work more specifically to help the user define in what type of datatype help to measure the value of the currently selected information group.

According to the NRM, the cost estimates during the project's early stage should be performed based on the available information. The information in BIM could support the cost estimates by providing the correlated value from simple to complex and from the initial concept model to the federated BIM model. The present DfV is defined to be operated from the strategic assessment until detailed design approval because the current rules of data extraction do not deal with the construction stage, which requires higher precision computations of the digital model quantities. However, the value calculated in the quantitative assessment can support the project's approval by using available information in the design stage. The DfV can be used for different circumstances by BIM-based context projects, in which the parties, such as the clients and project managers, can use such a BIM-based tool to stream the data for VfM. Through the process of quantifying the relevance of different entities to the particular type of measurement, this DfV tool enables a more convenient and efficient analysis for PPP projects.

Based the information accessibility, an airport project BIM model created in Autodesk Revit by design institution is selected to run the DfV tool to explain further how the proposed method can function on the BIM model by the project manager when taking multiple performance criteria into account. The airport procurement also is one of the most common PPP procurement and it requires massive information support from engineering perspectives. The model contains architecture and structure elements that satisfy most aspects of cost items for calculating the cost for substructure and superstructure. An IFC analyzer software that can generate spreadsheets from an IFC file is used to view the input and output IFC entities at once. Based on the FPs and users' defined scenarios, the input IFC which contains 908288 entities is retrieved and filtered for further assessment. In the report catalogs, the output of the DfV also includes an excel data sheet that contains the useful information sets defined in the ERs (Figure 29). By execution of the DfV, the corresponding quantities are extracted in different cost catalogs as well as the material and position information.

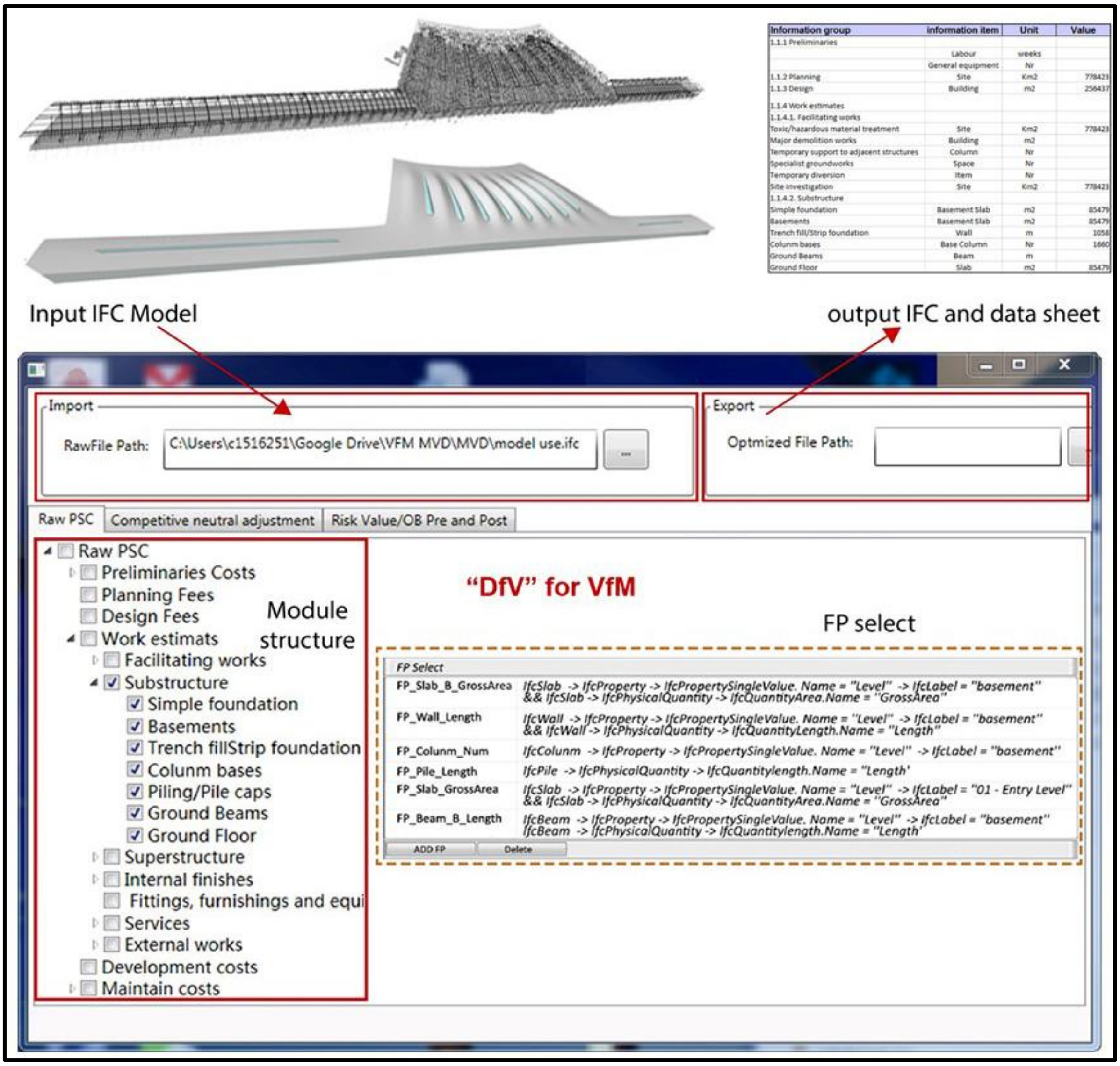


Figure 28 DfV interface and data extraction process on airport BIM mode

Input IFC Summary

IFC File	Input.ifc	
IFC Directory	C:\Users\c1516251\Desktop	
Excel File	C:\...\Input_ifc.xlsx	
Application	Autodesk Revit 2017 (ENU)	
Timestamp	2018-03-12T15:05:38	
Total Entities	908288	
Entity	**Count**	**IFC4**
IfcBeam	5560	Doc
IfcBuildingElementProxy	15	Doc
IfcBuildingElementProxyType	4	Doc
IfcColumn	1660	Doc
IfcColumnType	166	Doc
IfcCovering	651	Doc
IfcCurtainWall	34	Doc
IfcCurtainWallType	4	Doc
IfcDoor	1007	Doc
IfcElementAssembly	12	Doc
IfcFurnishingElement	104	Doc
IfcFurnitureType	12	Doc
IfcMember	3308	Doc
IfcOpeningElement	144	Doc
IfcPlate	1349	Doc
IfcPlateType	159	Doc
IfcRailing	35	Doc
IfcReinforcingBar	620	Doc
IfcRoof	5	Doc
IfcSlab	3781	Doc
IfcSpace	116	Doc
IfcStair	10	Doc
IfcStairFlight	20	Doc
IfcWall	987	Doc
IfcWallStandardCase	166	Doc
IfcWallType	5	Doc
IfcWindow	241	Doc
IfcLightFixtureType	3	Doc
IfcFlowTerminal	41	Doc
IfcArbitraryClosedProfileDef	252	Doc
IfcArbitraryProfileDefWithVoids	57	Doc
IfcCircleProfileDef	434	Doc

Output IFC Summary

IFC File	Output.ifc	
IFC Directory	C:\Users\c1516251\Desktop	
Excel File	C:\...\output_ifc.xlsx	
Application	Autodesk Revit 2017 (ENU)	
Timestamp	2017-12-19T02:04:03	
Total Entities	13893	
Entity	**Count**	**IFC4**
IfcBeam	5560	Doc
IfcColumn	1660	Doc
IfcCovering	651	Doc
IfcDoor	1007	Doc
IfcSlab	3781	Doc
IfcWall	987	Doc
IfcWindow	241	Doc
IfcBuilding	1	Doc
IfcBuildingStorey	4	Doc
IfcSite	1	Doc

Useful Value

Information group	information item	Unit	Value
1.1.1 Preliminaries			
	Labour	weeks	
	General equipment	Nr	
1.1.2 Planning	Site	Km2	778423
1.1.3 Design	Building	m2	256437
1.1.4 Work estimates			
1.1.4.1. Facilitating works			
Toxic/hazardous material treatment	Site	Km2	778423
Major demolition works	Building	m2	
Temporary support to adjacent structures	Column	Nr	
Specialist groundworks	Space	Nr	
Temporary diversion	Item	Nr	
Site investigation	Site	Km2	778423
1.1.4.2. Substructure			
Simple foundation	Basement Slab	m2	85479
Basements	Basement Slab	m2	85479
Trench fill/Strip foundation	Wall	m	1058
Column bases	Base Column	Nr	1660
Ground Beams	Beam	m	
Ground Floor	Slab	m2	85479

Figure 29 Summary of input and output of DfV

This chapter presents the use of the standardized IDM approach to defining the categories information required for different VfM indicators and can cover more information items based on measurement requirements in the future. First, the standardized application of BIM as the precondition to guarantee the automatic assessment should be well stressed in the PPP procurement contracts. IFC data management is not used to store and deliver project information to a great extent. The current financial management system at the procurement level is completely separated from the engineering management system at the project level. There is no suitable and efficient connection between these information management systems. A considerable amount of information in infrastructure projects exists; the unintegrated information management systems will influence the accuracy and reliability of information delivery, which leads to the low efficiency of management quality. At this point, IFC may become the possible unified project information delivery standard in the future. This is mainly because, in IFC, the structure of the data is rationalized and can be recognised by various language systems. The established assessment methods and standards are difficult for computers to recognize. Ontology, at this point, may function as an efficient way to develop the knowledge base and deliver the project information requirement in different scenarios. The rules defined in the ontology can be used to query or evaluate the information index to achieve better concessionaires' benefits.

Chapter 5. Knowledge development

This chapter outlines the core contributions of this research. The ontology development in this chapter contains most of the knowledge construction used in the current VfM assessment framework. The chapter is divided into three main parts, which are knowledge base development (Section 5.1), LD–supported knowledge reasoning (Section 5.2), and proposed workflow of VfMO (Section 5.3).

In Section 5.1, the conceptual system framework is first introduced to define the logic expression of the VfMO system. The developed environment is presented in Section 5.1.1. The generation process of the VfMO ontology is presented in Section 5.1.2, and it defines the semantics and domain knowledge between related concepts extracted from the standardized process and guidance. The main body covers the VfM assessment, while the section also includes elements of other green performance measurements. Other separate ontologies were developed to represent the common knowledge in project management and the financial system. All the integrated ontologies were merged into the VfMO.

After the knowledge base was built up, Section 5.2 aims to present a cohesive alignment between IFC data and the designed ontologies based on practical purposes. This is unlike previous research approaches, which aimed to convert IFC to RDF as the ontological format for BIM geometries. This research presents a more direct way of achieving this and follows a LD theory. The alignment was divided into three parts: First, the reasoning rules and queries concerning the VfM are presented in 5.2.1. Second, Section 5.2.2 introduces the alignment of all the related concepts between the VfMO and other information sources, such as the IFC-based information management structure, which together form the ontological environment. At last, the systematic workflow in Section 5.3 stress all the developed knowledge are presented.

5.1 The VfM knowledge base

Several studies have addressed the feasibility of using ontology to create a knowledge base in the AEC industry. For example, Hou et al. (2015) developed an ontological system named the Ontology for Sustainable Concrete Structure (OntoSCS) and an SWRL rules-based reasoning mechanism to offer optimized structural design solutions. In the research, the structural design and sustainability-related domain knowledge were modelled using formal structured ontology. The SWRL rules attached in the OWL files were used to calculate the values of embodied energy and to select the material suppliers. Tomašević et al. (2015) proposed the airport facility ontology model, which represented the general facility management knowledge related to the significant energy consumers of the infrastructure. Zhang et al. (2018) presented a holistic approach based on ontology to support early design stages by considering the safety, environmental impact and cost. Boje (2018) developed a crowd simulation ontology that supported building evacuation design; this method provided a reasoning-based quantitative understanding of the material selection and its overall performance based on different design alternatives.

There exists an increasing trend of OWL adoption in many domains. In terms of the compatibility of the ontology editor used in this research, the software supports most language syntax selected to build a knowledge base.

5.1.1 Used Ontology editor

Protégé (version 5.2) is an open-source developer tool that enables both developers and end-users to build up an ontological knowledge base. Protégé is compatible with OWL syntax including OWL/DL and OWL-related syntax, including OWL/XML, RDF/XML, Turtle, OWL functions, LaTex and JavaScript Object Notation for Linked Data (JSON-LD). Protégé 5.2 was also chosen for use in this research because of its supported plug-ins for research purposes.

• Ontology reasoner

Pellet is a reasoner that supports OWL 2 and provides standard and cutting-edge reasoning services.

• Rule and query function

SWRLTab is a plug-in that provides the development environment for creating SWRL rules and Semantic Query-Enhanced Web Rule Language (SQWRL) queries. SQWRLTab is a graphical interface supported by SWRLAPI to execute SQWRL queries. It provides a convenient way to accept results in Protégé.

The build-up process references 'Ontology Development 101' due to its easy feasibility and the specific guidance provided about the software environment (McGuinness, 2000). Also, the construction followed the principle defined in W3C to create substances and rules.

5.1.2 VfM Ontology development

There are several steps used in building up the VfMO, which are outlined as follows:

Step 1: Determine the domain and scope of the VfMO.

It is essential to define the domain and scope at an early stage of ontology development. The purpose and scope have to be determined by considering the current application. In this step, the competency questions are made which is either open or closed-answer questions will be asked using straightforward natural languages to indicate the contents and level of details in the newly created ontology. answering competency questions allows knowledge engineers to determine the scope of the ontology. Some of the questions that were asked to create the ontology that was employed in this study, together with the corresponding answers, are as follows:

Q: Why develop the VfMO?

A: The aim is to improve the management efficiency concerning multi-domain knowledge and support the financial sector in PPP procurement, allow the management team to clarify work tasks and provide valuable information to decision making.

Q: What will this VfMO be used for?

A: This developed ontology will be used in the early stages of the procurement justification phase and can provide measurement and query functions for decision making.

Q: What domain knowledge will be covered in this ontology?

A: VfM assessment, construction codes, required materials, cost structures, project parties, financial management, project management gateways and risk management will be covered.

Q: Who will use the ontology?

A: Procurement managers, clients and finance managers will use this ontology.

Q: What are the sources for the knowledge base?

A: The basic source used for building up the knowledge base was the VfM guidance published by national departments such as HM Treasury from the UK and the Ministry of Finance in China. The VfMO also directly references the existing cost measurement guidance in engineering procurement and other information relating to project management and information delivery standards, such as ISO standards.

Q: How can the VfM be evaluated using a developed knowledge base?

A: VfM assessment requires more compatible results in line with both quantitative and qualitative aspects. For qualitative assessment, the evaluation of the VfMO is achieved by listing certain levels of independent control indexes. Each index should be evaluated based on the information supported in the knowledge base. For the quantitative aspects, the VfMO also aims to provide information exchange, query and calculation. Through the LD approach, the combined interface also allows for automatic assessment.

Step 2: Consider reusing existing ontologies.

There exist developed ontologies or proper translations from existing schemas that can be used or merged into a new VfMO. By sourcing the available reusable ontology from the web, the following reusable ontologies can contribute to the knowledge framework:

1) IFC 4 Ontology (ifcOWL): This ontology was established under standard IFC schema and can be used to share and exchange building information between project parties (‘IFC Introduction - buildingSMART’, n.d.). The Industry Foundation Classes Web Ontology Language (ifcOWL) provides a web ontology language that is represented in OWL format (Figure 30). Due to the fact that the IFC is the open standard for representing construction data, the ifcOWL makes the entire IFC EXPRESS schema available in the ontological environment. Using the ifcOWL, the related building data can be presented using state-of-the-art web technologies and can enable IFC data to become editable in directed labeled graphs (RDF) and integrated with all the other data sources. In this way, using the existing ifcOWL in the VfMO can improve data management and exchange in the construction industry and beyond.
2) Financial Industry Business Ontology (FIBO): The FIBO was developed as the open industry common language standard for defining the relations and terms used in financial activities (EDM Council, 2018). The FIBO was developed based on the ‘build, test, deploy, maintain’ methodology, which is an integration of a series of ontologies in OWL. It is a representation of the ‘things’ of financial services. The use of FIBO in VfMO ensures that all the related financial concepts in the real world can be unambiguously framed and provide readable information to both humans and machines (Fig 31).

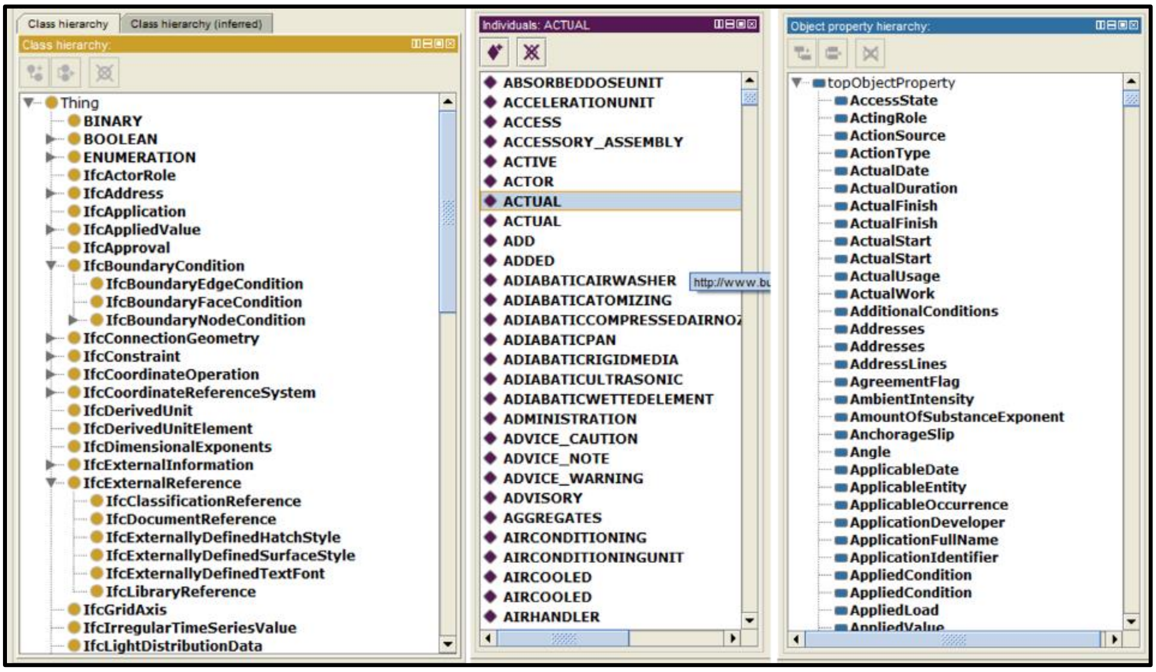


Figure 30 The IfcOWL in Protégé

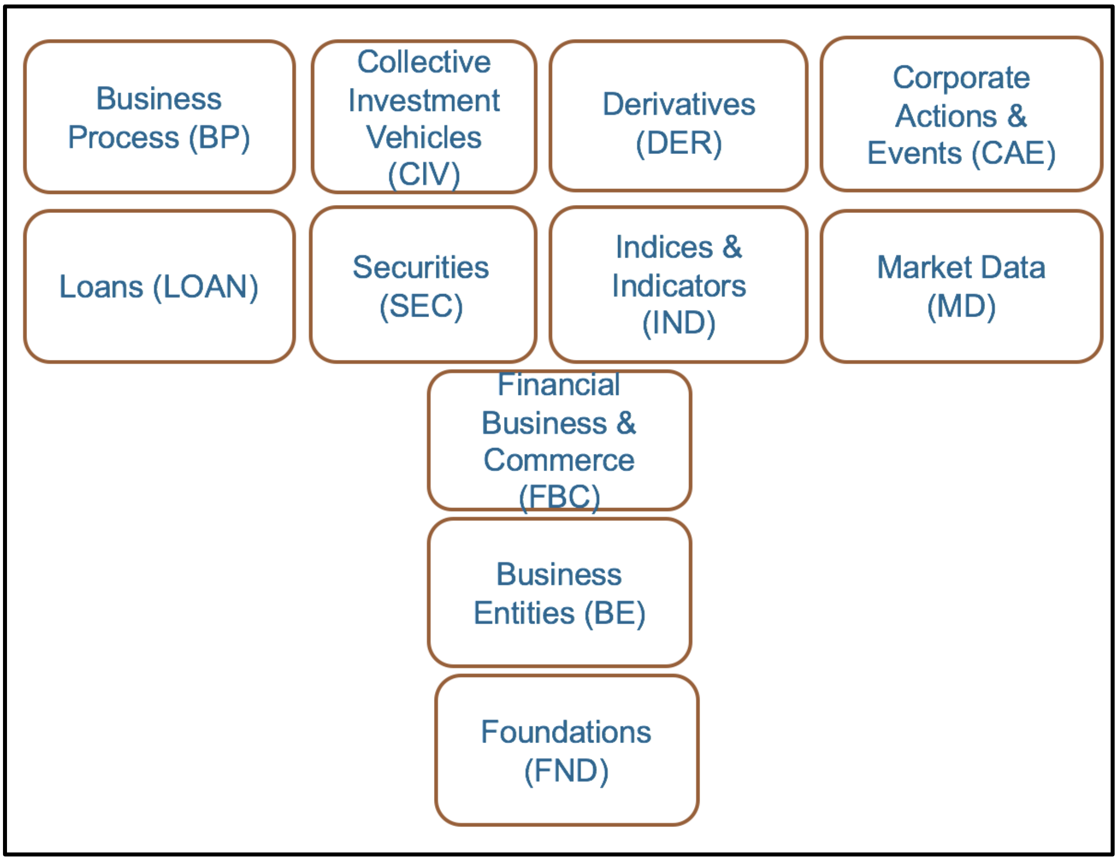


Figure 31 The FIBO ontology.

Step 3: Define the crucial terms (entities) used in the VfMO.

Based on the scope of the research, a glossary of essential work items was obtained from different sources in the literature and from governmental bodies, as presented in Table 11. The key concepts were associated with the VfM assessment itself and include detailed working items in cost estimate guidance and procurement management gateways. Based on these available resources, comprehensive knowledge of all the concepts related to VfM was generated in this step.

Table 11 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 Green 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

Step 4: Define the classes.

In this research, a top-down approach was used to build up related entity classes. The general classes were added first, and then the subclasses were attached and broken down into additional classes. Specifically, these main super-classes include 'CostEstimatesLibrary', which contains the standardized measurement structure for cost estimates; 'DocumentInformation', in which the required documents are defined in BS-1992 and ISO-12006 for the procurement information; 'Object entity', which contains all the related objects, including 'project' and the corresponding IFC entities; and 'Material', which contains the material information relating to construction elements. 'OrganizationStructure' and 'Party' contain all the related business sectors and the project or procurement roles that were extracted from the existing FIBO ontology. 'VfMProfile' includes both the qualitative and quantitative measurement approaches and detailed structures. 'Risk' is used to gather the related risk-oriented costs or the allocation results of the procurement. 'Stage' was added to index the procurement phases defined in PPP guidance, Uniclass and other gateways. After the definition of these related concepts, new properties should be attached to most general classes for further development. The class hierarchy is presented in Figure 32.

Step 5: Define the properties.

To make the reasoning functions, the properties must necessarily incorporate class hierarchy. A property, as defined in OWL, consists of three types: 'ObjectProperty', 'DataTypeProperty' and annotation properties. The object property is used to describe the relationship between objects and the instances or individuals within the class. For example, the '*HasDocument*' property is used to connect the entity 'Project' and the class 'DocumentInformation'. Figure 33 indicates the relationship between different classes using an object property. The data type property can be set to construct links between object and data values in both a quantitative and qualitative way. 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 types of facets, such as 'string' or 'int' can also be attached within user-defined data properties such as thickness and width (Figure 34). All the properties are built based on collective knowledge to link different classes and instances. The annotation property is used to describe the classes and properties and to explain the instances. As shown in Figure 35.

Step 6: Create instances.

Instances are crucial elements that can be used for information sharing and exchange. In the VfMO, instances referring to particular classes were added. The following activities must be performed to build an instance: 1) instances were 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 pre-defined between different instances using pre-defined object properties. For example, the instance 'Project' should have the '*HasDocument'* property, which links to a specific instance, such as 'SiteInformation'. An example of an instance that contains several data properties is shown in Figure 36.

