Building Information Modelling and Asset Management: Semantic and Syntactic Interoperability

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A thesis submitted to the School of the Built Environment,

Oxford Brookes University, in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy in Construction Management

April 2020

Declaration

I Karim Farghaly hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

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Abstract

Building Information Modelling (BIM) has the potential to improve the design, construction and operation of assets using a standardised machine-readable information model. Despite the rapidly increasing adoption of BIM in design and construction stages, the adoption of BIM for Operation and Maintenance (O&M) is still relatively weak. While there are multifaceted challenges behind that weak adoption, there are recurring themes of the poor data integration between BIM and existing Asset Management (AM) systems and of how to structure BIM models for use in the O&M phase.

Reflecting on that interoperability challenge, this research aims to provide a methodology to design, develop and transfer the information required to support O&M from BIM models. To achieve the research aim, firstly a critical review of the literature was undertaken to develop a conceptual framework of the interoperability aspects for BIM implementation in AM. The proposed conceptual framework would facilitate the transfer of information from BIM models to AM tools through the development of a specific Model View Definition (MVD) and a Revit Plug-in. The MVD and Revit Plug-in are developed based on a taxonomy of the required data and based on a cross-mapping between the different standards and guidelines used in the Architecture, Engineering, Construction and Operation (AECO) industry. To achieve these aspects, semi-structured interviews and focus group are adapted to identify the required information and an effective cross-mapping between the standards where ontologies are utilised to publish and share machine-readable inter-Linked Data on the web. On the other hand, a prototyping approach is employed for the MVD and the Revit Plug-in development, while a case study method is used for evaluating the developed concepts and prototypes.

The developed capabilities can enable facility managers to semantically link the BIM objects to the maintenance records in the Semantic Web during the O&M phase in order to provide a BIM environment without the specific BIM authoring application. Due to the assets' heterogeneity, this research provides an interoperability solution for the data exchange of assets that consume energy from the BIM systems to the AM systems during the handover stage. Although the stated contributions of this research are anchored on assets that consume energy only, the outputs can still be updated and adapted to cover all of the operable and maintainable building assets.

Dedication

To my father.

Acknowledgements

This research has been made possible through the award of a university 150th anniversary research scholarship by Oxford Brookes University. I am grateful to my academic supervisors, Dr Henry Abanda Fonbeyin, Dr Christos Vidalakis and Dr Graham Wood, for their expert guidance and support during this research. I would like to thank all my family and friends for all their encouragement throughout. For my father who always motivated me to chase my dreams and supported me in all my pursuits (asking ALLAH to forgive and have mercy on him), for my mother who always prayed for the best to me. Finally, for my close friends and siblings, whose faithful support and love is so appreciated. Thank you all.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

AEC	Architecture, Engineering and Construction
AECO	Architecture, Engineering, Construction and Operation
AIM	Asset Information Model
AM	Asset Management
API	Application Programming Interface
BIM	Building Information Modelling
CAFM	Computer Aided Facility Management
COBie	Construction Operation Building Information Exchange
EIR	Exchange Information Requirements
FM	Facilities Management
GSL	Government Soft Landing
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
KE	Knowledge Engineering
MVD	Model View Definition
NRM	New Rules of Measurement
O&M	Operation and Maintenance
OWL	Ontology Web Language
PAS	Publicly Available Specification
PSD	Property Set Definitions
RDF	Resource Description Framework
URI	Uniform Resource Identifier

List of Publications

Parts of this thesis have been published by the author in the papers listed below.

Published - Journals

- Farghaly, K., Abanda, F. H., Vidalakis, C., and Wood, G. (2018). “Taxonomy for BIM and Asset Management Semantic Interoperability.” Journal of Management in Engineering, 34(4), 04018012.
- Farghaly, K., Abanda, F., Vidalakis, C. and Wood, G. (2019), "BIM-Linked Data integration for asset management", Built Environment Project and Asset Management, Vol. 9 No. 4, pp. 489-502. https://doi.org/10.1108/BEPAM-11-2018-0136.
- Farghaly, K., Abanda, F.H., Vidalakis, C. and Wood, G., 2020. BIM-Enabled Asset Management Information Exchange: IDM/MVD Approach. International Journal of Digital Innovation in the Built Environment (IJDIBE), 9(1), pp.49-62.

International Conference Papers

- Farghaly, K., Abanda, F.H., Vidalakis, C., and Wood, G., (2016). “BIM for FM: Input Versus Output Data.” In Proceedings of the 33rd CIB W78 Conference, 31st October–2nd November, Brisbane, Australia
- Farghaly, K., Abanda, F.H., Vidalakis, C., and Wood, G. (2017). “BIM Big Data System Architecture for Asset Management: A Conceptual Framework.” In: Proc. Lean & Computing in Construction Congress (LC3), Vol. 1 (CIB W78), Heraklion, Greece.
- Farghaly, K., Abanda, F.H., Vidalakis, C., and Wood, G. (2017). “BIM for Asset Management: A Taxonomy of Non-geometric BIM Data for Asset Management.” In Proceedings of EG-ICE 2017 conference, Birmingham, England.

- Farghaly K., Abanda, F.H., Vidalakis, C., and Wood, G. (2019). “Semantic and Syntactic Interoperability of BIM and Asset Management Data.” 2019 European Conference on Computing in Construction, Crete, Greece.

Oral Presentations

In addition, parts of this thesis have been orally presented by the author at the following conferences:

- PhD School - Lean & Computing in Construction Congress 2017, Heraklion, Greece.
- IAM Asset Management Conference 2018, London, England.
- TDE Research Student Conference 2018, Oxford Brookes University, Oxford, England

Chapter 1 Introduction

1.1 Background

Asset management (AM) is a systematic, organised process of maintaining, operating and upgrading physical assets and asset systems efficiently, environmentally and economically (McElroy, 1999). Also, AM is a term measuring the capacity and ability of an asset to achieve its objectives (Riso, 2012, BSI, 2014). An asset could be an item, equipment or space or any other entity that generates financial or non-financial value for the organisation. In order to achieve the organisational strategic asset management plan, asset information has to be provided appropriately, such as asset location, specifications, warranties and maintenance schedules (Love et al., 2015).

Due to the fragmented nature in the Architecture, Engineering, Construction and Operation (AECO) industry, the required information for AM during the handover stage is often missing and/or is inadequate data as a result of the human errors in data collection, entry and analysis. Excessive time and costs are spent to locate and verify the information required from design, planning and construction activities for operating and maintaining the building assets (Teicholz, 2013).

Providing an interoperable environment where data can be exchanged smoothly between two or more systems during handover and operation stages can decrease the chances of errors and increase efficiency.

Consequently, AM requires an information system that captures, stores and integrates the required data automatically to support better decision making. An ideal information system is required which can store and provide the asset data during all the phases of the building and record the changes in conditions of the maintained and operated set of assets (Amadi-Echendu et al., 2010).

Building Information Modelling (BIM) has emerged as the new international approach for better efficiency and collaboration in the Architecture, Engineering and Construction (AEC) sectors and recently in the Operation and Maintenance (O&M) sector. In ISO 19650-1:2018, BIM is defined as the "*use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions*". BIM can enhance AM where BIM data functions as 'back-end data' in the Computer Aided Facility Management (CAFM) systems for activities such as space management and maintenance management (Carbonari et al., 2015, Matarneh et al., 2018). Moreover, BIM can provide ways for managing knowledge about building operation which can be utilised in future designs (Matarneh et al., 2019). The UK Government Soft Landing (GSL) policy (2012) stated that BIM can provide a valuable dataset for CAFM systems; however, this dataset should be maintained through the facility's lifecycle. The information required for AM has to be extracted from the BIM model and linked to a relevant database that stores all information related to the built asset in order to form an Asset Information Model (AIM) (Kivits and Furneaux, 2013). The AIM provides the underlying foundation for AM improvement.

Despite BIM's capabilities and promise for improving AM practice, the implementation of BIM in Facilities Management (FM) generally and in AM particularly is very limited (Eadie et al., 2015, Gao and Pishdad-Bozorgi, 2019). The facility mangers have yet to embrace the benefits of BIM for O&M

stage. Several surveys indicate that, even for companies that have already implemented BIM in the design and construction phases, the added value of BIM in the operation phase is marginal (Bosch et al., 2015). There are three main challenges hindering the adoption of BIM for FM: interoperability in the BIM-FM context, understanding the underlying FM principles for BIM implementation and return of investment (Gao and Pishdad-Bozorgi, 2019, Matarneh et al., 2019). The interoperability challenge is the key barrier to firstly overcome, as the entire theoretical framework of BIM data being used for FM is predicated on the assumption that data can be exchanged simultaneously between software programs (Kensek, 2015). The next sub-section presents the state-of-the-art related to BIM and AM interoperability challenge and work done to address that challenge and highlights the need for the research.

1.2 Problem Formulation

Interoperability is the ability to exchange data between two or more diverse systems to facilitate automation and avoidance of data re-entry. To achieve effective data exchange between applications, the proposed solution should achieve both semantic and syntactic interoperability (Veltman, 2001). Syntactic interoperability solutions identify an agreed exchange format to transfer data, and semantic interoperability solutions identify a set of terms and data requirements to enable interoperation using the agreed exchange format defined by syntactic interoperability.

Most of the research into BIM-AM interoperability has concentrated on developing technology-driven functions and applications to overcome the syntactic interoperability barrier rather than developing computable information requirements for better semantic interoperability (Cavka et al., 2017). Available syntactic interoperability approaches include the Industry Foundation Classes (IFC), Construction

Operation Building Information Exchange (COBie) and proprietary middleware (such as: Ecodomus). However, even with these approaches, syntactic interoperability solutions alone cannot ensure that the integration of BIM-AM achieves the required expected benefits and results.

Pärn et al. (2017) critiqued that semantic interoperability is the single most important interoperability challenge to overcome in the integration of BIM data with other systems, including AM platforms. Love et al. (2014) criticised that emerging handover standards such as Model View Definitions (MVDs) for AM provide only the structure of how information can be extracted and collected over the facility lifecycle. However, the available handover standards do not support the owner with a list of the required information for AM (Patacas et al., 2015). ISO 19650-1 (2018) states that a set of asset information requirements should be prepared in response to each event during asset operation. Ozorhon and Karahan (2016) emphasised that the availability of the required information and technology is one of the most important factors in BIM implementation in AM. Kim et al. (2018) argued that identifying only the required information will not achieve an efficient semantic interoperability between BIM and asset management; they suggested that providing object-oriented cross-domain linking with the required information can be a more efficient and adequate solution.

Hu et al. (2018) also argued that an ontology is required to cross-link building performance with other building information, and Linked Data offers a mechanism to facilitate meaningful sharing of cross-domain building information. Ontologies and Linked Data provide a process to publish and share machine-readable inter-Linked Data on the web, based on a set of design principles. These capabilities can enable facility managers to semantically link the BIM objects to the maintenance records in the

Semantic Web during the O&M phase in order to provide a BIM environment without the specific BIM authoring application (Kim et al., 2018).

Thus, for enabling full data interoperability between BIM and AM platforms, syntactic and semantic interoperability between building information models and different asset databases should be achieved together. Accordingly, a research question was formulated to provide a holistic approach where semantic and syntactic interoperability are achieved and examined. The research question is "What are the requirements for effective integration between BIM and AM data?". This question led to the formulation of two other questions to achieve the identified requirements:

1) How can Ontologies and Linked Data improve the integration between BIM and AM data?

2) How can the required BIM data for AM be extracted, checked, shared and integrated?

1.3 Research Aim and Objectives

The research aim is to improve the semantic and syntactic interoperability between BIM and AM and to improve the handover of information to the operational phase of built assets. To achieve the aim of the research, six objectives are identified as follows:

1. Evaluate the theory and practice of BIM implementation for enhancing AM.
2. Develop a conceptual framework of the semantic and syntactic interoperability aspects for BIM implementation in AM.

3. Identify the required information to be exchanged from building information models for AM during handover stage.
4. Establish a cross-mapping amongst all the different AECO standards and guidelines using ontology and Linked Data.
5. Develop a syntactic interoperability solution to exchange data from BIM to AM platform.
6. Demonstrate and evaluate the usage of the developed semantic (Objective 3&4) and syntactic (Objective 5) interoperability solutions through a real-world case study.

1.4 Summary of Research Methodology

Research methodology can be considered as the overall strategy used in a scientific investigation to facilitate the achievement of the aim and objectives of the research in an effective way. The research starts with an extensive review of literature in the BIM-AM domain. At the end of this stage, the research objectives are formulated, and the research methodologies are designed to address the research objectives. Based on that, the research process is divided into four main phases and their corresponding methods are built on earlier outcomes from the review of literature and problem formulation (Chapter 6).

Phase 1 is the phase where an additional literature review is carried out strictly on BIM and AM integration; this review provides an in-depth study of BIM-AM implementation benefits and challenges, and a detailed comparison of the different interoperability approaches and methods. This leads to the development of the ACE_IM framework which illustrates the different aspects that have to be covered to achieve successful integration between BIM and AM. Phase 2 includes the engagement of experts through semi-structured interviews and also focus groups for developing the required taxonomies and ontologies, and cross-linking the different ontological sources. These constructs could simplify, structure and describe the data required from BIM and their relationships for successful implementation of BIM in AM practice. Consequently, they would organise domain knowledge and link between the different domains. Once domain knowledge is organised, practicable knowledge can be developed to facilitate performance improvement using knowledge model tools such as Protégé. The theoretical contribution of this research takes place in phases 1 and 2 (Chapter 7).

Phases 3 and 4 include the development of MVD and the Revit plug-in. In this phase, the software development methodology and the technologies and coding languages for prototype development are selected. At the end of Phase 4, the developed Revit plug-in is evaluated and demonstrated through a real case study. In this research, practical contribution occurs in phases 3 and 4 (Chapter 8).

1.5 Research Findings, Scope and Limitations

The findings of this research can be organised into two contexts, which are theoretical and practical. Within the theoretical context, two key research outcomes are identified. Firstly, a taxonomy is developed where the critical information to be extracted from the building information models for asset management practice is identified, and workflows and roles and responsibilities to integrate this data are stated. Moreover, the taxonomy is polished in light of the case study evaluation. Secondly, an ontology is developed where all the different standards and classifications used in the AECO domains are linked to each other to enhance the semantic interoperability among BIM and AM systems.

On the other hand, within the practical context, an innovative MVD that would improve the integration between BIM data and Asset data for better FM decisions is developed. The developed MVD specifies the appropriate entities required from the IFC schema to maintain and operate assets in a building that consume energy. Also, a possible application in a BIM platform to identify and extract the required data based on the proposed ontology is developed and demonstrated.

Due to the heterogeneity of the assets and buildings, the required information cannot be generalised for all assets or even by an asset system (Cavka et al., 2017). However, a required information taxonomy can be developed for assets based on their functionality in certain building types (Farghaly et al., 2018). Due to the increasing emphasis on providing a sustainable performance during a building's lifecycle, the research concentrates on assets which consume energy, as buildings consume enormous amounts of energy: for example, it is estimated that they consume an average of 41% of the world's energy use during the operation phase (Boss Controls, 2016). Specifically, the research concentrates on buildings used for education purposes, and a university building has been selected as the research case study. That is because the total energy use within such buildings in the UK in 2018 exceeded 11% of the UK's total energy use (based on the report published by the UK Department for Business, Energy and Industrial Strategy, (2019)).

Although the stated findings of this research are anchored on assets that consume energy only in buildings used for education, the outputs can still be updated and adapted to cover all operable and maintainable building assets. Therefore, this research contributes to knowledge by identifying the main semantic and syntactic interoperability concepts, while commenting on their implementation methods and challenges. Also, it has outlined how Linked Data can enhance BIM-AM data integration. The proposed process of development and publishing of Linked Data outlined in this research would also be easily replicated for other purposes and further benefitting from Linked Data concepts.

1.6 Thesis Outline

The thesis contains 10 chapters. A brief description of each chapter is illustrated in this section to demonstrate the progression of the thesis work. An illustration of the thesis breakdown structure is shown in Figure 1-1.

Chapter 1 introduces the research background with the gap that needs to be covered, research problem and questions, and research aim and objectives. It then clarifies the overview of the research methodology, research scope and limitations, and the thesis design and arrangement.

Chapter 2 forms the literature review of the research that underpins the research aim articulated in 1.3. It investigates BIM and FM domains and their integration by reviewing their definitions, applications, benefits and challenges in implementation. Also, this chapter synthesises the different approaches and strategies aimed at improving the implementation of BIM in the AM sector.

Chapter 3 presents the different aspects related to syntactic interoperability and starts by presenting the different available methods of syntactic interoperability between BIM and AM systems. Then it investigates the history of IFC and other related efforts and standards such as IDM and MVD. Finally, it illustrates the process of MVD development.

Chapter 4 presents the concepts of Ontology and Linked Data as Models of Knowledge. These knowledge models are adapted in this research to develop the semantic interoperability solution. The chapter starts with the ontology definitions, related expressions, components and development tools. This is followed by presenting Linked Data and how ontologies are utilised in Sematic Web and Linked Data. Finally, existing work related to ontologies in AECO domain is discussed.

Chapter 5 presents the research philosophy and methodology employed in the investigation undertaken in this research, including the implications of the chosen multi-method approach. While, chapter 6 presents the research design and concludes with the research methods adopted to achieve the research aim and its objectives.

Chapter 7 focuses on the development of the taxonomy and ontology for the required information and assets. It covers the identified non-geometric data required during the handover stage to maintain and operate assets that consume energy. Also, it contains the proposed Linked Data between the different standards and classifications in the AECO domain for assets that consume energy.

Chapter 8 presents the MVD developed for extracting the required data and assets to manage the building's energy consumption. It covers the process of the MVD development starting from creating an IDM till the MVD documentation. The implementation environment, the development of the prototype and the demonstration of the prototype through a case study are also discussed.

Chapter 9 revisits the main research objectives followed by a critical reflection on the observations and findings from the previous chapters. Chapter 10 articulates the main contributions of this research to the current paradigm of BIM implementation in AM. The chapter highlights the knowledge created by the research based on the chosen research methods as evidenced in the four main research outcomes. Thereafter, the limitations of and constraints to the research and recommendations for further work are presented.

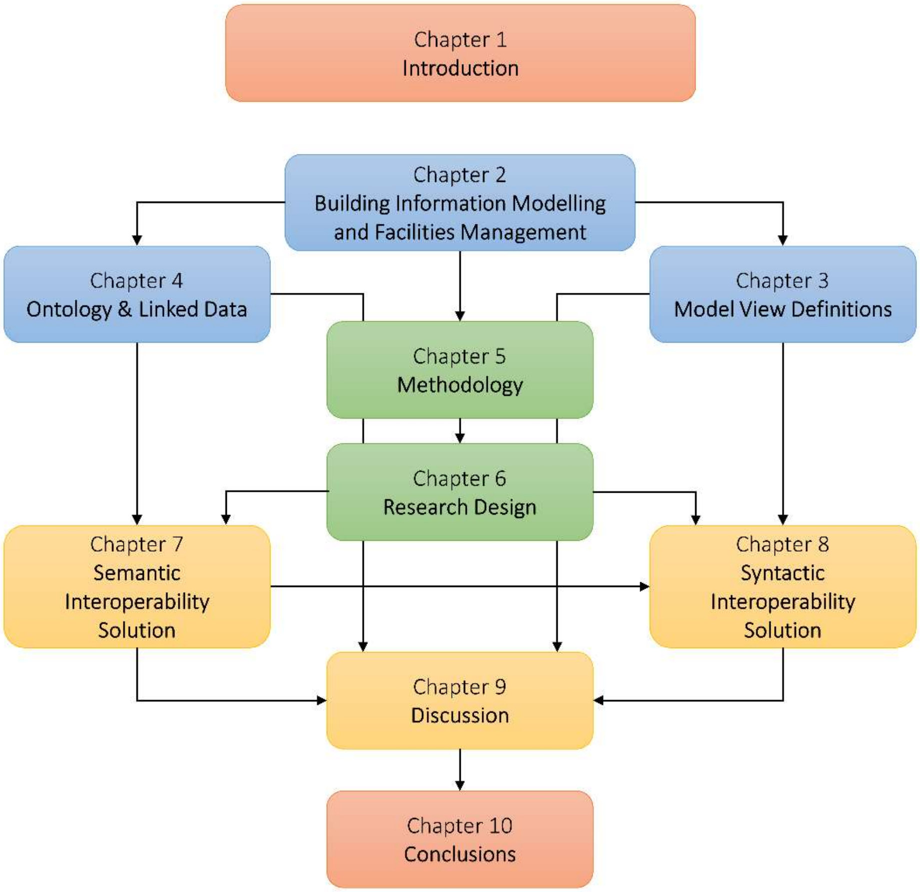


Figure 1-1: Breakdown of the thesis structure

Chapter 2 Building Information Modelling and Facilities Management

2.1 Introduction

The chapter sets out a comprehensive literature review where the theory and practice of BIM and AM are discussed and the challenges and gaps of the BIM implementation in AM domain are identified. The findings of this chapter direct the following literature review in chapters 3 and 4 to achieve the research aim and objectives.

2.2 Building Information Modelling (BIM)

2.2.1 BIM Definitions

BIM is not only defined in various ways according to particular professions but some confusion exists at three different levels, where some professionals define BIM as a software application (technology perspective), while for some it is a process for designing and documenting building information (process perspective), and others define BIM to the level where it is a whole new approach to practice which requires the implementation of new policies, contracts and relationships amongst project stakeholders (policy perspective). However, Penttila (2006) defined BIM as a set of interacting policies, processes and technologies producing a "*methodology to manage the essential building design and project data in* *digital format throughout the building's lifecycle*". Also, Succar (2007) defined BIM as three interlocking knowledge nodes: BIM policy, BIM process, and BIM technology. The current researcher studied the various definitions of BIM and its maturity through the years to clearly understand what it means and also the capabilities and characteristics of BIM which can benefit the FM sector.

2.2.1.1 BIM before 2000

Until 2000, there were different views within the construction industry and the research community on what defines and describes BIM (which is also sometimes referred to as integrated project database or shared construction project model) (Faraj, 2001). However, the philosophy of BIM was coined early on, by Bono (1970), as "*vital for communication and useful for understanding a situation*" and by Eastman et al. (1974) at the Georgia Tech School of Architecture as a 'Building Description System (BDS)'. The BDS was defined as a single database capable of describing buildings through design and construction phases. 'Building Information Model' was firstly coined in 1992 (Van Nederveen and Tolman, 1992). The term Building Information Modelling appeared later and was mentioned in 1999 (Tolman, 1999). It is clear that, in the period before 2000, the definition of BIM went from a model to a database to a model with information to an integration strategy, process and information technology.

2.2.1.2 BIM after 2000

In the century of technology, BIM is identified as modelling technology associated with process and information management (Eastman et al., 2011a). Nowadays, BIM is defined as the shared digital representation of the physical and functional characteristics of any built object that forms a reliable basis for decisions (ISO, 2018). These definitions promote information integration, where multiple types of information embedded in the same digital database could benefit and facilitate collaboration among all stakeholders, e.g. designer, contractor, facility manager, etc. (Rezgui et al., 2013). More specifically, BIM integrates the following new functionalities into the traditional construction process: project feasibility study, 3D design/drawings, a typical shape design, engineering analysis, clash detection, time line management, costing analysis, sustainability analysis, constructability and FM (Ding et al., 2014, Lee et al., 2013).

In the last decade, BIM has evolved as an approach driven by technology for generating, managing and exchanging a well-structured facility's data throughout its lifecycle. There is an agreement in the literature about three main characteristics in BIM. Firstly, the process that facilities data integration during all the building phases. Secondly, the methodology that enables effective collaboration and communication between different stakeholders. Finally, the digital representation of the physical and functional characteristics of a facility and the capability of inserting, extracting and updating the facility information during all the building phases. Several works have been conducted for fulfilling these three characteristics and facilitating the implementation of BIM starting from standards and guidelines (sub-section 2.2.4) to tools and platforms (sub-section 2.2.3) to be implemented for different applications (sub-section 2.2.2).

2.2.2 BIM Benefits and Applications

BIM can provide many benefits throughout the whole lifecycle of a building, from having a better design and increasing information integration to having better collaboration and increasing productivity efficiency (Hill, 2012, Bryde et al., 2013). BIM provides the following benefits for the whole life of buildings through its different applications (Azhar, 2011, Ghaffarianhoseini et al., 2017, Costin et al., 2018):

- Clarifying the client requirements in the earliest stage of design.
- Clarifying scopes for project stakeholders.
- Improving information integration during the building lifecycle.
- Improving and controlling quality.
- Improving communication between project stakeholders.
- Improving coordination between project disciplines.
- Improving visualisation.
- Reducing or controlling project cost.
- Reducing or controlling project time and schedule.
- Reducing negative risk.
- Developing data to knowledge for better decisions.

These benefits can be achieved in different applications. The perceived BIM applications differ across stakeholders and building phases. However, the extreme benefits of BIM require engagement with BIM during the whole lifecycle of the building (BSI, 2013). From the review of BIM research and projects (Shou et al., 2015), BIM applications can be summarised as illustrated in

Table 2-1.

Table 2-1: Summary of the main BIM applications

Application	Description
Existing Conditions	Existing buildings, site and topography using laser scanning.
Design Options	Quality comparison through visualisation.
Engineering Analysis	Structural, electrical, mechanical and lighting analysis.
Coordination	Clash detection (hard clashes), clearance checking (soft clashes) and clash resolution.
Code reviews	Fire department and other involvement in design.
Quantity Extraction	Quantity take-off can be provided as Bill of Quantities.
Construction sequences	Phases, zones and schedules.
Site logistics planning	Traffic (diversions, truck routes, lane closures, etc.), parking and site planning (temporary offices, storage, zones, etc.).
Construction cost estimation	Linking the automated QTO to an estimation tool.
Fabrication/shop-drawings	Directly extracting drawings from the coordinated models.
Turnover/As-built BIM	Submission of the As-built model to the owner for FM in the operation and maintenance phase.
Asset Management	Managing and auditing assets which have to be upgraded, operated and maintained.
Space Management	Space planning, building optimisation.
Building Performance Management	How much energy a building uses, how the mechanical system operates, a solar analysis, external and internal airflow, a lighting analysis, and ventilated facade studies.

2.2.3 BIM Platforms

BIM is not one single process enabled by a single piece of software; nevertheless, BIM integrates and interoperates many cross-cutting processes that require many different software solutions (Thomassen, 2011). Consequently, BIM models are produced by various software packages depending on the project stage and the functions the tool provides (Eastman et al., 2011a, Latiffi et al., 2013). Published research shows that Autodesk, ArchiCAD and Bentley software programs are the most popular among the construction industry (Arayici, 2015, Latiffi et al., 2013, Thomassen, 2011). Some platforms are developed for providing a collaborative environment for all the stakeholders and not specified for specific discipline, these are categorised as data server in the below table.

Table 2-2 illustrates the most popular BIM authoring software programs (platforms), in which discipline contributes, such as: structural, architectural, mechanical and electrical (Reinhardt, 2009, CAD, 2013). Some platforms are developed for providing a collaborative environment for all the stakeholders and not specified for specific discipline, these are categorised as data server in the below table.

Table 2-2: Most popular software programs (platforms)

Software Name	Discipline
Autodesk Revit Architecture	Architecture
Graphisoft ArchiCAD	Architecture
Bentley Architecture	Architecture
RhinoBIM (BETA)	Architecture
Autodesk Revit Structure	Structure
Bentley Structural Modeler	Structure

Software Name	Discipline
Bentley RAM, STAAD and ProSteel	Structure
Tekla Structures	Structure
Autodesk Robot Structural Analysis	Structure
Autodesk Revit MEP	MEP
Bentley Hevacomp Mechanical Designer	MEP
4MSA FineHVAC + FineLIFT + FineELEC + FineSANI	MEP
CADMEP (CADduct / CADmech)	MEP
Autodesk Navisworks	Construction
Solibri Model Checker	Construction
Vico Office Suite	Construction
Bentley ConstrucSim	Construction
Tekla BIMSight	Construction
Glue (by Horizontal Systems)	Construction
Synchro Professional	Construction
Bentley Facilities	Operation
FM: Systems FM: Interact	Operation
Vintocon ArchiFM (For ArchiCAD)	Operation
EcoDomus	Operation
Concerto	Operation
Aconex	Data Server
Prolog	Data Server
Projectwise	Data Server
BIMserver	Data Server
Autodesk BIM 360	Data Server

The Revit platform is a BIM tool for structural engineering, architecture design, Mechanical, Electrical and Plumbing (MEP) engineering, and construction. Revit is the world’s first fully parametric design software and it is the most popular BIM software in the world (Stine and Hansen, 2018). The reasons behind that popularity are because it provides a multi-discipline solution in one platform, achieves interoperability due to its compatibility with other Autodesk platforms and, finally, provides rich Software Development Kit documentation for developers. Consequently, an API Revit plug-in can be developed for a specific purpose.

2.2.4 BIM Standards in the United Kingdom

In 2011, the UK government (Government, 2011) stated that a fully collaborative 3D BIM Level 2 (with all project and asset information, documentation and data being electronic) would be mandated as a minimum by 2016 for all governmental projects. It is a Push-Pull Strategy which supports the adoption of a push strategy from the supply side of the industry to enable all players to reach a minimum performance in the area of BIM use in five years, and also supports the adoption of a pull strategy from the client side to specify, collect and use the derived information in a value-adding way over a similar timescale (Arayici, 2015). Furthermore, in 2015, the UK government produced the Digital Built Britain strategy (Government, 2015) to take the next step in integrating these technologies, transforming its approaches to infrastructure development and construction and consolidating the UK’s position as a world leader in these sectors. The vision of the government’s construction strategy and the Digital Built Britain strategy is to achieve the construction 2025 goals. To enhance and speed up the BIM implementation in the UK, the British Standard Institute, Centre for Digital Built Britain and UK BIM Alliance developed standards and guidance to support individuals and organisations in the UK to understand the fundamental principles of BIM (Table 2-3).

Table 2-3: UK BIM standards and guidelines

Document Name	Description
BS EN ISO 19650-1: 2018	Organisation and digitisation of information about buildings and civil engineering works, including building information modelling — Information management using building information modelling: Concepts and principles.
BS EN ISO 19650-2: 2018	Organisation and digitisation of information about buildings and civil engineering works, including building information modelling — Information management using building information modelling: Delivery phase of the assets.
PD 19650-0: 2019	Transition guidance to BS EN ISO 19650.
PAS 1192-5:2015	Specification for security-minded building information modelling, digital built environments and smart asset management.
PAS 1192-3:2014	Specification for information management for the operational phase of assets using building information modelling (BIM).
PAS 1192-6:2018	Specification for collaborative sharing and use of structured Health and Safety information using BIM.
BS 1192-4:2014	Collaborative production of information. Fulfilling employer's information exchange requirements using COBie (Construction Operations Building information exchange). Code of practice.
BS 8536-1:2015	Briefing for design and construction. Code of practice for facilities management (Buildings infrastructure).
BS 8536-2:2015	Briefing for design and construction. Code of practice for asset management (Linear and geographical infrastructure).
Guidance Part 1: Concepts	The Concepts Guidance first released in April and updated in July 2019 is brief and high level and is aimed at a broad audience. It explores the general requirements of the ISO 19650 series alongside the case for building information modelling and digital transformation.

Document Name	Description
Guidance Part 2: Processes for Project Delivery (Third Edition)	The Processes for Project Delivery Guidance is an evolving resource. This 3rd Edition's focus includes completion of the analysis of ISO 19650-2 clause 5 with new content introduced in respect of clauses 5.5, 5.6 and 5.7.
Government Soft Landings	Revised guidance for the public sector on applying BS8536 parts 1 and 2.

This research is heavily influenced by PAS 1192-3, Specification for information management for the operational phase of assets using BIM. PAS 1192-3 focuses especially on project delivery of graphical and non-graphical data which is collected for and/or related to the operation and the maintenance of building assets. However, this standard does not cover data content for the asset's management. PAS 1192-3 is an important document for the FM industry as it sets out the need for comprehensive and accurate asset information, which can be used as the basis for all asset-related decision-making.

The two new ISO standards, which are BS EN ISO 19650–1 Organisation of information about construction works – Information management using building information modelling – Part 1: Concepts and principles, and BS EN ISO 19650-2 Organisation of information about construction works – Information management using building information modelling – Part 2: Delivery phase of assets, supersede BS 1192 (principles) and PAS 1192 part 2 (capital/delivery phase) respectively.

2.3 Facilities Management (FM)

FM is a fairly new method of business management in the private sector (Barrett and Baldry, 2009). However, it has been part of the public sector for many years as post engineering, public works and administration (Roper and Payant, 2009). Meanwhile, FM is one of the fastest-growing professional business in the UK (Barrett and Baldry, 2009). This section presents a review of FM. The evolution and definition are discussed in the opening paragraphs. This is followed by a discussion of technology in the FM domain.

2.3.1 FM Definitions

FM is a management method that goes back to the Romans. The word facility is derived from the Latin word 'facio' (I do) and the adjective 'facilis' (easy to do), through a medieval French intermediary (Bröchner, 2010). The term 'facilities management' originated around the year 1970, when a lot of offices in the United States of America applied freestanding screens known as cubicles, and the computer terminal was introduced to the workstations. FM were more adopted in the operation sector as a solution for cost-cutting initiatives related to the high costs of running facilities that accounted for more than 50% of the total overheads (Park, 1994). Those significant events and cost cuttings set the evolution of FM in the world. In the 1980s, a new concept of FM that emphasised the integration between people, process and place was introduced by the International Facilities Management Association. In 2003, the same association defined Facilities Managers as "*a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology*". It is interesting to note that the importance of technology was highlighted in the new definition, which was lacking previously (Figure 2-1).

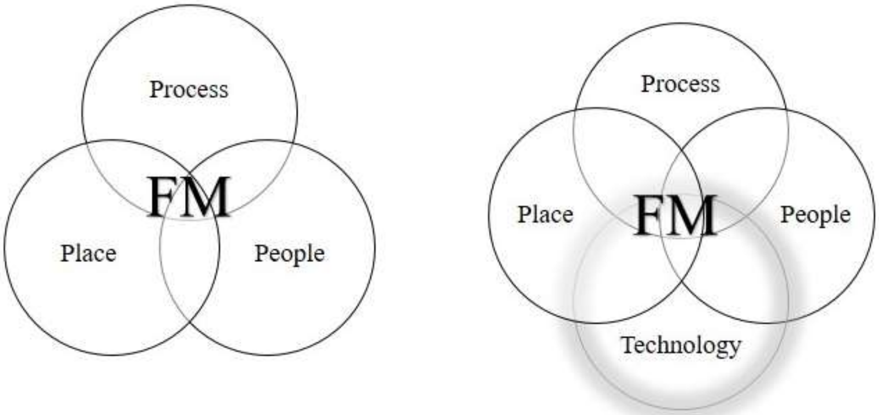


Figure 2-1: IFMA FM definition 1980 (left side) and definition 2003 (right side)

FM has various numerous definitions produced by individuals and organisations. The main reasons for FM definitions developing through time are the rapid growth of technology, changes in management methods and people's adoption of the new processes. The following discusses the definition of FM from various known organisations:

British Institute of Facilities Management

"*Facilities management is the integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities.*"

South African Facilities Management Association

"*Facilities Management is an enabler of sustainable enterprise performance through the whole life management of productive workplaces and effective business support services.*"

Royal Institute of Charted Surveyors

"*Facilities Management is the total management of all services that support the core business of organisation.*"

The National Research Council called FM asset management, which introduced a different terminology (NRC, 2008). On the other hand, in the building industry, while there are differences between FM, facility operations and facility maintenance, they are always used synonymously (East, 2007). FM is holistic in nature, covering everything from real estate, financial management and human management to operation, maintenance and cleaning (Atkin and Brooks, 2009). FM can also assist in financial decision-making, short-term and long-term planning, and the generation of scheduled work orders. According to Kincaid (1994), FM was developed from three main areas of management: property management (real estate), property operation and maintenance, and office administration. Figure 2-2 shows the context of FM presented by Nordic FM associations (Jensen and Andersen, 2010). To cover all these domains and provide just-in-time decisions based on knowledge, FM adapted several technologies and techniques. The following sub-section discusses technology in the FM domain.

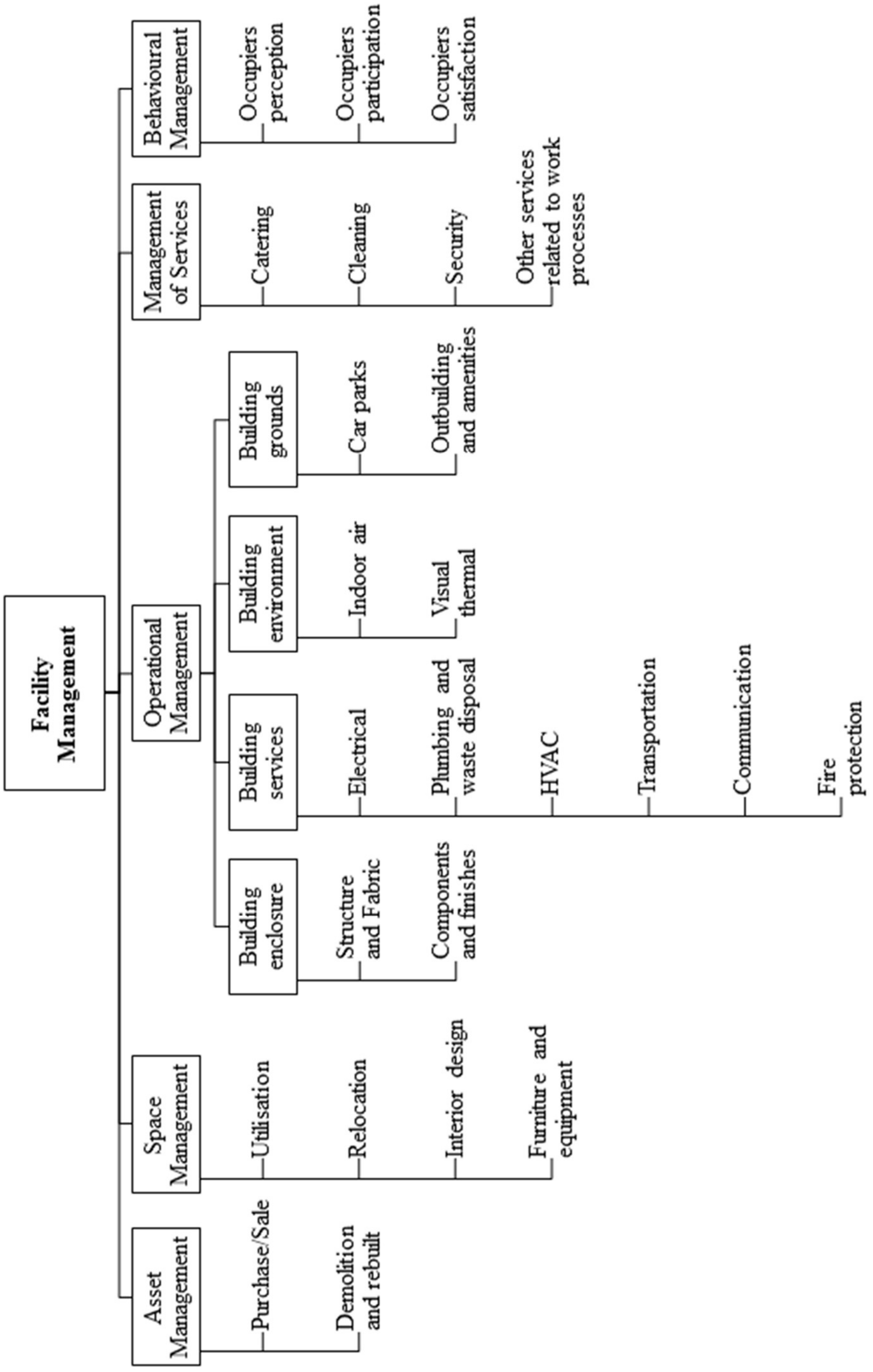


Figure 2-2: The different applications in FM

2.3.2 Technology in FM

As mentioned before, the main components of FM are people, place, process and technology (IFMA, 2013). Technology in FM automation has made significant progress over the past 25 years. There are two main types of automated computer FM systems which support FM functions and competencies: Computer Maintenance Management Systems (CMMS) and Computer Aided Facility Management (CAFM) systems (Arayici, 2015). The CMMS's core focus is on the management of maintenance tasks (preventive maintenance, reactive maintenance and asset management) and its goal is to ensure the smooth and safe operation of buildings through managing day-to-day operations. The CAFM includes a rich database system which manages space and it offers a complete integrated computerised solution including all areas of FM and a drawing. Typically, CAFM systems touch all areas of an organisation by encapsulating Reactive Maintenance and Planned Preventative Maintenance (PPM) task management, Room Booking and Resource Scheduling, Stock Control, Purchase Ordering, Health & Safety, and Fleet Management to name a few. Links to other applications such as accounting packages and space management are popular.

However, the success of technology can be evaluated based on the value provided, not by evaluating the technology itself (Teicholz, 2012). There are still challenges like limited graphical capabilities, lack of monitoring performance, and interoperability of these existing FM systems (Wong et al., 2018). Current solutions for interoperability rely on the duplication of data, which leads to the over-processing of data and information overload (Barrett and Baldry, 2009). It is therefore important that FM organisations/clients balance between their objectives and technology by selecting and implementing tools that can support processes that achieve the defined objectives clearly (Teicholz, 2012) and also ensure that they are approachable to change, able to take advantage of technological innovations such as augmented reality, radio frequency identification, 3D laser scanning, wireless sensor network and BIM, and adapt and interact these technologies in their strategies accordingly (Codinhoto et al., 2013, Price and Shaw, 1998, Mahdjoubi et al., 2015). The next sub-section assesses the benefits and applications that can be achieved from the integration of BIM and FM data as it is the main scope of this research. Also, it discusses the main challenges in this integration.

2.4 BIM-FM Integration

The implementation of BIM can provide the FM team with access to digital information about facility components and equipment from one unified source and also provide a Common Data Environment (CDE) where all the asset's data is stored and managed through all the asset's lifecycle. These BIM capabilities can provide several benefits in different FM applications. This section presents the benefits of implementing BIM in FM. Several applications are discussed. This is followed by a discussion of the main challenges in the implementation of BIM in the FM domain.

2.4.1 BIM-FM Benefits

The integration of BIM into the Facilities Management (FM) stage of a building's lifecycle portends a significant boost to maintenance and operations procedures. Since each phase of the project lifecycle depends on different levels of accuracy detailing and completeness of data, the system could be delayed by updating and checking the needed information. For example, in the handover stage between construction and operation, most of the handover of paper documents and 2D drawings is performed manually, which will result in the handed-over information often being incomplete or inaccurate (Kelly et al., 2013).Therefore, BIM and FM integration is seen as the "short answer" to many problems faced in traditional FM practice and a solution to assist in the operation phase and significantly help to prevent the loss in information through the handing-over process (Teicholz, 2013). Figure 2-3 illustrates the main benefits that can be expected from the integration of the BIM and FM. These benefits are explored in further detail as following:

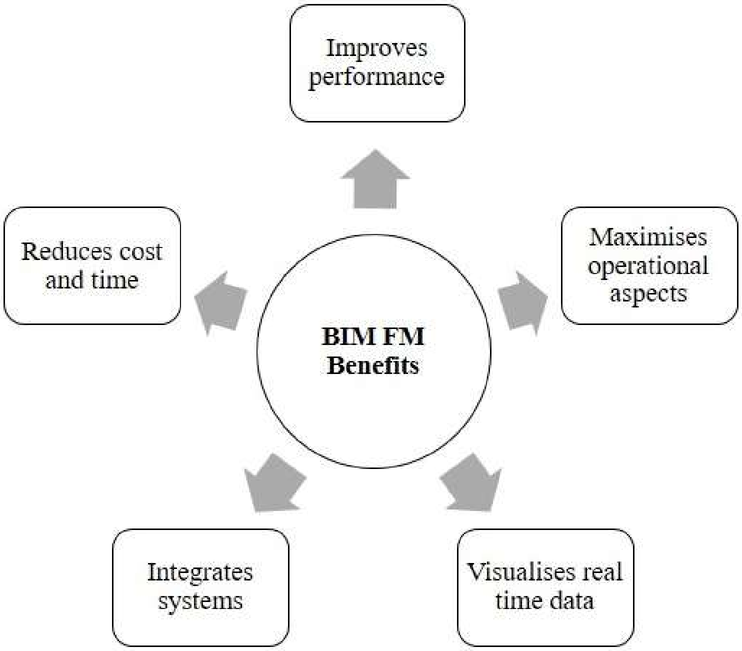


Figure 2-3: Summary of the main benefits that can be achieved by BIM-FM integration

2.4.1.1 Improving Performance

BIM as a process will improve the quality and the reliability of data, and consequently increase workforce efficiencies (Teicholz, 2013). The greater the improvement in the process of information handover, the greater the improvement in the accuracy of FM data. Meanwhile, BIM will improve the accessibility of the FM data, which will lead to faster analysis and correction of problems, and fewer breakdowns.

2.4.1.2 Integrating Systems

FM information systems support FM practices individually; however, the exchange of data between the systems is fragmented and, even worse, the data is entered manually. BIM can integrate the data from the planning, designing and construction phases with the FM information systems such as CMMS, electronic document management systems, building automation system, and energy management systems updated over the building lifecycle (Becerik-Gerber et al., 2012, Carbonari et al., 2015). In other words, BIM could be the common data environment for all the building phases and all the FM information systems (BSI, 2013).

2.4.1.3 Reducing Cost and Time

BIM data and information collected during the building lifecycle will reduce the cost and time required to collect and build FM systems (Teicholz, 2013). Furthermore, a BIM visualised database can increase the efficiency of work order execution, in terms of speed, to accessing data and locating interventions (Kelly et al., 2013).

2.4.1.4 Visualising Real-time Data

BIM is an intelligent model with a parametric engine which updates the entire model once a change is made; this can help the facility managers to avoid ineffective decisions made in the absence of real-time data about the building and its performance (Becerik-Gerber et al., 2012). Meanwhile, the information stored within the model can create a learning cycle, a deeper understanding and a constant improvement in the building facility lifecycle (Carbonari et al., 2015).

2.4.1.5 Maximising Operational Aspects

The integration between BIM and FM enables the performance, presentation and stimulation of the what-if analyses proposals, especially for high-density areas, where, through modelling, the equipment access and operation can be checked (Atkin and Brooks, 2009, Becerik-Gerber et al., 2012). Furthermore, facilities manager can use BIM not only for location and visualisation purposes but also as a tool to maximise operation and maintenance: the data stored within the model can be used for analysis of the building during its life, revealing information useful for future strategies (Carbonari et al., 2015).

To summarise the benefits of the adoption of BIM in FM, the BIM Task Group (2012) stated that "*BIM will provide a fully populated asset dataset into Computer Aided facility management 'CAFM' systems and therefore reducing time wasted in obtaining and populating asset information enabling us to achieve optimum performance quicker, reduce running cost and refine target outcomes*". Also, they added that the adoption of BIM in FM is expected to provide ways for managing knowledge about building operation which can be utilised in future designs. The next sub-section introduces the different applications of BIM implementation in the FM domain.

2.4.2 BIM-FM Applications

There are extensive indications within the literature about the benefits of implementing BIM in FM, as stated in the previous section (Becerik-Gerber et al., 2012). However, it is still unclear what the different applications are where these benefits can be achieved. There are several areas and tasks in FM which can be accomplished satisfactorily with current practice and the added value of BIM implementation is very limited to these areas (Gao and Pishdad-Bozorgi, 2019). The following comprehensive summary identities the main applications that could be enhanced by the implementation of BIM. The summary is based upon a combination of work conducted by Becerik-Gerber et al. (2012), Eastman (2011a), Teicholz (2013), Kassem et al. (2015), Arayici (2015), and Gao and Pishdad-Bozorgi (2019) (Figure 2-4).

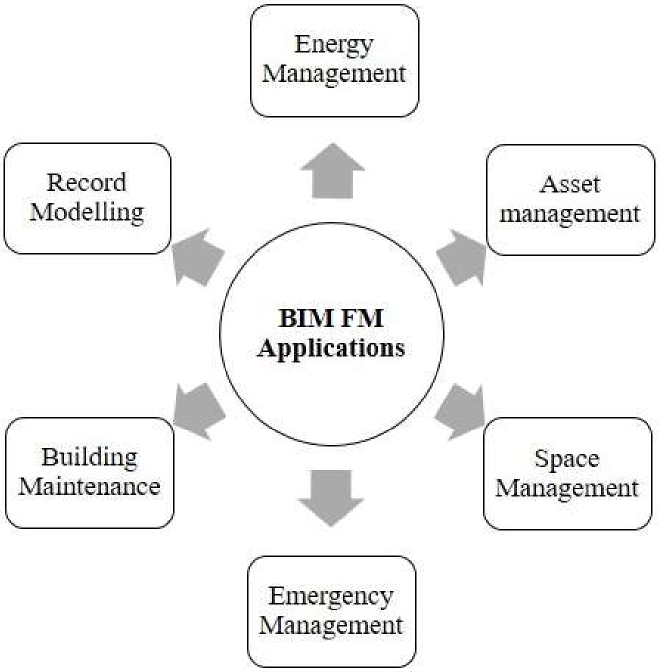


Figure 2-4: Summary of the main applications that can be achieved by BIM-FM integration

2.4.2.1 Record Modelling

Record Modelling is the process used to depict an accurate representation of the physical conditions, environment and assets of a facility in the handover stage. The record model should, at a minimum, contain information relating to the main architectural, structural, and Mechanical and Electrical (ME) elements. It is the culmination of all the BIM Modelling throughout the project, including linking Operation, Maintenance, and Asset data to the As-Built model (new or existing buildings) to deliver a record accurate model to the owner or facility manager. These As-Built models can visualise the components which are located in places not readily visible, such as above the ceilings, instead of relying on paper-based blueprints. This would provide the location quickly, especially in an emergency, and save time and cost. FM personnel could use BIM features such as view, search, filter and highlight and other BIM features on mobile digital devices to navigate into a virtual model and guide themselves to target components, display relevant data and reduce dependence on office personnel and paper-based systems. In addition, for renovation and retrofits, the data from As-Built BIM models can be transferred to a cost-estimating software package to calculate the cost of retrofits.

2.4.2.2 Asset Management

Asset Management is a process in which an organised management system is bi-directionally linked to a record model to efficiently aid in the maintenance and operation of a facility and its assets. These assets, consisting of the physical building, systems, surrounding environment and equipment, must be maintained, upgraded and operated at an efficiency which will satisfy both the owner and users in the most cost-effective manner. AM assists in financial decision-making, short-term and long-term planning, and generating scheduled work orders. For the bi-directionally link, these assets have to be available in electronic formats with proper classification and organisation to simplify the access to the information. For that purpose, research efforts have been made to improve data interoperability between the different FM systems (Wong et al., 2018). However, the main challenge is manually creating and updating the data of these assets with the correct information and the relative documents in various databases, which is a long process and one which contains a high possibility of human error. BIM models/database seem to be the ideal platform for collecting, capturing and visualising data and information from different techniques such as standardised barcode and Radio Frequency Identification (RFID) labels and different stages such as planning stage, design stage, construction stage, and operation and maintenance stage (Lin et al., 2014) .

2.4.2.3 Building Maintenance

Maintainability is the ability to restore a piece of failed equipment, machine or system to its normal operable state within a given timeframe using the prescribed practices and procedures. Maintainability contains three main components: ‘accessibility’ – examining the possibilities of physical inspection capacity for a piece of equipment, ‘sustainability’ – avoiding the use of materials that cause defects, and reparability, and ‘preventive maintenance’ – ease of restoring the service after a failure. As-built BIM models can automate the maintainability-checking process during the operation and maintenance stages using the graphical and non-graphical information about the actual dimensions and locations, spatial relationships, and maintainability-related documents. In addition, the BIM capabilities for visualisation and simulation can help in planning and scheduling a successful maintenance programme, which will improve building performance, reduce repairs arising from design and construction workmanship, and reduce overall maintenance costs. However, to achieve this application/benefit, the inclusion of FM personnel during the design and construction stage is totally obligatory (Patacas et al., 2015).

2.4.2.4 Space Management

Space management is the process utilised to control and supervise the physical spaces a business or organisation occupies. Using a BIM model for space management enables the facility team to analyse the existing use of space, evaluate proposed changes, and effectively plan for future needs. Having accurate and detailed space information is especially useful for planning renovation projects, where some building segments will remain occupied and change during the construction phase. Space Management and Tracking ensures the appropriate allocation of spatial resources throughout the life of the facility. However, integration with spatial tracking software is needed to achieve this application.

2.4.2.5 Energy Management

Energy management is measuring, controlling and monitoring how a building's actual performance and consumption compare to design model predictions. Energy management is challenging because optimising the energy consumption requires understanding of the real energy needs and adjusting of the operation activities. Tracking performance data from the building systems and comparing these values to design model predictions enables facility managers to ensure that the building is operating to specified design and sustainability standards, and identify opportunities to modify operations to improve system performance. For the moment, FM personnel rely on energy management systems, which measure the energy usage in a building over a period of time.

However, these systems are separate silo systems, resulting in lack of interconnectivity with other systems and an inability to present graphical information clearly. Using BIM in its 3D graphical environment and integrating it with building sensors could provide real-time monitoring and automated control (Pinheiro et al., 2018). Also, historical energy usage data could be used for prediction of consumption behaviour, energy-related budgeting and support of conservation activities, and building designers can also use this data to validate and refine their prediction models and evaluate the impact of proposed materials and system changes to improve the performance of future buildings. Building energy management is the main focus in the building systems analysis; however, ventilated facade studies, lighting analysis, airflow analyses using computational fluid dynamics, and solar analysis could be areas for future focus (Gao and Pishdad-Bozorgi, 2019).

2.4.2.6 Emergency Management

Emergency management is the managerial function charged with creating the framework within which communities reduce vulnerability to hazards and cope with disasters. Types of emergencies are human-caused, natural disasters, internal disturbance and attacks. During an actual emergency, it is critical to have data visualised and organised to help in taking appropriate actions. BIM can store most of the data required for emergency management, which is mostly spatial data. Integrating building information, such as floor plans and equipment schematics, with the dynamic real-time state information provided by a building automation system (BAS) in a BIM visualisation environment would provide emergency responders with valuable information to support better decision-making during crisis and disaster response. The BIM model could be used to clearly display where the emergency was located within the building, possible routes to the area, and any other dangers that first responders should be aware of in real time.

BIM data can function as ‘back-end data’ in the CAFM systems for activities such as space management and maintenance management. Also, BIM can dramatically improve building operation through more effective energy use, and emergency and maintenance management. In general, BIM has shown potential in improving FM and providing new functionalities for facility managers, such as 3D visualisation, comprehensive analysis and real-time building information access (Gao and Pishdad-Bozorgi, 2019). However, despite all these potential applications of BIM implementation in FM and the ability to overcome the deficiencies of FM systems, BIM is rarely implemented in the FM sector in comparison in the AEC sector (Heaton et al., 2019). The next sub-section presents the main challenges in the implementation of BIM in FM.

2.4.3 BIM-FM Challenges

The agreed benefits of and applications for BIM in FM practice should encourage the FM organisations and client to invest in order to implement BIM in their practice. However, according to a survey (Eadie et al., 2015), BIM implementation rarely occurs (4.05%). There are three main barriers to the adoption of BIM in FM practice: business and legal, technical, and human and organisational problems. The following comprehensive summary identifies all the challenges which can be the result of one barrier or a combination of more than one.

2.4.3.1 Perception of BIM

Despite all the benefits and applications of BIM for FM, BIM's added value for FM is marginal and there is still no enough evidence that BIM provides more benefits in FM practice to convince facilities managers/clients to full embrace this new technology (Sabol, 2013). The main reason behind the low value realisation is "*lack of alignment between people, process and systems in a manner that agrees with the basic principles of BIM*" (Bosch et al., 2015). Also, it is still unclear how BIM can be used and what are the requirements for successful BIM implementation in FM (Carbonari et al., 2015, Becerik-Gerber et al., 2012). The current lack of standards, guidelines and evidence of the benefits of implementing BIM in FM practice can lead to a lack of interest from facility managers and a lack of demand from clients, which is consequently slowing the process of implementing BIM for the operation and maintenance stage in contrast with what is happening in the rest of the construction industry phases (Carbonari et al., 2015). This issue should be explored and assessed through real projects, and organisational BIM guidelines developed that define BIM usage in FM practice and detail BIM project delivery requirements (Teicholz, 2013).

2.4.3.2 Fundamental Difference and Existing Buildings

The fundamental difference in project-based business and lifecycle management is one of the main challenges in implementing BIM in FM practice (Kiviniemi and Codinhoto, 2014). Most FM/client firms that own or operate and manage buildings in operation and maintenance phase already have existing guidelines and some existing tools and software platforms to manage the FM information. These guidelines, tools and software platform are developed and chosen to be compatible with different inventories of building information, which may include CAD, scanned drawings, physical drawings, and point cloud files but definitely not BIM (Pärn and Edwards, 2017). Therefore, implementing BIM in FM practice without a new strategy will lead to waste, redundancy and unsupportable needs of information maintenance (Teicholz, 2013). In other words, FM contracts are historically bipartite agreements, while BIM is a collaborative process.

The conflict will not be solved except by implementing a new strategy which fits both (McAdam, 2010). Meanwhile, 70% of the buildings that will be occupied in 2050 are already in existence (eu.bac, 2015), and these existing buildings represent the greatest opportunity to improve building energy efficiency and reduce environmental impacts (Volk et al., 2014). Implementing BIM within FM organisations that already have many existing buildings in their portfolios is seen as a big concern and will require a coherent road map and strategy as well. Researchers have raised several questions related to the adoption of BIM for existing buildings' operation and maintenance (Volk et al., 2014): 'Should the existing buildings be modelled for the new system? What is the required level of information? How much would the modelling process cost? What are the measurable benefits? Is it possible to use a hybrid system managing existing and new buildings in different environment and using different data? What problems could this cause and how long is it feasible to maintain two different systems?'

2.4.3.3 Contractual and Legal Framework

Most contract forms still require the handover in paper documents and 2D drawings containing the 2D drawing sheets, equipment lists, warranties and other information. This way of handing-over deliverables is 2D, and yet the project is constructed in accordance with the virtual, collaboratively produced BIM design, which will create some potential for ambiguity, conflict and complexity. For example, the BIM model may contain more updated data than the paper documents (Arayici, 2015). To avoid that challenge, a legal contractual agreement has to be created where all parties should outline, detail and agree on what data should be involved, the model ownership regarding an owner being able to reuse the information through the lifecycle of the facility, the data format to be transferred between building phases and how it is transferred between stakeholders to avoid any congestion with unnecessary data, any repetition of work and any legal risks (Teicholz, 2013, Program, 2013).

Furthermore, the exchange of the BIM model through the design, preconstruction, construction and operation phases also raises another challenge, which is the model's liability. The model's legal liability can hinder the adoption of BIM in FM practice due to the other stakeholders' concerns (designer and contractors) related to their contribution in providing the FM data (Teicholz, 2013). Therefore, defining each stakeholder's contribution and authority is extremely critical in the Exchange Information Requirements (EIR). Fortunately, professional groups are developing guidelines for contractual language to cover issues raised by the use of BIM technology (Eastman et al., 2011a).

2.4.3.4 Training, Roles and Responsibilities

The majority of FM personnel do not yet have comprehensive knowledge of the available BIM implementation guidelines, standards and processes in FM practice (Gao and Pishdad-Bozorgi, 2019). This lack of knowledge regarding the potential of BIM in FM practice will lead to FM firms and clients being unwilling to invest money, time and effort to implement it, therefore losing future opportunities and benefits and hindering the adoption of BIM in FM practice (Carbonari et al., 2015). Training and upskilling will help FM personnel to become familiar with the BIM 3D environment, to contribute in all the building phases, and to understand what can be achieved using a BIM model and how it can be helpful to accomplish the FM firm's goals. Meanwhile, BIM does not offer new technology only, it also offers new methods of collaboration, which force all the stakeholders to collaborate for modelling and model utilisation (Eastman et al., 2011a, Becerik-Gerber et al., 2012). Finding the right time to include these people will undoubtedly be a challenge for owners. On the other hand, integrating BIM in FM practice will address new roles and responsibilities as to who will specify the data needed and control the entry of FM data into the model during all the building phases and be responsible for any inaccuracies in it, and who will take the responsibility for updating the BIM data and ensuring its accuracy. All these roles and their responsibilities and duties have to be identified and mentioned in the FM/Client-focused BIM strategies and EIR.

2.4.3.5 Cost

The cost of implementing BIM in FM firms is considered to include: BIM software cost, hardware cost, training and upskilling cost for the new process and technology, hiring new employees with BIM competence for the new roles, and even sometimes hiring a BIM consultant for implementation and integration and to perform a pilot project to ensure that the firm is on the right track. Meanwhile, adopting BIM in the FM process needs a change in the previous process and standards, which will lead to increased cost. Although this new cost may be more than offset by efficiency and schedule gains, it is still a cost that someone on the project team will have to bear. Thus, before BIM technology can be fully utilised, the risks of its use must not only be identified and allocated, but the cost of its implementation must be paid for as well.

2.4.3.6 Interoperability

Due to the diversity between the BIM platforms and the FM platforms, the interoperability between them is one of the main challenges in implementing BIM in AM practice. Huge efforts are being made to introduce open data standards, such as the industry foundation classes (IFC) and XML schemas, and structured specifications such as the construction operations building information exchange (COBie) to solve the interoperability issue (Azhar et al., 2015). These open data standards can link easily and smoothly between the BIM data and the FM data. However, these mentioned approaches still have their inherent limitations. These interoperability aspects and approaches are discussed in detail in sub-section 2.5.

Table 2.4 summarises the challenges of implementing BIM in FM practice. Different standards and guidelines have been published such as PAS1192:3 and government soft landing strategy (presented in sub-section 2.2.4). However, these standards and guidelines focus only on the business and legal barriers and human and organisational barriers, neglecting the technical barrier. A methodology to support the definition, exchange and validation of the asset data throughout the lifecycle of the building is still absent (Patacas et al., 2016, Heaton et al., 2019). The next sub-section discusses in detail the challenge regarding interoperability between BIM and AM (the FM branch that the research focuses on).

Table 2-4: BIM-FM challenges and their descriptions.

Challenge	Description
Perception of BIM	Lack of benefits, real-world projects Lack of proof of positive return of investment Lack of standards and guidelines
Fundamental difference and existing buildings	Different methodology between BIM and FM BIM implementation for running existing projects/buildings
Contractual and legal framework	Model contents and required data for FM Model ownership and protection of data Model exchange format Model design liability Intellectual property ownership
Training, roles and responsibilities	Training Shortage of skilled BIM-FM employees Unclear roles and responsibilities Lack of collaboration between project stakeholders
Cost	Cost of software and hardware Cost of training and BIM consultant Cost of hiring new employees

Challenge	Description
Interoperability	Diversity between BIM and FM tools and platforms Open standard limitations Lack of common interest between the software's vendors

2.5 BIM-AM Interoperability

Asset management (AM) is one of the main branches of FM. Generally, AM has often been a practice of activities responding to the need to maintain and operate an asset following the simplistic guideline of cost saving. An effective asset management approach can decrease the operation cost of assets by 20% and decrease the energy consumption of the facility by 30% (Pinheiro et al., 2018). Nowadays, many organisations and researchers have introduced different innovations and technologies such as BIM, Linked Data and Big Data to achieve more effective asset management (Farghaly et al., 2017). It is argued that AM can benefit most of the implementation of BIM in the handover and operation stages (Ibrahim et al., 2016).

To achieve the integration between BIM and AM systems, the information required for AM has to be extracted from the BIM model and linked to a relevant database that stores all information related to the built asset in order to form an AIM (Kivits and Furneaux, 2013). The AIM provides the underlying foundation for AM improvement. However, this process is filled with interoperability obstacles (Eadie et al., 2015).

Lee et al. (2013) observed that the technology quality variable for BIM acceptance has to achieve both compatibility (syntactic interoperability) and output quality (semantic interoperability). Semantic interoperability is defined as "*the ability of information systems to exchange information on the basis of shared, pre-established and negotiated meanings of terms and expressions*" (Veltman, 2001). In other words, the data is not only exchanged between two or more systems but also understood by each system. Semantic interoperability is required in order to achieve other types of interoperability such as syntactic ones. Syntactic interoperability is the ability to prepare two or more systems for communicating and exchanging data using specified data formats and communication protocols (Kubicek et al., 2011). As the interface and programming languages are usually different systems, several obstacles need to be overcome to achieve the syntactic interoperability, such as: a) identifying all the elements in the various systems; b) establishing rules for structuring these elements; c) mapping, bridging, creating cross-mapping between equivalent elements using schemas, etc.; d) agreeing on equivalent rules to bridge different cataloguing and registry systems.

Most of the available work on BIM-AM interoperability has concentrated on developing technology-driven functions and applications to overcome the syntactic interoperability barrier rather than developing computable information requirements for better semantic interoperability (Cavka et al., 2017). These efforts have provided different approaches to link easily and smoothly between BIM and AM data through a common data format. These approaches include the IFC, MVD and proprietary middleware (for example, Ecodomus) (Ibrahim et al., 2016). The different approaches and the process of developing an MVD are discussed in detail in Chapter 3.

Even with these approaches, syntactic interoperability solutions alone cannot ensure that the integration of BIM-AM could achieve the required expected benefits and results. Pärn et al.(2017) critiqued that semantic interoperability is the single most important interoperability challenge to overcome when integrating BIM data with other systems such as AM platforms. Ozorhon and Karahan (2016) added that the availability of the required information and technology is one of the most important factors in BIM implementation. A case study of an educational institution (Thabet et al., 2016) illustrated that the most common obstacle in BIM-AM integration is that asset data is scattered and unstructured while the components' data is not integrated or even referenced with other related data/information. Bercerik-Gerber et al. (2012) emphasised the heterogeneity of data by observing that more than 80% of the AM team's time is consumed finding relevant information which has often been disregarded by designers in earlier stages. Kim et al. (2018) argued that identifying only the required information will not achieve an efficient semantic interoperability between BIM and asset management; they suggested that providing an object-oriented cross-domain linking with the required information can be more efficient and adequate solution. Hu et al. (2018) also argued that an ontology is required to cross-link building performance with other building information, and Linked Data offers a mechanism to facilitate meaningful sharing of cross-domain building information. Ontology and Linked Data for BIM-AM semantic interoperability are discussed in Chapter 4.

2.6 Chapter Summary

This chapter reviewed the literature on BIM and the integration of BIM and FM, in order to examine how to improve the implementation of BIM in the AM domain and also to identify the relevant knowledge gaps. Two main issues were established by the literature review. First, there are still challenges in FM technology such as limited graphical capabilities, lack of monitoring performance and interoperability of these existing FM systems, and BIM implementation can significantly enhance these limited capabilities. Second, the interoperability challenge is the main barrier to overcome first for effective integration of BIM and AM. Also, the literature review showed that most of the available work has concentrated on developing technology-driven functions and applications to overcome the syntactic interoperability barrier rather than developing computable information requirements for better semantic interoperability.

However, in order to enable full data interoperability between BIM and AM platforms, syntactic and semantic interoperability between building information models and different asset databases has to be achieved together. Accordingly, this research aims to provide a holistic approach where the semantic and syntactic interoperability are achieved and examined in a real case study rather than concentrating on one aspect only, as most of the previous research. The chapter considered the role of ontologies and Linked Data for achieving semantic interoperability as well as MVD development for achieving syntactic interoperability. As a result, the chapter identified the need for research in these two areas, before concluding with the formulation of the research conceptual framework. The following chapter reviews the literature on MVD development and existing approaches for BIM-AM data integration.

Chapter 3 Model View Definition

3.1 Introduction

The chapter discusses the different aspects related to syntactic interoperability, starting by presenting the different available methods of interoperability between BIM and AM systems. This is followed by the review of the development of IFC and other related efforts and standards such as IDM, MVD and PSD. Finally, an overview of the National BIM Standards (NBIMS) development process of MVDs is provided, as the NBIMS process phases have influenced the formulation of the research design (Chapter 6).

3.2 BIM-AM Interoperability Methods

To overcome the syntactic interoperability challenge between BIM and AM, prototype systems for the link between the two systems are currently being developed by software vendors (Kang and Choi, 2015). Different approaches have been developed and suggested using one of five different methods or a combination of some/all of these methods. The five different methods are as follows:

Design Pattern and Application Programming Interface (API)

The phrase 'design pattern' can be explained in two different ways: as an analytical tool in a real-world application that can contribute to the process based on the software designer's experience or software user's experience; and also as a method to develop a reusable prototype to reduce production time and human errors (Ozel, 2007). In other words, the design pattern is a method of embedding knowledge based on experience into a process. In contrast, API is simply explained as a set of routines, protocols and tools to connect one piece of computer software to another or to automate the number of tasks/actions in a specific piece of software.

Web Service

Web services allow loose coupling of applications over the web, which means several applications can communicate and interact with each other without needing to know the details of their working environment (Isikdag, 2012). Each of these applications (or software components) which takes part in such a web interaction as a piece of data, component or an application service is known as a web service. A web service can host a BIM-based service-oriented platform where the exchange and integration of the data can occur with the FM data in a heterogeneous system.

Extract, Transform & Load (ETL) and Data Warehouse

Extract, transform and load (ETL) is a method of automatically generating a data warehouse by extracting information from particular perspectives from a variety of heterogeneous systems. The BIM ETL can be implemented locally in the BIM platforms or remotely using another database (Cerovsek, 2011). The ETL enables open integration, adaptation, intelligence, management and data reuse between CAD/BIM/GIS/FM data and models.

BIM-based Neutral File Format

A BIM-based neutral file format, such as industry foundation classes, is an open file format not controlled by a single vendor or group of vendors. However, using the BIM-based neutral file format (IFC) method for BIM-FM integration has been criticised for its ambiguity (Patacas et al., 2015). This ambiguity is the result of the schemas that have been developed to enable IFC to express the data in a very generalised manner (Kang and Choi, 2015). Although IFC is the BIM-based neutral exchange format, some of the FM platforms are not compatible with it. Moreover, the IFC cannot cover all the diverse attributes and information attached to the objects depending on discipline, applications, stakeholders, lifecycle phase and project regulation. To overcome that challenge, more exchange standards are proposed such as IDM, MVD and Property Set Definitions (PSD). This is discussed in detail in sub-section 3.3.3. Therefore, a detailed discussion is not provided in this section, to avoid repetition.

Information Delivery Manual (IDM) and Model View Definition (MVD)

IDM and MVD were developed to solve the ambiguity of IFC (Figure 3-1). The IDM is designed to define industry processes and information exchange requirements of IFC data that will meet the end-user's needs, and provides a universal, repeatable and verifiable methodology for creating information exchanges by industry professionals (Wix and Karlshoej, 2007). The Model View Definition (MVD) format is designed to document that exchange approach to be implemented with the least ambiguity possible and to define a subset of the IFC schema that is needed to satisfy one or many exchange requirements defined in one or more IDMs (Wix and Karlshoej, 2007).

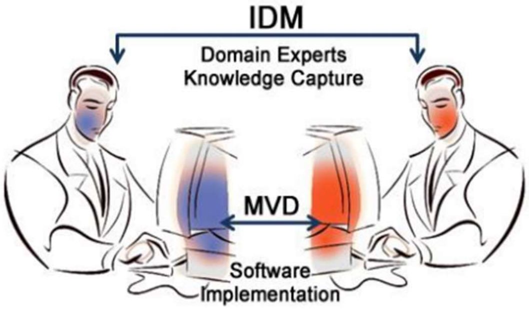


Figure 3-1: Information Delivery Manual (IDM) and Model View Definition (MVD)

Summary and Selected Interoperability Method

Kang and Cho (2015) summarised the different methods for linking BIM with FM systems such as CMMS and CAFM and their characteristics (Table 3-1). The IDM/MVD approach is selected in this research to overcome the syntactic interoperability challenge as any developed MVD can be exported as mvdXML and reused for future purposes. This approach is also defined by the BuildingSMART community for specifying sub-parts of the IFC. The following sub-section discusses the available MVDs, IFC and associated efforts and standards such as IDM.

Table 3-1: BIM-FM linking methods and their characteristics.

Method	Characteristics
Design pattern and application programming interface (API)	Design patterns and API are limited to research into the architecture that composes the system itself, and their method of implementation is fixed during programming.
Web service	Web service is a common method of support for interoperability which makes use of OpenAPI and is merely a fundamental technology for developing a standpoint view. This method is also limited in that its method of implementation is fixed during system development.
ETL and data warehouse	The focus is on methods for data input/output and multidimensional data generation between diverse database sources. Also, the method of extracting and processing data during system development is fixed.
BIM-based neutral file format	The focus is on research on data exchange between heterogeneous systems, such as FM systems, using neutral file formats such as IFC.
IDM and MVD	IDM and MVD are merely methodologies for defining necessary data specifications from the perspectives of particular applications.

3.3 IFC and Existing MVDs

The first IFC was developed in 1996 by the International Association for Interoperability and it has seen a number of minor and major versions since then (Steel et al., 2012). IFC is a construction industry standard for data exchange developed through an EXPRESS schema and it is the accepted standard for BIM exchanges. The EXPRESS language consists of the concepts (e.g. entities, types, properties) which provide a powerful inheritance mechanism to model data and data relationships, and the rules which specify constraints on data instances to build a specific express (.exp) (Wilson, 1998). In IFC, there are several EXPRESS schemas; the most well-known are: IFC2X3.exp, IFC4_ADD1.exp and IFC4_ADD2.exp. Figure 3-2 summarises the IFC releases with key enabling technologies for IFC implementation together with MVD development over the years (Pinheiro et al., 2018).