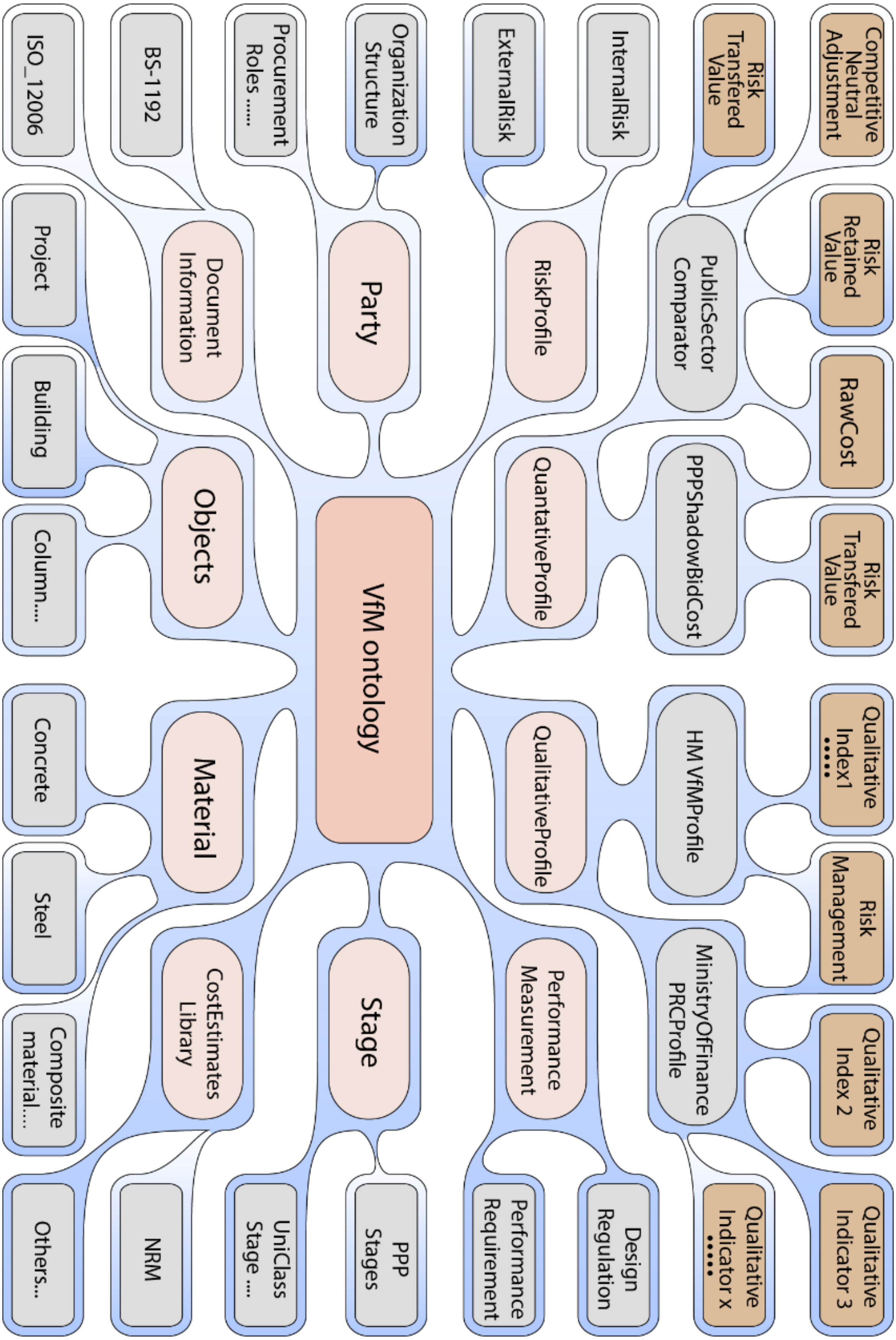


Figure 32 The Class hierarchy in VfM ontology

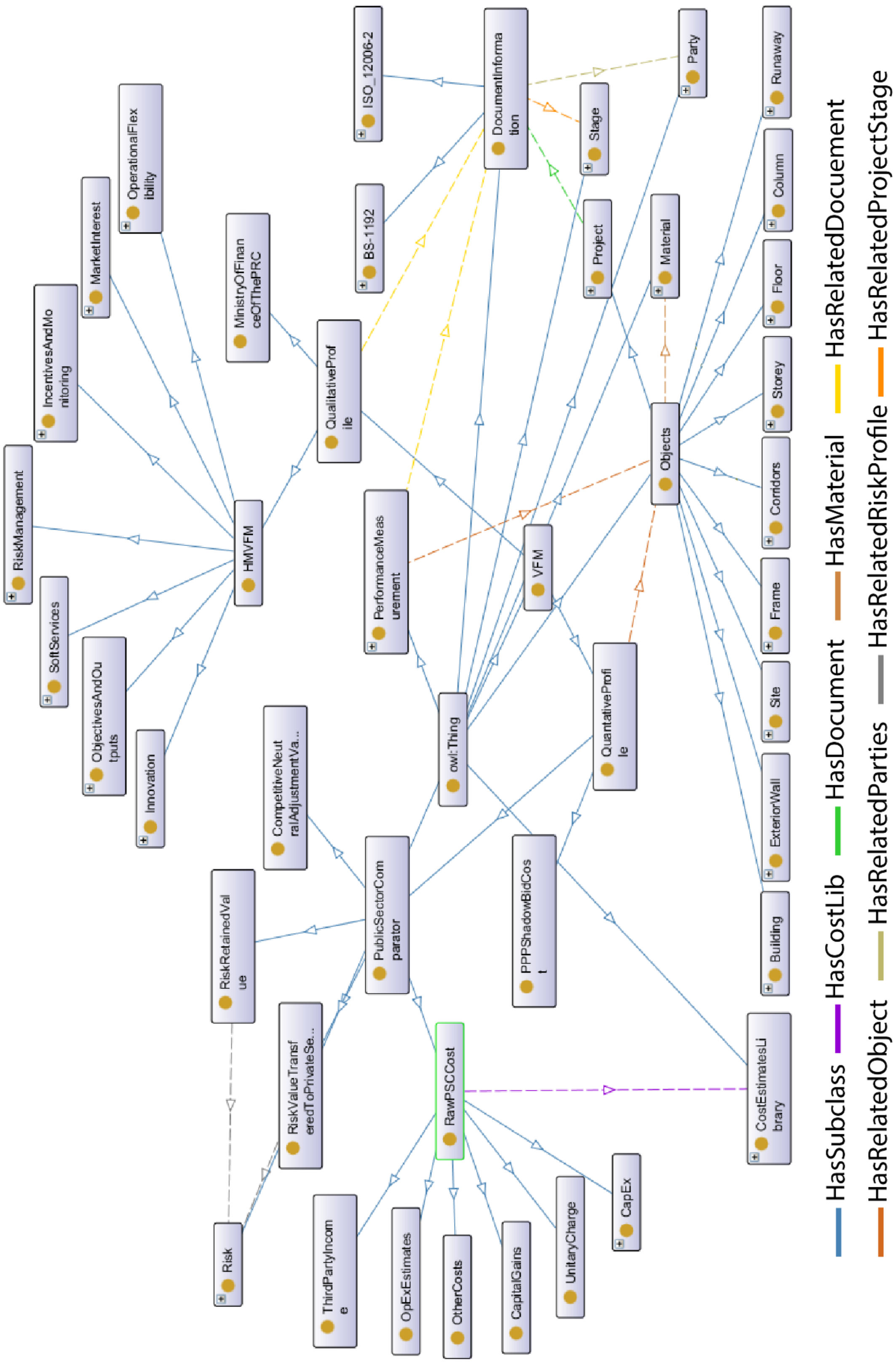


Figure 33 A High-level overview of VfM ontology

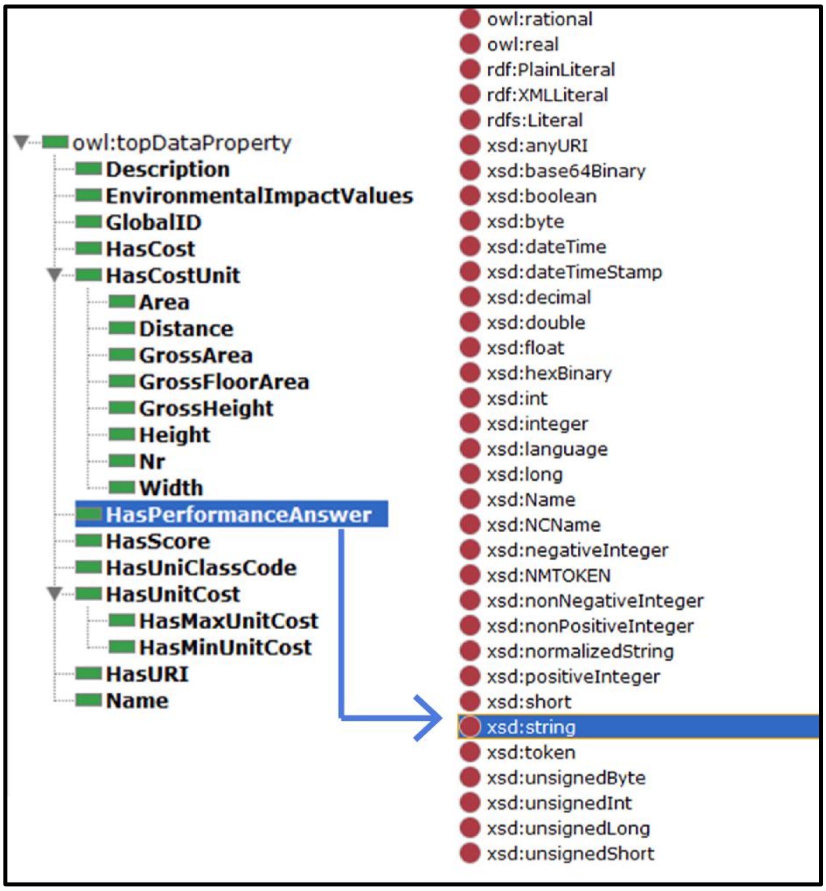


Figure 34 The data property and the corresponding facets defined in VfM ontology

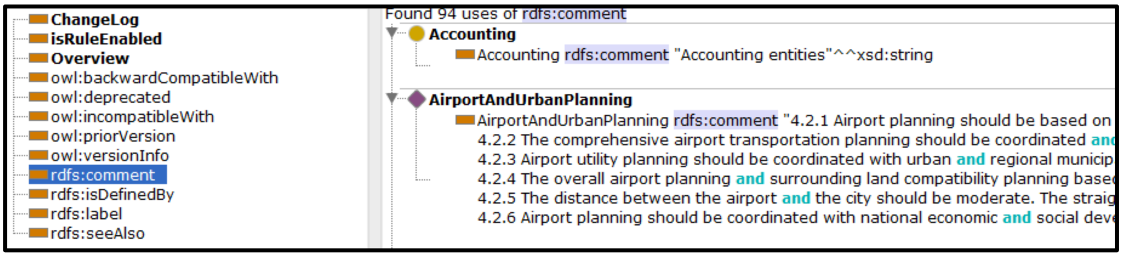


Figure 35 The annotation property defined in the VfM ontology

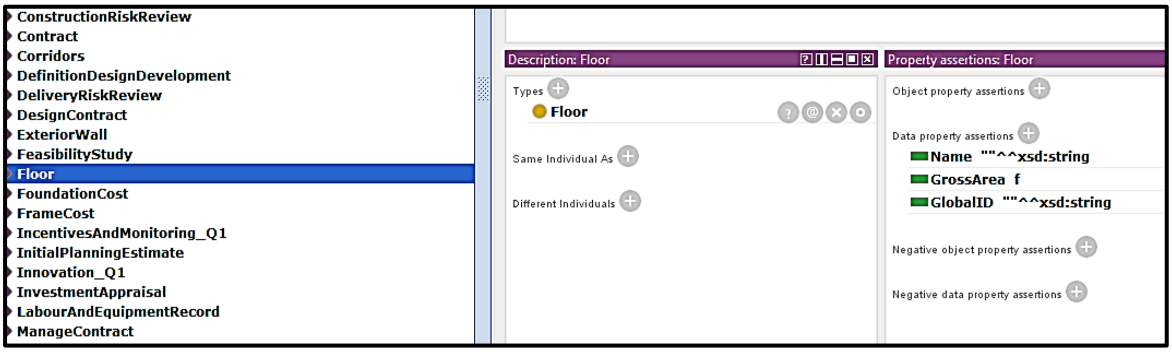


Figure 36 An instance of a floor in VfM ontology

Step 7: Define and clarify the fundamental relations in the VfMO.

There are few questions and corresponding answers that help indicate the relationships defined in the VfMO. They are as follows:

Q: How can the requirements be captured by the ontology?

A: As discussed in previous chapters, most of the ontology was created manually to work as a knowledge base. This knowledge base has the flexibility to be edited by end-users as well. The SWRL written in this knowledge base represents the most functional rules defined in standardized guidance or processes.

Q: What element exists within the VfMO, and specifically the main body?

A: The VfM class contains hierarchical concepts that are included in the assessment structure. It contains two main categories: 'QualitativeProfile' and 'QuantitativeProfile'. At present, they closely resemble the features and objects defined in most financial ontologies. There are two subcategories included in the qualitative and quantitative profiles: 'HMVfM' and 'MinistryOfFinanciOfThePRC' separately contain the qualitative evaluation indexes, such as 'ObjectiveAndOutputs'. The entity classes 'PPPShadowBidCost' and 'PublicSectorComparator' contain the cost-related elements, following the structural orders.

Q: How is the relationship defined in the VfMO for qualitative assessments?

A: Figures 37 and 38 indicate the basic logic defined in the qualitative assessment. The blue represents the defined entity class, which contains the subclass and individuals. Each individual of the subclass has inherited the fundamental relations using the object and data properties defined from the upper class. For instance, take the qualitative assessment profile; here, each individual belongs to the subclass 'ObjectiveAndOutputs', representing an assessment instance that has the basic data property '*HasPerformanceAnswer'* to conclude the evaluation feedback, while the '*HasScore'* represents the assessment results. In addition, '*HasRelateDocument'* properties were set up to build links between the qualitative index and documentations. The instance in the documentation represents the procurement document, which contains basic data such as URI and identification information. In this way, based on the requirement of qualitative performance indicators and ISO 12006, the corresponding document can be aligned with the assessment. It is worth mentioning that, due to the various explanatory notes on indicators, this connection method can still be effectively workable by applying particular connections to standardized documents. The individual and corresponding annotations in the qualitative class are presented in Figure 39.

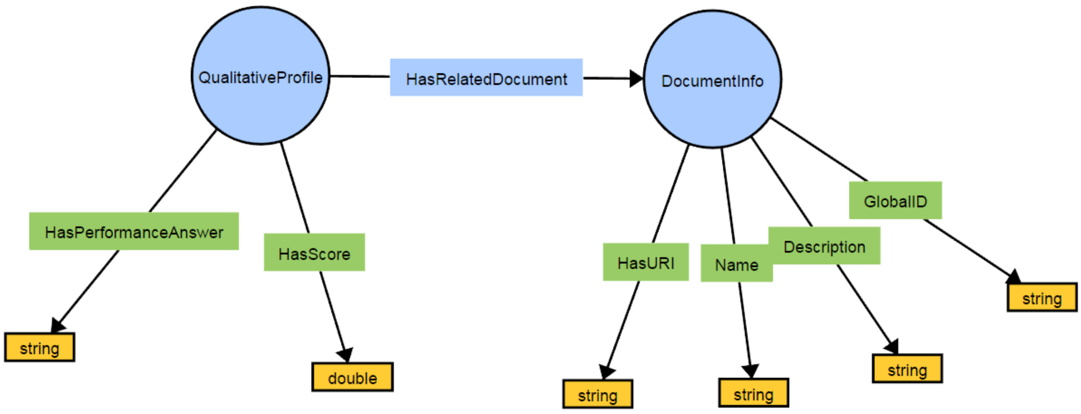


Figure 37 Main classes in qualitative profile (a)

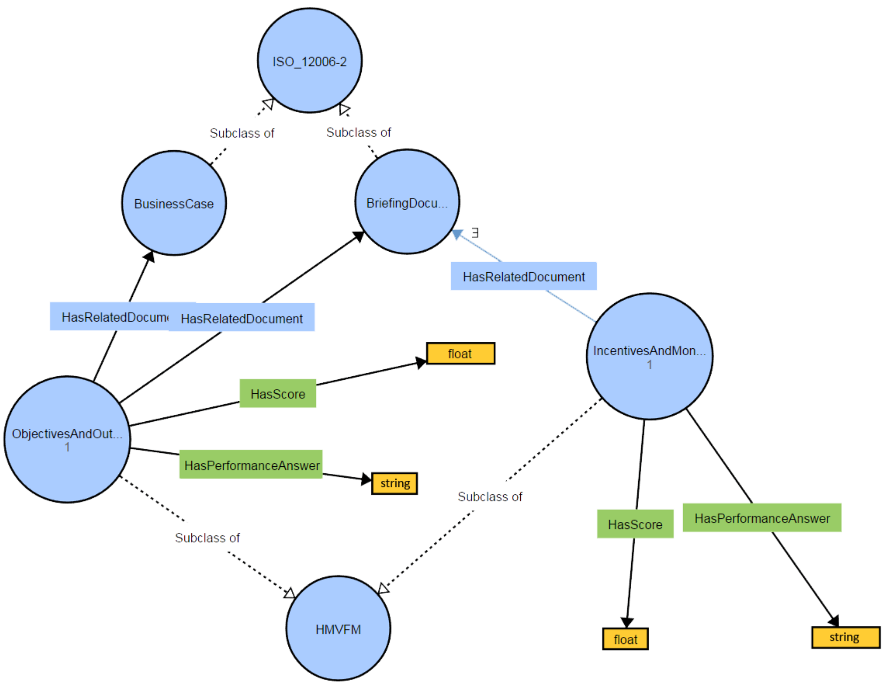


Figure 38 Main classes in qualitative profile (b)

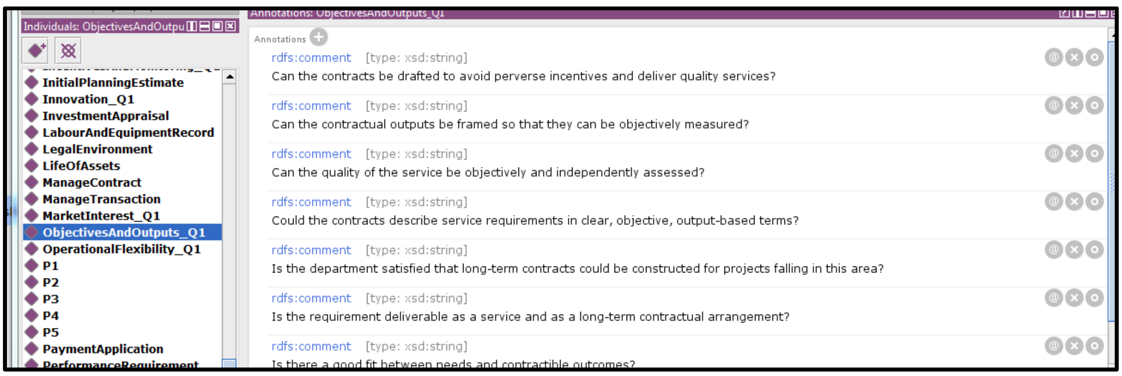


Figure 39 Instance and corresponding annotations in the qualitative class.

Q: How is the relationship defined in the VfMO for quantitative assessments?

A: Following a similar logic to build up a relationship using object and data properties, as showed in Figure 40, the most characteristic upper-level entity class is defined for all the cost-related activities in the quantitative profile (i.e., ‘Object’, which contains the most generalization of any semantically treated thing or process). In this research, the development only refers to physically tangible items in construction and includes ‘Project’ to represent the entire thing in the procurement boundaries. Future development also can involve processes such as work tasks. ‘Object’ is represented virtually within a digital model and was used to represent the building elements. Additionally, when considering a cost scenario (e.g., measuring the construction frame costs), an alignment between frame objects is used to create a functional connection. Each cost index also has a corresponding cost estimates library (‘CostEstimatesLib’), which can be used to store unit cost information. The instance in the object class represents the work items and has different datatypes attached for cost measuring. It is important to stress at this point that not all subclasses in ‘CapEx’ or ‘OpEx’ of the quantitative profile can be related to objects. However, the cost database or information sources can still be related to those subclass elements by creating links to the project document or by manually inputting values.

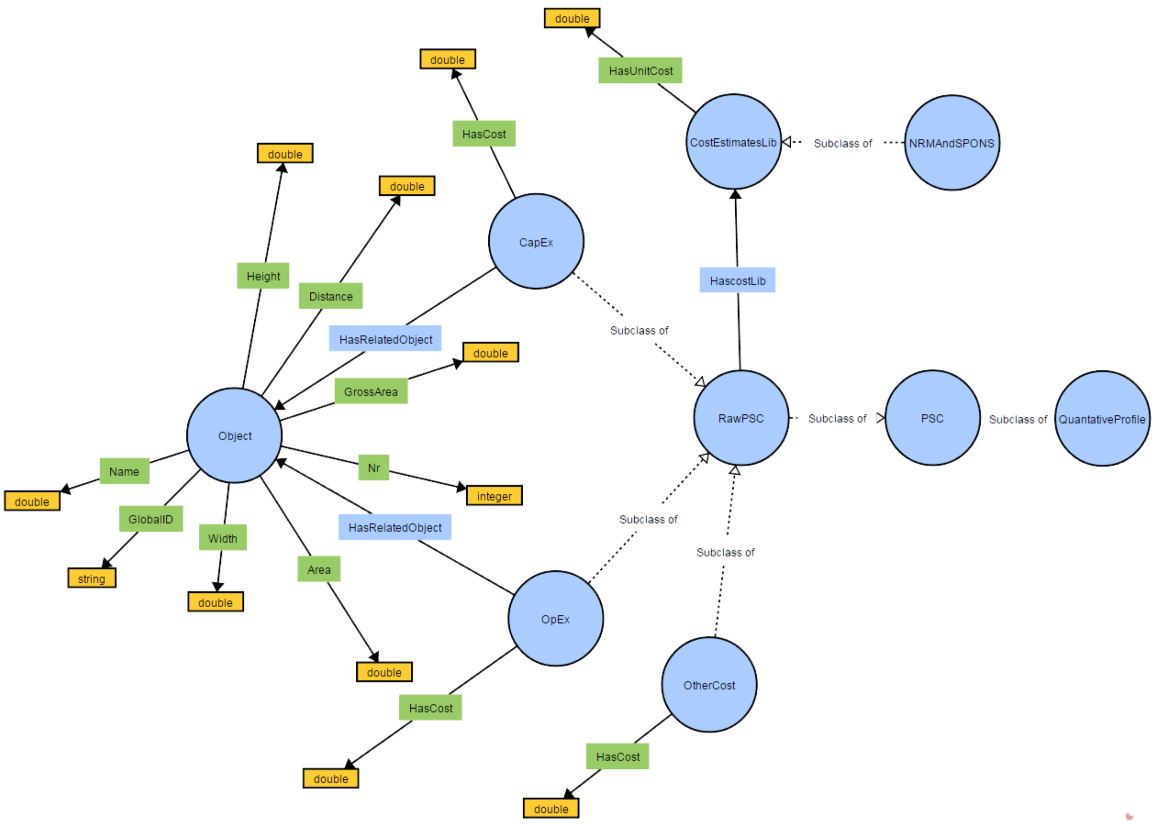


Figure 40 Main classes in quantitative profile

Q: How are relationships defined in PM?

A: PM can vary significantly between different project types. Due to the limited time and available resources, this research only gathered performance checking rules from the 'Chinese Green Airport Planning Performance Guidance' targeted at the early design stage. A performance indicator (PI) can be outwards either to documentation information or to object information. The subclass instance represents the performance indicators. An instance such as 'AirportAndUrbanPlanning' has 'rdf: comments' that indicate the specific requirements. Based on the annotations, the instance can be connected to the 'Object' or 'DocumentationInformation' class. The specific links can be editable for the project users to make it dynamic based on scenarios. Figure 41 and 42 separately show the main classes and instance in PM profile.

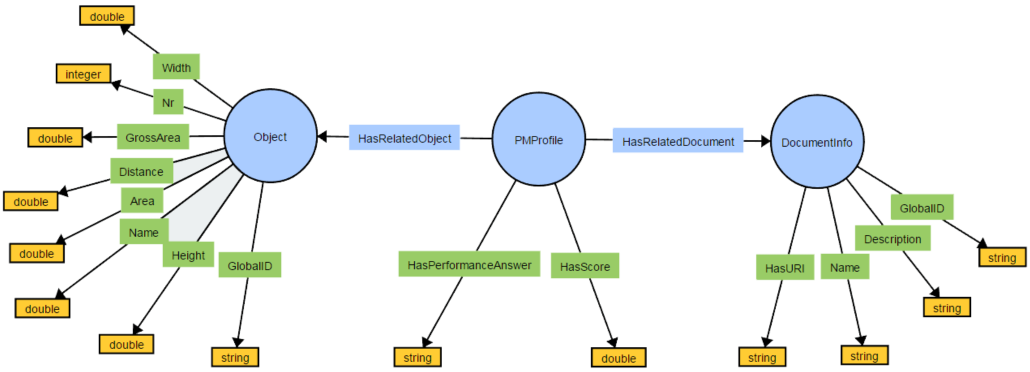


Figure 41 Main classes in other design performance profile

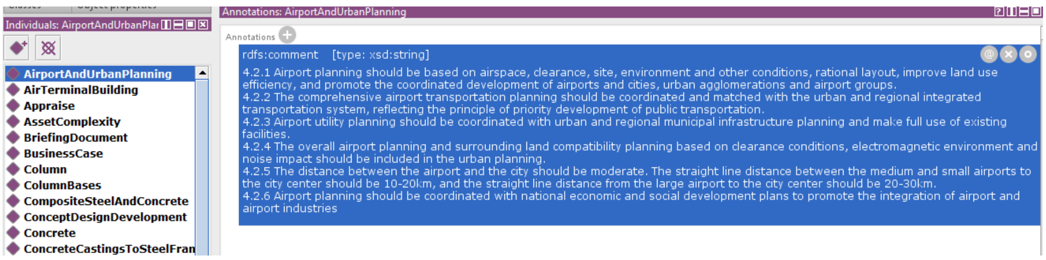


Figure 42 Instance and corresponding annotations in the design performance class

Q: How is the relationship defined for the project parties and stages?

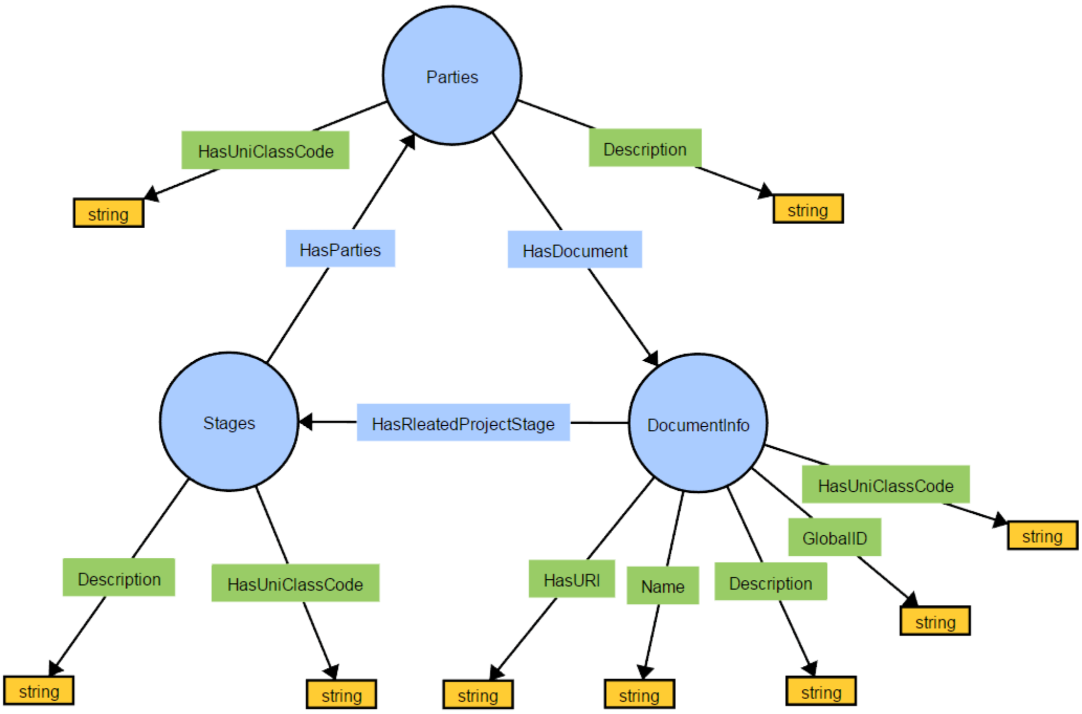


Figure 43 The relationship between project parties and stages

A: This VfMO was constructed based on existing knowledge, which was, in most cases, standard definition with codes. UniClass2015, as the consistent classification structure for disciplines in the construction industry, can be referenced for different project stages, parties and documentations with specific codes. In the classification, instances of documentation can also link to the instance stages through the '*HasRelatedProjectStage'* property. The 'Parties' instance is connected with instances in 'Stages' using '*HasParties*'. The subclass of the parties also followed the pre-defined class type in the FIBO, following the ISO standard. Meanwhile, the instance parties can also link to documentation information using '*HasDocument*'. In this way, the project documentation can be connected with project stages, and more parties and reasoning functions can be integrated (Figure 43).

Q: How is the relationship defined for risk management?

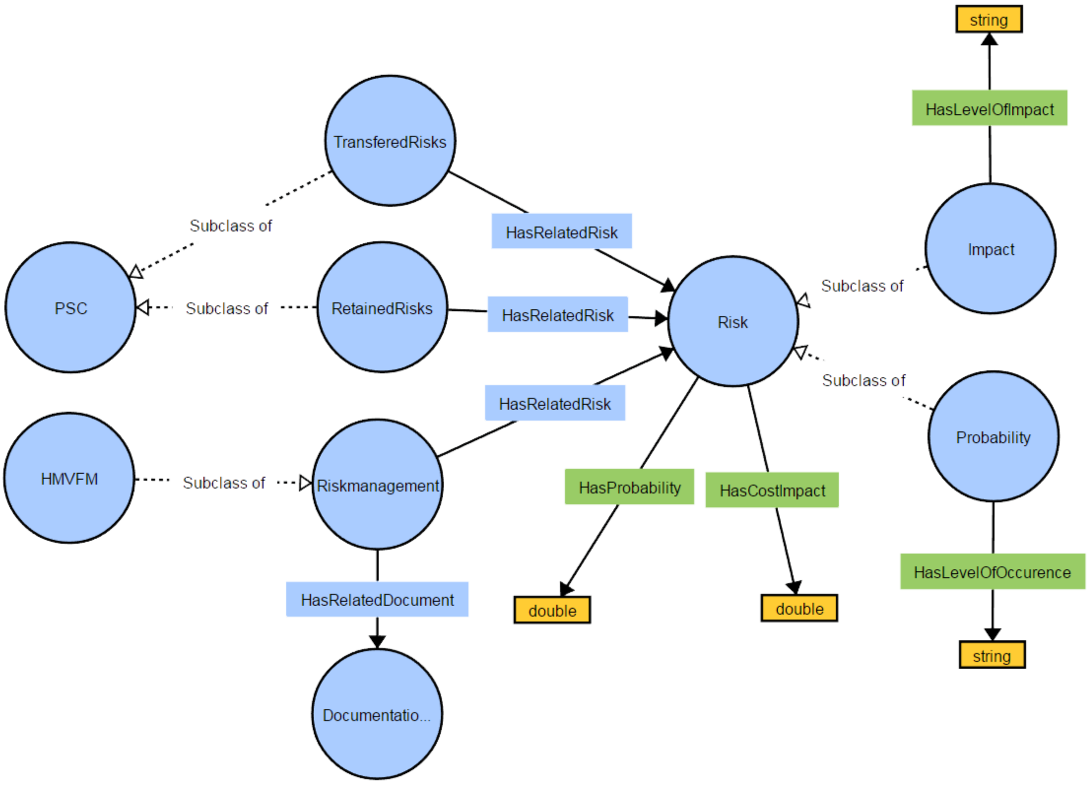


Figure 44 Main classes in other Risk management profile

A: The developed VfMO relates to risk management in that it lists all the related risk events concerning internal and external risk indicators extracted from literature reviews and project risk reports. These risk indicators are set in the 'Risk' class; this class contains both 'Impact' and 'Probability', which help in identifying and measuring risk results. 'PerformanceRiskMangement' in 'QualitativeProfile' can be connected to 'DocumentationInformation' using '*HasRelatedDocument'* properties (Figure 44). The risk atoms should be able to link to the external information sources automatically; however, this is not currently the case due to the fact that there are still no available resources to utilize for more comprehensive risk forecasting, such as a big data analysis approach. The current development only uses a probabilistic method to capture the possible risk costs and can also be used for risk allocation by end-users. In this process, pre-defined information is needed to set up a possible risk probability or impact.

Step 8: Create query and reasoning rules.

To implant the semantic functions, rules should be established and integrated with ontological items. This research aims to integrate the reasoning and query rules with the constructed ontology. Hence, the SWRL rule is used to create such interoperability, as it provides the reasoning functions and contains a straightforward approach to connect different atoms using the symbol '∧'. SWRLTab in Protégé is used to develop rules. In addition, the query functions are needed to identify specific work items or work scenarios. SQWRL, which is the query language aligned with SWRL, allows the end-users to obtain the required information. SQWRLQueryTab is used to develop query rules. Using both functions, the following types of atoms can be connected:

1) The class atom, which includes a named class in the VfMO.
2) The individual property atom, which contains object properties in OWL.
3) The data valued property atom, which includes data property in the OWL ontology.
4) The built-in atom, which can support a lot of complex predicates. This is a particularly useful feature of SWRL.

Rule Description	Based on the Rules defined in the SPONS – the construction cost database (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)

In the rules, an implicit symbol '∧→' is used to connect different classes and individual atoms. Additionally, the symbol '→' is used to connect antecedents. Variables in atoms are represented using the interrogation identifier '?'. Based on the rules defined in the standardized references, an entity such as 'UpperFloorCost' or 'IncentivesAndMonitoring' represents the named class that contains individuals, such as '(?U)' or '(?IM)', that represent the information instances. Object property atoms, such as '*HasCostLib'* and '*HasDocument'*, were previously set up to construct the relationship in the ontology. The rules will 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 that corresponds 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 syntax 'swrlb: multiply' and 'sqwrul: select' work as built-in atoms to carry out the basic calculation and section functions. Table 12 illustrates the meaning and function of the example of the atoms used in the reasoning rules in the VfMO.

Table 12 Description and function of used atom in VfMO

Atom Type	Atom Name	Description
Class atom	GreenPerformance(?G)	GreenPerformance(Class) contains instance?G
	Site(?S)	Site(Class) contains instance?S
	Building(?B)	Building (Class) contains instance?B
	Project(?P)	Project (Class) contains instance?P
	ObjectivesAndOutputs(?O)	ObjectivesAndOutputs(Class) contains instance?O
	BriefingDocument(?B)	BriefingDocument (Class) contains instance?B
	IncentivesAndMonitoring(?I)	IncentivesAndMonitoring (Class) contains instance?I
	Runaway(?R)	Runaway (Class) contains instance ?R
	FrameCost(?FC)	FrameCost(Class) conatins instance?FC refers to the frame cost
	Frame(?F)	Frame (Class) contains instance?F refers to the frame object
	FrameLib(?x)	FrameLib(Class) contains instance ?x refers to the material
	FoundationCost(?FC)	FoundationCost(Class) contains instance?FC refers to cost value
	Column(?C)	Column(Class) contains instance?C refers to the Column object
	FoundationCostLib(?x)	FoundationCostLib(Class) conatins instance ?x refers to the material
	RiskEvents(?x)	The Risk events (Class) contains risk event instane?x.
Object property atom	HasDocument(?S, ?x)	Instance ?S has document which contains instance ?x
	HasRelatedDocument(?S,?x)	Instance ?S has related document which contains instance ?x
	HasRelatedObject(?S,?x)	Instance ?S has related object which contains instance ?x
	HasMaterial(?F,?x)	Instance ?F has material which contains instance ?x
	HascostLib(?FC,?x)	Instance ?FC has cost Library which contains instance ?x
	HasCost(?FC,?s)	Instance ?FC has cost which contains value ?s
Data property atom	Name(?S,?x)	Instance ?S has name which contains value ?x
	HasUnitCost(ConcreteFrames, ?c)	Instance 'Concrete' has unit cost which contains value ?c
	HasURI(?S,?x)	Instance ?S has URI address which contains value ?x
	Description(?S,?x)	Instance ?S has description which contains value ?x
	Height(?S,?x)	Instance ?S has height which contains value ?x
	GrossArea(?F,?a)	Instance ?F has gross area which contains value ?a
	Width(?F,?w)	Instance ?F has width which contains value ?w
	Nr(?C,?n)	Instance ?C has number which contains value ?n
	Rating(?C,?x)	Instance ?C has the rating which is ?x.
	DeliveryTime(?C, ?DT)	Instance ?C has the delivery time which is ?DT.
	BiddingPrice(?C,?BP)	Instance ?C has the bidding price time which is ?BP.
Individual Property atom	SiteInformation	Instance named 'SiteInformation'
	AirportAndUrbanPlanning	Instance named which refers to green performance measurement rules
	BusinessCase	Instance named 'BusinessCase' of the Class refers to the document
	BriefingDocument	Instance named 'BusinessCase' of the Class refers to the Document
	AirTerminalBuilding	Instance named 'AirTerminalBuilding' refers to the building object
Built-in atom	sqwrl:select(?x)	Select the instance ?x
	swrlb:lessThan(?w, ?x ^^xsd:float)	A value ?w is less than the value ?x which is defined as float type
	swrlb:multiply(?s, ?w, ?a)	A value ?s is the product of value ?w and ?a

Step 9: Applying VfMO.

In this research, due to limited time and various regulations in different procurement types, the developed VfMO now focusses on the currently available resources. The reasoning and query functions have touched different aspects relating to VfM assessment, and a thorough knowledge base will be developed in the future. The defined SWRL and SQWRL rules responding to the measurement requirements are listed in Appendix C. Several main functions of the VfMO are presented below:

1) It provides automatic calculation/assessment: Based on the rules defined in the VfM guidance, the VfMO can identify working items and the related information items. The cost of calculating the working items can be implemented. Meanwhile, the assessment approach relating to the qualitative evaluation is also pre-defined in the ontology.

2) It assists in selecting procurement parties: The ontological model contains a list of procurement parties, including essential information such as company names, addresses, contract details, contract information, and so on. Adding the procurement parties into the reasoning functions can allow end-users to identify a suitable resource based on business management (for instance, if a document should be developed by a particular party). It can also be used for responsibility checks.

3) It assists in identifying document information: Project documentation is vital information to assemble because it supports the assessment. Having the standardized documents gathered with codes can improve the information index. The instance within the document class represents the document itself, which can be connected to procurement parties, project stages, risk allocation events, qualitative assessment.

4) It provides events reasoning for risk management: The developed knowledge base can be used to help in risk management to identify the events that might cause fluctuation on costs. The risk events are classified into catalogs relating to both external and internal perspectives. The risk entity set in the ontology can support decision-makers in visualizing the relationship between the involved elements, and users can also sort these events in chronological order, define them and understand their influence more efficiently.

In terms of the standardized VfM assessment, the developed SWRL rules can be used to support procurement decision-makers to manage risk events and select the required parties. The information can be sourced from different management sectors or market reports. In addition, the VfMO can be used to rate performance based on existing information. To do this, the expert can query all the crucial information about procurement elements, such as the location, parties, and related document information.

5.2 Semantic and syntactical validation of the VfMO

Some methods for evaluating an ontology's quality and validity have already been developed. This validation consists of ensuring the semantic correctness, ensuring the syntactic correctness and verifying if the ontology meets the required conditions or does what it was intended to do.

The ontology in the present study was developed to use existing ontologies and can use semantic validation to validate its alignment, and merging or comparison techniques can be used for semantic validation (Noy and Musen, 2003). Consulting domain experts and performing a comparison with other ontologies that can be sued newly developed VfMO are based on existing knowledge that is further integrated as one. All the concepts that were incorporated into the VfMO were extracted from standardized knowledge guidance and have been identified and proven to be practical. Domain professionals then evaluated the logic built up in the VfMO.

After semantically validating the ontology, it is imperative to validate the knowledge base syntactically. It is necessary to check the subsumptions, equivalence, instantiation and consistencies (Antoniou *et al.*, 2012). There are two main steps to complete within syntactical validation: manual checks and automatic checks. In this research, the automatic checking process uses the ontology reasoner Pellet, which is a functional plug-in in Protégé. Pellet allows the user to check and eliminate errors followed the syntax defined in the ontology, as shown in Figure 45, which displays the applicable reasoner. Based on the messages, anomalies can be identified and presented to the user. In this study, syntactical validation was successfully conducted. After semantic and syntactical validation to check the developed VfMO as a knowledge base, the VfMO was further validated through the use of a case study, as described in the following section.

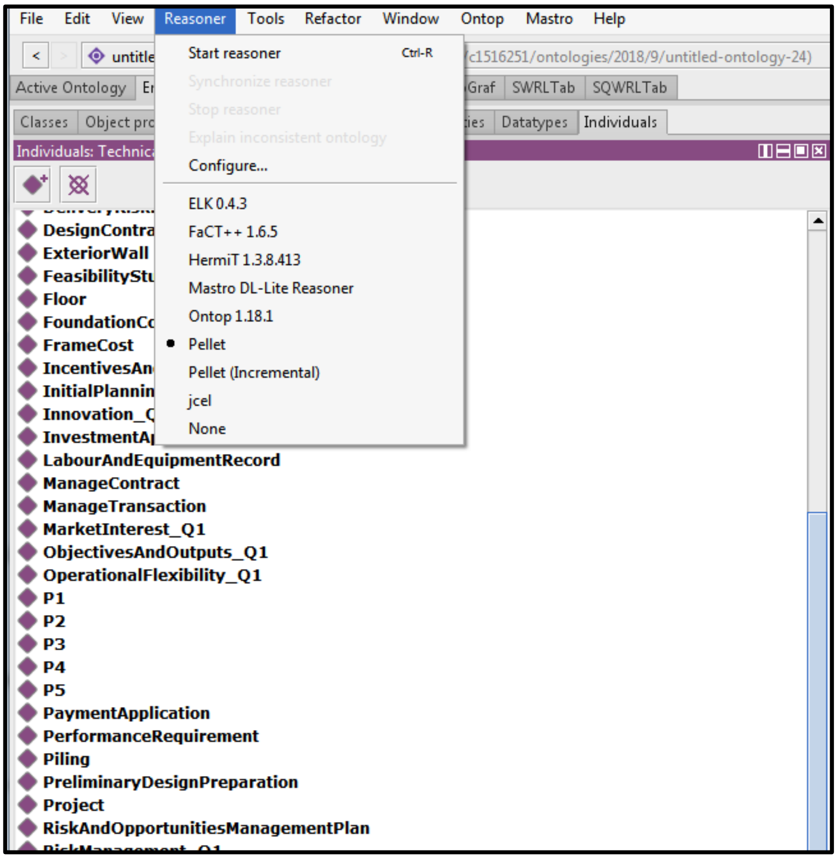


Figure 45 Reasoning process in VfMO

5.3 Alignment in the VfMO

In the area of computer science, defined concepts are expressed as labels in different data formats. There is, therefore, a need for ontology alignment to integrate those heterogeneous databases. The SW involves newly developed ontologies, which is critical to link with each other. The tools used within ontology can enable a semantic equivalency for the defined terms. Euzenat and Shvaiko (2007) identified three dimensions that can be used to define such similarities, stressing the syntactic, external and semantic features. An ontology alignment scheme is used in XML, taxonomies and entity-relationship models that can be converted to a graphical representation. Within this, two main methods are used: monolingual ontology mapping, which refers to mapping in the same natural languages, and cross-lingual ontology mapping, which refers to the establishment of the relationship among different ontological resources from different natural languages (Fu, Brennan and O'Sullivan, 2012). This research mainly gathered existing knowledge using the same OWL representations and progressed the alignment of these representations to a relatively small degree.

In addition, alignment of the ontology to the data source is necessary, but this is not represented using ontology data formats such as the IFC supported BIM system. An approach to translating the represented IFC scheme into an OWL or RDF format does exist; however, the translation process can be time-consuming, and the results can frequently lead to missing-data (Pauwels, Pauwels and Deursen, 2015). At the moment, the LD approach is used to align ontology and other data sources to fulfill semantic queries (Bizer, Heath and Berners-Lee, 2009). For this approach, the platform builds open standard web technologies using RDF for sharing and functions automatically in computer applications. However, the conversion of IFC data to RDF data is not suitable for a large construction project and is hard to visualize, making rule functions complicated when using a large BIM model. The translation between IFC and RDF has its advantages in collaborating with SWRL rules; however, this is still limited to certain development engines and makes it difficult to collaborate with other development environments and data sources at the production level. The currently developed automatic conversion method is time-consuming and requires a high-performance computer to process the conversion when dealing with high-capacity BIM models. By using the concept of LD to align an open data source (i.e., the BIM server) with a developed knowledge base, this research proposes using a Java parser and XML syntax to integrate the operation of pre-defined rules and query functions.

Figure 46 clarifies the technical representation used in the VfMO in this research. The developed VfM aims to integrate related knowledge from different project management domains and dynamically link data between the BIM server and developed knowledge base.

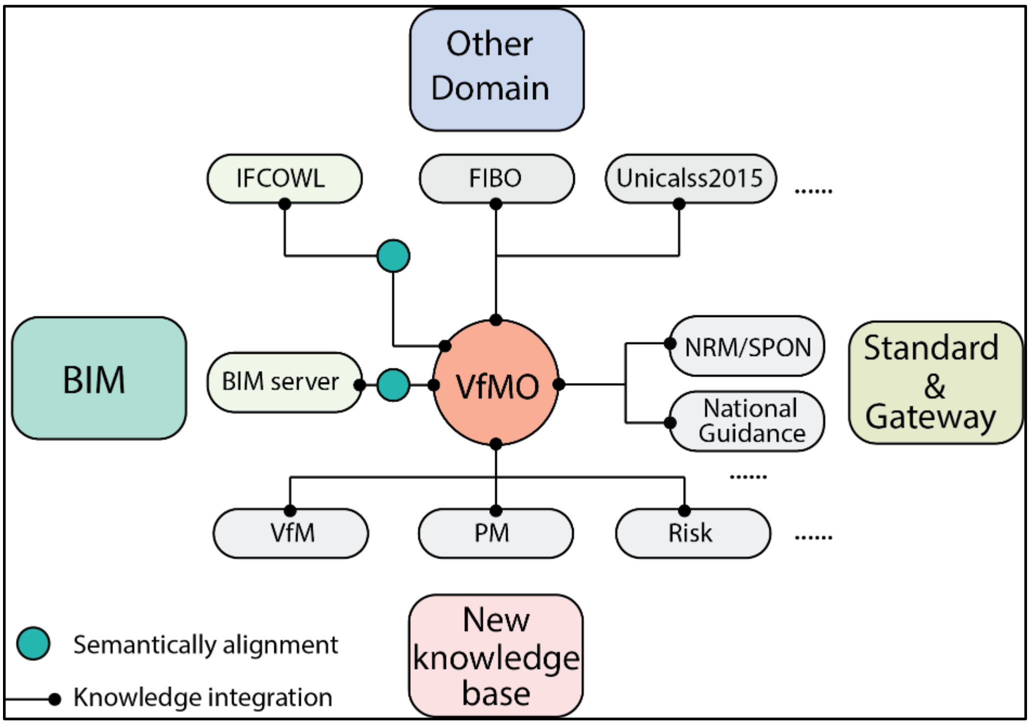


Figure 46 The primary knowledge used in the VfMO development

As mentioned above, there are two basic approaches used to align different knowledge and information sources. First, newly developed knowledge in ontology refers to VfM and risk management as semantically connected with the used standard and gateway and other domain ontologies (Section 5.2.1). This is achieved using the basic functionality provided in Protégé. By creating relationships between different entity classes within their individuals, these domain knowledge bases are combined and ready for further functionality to set up rules. Second, the LD approach presented in Section 5.2.2 will highlight the alignment between BIM and ontology. During this process, both IFC and the developed SWRL rules will be restated as XML syntactical structures for further analysis. This process is presented manually in this research to explain the underlying logic at the data level, but it can be automatic in future development.

5.2.1 Ontological alignment of concepts

There are multiple ways in which ontologies can be aligned (Fu, Brennan and O'Sullivan, 2012). The type of semantic alignment can use 'subsumption', 'equivalence' and part of any user-specified relationship. One of the most reliable methods for OWL used in this study is to use similarities to equalize the different concepts in terminology and structure. Predicating the similarity of the defined terms and concepts by typically expressing logical equivalence or inclusion is an efficient way to align separate semantic structures. The logic used in this research is explained as follows:

$$VfMO = \{C_i, R_i, I_i, T_i, V_i\};$$

$$IFCO = \{C_j, R_j, I_j, T_j, V_j\};$$

$$\exists x \in Ci; \exists y \in Cj; x \approx y$$

where VfMO represents the value for money ontology (the main body) and IFCO represents the ifcOWL. Within them, C is the set of classes, R is the set of relationships (object properties), I is the set of individuals, T is the set of data types and V is the set of values. As stated in previous chapters, BIM is regarded as the current core of processes in engineering practice, and its function is to manage project information at multiple levels. The IFC model should be connected, allowing the VfMO and another knowledge base to collaborate for information access. The ifcOWL is the ontological representation of the IFC schemas, and it was able to map across hierarchies of classes. In this way, the aligned schema can help the software vendor to capture the key information directly from the IFC rather than doing unnecessary work. The common concepts used in the IFC are illustrated in Figure 47.

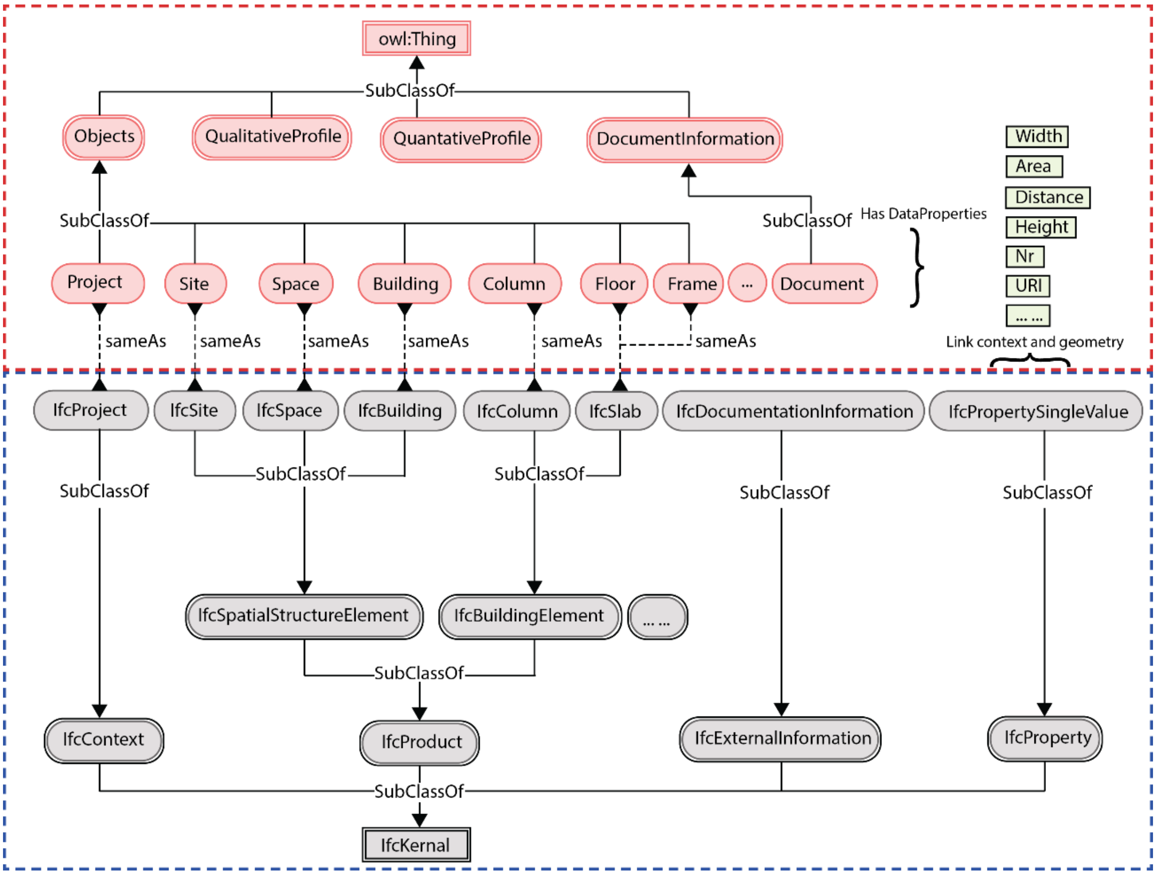


Figure 47 Alignment of classes between the VfMO and IfcOwl.