The IFC schemas are chronologically ordered versions, meaning that IFC4_ADD2 is the most recent schema available. IFC5 now is under construction to fully support different domains in infrastructure projects (BuidingSMART, 2016). An IFC schema is a rich, vast data model that can contain the required data for different applications and needs in the AEC domain. However, Pauwels and Terkaj (2016) stated that IFC is not the only standard for data exchange in the construction industry and it has to be combined with other standards and efforts such as IDM, MVD and Property Set Definitions (PSD).

To implement the IFC schema, construction professionals and software developers have worked on developing processes of the IFC sub-schemas for each discipline. During these processes, the required parts of specification of the IFC, needed to develop IFC binding processes of each domain knowledge and native BIM authoring tool object data, are selected and assembled (Lee, Eastman and Lee, 2015). This IFC sub-schema is also referred to as a Model View Definition (MVD).

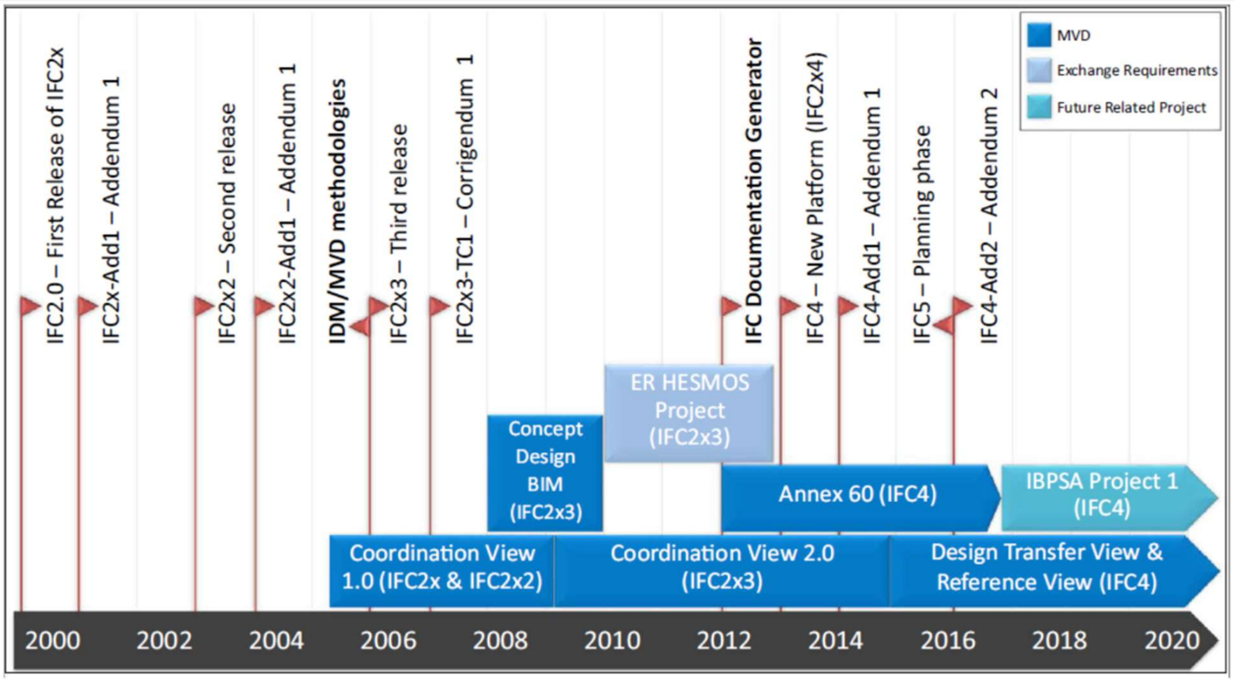


Figure 3-2: Summary of the IFC releases and MVD development over the years

3.3.1 Model View Definition (MVD)

An MVD is understood as a subset of the IFC model specification which includes only the required information for the specific exchange purpose (Eastman et al., 2011c). MVDs are designed to translate from end-user domain definitions to software implementation definitions (See et al., 2012). The specification of an MVD gives the project stakeholders the ability to validate the project deliverables against the exchange requirements automatically (Sacks et al., 2018). The first official MVD by BuildingSMART is the Coordination View (CV); the most recent ones are Reference View (RV) and Design Transfer View (DTV). Researchers and companies have developed different MVDs for information exchange for several different purposes. Pinheiro et al. (2018) developed the Annex 60 MVD for data exchange from BIM platforms and Building Energy Performance Simulation (BEPS) tools. The developed MVD aims to overcome the issues faced with adding data into energy simulation models by providing IFC files with the required BIM data for energy simulation. Similarly, Andriamamonjy et al. (2018) developed an MVD for data exchange to Modelica (BEPS tool). They also developed a Python-based tool (Ifc2Modelica) capable of translating the geometry, system and control information contained in IFC into a Modelica-based BEPS. In other research, MVDs have been developed concentrating on data exchange for structural analytical models (Ramaji and Memari, 2018), precast concrete fabrications (Jeong et al., 2009) and bridge inspections (Sacks et al., 2018).

Construction operation building information exchange (COBie), used from a FM standpoint, is a neutral file format defined by the MVD of IFC (Kang and Choi, 2015). The COBie approach is to enter the structured data as it is created during design, construction and commissioning (East and Carrasquillo-Mangual, 2013), which would facilitate the process of transferring information from BIM platforms to CAFM platforms. Designers provide floor, space and equipment layouts. Contractors provide manufacture, model and serial numbers of the installed equipment. Much of the data provided by contractors comes directly from product manufacturers who also participate in COBie (Figure 3-3). At the early stages of design, the vertical and horizontal spaces that are necessary to fulfil the district's requirements for the building, facility or infrastructure project are defined. Within these buildings and facilities, the different types of systems are also defined, which can include electrical, heating, ventilating and air conditioning (HVAC), potable water, wastewater, fire protection, intrusion detection and alarms, and other systems.

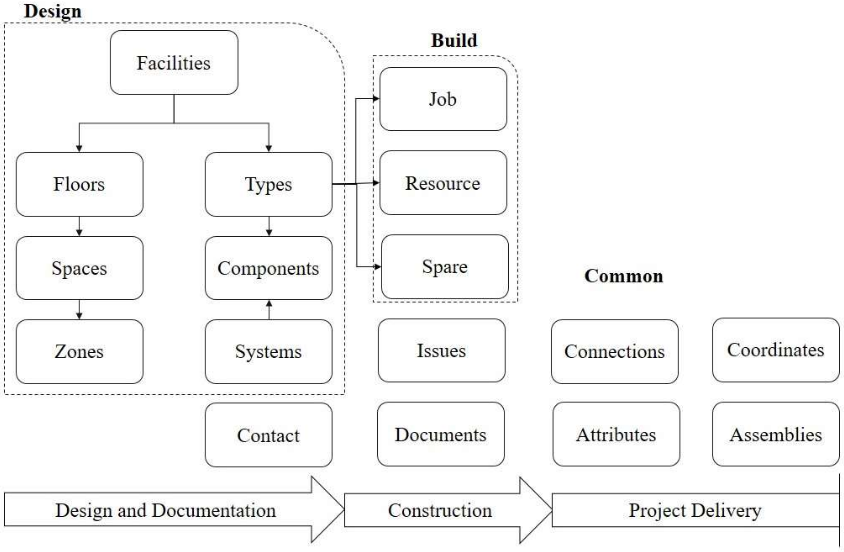


Figure 3-3: COBie division sheets

The merit of COBie is that it can be viewed not only in several BIM platforms but also in simple spreadsheets; however, the most important feature is the precise definition of requirements, not the delivery format (East, 2013). COBie looks promising to provide an effective interoperability bridge between the design and construction stages with the operation and maintenance stage. However, COBie has not yet reached maturity enough to promote its implementation successfully. The main problems with COBie implementation are that it is seen as a spreadsheet instead of an xml-based information exchange, it was developed in silos, it does not work with software firms and guideline organisations to better integrate with systems and classifications (John, 2013). Also, to manage, maintain and operate a complete building system, more information is required than COBie provides (NIBS, 2015). Consequently, the U.S. Army, Corps of Engineers, Engineer Research and Development Center initiated several projects for each system model. An MVD has been developed for each system such as HVACie for the heating, ventilation, and air conditioning (HVAC) system, SPARKie for the electrical system and WSie (Water System Information Exchange) for the water system (NIBS, 2015). The scope and the size of an MVD are generally determined by the defined required information in the IDM, domain types and relative applications (Lee et al., 2015).

3.3.2 Information Delivery Manual (IDM)

IDM is an approach to identify the data and process maps required for data exchange between at least two software systems. It also has to meet the end-user's needs and provide a universal, repeatable and verifiable methodology for creating information exchange by industry professionals (Wix and Karlshoej, 2007). Practically, IDM is the state-of-art methodology to link BIM tools and methods with AECO industry processes. IDM was the proposed solution in 2005 for the IFC's inability to handle individual processes and the related information within a single application during the building phases (AEC3, 2012). Several standards have been published for the development of IDM, such as BS EN ISO 29481-2:2016 and BS EN ISO 29481-1:2017. IDM can be beneficial for both BIM users and software solution providers as it provides a split framework for exchange requirements definitions (Pinheiro et al., 2018). For developing IDM and MVD, the National BIM Standard (NBIMS) offered a process of 13 steps in four major phases; namely, program, design, construct and deploy.

3.3.3 Property Set Definition (PSD)

PSD schema is an XML schema, defined as IFC-PROPRTY-SET, to define all properties and property sets inside and outside of the IFC specifications. Each property set holds the required non-geometric information for specific application and can also be a way to exchange this information, which is attached to specific spaces, building elements and other components. The reason for the development of the PSD schema is that there are diverse numbers of attributes and information attached to the objects depending on discipline, applications, stakeholders, lifecycle phase and project regulation which cannot be all covered in the IFC schema. Therefore, BuildingSMART developed the PSD schema to provide capabilities for the stakeholders to add the required information to achieve their exchange purposes. Some property sets are already identified and referred to as a basic set of properties in the IFC schema, such as IfcArchitectureDomain, IfcBuildingDomain and IfcHvacDomain. The PSD schema for IFC4 provided by BuildingSMART consists of seven different entities, namely: ifdguid, templatetype, Ifcversion, Name, Definition, Applicability, ApplicableClasses, ApplicableTypeValue, PropertyDefs and PsetDefinitionaliases. All the attributes of PropertySetDef and PropertyDef are illustrated in Figure 3-4.

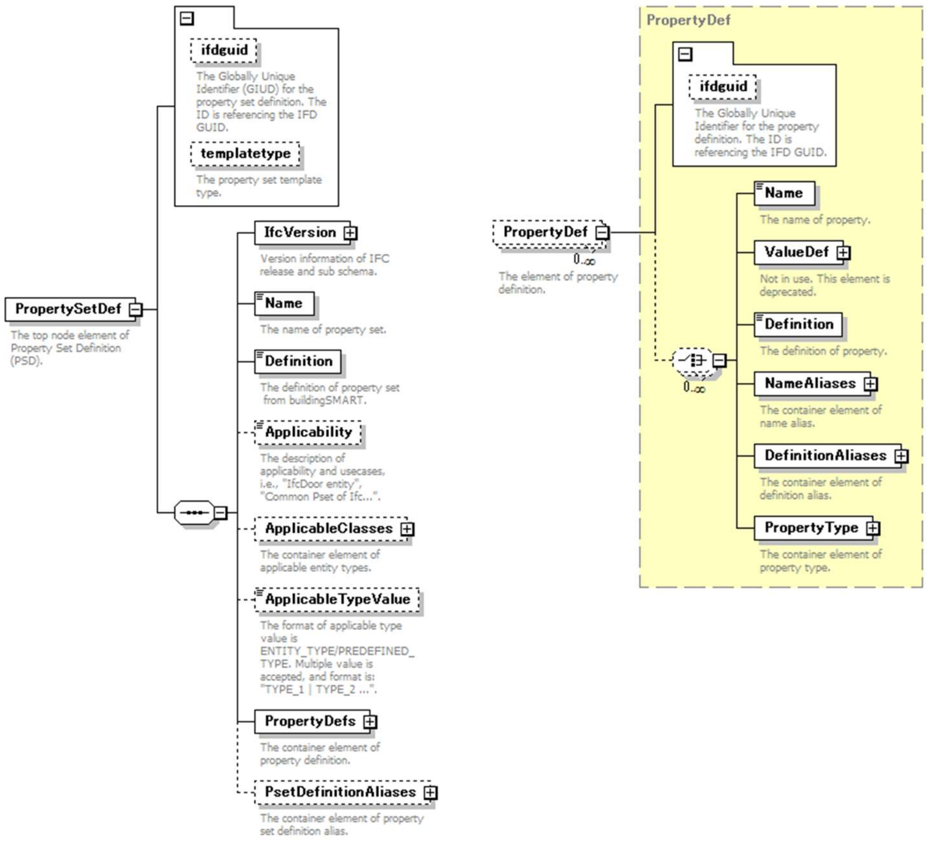


Figure 3-4: IFC property set definitions

The development of the MVD and associated standards requires a well-thought-out process. The following sub-section presents the MVD development process proposed by the National BIM Standard (NBIMS).

3.4 NBIMS MVD Development Process

The NBIMS specifies the process of MVD development which includes a variety of tasks that identify the required domain knowledge and translate it into a computer-understandable language using the IFC Express Schema. The development process consists for four main stages and their related activities (Figure 3-5). Stage 1 aims to identify the scope and context for the required case exchange by forming a workgroup with experts in information exchange technology and experts in the knowledge domain being considered. In this stage, the required information to be exchanged is identified and the process required to collect and exchange this information is illustrated. The identified exchange requirements and the process maps combined form the IDM.

The purpose of stage 2 is to structure the exchange requirements into a computer-understandable set of information modules to be easily and effectively used for MVD development. Each set of information modules is defined as a concept. A concept consists of instructions for implementation, the requirements of attributes, the mapping of the IFC schema, and the rules regarding attribute accuracy (Lee et al., 2016b). Concepts composed iteratively for various MVD requirements support the reusability of existing definitions (Venugopal et al., 2012).

Stage 3 addresses the implementation and certification of the MVD developed in stage 2. The testing of certification is usually done in an MVD concept by concept. There are two main organisations performing certification testing under contract: the Institute for Applied Building Informatics (Germany) (for BuildingSMART International) and Digital Alchemy (USA) (for the US General Services Administration (USA), Statsbygg (Norway), and Senate Properties (Finland)) (See et al., 2012). Finally, the last stage includes the deployment of the certified MVDs and reuse of those MVDs in industry projects. The following sub-sections discuss in detail each stage of the MVD development.

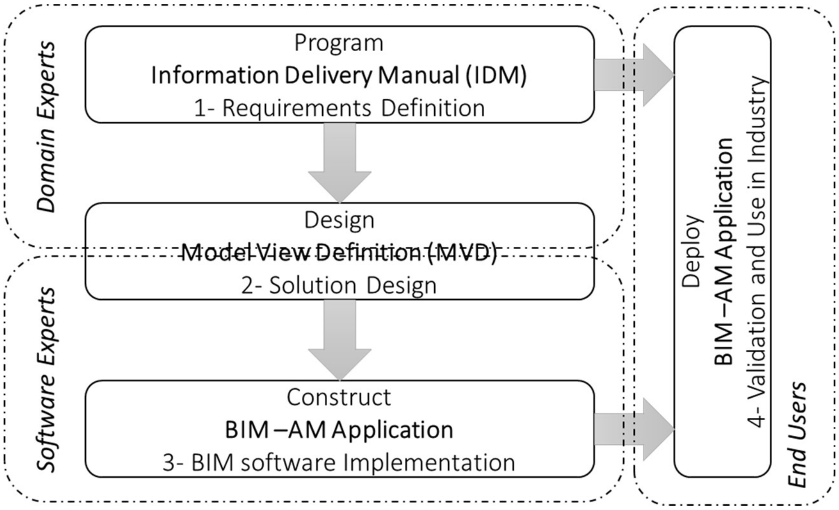


Figure 3-5: Four-phase integrated process for MVD development

3.4.1 NBIMS Phase 1: Information Delivery Manual (IDM) Development

The IDM development phase step starts when AECO industry domain experts collaborate to form a working group to develop an IDM for a specific exchange domain (See et al., 2012). The IDM provides a simple description for the BIM users concerning the required information, and the associated process and workflow for exchanging data for a specific application between two different software systems. Also, it delivers a comprehensive functional breakdown of the required process and IFC capabilities which should be supported by the applications provided by BIM software vendors. The IDM consists of four main deliverables using standard formats defined by users, domain experts and software vendors (Lee et al., 2016b, See et al., 2012). These four deliverables are process maps, exchange requirements, exchange requirements models and a generic BIM guide.

A process map identifies the flow of tasks within the boundary of a specific topic. It also includes the exchange data required (consumed and produced) and the stakeholders responsible for sending and receiving that data. For the IDM, the main roles of the process map are setting the boundary for the extent of the information contained within the process, establishing the activities within the process and their logical sequence, and identifying the exchange requirements that support the activities within the process (See et al., 2012). The preferred approach to develop an IDM process map is to use the Business Process Modelling Notations (BPMN). The BPMN is also recommended and adopted by the NBIMS and BS EN ISO 29481-1:2017 standards. The process map can be developed during the IDM workgroup in a fairly systematic manner by undertaking the following task: identify the significant disciplines and stakeholders, validate the project phases, identify the activities that have interaction among the disciplines and the phases, and, finally, link the different activities that exchange information with a use case exchange (Eastman et al., 2011b).

An exchange requirement (EM) identifies a set of information to fulfil the requirement of an information exchange between two business processes at a particular stage of a project (See et al., 2012). This set of information identifies which objects, object properties, relations between objects, classifications and project information are relevant to the receiving application and available in the sending application. The exchange requirements are initially identified as task deliverables in the process maps and are then defined in generic text in the exchange requirements descriptions. An EM is intended to provide the information in non-technical terms for the users, such as: architects, engineers and facility managers. However, it is also used by solution providers, since it is the key pillar for developing the technical solutions. Therefore, it has to be delivered in a specification template to expedite the development of the MVD. The specification template should be based on the used platforms and their capabilities and also on the current IFC capabilities (Eastman et al., 2011a).

An exchange requirement model (ERM) is the technical clarification of an exchange requirement. It provides a comprehensive machine-readable schema that can be adapted by a software application for successful information exchange for a specific purpose (See et al., 2012). Although ERM is a technical solution for information exchange, it does not rely on the schema of a specific release version of the information model from which it is derived. In other words, an exchange requirement can have several ERMs as a technical solution for several IFC releases. An ERM is formed by assembling a set of conceptual/functional parts and business rules.

Function parts describe in detail the technical specification of the information that should be exchanged as a result of action within a business process. Since that action may take place in several exchange requirements, the related function part has to be specifically well defined to be reusable within several exchange models (Arayici et al., 2018).

Business rules describe definitions and/or constraints that can be applied to a set of data used for a particular purpose or activity. Exchange requirement models (ERM) are represented in diagrams showing the set of data (exchange concepts) to be exchanged and the relationships between them. The format for ERM diagrams and configurations is defined by an XML schema. Finally, the last IDM deliverable is a generic BIM document for the end user stating the objects and the data required to be exchanged through the MVD. A product-specific vendor of the BIM guide is developed in the software implementation stage by the BIM vendors.

3.4.2 NBIMS Phase 2: Model View Definition (MVD) Development

Once all the IDM deliverables have been developed and there is consensus among the development team, it is time to start the development of the MVD. This step aims to develop an MVD which meets the end-user's needs as defined in the IDM and also provide an implementable format for sending and receiving software applications. An MVD is a computer implementation of an IDM where the exchange requirements are mapped to the IFC schema (Sacks et al., 2018). An MVD that is dedicated to a single IDM can be used to filter information in software tools to a specific exchange requirement. For generating a MVD, four different approaches and standards can be adapted, namely: mvdXML, Generalised Model Subset Definition (GMSD), eXtended Process to Product Modelling (xPPM) and Semantic Exchange Module (SEM) (Zhang et al., 2015).

The mvdXML is an open standard developed by BuildingSMART to define model subsets and validation rule sets and generate MVD documentations, while the GMSD is an Express schema developed for creating view definitions and object selection sets based on the IFC schema. The xPPM is a tool to provide an integrated solution for the IDM-MVD process, while SEM is a complete subschema of a set of IFC entities, attributes, relations and functions which can be used as basic blocks for different MVDs. The main goal of SEM is to provide a layer of specificity above the base layer of IFC. Based on the results of a comparative study by Zhang et al. (2015), the mvdXML development method is the only open standard and can be developed by the official IfcDoc tool as well as by common XML editors (Chipman et al., 2012). Also, it provides the ability to generate validation rules where the extracted models can be validated against the developed MVD. Therefore, it emerged that the mvdXML is the most appropriate approach to develop the proposed MVD and achieve the research objectives.

Four primary deliverables, each one using a specific standard format, are required for the transition from exchange requirements and associated ERMs to MVD. The first deliverable is a one-page description and overview of the new MVD where any general decisions regarding the IFC binding such as IFC release, version, reference, and status and document owner are documented (See et al., 2012). The MVD Overview/Description page has to be reviewed by all the stakeholders involved in the data exchange.

The second deliverable is MVD diagrams and the third deliverable is MVD concepts. These two deliverables are interrelated as the MVD diagrams consist of MVD concepts and the relation between the concepts. As mentioned in the IDM section (Section 4), exchange concepts in the ERM are defined as a series of reusable specifications units to be exchanged for a particular exchange scenario (Lee et al., 2018a), while an ERM diagram represents these exchange concepts and the relationships between them. In MVD development, MVD concepts are a machine-readable version of the exchange concepts. MVD concepts define their corresponding exchange concepts into a specific IFC release binding. Each ERM exchange concept can have one or more MVD concepts which represent the concept in software, and also it can have several MVD concepts based on the IFC release (See et al., 2012). The MVD concept is supported by a concept template which represents graphically the object attributes, relationships and constraints. The information in the concept template enables the generation of MVD diagrams. The MVD diagrams, as the ERM diagrams, represent the data to be exchanged about the top-level 'Variable

Concepts' and are defined by an XML schema. The MVD diagrams also define additional concepts for software implementation purposes.

The fourth deliverable is the MVDXML file, which is a machine-readable definition of the subset of IFC used in the MVD. According to Chipman et al. (2012), the purpose of MVDXML generation is one or more of the following: i) to generate documentation for specific model views and the IFC specification itself, ii) to support software vendors providing filtering of IFC data based on model views, iii) to limit the scope of IFC to well-defined subsets applicable for particular applications, and iv) to support automated validation of IFC datasets for quality assurance and software certification. The IFC Documentation Generator (IfcDoc) is a free tool issued by BuildingSMART based on MVDXML. IfcDoc reads and writes mvdXML files and also provides a graphical user interface for defining all the different content within an mvdXML file, such as concepts, concept templates, and model views. This tool also auto-generates MVD diagrams, output HTML documentation for model views, and the MVD documentation.

3.4.3 NBIMS Phase 3: IDM/MVD Implementation in the BIM Platform

After the requirements and process maps are defined in the form of an IDM and the implementable machine-readable solution is developed in the form of MVD, it is time to implement the solution in the software environment and apply it in different projects. MVDs should be supported by at least two software applications – the sender and the receiver of the exchange. However, See et al. (2012) argued that implementation of the MVD in BIM software is not sufficient to ensure reliable exchange of information in the BIM projects and a third party is required for the certification of the software products.

BuildSMART and Building Lifecycle Interoperable Software (BLIS) both recommended several third parties to perform that certification testing as the type of testing required is very detailed and specialised. The tests include checking each object instance against the requirements defined in the IDM and MVD for several test case files. This type of test has not yet been performed on the proposed MVD. However, the expected quality criteria for the test cases have been prepared for submission to one of the recommended third parties.

3.4.4 NBIMS Phase 4: Case Study Validation

The validation step aims to confirm that the BIM model accurately includes the information defined in the data exchange requirements and the model view specifications. Several checking routines, named validation rules, are performed at this stage to guarantee that the BIM models are generated and operated correctly. In project validation, data validation tools compare two files: the IFC file of the project (Design Data) and the reference MVD (Constrain Data) (See et al., 2012). Two different approaches are adopted for the validation of IFC models, which are using IfcDoc (MVDXML checker) and Semantic Web Rules Languages (SWRL). The IfcDoc tool can automatically validate an IFC model against a particular model view and also generate a report in HyperText Markup Language (HTML) format demonstrating the passes and failures of the IFC model according to the specified model views. The IfcDoc tool also can support syntactic validation in terms of compliance with the IFC schema (Lee et al., 2015). The required specifications can be coded in IfcDoc using modularised unit testing for each concept (Lee et al., 2018a).

On the other hand, a Semantic Web leverages the power of ontology and the ontology's ability to represent knowledge. Ontologies in a semantic web are expressed in graphic format using one of a two languages, namely: Resource Description Framework (RDF) and Ontology Web Language (OWL). For querying RDF data as well as OWL ontologies, SQWRL is used, while SWRL rules are designed on the top of ontologies to infer new knowledge. SWRL rules with an ontology based on IFC specification can be used to validate IFC models against model view specifications (Fahad et al., 2016). Each approach has its own advantages and disadvantages and the selection of the approach is based on the requirements of the research project. In this research, the selected approach for validation is discussed in Chapter 6.

3.5 Chapter Summary

The chapter aimed to provide an appropriate approach to develop an MVD for enhancing the syntactic interoperability between BIM and AM platforms. Thus, it reviewed the different approaches for integrating BIM and AM data. It showed that an IDM and MVD approach is the most suitable approach for the research objectives. Accordingly, it discussed the process proposed by the NBIMS for developing IDM and MVD. This process is adapted in Chapter 8 to develop the syntactic interoperability solution. For the purpose of Exchange Requirements Models and Process Maps in developing the IDM domain and generating a robust link between IDM and MVD, it is vital to define a concise set of terms and their relationships which are used to develop the ontologies and cross-linking between BIM and AM domains. The following chapter presents the basic literature on ontologies and Linked Data.

Chapter 4 Ontologies and Linked Data

The chapter discusses how ontologies and Linked Data can provide cross-linking between the two domains – BIM and AM – semantically. The chapter starts by defining ontology in variety of domains ranging from philosophy to construction management and BIM domains, and it discusses some ontology aspects including components, tools and techniques. Then, it presents Linked Data and how ontologies are utilised in Sematic Web and Linked Data. Finally, existing work related to BIM and IFC ontologies is discussed to steer the adaption of ontologies to achieve the research aim and objectives.

4.1 Ontology

The Latin word 'Ontologiae' was coined in the sixteenth century by Lorhard to represent the study of existing/being and first mentioned as Ontology in the English Language in 1663 by Gideon Harvey (Corazzon, 2016). Ontology can be classified into two main types: pure philosophical ontology and applied scientific ontology. Pure philosophical ontology is concerned with the study of being or the theory of existence and it is discussed thoroughly in sub-section 5.3.1. On the other hand, applied scientific ontology is concerned with the study of concepts, entities, and their structure, relationships, processes and properties in a specific domain knowledge. Applied scientific ontology, as a knowledge model, plays a significant role in knowledge sharing, managing and reuse. This sub-section starts with the knowledge ontology definitions and related expressions. Then, it presents the different ontology components and tools.

4.1.1 Ontology Definition

Ontology identifies the basic terms and relations of a topic's domain knowledge by comprising the vocabulary for defining the terms, and the rules for combining the terms and relations (Neches et al., 1991). Information sciences moved ontology from the abstract to the more concrete. Later, the term ontology was adopted by Knowledge Engineering researchers to create ontologies as computational models that enable automated reasoning.

Guarino and Giaretta (1995) proposed to use the words Ontology (with a capital 'O') and ontology to refer to the philosophical and Knowledge Engineering (KE) aspects respectively. This proposal has been adapted in this research for simplicity. In KE, the most appropriate definition for ontology is "*an explicit specification of a conceptualisation*" (Neches et al., 1991). Conceptualisation is an abstract, simplified view of concepts, entities, objects and their properties and relationships for domain knowledge. The main difference between conceptualisation and ontology is that conceptualisation is language-independent, while ontology is language-dependent (Guarino, 1998). Based on the conceptualisation definition of ontology, more researchers defined ontology in computer science and added further requirements. Borst (1997) added two requirements to the definition of ontology: formal, which means that the ontology is written in a machine language where it is easily processed, and sharable, which means that the ontology is developed based on agreement between a community of experts in the knowledge domain, both of which consequently guarantee the usage of the ontology in different applications.

Uschold and Jasper (1999) observed that the ontology also has to include a vocabulary of all used terms and some specification of their meaning. Spyns, Meersman and Jarrar (2002) added that the ontology in computer science has to be a computer-based resource and relatively generic for reuse in different applications and tasks in the same domain knowledge. Guarino and Giaretta (1995) also stated that ontology has to explicitly describe the conceptualisation. One of the most complete definitions pertaining to this research comes from Noy and McGuinness (2001): an ontology can be defined as "*a formal explicit description of the concepts in a domain of discourse, properties of each concept describing various features and attributes of the concept, and restrictions on slots*". This definition sets the stage for the BIM and AM use of Ontology.

Other terms are often discussed within the presence of ontology term such as dictionary and taxonomy. A dictionary lists the words of a language and gives their meaning and/or the equivalent words from the same or different language. However, the dictionary does not give a structure and relations for the terms that it contains. Taxonomy is a scheme of hierarchal classification where the description of terms or concepts and their relationships in the context of a knowledge area are identified. However, a taxonomy does not give a full definition of the terms within it. Consequently, ontology can be described as a combination between a dictionary and a taxonomy within a specific domain, as an ontology can establish both a meaning for the terms and a classification system.

Knowledge engineering ontologies in general have been used in different applications such as Artificial Intelligence and Information Systems, business process re-engineering, to facilitate communication, sharing and annotation of information, and reuse of domain knowledge (Frolov et al., 2010, Noy and McGuinness, 2001). Regardless of their application, two main challenges are not easily overcome during ontology development. These challenges are use of ontology and construction difference. The use of ontology refers to the difficulty of applying the same ontology to cover all the different uses in the same domain (Chandrasekaran et al., 1999), while construction difference refers to the difficulty of selecting the correct methodology for building an ontology (Noy and McGuinness, 2001) .

4.1.2 Ontology Classifications

Knowledge engineering ontologies can be classified based on their contents, the area of conceptualisation, the degree and the benefits of ontology (Gomez-Perez et al., 2006). Additionally, the ontology can be classified into taxonomic ontologies and semantic ontologies. A taxonomic ontology is a hierarchically structured set of terms for identifying a domain that can be used as a skeletal foundation for a knowledge base (Swartout et al., 1996). Developing a taxonomic ontology of the objects of a knowledge field can provide a common terminology which eases the sharing of knowledge, helps in identifying the knowledge gaps in the field and supports decision-making (Usman et al., 2017). It enables the usage of the same ontology to build several knowledge bases.

In contrast, semantic ontologies model the domain knowledge in a deeper way and provide more restrictions on domain terms and relations. Also, the ontologies can be classified based on their level in the knowledge domain. They can be classified into upper-level ontologies and domain ontologies (Calero et al., 2006). The upper-level ontologies are more generic and provide the basic main concepts across a domain and give general notations to which the terms in the domain ontologies can be linked (Gomez-Perez et al., 2006). In contrast, domain ontologies are more specific and provide detailed relationships and definitions for the related concepts. Sometimes domain ontologies are inherited from the upper level, but often they are built then linked to upper-level ontologies.

Moreover, ontologies are differentiated into lightweight ontologies and heavyweight ontologies. Lightweight ontologies include concepts, relationships between concepts, hierarchical classification of the concepts (taxonomy), and attributes or properties associated with the concepts. In contrast, heavyweight ontologies add more constraints and axioms to the lightweight ontologies to fix the semantic interpretation of concepts and relations (Fürst and Trichet, 2006). The ontology components for the lightweight and heavyweight ontologies are discussed in the next sub-section.

4.1.3 Ontology Components

Several knowledge representation languages exist for ontology development. Each of them adapts different components that can be used to build ontologies. However, the following components are shared among most of the ontology representation languages. The first five components are used to develop lightweight ontologies (Calero et al., 2006), while the others are used to develop heavyweight ontologies form the developed lightweight ontologies. The components are namely: classes and sub-classes, individuals, relations, properties, function terms, axioms, rules, restrictions and events.

Classes and Sub-Classes are defined as a group, set or kind sharing common attributes (Merriam-Webster 2013). A Class represents a concept of the domain. For instance, in the travelling domain, concepts are locations and means of transport. Each concept (class - C) can contain other concepts (sub-classes - C'). Consequently, any individual in C' will be also an individual for C. The locations concept contains countries, cities, villages, while means of transport contains planes, trains, cars, etc. In the frame-based knowledge representation paradigm, metaclasses are used. Metaclasses are classes whose sub-classes are the instances of the class.

Classes in ontology are usually organised in hierarchical order (taxonomy) where inheritance mechanisms can be applied (Calero et al., 2006). Classes may also share semantic relationships with each other and that will describe how the individual of this class is related to another individual in another class. Individuals or instances represent elements in an ontology. Individuals are the basic components of ontology; they are the elements that the ontology describes. For instance, Egypt is an individual of the class County. Property or attribute is defined as a quality or feature which is considered as a characteristic of someone or something. A property is an inherent part for a class or even for an individual. A property itself can be a class or an individual. The kind of object and the kind of property determine the kind of relation between them. Relations represent a type of association between concepts of domain, concept and individual, and individual and individual.

Function Term is a word, or an expression used to describe a thing/individual or express a concept/class particularly in a domain of knowledge for a specific kind of language. An ontology usually includes lists of all the function terms that are relevant to the studied domain and also the terms related to the function terms in the same domain or even in other, related domains. Rules are if-then statements applied to the ontology components to describe the logical implications that can be concluded from an assertion in a particular form. Axioms are the logical assertions applied to classes, individuals and properties and fixed through their semantics, which make it possible to distinguish the hierarchical and semantic relations that satisfy the ontology rules from those that do not.

4.1.4 Ontology Development Tools

Although ontologies can be written as code, knowledge engineers utilise editor tools which enhance the development of ontologies. For ontology development, effective tools are an important requirement (Kapoor and Sharma, 2010). Fortunately, there are several available ontology editors such as Protégé and Apollo (Alatrish, 2013). Other ontology editors are specified for a particular domain, such as OBO-Edit for biomedical ontologies (Fung and Bodenreider, 2019).

Protégé is the most popular ontology editor and knowledge management system (Fung and Bodenreider, 2019); it was developed at Stanford University and the early versions included the collaboration of the University of Manchester (Noy and McGuinness, 2001). Protégé is freely available to use, is implemented in Java and contains a large library of plug-ins to enhance its capabilities. The tool also comes with embedded reasoners used to check the correctness and consistency of ontologies. Additionally, it allows the creation of rules and queries, which can be utilised to test the reasoning capabilities of ontologies. Finally, it offers several ways to dynamically visualise ontologies in graphs.

Apollo is another ontology editor tool which enables the user to model ontology with basic primitives such as classes, instances, functions and relations. It was developed by the Open University of the United Kingdom Knowledge Media Institute and is implemented in Java. The Apollo internal model is a frame system based on the Open Knowledge Base Connectivity (OKBC) protocol. The Apollo knowledge base consists of ontologies organised in a hierarchical order. Ontologies can inherit from other ontologies and use the classes of the inherited ontologies as theirs own. Each class can contain a number of instances and an instance inherits all the template and non-template slots of the class. Each slot consists of a set of facets. Apollo does not support graph view, web support or the merging of two or more ontologies. Also, it provides only two formats (OCML and CLOS) for importing and exporting ontologies.

Ontology development is an ad-hoc approach. Amongst several alternative approaches and tools, the selection should be based on which tool could be utilised effectively to achieve the project/research objectives. Several researchers (Alatrish, 2013, Kapoor and Sharma, 2010, Ukpe and Mustapha, 2016) have compared the different available ontology editors.

Table 4-1 illustrates a comparison between various editors. In Chapter 6, the tool for this research is selected based on which is most appropriate for achieving the research objectives (adapted from (Saeed, 2013).

Table 4-1: Comparison of various ontology editors

Feature	Protégé	Apollo	OntoEdit	KAON2
Availability of tool	Open/ Free	Open Source	Free evaluation	Open Source
Web Support	Yes	No	No	Yes
Import Formats	XML, RDFs	OCML, CLOS	XML, RDFs	RDFs
Export Formats	XML, RDFs	OCML, CLOS	XML, RDFs	RDFs
Graph View	Yes	No	No	No
Consistency check	Yes	Yes	Yes	Yes
Merging ontologies	Yes	No	No	No

4.2 Linked Data

Linked Data aims to define a process to publish and share machine-readable inter-Linked Data on the web, based on a set of design principles. Linked Data works in the same way as relational data in conventional databases: it is stored, processed and queried by computers not by humans (Bizer et al., 2009). The Semantic Web term was coined before the Linked Data term by Sir Tim Berners-Lee, 'the inventor of the Web' at WWW (World Wide Web) in 1994 and documented in a Scientific American article in 2001 (Berners-Lee et al., 2001). The semantic web is a "*Web of actionable information- information derived from data through a semantic theory for interpreting the symbols*" (Shadbolt et al., 2006). The semantic web is an extension to the current web where information (data and documents) is well defined to ensure better cooperation between computers and humans. The purpose of the semantic web is to achieve data universality and data linking with any other data. However, Berners-Lee (2006) noticed that some semantic data published on the web was not linked to other, outside, semantic data. Therefore, he outlaid four principles that need to be adopted to obtain truly Linked Data. The four principles are:

1. Use URIs (Uniform Resource Identifiers) as names of things,
2. Use HTTP URIs so that people can look up those names,
3. When someone looks up a URL, provide useful information using the standards and
4. Include links to other relevant URIs, so they can discover more things.

In 2010, Berners-Lee suggested a five-star deployment schema for Linked Data based on the four Linked Data principles. The five-star deployment schema is accumulative, it starts with one star and the data earns more stars when proprietary formats are detached, and more links are added. Table 4-2 summarises the five stars and provides an example of each in the operation and maintenance domain.

Table 4-2: The five stars of Open Linked Data

Star	Requirements	Format	Example
★	Available on the Web under an open licence	Any	PDF of asset specifications
★★	Available as structured data	E.g. Excel	PDT/COBie in Excel
★★★	Available in a non-proprietary open format	E.g. CSV	PDT/COBie in CSV
★★★★	Available in URIs to denote things	RDF/SPARQL	Ontology in RDF
★★★★★	Link data to other data to provide context	-	Linked with other ontologies

Inspired by the four Linked Data principles and five stars approach, several guidelines and best practices for Linked Data generation and publication have been developed. These Linked Data guidelines and best practices have been adapted by several data providers, significantly increasing the amount of Linked Data published. This has led to the creation of a global data space containing a high volume of assertions, named the web of data. The web of data – also named the Linked Open Data (LOD) cloud – enhanced data access by consumers and formed open-Linked Datasets.

Two main platforms enhanced the management of the published datasets, namely: Comprehensive Knowledge Archiving Network (CKAN) and LODStats. CKAN is an open-source data management system written and maintained by Open Knowledge. CKAN enables governments and organisations to upload, publish, distribute, find and describe data sources using comprehensive meta-data schemes. On the other hand, LODStats is a statement stream-based approach for gathering comprehensive statistics about RDF datasets. In 2015, 1091 datasets were published on the web, while in 2019, 9960 are published on the web, based on the LODStats. Accordingly, the four years from 2015 to 2019 saw an overall 913% growth in the number of published datasets.

The semantic web of data, unlike the document web, requires standards to ensure a highly interconnected network where the huge amount of heterogeneous data has been given a well-defined meaning. Therefore, an ecosystem of standards, named the Semantic Web Stack, to support LOD has been developed by the World Wide Web Consortium (W3C) team. The architecture of the semantic web stack had been modified several times; the latest stack is depicted in Figure 4-1 (adapted from Antoniou and Van Harmelen, 2004).

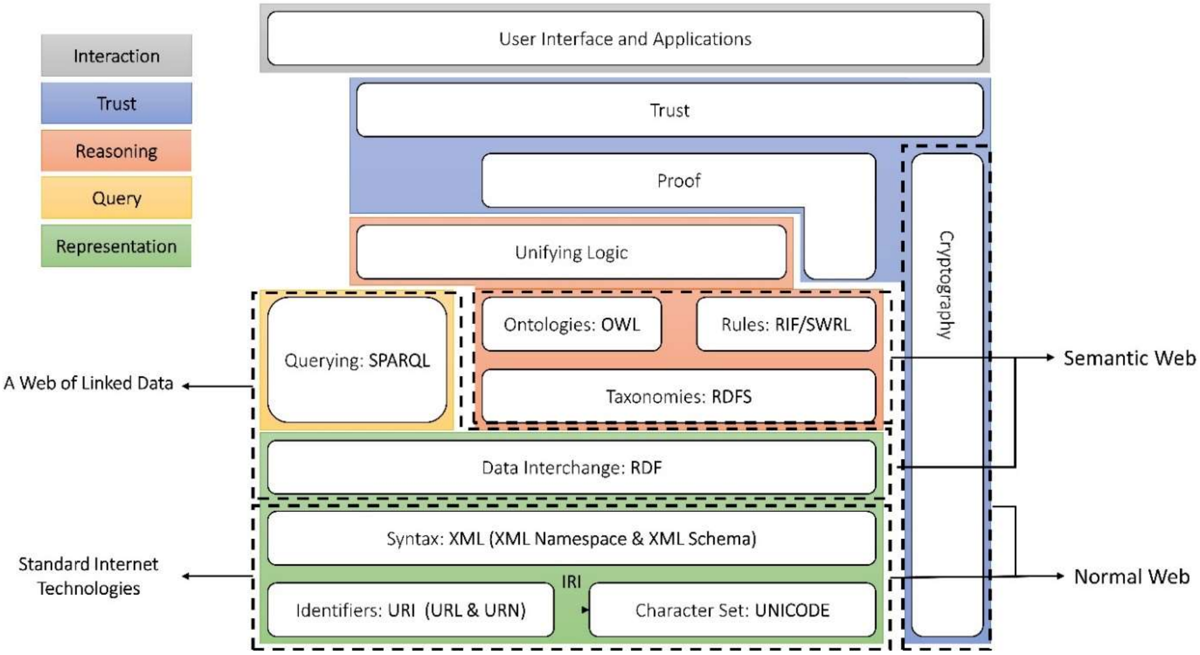


Figure 4-1: Semantic Web Stack

The stack consists of several layers; the first two layers are known as the standard internet technologies for providing data on the web. The combination of these two layers with the Cryptography, which verifies the reliability of the inputs such as the digital signature of the sources' origin, forms the structure of a normal web. The Resource Description Framework (RDF) layer is a semantic web core representation for data in graphical format. The RDF is a generic and flexible language that permits the presentation and integration of information from different knowledge domains. The RDF is a framework based on the triples concept 'subject-predicate-object' that form a graph of the data. Each concept in an RDF graph, whether it is subject, object or predicate, has its own URI. The resulting RDF graph can be represented using a number of syntaxes such as RDF/XML (.RDF), N-Triples (.N_T), Turtle (.TTL), and Notation-3 (.N3). The RDF Schema (RDFS) contains the most basic elements describing the ontologies built by the RDF triples such as the description of classes, sub-classes, comments, relationships and data types.

Ontologies represent knowledge in specific domains and enable semantic interoperability by linking to other external data sources. More rich and complex elements and greater machine interpretability for expressing ontologies and RDF statements are found within Web Ontology Language (OWL). For querying and manipulating RDF data as well as RDFS and OWL ontologies, Simple Protocol and RDF Query Language (SPARQL) is commonly used. It provides SQL-like operations to retrieve knowledge from OWL. RDF(S), OWL and SPARQL provide the foundation to allow working with rules and proofs. Relying on rules and proofs, several applications can be built and could reach a precise level of trust.

4.3 Ontologies, Linked Data and Semantic Web in the AECO Domain

Having discussed Ontologies and Linked Data principles, tools and concepts in the preceding sub-sections, this sub-section concentrates on the applications of ontologies, semantic data and Linked Data in the AECO domain. The application of ontologies and Linked Data has enjoyed great popularity in other domains, including biology, medical records, cultural heritage, accounting and social media (Schmachtenberg et al., 2014). These success stories encourage the implementation of ontologies and Linked Data in the AECO domain (Radulovic et al., 2015).

A workshop series named Linked Data in Architecture and Construction has been initiated to bridge the research results of the industry and academia in that topic (Pauwels et al., 2015). Two community groups have been formed based on the efforts of the workshop series, namely: the W3C Community Group on Linked Building Data and the BuildingSMART Linked Data Working Group. The W3C Community Group on Linked Building Data focuses on outlining the different use cases and requirements of Linked Data across the building lifecycle.

The use cases applications include data from BIM, GIS, sensors and material data to achieve greater data integration and interoperability between different datasets in different domains. On the other hand, the BuildingSMART Linked Data Working Group focuses on building and maintaining an ifcOWL ontology. The efforts of that group have resulted in the development of several updated versions of ifcOWL approved by BuildSMART and available on the organisation's website (Pauwels and Terkaj, 2016, Venugopal et al., 2015). The IfcOWL is currently under the process of becoming a part of the ISO 16739 standard (Pauwels et al., 2017a), which would pave the way for more BIM Web-based platforms and better interoperability with other systems.

Alternatively, several researchers have illustrated the different benefits that can be acquired by the implementation of Linked Data in the built environment domain, as well as the barriers to overcome the integration of data through the building lifecycle phases. Abanda et al. (2013) categorised semantic web implementation studies in the built environment domain based on area of application. The classification of four categories, namely: semantic web applications in traditional construction, semantic web applications in sustainability or sustainable construction, semantic web application and BIM, semantic web applications and carbon/energy management. Pauwels et al. (2017b) categorised the work differently, into three main categories based on aims and barriers to overcome, namely: interoperability, linking across domains, and logical inference and proofs.

Curry et al. (2013) proposed the use of Linked Data in order to manage and operate building assets holistically. They argued that Linked Data can provide a cross-domain integration between building silo systems in a homogenous format. Based on that, O'Donnell et al. (2013) combined Linked Data and complex event-processing technologies to enhance the efficiency of building energy management activities. Several silo domains such as human resources source and architecture source, which are represented in 3D models, inventory source, legislation source and Building Energy Performance (BEP) source can be cross-mapped and integrated using Linked Data. They argued that this approach can reduce the time required by building managers to analyse and optimise building energy performance. Corry et al. (2014) demonstrated several examples of integration and publishing of building-related data following semantic web rules to improve the building performance. One of the examples was the cross-domain integration of the scheduling data with the building operation strategy. They linked the data from Building Management Systems (BMS), the room booking system, Human Resources Management (HRM) systems and building information model based on the room entity.

Gómez-Romero et al. (2015) discussed that open BIM standards such as IFC have limited capabilities for cross-domain information integration and query; therefore, they proposed a fuzzy logic-based extension of the semantic BIM to create more formal and interoperable building information models. Lee et al. (2016a) proposed a framework for sharing construction defect information through the applicability of BIM and Linked Data. They argued that the framework can enable the integration between data in the BIM environment such as space, element and material, and defect data such as defect type and defect source. To create the ontology, they adapted OmniClass classification's taxonomy to build the classes and properties. Kim et al. (2018) proposed a method to link the IFC objects with the FM work information. They developed a semantic relation between the classes of IFC, COBie and historical maintenance work concepts. They argued that the proposed approach can enable facility managers to semantically link the BIM objects to the maintenance records in the Semantic Web during the O&M phase in order to provide a BIM environment without the specific BIM authoring application.

Other researchers concentrated on the implementation of only Ontologies for knowledge management. Motawa and Carter (2013) identified the information required to develop an ontology to support energy management activities in buildings. The ontology will enhance the linking between energy management systems and a BIM-modelled environment to ensure information related to energy use is available throughout the whole building lifecycle. Abanda et al. (2017) developed an ontology based on New Rules of Measurement (NRM1) concepts to facilitate the cost-estimation process in the AEC industry. In the AM domain, Campos (2007) developed several ontologies such as maintenance cost ontology, condition monitoring ontology and production ontology for better maintenance management of industrial assets with their objects, attributes and relationships.

Despite the available studies, the Linked Data generation and publications in the domain of AECO are still in their infancy. They need methodological guidelines to support their evolution towards maturity (Radulovic et al., 2015). Pauwels et al. (2017b) argued that the highest number of implementation of Linked Data for use cases in the construction industry lies under linking across domains. That is because cross linking requires limited number of involved technologies and also includes simpler approaches than other applications. The reviewed literature provides the foundation of the developed ontology and proposed process of Linked Data in Chapter 7.

4.4 Chapter Summary

This chapter introduced the basic concepts of ontologies and Linked Data utilised as part of the conducted work. Also, it offered an overview of the status quo of research into the implementation of ontologies and Linked Data in the AECO domain. This review showed that ontologies and Linked Data can dramatically enhance the interoperability between different platforms and linking across different domains. This chapter contributes to the research objectives by reviewing the different tools and methods for Linked Data applications with BIM to link across domains. It also provided the foundation for the developed ontology and Linked Data in Chapter 7. The following chapter discusses the methodology adopted for this research.

Chapter 5 Methodology

5.1 Introduction

This chapter seeks to explore and discuss all aspects of the research methodology. It considers various research strategies and the practical interpretation of those strategies within the context of this research. This chapter opens by presenting the different aspects of research philosophy. Then, it illustrates the different research approaches, strategies, and methods. Finally, it recaps the selected techniques and methods that enable the research aim and objectives to be successfully achieved. The following chapter presents the research design.

5.2 Research Methodology Components

The research methodology is considered to be the overall strategy used in scientific investigation, which consists of the three main components in a hierarchical structure, namely research philosophy, research methodological justification and research design (Figure 5-1). The outer rectangle represents the research philosophy, which is formulated by two main ways of thinking, namely ontology and epistemology. Research philosophy guides the selection of the research methods. Research methodological justification consists of three main elements, namely research approach, research strategy and research methods. It consists of the dominant theory generation and testing methods, whereas the research design comprises the research phases and research methods selected to comply with the research aim and objectives.

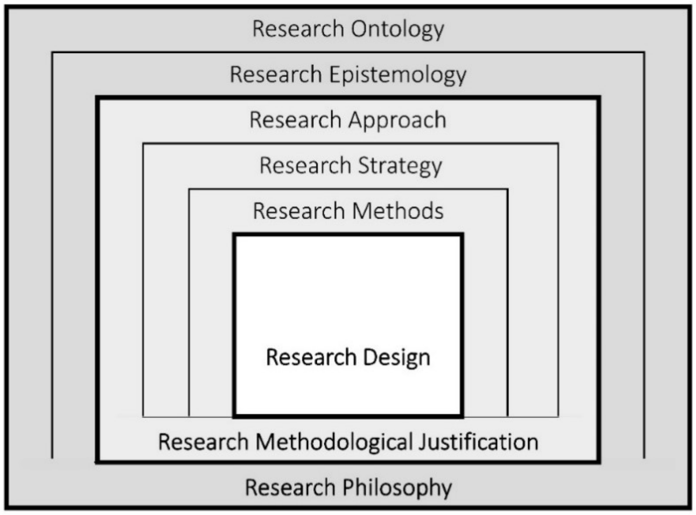


Figure 5-1: Research Methodology components

Table 5-1illustrates the research objectives and the selected research dimensions to achieve the objective. Each dimension of research methodology is discussed and the rational behind the selected approach is elaborated in the following sub-section.

Table 5-1: The research objectives and the adopted methodology and methods

	Objective 1&2	Objective 3&4	Objective 5	Objective 6
Ontology	Objectivism	Objectivism	Constructionism	Constructionism
Epistemology	Positivist	Pragmatism	Interpretivism	Interpretivism
Approach	Deduction	Deduction	Induction	Induction
Strategy	Qualitative	Qualitative	Quantitative	Quantitative
Methods	Literature Review Conceptual Modelling	Conceptual Modelling Interviewing Prototyping Development	Prototyping Development	Case Studies
Tools		Protégé	IfcDoc .Net	Revit IfcDoc

5.3 Research Philosophy

A research philosophy, often called a paradigm (Guba and Lincoln, 1994), refers to the set of beliefs and assumptions adopted by the researcher concerning the nature of the research reality being studied (Bryman, 2015). The type of knowledge being investigated in the research defines and governs the choice of the research philosophy (Saunders et al., 2011). The assumptions created by a research philosophy provide the justification for how the research will be undertaken (Flick, 2015).Therefore, a research philosophy is important as it provides the basis by which to choose the relevant research approaches, strategy and methods, and also underpins the research design for achieving the research aims and objectives (Martens, 2005). Within the layer of research philosophy, the formation is made by two way of thinking/viewing, namely ontology and epistemology (Crotty, 1998). Ontology is concerned with what is knowledge, while epistemology is about how we know it (Creswell, 2002). However, Crotty (1998) argued that ontology and epistemology tend to be merged and we cannot study either of them individually.

5.3.1 Research Ontology

Ontology can be explained as ‘the science or study of being’ (Blaikie, 2009, Crotty, 1998) and it deals with the nature of reality and the way of constructing this reality. The main question that research ontology has to answer is whether social entities are objective entities that have a reality external to social actors, or whether these entities are constructed based on the perceptions and actions of social actors (Bryman, 2015). In other words, Ontology can be understood as different viewpoints about social reality in a range from objectivism to constructionism. Additionally, Rand (1990) has identified ‘Intrinsicism’ as a third alternative, which can be defined as "*the belief that certain things are good 'in, by, and of' themselves.*"

5.3.1.1 Objectivism

Objectivism is an ontological position that states that social entities/phenomena and their definitions have an existence that is independent of social actors and their influence (Bryman, 2015). In objectivism, a phenomenon cannot be true for one person and false for another, except if there is a radical difference in the relevant perceptual evidence available to the two people (different perceptions). Objectivism does not depend on emotions, mental choices, subjective processing, or whims (Peikoff, 1993). However, people can still have different levels of evidence that change how the statement ranks on their ontology scale. The main basic axiomatic concepts of objectivism are existence, identity and consciousness (Peikoff, 1993).

5.3.1.2 Constructionism

Constructionism, also named subjectivism (Rand, 1990), is an ontological position that states that social entities/phenomena and their definitions are created and accomplished by social actors and their perceptions (Bryman, 2015). From the subjectivist perspective, a phenomenon can be true for one person and false for another, based solely on one's mental choices, subjective processing, analysing or emotions. The truth depends on whatever one believes, and there is no such thing as knowledge of reality or even logic, only some sort of experience inside one's own mind. Consequently, constructionism depends on emotions, mental choices, subjective processing, or whims (Peikoff, 1993).

5.3.1.3 Selected ontology

A researcher primarily adopts a particular standpoint towards the nature of knowledge (Objectivism or Subjectivism) of the research subject (Bryman, 2015). The ontological assumptions will underlie the formation of the research questions and even the entire research process and govern the particular theoretical perspective selected.

This research contributes to understanding the phenomenon of implementing BIM in asset management and achieving appropriate interoperability between BIM and AM through developing conceptual constructs such as taxonomies and ontologies for the required information and a prototype system to exchange the required information from the BIM systems to AM systems. Consequently, this research cannot ignore the knowledge of the experts in the field.

The first three objectives of this research seek to understand the process of asset information management and identify the required parameters and build constructs for managing assets which consume energy. To achieve these objectives, experts from the construction and FM domain are involved. In the light of the above, a constructivism (subjectivism) stance regarding the ontological perspective is adopted for the first three objectives. Concurrently, the other three objectives are related to developing a prototype and evaluating it through a case study; therefore, an objectivist stance is adopted.

5.3.2 Research Epistemology

Epistemology can be explained as ‘how we know what we know’ and it deals with the source of the knowledge and how problems should be understood and addressed for a specific subject/concept (Kuhn, 1962). The main question that research epistemology has to answer is whether the social world can and should be studied according to the same principles, procedures and ethos as natural science (Bryman, 2015). Epistemology is related to ontology in a way that each epistemological instance implies a particular ontological instance and vice versa (Crotty, 1998). Epistemology can be understood as the different sources of knowledge about social reality in a range from positivism to interpretivism (Guba and Lincoln, 1994). Positivism uses quantitative methods to test theory and increase the predictability of a measurable phenomenon, while interpretivism uses qualitative and naturalistic methods to understand and explain phenomena. Realism is also considered to be an epistemology position (Saunders et al., 2011).

Within management in general and construction management and asset management in particular, three epistemological paradigms are identified: positivist, interpretivist and pragmatism (combined approach). Pragmatism takes a middle stance between positivism and interpretivism, where researchers are empowered to use a variety of research approaches and methods (quantitative and qualitative) to find answers to their research questions (Onwuegbuzie et al., 2009).

5.3.2.1 Positivism

Positivism is an epistemological position that encourages and supports applying the methods of understanding natural science to the study of social reality and beyond Accordingly, in positivism, knowledge can be obtained and measured by quantitative research studies. However, positivist research loses the in-depth knowledge of the studied subject can be obtained by qualitative research and experts' knowledge and inputs. Positivist research generally attempts to create and test theory and increase the predictability of a measurable phenomenon independently to the researcher's opinion and observations (Myers, 1997).

5.3.2.2 Realism

Realism is an epistemological position related to scientific investigation. The philosophy of realism is that the existence of reality does not totally depend on the human mind. Realism is similar to positivism in that it assumes a scientific approach to the development of knowledge. There are two main forms of realism: direct realism and critical realism (Saunders et al., 2011). The main difference is that direct realism acknowledges the occurrence of the thing through one step only, which is the sensation of the thing. In contrast, in critical realism, it goes through two steps: firstly the sensation of the thing and then mental processing to validate the sensation observation (Saunders et al., 2011).

5.3.2.3 Interpretivism

Interpretivism is an epistemological position which is an alternative to positivism. Interpretivism advocates the application of methods which adopt only human sense, background and experience (social construction) to study the social and scientific reality of a phenomenon (Bryman, 2015, Myers, 1997). Interpretive researchers concentrate on studying people rather than objects, focusing on implications and explanations rather than on behaviour and actions (Meredith et al., 1989). Interpretivism aims to investigate and understand more the subject of research through collecting rich data (Creswell, 2013). Accordingly, in interpretivism, knowledge can be obtained and measured by qualitative research methods where people interact and contribute to the research outputs. However, interpretivist research can be biased and theories cannot be generalised by qualitative methods only, which rely on personal viewpoint and experience. Interpretivist research generally attempts to access reality and knowledge through inductively and holistically understanding human behaviour in context-specific settings (Amaratunga et al., 2002).

5.3.2.4 Selected epistemology

In this research, an interpretivist stance is adopted to achieve the first three objectives (theoretical contribution), while a positivist/critical realist stance is adopted to achieve the other objectives (practical contriution). Therefore, a combined approach (pragmatism) – interpretive more than positivist – regarding the epistemology perspective is adopted.

5.4 Research Methodological Justification

Research methodological justification is the strategy, plan of action and process responsible for the selection and the usage of particular research methods to achieve the research goals. The selection of research methods is resolved by a combination of different factors, such as whether the researcher is trying to discover an external truth or exploring different perspectives for a specific subject, and also whether the researcher is inclined towards positivism or interpretivism as an epistemological stance (Gray, 2013). This layer is created by three embodied elements, namely research approach (reasoning of research), research strategy (strategy of enquiry) and research methods (Creswell, 2013). The three elements are discussed in the following sub-sections.

5.4.1 Research Approach

Research approach can be explained as ‘the way to answer research questions’, and it deals with the logic of the way in which the research is conducted. The main question that the research approach has to answer is should we begin with theory, or should theory itself result from the research? (Gray, 2013). According to Saunders (2011), there are two main approaches, namely: deduction (testing theory) and induction (building theory), and a combination of them.

5.4.1.1 Deduction

Deduction is a research approach that attempts to draw a conclusion or confirm/dispute a theoretical prediction (Rothchild, 2006); however, it does not generate a prediction on its own. Deduction can only strengthen, weaken or disprove a theory or a framework – regarding how it was developed – by comparing it with reality and case studies (Saunders et al., 2011). This approach generally acquires and analyses a small amount of data/information from a large number of actors/participants. According to Robson (2002), deductive research goes through five different stages: 1) deducting a hypothesis (a testable suggestion about the relationship between two or more concepts or variables) from the theory, 2) expressing the hypothesis in operational terms (that is, indicating exactly how the concepts or variables are to be measured) which propose a relationship between two specific concepts or variables, 3) testing the hypothesis using research methods, 4) examining the specific output of the inquiry, and, finally, 5) modifying the theory based on findings.

5.4.1.2 Induction

Induction is a research approach that attempts to infer a general law or principle from observation of particular instances (Rothchild, 2006). In other words, it is an approach that pulls together several separate facts, particulars, etc., especially for the purpose of proving or describing a general statement or theory. According to Popper (2002, p. 27), an explanation or inference is considered ‘inductive’ when it passes from singular statements (sometimes called ‘particular’ statements), such as accounts of the results of observations or experiments, to universal statements, such as hypothesis or theories. This approach generally acquires and analyses a rich amount of data/information from a small number of participants as the researcher is more concerned with context (Saunders et al., 2011). Accordingly, an inductive approach can provide extremely valuable information; however, it cannot alone guarantee its conclusions. An inductive approach, through generating and analysing data and reflecting upon theoretical themes, is more appropriate for topics which are new and/or little represented in literature (Creswell, 2013).

5.4.1.3 Selected research approach

This research adopts the combined approach to achieve its aims and objectives. This research firstly aims to formulate a BIM-AM framework, identify the required information from BIM for asset management and create constructs for managing the assets that consume energy. To achieve this aim, an inductive approach has been employed to gather general statements from necessarily specific experiential knowledge. Simultaneously, this research also aims to develop and evaluate a prototype where data can be exchanged between BIM and AM platforms. To achieve this aim, a deductive approach has been employed where the five stages proposed by Robson (2002) are utilised to test whether the developed asset's information and taxonomy can be considered as an accurate representation of objective reality. The research is inferring BIM and AM concepts and relationships, generating conceptual constructs (frameworks, taxonomies, classifications and models) to represent concepts/relations, and then applying theses constructs to develop tools for practice. Such a combination of inductive and deductive approaches within the same piece of research is not strange, and it is often advantageous to do so (Saunders et al., 2011). However, such an approach is also considered to be an artificial reconstruction of reality (Downward and Mearman, 2009).

5.4.2 Research Strategy

The research strategy can be explained as how the research will be conducted' and it deals with the plan that provides specific direction for the research process. The main question that the research strategy has to answer is what is the most appropriate direction – which will govern the data collection techniques and data analysis procedures – to answer the research question (Saunders et al., 2011). According to Saunders (2011), there are two main approaches, namely: quantitative and qualitative, and a combination of the two. The mixed strategy (triangulation) allows the researcher to collect a stronger chain of evidence than can be done by employing any single method (Creswell, 2013, Yin, 2009). However, other researchers (Hammersley, 1992) have debated the benefits of the mixed approach and claim that this combination is dangerous to the research process and outcomes.

5.4.2.1 Quantitative strategy

A quantitative strategy can be defined as any strategy that uses systematic observations to account for and generalise about specific phenomena (Allen et al., 2008). Creswell (2013) describes a quantitative study as "*an inquiry into a social or human problem, based on testing a theory composed of variables, measured with numbers, and analysed with statistical procedures, in order to determine whether predictive generalisations of the theory hold true*." Quantitative strategy was developed in natural science (Myers, 1997). The use of quantitative strategy in social science can be traced back to the time of Aristole (Allen et al., 2008). The quantitative strategy feeds the positivism branch of epistemology; therefore, it plays an important role in the study of physical sciences such as physics, chemistry and mathematics.

Although quantitative research is useful and variable in all its variation, it is still often seen as a limited strategy by qualitative researchers as it neglects the actors' perspectives within the context of their lives. That is because quantitative strategy is not inherently concerned about human interaction or feelings, or the thoughts and perceptions of people in research, but with facts, measurable behaviour and cause and effect.

5.4.2.2 Qualitative strategy

Qualitative strategy can be defined as a strategy used to develop/test a theory by emphasising the meaning of action and the expression of mind (Bryman, 2015). Fellows and Liu (2015) describe qualitative study as '*an exploration of the subject is undertaken without prior formulations – the object is to gain understanding and collect information and data such that theories will emerge*'. Qualitative research has started to be used in the early decades of the twentieth century in anthropology, philosophy and sociology science fields. At that time, qualitative research was quite unsystematic and journalistic and, much as now seen, unscientific. Qualitative research often is interpretivism orientation, however, it can also be positivism orientation (Bryman, 2015). It follows from this that the choice of a specific qualitative research method (such as the case study method) is independent of the underlying philosophical position adopted (Myers and Avison, 2002). In other words, case study (as a qualitative method) can be selected by both research adopting a positivist stance and research adopting an interpretivist stance'. Qualitative researchers claim that the experiences of people are essentially context-bound; that is, they cannot be free from time and location or the mind of the human actor. A qualitative strategy seeks to arrive at an understanding of a particular phenomenon from the perspective of those experiencing it (Vaismoradi et al., 2013).

Qualitative methodology is not completely precise because human beings do not always act logically or predictably. Investigators in a qualitative enquiry turn to their human participants for guidance, control and direction throughout the research. However, the social world is not orderly or systematic; therefore, qualitative researchers need to progress their research in a well-structured and systematic way.

5.4.2.3 Selected research strategy

The proposed research adopts pragmatism philosophy, supported by a mixed approach (qualitative dominant mixed methods) where social and other contexts have been comprehensively considered within the research environment. Johnson, Onwuegbuzie and Turner (2007) defined qualitative-dominant mixed methods research as "*the type of mixed research in which one relies on a qualitative, constructivist-poststructuralist-critical view of the research process, while concurrently recognising that the addition* *of quantitative data and approaches are likely to benefit most research projects.*” Respectively in this research, qualitative data was used to develop the conceptual framework, taxonomies, classifications and models, while quantitative data was used to evaluate and polish the developed constructs, MVD and tool.

5.4.3 Research Methods

A research method is a strategy which moves from the underlying philosophical assumptions to research design and data collection (Myers and Avison, 2002). The research methods’ main goal is enabling the researcher to answer the particular research question(s) and meet the research objectives (Saunders et al., 2011). The choice of research methods influences the way in which the researcher collects data. Consequently, the outputs will be affected by the techniques and procedures used. Since different techniques and procedures will have different effects, using different data collection methods can lead to greater confidence being placed in the research conclusions (Saunders et al., 2011).

Research methods can be classified according to two ‘dimensions’ (Meredith et al., 1989). The first dimension (y-axis) is referred to as the rational/existential dimension. This dimension concerns the epistemological structure of the research design and is classified into four categories based on different degrees of formalism (from pure logic to existentialism). These four classifications are axiomatic, logical positivist/empiricist, interpretive, and critical theory object reality. The second dimension (x-axis) is referred to as the natural/artificial dimension. This dimension concerns the source and the kind of data/information used in the research, and is classified into three categories based on the researcher’s perception of the studied phenomenon’s reality (from object observation by researcher to computer simulation). These three classifications are object reality, people's perceptions of object reality, and artificial reconstruction of object reality.

Using the above-mentioned classifications of the two dimensions, Meredith et al. (1989) developed a matrix which positions different research methods along the two dimensions underlying the research design. The selected methods to address the research aims and objectives are represented as dotted polygons in Figure 5-2 (adapted from (Meredith et al., 1989, Succar, 2013). These methods and techniques are discussed in the following sub-sections, 5.4.3.1, 5.4.3.2, 5.4.3.3 and 5.4.3.4, and justified in sub-section 5.4.3.5.

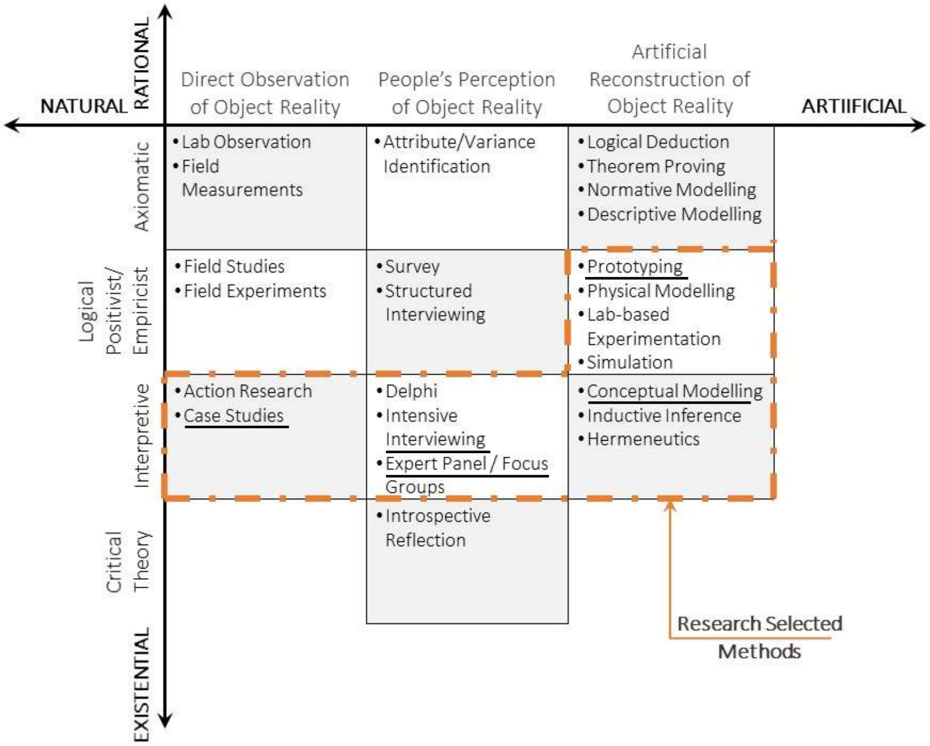


Figure 5-2: Framework of research methods

5.4.3.1 Interviewing

The data collection and analysis are the most important aspect of conducting research (Saunders et al., 2011). Data collection has some key issues, which are sampling, secondary data and primary data (Saunders et al., 2011). Sampling is the approach used to select the number of participants to engage and contribute in the data collection phase of the research. Secondary data refers to the existing data (previous research, organisational data and case studies) when it is considered when conducting a new study. In this research, the conceptual framework (phase 1 in the research design) was developed based on the secondary data. Primary data is data collected first-hand by the researcher. Primary data can be collected by three main methods: observation, semi-structured, in-depth and group interviews, and questionnaires (Saunders et al., 2011).

Depending on the method and procedures of data collection, data analysis will be conducted. Data analysis can be classified into qualitative data analysis and quantitative data analysis (Saunders et al., 2011). Interviews and focus groups, as data collection methods in the research, and their resultant data analysis methods are further elaborated on and discussed in the context of the current research.

Research Data Collection

Saunders, Lewis and Thornhill (2011) classified interviewing into three types of interviews, namely Structured Interviews, Semi-Structured Interviews and Unstructured Interviews (Figure 5-3). Structured interviews use a single set of pre-determined standardised questions and the interviewee responds usually with a pre-coded answer for each of those questions. Unstructured interviews, also referred to as in-depth interviews, use unstandardised questions to explore an aspect about which the researcher already has a clear idea, and the interviewee responds freely about events, behaviour and beliefs related to the questions' topic. Finally, semi-structured interviews can be considered as a middle ground between structured interviews and unstructured interviews. In this format, the researcher is guided by a list of themes and questions; however, the order of questions may be different, and some questions may be eliminated altogether, while new questions may be required, depending on the context. The interviewee in a semi-structured interview has more latitude to answer questions in an open manner; however, the researcher may guide the whole processes in order to obtain responses to all questions fully and in a timely fashion.

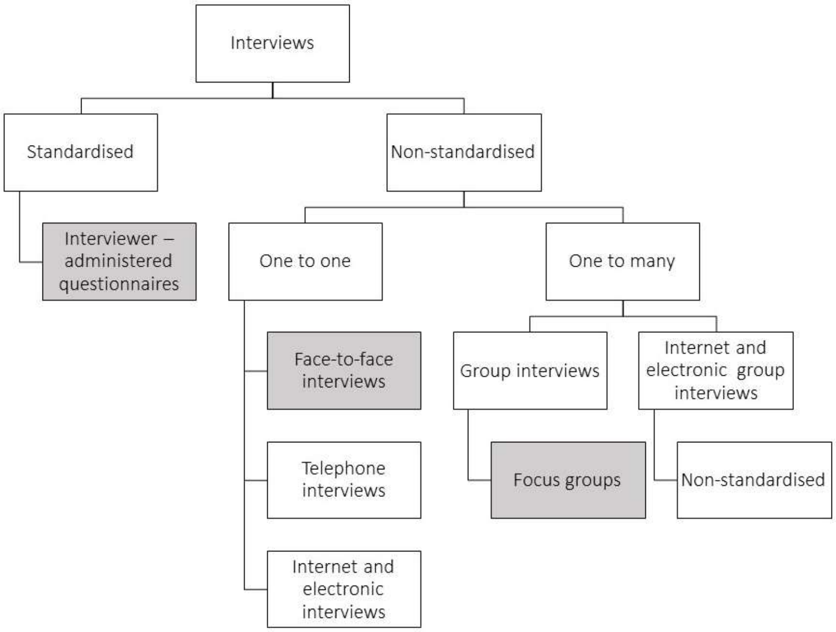


Figure 5-3: Forms of interviews

Face-to-face interview with a semi-structured approach provides an interactive environment between the researcher and the expert participant in the field of research. This environment permits the researcher to explore complex, contradictory matters, particularly on the points raised during the interview. The informality of the enquiry in semi-structured interviews will give sufficient space for the researcher to harness expected and unexpected answers that could arise. However, a list of questions/themes will be created to guide each interview. Bryman (2015) suggested that the semi-structured interview is an appropriate data collection technique when a researcher is somewhat familiar with the concepts being researched and the research focus is in a concentrated area.