There are a thousand classes and logical axioms in the ifcOWL ontology. In this study, a relatively small number of classes can be used and aligned because the IFC schema has been applied in the construction domain to describe objects with geometric representations. Entities such as '*IfcBuilding*', '*IfcColumn*' and '*IfcSlab*' are subclasses of '*IfcBuildingElement*' and can be linked with objects defined in the VfMO due to these concepts containing the same roles. The document set in the VfMO can also have a corresponding entity in '*IfcDocumentationInformation*'. The attributes in the object or models in the IFC schema are usually stored in '*IfcProperty*' within '*IfcPropertySingleValue*'. The defined data properties in the ontology, which are used for expressing the context and geometries, are connected to the attributes of the '*IfcPropertySingleValue*' attributes by defined specific alignment rules. Using the 'owl: SameAs' axiom or the 'equivalent to' function in Protégé, those concepts can be linked in class, which means all the instances can inherit the pre-defined object or data properties. The '*IfcProperty*' is necessary because there is a little ambiguity in identifying the equivalency; for instance, not all the '*IfcSlab*' datatypes in the building represent an element such as 'frame', which is used for measuring frame costs.

Therefore, the attribute annotation that is stored in '*IfcPropertySingleValue'* in most cases can be used to map the correct work items (see Section 5.2.2).

Using this alignment indicates that the complicated engineering information schema can be expressed in ontological formats. The SWRL rules can also present benefits in identifying IFC entities, such as the following SWRL rule:

Slab(?s) -> sqwrl:select(?s) now equivalent to IfcSlab(?s) -> sqwrl:select(?s)

It is worth highlighting that, from practical experience, defining the specific alignment based on assessment performance rules can be regarded as additional work. There can be significant differences in how specific geometry or attributes can be linked to the knowledge base. However, to improve the query times and provide a better understanding of software vendors, efficient alignment between the IFC and ontology is still needed and is necessary to declare in the knowledge base. On the basis of structural differences in how the information is stored, the storage and retrieval methods for complicated information is currently impossible using only simple matching. A more direct approach is recommended to translate the ontological rules to overcome this limitation. This study uses syntactic analysis to retrieve and convert the rules to the common computer-readable format and make it possible for software developers to translate SWRL rules. This process is described in the following section.

5.2.2 Alignment between IFC and VfMO

While the previous section aimed to help software vendors identify the entity alignment between the ontology and IFC express schema, this section stresses the alignment between IFC and OWL, particularly by parsing IFC and translating SWRL rules. The logic presented in this section follows the following structure: Section 5.2.2.1 introduces the BIM server as the IFC process environment. Section 5.2.2.2 gives a specific explanation of parsing and checking the IFC. Finally, Section 5.2.2.3 indicates the process of mapping SWRL into a Java-based environment.

5.2.2.1 BIM server

As mentioned in Chapter 3, the BIM server (BIMserver.org) platform enables users to build up their own BIM operating system. Based on the open standard IFC, the BIM data are interpreted using smart codes and can be stored as object information in the underlying database. The functional operations, such as model-checking, authorization, merging and logical reasoning, are available to process. As shown in Figure 48, many plugins can be merged into the server for different commercial and practical purposes.

The BIM server used in this research was chosen for its solid foundation to build fast and reliable niche applications. The BIM server also currently has the highest IFC rendering quality compared with other industry practical tools.

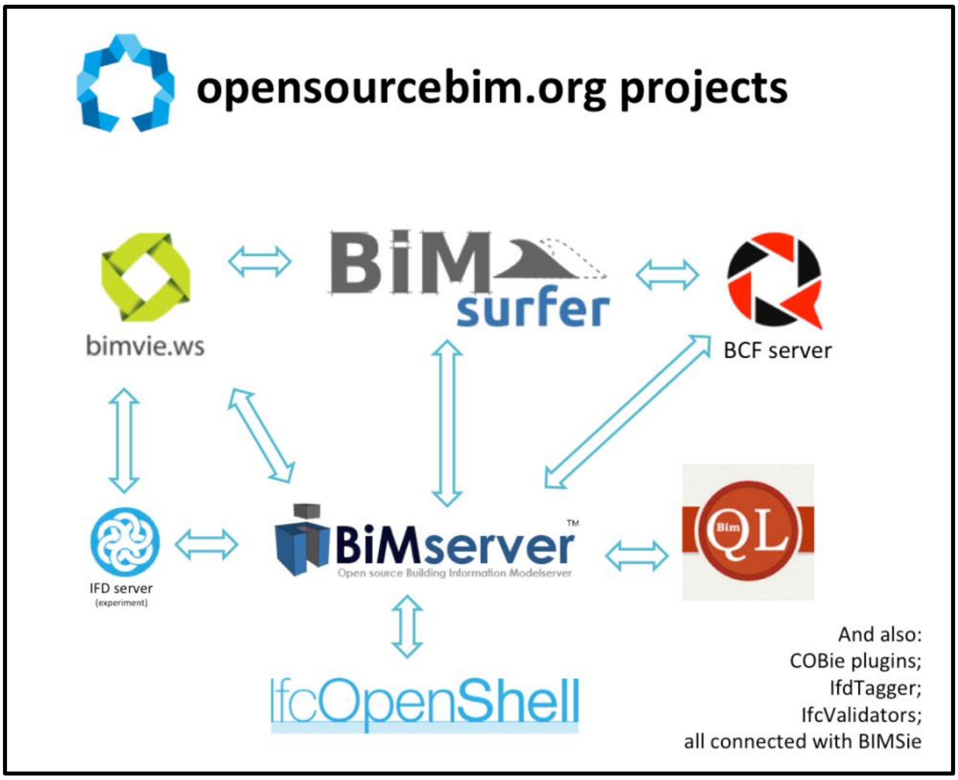


Figure 48 The open-source BIM server

5.2.2.2 Parsing and checking IFC in BIM server

By using the Eclipse IDE as the integrated development platform, the IFC model was uploaded into the server. The main steps below indicate the process that was conducted:

Step 1: Upload the IFC model to the server.

The BIM server was created using the localhost address. An airport IFC model was uploaded to the server. Using Java code aligned with the BIM Server to support uploading the existing IFC files, the developed engine was able to integrate multiple BIM objects and make them accessible on the Cloud. Figure 49 and Table 13 indicate the main functions used for this establishment.

```java
JsonBimServerClientFactory clientFactory = new JsonBimServerClientFactory("http://192.168.1.111:8010");
BimServerClient client = clientFactory.create(new UsernamePasswordAuthenticationInfo("test@admin.com", "123456
List<SProject> projects = client.getServiceInterface().getAllProjects(true, true);
for (int i = 0; i < projects.size(); i++) {
    SProject sp = projects.get(i);
    ClientIfcModel imi = client.getModel(sp, sp.getLastRevisionId(), true, false);
    // client.query(query, roid, serializerOid)
    List<IfcProject> all = new ArrayList<>();
    all.addAll(imi.getAll(IfcProject.class));
    IfcProject product = all.get(0);
    PID= sp.getLastRevisionId()+"";
    proData = new IFCObjData();
    proData = PrintHierarchy(product, proData);
```

Figure 49 The BIM server functions to load the IFC model

Table 13 The main function used to upload the IFC file

Main functions	Description
JsonBimServerClientFactory	connects to a locally running server on port 8010, authenticates with the default username/password, and then creates a new project.
BimServerClient	Set up the clients' information
clientFactory.create	Create a new BimServerClient and authenticate with the given authentication
client.getServiceInterface().getAllProjects	Get a list of all Projects the user is authorized for

Step 2: Parse the IFC.

The hierarchical structure of the IFC followed EXPRESS, a standard data-modeling language to deliver object-oriented information. The IFC file consists of entities organized for building elements such as '*IfcSlab*', geometry such as '*IfcExtrduedAreaSolid*' and property attributes such as '*IfcPropertySingleVlaue*'. The IFC format divides all the subject entities into rooted entities from '*IfcRoot*'. The presentation of a subject entity contains its Globally Unique Identifier (GUID), along with its attributes for names and descriptions. The string of numbers, followed by a '#', was used to index different entities. Three main abstract concepts existing in the IFC are as follows: 1) object definitions, which capture the object occurrences and types, 2) relationships, which capture the relationship among objects and 3) property sets, which capture the extensible properties on the objects. Using the Java function and following the same checking logic as that presented in Chapter 3, the IFC at the server was parsed and checked in Java.