Focus group is another method of interviewing; in this case, the researcher conducts the interview with multiple participants simultaneously (Saunders et al., 2011). This allows the participants to interact to agree/disagree/refine the data collected. This interaction between participants may produce spontaneous responses and more cognitive views; therefore, focus groups are suitable for exploratory studies in a new domain or/and when little is known about the topic. Another advantage of focus group is that they are loosely structured, which encourages a variety of viewpoints on the topic; however, they should never be entirely without structure. Focus groups involve several participants (from 6 to 10) and a moderator (Saunders et al., 2011). The researcher, who acts like the group's moderator, has to ensure that the focus group is controlled by the topic guide, and also ensure that all participants have an equal opportunity to present their perspective and that the group is not confined and dominated by only one or two participants.

Standardised interview questionnaires (structured interviews) are where the interviewee is asked to respond in a predetermined order. In other words, structured interviews, also referred to as interview schedules, are where the interviewer physically meets their interviewees/respondents and asks the defined schedule of questions, and the interviewees' answers are pre-coded and restricted to groups of answers to choose from (Saunders et al., 2011).

Research Data Analysis

Data analysis is conducted in line with the data collection procedures and methods. (Saunders et al., 2011) state the different procedures for analysing qualitative and quantitative data. As qualitative data collections methods only are conducted in this research, only the qualitative data analysis is discussed.

During the qualitative data analysis phase, this non-standardised data has to be categorised and analysed through conceptualisation. Thematic analysis and content analysis are two common methods for qualitative analysis (Vaismoradi et al., 2013). At the core of both content and thematic analysis, data is arranged into themes or codes by categorising raw text under meaningful labels or codes. However, thematic analysis works on developing these themes or codes without taking into consideration the frequency of the coded information, while content analysis works on quantifying the frequency of the coded information.

5.4.3.2 Conceptual Modelling

Conceptual modelling is the process of formally describing some aspects of the physical and social world around us for better understanding and communication (Mylopoulos, 1992). It is a fundamental ingredient of the way humans visualise and understand the surrounding phenomena (Lambe, 2014). Conceptual modelling, often referred to as conceptual schemata, requires the adoption of a formal notation, a conceptual model in our terminology.

In information and operation systems, conceptual modelling can be defined as the process of developing the conceptual model (Robinson, 2008). The conceptual model is a non-software-specific description of the computer simulation model describing the objectives, inputs, outputs, content, assumptions and simplifications of the model. Conceptual models are intended to be used by humans, not machines (Mylopoulos, 1992).

In addition, Robinson (2008) identified five key activities for conceptual models development. These key activities are, in order: understanding the problem situation, determining the modelling and general project objectives, identifying the model outputs, identifying the model inputs, determining the model content, and identifying any assumptions and simplifications. Meanwhile, Mylopoulos (1992) stated that conceptual models have to cover aspects relating to different kinds of knowledge during the development of an information system. The four aspects of knowledge are subject, system, usage and development worlds (Mylopoulos, 1992). The constructs such as theories, classifications, taxonomies, frameworks and mental models provide structure and organise information/knowledge for flexible applications in the real world (Lambe, 2014). In this research, different conceptual constructs are used such as frameworks, classifications and taxonomies, as described below.

Frameworks

A framework, within the context of research, is a structure which delivers guidance for the researcher as research questions are polished, methods for collecting, measuring and analysing variables are chosen, and the research process is planned (Smith and Liehr, 1999, Sabatier, 2007). Well-structured frameworks can assist the researcher in organising domain knowledge, eliciting tacit expertise and facilitating the development of new knowledge.

Frameworks, in implementation science, often have a descriptive purpose by pointing to factors believed or found to influence implementation outcomes (Runeson and Höst, 2009). From that perspective, Runeson and Höst (2009) classified the frameworks in science implementation based on the aim of the use. There are three main frameworks: process frameworks, determinant frameworks and evaluation frameworks. Process frameworks, also referred to as process models, aim to describe and/or guide the process of translating research into practice. These frameworks specify the stages and phases in the research process to translate knowledge to action. Determinant frameworks aim to understand and explain what influences implementation outcomes. These frameworks specify classes of determinants and the relationships between them. Finally, evaluation frameworks aim to evaluate the implementation. These frameworks specify aspects of implementation that could be evaluated to determine implementation success goals and success.

Classification

Classification is an approach to organise and cluster things or objects into categories based on similarity (Oxton et al., 2015). Classification provides a systematic arrangement where patterns can easily emerge. Also, classification is a heuristic tool valuable during the formative stages of discovery, analysis and theorising (Davies, 1989). Good classification delivers three main features: Filter, Browse and Rank (Oxton et al., 2015).

Taxonomies

Taxonomy – in Greek, ‘taxis’ means arrangement, and ‘nomos’ means law – is a structure for classification, nomenclature to describe a catalogue, a relationship map (Oxton et al., 2015). Lambe (2014) also agreed that taxonomy is a form of classification scheme. However, taxonomy has different characteristics such as it is mostly exhaustive, semantic and provides a relationship map between the data and identifies the related items or objects, not only grouping them based on similarity. In other words, the main difference between taxonomy and classification is taxonomy describes relationships in a semantic approach while classification basically groups similar items based on predefined codes. Taxonomy visually represents the subject as a whole in a map of the labels' relationships and the labels are more defined in the dictionary of taxonomy and the thesaurus (Lambe, 2014). Taxonomies can be presented in different forms such as list, tree, hierarchies, poly-hierarchies, matrices, facets and system maps (Lambe, 2014).

5.4.3.3 Prototyping Development

As system development is one of the main parts of this research, selecting an appropriate Software Development Methodology (SDM) to develop the proposed system is important. The SDM identifies the development process framework which construct, design and control the process of developing an information system (CMS, 2008). Different frameworks are available for the SDM and each has its own strengths and weaknesses. A framework can be used individually or combined with another framework. The selection of the framework is governed by the kind of project and technical, organisational and project considerations. However, in literature, SDM has different classifications based on different perspectives.

Chandra (2015) divided the software development lifecycle model into four categories: flow-based models, structure-based models, iteration-based model and object-oriented model. While Simão (2011) classified SDM differently into four main methodologies: traditional development methodologies, evolutionary methodologies, rapid application development methodologies and agile development methodologies. Meanwhile, Pressman (2010) grouped the methodologies – based on their activities and workflow – into four main groups: the waterfall model, incremental process models, evolutionary process models, and concurrent models. To avoid the variance in the literature classification, in this research the models are categorised based on the framework adopted. The categorisation includes three main frameworks, which are linear, iterative and incremental.

Linear and its resultant methodologies

A linear framework focuses on sequential phases. In other words, in a linear framework, a phase starts only when the previous phase has been completed and signed off. There are two main models in the linear framework: waterfall model and V model. The waterfall model is the first software process model introduced in the late 1950s (Simão, 2011). It is very simple and it is the start of the linear framework where the project is divided into sequential phases, with some overlap and splashback acceptable between phases (CMS, 2008). The stages in the basic waterfall method, presented in sequential order, are requirements, design, implementation/coding, testing and maintenance (Figure 5-4). There are many different waterfall models; however, all of them use the same original philosophy (Simão, 2011). The V model, which refers to verification and validation model, is similar to the waterfall model. The only difference in the V model is that testing of the product is planned in parallel with a corresponding development phase (Figure 5-5).

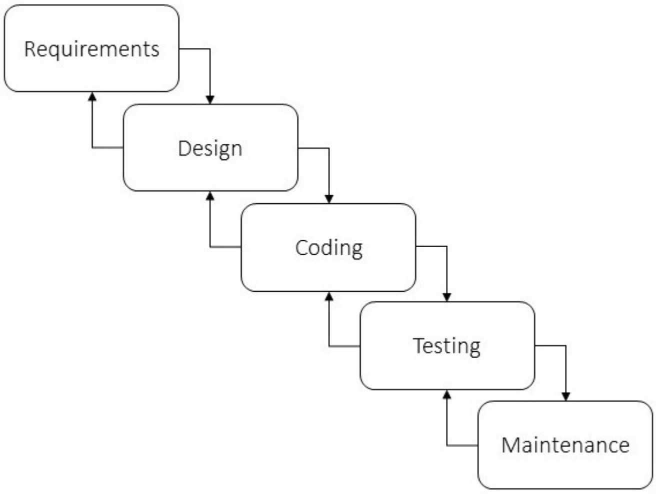


Figure 5-4: Waterfall system development model

Both waterfall model and V model, which are based on a linear framework, are simple, easy to use (less experienced teams can use them), manageable and function properly with projects where the requirements are defined and fixed from the early stage of system development. Also, the progress of the system development can be measured straightforwardly as each activity has its own deliverables. However, these models are rigid, time consuming and costly, and system problems are often not discovered until the testing phase. These models are best suited to very traditional software development projects and are not suitable for projects that are more research and development oriented.

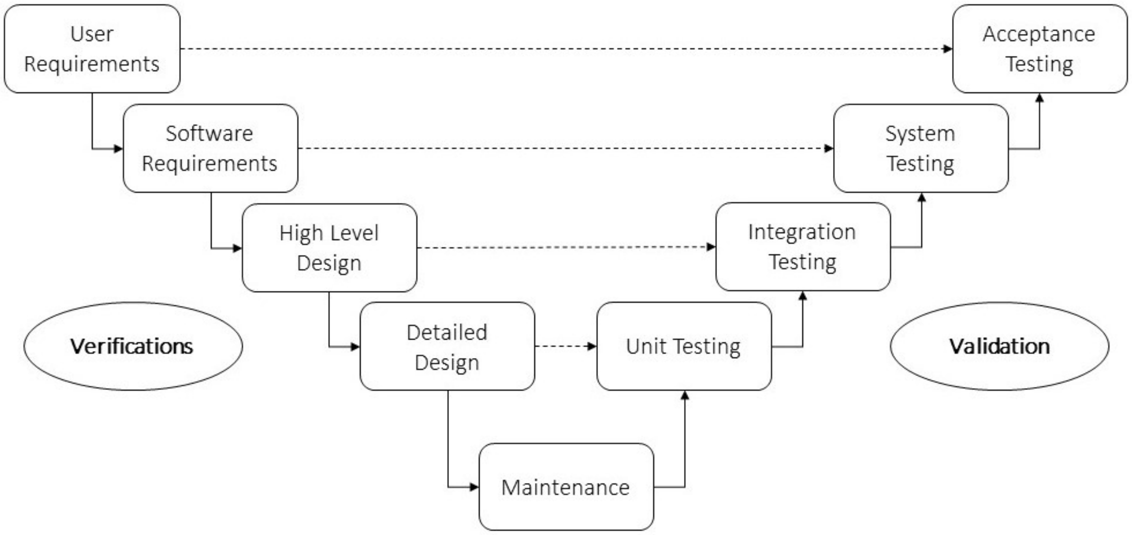


Figure 5-5: V-Model for system development

Iterative framework and its resultant methodologies

An iterative framework focuses on repetition. In an iterative framework, the project usually does not start with a full specification of required outputs. Instead, the software development starts by specifying and implementing the basic requirements, which can be reviewed to identify further requirements. This process is repeated until an operational system is released that fulfils all the requirements. There are two main models in the iterative framework: prototype model and spiral model. Also, an iterative framework can be implemented with a waterfall model and create an iterative waterfall model (Simão, 2011).

A prototype model, or prototyping, is a top-down approach. In the prototyping process, an initial prototype is developed based on the known requirements in the early stage of the process. The developed prototype acts as a baseline for communication between developers and client/owner. Therefore, this prototype will be refined based on the evolved requirements in each iteration until it meets the user's request (Figure 5-6). The prototype is not usually a fully-functioning product; it is developed only to provide the system with overall functionality. Prototyping is flexible, provides good communication in the system development process between the developers and the clients, and it is the best choice for projects where the requirements are not well defined in the initial stage. However, it includes a lot of iterations, which is costly and time consuming (Chandra, 2015).

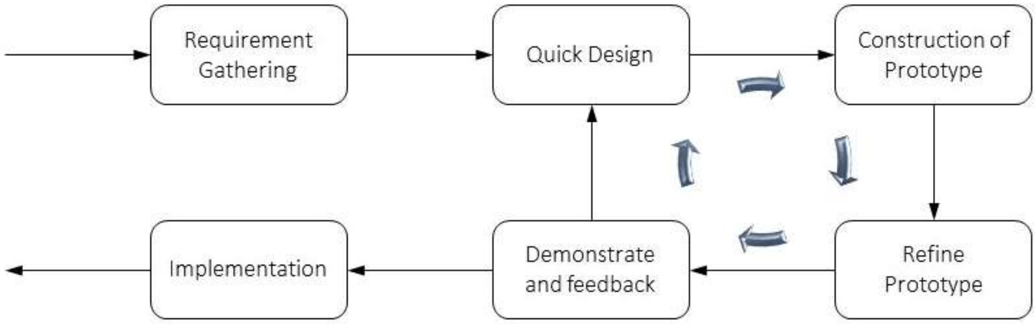


Figure 5-6: Prototype for system development

On the other hand, the spiral model, defined by Barry Boehm (1988), combines top-down and bottom-up approaches. This model is quite similar to prototyping as an iteration is based on the result of the previous one. The main difference between the two models is that the spiral model manages the risk of the software development project. The spiral model is represented as a Cartesian diagram with a spiral with its centre in the point (0,0) of the diagram (Boehm, 1988). The process is divided into four quadrants: (1) determine objectives, (2) identify and resolve risk, (3) development and test, and (4) plan next iteration (Figure 5-7). The spiral model enhances risk avoidance as it is flexible and can be incorporated with other frameworks and models. However, it is costly, complicated and highly customised, and needs expertise in risk assessment and project management.

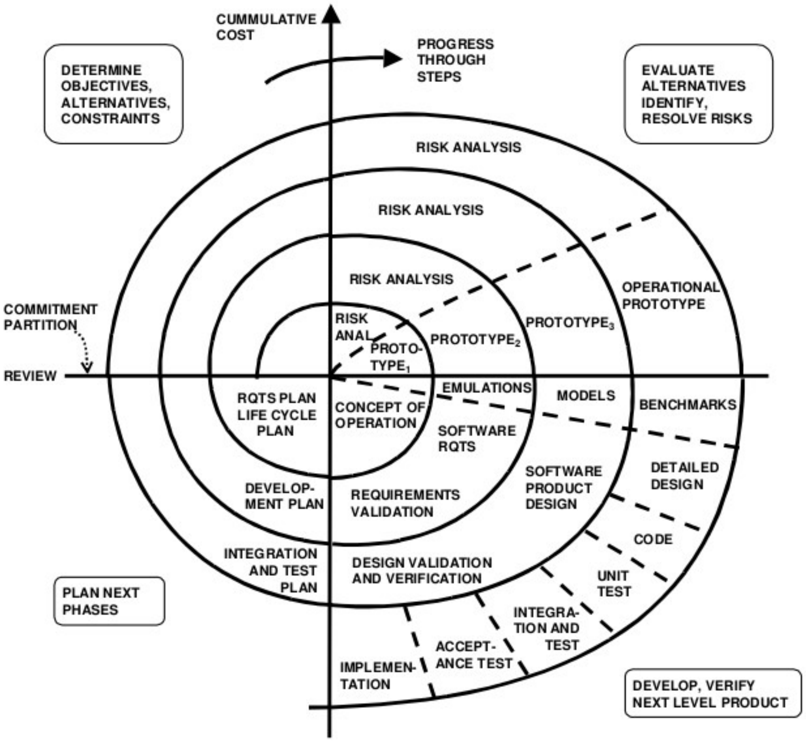


Figure 5-7: Spiral model for system development

Incremental framework and its resultant methodologies

An incremental framework focuses on partition. In an incremental framework, the whole requirement is divided into various objectives (small requirements). Each objective goes through all the different phases during the module development. Each subsequent release of a module adds function to the previous release. The process continues until the complete system is achieved. The modules can be developed in parallel or in series. There are two main models in the incremental framework: rapid application development (RAD) model and agile model. Also, an incremental framework can be implemented with a waterfall model and create a multi-waterfall model.

The RAD was formalised by James Martin (1991), based on a combination of SDM models, to accelerate the development and improve the quality of the software product. The RAD methodology is to concentrate less on planning tasks and concentrate more on development tasks. The RAD cycle starts with prototyping as a kick-off for design where a proof of concept is served for the client and the requirements are polished at a very early stage of development. RAD implies that development cycles are time boxed, multiple cycle can be developed at the same time and modern technology and management techniques are used (Martin, 1991). RAD phases are business modelling, data modelling, process modelling, application generation, and testing and turnover (Figure 5-8). RAD is fast and semi-flexible, offers the ability to make rapid changes in the system design, and is lower cost. However, the fast development may lead to low quality, poor documentation and/or misalignment due to missing information (DESPA, 2014).

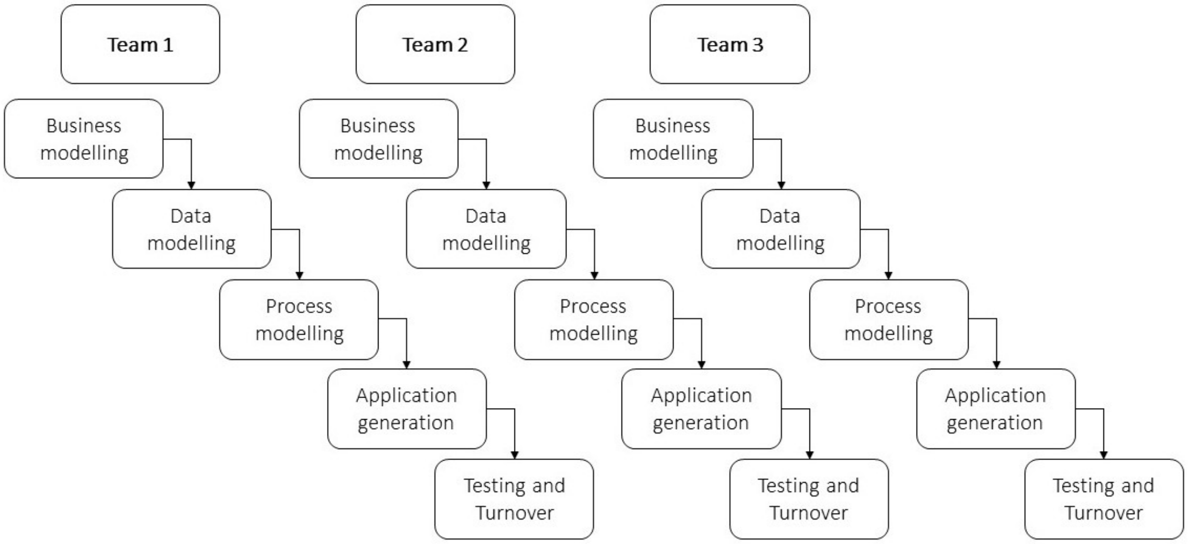


Figure 5-8: Rapid Application Development (RAD) for system development

The agile model is considered the new wave of software development. This model is known as the son/grandson of RAD (Simão, 2011). In the agile model, software is based on the development and delivery of small increments of functionality. The resultant small incremental releases with each release building on previous functionality (Figure 5-9). Each release is thoroughly tested to ensure software quality is maintained. There are different models under the agile model umbrella, such as agile manifesto, scrum and eXtreme programming (Simão, 2011). The agile model is fast, suitable for small-medium size projects and flexible for changes through the regular system release. However, it is difficult to use in large projects, requires client engagement during the whole development process and needs an expert team, and it is costly due the requirement for two developers during programming.

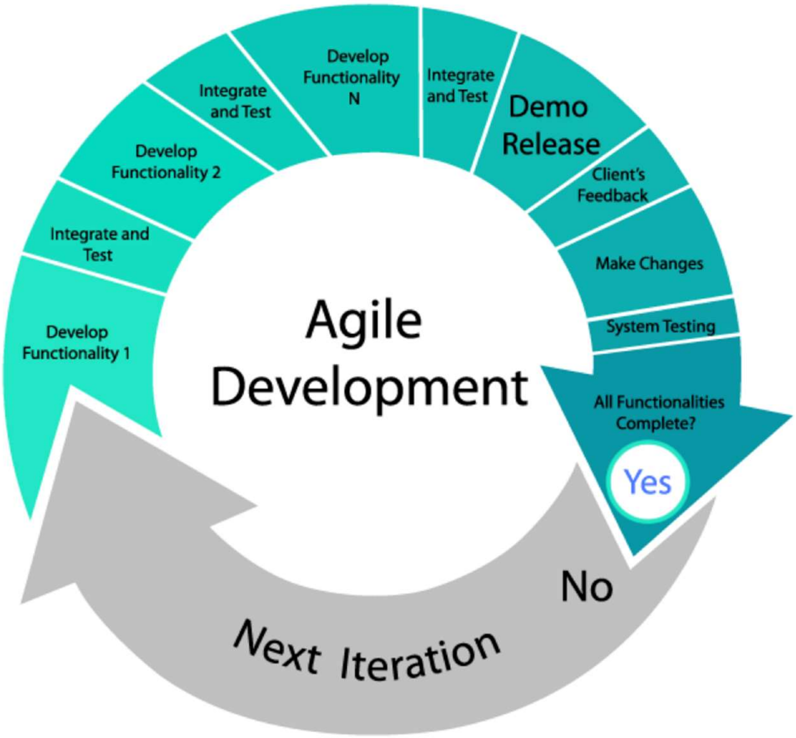


Figure 5-9: Agile model for system development

5.4.3.4 Case Studies

The case study method gives the researcher the chance to closely explore and examine contemporary phenomena in their natural context (Runeson and Höst, 2009, Zainal, 2007). Yin (2013) defines the case study research method "*as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used*." There are several advantages in conducting research using the case study method. Firstly, the examination of the data is usually carried out based on the context of its use (Yin, 2013). Secondly, the detailed examination conducted in case studies not only helps to explore or describe the data in a real-life environment, it also supports exploration and explanation of the complexities of real-life situations which may not be captured through experimental or qualitative research (Benbasat et al., 1987). Therefore, this method is suitable for the exploration, classification and hypothesis development and/or validation stages of the knowledge-building process. Also, it may be suitable for effective validation for research where phenomena are not supported by a strong theoretical base (Benbasat et al., 1987).

The case study method has different classifications in the literature (Zainal, 2007, Runeson and Höst, 2009). McDonough and McDonough (2014) classified case studies into two main categories, namely interpretive and evaluative case studies. In interpretive case studies, the researcher aims to interpret the data and increase his/her understanding of the phenomena by developing conceptual categories, supporting or challenging the assumptions made regarding them, while in evaluative case studies, the researcher add his/her opinion to the phenomena found in the data.

Conversely, Yin (2013) classified case studies into three categories, namely exploratory, descriptive and explanatory case studies. Exploratory case studies set out to explore any phenomenon in the data which serves the researcher's interest, while descriptive case studies set out to describe the natural phenomena which occur within the data in question. Finally, explanatory case studies set out to examine the data closely to explain/validate the phenomena in the data. Robson's (2002) classification added one more category named improvement case studies. Improvement case studies set out to improve certain aspects in the studied phenomena.

5.4.3.5 Justification of chosen research methods

The research aim concerns a generic practical problem across the construction industry, and the design of its solution is created within specific organisational contexts and relies on social actors to be effective. Based on this scenario, qualitative data collection methods such as semi-structured interviews and focus groups were adopted to serve as appropriate tools for the research. A prototyping approach is used for developing the prototype system, while a case study method is used for evaluating the developed concepts and prototype. These methods are the most suitable to answer the research questions; also, they are in line with the pragmatist, epistemological standpoint adopted in this research.

Semi-structured interviews were undertaken with participants solicited from the official website of a BIM proponent (BIM Task Group), list from the BIFM (British Institute of Facilities Management) membership page, asset managers and asset management software websites. Also, the researcher utilised a snowballing sampling approach where he asked initial participants if they were willing to refer other experts for participation in the research and asked them to pass on his contact details to these potential participants. Formal requests for interview were made via email and LinkedIn messages, using contact information publically available, referral through official channels, and by personal request. The selection criteria comprised:

- Professional members in a LinkedIn group site, BIM4FM, British Institute of Facility Management (BIFM), Building Services Research and Information Association (BSRIA), BIM Experts and university academics in the UK.
- A construction organisation which incorporates BIM-compliant project in the UK.
- BIM and AM experts in world-class BIM projects.

Seven semi-structured interviews were conducted to guide the researcher to collect primary data through the structured questions, while the open questions enabled the researcher to deepen the investigation into particular subjects judged essential to understand. The interviews lasted from 60 to 90 minutes and were recorded as digital audio files, which were transcribed into text format. The interview template included three main questions related to the implementation of BIM in AM approaches, the required information to transfer from BIM to AM platforms and, finally, the cross-mapping between the different AECO standards and guidelines. The interview templates were sent to the interviewees a week before the interviews to give them enough time to prepare their answers.

Focus groups were undertaken with experts in BIM and FM applications. Participatns were recruited from BIM and FM consultancy companies, and were selected by the relevant head of department. The consultants were identified via a review of available world-class consultants and existing professional networks such as LinkedIn. Also, the researcher used a snowballing sampling approach, as mentioned earlier, where he asked semi-structured interview participants if they were willing to refer their company or even other consultants for participation in the research, and asked to pass on the researcher's contact details to these potential entities. The selection criteria comprised:

- At least five years of experience in construction and BIM and/or FM applications.

- Expert in Revit – BIM and/or FM applications.

Two focus groups were conducted, and each lasted from 90 to 120 minutes. The first focus group with eight BIM experts was conducted to evaluate and validate the developed taxonomy, and another focus group with 10 BIM and FM experts was conducted to evaluate the developed ontologies and cross-mapping of standards. Table 5-2 summarised the information related to the participants in both the interviews and focus groups.

Table 5-2: Interviews and Focus Groups Participant Information

Position	**Number of participants**	**Years of Experience**	**Area of Experience**	**Interview**	**Focus Group 1**	**Focus Group 2**
Facility Manager	4	> 20 years	FM	Yes	-	Yes
Asset Data Manager	1	> 20 years	FM	Yes	-	Yes
Information Manager	2	> 20 years	BIM	Yes	-	Yes
BIM Managers	2	> 10 years	BIM – Construction	-	Yes	Yes
Mechanical Engineers	3	> 5 years	BIM – Design	-	Yes	-
Electrical Engineers	3	> 5 years	BIM – Design	-	Yes	-
Project Manager	1	> 20 years	Construction	-	-	Yes

Semi-structured interviews were the first data collection methods conducted in the research. A flexible qualitative analysis method was required which could allow the researcher to start the analysis based on data obtained from previous relevant research and from the researcher’s own experience, and sort out the collected data into existing themes or create new themes (Grbich, 2012). As thematic analysis is a flexible method, it was selected for analysing the data collected in this research from the semi-structured interview stage, while the date conducted from the focus groups stage was analysed using content analysis. In focus groups, the data from the interaction of the participants has to be analysed, even though it may be disorganised at the beginning. Content analysis can code the different perspectives of the participants into categories, which will simultaneously quantify the coded information (Kvale and Brinkmann, 2009). On top of that, the developed coding systems would clearly provide a better understanding of how the expertise/previous experience affects their inputs.

Based on the different qualitative data collection in this study, several frameworks, classifications and taxonomies were developed. Figure 5-10 illustrates several constructs developed in this research related to the classifications of the assets that consume energy and the required information to be exchanged from the building information models to AM platforms. Also, it represents the different processes to exchange the required information and the tools required in each platform to collect, transform and exchange the information from the BIM platforms to AM platforms. Consequently, these built conceptual models (human usage) acted as the foundations for the computer modelling (computer usage) of the developed prototype. Finally, in this research, the case studies method is used as explanatory where it tests, validates whether the framework, classifications, taxonomies and models developed actually work in the real case study, and finally improves the developed constructs.

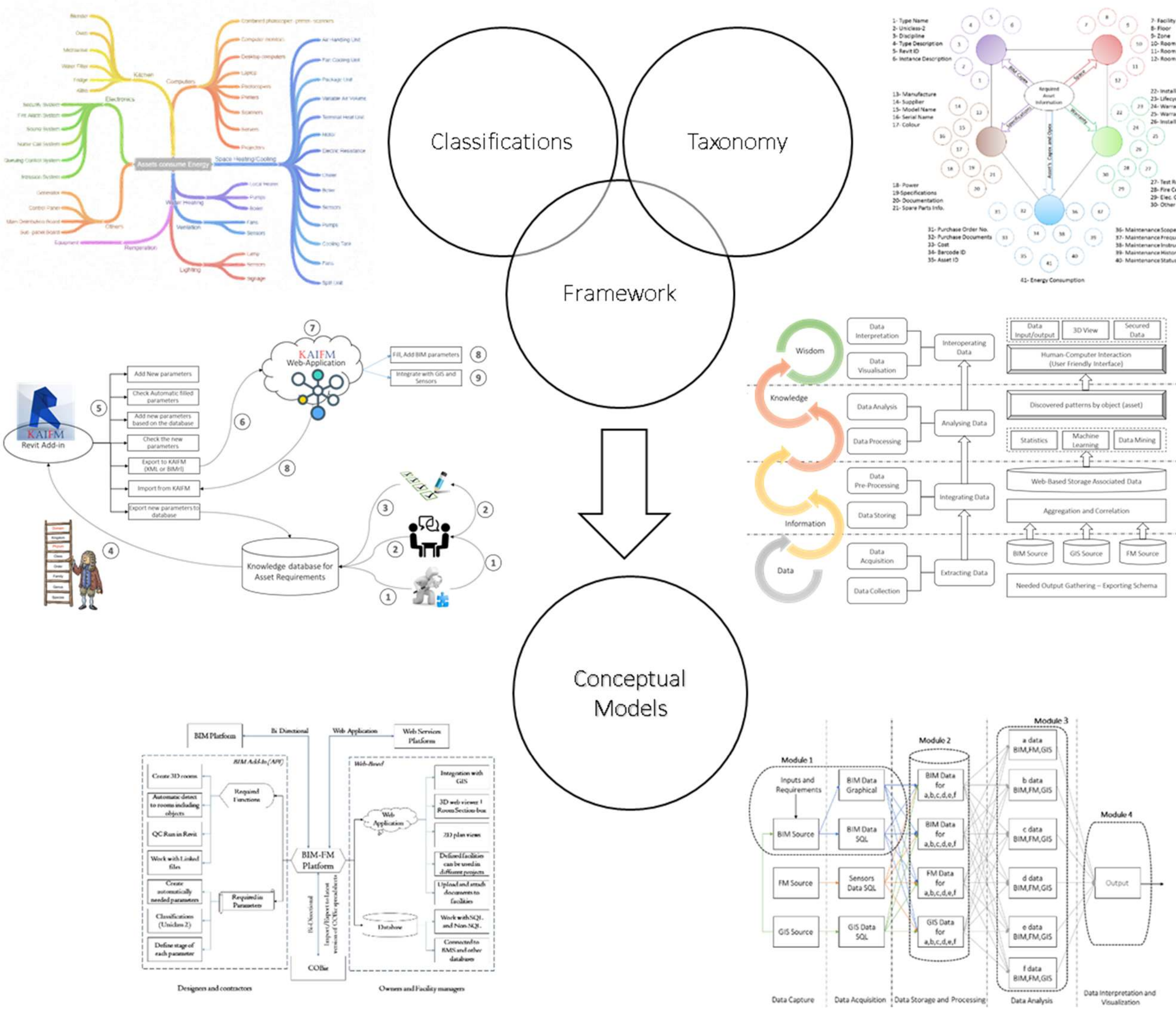


Figure 5-10: Conceptual modelling and its construct for the research development

5.5 Chapter Summary

This chapter has comprehensively provided the research methodology and methods applied within this study, which was undertaken from a pragmatism epistemology perspective and a mixed ontological position. Bearing in mind the aim of the research and the nature of the problem, different research approaches, methods and tools are utilised to achieve all the research objectives. Qualitative data collection methods such as semi-structured interviews and focus groups were adopted to serve as appropriate tools for the research. A prototyping approach was used to develop the prototype system, while a case study method was used to evaluate the developed concepts and prototype.

Chapter 6 Research Design

6.1 Introduction

Research is a journey towards an endpoint – to develop new knowledge that will contribute to practice – and the journey needs a theoretical map which can provide guidance. Research design is the map for the research process; it is a process map which presents the amalgamation of different research methods and techniques within an overall sequence of actions that enables the research aims and objectives to be successfully achieved.

This chapter presents the research design of this study, as illustrated in Figure 6-1. The four main phases are discussed at length in the following sub-sections and the chapter ends with a summary of the research process and selected research methods and techniques.

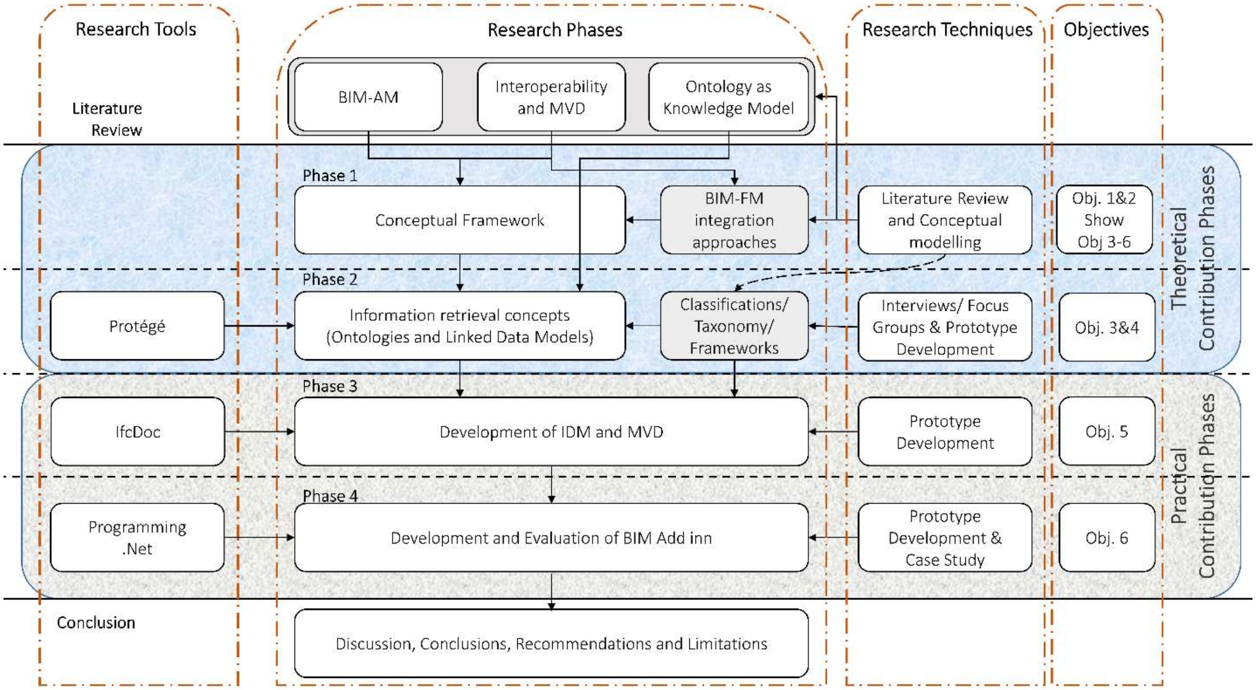


Figure 6-1: Research Design of the study

6.2 Phase 1: Conceptual Framework

The conceptual framework is a logically structured representation of the concepts, variables and relationships involved in a piece of scientific research with the purpose of clearly identifying what will be explored, measured or described. Imenda (2014) argues that there is a difference between theoretical and conceptual framework based on the research approach and data collection techniques. As the research is based on qualitative dominant mixed methods, a conceptual framework is a more suitable expression for this research's objectives (sub-section 5.4.2.3). A conceptual framework is constructed not found, it is built from integrating and combining paradigms, theories and concepts with the research goals and objectives. The main sources of these sets of information are: i) previous research ii) applicable theories, iii) the researcher's own experience knowledge (Maxwell, 2008). These are discussed below.

i. Previous research includes academic research, previous case studies and available platforms for BIM/FM interoperability. This review covered the challenges in the integration between BIM and AM, the different approaches for integrating BIM and AM data and the challenges in each approach. These main reviews guided the researcher in identifying the main aspects that need to be covered to govern interoperability between BIM and AM.

ii. Several existing theories and concepts can offer clear insight into how to achieve the research aims and objectives. The research initially considered five applicable theories/concepts to guide the research: scientific management theory, system thinking, system theory, contingency approach and management performance concept. Scientific management theory critiques that all work processes could be analysed into discrete tasks and that, by using a scientific method, it is possible to find the one most efficient way to perform each task. A system-thinking approach focuses on how the things being studied interact with the other elements in the system. In other words, it does not isolate the elements of the system while studying a specific element. A system theory highlights the complexity of the interdependent components of organisations within equally complex environments (Caldwell, 2012). A contingency approach builds on the diagnostic qualities of the systems approach in order to determine the most appropriate system design and management style for a given set of circumstances (Zhu, 2002). Finally, management performance is concerned with the quality of management. These theories/concepts can guide the research in analysing the integration of BIM and AM and developing a conceptual framework for implementation of BIM in AM practice. For developing the practicable tools, software engineering and information retrieval theories were adapted and are discussed in sub-section 5.4.3.3.

iii. The researcher's BIM experience has played a role in the development of the conceptual framework. Although there is a possibility of bias, Maxwell (2008) argued that, if the researcher uses his/her experience in his/her research, it can provide him/her with a major source of insights, hypotheses and validity checks. In this research, the research used his experience with a critical subjectivity. Critical subjectivity is defined as the quality of awareness in which the researcher does not suppress his/her primary experience; rather, the researcher brings it to the forefront of his/her consciousness and uses it as part of the enquiry process (Louis and Barton, 2002). Finally, thought experiments are inspired by theory and experience to generate a logical creative representation for various data and aspects in a specific field of study (Maxwell, 2008).

The integration of the findings from the previous research, the applicable theories and the researcher's experience in BIM, AM and the interoperability field led to the development of the ACE-IM conceptual framework.

6.2.1 ACE-IM Conceptual Framework

Due to the heterogeneity of the assets and buildings, the required information cannot be generalised for all assets or even by the asset system (Cavka et al., 2017). However, a taxonomy of the required information can be developed for assets based on their functionality in certain building types (Farghaly et al., 2018). Asset management frameworks should be in place to improve the energy performance of buildings (Ruparathna et al., 2016). Zadeh et al. (2017) stated that three different AM aspects can improve the building energy performance and reduce energy consumption, i.e. early decision-making for sustainability, timely maintenance and accurate occupant operations. Cavka et al. (2017) stated that developing a conceptual framework that identifies the owner's requirements and links them with the digital and physical products can improve the asset management performance in general and sustainability in particular. Due to the increasing emphasis on providing a sustainable performance during a building's lifecycle, the research concentrates on assets which consume energy. Additionally, the research concentrates on a case study for a university. The selection of a university, education buildings in general, is because the total energy use within such buildings in the UK in 2017 exceeds 11% of the UK's energy use.

The considerations and suggestions in Chapter 2, Chapter 3 and Chapter 4 provide the basis for the development of a new Asset Consuming Energy Information Management (ACE-IM) framework. The five main key aspects can be classified according to two dimensions (Figure 6-2). The first dimension (y-axis) is referred to as the endogenous/exogenous dimension. This dimension concerns if the aspects are achieved in the BIM environment or not. The second dimension (x-axis) is referred to as the theoretical/practical dimension. This dimension concerns if the aspects is more theoretical and related to the development of conceptual constructs or more practical and related to the development of prototype and plug-in. Using the above-mentioned classifications, the ACE-IM framework consists of five main aspects, as follows:

i. A taxonomy for the required data for each asset and its responsible stakeholders.
ii. A Linked Data generation between all the different standards and classifications.
iii. A well-structured MVD for storing and integrating BIM data with external assets' data.
iv. A model for extracting the required data with appropriate classification for each asset.

v. Validation using a case study in which the BIM model includes the required information and the MVD concepts.

The first two aspects are related to semantic interoperability; the related concepts are discussed in Chapter 4 and their applications for the research aim are presented in Chapter 7. The other three aspects are related to syntactic interoperability; the related concepts are discussed in Chapter 3 and their applications for the research aim are presented in Chapter 8. The following sub-section presents the second phase for developing the different aspects represented in the framework.

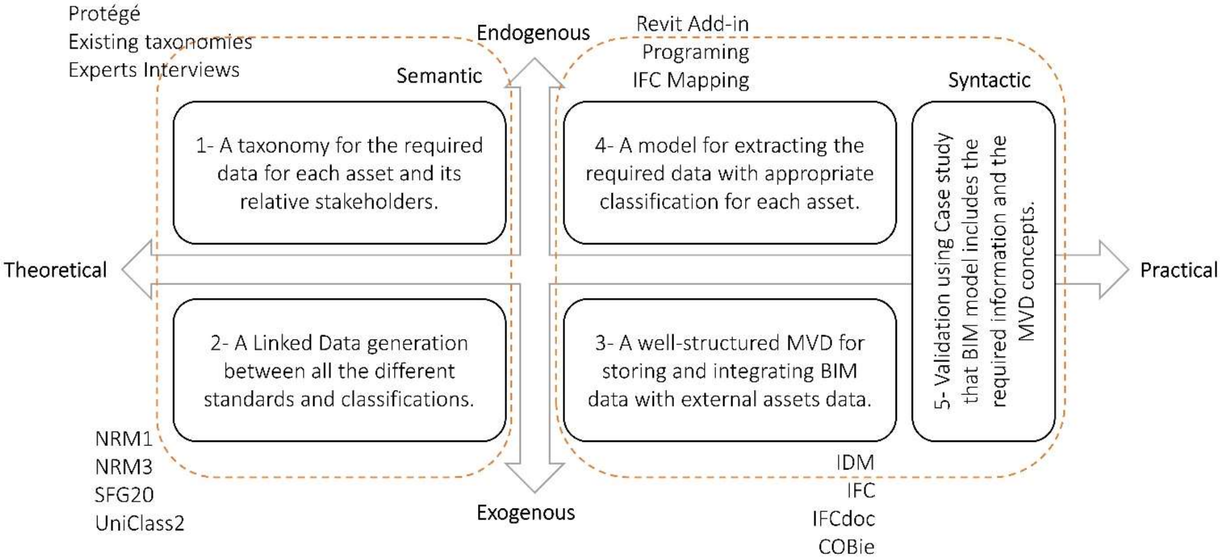


Figure 6-2: ACEie conceptual framework including the utilised tools and standards

6.3 Phase 2: Conceptual Modelling

The conceptual framework created in phase 1 is a logically structured representation of the concepts, variables and relationships involved in achieving a successful interoperability between BIM and AM. However, this framework needs to be expanded by adding new – or refining existing – interrelated nodes (constructs): ontologies, taxonomies, classifications and models. These constructs are developed in this phase. Two main constructs are developed in this stage, namely: the taxonomy of the required information for AM from the BIM models and the cross-linking of the different AECO ontological sources.

6.3.1 Taxonomy of Required Information Development

The taxonomy of the information that has to be exchanged from the BIM models to AM platforms is developed by utilising and synthesising different research methods including a literature review, semi-structured interviews and a focus group (sub-section 5.4.3.5). An iterative approach of four main steps proposed by Cavka et al. (2017), to understand the owner's requirements, and identify the required information and how it relates to BIM, is adopted in this stage. First, an extensive review of the current academic literature, three project documents, international reports and practice guidelines and standards is carried out focusing on the recommended/proposed non-geometric asset data extracted from BIM models for AM. Also, a set of existent case studies are used as exemplars to indicate which BIM information is utilised for AM. The case studies are purposely selected in order to guarantee industry engagement in the reviewed literature.

Subsequently, seven semi-structured interviews are conducted with four facility managers, an asset data manager and two information managers who are involved in the decision to adopt BIM for FM in their companies. Jette et al. (2003) suggested that proficiency in the chosen topic can reduce the number of participants needed in a study. The selected interviewees have more than 20 years of experience in the construction and/or asset management industry and have each delivered at least five BIM projects.

Therefore, the number of interviewees does not represent the actual sampling as each interviewee's input is based on participating in several projects. The interviewees are asked to comment on the research's main questions; however, they are free to elaborate on AM challenges as they experienced these in their projects. The interviews are aimed at confirming and clarifying the required asset data from BIM identified by the literature review. Based on the findings from the literature and the semi-structured interviews, a thematic analysis is carried out using an appropriate coding scheme in order to develop and classify the taxonomy of the BIM parameters required. After the seventh interview, it was found that the taxonomy had reached saturation point.

To validate the saturation achieved, Fusch and Ness (2015) suggested that a focus group is one way to provoke a number of perspectives on a given topic to reach data saturation. They added that a focus group is also an appropriate approach after interviews with a small number of participants for validation of data saturation. Consequently, a focus group with eight BIM experts was conducted to evaluate and validate the developed taxonomy, and link it to Revit, one of the most popular BIM platforms. The developed taxonomy is presented in sub-section 7.2.2.

6.3.2 Ontology and Linked Data Development

There are several methodologies for developing ontologies; each methodology has its pros and cons and usually it consists of an iterative process. For the development of ontologies and the linkage between the different ontological sources in this research, a process of six main steps is adapted based on the process suggested by Villazon-Terrazas et al. (2012) . Each step in the development process requires different research methods to enrich the ontologies with the required information (Figure 6-3).

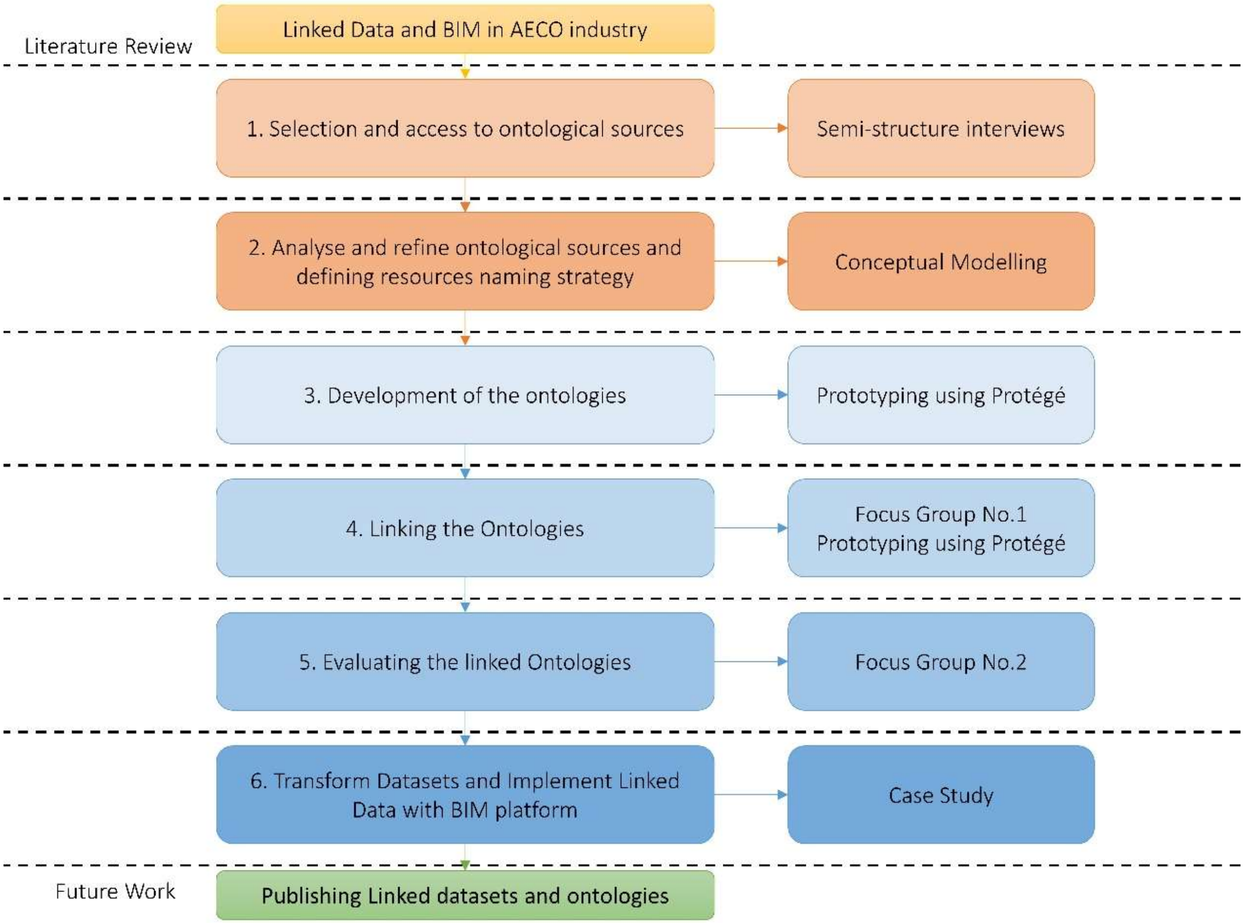


Figure 6-3: The process for developing and linking ontologies

The first step includes the engagement of experts to identify the required standards for the mapping of different domains. The same seven semi-structured interviews conducted for the taxonomy were utilised for that purpose. The ontological sources were identified and accessed which are : NRM 1 & 3, Uniclass2, SFG20, Industry Foundation Classes (IFC) and, finally, Revit as a BIM Platform.

Step two requires analysing and refining the ontological sources to be suitable for the research scope. Ontologies has been adapted to build the required datasets. The main sources of the developed ontologies are previous research, applicable theories, and the researcher’s own experience knowledge (Maxwell, 2008). Step three has been achieved through prototyping, which is an approach from Software

Development Methodology (SDM). The prototype model is selected as the approach in this research as it is a top-down, iterative approach that continues until the user's requirements are accomplished. In this stage, Protégé is utilised as the ontology editor tool. Protégé is freely available to use, is implemented in JAVA and contains a large library of plug-ins to enhance its capabilities. Also, Protégé is the ontology editor tool for several of the available ontologies used in this research.

The fourth step includes the involvement of experts in the domain to define the link between classes in different ontologies. Cross-domain integration of assets' data and data from building information models is relatively new and there is insufficient information around that topic. Therefore, focus groups were conducted in this stage as the qualitative data collection method. Focus groups allow the participants to interact to agree on the data collected and also to disagree and refine it, to improve the developed datasets. This interaction between participants may produce spontaneous responses and more cognitive views. The focus group was conducted with 10 experts in the construction and/or operation industry (more details are provided in sub-section 5.4.3.5). The focus group started with a high level of involvement from the researcher, by giving an introduction to the different classifications for the building assets and a brief introduction to Linked Data and ontologies. The first question was then asked, leading to an unstructured discussion about the potential answers. During the discussion, the researcher's level of involvement was low, then moved to high by concluding the discussion and then moving to the next question.

After the researcher had analysed the outcomes of the first focus group, in the fifth step a second focus group was conducted with the same participants as in the first focus group. The second focus group was required to evaluate and validate the mapping developed between all the different ontologies for each individual asset that consumes energy during the development of ontologies stage. The researcher showed the developed mapping between the different standards for each asset and consequently the participants interacted to agree/disagree/refine the developed mapping. The focus group's discussion was on whether the abstracted concepts and relationships were precise and accurate or not. Finally, a case study was conducted for a new extension of an educational building in phase six to evaluate the implementation of the proposed mapping between the different ontological sources.

6.4 Phase 3: MVD Development

One of the main research objectives is to develop an MVD to facilitate the integration of BIM and AM data for assets that consume energy. However, the intent of this research is not only to create an MVD, it is also to test and demonstrate the implementation of the models and ontologies developed in phase 2 of this research (phase 4). The National BIM Standard (NBIMS) process has been adapted as a research process map for achieving the research objectives 5 and 6.

Figure 6-4 illustrates the four main stages for the development of the IDM/MVD, their inputs, outputs and tools. The first stage provides the overall requirements specification for data exchange through the engagement of experts with a background in BIM and AM. The context is defined through two main deliverables, process maps and exchange requirements, which together form the IDM. This step utilised the same focus group that was conducted to develop the ontology. The focus group concentrated on the implementation of BIM to effectively manage assets that consume energy for existing buildings and their new extensions, particularly buildings in the education sector. During the focus group, existing work and studies were considered for reuse, especially the IDM/MVD of SPARKie and Level of Development (LOD) guide 2017 part 2, as they can form a solid baseline for the newly developed MVD.

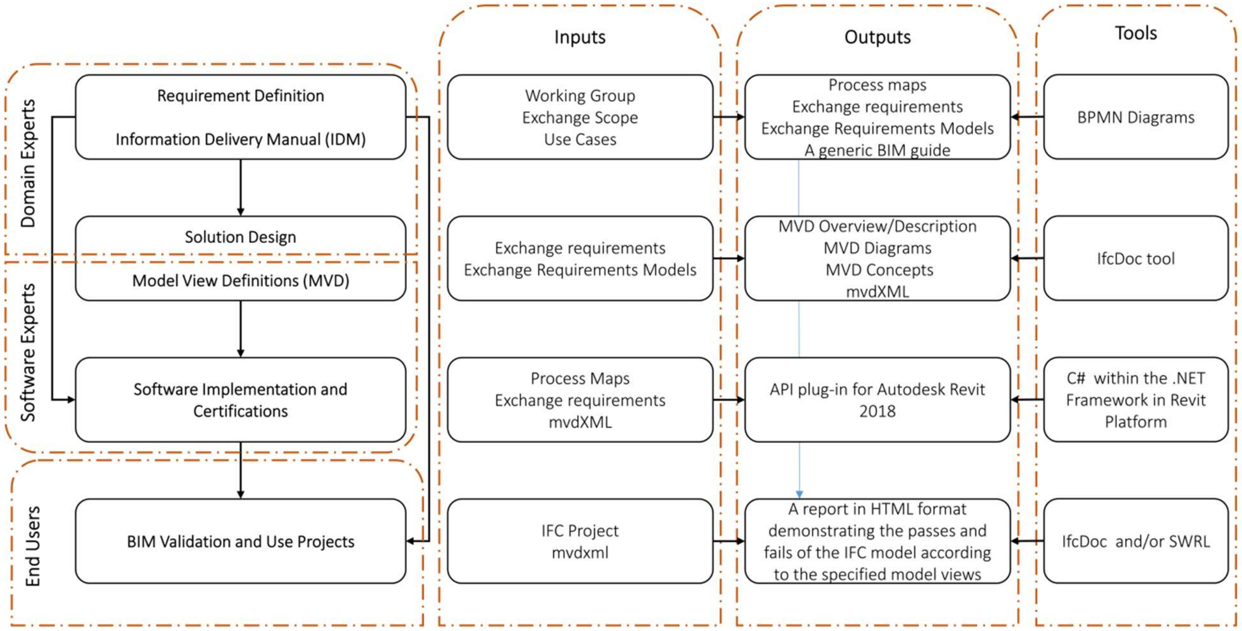


Figure 6-4: Overview of the IDM/MVD development process, its outputs and tools

The second stage delivers the MVD through mapping the different concepts obtained from the Exchange Requirement Models (ERM) diagrams with the IFC schema. MVD development is much more technical work that requires experience in MVD software development tools, standards and practices such as IfcDoc, IFC schema, construction industry and data modelling. Based on the results of the comparative study by Zhang et al. (2015), the mvdXML development method is the only open standard and can be developed by the official IfcDoc tool as well as common XML editors (Chipman et al., 2012). Also, it provides the ability to generate validation rules where the extracted models can be validated against the developed MVD. Therefore, it emerged that the mvdXML is the most appropriate approach to develop the proposed MVD. The third and fourth stages of the NBIMS process are discussed in phase 4 of the research design.

6.5 Phase 4: Prototype Development and Evaluation

In this phase, the software development methodology, technologies and coding languages for prototype development are selected. The selection of the software development methodology is based on the comparison between the different SDM frameworks and models illustrated in sub-section 3.3.3.3. The aim of this stage is to select the most appropriate method to develop the tools for exchanging information from the building information models to AM platforms. A prototyping model with incremental perspective aspects was chosen for designing and creating the research prototype. Since the development of the proposed software systems requires clients/experts' acceptance, prototyping is appropriate for this study. Also, the prototyping approach can be employed to test the frameworks and models created in this research, while the reason for choosing prototyping for the incremental perception is to divide the prototype into three different prototypes based on the objective of each prototype (extracting data prototype, storing and analysing data prototype, and visualising data prototype). API, C# language and Microsoft Visual Studio were used in developing the plug-in implemented in the Revit platform. Revit 2019 is the version utilised in the research as it was the latest version at the time the research was conducted.

The evaluation of a piece of research denotes the trustworthiness of the results, to what extent the results are accurate and not biased by the researcher's subjective point of view (Runeson and Höst, 2009). Therefore, the evaluation of the research outputs and the developed prototype was conducted by demonstrating the functions of the developed prototype using an educational building as a case study. The outcomes of this stage are used to improve and polish the developed taxonomy, ontologies and MVD in stages 2 and 3. Also, it has helped to provide guidance for further improvements in the developed system.

6.6 Chapter Summary

This chapter presented the research design of this thesis including the different stages and utilised research methods and techniques. The process began by exploring the theory and practice of BIM implementation in asset management, identifying challenges and gaps in the FM sector, and considering the role of MVD in syntactic interoperability and 'ontology as a knowledge model' in semantic interoperability. The theoretical contribution of this research takes place in phases 1 and 2 (Chapter 7), while the practical contribution occurs in phases 3 and 4 (Chapter 8). Finally, the discussion (Chapter 9) and conclusions (Chapter 10) are drawn based on the research results and further recommendations are framed, and the limitations of the research are identified.

Chapter 7 Semantic Interoperability Solution

7.1 Introduction

This chapter presents the two different outcomes of semantic interoperability (shown in the ACEie Framework – Figure 6-2) for effective implementation of BIM in AM. It starts by presenting the development of taxonomy for the required information from the building information models for effective AM. Next, it illustrates the process of providing object-oriented cross-domain linking to enhance the BIM-AM integration through Linked Data. Finally, the semantic outputs are summarised.

7.2 Taxonomy Development

7.2.1 Related Taxonomies

Most studies in BIM implementation in FM have largely focused on geometric data requirements (Pishdad-Bozorgi et al., 2018). However, there is an urgent need to concentrate on identifying the non-geometric requirements as well in order to support successful implementation (Becerik-Gerber et al., 2012). Becerik-Gerber et al. (2012) identified the required information to be exchanged in a pyramidal classification from the early stages down to the operation and maintenance. Wang et al. (2013) proposed the structure of a BIM database for FM in the early engagement of AM in the design stage. This database of equipment and systems was divided into two categories: attributes and data, which includes information related to vendor, location, etc.; and portfolios and documents, which includes information related to specifications, manuals, certificates, etc. Hunt (2011) proposed another hierarchical classification in the closeout and handover stage with two main levels: first, description system level with sub-levels related to location, manufacture information, vendor, ID name and number; and, second, technical content level with sub-levels related to warranties, maintenance instructions, etc. Mayo and Issa (2015) refined these taxonomies further through conducting a Delphi survey with 21 FM experts. They classified the required data based on FM applications. For example, they proposed four main types of data required for building AM: asset location, asset purchase information, barcode information and asset identifier. Patacas et al. (2015) identified a list of data to be extracted from the BIM models based on the requirements of asset register creation and service life planning.

COBie can also be considered as a taxonomy of information required for AM. COBie classifies the data into 10 main categories: facility (project, site and building/structure information), floor (the mandatory spatial structure), space (the spatial locations where inspection, maintenance and operation jobs occur), zone (additional functional groupings of locations), type (mandatory grouping of components as types or products, used to organise maintenance tasks), component (the physical assets), system (additional functional groupings of components), spare (the physical objects), job (the processes and tasks used to maintain and operate the assets) and resources (support the processes and the tasks). COBie UK 2012 has been extended to include two more categories: cost and carbon (Spilling, 2016). COBie is a repetitive process with four defined ‘data drops’ taking place at crucial stages of the project lifecycle to capture the available and required data for AM (East and Carrasquillo-Mangual, 2013). Pishdad-Bozorgi (2018) selected only 18 attributes as the data required to be exchanged during the handover for an educational building and these attributes were mapped to COBie’s tabs and columns. In a £185m new-build prison project in the UK, the Ministry of Justice created a set of Plain Language Questions (PLQs) to be combined with COBie data for handing over a series of asset schedules at the end of the project. These include lists of building services equipment such as plant, air handling units, pumps, fans, and fixtures and fittings, all of which are asset tagged within the model (Cousins, 2015).

On the other hand, the information that needs to be exchanged for better asset management is identified in guidelines and project documents. Several projects have identified specific information that needs to be exchanged from the models to AM platforms during the handover stage. For example, the Sydney Opera House (SOH) project was one of the first projects to implement BIM for FM. Due to the long design life of the SOH and its complexity, the engagement of BIM was mandatory in order to provide open interoperability and serve as a data management pool (Schevers et al., 2007). In the SOH Model Management Plan (MMP) document, 36 parameters were identified as the required data from BIM models for AM. According to the building information manager of the SOH, the MMP is a live document which is revised and updated from time to time to achieve successful AM. The identified required data is classified into six main categories: 1) BIM4FM including the capex data related to the assets from the design and construction stage, 2) element details suggesting the location and unique details for each asset, 3) element specification, 4) warranty, 5) certifications and 6) asset control.

Another project where BIM has been implemented for AM is the Manchester City Hall (MCH). Before BIM implementation, the asset information in the CAFM system was inadequate and inaccurate, and thus was highly inefficient in terms of creating an onward maintenance plan. Therefore, BIM was implemented to create an AIM where NRM3 was selected as guidance for the asset taxonomy (Oluteye and Marjanovic-Halburd, 2015). NRM3 is an asset classification standard for structuring the cost data of assets relevant to the operation and maintenance phase of a facility (Green, 2014). The collected asset data included information related to asset location, maintenance history, operation history and costs.

The Doha Metro is another project where the researcher worked as a BIM manager. Doha Metro is a project in the capital of Qatar consisting of four lines and 37 stations. Qatar Rail, the owner of the project, published a document to stipulate the asset information requirements for the maintenance management system (MMS). Seven mandatory sets of information were identified as asset information requirements (AIR): item name and number, location, manufacture details, vendor details, price, installation date and warranty.

Further to the specific project developments described above, the consultancy Microdesk has also published a white paper named ‘Transitioning BIM Data to Asset Management’ (Broadbent, 2016). The paper identifies 72 critical parameters to be captured for asset and maintenance management. It also highlights that 62 of these parameters can be captured from the BIM model and can be categorised in seven main classifications: purchase information, facility information, asset specification, system specifications, maintenance procedures, manufacturer and vendor, and extended warranty. Generally, in the current on-going BIM projects, the required information is identified based on PLQs, educated experience and, sometimes, on assumptions regarding data that might be needed for better AM (Tune, 2017).

In the meantime, in the last couple of years, three leading construction bodies in the UK – the Building Engineering Services Association (BESA), the Construction Products Association (CPA) and the Chartered Institution of Building Services Engineers (CIBSE) – have been developing standardised product information for successful implementation of BIM in all the phases of AECO (Caplehorn, 2017).

CIBSE formed a working group and engaged industry experts to create standardised Product Data Templates (PDTs) under a project called BIMHawk.

Furthermore, CPA in cooperation with the BIM Task Group and the UK BIM Alliance are leading the development and implementation of LEXiCON, the plain language approach to product data definition and exchange in the UK. As part of this development, the key source of product information requirements comes from the Harmonised European Standards (hENs), standards requirements, industry recognised requirements, and client requirements (Thompson et al., 2016). The concept of LEXiCON is to create so-called Product DNA, i.e. information that stays with a product throughout its lifecycle. LEXiCON provides the governance to ensure the defined properties are the correct ones and are aligned with the BuildingSMART Data Dictionary (Caplehorn, 2017). In other words, LEXiCON will guarantee that the AECO industry has one common fixed PDT for each product type, including agreed parameters and their standardised naming convention, which is managed by the CPA and relevant trade associations (Small, 2017). the Building Engineering Services Association (BESA), the Construction Products Association (CPA) and the Chartered Institution of Building Services Engineers (CIBSE) have agreed on the respective roles of the 'LEXiCON' and 'BIMHawk' to avoid any confusion or even competition (Caplehorn, 2017).

The PDT is meant to be a standardised way through which manufacturer product attributes/parameters can be made available in machine-readable format during all the phases of the facility. Parallel efforts have been exerted by CIBSE, National Building Specification (NBS) and Norway coBuilder to create their own PDTs. CIBSE's PDT is an Excel spreadsheet with five columns. The first column defines the information category, which is divided into three sub-categories, i.e. specification, suitability and asset management. The second, third and fourth columns in the spreadsheet represent the parameter required to be defined, the value of the parameter, and the value unit respectively. Finally, the fifth column is for guide notes. It has to be noted that only the third (value) column needs to be completed as all the others are fixed for each asset. Once this data is added, the PDT becomes a Product Data Sheet. The total number of fields/parameters varies from PDT to PDT depending on the asset's functions and its manufacturer (Thompson et al., 2016). NBS produced its own PDTs as part of its BIM toolkit which contains more than 5700 consistently structured templates covering buildings and infrastructure that state the minimum product data requirements for Level 2 BIM. Norway coBuilder developed more than 700 PDTs based on IFC where the PDT parameters are aligned with the Construction Product Regulations (CPR) (Tune, 2017). Tune (2017), the CEO of coBuilder in the UK, suggested that coBuilder PDTSs are the only PDTs created based on European standards such as CEN/CENELEC standards and Environment Product Declaration, national standards such as classifications and object naming conventions and market requirements.

Based on the literature review, different classifications and long lists of diverse required information were formed. Based on the available lists, a preliminary taxonomy was developed to collate and consolidate results of the discussed studies. This also served as the groundwork for conducting the semi-structured interviews. In the following sub-section, 7.2.2, a taxonomy for the information required for management of assets that consume energy is developed.

7.2.2 Taxonomy Development

Developing a taxonomy of the objects of a knowledge field can provide a common terminology which improves the sharing of knowledge, helps in identifying the knowledge gaps in the field and supports decision-making (Usman et al., 2017). There are four main approaches to structure a classification schema: hierarchy, tree, paradigm and faceted analysis (Kwasnik, 1999). Hierarchy leads to taxonomies with a single top class and its sub-classes, i.e. a hierarchical relationship with inheritance. The tree approach is similar to hierarchy; however, there is no inheritance relationship between the classes of tree-based taxonomies. Kwasnik (1999) added that there is another type of tree approach in which the entities are related by the partitive relationship. This means that each class is divided into its components (part/whole relationship). The paradigm methodology leads to taxonomies with two-way hierarchical relationships between classes and the faceted analysis leads to taxonomies whose subject matters are classified using multiple perspectives (facets). The characteristics of the tree structure approach are the most suitable for developing the required taxonomy in this study.

The taxonomy was developed taking into consideration the taxonomy method developed by Bayona-Oré et al. (2014) and revised by Usman et al. (2017) and also the guide to creating ontology by Noy and McGuinness (2001). Usman et al.'s (2017) approach consists of four main stages: planning, identification and extraction, design and construction, and validation, as well as 13 different activities. On the other hand, Noy and McGuinness's (2001) method consists of four iterative steps, namely to: determine the domain and the scope of the taxonomy, consider reusing existing ontologies, define the class and the class hierarchy, and, finally, define the properties and slots of classes.

Armed with tree taxonomy approach and analysing different classifications and long lists of diverse parameters have been produced in literature, the top level could be classified into five main categories namely, space/location, BIM capex, specifications, warranty, and asset's capex and opex. While at the second level, forty parameters are presenting the required BIM data/parameters for asset management during handover stage. These forty parameters existed in more than two of the classifications in literature. That preliminary taxonomy was the foundation for the start of the interviews with the experts. The preliminary taxonomy was modified and updated based on the inputs from interviews conducted with the experts. The saturation of the proposed taxonomy was reached when it was found that no new codes occur in the data during the last two interviews. Although, there were mounting instances of the same codes, but no new ones were presented.

Figure 7-1 is a diagrammatic representation of the proposed taxonomy of the required data for successful implementation of BIM in AM. The taxonomy adopts a two-level tree structure with a top-down development process. The top level is classified into six main branches/classes: location/space, classifications, specifications, warranty, assets capex and maintenance. At the second level, 60 sub-classes represent the required BIM data/parameters for AM at the handover stage. These parameters can be collected in any of the following stages: planning and design, construction, commissioning, handover and closeout, and, finally, operation and maintenance. Further properties and slots are identified for these parameters in Table 7-1. The six top categories/classes are discussed below with their required parameters.

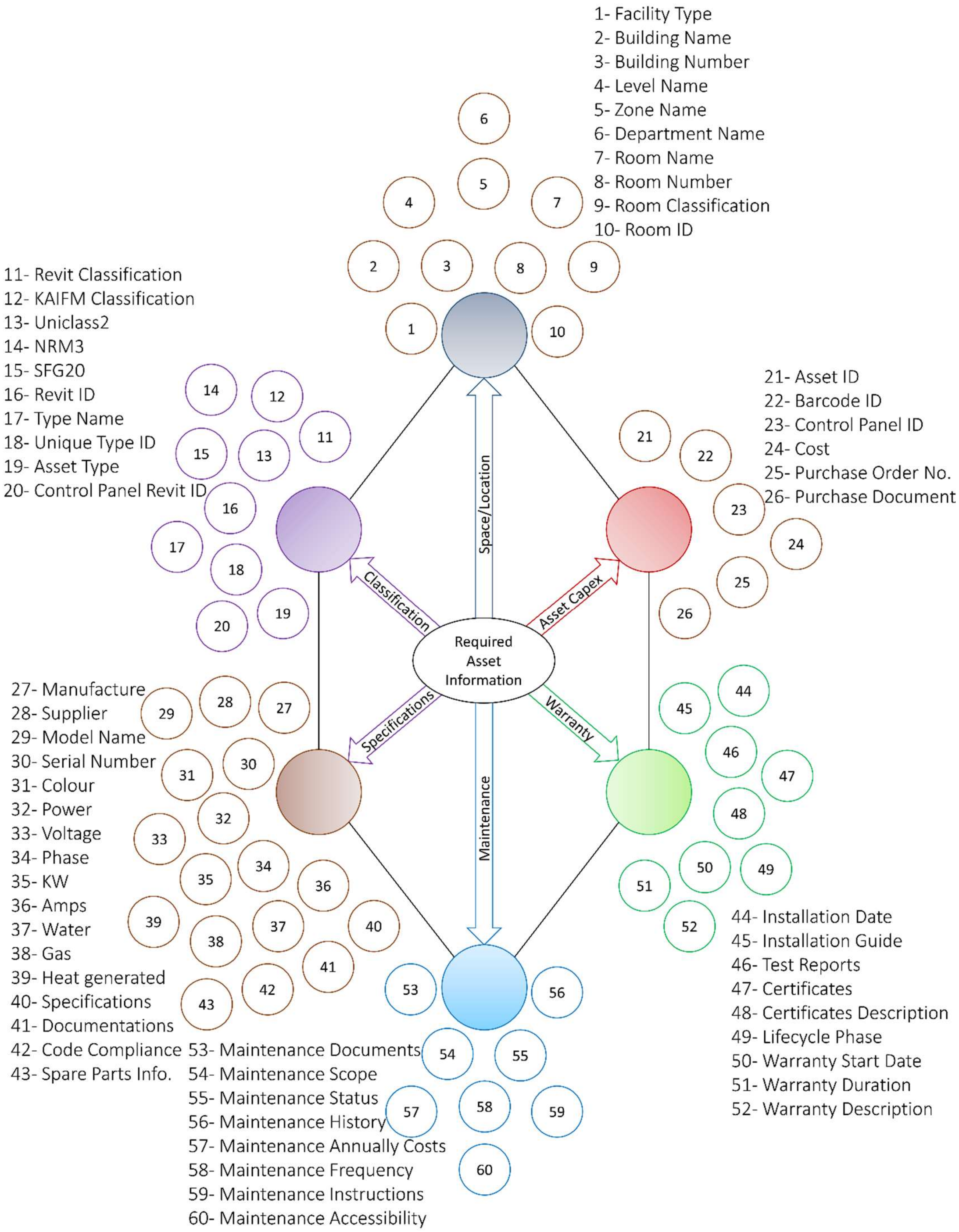


Figure 7-1: ACE-IM taxonomy for the information required for AM

Space/Location category includes 10 parameters: facility type, building name, building number, level name, zone name, department number, room name, room number, room classification and room ID. All of these parameters are related to the spatial location of the asset and they can be identified and captured from the architectural models during the design stage. All the space/location parameters are instance parameters, which differ for the same type of asset depending on location. However, the parameters facility type, building name and building number are related to the building and are required when the assets of clusters of buildings are managed and operated together. Some of these parameters and parameters in the other categories (such as NRM3, specifications and maintenance duration) must be added to the Revit model as a shared parameter as they are not available by default in the Revit platform.

Classification comprises the following parameters: Revit classification, ACE-IM Classification, Uniclass2, NRM3, SFG20, Revit ID, Type Name, Asset Type and Control Panel Revit ID. This category provides a common data classification from different perspectives. All of these parameters can also be collected during the design stage; however, some of them, such as NRM3 and SFG20, are usually collected in the operation stage. Revit Classification is the default classification for the mechanical and electrical Revit elements and is called system classification for mechanical objects. The ACE-IM classification parameter is developed based on the proposed classification of the assets that consume energy (Figure 7-2). The main classification is based on the classification of energy consumption proposed by Sadeghifam et al. (2013), while the elements were identified during the focus group work in collaboration with the BIM experts. The participants were asked to list all the different assets that they usually create in BIM models which consume energy and write each down under the relevant classification.