After parsing the hierarchy of the IFC files, several checking functions were made based on previous information ERs that were used to obtain the entities' properties using various functions; the main functions used to check the IFC are listed in Table 14, with an example given in Figure 50.

```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 50 The checking functions in Java

Table 14 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'

Taking the information ERs presented in Chapter 4 for example, to measure the design cost in quantitative assessment using the area method, the gross areas of the building slabs are required, and the query logic should be based on the following expression:

Expression Name: Upper floor; FOL expression: $\forall\alpha(\mathrm{IfcSlab}(\alpha)) \wedge \exists\alpha((\mathrm{IfcSlab}(\alpha) \wedge \mathrm{Query}(\alpha, \text{"GrossArea"})$

Using the pre-defined functions—which can check specific IFC properties as the query functions—the reasoners in Java can understand which function should be used and what the return value should be. The XML syntax can be written as follows:

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

This syntax is used to represent the rule functions in a structured XML format, which can be parsed by Eclipse to define the specific functions used and the results that should be stored. The 'text' represents the query's name based on the information exchange requirement. The 'content' represents the required IFC entity corresponding to the ERs; the 'result' indicates the different returned value type, which can vary, including such possibilities as 'Sum', 'String', 'List' or 'Count'. The 'type' connects to the specific mathematical method defined in the functions (See in Appendix B). The 'attribute' locates the patent corresponding to the required information items. The examples used in this study are shown in Table 15:

Table 15 The description of the XML representation of information query

<table>
<tr><th colspan="2">Quantitative assessment - Planning costs - P1</th></tr>
<tr><td>XML representation</td><td><function text="Planning Fees" content="IfcSite" result="Sum">
<step type="var" attribute="Projected Area"></step>
</function></td></tr>
<tr><td>Description</td><td>To measure the Planning Cost, an IfcSite entity is required and its area should be added to get the project area.</td></tr>
<tr><th colspan="2">Quantitative assessment – Work estimates – Substructure- foundation-01</th></tr>
<tr><td>XML representation</td><td><function text="substructure-simple foundation" content="IfcSlab" parent="IFCBUILDINGSTOREY" pcontent="01 - Entry Level" result="Sum">
<step type="var" attribute="GrossArea|Area"></step>
</function></td></tr>
<tr><td>Description</td><td>To measure the simple foundation cost in substructure, the entry-level IfcSlab entity is required and its area should be added to get gross area.</td></tr>
<tr><th colspan="2">Quantitative assessment – Work estimates – Substructure- foundation-02</th></tr>
<tr><td>XML representation</td><td><function text="substructure-Colum bases" content="IfcColumn" parent="IfcBuildingStorey" pcontent="01 - Entry Level" result="Count">
</function></td></tr>
<tr><td>Description</td><td>To measure the column-based foundation cost in substructure, the entry-level IfcColumn entities are required and its counting number should be returned.</td></tr>
<tr><th colspan="2">Quantitative assessment – Work estimates– Superstructure- UpperFloor-01</th></tr>
<tr><td>XML representation</td><td><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></td></tr>
<tr><td>Description</td><td>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.</td></tr>
<tr><th colspan="2">Quantitative assessment – Work estimates– Superstructure- Frame -01</th></tr>
<tr><td>XML representation</td><td><function text="FrameLib" content="IfcSlab" result="List">
<step type="var" attribute="Structural Material"></step>
</function></td></tr>
<tr><td>Description</td><td>For measuring the frame cost, get the structural material information from all the IfcSlab entities (excluded the roof slab) and presented as a list.</td></tr>
<tr><th colspan="2">Quantitative assessment – Work estimates– Superstructure- Frame -02</th></tr>
</table>

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.
Green design performance – Green Planning– AirportAndUrbanPlanning-01	
XML representation	<function text="AirportAndUrbanPlanning" content="IfcSite" result="String"> <step type="var" attribute="SiteInformation"></step> </function>
Description	For measuring the PI 'airport and urban planning', the site information attached in the IfcSite should be retrieved to get the string value.
Qualitative assessment – Objectives And Outputs – 01	
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.

Based on the ERs corresponding to the different IFC entities, the returned value can be stored in the engine for further knowledge reasoning rules to execute more complicated functions.

Step 3: Translate and map the SWRL rules into Java.

Because the SWRL rules in 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. In recent years, many studies have focussed on the translation of IFC into IFC/OWL or IFC/RDF so that the SWRL rules can work in an OWL- or RDF-supported development engine (Boje and Li, 2018; Pauwels and Terkaj, 2016a; 2016b). Ma and Liu (2018) also proposed that such ontology- and freeware-based platforms be used for BIM application with reasoning support and that an implementation framework be developed. In that research, the IFC to RDF/OWL converter was used to translate IFC data into an ontology-supported environment. However, so far, this converter only functions on a small-scale IFC model and is difficult to implement when using a large-capacity model. Therefore, this thesis uses a Java-based environment to translate SWRL rules and maps it with the BIM server to avoid practical issues.

To conclude, the scheme and architecture for mapping ontology reasoned using SWRL rules are presented in Figure 51.

The SWRL has written in Protégé can be exported and represented as a DL safe rule in OWL/XML (on the left side of Figure 51). However, SWRL writing, either as a human-readable syntax or as a DL safe rule, is difficult to parse and execute in a more compatible software environment. Thus, the SWRL rules are mapped into XML syntax, which can be identified by Java- and C++/C#-based development engines.

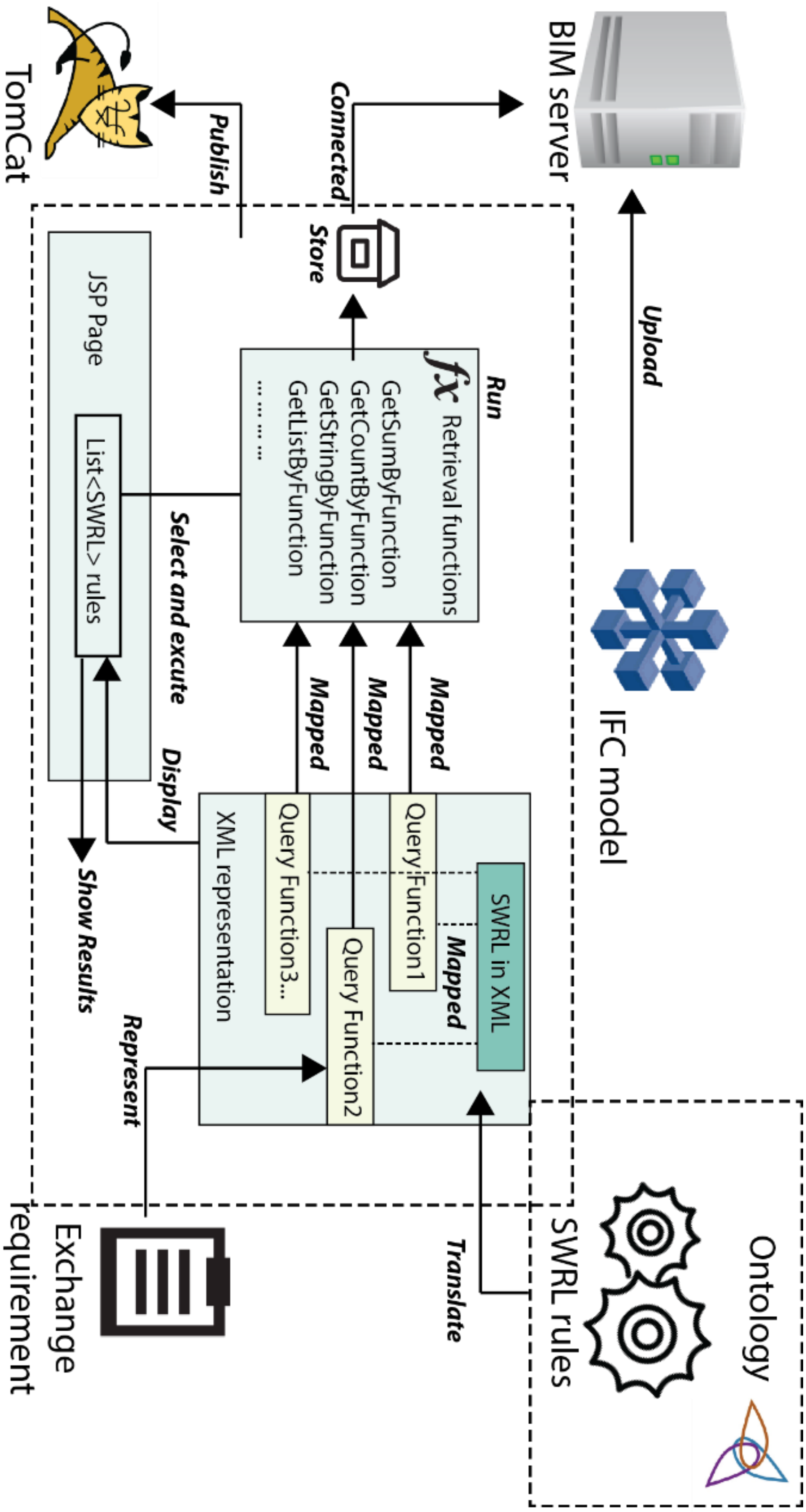


Figure 51 Architecture of aligning SWRL rules with IFC

This process can be automated by creating mapping tables that describe the matches between OWL/XML and SWRL/XML. Figure 52 shows the mapping translation pertaining to a single rule.

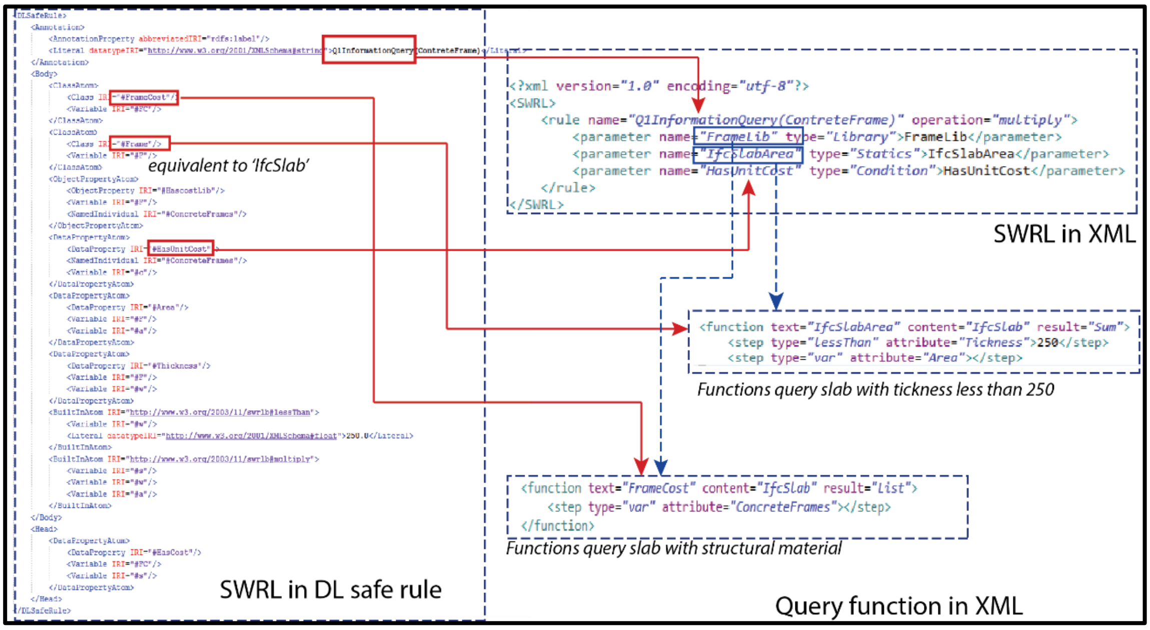


Figure 52 The integrated connections between SWRL and query functions

An ontology-based knowledge base within SWRL rules can contain several query functions; for example, the SWRL rule named 'Q1InformationQuery' 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, the parameter was used to align with the query functions, such as 'FrameCost', which is used to check all the 'IfcSlab' with concrete attributes, and 'IfcSlabArea', which is used to get 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 in step 2, as presented in Table 16.

The rules contents in the SWRL/XML 'operation' contain elements such as 'multiply', 'lists' and 'show' to progress the logic algorithm. In this way, the SWRL can be efficiently translated as formal XML syntax while connecting with the pre-defined query functions in XML. This is unlike the previous approach for converting IFC to OWL; such a translation or mapping method transforms the written OWL rules into the machine-readable environment, which can also be an automatic process. Moreover, the integrated development process can run on the BIM server and publish using a private server, such as TomCat, to assemble the functions. The developed VfMO is presented in Section 6.2.2.

Table 16 The parameter description in swrl.xml

Type name 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

5.4 the workflow of developed VfMO

The developed VfMO contains functional rules that can be used to improve the VfM practice meanwhile creating the decision-making methods need within procurement management.

In terms of the underlying knowledge base, all relevant domain ontologies can be combined into one that contains all related project information, such as cost, documentation and evaluation indicators. The management gateway, such as VfM assessment and project procurement stages, can also be included to help the user identify the process.

At the knowledge-application level, under the authorization of the client, the end-user (i.e., expert team or decision-maker) can use the ontology software platform to edit and formulate the VfM requirements and carry them out as domain-related rules in semantic forms. The knowledge base in the center of the framework is connected with different ontological models and information exchange requirements. These rules or requirements are presented in a computer-editable format in the application. With the guidance of the procurement consultant, the knowledge engineer can modify and update the user-defined rules in a timely manner. By integrating the ontologies, rules and query functions, the decision-making framework is able to execute assessment automatically.

At the information and data levels, the BIM server can aggregate the engineering information into a cloud platform that is easy to operate and can store and visualize the information to facilitate operations. The established knowledgebase can closely link with real-world data and achieve user-friendly management. The information exchange applies a standardized process, while the data is filtered using standardized data carriers. In this way, the established framework can be merged into different decision-making phases in infrastructure procurement. The VfMO framework is presented in Figure 53.

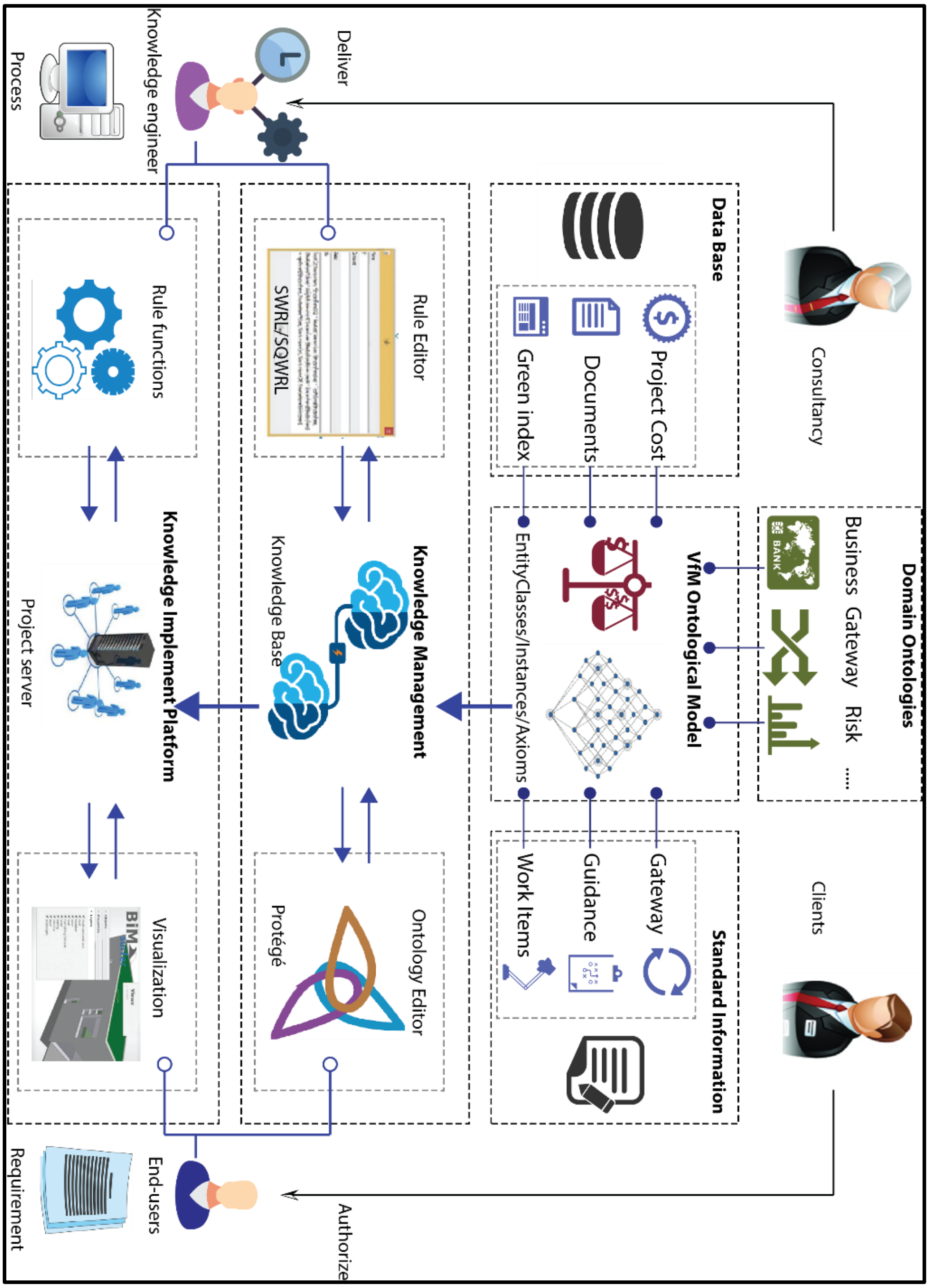


Figure 53 The workflow of the VfMO framework.

Chapter 6. Testing and validation

The developed VfMO is proposed to be validated by using a case study model to obtain accurate results based on the designed scenarios. In this chapter, a case study carried out on an airport BIM model is used for the VfMO validation. The few critical perspectives in terms of functionality and accuracy are considered to build up the scenarios relating to VfM contents. In the later stage of the case study, a software demo is delivered to project and procurement experts to further validate its functionality and feasibility. The VfMO validation process was carried out to prove that the system is functional and reliable when performing reasoning functions for VfM assessment.

6.1 Description of the case study model

In this section, a practical assessment and output report are introduced to validate the VfMO and illustrate how the developed ontology works for VfM processes. The case study infrastructure uses the BIM model of an airport located in Nanjing, a city in Jiangsu, China. The VfMO features will be demonstrated by considering particular groups of scenarios covering VfM assessment contents. Due to time constraints, the resources extracted from a wide breadth of the PPP project model are limited. However, the developed ontology can evaluate the specific sub-elements of the corresponding assessments according to the supporting information and regulations.

The chosen BIM model contained several construction and architecture elements (Figure 54). More specifically, it contained two-level floor slabs, the structure beams, the concrete frameworks, the substructure and superstructure columns and the foundation slabs. To help identify the information available for testing, Figure 55 divides the construction elements into several categories for simplicity. To combine the large model using separate Revit files, Naviswork was used to merge all the structure models for visualization and presentation. The IFC file was extracted from the BIM model and uploaded to the BIM Server. To strengthen the validation, several documentations' URI addresses and project-level information were put into the IFC model for qualitative performance queries.

Based on the assessment index and rules, the ontology can compute the costs of specific information items and output information query results. Taking the work estimates as an example, unlike previous ontology applications—in which the required data had to manually input from slab objects to measure the upper floor cost—the quantity take-off to get the floor area can now be gained automatically from the BIM Server. Based on the ability of NRM and SPONS to obtain the unit cost data, the cost estimates of the upper floor could be processed. After inputting all the unit cost data into ontology and constructing the corresponding SWRL rules, the developed system automatically calculated all the capital costs in the quantitative assessment. Figure 56 lists the overall information of the BIM model used in the case study.

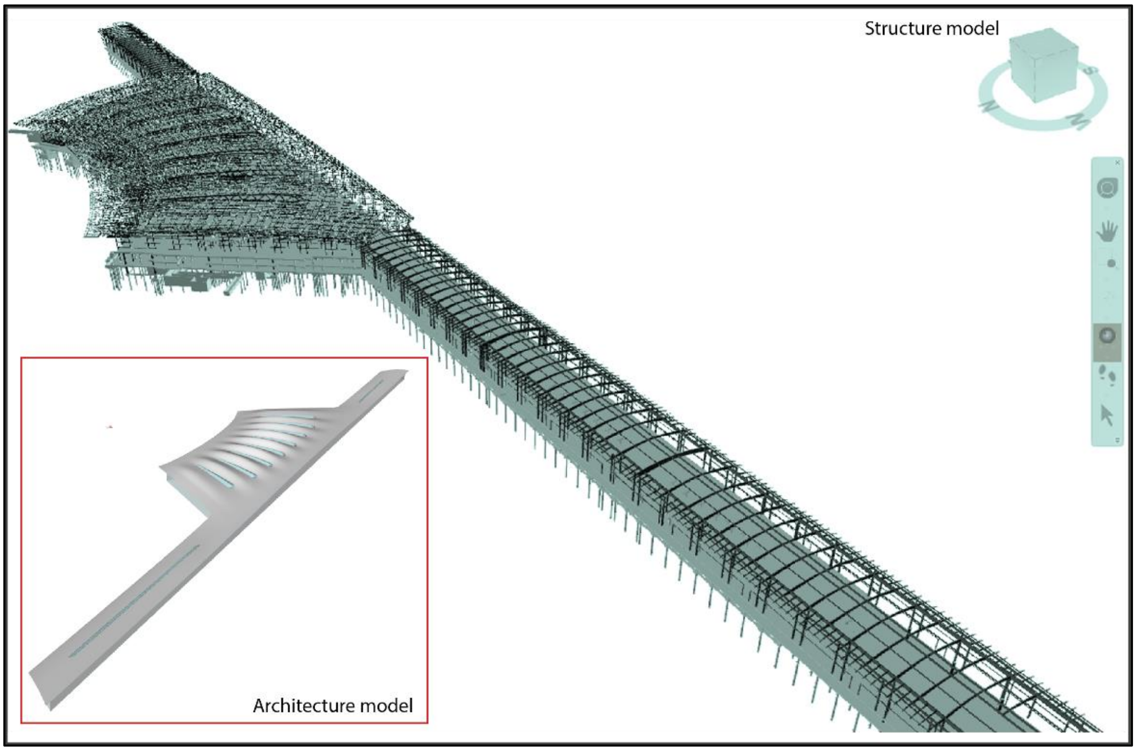


Figure 54 Airport model used for the case study.

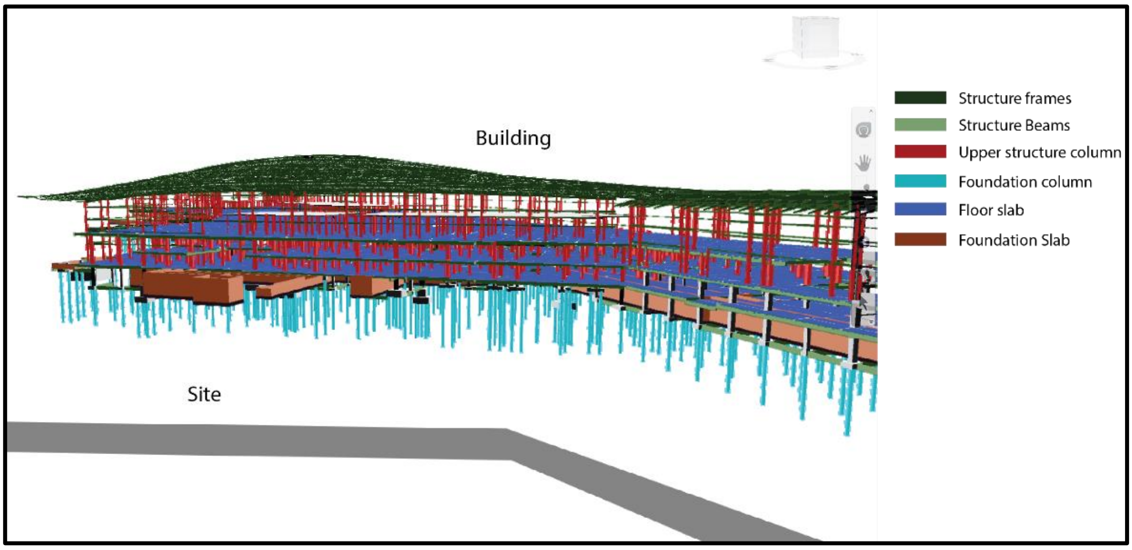


Figure 55 The objects element contained in the case study model.

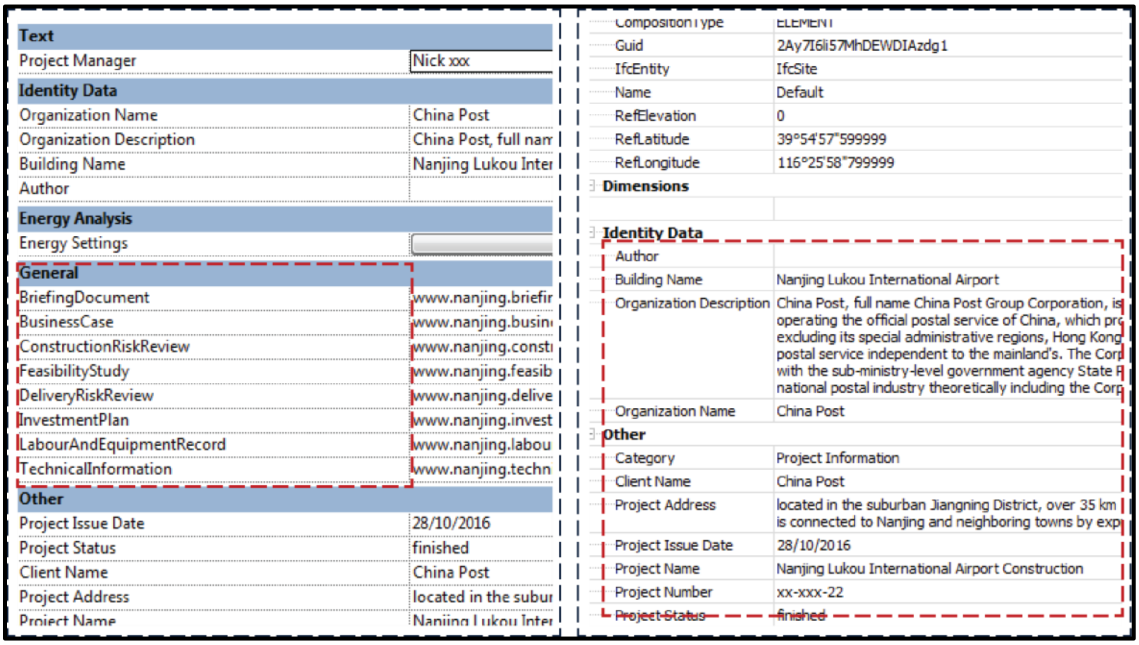
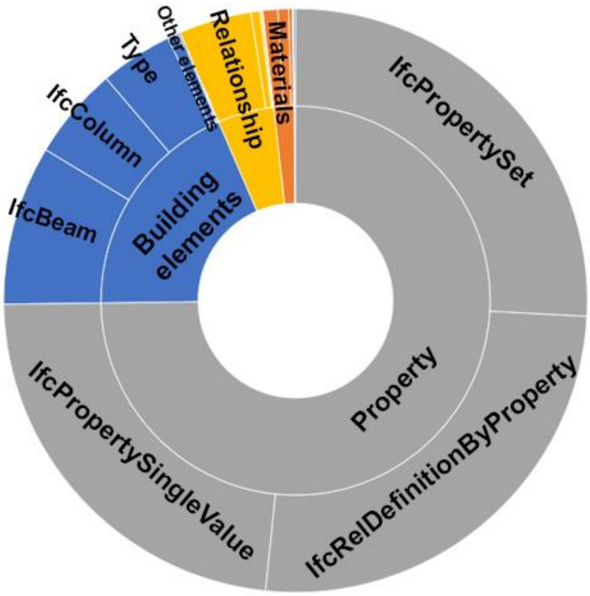


Figure 56 The documentation information contained in the case study model

Figure 57 shows all the information about the IFC in the model analyzed in this case. In total, 112191 IFC entities were retrieved, which contain a large number of IFC attribute information sets and IFC building elements. The airport structure model mainly contained substructures such as concrete beams, concrete columns and concrete slabs; superstructures such as concrete frames (presented as concrete beams in IFC files), steel frames (presented as steel beams in IFC files); and upper floor structures such as *in situ* columns (concrete columns), upper slab sections, roof columns and steel framework. Due to the initial design of the project model and the limitation of the BIM software used, Revit, much project information as also included in the BIM model and was mainly stored in high-level IFC instances such as '*IfcProject*', '*IfcSite'* and '*IfcBuilding'*. A lot of other project model information and annotation information were also stored in the corresponding IFC elements. The four scenarios outlined below are were verified for processing based on all the available information in this model.



IFC file used	10
Size	58.6 Mb
Entity	Total
IfcBeam	9926
IfcColumn	5752
IfcColumnType	4517
IfcOpeningElement	121
IfcSlab	148
IfcWall	548
IfcWallType	7
IfcRoof	3
IfcMaterial	18
IfcMaterialLayer	20
IfcMaterialLayerSet	20
IfcMaterialLayerSetUsage	670
IfcMaterialList	234
IfcRelAssociatesMaterial	922
IfcPropertySet	29033
IfcPropertySingleValue	26000
IfcRelDefinesByProperties	28941
IfcRelAggregates	30
IfcRelAssignsToGroup	14
IfcRelConnectsPathElements	549
IfcRelContainedInSpatialStructure	20
IfcRelDefinesByType	4524
IfcRelVoidsElement	121
IfcApplication	10
IfcBuilding	1
IfcBuildingStorey	4
IfcGroup	11
IfcSite	1
IfcProject	1

Figure 57 The IFC files used to query the project information in defined Scenarios

6.2 Case study objectives and Scenarios

The objective of using the case study was to test if the developed VfMO can cover the specific content required for VfM assessment and provide functional abilities for procurement decision-making to test and validate the feasibility by calculation/query results.

Three groups of scenarios (questions) were created to cover both VfMO qualitative assessment and quantitative assessment and for the automatic regulation checking. The objective of using scenario questions is based on the VfM assessment contents. To be more specific, scenario 1 contains a serious of questions for the CapEX costs relating to quantitative assessment. Scenario 2 contains the questions relating to the requirement of qualitative assessment indicators. Scenario 3 contains questions regarding the green design performance requirements to indicate the knowledge base can also be utilized for early-stage design performance assessment.

For measuring the designed scenarios, the previous BIM airport project model which contains 10 IFC files were uploaded to the BIM Server. Align with the scenario questions, this process aims to indicate the feasibility to implanted the VfMO knowledge base in the real project. The results are next outlined.

Scenario 1

The scenarios 1 contains several questions in the following Table 17:

Table 17 Scenarios 1 questions relating to quantitative assessment

Question	Contents
Q1	For the CapEX costs referred to in the quantitative assessment, using this model, what is the cost estimate on the substructure elemental cost plan?
Q2	For the CapEX costs referred to in the quantitative assessment, using this model, what is the cost estimate on the superstructure elemental cost plan?
Q3	For the CapEX costs referred to in the quantitative assessment, using this model, what is the cost estimate on the upper floor structure elemental cost plan?
Q4	For the CapEX costs referred to in the quantitative assessment, using this model, what is the cost estimate on the internal walls elemental cost plan?

To perform the defined scenarios, reasoning SWRL rules were created in the ontology with specific query functions. Table 18 lists the details of the rules used along with the entities checked in the scenario.

Table 18 The Rules, query functions and entity used in Scenario 1

Scenario	SWRL rule included	Query included	Entity checked
Q1	3	6	15678
Q2	3	5	14563
Q3	1	2	11341
Q4	1	2	548

After VfMO's reasoning process, all the results were written in the following Table 19. First, an SWRL rule was written to contain all the conditions to be executed, including the required IFC elements and materials. The quantity take-off applied the query functions to get the required quantity values based on the SWRL rules. In general, a single SWRL rule corresponded to two detailed query functions, which separately checked the elements based on the material information and the elements' attributes based on the quantity requirement. After the screening, by referring to a cost book such as the SPON, the value of the unit cost was manually input into the system, and the total cost could be calculated according to the different element types. In conclusion, Table 20 is presented to answer the proposed scenario questions.

Table 19 The results of scenario 1

Scenario	Entity	Required Quantity	Material	Unit cost (£)	Cost (£)
Q1	Slab	27500 .5 m^2	Concrete	84	2,310,042
	Column	1302.4 nr	Concrete	180	234,432
	Beam	31131.5m	Concrete	85	2,646,177.5
Total					5190651.5
Q2	Beam	11376.0 m	Concrete	120	1364400
	Beam	11170.8 m	Steel	145	1619766
	Column	13066.2 m	Concrete	71	927700.2
Total					3911866.2
Q3	Slab	110779 m^2	Concrete	69	7,643,751
Total					7,643,751
Q4	Wall	56115.2 m^2	Concrete	130	7,294,976
Total					7,294,976

Table 20 Answers to Scenario 1 questions

Answers	Answers
Q1	For the CapEX costs referred to in the quantitative assessment, the cost estimate on the substructure is 5,190,651.5.
Q2	For the CapEX costs referred to in the quantitative assessment, the cost estimate on the superstructure is 3,911,866.2.
Q3	For the CapEX costs referred to in the quantitative assessment, the cost estimate on the upper floor structure is 7,643,751.
Q4	For the CapEX costs referred to in the quantitative assessment, the cost estimate on the internal walls is 7,294,976.

These answers are direct outputs based on the setting in the VfMO platform and are validated further to prove to be correct results.

Scenario 2

The scenarios 2 contains several questions in the following Table 21:

Table 21 Scenarios 2 questions relating to qualitative assessment

Question	Contents
Q1	For measuring the indicator ‘Incentives and Monitoring’, what is the related document URI address?
Q2	For measuring the indicator ‘Objectives and Output’, what is the related document URI address?
Q3	For measuring the indicator ‘Risk Management’, what is the related document URI address?
Q4	For measuring the indicator ‘Operational Flexibility’, what is the related document URI address?

As discussed in the previous section, qualitative assessments often require proper contract documentation support rather than related single information. According to the model settings, all files were stored in the upper IFC instance, and the data type of the storage file is URI. According to the previous definition and the set scheme, Table 22 lists the details of the rules used along with the entities checked in the scenario. The URI of the relevant file was extracted and is expressed in Table 23.

Table 22 The Rules, query functions and entity used in Scenario 2

Scenario	SWRL rule included	Query included	Entity checked
Q1	3	6	71
Q2	3	5	71
Q3	1	2	71
Q4	1	2	71

Table 23 The results of scenario 2

Scenario	Entity	URI information
Q1	Project; Building; Site	www.nanjing.briefingdocument.org
Q2	Project;Building;Site	www.nanjing.briefingdocument.org www.nanjing.businesscase.org
Q3	Project;Building;Site	www.nanjing.riskandopportunitiesmanagementplan.org www.nanjing.deliveryriskreview.org www.nanjing.riskpotentialassessment.org
Q4	Project; Building; Site	www.nanjing.feasibilitystudy.org

Due to the limitations of the current software, the URI of the file was not set to be stored in the appropriate IFC entities, but rather the majority of the information was placed under the IFC instance for easy extraction. According to the evaluation requirements, the user can choose to develop when evaluating rules (SWRL rules) and can select relevant documents to support the evaluation process. The following Table 24 answers the scenario questions.

Table 24 Answers to Scenario 2 questions

Question	Answers
Q1	The briefing document with the URI www.nanjing.briefingdocument.org can support measuring 'Incentives and Monitoring' in the qualitative assessment.
Q2	The briefing documents with the URIs www.nanjing.briefingdocument.org and www.nanjing businesscase.org can support measuring 'Incentives and Monitoring' in the qualitative assessment.
Q3	The 'Risk and Opportunities Management Plan' document with the URI www.nanjing.riskandopportunitiesmanagementplan.org, the delivery risk review document with the URI www.nanjing.deliveryriskreview.org and the risk potential assessment document with the URI www.nanjing.riskpotentialassessment.org can support measuring 'Risk Management' in the qualitative assessment.
Q4	The feasibility study document with the URI www.nanjing.feasibilitystudy.org can support measuring 'Operational Flexibility' in the qualitative assessment.

It is worth mentioning that all the documents contain the required UniClass codes. The query functions used in these scenarios can also use UniClass code rather than using the keyword to retrieve documents. All the answers are proved to be correct as this extracted information matches the pre-defined information in the BIM model.

Scenario 3

The scenarios 3 contains several questions in the following Table 25:

Table 25 Scenarios 3 questions relating to green design performance

Question	Contents
Q1	For green performance, code 6.2.4 ('Airport and Urban Planning') refers to site information. What documentation should be used, and what IFC entity information should be used?
Q2	For green performance, code 6.2.5 ('The appropriate number of layers and height should be determined in combination with the functional positioning of the terminal building. The height of the building should not exceed 45 meters') refers to the building information. What documentation should be used, and what IFC entity information should be used?
Q3	For green performance, code 6.2.6 ('The height of the building and the height of the indoor space should be reasonably controlled. The average net height of the large space in the main building and the fingering room should meet the requirements, while the area [should be] > 40000, the height of the terminal < 25 and the height of the corridors < 12') refers to the building information. What documentation should be used, and what IFC entity information should be used?

Scenario 3 questions are designed to cover several perspectives relating to green performance assessment in the early design stage. The design performance requirement also matches the VfM qualitative assessment indicators. By demonstrating the application of the VfM knowledge base in design performance checking also indicates the feasibility to implement the VfM in other domain assessments. As mentioned earlier, the rules for green performance can cover comprehensive project information not only at the project level but also at the procurement level. The proposed Scenario 3 focuses on the other project performance assessment regulations that relate to BIM systems, primarily referring to the provision of documentation, object information, and visualization support. The defined evaluation criteria are expressed in the simplest form of semantics. The output of the rule is the URI address of the corresponding evaluation file and the corresponding IFC entity information. Table 26 lists the rules used along with the entities checked in the scenario.

Table 26 The Rules, query functions and entity used in Scenario 3

Scenario	SWRL rule included	Query included	Entity checked
Q1	2	3	1781
Q2	1	1	982
Q3	2	4	9721

The results for measuring the other green performance scenarios are presented in the following table 27.

Table 27 The results of scenario 3

Scenario	Entity	URI	Required Quantity
Q1	Project; Site	www.nanjing.siteinformation.org	/
Q2	Building; Building storey	/	23.31 m
Q3	Building storey; Slab; Roof	/	40917 m^2; 23.31 m; 11.87 m

The scenario defined in this case study was mainly derived from the green indicators in the green airport design/planning guidance. Because the rules defined in the Q1 contain massive amounts of site information and regulations, it is hard to refer to one single value. Therefore, in this case, the site information document the information file of the venue will be related. Based on the performance requirement set in Q2 and Q3, which is to filter the relevant elements of the airport model, the relevant information is constrained, as the output went through the specific query functions. The end-user can compare the output information to determine whether the result has achieved the requirement. More specifically, in Q3, the area of the airport terminal corresponds to the area information of '*IfcBuildingStory'* in the IFC files; it can also be obtained by getting the sum of the area of all the building slabs at the first floor. Due to the fact that the BIM model containing the area information of the airport gallery is not stored in the '*IfcBuildingStory'* entity, the method of indexing the area of the '*IfcSlab'* was adopted. In addition, the height of the main terminal and the gallery were obtained by indexing the net height of the roof. Based on the results in Table 28, the scenario queries are answered in Table as follows:

Table 28 Answers to Scenario 3 questions

Question	Answers
Q1	To measure PI 'Airport and Urban Planning', site information with the URI address www.nanjing.siteinformation.org and the site entity can be related to support the measurement.
Q2	To measure the PI 6.2.5, the results indicated the following: 'The height of the building should not be 23.31 m < 45 m, which meets the requirement'.

Q3	To measure the PI 6.2.6, 'the area of the first-floor building of the airport model is 40917 m^2 > 40000 m^2, the height of the terminal building is 23.31 m < 25 m and the height of the corridors is 11.87 m < 12 m'. The results indicate that the airport design meets the requirement.

To conclude the case study, in the case of available resources, it has been established through case studies that the VfMO system is able to process the BIM model. The results obtained were also compared with the measured results in the digital model and proved to be accurate. The built-in rules clarify the required documentation information or object information in an efficient form. The constraints of the rules point to different query functions to retrieve the data needed from the IFC file. The result is proved to be more efficient than is the manual process.

For further validation of the VfMO functional aspects regarding the accuracy, the developed VfMO was packaged as a software demo and delivered to engineering procurement constancy companies in China which are ASEAIR co ltd; Zhixing co. Ltd and JianluZhihua co. Ltd. The demonstration video is attached to the demo to explain the logic and functional application of VfMO to the end-users. As indicated in Appendix D, the end-users are able to select the measurement rules to check or query existing data stored in the BIM platform. Meanwhile, the BIM viewer functions attached with BIM server are used to visualize the digital model and highlight the object corresponding to specific query functions. The users also can input the external data which is not stored in the IFC or knowledge base. Ex. The unit cost.

After the demonstration of the software demo, users are asked the accuracy as "to what extent you think this developed demo can improve the assessment accuracy compared with the traditional approach?''. According to the feedback showed in the following Figure 58, most of the respondents' feedback indicates that using BIM data to assist automatic calculation or index the assessment catalogs can provide reliable results for the assessment. This automated evaluation model from the company's representative has been consistently recognized by both the project management and the engineering design departments. This is because BIM can provide users with reliable IFC data in combination with real-time updated information requirements. The systematic management of engineering and project information in the current application of large-scale public construction projects also provides a stable basis for automated assessment.

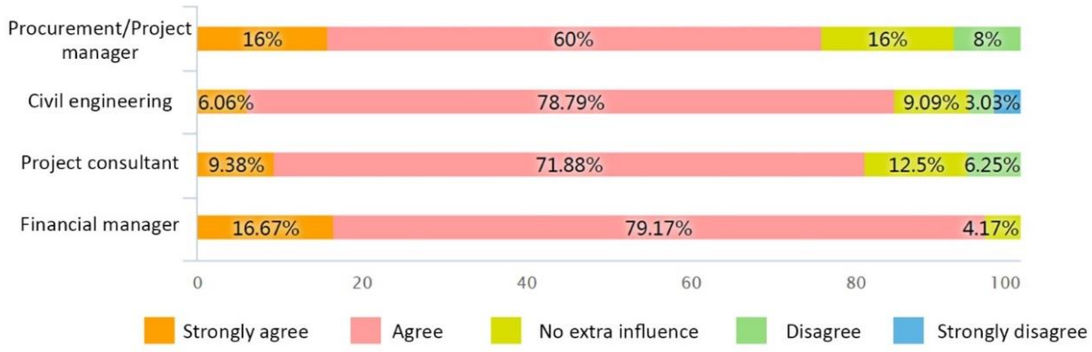


Figure 58 Distribution of agreement on accuracy improvement accuracy in comparing VfMO with traditional methods

To summarize, this chapter illustrates the case study validation approach regarding its feasibility and accuracy. The VfMO demo is able to process the BIM model to execute the pre-defined functions and generated reliable results based on IFC data and reasoning rules. The Delivered VfMO model with its BIM Viewers visualization interface indicates its working feasibility to industry parties. Compared with current assessment status concerning VfM and other projects' green performance measurement, the proposed VfMO approach has its potential to further expanded to be used in project management and decision-making. The feedback forms from industry managers are presented in Appendix D.

However, as mentioned above, the existing financial system has a relatively mature system for the application of different evaluation models. From this perspective, the developed VfMO needs to be further developed in the future to involve more financial related factors.

Chapter 7. Conclusion

Based on the research process and results, this thesis first provides rational answers to the pre-defined research questions (Section 7.1).

Second, the research restrictions of the study and the potential for improvement are discussed in Section 7.2. After this, focus on the research topic, practical directions for future research and potential planning methods are discussed. Finally, a summary of the research contributions of this thesis is presented in Section 7.3.

7.1 Research questions discussion

To clarify the research aim, the proposed research hypothesis (below) was assumed, and it was decided that each chapter in this thesis would focus on certain research questions. These findings were then used to evoke more comprehensive answers.

Research hypothesis: *To establish a knowledge-represented approach that provides automatic information retrieval, exchange and processing that can help to support the decision-making process on ex-ante VfM assessment in PPP procurement by leveraging different data sources, such as the existing BIM system.*

Answering the research questions

Q1: *What are the contents defined in the VfM and how are the current implementation methods and tools used for assessing the VfM in the PPP procurement process worldwide?*

Through the previous review work, this study focussed on the literature review and project report statistics for VfM assessment. By profiling the definition of ‘VfM’, it was determined that the procurement parties identified VfM as an assessment that can be carried out in the early project stages or even throughout the lifecycle. The financial departments of many developed countries also have definitions or official guidance for VfM assessments. In the UK, for example, a VfM assessment manual was released in 2006.

In terms of the literature review, within PPP projects, VfM assessment in the early project stages is regarded as a more essential process than it is in traditional procurement models. The development of post-performance assessment indicators can be considered part of the VfM index. Developing countries such as China and India have developed practical recommendations for VfM assessment. In addition to the cost budget, quantitative assessment in VfM now adds more risk factors and other factors as statistics. However, although the indicators in the qualitative assessment involve various aspects of the project, the specific content of such an assessment is still limited. This study presented a list of the existing quantitative and qualitative indicators and cases of other green design performance scenarios were also included in the developed VfMO.

In the review of practical reports related to VfM, due to the limited resources, this research used the resources available in the project library of the China PPP Project Center and performed a detailed analysis of released project documents from hundreds of model PPP projects. The review revealed that the current performance status of VfM assessments is poor. In most cases, the quantitative assessment was not effectively implemented, and the form and method of qualitative assessment tended to be simple. Moreover, in terms of software assistance assessment, the existing VfM platform is also quite limited and lacks further development.

Q2: *What is required for VfM analysis and to what extent can the contents of VfM assessment be integrated with the BIM system?*

Based on the content defined in VfM assessment, this research extracted critical information sets that satisfied VfM from the existing guidance issued by the UK Ministry of Finance, the Ministry of Finance of China, and the US Department of Transportation. It was found that, in the quantitative assessment part, the calculations in VfM and the estimates of cost were relatively close, but the areas involved were wide-ranging. This is because the types and scales of PPP projects are usually involved in urban transportation or the construction of large-scale urban infrastructure, including large-scale municipal projects such as railways, airports and wastewater plants. Based on the information required for the standardized cost estimates, the NRM/SPONS standard book series were taken as a reference and was used to break down the quantitative assessment of VfM corresponding to the required information set.

In the qualitative assessment, after reviewing a large number of qualitative assessment reports, because most qualitative assessments did not have corresponding information and document support, the experts scored the indicators based on experience. This resulted in significant one-sidedness in the results. This study cited the definition of each indicator qualitative assessments according to the UK and China, and linked those indicators to the project information, thus starting to establish an assessment documents archive.

According to the authors' ambitions, the automated assessments that assist human decision making in introducing VfM systems were developed in this research. Therefore, BIM, which is regarded as a platform for providing a large number of engineering standardization information collections, became an indispensable part of the research. It is worth mentioning that BIM's current standard layer development does not cover the full range of all types of construction engineering projects; the expansion of IFC data types is still ongoing, and the interaction standards between BIM and large-scale engineering construction projects such as airports, railways and wastewater treatment are also in development. In the cost and other qualitative assessment requirements, the project library is also being continuously added in order to lay a foundation for standardized information indexing.

BIM can provide almost all the necessary internal project information, such as object information (including the quantity-off data) to calculate the cost. In addition, project-related documents can theoretically be kept in IFC-supported databases to support qualitative assessments in VfM. Moreover, BIM retains its visual capabilities while providing information. From this point of view, this study aimed to use BIM as a primary platform for providing project information, trying to establish logics concerning VfM to achieve automated assessment.

Q3: *How can an information exchange requirement for automatic VfM assessment be defined, and how can such BIM-based information exchange be implemented?*

In Chapter 4, the research focused on how to establish the basis for VfM assessment—the information exchange delivery required for VfM. It was stressed at the beginning that, due to the variety of PPP projects, it is difficult to establish extensive and comprehensive information exchange delivery in a limited time. Therefore, this study aimed to illustrate the feasibility of this method and present it in the form of a software demo.

The method for establishing information interaction in the study applied the international standardization method IDM, which is defined in ISO 29481. IDM requires a clear process for expressing information exchange, the involved project parties and detailed information exchange requirements set to establish a clear logic. It was started from scratch, following the VfM assessment process and the corresponding break-down content. The information exchange requirement for VfM was also developed. It is worth noting that, regarding performance evaluation, there was not much involved in the process of development in the research because the requirements vary significantly according to the requirements of different project users and customers. It is therefore impractical to capture detailed information requirements.

After establishing a reasonable information exchange method, the expressed information definition can be reproduced to different project parties and software engineers for subsequent functional development. This study facilitates more detailed correspondence between the data types of IFC and the information required for the exchange, and these detailed requirements are passed in the form of ontology so that the software vendor can capture the necessary requirements in computer-readable language. Such a method of using IFC to express information exchange can also be further developed as a standardized MVD.

A small IFC data filtering demo was developed to verify the feasibility of this method. According to the essential information-level requirements, the method uses the IFC engine to achieve the IFC screening function. What is worthwhile is that the BIM server used in the latter part of the research can also achieve the corresponding functions using similar query logic. In summary, this study referred to the standard IDM approach, and a demo was built using the IFC screening function to express the possibility of VfM information interaction.

Q4: *How to implement an ontological knowledge representation for all the related contents of VfM in PPP procurement, and what are the benefits of using ontology for knowledge representation considering the VfM requirements?*

As one of the research focusses of this article, this question emphasizes the feasibility of establishing a VfM knowledge base. Ontology, as a method that has been advocated by academics in recent years, was selected as a means and tool for developing a VfM knowledge base in this research.

The software Protégé, based on the ontology language OWL, functionally satisfied the conditions for building the semantic logic. The concepts related to VfM were manually added to the knowledge base according to the computer logic; the entity class contained the hierarchy structure of the VfM assessment, and other essential factors in the assessment—such as risk, project index, and project parties—were also concluded in the ontology. The purpose of this was to enable the assessment to involve more comprehensive factors in the process of rationalization. In Chapter 5, the object properties set up in the ontology connected different concepts so that the knowledge base could support the operation of rational rules (SWRL or other rule reasoning), and the knowledge base supported the establishment of all numerical types to establish different datatype properties to store the corresponding object properties and file addresses. Ontology, when built efficiently, can capture the user and project assessment requirements and build up a computer-recognizable semantic architecture. From the financial field to the commodity shopping field, the ontology itself has proved that it can write knowledge attributes and standard processes, among other things, in the field and can efficiently connect different semantics. After the ontology built-up, the thesis verified the semantic and syntactical aspects of the VfMO.

In addition to the knowledge concepts required for VfM assessment, the ontology established in this study also covered some rules of other design performance (mainly based on green airport performance evaluation). The SWRL rule can conveniently define the concepts and relationships needed in the assessment rules so that the established knowledge base has the function of reasoning.

Q5: *How to align the constructed knowledge base with multi-domains, such as the BIM management platform, to realize the required functionalities?*

Linking ontological knowledge bases to other data sources has always been a critical process, from academic research to practical application. As mentioned in previous studies, BIM is regarded as the means for internal data source integration for automation in engineering procurement. Therefore, it is necessary to combine the knowledge base with BIM effectively.

IFC is widely used as a collection of BIM information. Information screening and visualization can be achieved by obtaining information from IFC. In this study, the BIM server was chosen as the representative data platform, based on the following considerations:

1) The BIM server works as an IFC data platform for cloud storage and delivery, it saves resources more efficiently, especially when using larger scale BIM projects, and it helps to avoid bottlenecks caused by inaccessibility.
2) The BIM server minimizes network traffic in the office and on the Internet, and it enables instant and reliable data exchange for better collaboration between project teams. Team members can collaborate in real-time on BIM models through Internet connections anywhere in the world.

In this way, the BIM server is gradually expanding its fields of application. The connection between the knowledge base and the BIM server was described in detail in Chapter 5. Using SWRL, the ontology was mapped into the Java-based development environment. Each SWRL rule corresponds to different query functions, which were pre-defined in the ERs in Chapter 4 to retrieve IFC entities. It is worth noting that the SWRL rules can be automatically translated into SWRL from the original OWL form (DL safe rule) to a simplified form of XML. This is to facilitate the connections between the SWRL rule and the query functions so that this approach can help to achieve the data retrieval corresponding to the specified rule's atoms.

As the platform for providing data retrieval and visualization, the BIM server can publish the established system on the open server. Users can upload project models and use the ontology to assist in the development of assessment rules for project decision making.

Q6: *How reliable is a knowledge-represented system in understanding the digital engineering project model and other data resources in facilitating efficient VfM assessment? For instance, is the proposed system can support the decision-making by exchanging information and process the data accurately and automatically?*

This question related to the validation of the developed VfMO and was described in detail in Chapter 6. Case study validation is implemented. The result of the verification proved that the developed VfMO satisfied the logical requirements of VfM. Moreover, through the case study and the development of related rules to simulate the function, the VfMO proved its functionality and indicated its practical aspects. This case study reflects the accuracy of the VfMO compared to the traditional approach. After the VfMO was developed, a software UI was delivered to different groups of PPP procurement experts to obtain their feedback. The result further explained the advantages of the VfMO in practice.

7.2 Research roadmap

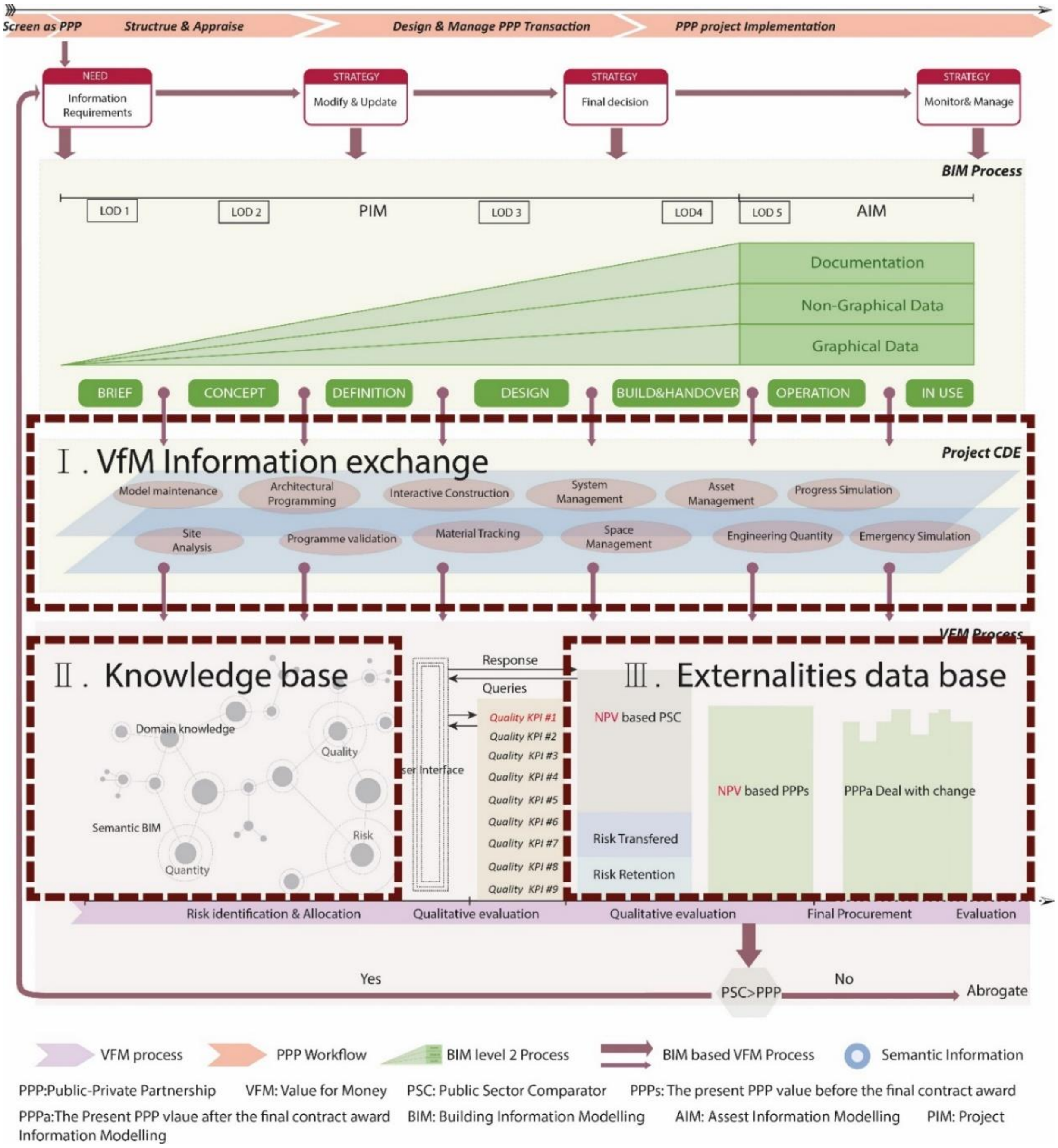


Figure 59 Proposed BIM-based VfM roadmap align with the current standardized BIM process.

Since 2009, the UK Government has based its approach on the concept of 'BIM levels' (Porwal and Hewage, 2013). This highlights integrated data sharing and exchange capabilities in a way that combines all of the geographical, administrative, and object information. BIM level 2 framework comprehensively covers client and contractor interests and has been applied to massive projects (HM Government, 2015). Regarding the technological development of BIM, strategies were proposed that encompassed cross-sector collaboration and focused on more efficient procurement, delivery, and operations to meet the life cycle's fiscal and sustainability objectives (Motawa and Carter, 2013).

The BIM Level 2 structure in the UK could contribute a great deal to the future research roadmap (Figure 59). BIM not only provides a digital platform but more importantly, it provides a common data exchange platform that could be used throughout a PPP project's lifecycle. BIM-based VfM could also play a greater role at an earlier stage. The information extracted from the business outline could be stored in a CDE; for example, BIM could help to fulfill the requirement from a client's point of view. Even if the information is not rich enough to entirely process VfM, a referenced project should be set up at this stage to gather all the relevant information for initializing the PSC value. The acquisition of raw PSC data is achieved through strict cost-effectiveness analysis, which provides a basic data profile for quantitative assessment throughout the project.

Along with the exchange scheme, information from BIM is added to the project's shared data environment and delivered to the ontological framework. The ontology should directly link IFC/XML from the BIM to the key performance indicators of the VfM. Ontology can connect to other knowledge domain sources to align with information in financial and economic affairs. The ontological structure is also built to maximize project quality performance and provide information query abilities to qualitative assessment. With the procurement strategy continually updated, the semantic framework will contribute to the assessment. For more comprehensive WLCC computing features, such as the cost of risk transferred, other external performances could be simulated based on the historical data. The decision will be based on the VfM outputs. Once targets in both quality and quantity aspects are fulfilled, the project flows to the next step. The value is decided by the final procurement strategy and will continually function with project supervision.

The advantages of BIM aligned with a semantic approach in PPP could benefit the procurement decision as follows:

- The semantic environment has the potential to connect to the project information from a shared data environment. Information query and qualitative assessment could be facilitated by building up knowledge bases for different types of PPP projects.

• The information extracted from the BIM, which is a vital element of information initialization, provides high-quality data input to guarantee accuracy and high levels of synchronization for quantitative assessment. The PPP lifecycle project flow is considered, and the BIM enhances information exchange.

7.3 Research restrictions and future works

The limitations of this research concerning information exchange, the VfMO system and the developed LD approach used in implementation and testing are discussed below.

Information exchange restrictions

1) Standardized information as an indispensable foundation plays a vital role in information exchange in engineering projects. As discussed in the thesis, the existing BIM standard has not yet completed the expansion of more municipal or large public buildings at the data level. The latest IFC release package, IFC4, is still limited to certain types of public construction work. Many projects currently use temporary IFC data types to store and edit project information that has been defined variously. Therefore, in order to achieve a complete information exchange, the IFC standard is the foundation, and the existing IFC data foundation no doubt affects the automation of information exchange in VfM and other activities in the engineering procurement field.
2) The details of the procurement of engineering projects and other evaluation information need to be further strengthened. Particularly when it comes to human judgment, the level of detail on the VfM assessment will influence the decisions made by the VfMO, so detailed standardized information definitions become necessary.