Uniclass2 is the new UK implementation of the international framework for construction information. Uniclass2 classification is not identified in the Revit database; however, it can be easily mapped to the elements in the building information models. The NRM3 provides the data structure to integrate construction with operation and maintenance. The NRM3 has only been published as a hard copy and a PDF format. During one of the interviews with a BIM manager, they criticised that the data of the NRM standard has to be added manually to the Revit platform. In PAS 1192 previously and in IS0 19560, uniclass2 is classified as the relevant BIM data classification for the design and construction stage, while NRM3 is classified for the operation and maintenance. SFG20 is another well-known standard for maintenance specifications in the UK. It is a web-based online application where the different maintenance tasks can be assigned to project assets. The SFG20 core library offers users more than 400 industry-standard maintenance specifications covering all principal types of heating, cooling and ventilation, installation, plant and electrical services, complete with regular technical updates. Although SFG20 is not specified in BIM guidelines, it can be easily figured out as it is aligned with NRM3. Revit ID and Control Panel Revit ID are unique identification information generated by Revit for the objects that need to be maintained and operated and for the control panel responsible for the objects that consume energy respectively. Type Name is the name assigned for the asset in the design stage, while asset type defines whether the asset is fixed or movable. Revit ID and Control Panel Revit ID are instance parameters, while the remaining ones are type parameters.

Asset Capex category includes six parameters, namely: Asset ID, Bar Code ID, Control Panel ID, cost, purchase order number and purchase documents. The Asset ID is the identification assigned to an asset that enables its differentiation from other assets. The Bar Code ID parameter identifies the bar code, or RFID, given to an occurrence of the product (per instance). The control panel ID is the identification assigned to a control panel by the asset managers enabling its differentiation from other control panels in order to control, manage and evaluate each control panel separately. The cost parameter indicates the purchase cost of the asset and its replacement cost. Purchase order number and purchase documents are two parameters related to the procurement of assets. Purchase order number is a unique number for each purchase for easier classification while the purchase documents parameter is a URL path for the document.

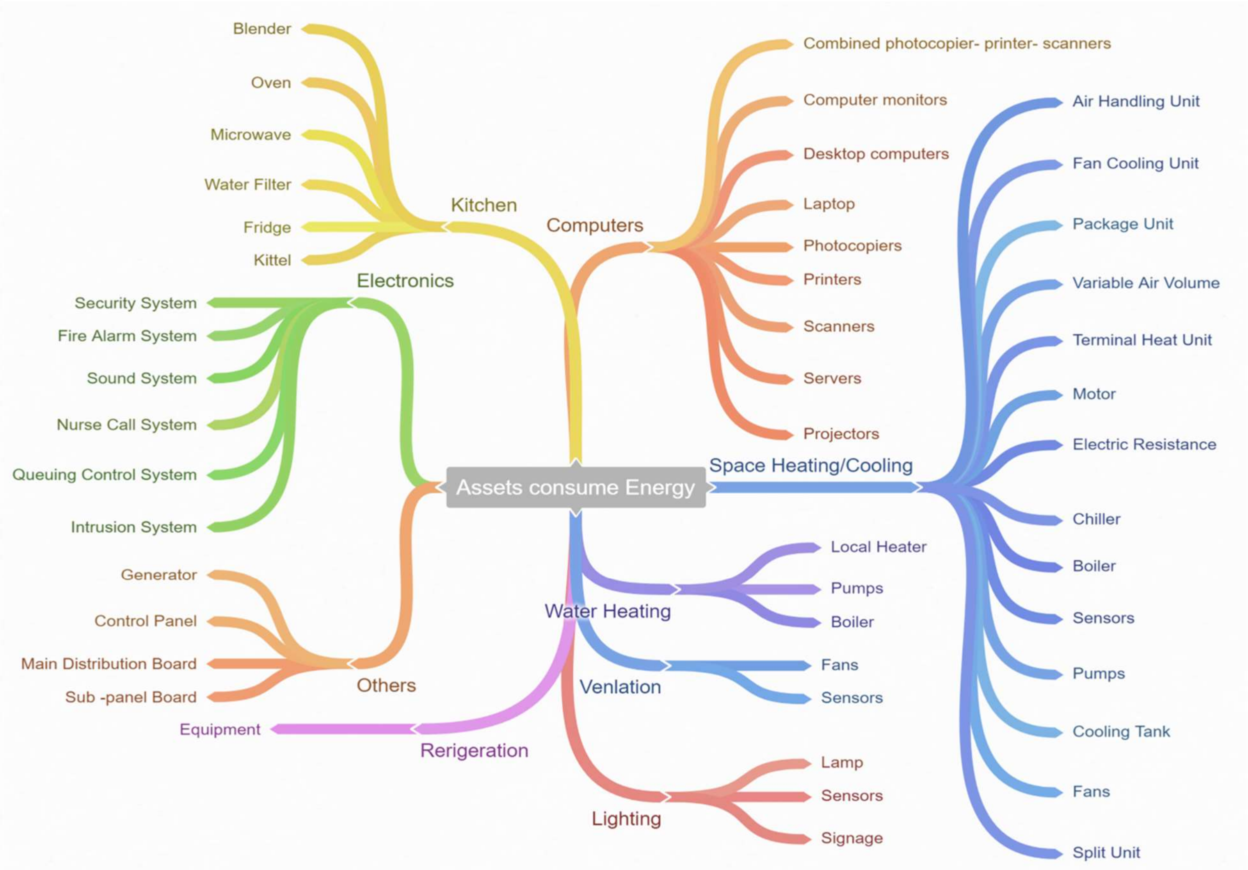


Figure 7-2: ACE-IM classification of the assets consume energy

Specification category comprises 17 parameters: manufacture, supplier, model name, serial name, colour, power, voltage, phase, kW, amps, water, gas, heat generated, specification, documentation, code compliance and spare parts document. These parameters are related to the specifications of the assets and all are type parameters, except the parameter serial name. This data can be collected during the commissioning and handover stage. The manufacture parameter includes the email address or the name of the organisation responsible for manufacturing the asset. The supplier parameter identifies the organisation responsible for delivering the asset. The model name is an asset label assigned by the manufacturer and usually its value is the same as the type name parameter. The serial name is the product, item or unit number assigned by the manufacturer of the asset. Colour is the characteristic or primary colour of the product/asset, while the insulation class provides basic protection information against electric shock. Voltage, phase, power (kW), current (amps), water, gas, and heat generated parameters state the energy properties for the asset. Specification, documentation and spare parts are URL value parameters for the documents stating the specification of the asset, any relative documentation and the spare parts' specifications respectively. Code compliance is a parameter where the object performance towards its compliance is defined.

Warranty category comprises nine parameters: installation date, installation guide, test reports, certificates, certificates description, lifecycle phase, warranty start date, warranty duration and warranty description. Installation data is the time when the manufactured item was installed and this parameter is an instance parameter. Installation guide is the documentation describing the installation procedures and techniques. Installation guide, test reports and certificates are URL value parameters for the installation and certification documents. Certificates description and warranty description are parameters summarising the available certificates and warranties for the asset respectively. Lifecycle phase states the expected life duration of an asset. Warranty start date is the date the warranty commences for an asset, and it usually has the same value as the installation date, while the warranty duration is the duration of warranties for individual asset parts. When some assets include different parts with different warranty durations, a new parameter is added which includes the URL for the document of the different warranty durations for the parts.

Finally, maintenance category consists of eight parameters: maintenance documents, maintenance scope, maintenance status, maintenance history, maintenance and operation annual costs, maintenance frequency, maintenance instructions and maintenance accessibility. Table 7-1 illustrates and summarises the 60 parameters, their category, their unit and type or instance, and the phase where the data can be collected. The parameter unit is the named ‘parameter type’ in the Revit platform and is responsible for identifying the nature of the parameter (alphanumeric, numeric, URL, integer, material or yes/no question). The non-graphical parameters in Revit can be divided into two kinds of predefined parameters: Type Parameter and Instance Parameter. Type parameters of an asset are the same for all occurrences of that asset. Parameters that have their own properties and are unique to their installation are categorised under the Instance Parameter type. However, as already mentioned, the predefined parameters do not include all the required parameters for the ACE-IM taxonomy and, as a result, new parameters are identified as such. Finally, the ACE-IM required information is extracted and collected at different stages of the building lifecycle as the COBie data drops. The four ACE-IM data drops are akin to the Royal Institute of British Architects (RIBA) Stages 4, 5, 6 and 7.

Table 7-1: ACE-IM Parameters for the required information for AM

Category	Parameter Name	Unit	Type/Instance	Defined New	Phase
Space/Location	Facility Type	Alphanumeric	Project	New/Write	1
	Building Name	Alphanumeric	Project	Available	1
	Building Number	Alphanumeric	Project	Available	1
	Level Name	Alphanumeric	Instance	New/Read	1
	Zone Name	Alphanumeric	Instance	New/Write	1or3
	Department Number	Alphanumeric	Instance	New/Write	1or3
	Room Name	Numeric	Instance	New/Read	1
	Room Number	Numeric	Instance	New/Read	1
	Room Classification	Alphanumeric	Instance	New/Write	1
	Room ID	Numeric	Instance	New/Read	1
Classification	Revit category	Alphanumeric	Type	Available	1
	KAFIM Classification	Alphanumeric	Type	New/Write	1
	Uniclass2	Alphanumeric	Type	New/Write	1
	NRM3	Alphanumeric	Type	New/Write	1or3
	SFG20	Alphanumeric	Type	New/Write	1or3
	Revit ID	Numeric	Instance	Available	1
	Type Name	Alphanumeric	Type	Available	1
	Unique Type ID	Alphanumeric	Type	New/Write	1

Category	Parameter Name	Unit	Type/Instance	Defined New	Phase
	Asset Type	Alphanumeric	Type	New/Write	1or3
	Control Panel Revit ID	Numeric	Instance	New/Read	1or2
Asset Capex	Asset ID	Alphanumeric	Instance	New/Write	3
	Barcode ID	Alphanumeric	Instance	New/Write	3
	Control Panel ID	Alphanumeric	Instance	New/Write	3
	Cost	Numeric	Type	Available	2or3
	Purchase Order No.	Alphanumeric	Instance	New/Write	2or3
	Purchase Documents	URL	Instance	New/Write	2or3
Specifications	Manufacture	Alphanumeric	Type	Available	2or3
	Supplier	Alphanumeric	Type	New/Write	2or3
	Model Name	Alphanumeric	Type	Available	2or3
	Serial Number	Alphanumeric	Instance	New/Write	2or3
	Colour	Alphanumeric	Type	New/Write	2or3
	Insulation class	Alphanumeric	Type	New/Write	2or3
	Voltage	Numeric	Type	New/Write	2or3
	Phase	Numeric	Type	New/Write	2or3
	Power - KW	Numeric	Type	New/Write	2or3
	Current - Amps	Numeric	Type	New/Write	2or3
	Water	Numeric	Type	New/Write	2or3

Category	Parameter Name	Unit	Type/Instance	Defined New	Phase
	Gas	Numeric	Type	New/Write	2or3
	Heat Generated	Numeric	Type	New/Write	2or3
	Specifications	URL	Type	New/Write	2or3
	Documentations	URL	Type	Available	2or3
	Code Compliance	Alphanumeric	Type	New/Write	2or3
	Spare Parts Info.	URL	Type	New/Write	2or3
Warranty	Installation Date	Numeric	Instance	New/Write	2
	Installation Guide	URL	Type	New/Write	2
	Test Reports	URL	Type	New/Write	2
	Certificates	URL	Type	New/Write	2
	Certificates Description	Alphanumeric	Type	New/Write	2
	Lifecycle Phase	Numeric	Type	New/Write	2
	Warranty Start Date	Numeric	Instance	New/Write	2
	Warranty Duration	Numeric	Type	New/Write	2
	Warranty Description	Alphanumeric	Type	New/Write	2
Maintenance	Documents	URL	Type	New/Write	2or3
	Scope	Alphanumeric	Type	New/Write	2or3
	Frequency	Numeric	Type	New/Write	2or3
	Annual Cost	Numeric	Instance	New/Write	4

Category	Parameter Name	Unit	Type/Instance	Defined New	Phase
	Instructions	Alphanumeric	Type	New/Write	2or3
	Status	Alphanumeric	Instance	New/Write	4
	History	Alphanumeric	Instance	New/Write	4
	Accessibly	Alphanumeric	Instance	New/Write	2or3

The development of taxonomy for the required information alone cannot provide effective integration between BIM and AM systems and databases. An ontology is required to cross-link building performance with other building information, and Linked Data offers a mechanism to facilitate meaningful sharing of cross-domain building information. Therefore, the next sub-section explains that providing object-oriented cross-domain linking with the required information can enhance the semantic interoperability between BIM and AM systems.

7.3 Linked Data Development

In Linked Data generation and publication, several general guidelines and best practices have already been developed, such as: the book by Health and Bizer (2011), the outcomes from the LOD project (Auer et al. 2014), the research paper by Bizer et al. (2009), and the adoptions of linking, metadata and vocabularies best practices in different domains by Schmachtenberg (2014). Although the guidelines and best practices have been developed taking into account the intensive engineering process of Linked Data generation and publication, it has been argued that these guidelines are often too high level, cannot provide a specific level of detail, and do not consider specific characteristics and related technologies of particular domains (Radulovic et al., 2015; Villazon-Terrazas et al., 2012).

The process consists of six main phases: specification, modelling, RDF generation, linking generation, publication and exploitation (Villazon-Terrazas et al., 2012). Figure 7-3 represents an overview of the whole process of Linked Data development and its relevant tasks (adapted from Radulovic et al., 2015). The sequential relations between the tasks are represented by full lines, while the outputs from each task are represented by continuous lines. The process is also represented by four other main phases: Data, Information, Knowledge and finally Wisdom. These phases have been adapted from the Big Data domain where the data is acquired in the data stage, then it turns to information through being stored and pre-processed, then this turns into knowledge through analysis and identification of the patterns, and, finally, better decisions can be gained by visualising and interpreting the outcomes from the knowledge stage. Each stage of the Linked Data development process is discussed in detail below.

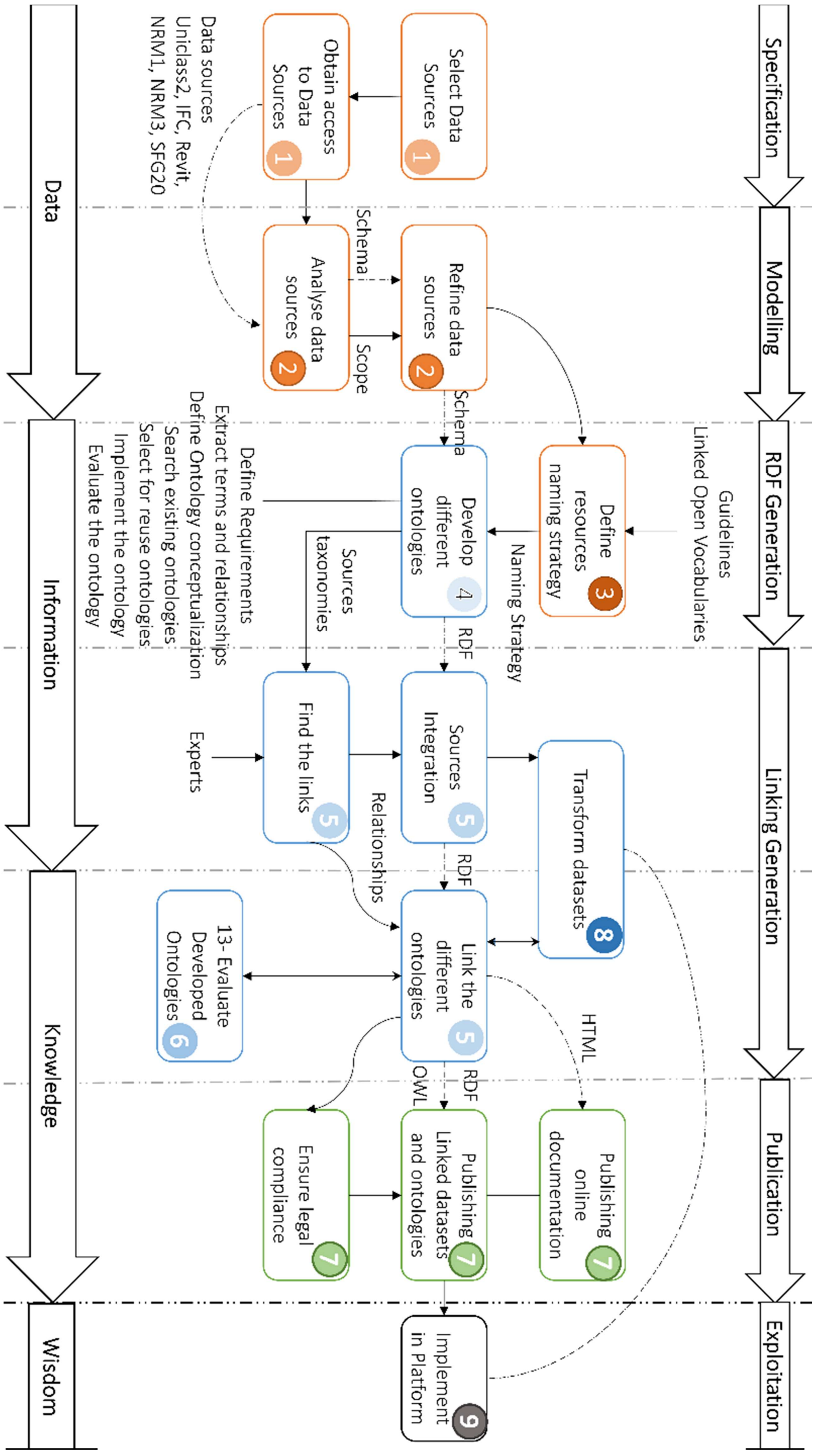


Figure 7-3: Process of generation and publication of Linked Data Specification

The first two tasks in the Linked Data generation process are the selection of the required ontological sources and obtaining access for the selected ontological sources respectively. Such ontological sources are usually owned by organisations which are in most of the cases easily accessed (Radulovic et al., 2015). Different ontological sources were selected in the research to achieve the required goal which are NRM 1, NRM 3, Uniclass2, SFG20, IFC and, finally, Revit as a BIM Platform. All these ontological sources achieved the specified requirements explicitly: to include data/classification or vocabularies about assets in buildings, to be available to use, standards and/or guidelines related to the best practice in the UK, and, finally, to be presented in a structured way to be easily adopted.

NRM is a series of documents issued by the Royal Institution of Chartered Surveyors (RICS) quantity surveying and construction professional group. NRM1 does not explain estimating methods, cost planning techniques and procurement methods; it provides a direction on how to describe, classify and deal with costs forming part of the cost of the building (RICS, 2012). NRM3, as discussed before, has been written to provide a standard and guideline for the quantification and description of the maintenance works for cost-estimating purposes during all the phases of the building. NRM1 and NRM3 together present the basis of lifecycle cost management of capital building works and maintenance. Both NRM1 and NRM3 have been selected for the proposed Linked Data as they are understandable by all stakeholders involved in the project and associated elemental classifications can aid the communication between the project team and the employer (RICS, 2012). The data source of the NRM1 and NRM3 dataset are is available in the public domain from the rics.org.uk webpage (RICS, 2012) and they are provided in PDF format as tables.

IFC provides the benchmark for the sharing of information about any built environment asset through its lifecycle between all the stakeholders, notwithstanding the software application used. The data source for the IFC dataset and vocabulary is available on the BuildSMART website and is provided in ifcXML and .OWL formats. SFG20 provides the benchmark for optimum maintenance, avoiding over or under maintaining of assets, and is the backbone to the building engineering services maintenance industry. The SFG20 core library offers users more than 400 industry-standard maintenance specifications covering all principal types of heating, cooling and ventilation, installation, plant and electrical services, complete with regular technical updates. Although SFG20 is not specified in PAS 1192, it can be easily figured out as it is aligned with NRM3. The authors accessed the SFG20 through a free trial request where the standard is provided in a tree online taxonomy.

Uniclass2, as mentioned before, is the new UK implementation of the international framework for construction information. Uniclass2 has been developed to form a structured classification, freely available for all participants throughout the lifecycle of a project and beyond, which is endorsed by all construction and property bodies and professional institutions. The data source of the Uniclass2 dataset and vocabulary is available as structured tables on the NBS BIM toolkit website and is provided in PDF and xls formats. Finally, Revit is one of the most popular BIM platforms. It is important to the classification of Revit to be able to link all the different standards with the Revit elements.

7.3.1 Modelling

Once the ontological sources are selected and access is obtained, the next step is to analyse the data in order to observe how far it is structured and organised, understand its structure/schema and the relationships between its data and, finally, define the required datasets to form the classes and concepts for an ontology. Subsequently, the next step is to refine the data by correcting errors in the schema and creating mapping between columns and rows if the schema is SQL-based.

As this research concentrates on assets that consume energy, all datasets related to assets that consume energy are used to develop the ontologies in the next stages. The developed taxonomy of assets in the previous sub-section has been chosen for the refinement of the datasets. The taxonomy classified the assets that consume energy into nine main categories: water heating, ventilation, refrigeration, lighting, electronics, kitchen, computers, space cooling/heating and others. Each category contains the related assets.

7.3.2 RDF Generation

The RDF generation of Linked Data consists of two main tasks: defining the resource naming strategy and developing the ontologies. The vocabularies used to represent data are a key to forming Linked Data in general and defining the resource naming strategy in particular. In the meantime, one of the main principles of Linked Data states that URIs (Uniform Resource Identifiers) must be used for naming resources such as vocabularies and terms. In this section, the strategy to define the URIs for generating resources is discussed. Several guidelines have defined the URI construction aspects, such as: cool URIs (Maali et al., 2011), design guidelines for the UK public sector (Davidson, 2009), 223 Best Practices URI Construction by W3C, URI Design Principles: Creating Persistent URIs developed by Linked Open Data Government (LOGD, 2013), and Linked Data patterns (Dodds and Davis, 2011). The design process of URIs consists of three main steps: selection of URI form, selection of URI domain and path, and selection of patterns and vocabularies for ontology classes, properties and individuals.

There are two main forms of URI: slash URI and hash URI. The slash URIs are the normal URI and they imply a 303 redirection to the location of a document that represents the resource and content negotiation (Radulovic et al., 2015). In slash URIs, the resource is accessed as an individual or a group, while the hash URIs contain a fragment which separates the normal URI and fragment identifier by a hash character ('#'). The hash URI accesses data as a whole and, when the URI is requested from the server, the fragment part is torn. Hash URI is easier to be dereferenceable as there is no content negotiation needed. Since the development of the Linked Data project in 2007, dereferencing URIs in the RDF models should return information back for both humans and application usage (Yu, 2011). There are several available domains where content beyond the boundaries of the websites and different applications can be shared. The most well-known domains are the semantic web, DBpedia and RDF-ised version of Wikipedia (Heath and Bizer, 2011). Radulovic et al. (2015) argued that the usage of domains under direct control of the organisation generating the data can provided better resource management and redirection settings. The proper selection of patterns and vocabularies for classes, properties and individuals can provide easier access to information and refer many different URIs to the same world object (Heath and Bizer, 2011). They added that, to avoid data heterogeneity, terms from widely deployed vocabularies in standards and classifications have to be used.

Accordingly and armed with the tips provided by Heath and Bizer (2011), as the datasets will contain a significant amount of data and it can grow in the future, slash URIs are adopted. However, a smaller amount of data is entered in the development of ontologies; therefore, the hash URIs are used. The ontologies will have the path form/ontology/<ontologyName>#<className> for classes and /ontology/<ontologyName>#<propertyName>. The domain semanticweb.org is selected to adapt the developed ontologies and the naming conventions of the classes are written as the selected construction standards and classifications.

Once the defining naming strategy is selected, the ontologies are developed through seven different steps (Noy and McGuinness, 2001) (Figure 7-4). The first step is to define the requirements, such as the scope and the covered domain, that have to be fulfilled by the ontology. As mentioned before, the research concentrates only on assets that consume energy. Therefore, the developed ontologies will only cover these assets and will not include the other assets mentioned in the different selected classifications and standards. Since the datasets for that scope are small and the speed of processing is not an issue, the Turtle serialisation was selected because it is easy for humans to read. Most of the datasets are available in PDF format; therefore, the ontologies have been created from scratch using Protégé 5.2 as the ontology editor.

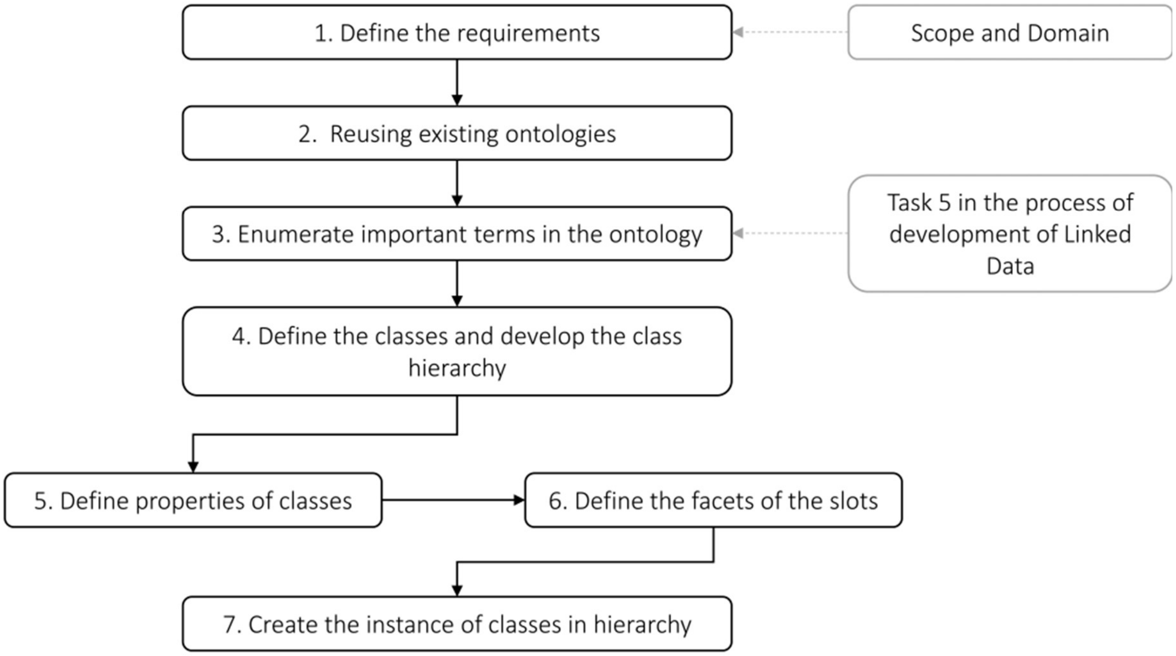


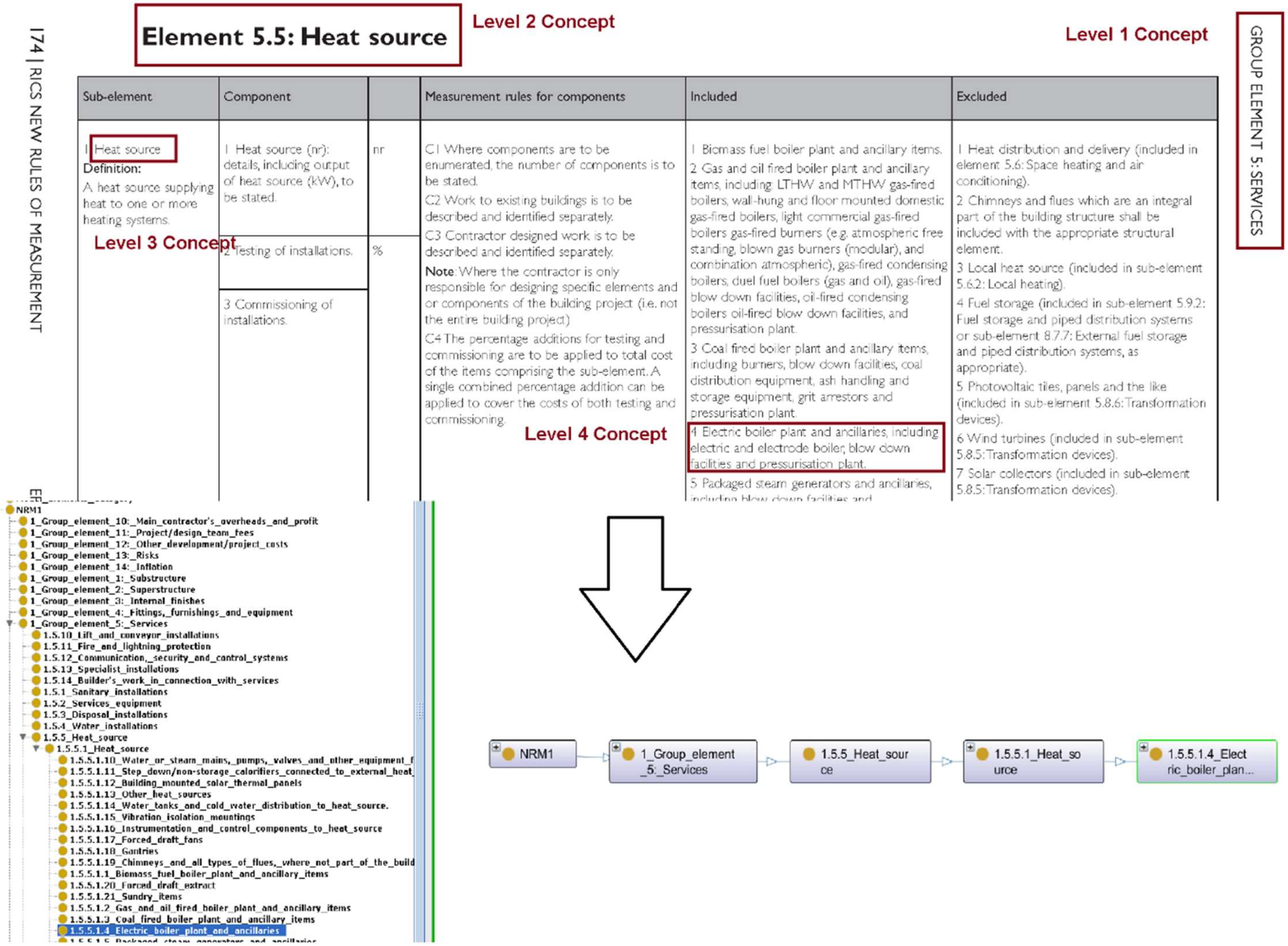
Figure 7-4: The process of ontology development

The second step is to consider reusing existing ontologies. Sometimes reusing existing ontologies is a requirement to attain integration with other applications which are already committed to particular ontologies. Abanda et al. (2017) developed an ontology based on NRM1 concepts to facilitate the cost-estimation process in the AEC industry. Pauwels and Terkaj (2016) developed an ontology based on IFC EXPRESS schema to allow the conversion of IFC instance files into equivalent RDF graphs. The reuse of these existing ontologies has been taken into consideration in the ontologies development by referencing them, instead of by importing the existing ontologies as a whole. It has been observed that developing ontologies with the required classes for the research scope is simpler and quicker than importing all the existing ontologies.

The third step is to enumerate important terms in the ontology. In this step, terms are extracted to form a list of concepts (classes, relationships and slots) from the data schema regardless of any overlap between concepts they represent. The names of the selected terms have to follow a specific strategy as specified in the define resource naming strategy task.

The fourth step is to define the classes and develop the class hierarchy. Several approaches can be used for developing class hierarchy: top-down, bottom-up and combination. The top-down approach starts by defining the most general concept in the domain and subsequently the specialised concepts. The bottom-up approach starts by defining the most specific classes in the domain and subsequently grouping them into more general classes. The combination approach is a mix of the top-down and bottom-up approaches. In this research, the top-down approach was adopted in the development of the class hierarchy in the different proposed ontologies. For example, as the schema of the NRM1 and NRM3 are available in a tabular format in PDF documents, the ontology concepts were extracted manually from the elemental work breakdown structure (WBS) illustrated in the NRM documents.

The WBS comprises eight different classes/concepts: Group 1: Substructure; Group 2: Superstructure; Group 3: Internal Finishes; Group 4: Fittings, Furnishes and Equipment; Group 5: Services; Group 6: Prefabricated Buildings and Building Units; Group 7: Work to Existing Buildings; and Group 8: External Works. Concepts were categorised into four hierarchical levels (Figure 7-5). The top (first) level concepts adopted are Substructure; Superstructure; Internal Finishes; Fittings, Furnishes and Equipment; Services; Prefabricated Buildings and Building Units; Work to Existing Buildings; and External Works. The second-level concepts were obtained from the immediate breakdown of first-level concepts as in the NRMs. The third and fourth concepts were obtained from the first and fourth columns respectively from the tables under each second-level concept. Columns four and five in the NRM1 and NRM3 tables represent the included and excluded elements respectively.



174 | RICS NEW RULES OF MEASUREMENT

GROUP ELEMENT 5: SERVICES

Element 5.5: Heat source

Sub-element	Component		Measurement rules for components	Included	Excluded
1 Heat source **Definition:** A heat source supplying heat to one or more heating systems.	1 Heat source (nr): details, including output of heat source (kW), to be stated.	nr	C1 Where components are to be enumerated, the number of components is to be stated. C2 Work to existing buildings is to be described and identified separately. C3 Contractor designed work is to be described and identified separately. **Note**: Where the contractor is only responsible for designing specific elements and or components of the building project (i.e. not the entire building project) C4 The percentage additions for testing and commissioning are to be applied to total cost of the items comprising the sub-element. A single combined percentage addition can be applied to cover the costs of both testing and commissioning.	1 Biomass fuel boiler plant and ancillary items. 2 Gas and oil fired boiler plant and ancillary items, including LTHW and MTHW gas-fired boilers, wall-hung and floor mounted domestic gas-fired boilers, light commercial gas-fired boilers gas-fired burners (e.g. atmospheric free standing, blown gas burners (modular), and combination atmospheric), gas-fired condensing boilers, duel fuel boilers (gas and oil), gas-fired blow down facilities, oil-fired condensing boilers oil-fired blow down facilities, and pressurisation plant. 3 Coal fired boiler plant and ancillary items, including burners, blow down facilities, coal distribution equipment, ash handling and storage equipment, grit arrestors and pressurisation plant. 4 Electric boiler plant and ancillaries, including electric and electrode boiler, blow down facilities and pressurisation plant. 5 Packaged steam generators and ancillaries,	1 Heat distribution and delivery (included in element 5.6: Space heating and air conditioning). 2 Chimneys and flues which are an integral part of the building structure shall be included with the appropriate structural element. 3 Local heat source (included in sub-element 5.6.2: Local heating). 4 Fuel storage (included in sub-element 5.9.2: Fuel storage and piped distribution systems or sub-element 8.7.7: External fuel storage and piped distribution systems, as appropriate). 5 Photovoltaic tiles, panels and the like (included in sub-element 5.8.6: Transformation devices). 6 Wind turbines (included in sub-element 5.8.5: Transformation devices). 7 Solar collectors (included in sub-element 5.8.5: Transformation devices).
	2 Testing of installations.	%			
	3 Commissioning of installations.				

- NRM1
  - 1_Group_element_10:_Main_contractor's_overheads_and_profit
  - 1_Group_element_11:_Project/design_team_fees
  - 1_Group_element_12:_Other_development/project_costs
  - 1_Group_element_13:_Risks
  - 1_Group_element_14:_Inflation
  - 1_Group_element_1:_Substructure
  - 1_Group_element_2:_Superstructure
  - 1_Group_element_3:_Internal_finishes
  - 1_Group_element_4:_Fittings,_furnishings_and_equipment
  - 1_Group_element_5:_Services
    - 1.5.10_Lift_and_conveyor_installations
    - 1.5.11_Fire_and_lightning_protection
    - 1.5.12_Communication,_security_and_control_systems
    - 1.5.13_Specialist_installations
    - 1.5.14_Builder's_work_in_connection_with_services
    - 1.5.1_Sanitary_installations
    - 1.5.2_Services_equipment
    - 1.5.3_Disposal_installations
    - 1.5.4_Water_installations
    - 1.5.5_Heat_source
      - 1.5.5.1_Heat_source
        - 1.5.5.1.10_Water_or_steam_mains,_pumps,_valves_and_other_equipment_f
        - 1.5.5.1.11_Step_down/non-storage_calorifiers_connected_to_external_heat_
        - 1.5.5.1.12_Building_mounted_solar_thermal_panels
        - 1.5.5.1.13_Other_heat_sources
        - 1.5.5.1.14_Water_tanks_and_cold_water_distribution_to_heat_source.
        - 1.5.5.1.15_Vibration_isolation_mountings
        - 1.5.5.1.16_Instrumentation_and_control_components_to_heat_source
        - 1.5.5.1.17_Forced_draft_fans
        - 1.5.5.1.18_Gantries
        - 1.5.5.1.19_Chimneys_and_all_types_of_flues,_where_not_part_of_the_build
        - 1.5.5.1.1_Biomass_fuel_boiler_plant_and_ancillary_items
        - 1.5.5.1.20_Forced_draft_extract
        - 1.5.5.1.21_Sundry_items
        - 1.5.5.1.2_Gas_and_oil_fired_boiler_plant_and_ancillary_items
        - 1.5.5.1.3_Coal_fired_boiler_plant_and_ancillary_items
        - 1.5.5.1.4_Electric_boiler_plant_and_ancillaries

Figure 7-5: Abstraction of concepts from NRM to Protégé

The fifth and sixth steps are closely interconnected and are usually performed together. The fifth step is to define properties of classes (slots). The definition of classes alone will not provide enough information to answer competency questions asked in step 1. Slots describe the internal structure of concepts in ontology and they have to be attached to the most general class that can have these properties. The sixth step is to define the facets of the slots. The values of slots are described in different facets, such as: value type, allowed values, cardinality and other facet features. The value type facet can be described in different value types, such as: string, number, Boolean and enumerated. Allowed values facets define the range of slots and cardinality facets define how many values the slot can have. In this research, the properties attached to the classes and sub-classes describe the value type facet, and the string and number value types are used for defining most of the slots. Finally, the seventh step is to create the instance of classes in the hierarchy. This step requires three tasks: choosing the class, creating the instance of that class and, finally, filling in the slots' values. Figure 6-6 presents a screenshot for the developed ontologies using Protégé 5.2.0. Once the ontologies are developed, the next step is to cross-map the different classes of the ontologies and evaluate the ontologies and linkage between them.