3) The generation of the BIM model in practice also affects the use of automatic information exchange. The details of the information exchange requirements should be effectively defined before use. In this way, the BIM model should effectively place information in the corresponding IFC entity. However, the use of BIM, in reality, may vary according to the user's preference, which increases the complexity of the automatic exchange.

Knowledgebase restrictions

1) The establishment of ontology itself has limitations, and the semantics of OWL is now gradually becoming more familiar to more developers. Based on a large number of studies, we chose to bypass the IFC convert-to-OWL/RDF route and instead chose to connect the ontology to the BIM server through the Java spray platform. The limitation of this method is that there are a large number of concepts in the semantics itself. Moreover, the process of connecting semantics to the BIM system may become lengthy, depending on the complexity of the rule definitions. The knowledge engineering of the intermediate link is therefore needed to make an effective connection.
2) The retrieval and rules defined in the ontology depend on the available resources due to time constraints. The developed VfM only covers limited knowledge from appropriate guidance or standards, which requires extensive construction.

Practical restrictions

1) Due to resource constraints and the sensitivity of project information, the project information used in the BIM model varies according to the actual situations. The information only contains structure and architecture design information as well as limited project and documentation information. Therefore, there exists a difference in authenticity in the assessment of the method/platform compared with their use in reality.
2) Due to limited time, the rules created in the knowledge base are limited. Although the SWRL rules involve the field of VfM, the number of rules is not sufficient. In the case of large-scale public construction projects, the developed rules cannot involve with all the assessment requirement at the moment.
3) The information and documentation index for quantitative and qualitative assessments is based on the application of IFC, which can be used to manage procurement documents and object data. If the user does not adequately identify IFC as the applicable database, the established VfMO may be limited because the use of BIM is a prerequisite.

Future work

Referring to the research road map proposed in a previous chapter (Chapter 2), this study has initially achieved its main aims throughout its development. Considering the above limitations, however, the following will be addressed in future work:

1) The information exchange will be developed to further explore the standardisation of information exchange. This may involve the expansion of the IFC and a new proposed definition of 'information delivery' at the procurement level.
2) The ontology needs to be further refined; while the quantitative and qualitative parts of the VfM have been expressed functionally and logically in the developed ontology, the rest remains to be developed. Risk information, as an essential part, should be more effectively presented in the ontology. Therefore, risk assessment as an essential domain will be extended in future research.
3) Other data analysis approach should be used to cooperate with developed methodologies. The procurement of external data and the historical project data should be collected to construct a PPP VfM assessment library so that the advanced data analysis approach can be applied to expand the scope of assessment.

7.4 Research contribution

Taking into account the findings and developments presented in the previous chapters, this study can draw several conclusions.

A comprehensive review of the content and status of the PPP VfM assessment in Chapter 2 was made. In the existing literature review, the importance of VfM in research was emphasised, and the limitations of the practice were found through a review of government-published VfM reports. Due to the lack of a corresponding index of information for quantitative and qualitative assessments, automatic assessment has not been developed so far. By using the PPP data in the ministry of Finance of China, the methods used in the review chapters also connects to the data analysis approach and was proposed to publish in the PPP oriented journals.

The review paper was published in the Pro-VE Working Conference on Virtual Enterprises entitled '*BIM Based Value for Money Assessment in Public-Private Partnership'.* A more comprehensive review paper：'*A BIM-based value for money assessment in Public-Private Partnership: An overall review'* is submitted to the project management journal and currently under review.

Chapter 3 established the methodology of this study based on the original intention of establishing automated VfM assessment. To achieve a comprehensive VfM assessment, this study followed the principles of the DSR method, which can apply to categories of artefacts referring to engineering and computer science disciplines and aims to solve a generic problem. The results and processes of the study exemplify the applicability of the methodology for this study.

Following the specified methodology, Chapter 4 used a standardised process, IDM, to initially establish a process that satisfied the VfM and the required information and that connected it to IFC entities. Based on the developed schema, a software demo was developed to verify its feasibility. Based on the developed contents in this chapter, a conference paper: 'Data Exchange Requirement Analysis for Value for Money Assessment in Public-Private Partnerships' was published in the 25th EG-ICE international workshop 2018 and was indexed in the book 'Advanced Computing Strategies for Engineering' in Lecture Notes in Computer Science. A more combined information exchange schema article entitled '*Developing an information exchange scheme concerning value for money assessment in Public-Private Partnerships'* was published in the Journal of Building Engineering.

Based on the developed function of automated information exchange, Chapter 5 established a smart knowledge base using the VfM framework and rules. The knowledge base collects a large number of related concepts and builds logic through object properties and data properties. The semantic expression of the assessment rules was achieved through SWRL representation and established concepts, relationships and numerical types in the ontology. By using a similar logical approach to construct engineering domain knowledge base during the PhD, a joint paper '*An ontology-based approach supporting holistic structural design with the consideration of safety, environmental impact and cost*' and a paper '*Building an ontological knowledge base for bridge maintenance*' were published in the Advances in Engineering Software journal which separately presents holistic methods based on ontologies to achieve automatic rule checking and improve the management and communication of knowledge related to structural engineering and bridge maintenance domain. Through the Java development environment, the BIM server and the developed knowledge base were combined to execute the SWRL rules. This approach implemented the functional support of the VfM knowledge base for engineering projects. The semantic, syntactical, functional and practical aspects of the VfMO were validated in Chapter 6. This LD approach which is used to connected developed knowledge base and the engineering data source is summarized as a journal paper entitled '*BIM and ontology-based approach for automatic value for money and performance measurement'* was proposed to submit to engineering project management journal.

Through steps that facilitated continuous progress, this study demonstrates the possibility and feasibility of implementing knowledge management in PPP decision making concerning VfM. Although the thesis mainly represents the perspective of VfM, the system established can be applied to any computer-aided human decision making in large-scale engineering construction projects. Ontology language works as the artwork of a knowledge centre that can be published and can be semantically connected to different application areas. Combined with a highly efficient database, such as IFC, the established knowledge base has the practicality of combining project information. Because both the ontology and the cloud-managed BIM server can be implemented in an open-source environment, along with their increasingly developed standards, the integration between ontology and BIM can be more authoritative and effectively used in engineering decision making.

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Appendix A Review Supplement

Table A VfM application status in major PPP countries. Source: Benchmarking Public-Private Partnerships Procurement reports and national Value for money guidance.

Country	VfM application Status	PPP legal Framework	VfM Toolkit	Information support
Turkey	No specific methodology developed	No	No	No clear sources
China	Specific methodology developed	Guidelines for the Operation of Public-Private Partnership (trial)	Government and social capital cooperation project value for money assessment guidelines	No clear source
Indonesia	No specific methodology developed	The Presidential Regulation No. 38 of 2015; The Ministry of National Development Planning/ National Development Planning Agency (BAPPENAS) Regulation No. 4 of 2015; The Government Goods and Services Procurement Policy (LKPP) Regulation No. 19 of 2015	No	No clear source
Brazil	No specific methodology developed	The General Law for Public-Private Partnerships	Public-Private Partnership in Roads and Highways (P3 Toolkit, 2013	No clear source
India	Specific methodology developed	General Financial Rules; Model RFQ & RFP; Model concession agreements;	PPP Structuring Toolkit;	No clear source

UK	Specific methodology developed	Public procurement law;	Value for money assessment guidance; Assessing value for money; CIPFA Toolkit;	No clear source
France	Specific methodology developed	PPP and concession law (two regimes);	MAPPP guidance template for the Preliminary Assessment; Reference guide for a financial model for the Preliminary Assessment;	No clear source
USA	Specific methodology developed	Different PPP laws in different states	Value for money analysis for P3s; P3-VALUE Analytical Tool;	No clear source
Chile	No specific methodology developed	Concessions Law and regulations	No	No clear source
South Africa	Specific methodology developed	National Treasury PPP Practice Note	Public-Private Partnership Manual, South Africa	No clear source
Canada	Specific methodology developed	P3s guidance for public sponsors	PPP public sector value for money guidance	No clear source
Australia	Specific methodology developed	National PPP Policy Framework	Value for money guidance	No clear source

Table B The key input in the quantitative assessment (National Audit Office, 2013)

Area	Public sector comparator (PSC	Private Finance Initiative (PFI)

The initial capital cost of construction	Charged when incurred – usually in early years of the project.	Included in the annual unitary charge paid to the contractor, and thereby spread over the whole life of the contract.
Cost of maintaining the asset over the life of the contract/Cost of operating the asset	Charged when incurred.	Included in the annual unitary charge paid to the contractor, and thereby spread over the whole life of the contract.
Cost of finance and time value for money	The actual cost of public debt not reflected. All costs discounted at the social time preference rate.	Cost of finance included in the annual unitary charge paid to the contractor. However, because all costs were discounted at the social time preference rate, only financing costs above 6.09 per cent were recognised.
Optimism bias (risk of increases in the cost up to contract signature)	Included.	Included.
Optimism bias (risk of increases after the contract is signed)	An estimate was added to represent the the tendency of public sector contracts to overrun in time and cost.	Not included as the PFI cost is fixed by this point.
Tax charge	An estimate was added to reflect the tax that would be charged on the PFI option. It was added to the PSC rather than the PFI option in order to allow the PFI option to be compared to actual bids as they were received.	
Public sector transaction costs	Same value for both options.	
Flexibility charge	Some projects included an estimate for the likelihood that contractual changes would be required mid-contract. This was included in both options but the adjustment to the PFI option was usually higher than the adjustment to the PSC to reflect the premium the contractor would charge to make the change.	
Residual costs	If the maintenance and lifecycle costs of the public sector comparator were lower than those of the PFI option, then residual repair costs were added to the PSC to reflect the cost of bringing the asset up to the PFI standard of repair at the end of the project.	

Table C HM Treasury Value for money qualitative assessment contents (HM Treasury, 2006)

Qualitative assessment indicator	**Question**
objectives and outputs	Is the department satisfied that long-term contracts could be constructed for projects falling in this area? Can the contractual outputs be framed so that they can be objectively measured? Is the requirement deliverable as a service and as a long-term contractual arrangement? Could the contracts describe service requirements in clear, objective, output-based terms? Can the quality of the service be objectively and independently assessed? Is there a good fit between needs and contractible outcomes? Can the contracts be drafted to avoid perverse incentives and deliver quality services? Will there be significant levels of investment in new capital assets? Are there fundamental issues relating to staff transfer or other workforce issues? If there are interfaces with other projects, are they clear and manageable?
Soft services	Are there good strategic reasons to retain soft service provision in-house e.g. longer-term implications of skill transfer? What are the relative advantages and disadvantages? Is optimal risk allocation achieved by transfer or not? Is there a commitment that the assumed benefits can be delivered without eroding the overall terms and conditions for staff?
Operational flexibility	Is there a practical balance between the degree of operational flexibility that is desired and long term contracts based on up-front capital investment? What is the likelihood of large contract variations being necessary during the life of the contract? Can the service be implemented without constraining unacceptably the flexibility of the department to deliver future operational objectives?
Equity, efficiency and accountability	Are there public equity, efficiency or accountability reasons for providing the service directly, rather than through a PFI contract? Does the scope of the service lend itself to providing the contractor with “end-to-end” control of the relevant functional processes? Does the service have clear boundaries? Are there regulatory or legal restrictions that require services to be provided directly?
Risk management	Is the private sector likely to be able to manage the generic risks associated with the programme more effectively than the procuring authority? Bearing in mind the relevant risks that need to be managed for the programme (see Box 3.2), what is the ability of the private sector to price and manage

	these risks? Can the payment mechanism and contract terms incentivize good risk management?
Innovation	Is there scope for innovation in either the design of the solution or in the provision of the services? Does some degree of flexibility remain in the nature of the technical solution/service and/or the scope of the projects? Is the solution adequately free from the constraints of imposed by the procuring authority, legal requirements and/or technical standards? Does a preliminary assessment indicate that there is likely to be scope for innovation in the programme?
Contract Duration & residual value	How far into the future can service demand be reasonably predicted? What is the expected life of the assets? What are the disadvantages of a long contract length? Are there constraints on the status of the assets after the contracts end?
Incentives and monitoring	Can the outcomes or outputs of the investment programme be described in contractual terms, which would be objective, specific and measurable? Can the service be assessed independently against an agreed standard? Would incentives for the delivery of service levels be enhanced through a PFI payment mechanism?
Lifecycle costs	Is it possible to integrate the design, build and operation of the projects in the programme? Are there significant ongoing operating costs and maintenance requirements? Are these likely to be sensitive to the type of construction?
Market Interest	Is there evidence that the private sector is capable of delivering the required outcome? Does a significant market with sufficient capacity for these services exist in the private sector? Is there likely to be a sufficient market appetite for the projects in the programme? Has this been tested robustly? Is there any evidence of market failure for similar projects? Have any similar programmes been tendered to the market? Has the procuring authority's commitment to a PFI solution for projects of the type covered in this programme been demonstrated?
Efficient Procurement	Is there a realistic project plan, and has this been adhered to without undue delays? Are bid costs likely to be proportionate to the contract value? Will any aspect of the procurement impact adversely on market interest? (e.g. restrictions imposed by Competitive Dialogue procedure) Are there any

	problems emerging with the way the procurement is structured?

Table D PPP lifecycle indicators and corresponding BIM function. Source: The World Bank Group PPP reports selected literature, BIM management Tools.

Stages	PPP lifecycle indicators	BIM functions	Tools/carriers	Description
Screen as PPP	Project selection methodology	Information formatting	*dPOW; OIR*	Initialise the need to develop the project brief
	Project plan/programming	Site information; Survey formatting	*3D scan*	information used to specify the feasibility
Structure & Appraise	***VfM qualitative assessment*** (Whole project lifecycle integration; Operation flexibility Risk management; Contract and assets Duration; Incentives and Monitoring; Market interest; Efficient procurement)	Compliance checking; Semantic BIM approach; Documentation Query; Information exchange; Model simulation;	*Projectwise InfraWorks 360 BIM 360™; Viewpoint The semantic approach aligns with BIM*	The application of BIM used to improve the performance of quality aspects focusing on document management.
	VfM Quantitative assessment(PSC) FM costs, Construction costs, Operation costs, Transportation costs, Human resource costs, Risk related costs, Other costs	Cost analysis; Quantities take-off	*5D BIM tools; PEP Solibri; CostX®; The semantic approach aligns with BIM*	The BIM approach helps to build project cost structure and Quantities take-off are provided to measure the cost in real-time.
	Feasibility of task	Cost analysis; Scheduling	*BIM 360™; Viewpoint*	Format the project schedule updated with the project data
Design & Manage	Tender process and competition	Information exchange; Visualisation	*EIR; Bentley; Naviswork*	Deliver the requirement of stakeholders in the bidding stage
	Requirements of stakeholders/goals	Information formatting; Information exchange	*OIR; EIR;*	Deliver the requirement of stakeholders
	Clear project brief/Contract documents	Information formatting; Information exchange	*OIR; EIR; BIM PEP*	Deliver and translate the objectives of contract digitally
	Transparent procurement process/verify/monitoring	Document management	*BIM 360™; Viewpoint*	Provide progress monitoring and management
	Change in contract/private sector change	Document management	*EIR; BIM 360™; Viewpoint*	Highly efficient deal with progress change

Imple ment PPP	Site availability	Survey formatting; Space analysis	*IES; Green Building studio*	Information input into later design and construction
	Completion/Time Delay	Construction Scheduling	*Navisworks; ProjectWise; Tekla*	Format the scheduling and reduce the costs and delays
	Design deficiency/buildability	Clash detection; Compliance checking	*Navisworks; Solibri; Xsteel*	Improve design quality and benefits construction
	High-quality workmanship	Scheduling; Quantities take off	*3D scan; QTO; Vico*	Improve construction quality by accurate measurement
	Site construction safety	Compliance checking; Clash detection	*3D scan; Naviswork; BIM 360™; Solibri*	Improve safety planning by interactive as-build information
	Technical innovation in design to construction	Information exchange	*EIR; AIR; BIM 360™*	Deliver/format the information from design to construction
	Material/Labour/Equipment	Project management	*AIR;BIM 360™;Revit*	Asset Information in CDE for F&M
	Construction Cost overrun	Cost analysis; Construction Scheduling	*Solibri; CostX®; Navisworks*	Accurate measurement of cost in construction
	Operation cash flow	Maintenance	*ArchiBUS*	Deliver the information from construction to operation
	Operation performance	Energy management	*AIR; Energy Plus*	Cost of energy or electric use in the operation stage
	Residual assets	Project management	*AIR;BIM 360™*	Asset information in CDE

Appendix B Information exchange requirement

Table E Sample of Information exchange specification

Information Group	Information Sup-group	Information items	Attribute set	Attributes	Related/Optional
Work estimates (Quantitative assessment)	Upper floors	Building Slab systems	Geometry	Extruded shapes/Solid forms	O
				Dimensional tolerance	O
			Type	Structural type	R
			Material	Material type	R
			Finishes	Geometry	O
				Surface treatments	O
			Quantity Sets	Gross area	R
				Width	O
			Property Sets for Objects	Function	R
				Nominal thickness	R
				Position	R
				Structural material	R
			Relations	Implements structural objects	O
				Part of building element	O
				Contains components	O
			Meta Data	Reference level	R
Maintenance estimates (Quantitative assessment)	Scaffolding	Wall systems	Geometry	Shape/Solid forms	O
				Dimensional tolerance	O
			Type	Structural type	R
			Material	Material type	R
			Finishes	Geometry	R
				Surface treatments	R
			Quantity Sets	Gross side area	R
				Height	R
			Property Sets for Objects	Function	R
				Position	R
				Structural material	R
			Metadata	Reference level	O
			Relations	Implements structural objects	O
				Part of building element	O
				Contains components	O
Objects and outputs (Qualitative assessment)	Project information	Project	Identity	Name	R
				Function	O
			Description	Text	R
			Contact information	Addresses	O
			Briefing document	Scope	R
				Location	R
				Description	R
				Purpose	R
				Name	R

Table F Quantitative and qualitative assessment information exchange item groups Source：NRM and SPONS

Quantitative assessment information exchange groups				
Information Group	**Information Sup-group**	**Information items**	**Attribute set**	**Attributes**
Work estimates - Substructure (Quantitative assessment)	Basements	Building Slab systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Trench fill foundations	Building Column systems	Quantity Sets	Length
				Width
				Height

	Strip foundations	Building Column systems	Quantity Sets	Length
				Width
				Height
	Column bases	Building Column systems	Quantity Sets	Length
				Width
				Height
	Piling	Building Slab systems	Quantity Sets	Volume
				Height
				Width
	Ground Beams	Building Beam systems	Quantity Sets	Height
				Width
				Material and structure
	Ground Floor	Building Slab systems	Quantity Sets	Gross area
				Thickness
				Material and structure
Work estimates - superstructure (Quantitative assessment)	Underpinning	Building Wall systems	Quantity Sets	Gross area
				Height
	Frame	Building Slab systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Frame only(Columns)	Building column systems	Quantity Sets	Height
				Thickness
				Material and structure
	Frame only(Columns)	Building Beam systems	Quantity Sets	Length
				Width
				Height
	Fire protection	Building Slab systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Upper floors	Building Slab systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Roof	Building roof system	Quantity Sets	Gross area
				Thickness
				Material and structure
	Stairs and Ramps	Stairs and Ramps system	Quantity Sets	Height
				Nr
				Material and structure
	External Walls	Building Wall systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Windows and External Doors	Building Windows and Doors system	Quantity Sets	Gross area
				Material and structure
				Nr

	Internal walls and Partitions	Building Wall systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Internal doors	Building Windows and Doors system	Quantity Sets	Material and structure
				Nr
	Wall Finishes	Building Wall systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Floor Finishes	Building Slab systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Ceiling Finishes	Building Roof system	Quantity Sets	Gross area
				Thickness
				Material and structure
Scaffolding	Scaffolding externally	Building Wall systems	Quantity Sets	Height
				Gross area
				Material and structure
	Scaffolding internally	Building Wall systems	Quantity Sets	Height
				Gross area
				Material and structure
Demolitions	Partitions and Walls for Demolitions	Building Wall systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Boilers	Building boilers systems	Quantity Sets	Nr
	Flood protection	Building Door systems	Quantity Sets	Nr
Alterations	Fill in Door openings	Building Door systems	Quantity Sets	Nr
	Fill in Windows openings	Building the Windows system	Quantity Sets	Nr
	New door openings	Building Door systems	Quantity Sets	Nr
	New Window openings	Building the Windows system	Quantity Sets	Nr
	Concrete work	Building Slab systems	Quantity Sets	Thickness
				Volume
Other maintenance work	Brickwork	Building Wall systems	Quantity Sets	Gross area
				Thickness
				Material and structure
	Lintels and Beams	Building Beam systems	Quantity Sets	Nr
	Roofing			Gross area

		Building Roof system	Quantity Sets	Thickness
				Height
				Material and structure
	Plumbing	Building pipe system	Quantity Sets	Thickness
				Nr
				Length
Qualitative assessment information exchange groups				
Objects and outputs (HM Qualitative assessment)	Project information	Project	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Soft Services (HM Qualitative assessment)	Assets information	Building	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Operational flexibility (HM Qualitative assessment)	Assets information	Building	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Risk management (HM Qualitative assessment)	Risk information	Project	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Innovation (HM Qualitative assessment)	Contract information	Project	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Contract and assets Duration (Ministry of finance of China)	Contract information	Project	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Incentives and Monitoring (HM Qualitative assessment)	Contract information	Project	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Market Interest (HM		Project	Identity	Name
			Description	Text

Qualitative assessment)	Project Feasibility report		Briefing document	Scope,Location,Description, Purpose,Name
Finance feasibility (Ministry of finance of China)	Project Feasibility report	Project	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Efficient Procurement (HM Qualitative assessment)	Procurement information	Project	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name
Authority Resources (Ministry of finance of China)	Procurement information	Project	Identity	Name
			Description	Text
			Briefing document	Scope,Location,Description, Purpose,Name

Appendix C SWRL rules in VfMO

Table G SWRL rules for document query in qualitative assessment.

Q1	*To measure the performance 'Incentives and Monitoring', if the project has a business case document. The PI will be linked to the document.* IncentivesAndMonitoring(?IM) ^ Project(?P) ^ HasDocument(?P, BusinessCase) ^ BusinessCase(?b) -> HasRelatedDocument(?IM, ?b)
Q2	*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)
Q3	*To measure the performance* 'Innovation', *if the project has a Technical information document. The PI will be linked to the document.* Innovation(?I) ^ Project(?P) ^ HasDocument(?P, TechnicalInformation) ^ TechnicalInformation(?T) -> HasRelatedDocument(?I, ?T)
Q4	*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)
Q5	*To measure the performance '*Objectives and output', *if the project has a Briefing information document. The PI will be linked to the document.* ObjectivesAndOutputs(?O) ^ Project(?P) ^ HasDocument(?P, BriefingDocument) ^ BriefingDocument(?B) -> HasRelatedDocument(?O, ?B)
Q6	*To measure the performance* 'I Objectives and output', *the Briefing information document's URI of is queried for measurement* *ObjectivesAndOutputs(?O) ^ Project(?P) ^ HasDocument(?P, BriefingDocument) ^ BriefingDocument(?B) ^ HasURI(?B, ?u) -> sqwrl:select(?B, ?u)*

Table H 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 catalogue should be used and attached with 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 catalogue 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 by composite steel and concrete, then the cost library catalogue should be used and attached with 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)

Table I SWRL rules for green design performance measurement(references the China Green Airport Planning guidance)

P4.2.1(1)	*To measure the rules 4.2.1 (airport and urban planning) that required site information, the site information document is needed and the URI address of document can be queried.* GreenPerformance (AirportAndUrbanPlanning) ^ Site(?S) ^ HasDocument(?S, SiteInformation) ^ SiteInformation(?s) ^ HasURI(?s, ?u) -> sqwrl:select (?u)
P4.2.1(2)	*To measure the rules 4.2.1 that required site and environment information, the site model is needed and the description of the site can be queried.* Site(?S) ^ Description(?S, ?s) -> sqwrl:select(?s)
P6.2.1(1)	*To measure the rules 6.2.1 (Green performance) that required the terminal building information, the building model is needed and the description, a name can be queried.*

	GreenPerformance(ConfigurationPlanning) ^ Building(?B) ^ Description(?B, ?b) ^ Name(?B, ?n) -> sqwrl:select(?B, ?n, ?b)

Table J Other example using SWRL rules in procurement management

Risk events	*Calculating the risk costs by using the probabilistic method Vr= PC.* RiskEvent(?E) ^ CostConsequences(?E, ?c) ^ swrlb:multiply (?x, ?s, ?c) -> HasRiskCost (?E,?x)
Rating functions	*To measure the 'soft services' qualitative indicator, if the project has existing 'labour and equipment record' and 'delivery risk review' documents. The rating is 'very good'.* SoftServices(?S) ^ Project(?P) ^ HasDocument (?P, LabourAndEquipmentRecord) ^ HasDocument (?P, DeliveryRiskReview) -> Rating (?S "Very good")
Selecting parties	*Selecting all the possible civil engineering company with multiple constraints.* CivilEngineer (?C) ^ Rating(?C, "Very good") ^ BiddingPrice (?C, ?BP) ^ swrlb:lessThan(?BP, 10000) ^ DeliveryTime(?C, ?DT) ^ swrlb:lessThan(?DT, "5"^^xsd:int) -> *sqwrl:select(?C)*

Table K SWRL rules in qualitative assessment in VfMO

Q1	*To measure the performance 'Incentives and Monitoring', if the project has a business case document. The PI will be linked to the document.*
	IncentivesAndMonitoring(?IM) ^ Project(?P) ^ HasDocument(?P, BusinessCase) ^ BusinessCase(?b) -> HasRelatedDocument(?IM, ?b)
Q2	*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)
Q3	*To measure the performance* 'Innovation'*, if the project has a Technical information document. The PI will be linked to the document.*
	Innovation(?I) ^ Project(?P) ^ HasDocument(?P, TechnicalInformation) ^ TechnicalInformation(?T) -> HasRelatedDocument(?I, ?T)
Q4	*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)
Q5	*To measure the performance* 'Objectives and output'*, if the project has a Briefing information document. The PI will be linked to the document.*
	ObjectivesAndOutputs(?O) ^ Project(?P) ^ HasDocument(?P, BriefingDocument) ^ BriefingDocument(?B) -> HasRelatedDocument(?O, ?B)
Q6	*To measure the performance* 'I Objectives and output'*, the Briefing information document's URI of is queried for measurement*
	ObjectivesAndOutputs(?O) ^ Project(?P) ^ HasDocument(?P, BriefingDocument) ^ BriefingDocument(?B) ^ HasURI(?B, ?u) -> sqwrl:select(?B, ?u)
Q7	*To measure the performance* 'MarketInterest'*, if the project has a Feasibility study. The PI will be linked to the document.*
	MarketInterest(?M) ^ Project(?P) ^ HasDocument(?P, FeasibilityStudy) ^ FeasibilityStudy(?F) -> HasRelatedDocument(?M, ?F)
Q8	*To measure the performance* 'MarketInterest'*, the Feasibility study's URI is queried.*
	Project(?P) ^ HasDocument(?P, FeasibilityStudy) ^ FeasibilityStudy(?f) ^ HasURI(?f, ?u) -> sqwrl:select(?f, ?u)
Q9	*To measure the performance* 'OperationalFlexibility'*, if the project has a Feasibility study. The PI will be linked to the document.*
	OperationalFlexibility(?O) ^ Project(?P) ^ HasDocument(?P, FeasibilityStudy) ^ FeasibilityStudy(?F) -> HasRelatedDocument(?O, ?F)
Q10	*To measure the performance* 'OperationalFlexibility'*, the Feasibility study's URI is queried.*
	Project(?P) ^ HasDocument(?P, FeasibilityStudy) ^ FeasibilityStudy(?b) ^ HasURI(?b, ?u) -> sqwrl:select(?b, ?u)

Q11	To measure the performance 'RiskManagement', if the project has a DeliveryRiskReview, or RiskPotentialAssessment. The PI will be linked to the document.
	Project(?P) ^ HasDocument(?P, DeliveryRiskReview) ^ HasDocument(?P, RiskPotentialAssessment) ^ DeliveryRiskReview(?d) ^ RiskPotentialAssessment(?r)^ HasURI(?d, ?u) ^ HasURI(?r, ?u') -> sqwrl:select(?d,?r, ?u, ?u')
Q12	*To measure the performance '*RiskManagement'*, the DeliveryRiskReview and RiskPotentialAssessment 's URI is queried.*
	Project(?P) ^ HasDocument(?P, DeliveryRiskReview) ^ HasDocument(?P, RiskPotentialAssessment) ^ DeliveryRiskReview(?d) ^ RiskPotentialAssessment(?r) ^ HasURI(?d, ?u) ^ HasURI(?r, ?u') -> sqwrl:select(?d, ?r, ?u, ?u')
Q13	*To measure the performance '*SoftServices'*, if the project has a 'Labour And Equipment Record'. The PI will be linked to the document.*
	SoftServices(?S) ^ Project(?P) ^ HasDocument(?P, LabourAndEquipmentRecord) ^ LabourAndEquipmentRecord(?L) -> HasRelatedDocument(?S, ?L)
Q14	*To measure the performance '*SoftServices'*, the LabourAndEquipmentRecord 's URI is queried.*
	Project(?P) ^ HasDocument(?P, LabourAndEquipmentRecord) ^ LabourAndEquipmentRecord(?l) ^ HasURI(?l, ?u) -> sqwrl:select(?l, ?u)

Table L SWRL rules in Quantitative assessment in VfMO

FoundationCost1.1	*To measure the foundation cost of a certain object, if the foundation is column-based, then the column bases cost library catalogue should be used and attached with the object.*
	FoundationCost (?FC) ^ Column(?C) ^ HasMaterial(?C, ColumnBases)^ FoundationCostLib(ColumnBases) -> HascostLib(?FC, ColumnBases)
FoundationCost1.2	*To measure the column bases foundation cost, followed the formula C ≈ ∑_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)
FoundationCost2.1	To measure the foundation cost of a certain object, if the foundation is Trench fill based, then the related cost library catalogue should be used and attached with the object.
	FoundationCost(?FC) ^ Trench(?C) ^ HasMaterial(?C, TrenchFill) ^ FoundationCostLib(TrenchFill) -> HascostLib(?FC, TrenchFill)
FoundationCost2.2	*To measure the Trench fill based foundation cost, followed the formula C ≈ ∑_k^n C^k U^k, the height of Trench is needed to multiply the unit cost in the cost library.*
	FoundationCost(?FC) ^ Trench(?C) ^ HascostLib(?FC, TrenchFill) ^

	HasUnitCost(TrenchFill, ?c) ^ Height(?C, ?n) ^ swrlb:multiply(?w, ?n, ?c) -> HasCost(?FC, ?w)
FoundationCost3.1	To measure the foundation cost of a certain object, if the foundation is Strip based, then the related cost library catalogue should be used and attached with the object.
	FoundationCost(?FC) ^ Strip(?C) ^ HasMaterial(?C, Strip) ^ FoundationCostLib(Strip) -> HascostLib(?FC, Strip)
FoundationCost3.2	*To measure the Strip based foundation cost, followed the formula C ≈ ∑_k^n C^k U^k, the height of Strip is needed to multiply the unit cost in the cost library.*
	FoundationCost(?FC) ^ Strip(?C) ^ HascostLib(?FC, Strip) ^ HasUnitCost(Strip, ?c) ^ Height(?C, ?n) ^ swrlb:multiply(?w, ?n, ?c) -> HasCost(?FC, ?w)
FoundationCost4	*To measure the Piling cost, followed the formula C ≈ ∑_k^n C^k U^k, the height of Piling is needed to multiply the unit cost in the cost library.*
	PillingCost(?PC) ^ PillingMat(?C) ^ HascostLib(?PC, Pilling) ^ HasUnitCost(Pilling, ?c) ^ Height(?C, ?n) ^ swrlb:multiply(?w, ?n, ?c) -> HasCost(?PC, ?w)
FoundationCost5	*To measure the ground beam cost, followed the formula C ≈ ∑_k^n C^k U^k, the Length of Beam is needed to multiply the unit cost in the cost library.*
	GoundBeamCost(?GC) ^ GoundBeam(?C) ^ HascostLib(?GC, GoundBeam) ^ HasUnitCost(GoundBeam, ?c) ^ Length(?C, ?n) ^ swrlb:multiply(?w, ?n, ?c) -> HasCost(?GC, ?w)
FoundationCost6	*To measure the ground floor cost, followed the formula C ≈ ∑_k^n C^k U^k, the area of Beam is needed to multiply the unit cost in the cost library.*
	GroundFloorCost(?GC) ^ GroundFloor(?C) ^ HascostLib(?GC, GroundFloor) ^ HasUnitCost(GroundFloor, ?c) ^ Area(?C, ?n) ^ swrlb:multiply(?w, ?n, ?c) -> HasCost(?GC, ?w)
FrameCost1.1	*To measure the frame cost of a certain object, if the frame is a concrete frame, then the concrete frame cost library catalogue should be used and attached with the object.*
	FrameCost(?FC) ^ Frame(?F) ^ HasMaterial(?F, Concrete) ^ FrameLib(ConcreteFrames) -> HascostLib(?FC, ConcreteFrames)
FrameCost1.2	*To measure the concrete frame cost, followed the formula C ≈ ∑^nC^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, ?c, ?a) -> HasCost(?FC, ?s)

FrameCost2	*To measure the frame cost of a certain object, if the frame is a Steel frame, then the steel frame cost library catalogue should be used and attached with the object.*
	FrameCost(?FC) ^ Frame(?F) ^ HasMaterial(?F, Steel) ^ FrameLib(SteelFrames) -> HascostLib(?FC, SteelFrames)
FrameCost2.2	*To measure the Steel frame cost, followed the formula C ≈ ∑^nC^k U^k, the gross area is needed to multiply the unit cost in the cost library.*
	FrameCost(?FC) ^ Frame(?F) ^ HascostLib(?F, SteelFrames) ^ HasUnitCost(SteelFrames, ?c) ^ GrossArea(?F, ?a) ^ Width(?F, ?w) ^ swrlb:lessThan(?w, "250.0"^^xsd:float) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?FC, ?s)
FrameCost3	*To measure the Fire protection to steelwork cost, followed the formula C ≈ ∑^nC^k U^k, the gross area is needed to multiply the unit cost in the cost library.*
	FrameFireProtectionCost(?FC) ^ FireProtection(?F) ^ HascostLib(?F, FireProtectionToSteelwork) ^ HasUnitCost(FireProtectionToSteelwork, ?c) ^ GrossArea(?F, ?a) ^ swrlb:multiply(?s, ?a, ?c) -> HasCost(?FC, ?s)
UpperFloor1.1	*To measure the upper floor cost of a certain object, if the floor is made by composite steel and concrete, then the cost library catalogue should be used and attached with the object.*
	UpperFloorCost(?U) ^ Floor(?F) ^ HasMaterial(?F, CompositeSteelAndConcrete) ^ UpperFloorLib(CompositeSteelAndConcrete) -> HascostLib(?U, CompositeSteelAndConcrete)
UpperFloor1.2	*To measure the composite steel and concrete upper floor cost, followed the formula C ≈ ∑^nC^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)
UpperFloor2.2	*To measure the composite precast concrete upper floor cost, followed the formula C ≈ ∑^nC^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, CompositePrecastConcrete) ^ HasUnitCost(CompositePrecastConcrete, ?c) ^ GrossArea(?F, ?a) ^ swrlb:multiply(?w, ?c, ?a) -> HasCost(?U, ?w)
UpperFloor3.2	*To measure the Post-tensioned concrete upper floor cost, followed the formula C ≈ ∑^nC^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, PostTensionedConcrete) ^ HasUnitCost(PostTensionedConcrete, ?c) ^ GrossArea(?F, ?a) ^ swrlb:multiply(?w, ?c, ?a) -> HasCost(?U, ?w)
Roof1.2	*To measure the Softwood roof structure, followed the formula C ≈ ∑^nC^k U^k, the gross area of the roof is needed to multiply the unit cost in the cost library.*
	RoofCost(?U) ^ Roof(?F) ^ HascostLib(?U, SoftwoodRoof) ^ HasUnitCost(SoftwoodRoof, ?c) ^ GrossArea(?F, ?a) ^ swrlb:multiply(?w, ?c, ?a) -> HasCost(?U, ?w)
Roof2.2	*To measure the Metal roof structure, followed the formula C ≈ ∑^nC^k U^k, the gross area of the roof is needed to multiply the unit cost in the cost library.*
	RoofCost(?U) ^ Roof(?F) ^ HascostLib(?U, MetalRoof) ^ HasUnitCost(MetalRoof, ?c) ^ GrossArea(?F, ?a) ^ swrlb:multiply(?w, ?c, ?a) -> HasCost(?U, ?w)
Roof3.2	*To measure the Concrete roof structure, followed the formula C ≈ ∑^nC^k U^k, the gross area of the roof is needed to multiply the unit cost in the cost library.*
	RoofCost(?U) ^ Roof(?F) ^ HascostLib(?U, ConcreteRoof) ^ HasUnitCost(ConcreteRoof, ?c) ^ GrossArea(?F, ?a) ^ swrlb:multiply(?w, ?c, ?a) -> HasCost(?U, ?w)
StairsAndRamps1.2	*To measure the Reinforced concrete stairs and ramps, followed the formula C ≈ ∑^nC^k U^k, the number of the stair is needed to multiply the unit cost in the cost library.*
	StairCost(?SC) ^ Stair(?S) ^ HascostLib(?S, ReinforcedConcreteStair) ^ HasUnitCost(ReinforcedConcreteStair, ?c) ^ Nr(?S, ?a) ^ Height(?S, ?w) ^ swrlb:greaterThanOrEqual(?w, "3"^^xsd:float) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?SC, ?s)
StairsAndRamps2.2	*To measure the Metal stairs and ramps, followed the formula C ≈ ∑^nC^k U^k, the number of the stair is needed to multiply the unit cost in the cost library.*
	StairCost(?SC) ^ Stair(?S) ^ HascostLib(?S, MetalStairs) ^ HasUnitCost(MetalStairs, ?c) ^ Nr(?S, ?a) ^ Height(?S, ?w) ^ swrlb:greaterThanOrEqual(?w, "3"^^xsd:float) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?SC, ?s)
StairsAndRamps3.2	*To measure the Timber stairs and ramps, followed the formula C ≈ ∑^nC^k U^k, the number of the stair is needed to multiply the unit cost in the cost library.*

	StairCost(?SC) ^ Stair(?S) ^ HascostLib(?S, TimberStairs) ^ HasUnitCost(TimberStairs, ?c) ^ Nr(?S, ?a) ^ Height(?S, ?w) ^ swrlb:greaterThanOrEqual(?w, "2.6"^^xsd:float) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?SC, ?s)
ExternalWalls1.2	*To measure the brick wall, followed the formula C ≈ ∑^nC^k U^k, the area of the wall is needed to multiply the unit cost in the cost library.*
	ExternalWallCost(?EC) ^ ExternalWall(?E) ^ HascostLib(?E, BrickWalls) ^ HasUnitCost(BrickWalls, ?c) ^ Area(?E, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?EC, ?s)
ExternalWalls2.2	*To measure the Reinforced concrete wall, followed the formula C ≈ ∑^nC^k U^k, the area of the wall is needed to multiply the unit cost in the cost library.*
	ExternalWallCost(?EC) ^ ExternalWall(?E) ^ HascostLib(?E, ReinforcedConcreteWalls) ^ HasUnitCost(ReinforcedConcreteWalls, ?c) ^ Area(?E, ?a)^Thickness(?E,?w) ^ swrlb:equal (?w, "150"^^xsd:float) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?EC, ?s)
ExternalWalls3	*To measure the Sheet claddings of the walls, followed the formula C ≈ ∑^nC^k U^k, the area of the wall is needed to multiply the unit cost in the cost library.*
	ExternalWallCost(?EC) ^ ExternalWall(?E) ^ HascostLib(?E, SheetCladdings) ^ HasUnitCost(SheetCladdings, ?c) ^ Area(?E, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?EC, ?s)
ExternalWalls4	*To measure the Metal cladding of the walls, followed the formula C ≈ ∑^nC^k U^k, the area of the wall is needed to multiply the unit cost in the cost library.*
	ExternalWallCost(?EC) ^ ExternalWall(?E) ^ HascostLib(?E, MetalCladdings) ^ HasUnitCost(MetalCladdings, ?c) ^ Area(?E, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?EC, ?s)
ExternalWalls5	*To measure the insulation of the walls, followed the formula C ≈ ∑^nC^k U^k, the area of the wall is needed to multiply the unit cost in the cost library.*
	ExternalWallCost(?EC) ^ ExternalWall(?E) ^ HascostLib(?E, Insulation) ^ HasUnitCost(Insulation, ?c) ^ Area(?E, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?EC, ?s)
WindowsAndExternalDoors 1.2	*To measure the softwood windows, followed the formula C ≈ ∑^nC^k U^k, the area of the windows is needed to multiply the unit cost in the cost library.*
	WindowsCost(?WC) ^ Windows(?W) ^ HascostLib(?W, SoftwoodWindows) ^ HasUnitCost(SoftwoodWindows, ?c) ^ Area(?W, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?WC, ?s)

WindowsAndExternalDoors 2.2	*To measure the Steel windows, followed the formula C ≈ ∑^nC^k U^k, the area of the windows is needed to multiply the unit cost in the cost library.*
	WindowsCost(?WC) ^ Windows(?W) ^ HascostLib(?W, StellWindows) ^ HasUnitCost(StellWindows, ?c) ^ Area(?W, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?WC, ?s)
WindowsAndExternalDoors 3.2	*To measure the softwood doors, followed the formula C ≈ ∑^nC^k U^k, the number of the doors is needed to multiply the unit cost in the cost library.*
	DoorCost(?DC) ^ Door(?D) ^ HascostLib(?D, SoftwoodDoors) ^ HasUnitCost(SoftwoodDoors, ?c) ^ Nr(?D, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?DC, ?s)
WindowsAndExternalDoors 4.2	*To measure the Steel doors, followed the formula C ≈ ∑^nC^k U^k, the number of the doors is needed to multiply the unit cost in the cost library.*
	DoorCost(?DC) ^ Door(?D) ^ HascostLib(?D, SteelDoors) ^ HasUnitCost(SteelDoors, ?c) ^ Nr(?D, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?DC, ?s)
InternalWalls1.2	*To measure the brick wall, followed the formula C ≈ ∑^nC^k U^k, the area of the wall is needed to multiply the unit cost in the cost library.*
	InternalWallCost(?IC) ^ InternalWall(?I) ^ HascostLib(?I, BrickWalls) ^ HasUnitCost(BrickWalls, ?c) ^ Area(?I, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?IC, ?s)
InternalWalls2.2	*To measure the glass wall, followed the formula C ≈ ∑^nC^k U^k, the area of the wall is needed to multiply the unit cost in the cost library.*
	InternalWallCost(?IC) ^ InternalWall(?I) ^ HascostLib(?I, GlassWalls) ^ HasUnitCost(GlassWalls, ?c) ^ Area(?I, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?IC, ?s)
InternalFinishes1.2	*To measure the Insitu wall finishes, followed the formula C ≈ ∑^nC^k U^k, the area of the wall is needed to multiply the unit cost in the cost library.*
	InternalFinishesCost(?IC) ^ InternalWall(?I) ^ HascostLib(?I, InsituWallFinishes) ^ HasUnitCost(InsituWallFinishes, ?c) ^ Area(?I, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?IC, ?s)
InternalFinishes1.2	*To measure the Insitu screed floor finishes, followed the formula C ≈ ∑^nC^k U^k, the area of the floor is needed to multiply the unit cost in the cost library.*
	InternalFinishesCost(?IC) ^ UpperFloor(?U) ^ HascostLib(?U, InsituScreedFloor) ^ HasUnitCost(InsituScreedFloor, ?c) ^ Area(?U, ?a) ^ swrlb:multiply(?s, ?c, ?a) -> HasCost(?IC, ?s)

Appendix D Delivered VfMO interface and Feedback Form

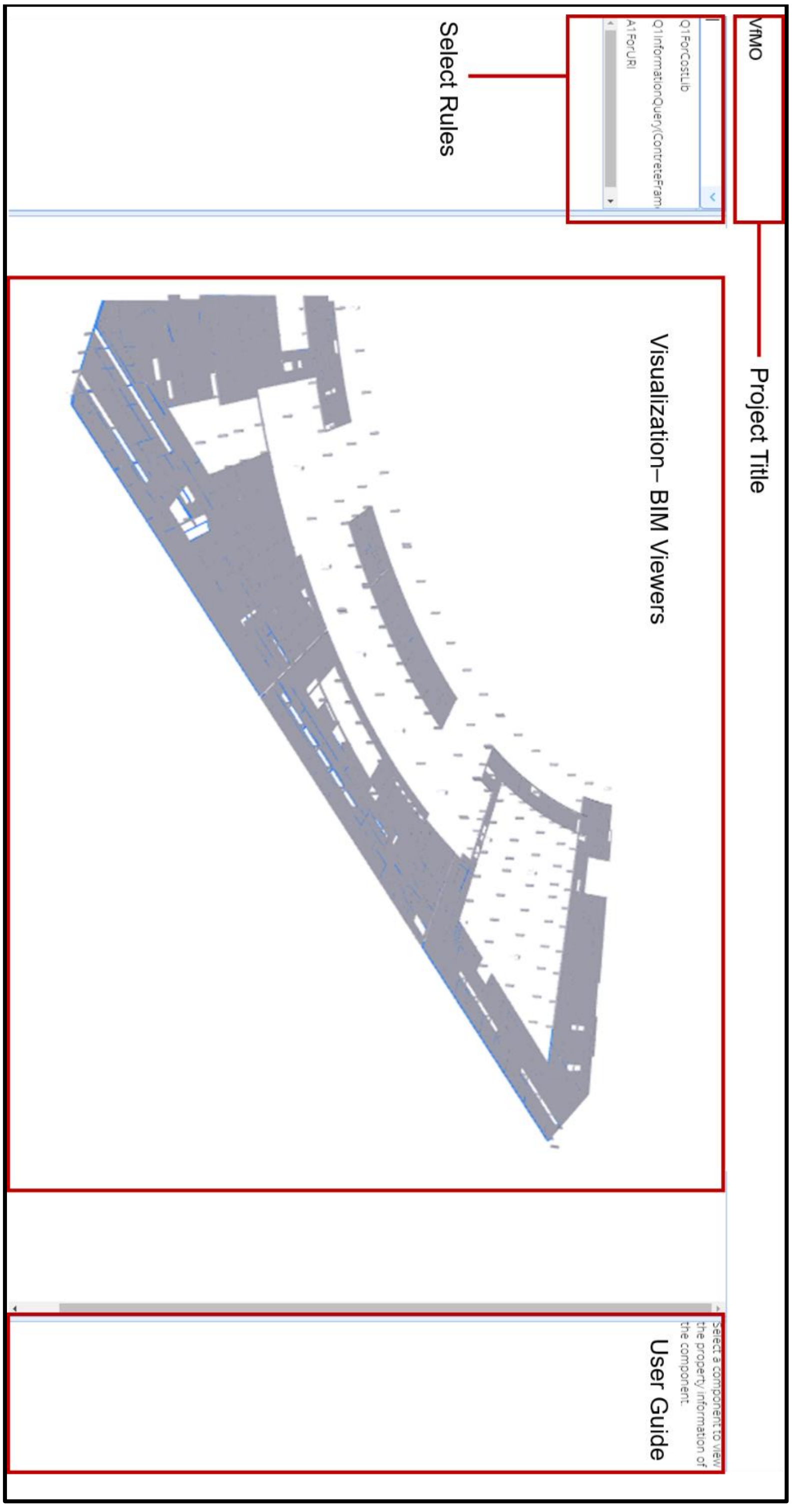

Figure A The VfMO interface (a)

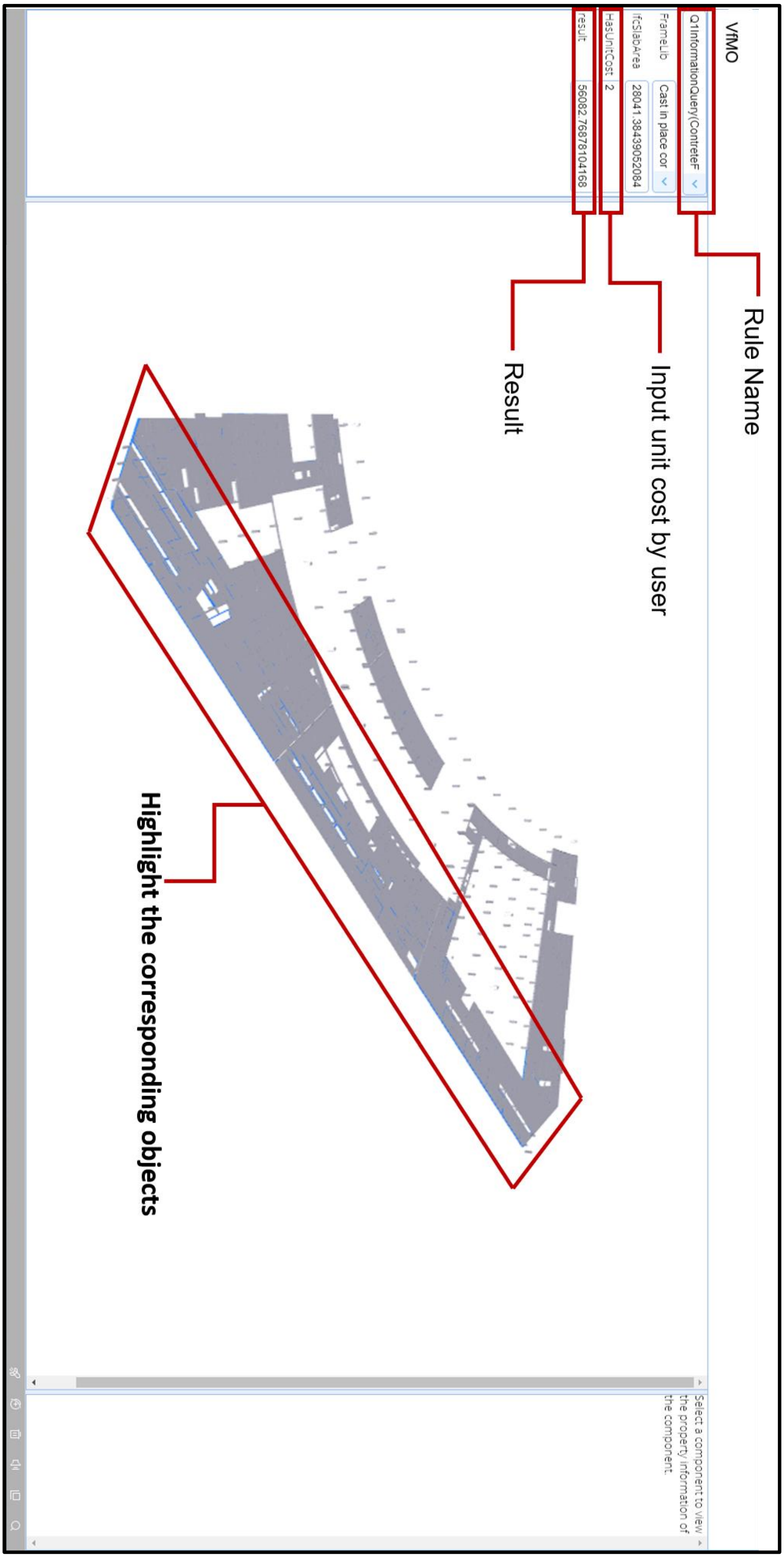

Figure B The VfMO interface (b)

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关于使用 BIMserver 的项目决策评估系统的验证情况说明

经任国乾博士推荐，通过使用 BIMserver 的项目决策评估系统对本公司珑悦府建设项目进行验证评估，该系统通过建立项目流程、评估流程，BIM 的 IFC 属性索引以及其他财务领域的属性关系的方式在建立智库的基础上，与 BIM server 实现对接，并按照评估的不同规则指向 BIM 中的信息、得到索引，使得项目的数据能够被纳入到输入的评估规则中，得到结果以支持决策。通过验证使用认为：使用 BIMserver 项目决策系统能够在项目建设初期进行三维渲染，可视化模拟施工，直观的把涉及评估，决策的各个因素和概念以及概念之间的关系在 semantic 软件中的表达出来，决策结果较为准确，评估效率较高。

验证结论：BIMserver 的项目决策评估系统具有较好的使用价值和推广价值。

建议：今后进一步延伸开发，为建设项目制定更多的规则和概念提供帮助。

山东澳信供热有限公司

2019 年 8 月 29 日

山东智星工程咨询有限公司

关于使用 BIMserver 的项目决策评估系统的验证情况说明

经任国乾博士推荐，通过使用 BIMserver 的项目决策评估系统对本公司韩仓河支沟桥建设项目进行验证评估，通过验证使用认为：该决策系统在建立智库的基础上，与 BIM server 实现对接，并按照评估的不同规则指向 BIM 中的信息、得到索引，从而使建立的评估规则通过自动化提取数据库的数据来实现实时的自动化评估，实用性好。且使用 BIMserver 项目决策系统能够直观的把涉及评估，决策的各个因素和概念以及概念之间的关系可视化，简明易懂，并且对项目建设周期、成本能够直观对比，能够实现建设项目全生命周期的把控。

验证结论：BIMserver 的项目决策评估系统评价较为准确，更直观、使评估人员能够可视化，能够为领导者提供较好的决策平台，可在决策阶段进行较为准确的方案对比，具有较好的使用价值和推广价值。希望今后进一步延伸开发，为建设项目制定更多的规则和概念提供帮助。

山东智星工程咨询有限公司

2019 年 8 月 29 日

山东省建鲁智华工程咨询研究院有限公司

关于使用 BIMserver 的项目决策评估系统的验证情况说明

经任国乾博士推荐，通过使用 BIMserver 的项目决策评估系统对本公司大柿子园社区安置房建设项目进行验证评估，通过验证使用认为：使用 BIMserver 项目决策系统能够通过建立项目流程，评估流程，BIM 的 IFC 属性索引以及其他财务领域的属性关系的方式，直观的把涉及评估、决策的各个因素和概念以及概念之间的关系在 semantic 软件中的表达出来。

该系统在建立智库的基础上（包含评估规则），与 BIM server 实现对接，使得项目的数据能够被纳入到输入的评估规则中，得到结果以支持决策，并按照评估的不同规则指向 BIM 中的信息，得到索引。从而使建立的评估规则通过自动化提取数据库的数据来实现实时的自动化评估。

验证结论：BIMserver 的项目决策评估系统评价直观、评估人员能够可视化，评估结果更准确。对领导者提供较好的决策平台，具有较好的使用价值和推广价值。

如进一步延伸开发，可为以后建设项目用来制定更多的规则和概念提供帮助，进一步优化使用者体验，使决策结果更加精确。

山东省建鲁智华工程咨询研究院有限公司

2019 年 8 月 29 日

The comments on the working accuracy of the developed demo? 针对研究产品执行评估准确性的评价？	与传统决策评估系统相比，该研究产品在建立智库的基础上（包含评估规则），与 BIM server 实现对接，从而使得项目的数据能够被纳入到输入的评估规则中，得到结果以支持决策，综合性的考虑项目特点，评估比较准确。进一步优化后考虑较多的相关影响参数，评估会更准确。
The comments on the working efficiency of the developed demo? 针对研究产品执行评估是否能够提升评估效率做出评价？	该研究产品与传统评价相比，利用此评估系统输入相关参数，得到有关评估数据，能够提升评估效率，该研究产品评估效率更高。进一步优化算法后，评估效率会进一步提升。
To what extent the developed demo can replace the traditional approach? 针对研究产品在发展后是否能够取代现有评估模式做出评价？	该产品建立的评估规则通过自动化提取数据库的数据来实现实时的自动化评估。全生命周期掌控项目进程，包括时间节点、成本控制，是绩效评估、投资评估的一个发展趋势，直观性强，可视化。进一步优化后，能够取代传统的评估模式。
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Figure C The feedback document and form Chinese procurement industries (a)

The comments on the working accuracy of the developed demo? 针对研究产品执行评估准确性的评价？	该研究开发的项目决策系统旨在通过建立项目知识库的方式，把涉及到评估，决策的各个因素和概念以及概念之间的关系以 ontology（本体论）的形式在 semantic 软件中的得到表达。该研究产品与传统评价相比，直观、评估准确。优化后评估会更准确。
The comments on the working efficiency of the developed demo? 针对研究产品执行评估是否能够提升评估效率做出评价？	使用该研究产品，用户可以自己使用语义软件来制定更多的规则和概念填充智库，评估更具有针对性，故而与传统评估系统相比，评估效率更高。
To what extent the developed demo can replace the traditional approach? 针对研究产品在发展后是否能够取代现有评估模式做出评价？	该研究产品是建设项目评估、投资决策的一个发展趋势，实现方案的可视化。将来进一步优化后，能够取代传统的评估模式。
专家签字 /Signature	[illegible]

The comments on the working accuracy of the developed demo? 针对研究产品执行评估准确性的评价？	该研究开发的项目决策系统通过建立项目知识库的方式高效直观的展现评估结果，与传统评价相比，更直观、评估比较准确。优化后考虑较多的相关影响参数，评估会更准确。
The comments on the working efficiency of the developed demo? 针对研究产品执行评估是否能够提升评估效率做出评价？	该研究产品与传统评价相比，输入相关参数，得到有关评估数据，因而能够提升评估效率。
To what extent the developed demo can replace the traditional approach? 针对研究产品在发展后是否能够取代现有评估模式做出评价？	该研究产品是评估的一个发展趋势，直观性强，可视化。将来进一步优化后，能够取代传统的评估模式。
专家签字 /Signature	[illegible]

Figure D The feedback document and form Chinese procurement industries (b)