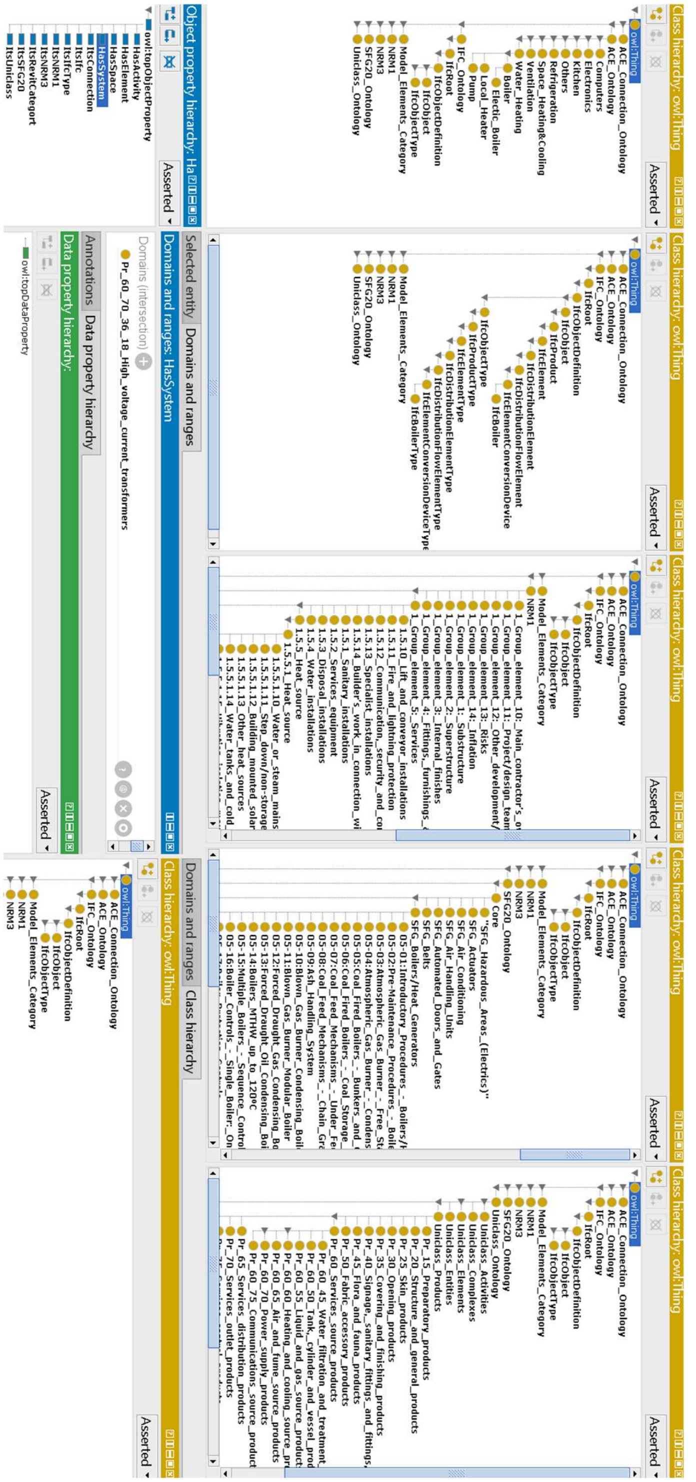


Figure 7-6: Screenshot from Protégé 5.2.0 for the developed ontologies

7.3.3 Linking generation

Linked Data relies on setting RDF links between URI aliases in order to be able to track the different information providers that refer to the same asset. This stage aims to make visible indicators that have not been previously harvested, such as: the interconnections, incoming and outgoing links between vocabularies/classifications. At the end of the first focus group, the link between the classes of the different classifications was documented. Figure 7-7 illustrates the link and mapping between the different ontological sources for a specific asset (a boiler). The hierarchical sequence for each standard is represented to reach the class to symbolise an electrical boiler. The different relationships are colour-coded, as depicted in the bottom left of Figure 7-7.

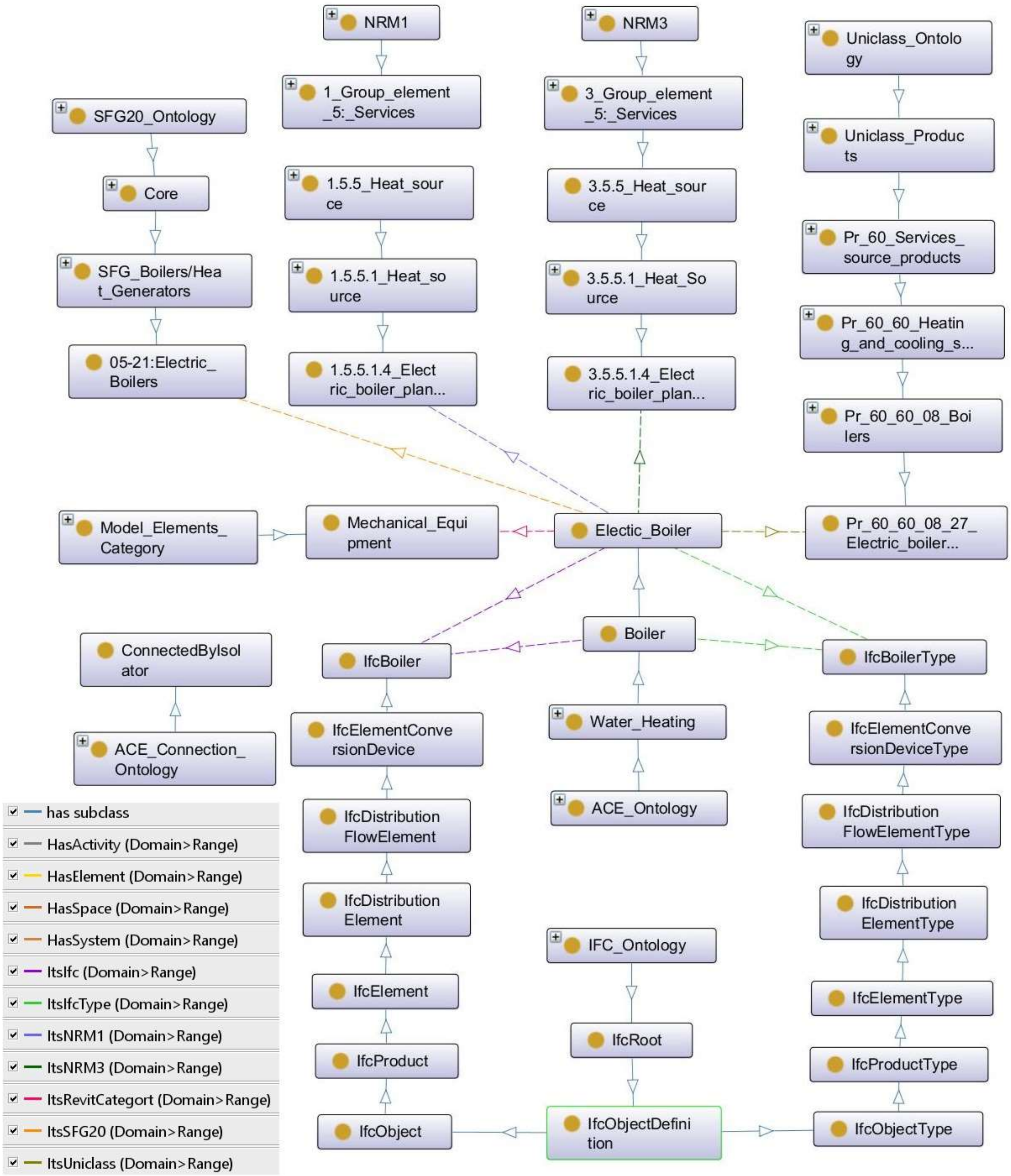
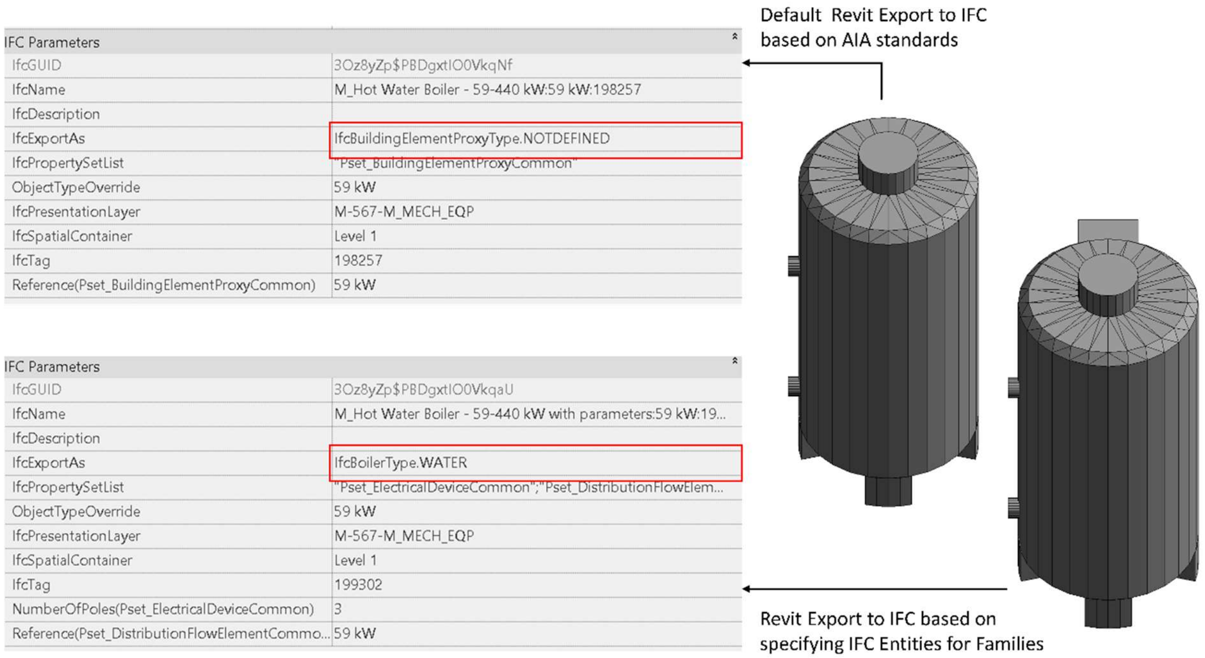


Figure 7-7: Example of linked classifications for an electrical boiler

Ontology evaluation is a vital activity to guarantee that what is developed meets the application requirement (Gomez-Perez et al., 2006). In this step, syntactic and semantic correctness of the developed ontologies and the mapping between the different ontologies have to be verified. Also, the developed ontology has to be evaluated against the purpose of development. A logical-based approach is adopted for syntactic evaluation. Logical-based approaches use rules which are built in the ontology languages and rule users are provided to detect syntactic conflicts in developed ontologies. Syntactic evaluation and validation aims to ensure that all the defined concepts are viable from a technical viewpoint (Tomašević et al., 2015). Several SPARQL queries were executed to observe the credibility of the obtained results and the HermiT reasoner was used to validate the consistency with the used ontologies. HermiT is a reasoner for ontologies written using the Web Ontology Language (OWL) and it is a preinstalled Protégé plug-in. Meanwhile, the Manchester OWL syntax validator was used to evaluate the OWL syntax compliance for the developed ontologies.

After the syntactic evaluation, the ontology was revised and the final version deemed to reflect practice was semantically correct. A feature-based approach was adopted for semantic evaluation of the developed ontologies. This evaluated the ontologies' quality by engaging users and experts. In the final revision, a new ontology was added which represents the connection of the asset to electricity. The sub-classes of this ontology are socket, diffuser, isolator, control panel and battery. Respectively, an object property was added to map the connection to electricity ontology and the main ACE ontology. Also, during the focus group, the author and the experts discussed several challenges and gaps which had to be overcome to achieve appropriate cross-linking between different sources. The first highlighted challenge was that the export option of IFC in Revit was unable to fulfil the link required by the experts. By default, Revit exports building elements to an IFC file based on the categories (and sub-categories) to which the elements belong based on the mapping defined by International Alliance for Interoperability (IAI) data exchange standards. However, it is required to map with Revit families instead. For example, Boiler and Air Handling Units (AHU) are families and both are under the mechanical equipment category. Once they are exported to IFC, both are exported as IfcBuildingElementProxy instead of IfcBoiler and IfcAirHandlingUnit respectively (Figure 7-8).



IFC Parameters	
IfcGUID	3Oz8yZp$PBDgxtIO0VkqNf
IfcName	M_Hot Water Boiler - 59-440 kW:59 kW:198257
IfcDescription	
IfcExportAs	IfcBuildingElementProxyType.NOTDEFINED
IfcPropertySetList	"Pset_BuildingElementProxyCommon"
ObjectTypeOverride	59 kW
IfcPresentationLayer	M-567-M_MECH_EQP
IfcSpatialContainer	Level 1
IfcTag	198257
Reference(Pset_BuildingElementProxyCommon)	59 kW

IFC Parameters	
IfcGUID	3Oz8yZp$PBDgxtIO0VkqaU
IfcName	M_Hot Water Boiler - 59-440 kW with parameters:59 kW:19...
IfcDescription	
IfcExportAs	IfcBoilerType.WATER
IfcPropertySetList	"Pset_ElectricalDeviceCommon";"Pset_DistributionFlowElem...
ObjectTypeOverride	59 kW
IfcPresentationLayer	M-567-M_MECH_EQP
IfcSpatialContainer	Level 1
IfcTag	199302
NumberOfPoles(Pset_ElectricalDeviceCommon)	3
Reference(Pset_DistributionFlowElementCommo...	59 kW

Default Revit Export to IFC based on AIA standards

Revit Export to IFC based on specifying IFC Entities for Families

Figure 7-8: Example of the default export of Revit to IFC and the one based on families

On the Autodesk knowledge network website, a solution is proposed to overcome that challenge. The solution requires two shared parameters named IFCExportAs and IFCExportType to be added, where the Revit user needs to fulfil with the IFC class for each family. The second challenge is that exporting the whole model is timing consuming and not required. One of the participants suggested adding two parameters for the Revit elements. The first parameter identifies if the asset is maintainable or not, while the second parameter classifies the asset's importance from the operation point of view. It was suggested that the asset importance parameter should be a Camel Case string type. Using the two parameters, we can distinguish which assets need to be exported and consequently develop an MVD to achieve the purpose. The third highlighted point is linking the different tables of uniclass2 to each other. Figure 7-9 shows an example of linking the different tables of uniclass2.

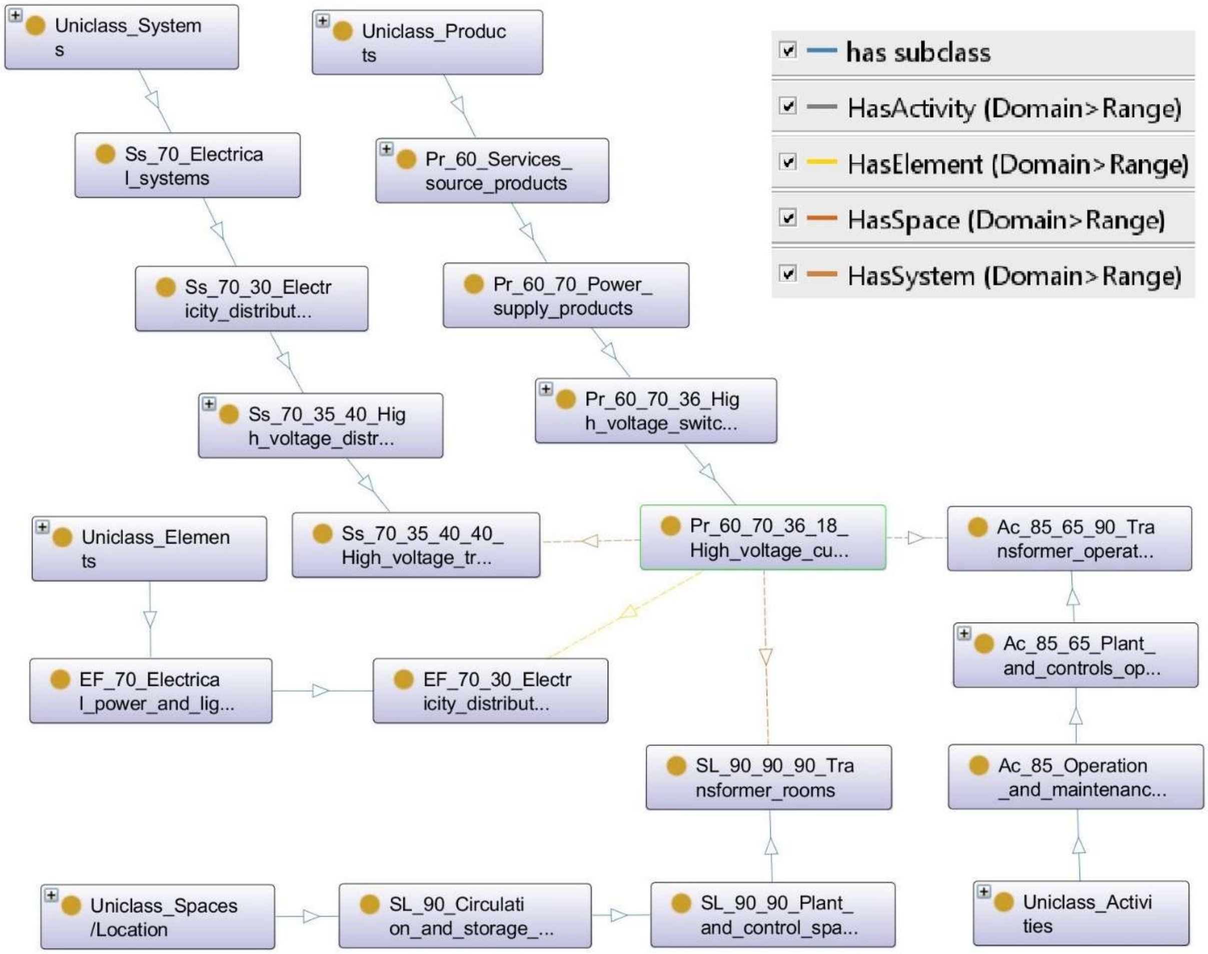


Figure 7-9: Example of linking classifications from different tables of Uniclass2

7.3.4 Publication

Publishing the Linked Data aims to ensure that the generated Linked Data set and associated ontologies are available and discoverable on the Web. The process of Linked Data publishing consists of three main steps: ensure legal compliance, Linked Datasets and ontologies publishing, and online documentation publishing. For further information related to dataset publishing, the research by Radulovic et al. (2015) can be reviewed.

The step to ensure legal compliance complies with two main techniques to safeguard privacy: anonymisation and access control. In anonymisation, private attributes in datasets are firstly identified and then an anonymisation model is implemented using one of the anonymisation techniques, such as suppression, anatomisation, generalisation and perturbation (Fung et al., 2010). In access control, data access can be given to authorised subjects and denied to unauthorised subjects. The access control technique is convenient for controlling data access and providing only full data access to trusted subjects/stakeholders (for example: building owners and facility managers); however, private datasets are still accessed to all authorised subjects. In this research, all data used to develop the associated ontologies is licensed for open usage. Therefore, it is not necessary to perform this step and it will only be required in the datasets transform for the future case studies involved.

The Linked Data sets and ontologies publishing step has to adhere to the Linked Data principles mentioned in Chapter 4 to achieve a unified mechanism for data access and inter-linkage distributed across several silos (Curry et al., 2013). Consequently, (i) the building's assets have to be identified using URI, (ii) the HTTP URIs are essentially used to refer to and look up the building's assets in a browser and/or software package (dereferenced) by users, (iii) standard formats such as RDF are selected to represent useful information related to the building objects, when their URIs are dereferenced, and (iv) related URIs are linked to each other for better discovery of relevant information on the Web. The fourth principle ensures the data returned provides links to other ontological sources. The developed ontologies have been published armed with the four Linked Data principles.

7.3.5 Exploitation

The developed ontologies and the defined resource naming strategy are used in the process of transforming data into RDF format. Figure 7-10 illustrates the proposed framework for data transformation in the pilot study of this research. Three different data sources were selected for our case study: the BIM models, the operations and maintenance schedules, and the procurement documents. The Turtle serialisation was selected as the research RDF serialisation. Turtle serialisation is easily readable by humans and the research dataset is small, which would not affect the speed of processing. Since the data is available in CSV and XML formats, OpenRefine with the RDF extension for transforming the data into RDF was selected. The OpenRefine tool is widely known in the community and it is easy to use. To achieve the transformation, a mapping between the data and the ontology has to be defined taking into consideration the defined resource naming strategy. This has been achieved in several tasks: firstly, initial transformations to the data were made in order to correct errors. Secondly, mappings were made between the columns and rows in the table and the ontology and the pattern for naming instances was specified according to the resource naming strategy. Consequently, the RDF syntax was chosen, and the datasets were generated and evaluated semantically and syntactically.

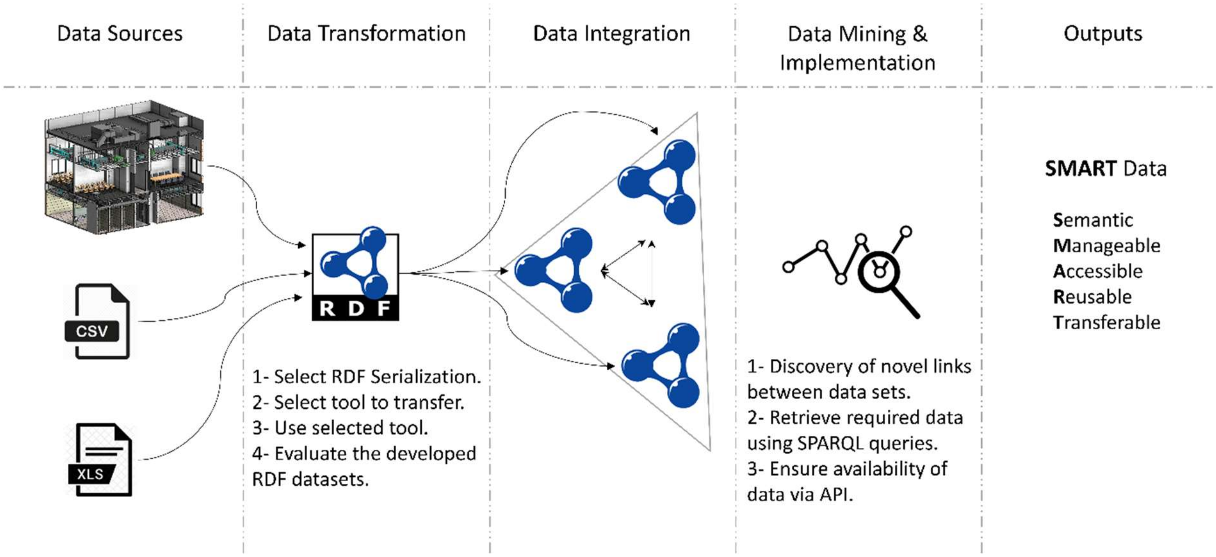


Figure 7-10: Proposed framework for data transformation

After the conversion of the datasets into RDF formats, they are now machine readable and more interoperable as they are represented using the defined standardised vocabularies. To cross-link the different datasets, the different assets were mapped manually to their related information in the several datasets. Further work will be conducted in the transformation of datasets; however, the pilot study showed that, with the different datasets inter-linked to each other, the discovery of novel links between the datasets and the retrieval of required data is now possible using SPARQL queries. Also, the proposed framework can provide outputs which are characterised with maximally semantical, manageable, accessible, reusable and transferable data. Finally, it will provide a potential for the availability of required information in the BIM models using API to import required data into the BIM platforms (presented in the following chapter).

7.4 Chapter Summary

This chapter focused on investigating and discussing the two main semantic aspects for the implementation of BIM in the AM domain. Firstly, it concentrated on developing a list of the information that has to be exchanged from the building information models to the AM systems. A taxonomy for the required data for assets that consume energy was developed based on peer literature review, semi-structured interviews and focus groups. Each attribute of this taxonomy was identified, and its associated information represented, such as: the format of the attribute, the phase where the attribute information can be collected, and the provider and the user of the data. Subsequently, the chapter presented the process for cross-linking between the BIM and AM systems through Linked Data. The proposed process offered a comprehensive description of the required standards and classifications in the construction domain, related vocabularies and object-oriented links to ensure effective data integration between the different domains. Also, the proposed process demonstrated the different stages, tools, best practices and guidelines to develop Linked Data. The following chapter of the study describes adapting the semantic solution of this chapter to develop an MVD and Revit plug-in to exchange data from the BIM systems to the AM systems.

Chapter 8 Syntactic Interoperability Solution

8.1 Introduction

This chapter presents the different outputs of syntactic interoperability for effective implementation of BIM in AM. The chapter is structured based on the four main stages of the NBIMS process. It opens by developing the IDM using the developed taxonomy and ontologies in the previous chapter. Next, it presents the MVD developed through mapping the different concepts obtained from the ERM diagrams with the IFC schema. The implementation of the developed MVD by software applications is then presented through the development of a Revit plug-in. The last stage is then illustrated where the extracted BIM models are validated across the developed IDM and MVD. Finally, the syntactic outputs and their process of development are summarised.

8.2 ACEie IDM Development

The development of IDMs usually involves the engagement of industry experts who can identify the required information and processes for special data exchange (Pinheiro et al., 2018). IDMs should specify where the process fits; why it is relevant; who are the actors creating, consuming and benefiting from the information; what is the information; and how software solutions should support this information (Laakso & Kiviniemi 2012). During the conducted focus group, the three main deliverables representing the ACEie IDM were formed; explicitly, i) a detailed process map defining the use cases, its component processes and its information exchanges, ii) a list of typical assets that consume energy grouped by system classification, their type of connection to the electricity source and their IFC class, and iii) definition of the required information contents of the exchanges specified in the process map.

A high-level process map for semantic enrichment of the 3D model in the handover stage is shown in Figure 8-1. The process map was developed using Bizagi (BPMN tool) where the roles of stakeholders and data exchange are shown in the horizontal swim lanes and the relevant lifecycle phase in the vertical swim lanes. The process map consists of three defined elements, i.e. activities, information flows and information exchanges. The activities define the specific task required for an exchange scenario between two stakeholders for a specific purpose. The information flows are represented as dashed arrows, while the activities flows are represented as solid arrows. The information exchanges identify the information used in each exchange and this information can be exchanged through the exchange model (EM) or it can be exchanged in a different way, and that is represented as deliverable name in Figure 8-1. Four EMs are proposed in the process map; each of the use cases defines an exchange scenario between two stakeholders and it consists of a set of information to be exchanged. EM1 consists of a set of information related to building space and asset location, and it is exchanged between the architects and the electrical and mechanical engineers, while EM2 consists of information related to the classification of the assets based on the different standards such as Unicalss2 and NRM, and also system classifications such as electronics and computers. The information/BIM manager will submit EM3 to the facility manager after enrichment of the BIM models with semantic information related to the assets' capital expenditure (capex) and warranty. Once the facilities manager receives the model, it needs to be enhanced with additional information related to the assets' maintenance (EM4). EM4 only occurs for existing buildings that are already in operation.

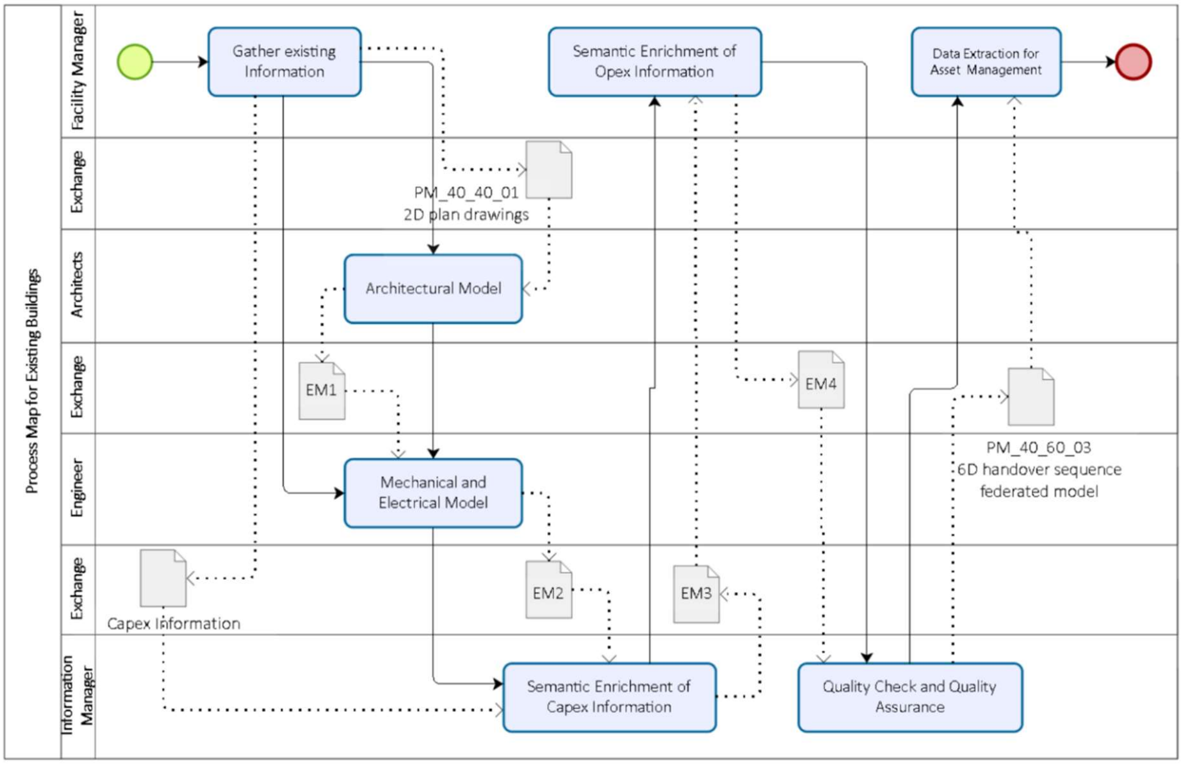


Figure 8-1: Process map of data exchange for building assets that consume energy during handover stage

The second deliverable is a list of typical assets that consume energy. Each of the selected assets represents a functional part in the ACEie exchange requirements. A functional part is a fully described unit of information to support an exchange requirement in its own right as well as being a subset of the information model on which it is based (Eastman et al., 2009). Also, a functional part can provide the information concerning systems, where a system is a group of elements. In that context, the IfcAlarm and IfcSensor, each of which is a functional part, are at the same time a subset of another functional part, which is IfcDistributionElement. Since functional parts are specific to an IFC release, the assets were mapped to relevant classes in IFC4 ADD2.

Table 8-1 illustrates the selected assets classified by their system classification, as presented in Chapter 7, and their correlated IFC class.

Table 8-1: List of assets that consume energy

Assets	System Classification	IFC class - Function Parts based on IFC 4 ADD2	Default Exported IFC Class from Revit
Air Handling Unit		IfcAirToAirHeatRecovery	IfcBuildingElementProxy

Assets	**System Classification**	**IFC class - Function Parts based on IFC 4 ADD2**	**Default Exported IFC Class from Revit**
Fan Cooling Unit	Space Heating and Cooling	IfcAirToAirHeatRecovery	IfcBuildingElementProxy
Package Unit		IfcCondenser	IfcBuildingElementProxy
Variable Air Volume		IfcDamper	IfcBuildingElementProxy
Heat Exchanger		IfcHeatExchanger	IfcBuildingElementProxy
Humidifier		IfcHumidifier	IfcBuildingElementProxy
Chiller		IfcChiller	IfcBuildingElementProxy
Cooling Tower		IfcCoolingTower	IfcBuildingElementProxy
Sensor		IfcFlowInstrument	IfcBuildingElementProxy
Cooling Tank		IfcTank	IfcBuildingElementProxy
Split Unit (Internal)		IfcCondenser	IfcBuildingElementProxy
Split Unit (External)		IfcEvaporator	IfcBuildingElementProxy
Local Heater	water heating	IfcSpaceHeater	IfcBuildingElementProxy
Pump		IfcPump	IfcBuildingElementProxy
Boiler		IfcBoiler	IfcBuildingElementProxy
Fan	ventilation	IfcFan	IfcBuildingElementProxy
Lighting Fixture	lighting	IfcLightFixture	IfcLightFixtureType
Signage		IfcLightFixture	IfcLightFixtureType
Combined Photocopier - Printer - Scanner	Computers	IfcElectricAppliance	IfcBuildingElementProxy
Computer Monitor		IfcElectricAppliance	IfcBuildingElementProxy

Assets	System Classification	IFC class - Function Parts based on IFC 4 ADD2	Default Exported IFC Class from Revit
Desktop Computer		IfcElectricAppliance	IfcBuildingElementProxy
Laptop		IfcElectricAppliance	IfcBuildingElementProxy
Photocopier		IfcElectricAppliance	IfcBuildingElementProxy
Printer		IfcElectricAppliance	IfcBuildingElementProxy
Scanner		IfcElectricAppliance	IfcBuildingElementProxy
Server		IfcElectricAppliance	IfcBuildingElementProxy
Projector		IfcElectricAppliance	IfcBuildingElementProxy
Blender	Kitchen	IfcElectricAppliance	IfcBuildingElementProxy
Oven		IfcElectricAppliance	IfcBuildingElementProxy
Microwave		IfcElectricAppliance	IfcBuildingElementProxy
Water Filter		IfcElectricAppliance	IfcBuildingElementProxy
Fridge		IfcElectricAppliance	IfcBuildingElementProxy
Kettle		IfcElectricAppliance	IfcBuildingElementProxy
Refrigeration Equipment	Refrigeration	IfcElectricAppliance	IfcBuildingElementProxy
Security System	Electronics	IfcSensor	IfcBuildingElementProxy
Fire Alarm System		IfcAlarm	IfcAlarm
Sound System		IfcCommunicationsAppliance	IfcBuildingElementProxy
Querying Control System		IfcCommunicationsAppliance	IfcElectricApplianceType
Intrusion System		IfcSensor	IfcBuildingElementProxy
Generator	Others	IfcElectricGenerator	IfcBuildingElementProxy

Assets	System Classification	IFC class - Function Parts based on IFC 4 ADD2	Default Exported IFC Class from Revit
Transformer		IfcTransformer	IfcBuildingElementProxy
Main Distribution Board		IfcElectricDistributionBoard	IfcBuildingElementProxy
Sub-Panel Board		IfcElectricDistributionBoard	IfcBuildingElementProxy
Motor		IfcElectricMotor	IfcBuildingElementProxy
Lift			
Control Panel		IfcElectricDistributionBoard	IfcBuildingElementProxy
Isolator (Disconnect Switch)		IfcSwitchingDevice	IfcBuildingElementProxy
Switch		IfcSwitchingDevice	IfcBuildingElementProxy
Socket		IfcOutlet	IfcBuildingElementProxy

The third deliverable is the required information to be exchanged. Sixty-four attributes are proposed to be exchanged; they are categorised into six main categories: Space/Location, Classifications, Specifications, Warranty, Asset Capex and Maintenance. For example, the space/location attributes are selected to be exchanged in the first exchange model (EM1) between the architecture model and the mechanical and electrical model. Four attributes are added to the taxonomy developed in sub-section 7.2 based on the suggestions during the Linked Data focus group.

These aforementioned deliverables represent the required outputs (process map, exchange requirements, functional parts, and exchange concepts) from the IDM development. The next step is to transform these outputs into an MVD, which is discussed in the following sub-section.

8.3 ACEie MVD Development

The first step in the transition from IDM to MVD is to identity and document any general decisions regarding the IFC binding and for the different stakeholders to reach an agreement. A description and overview of the new MVD document was produced and approved by the different stakeholders during the focus group; the document includes the selected IFC release 'IFC 4 ADD2', the name of the MVD, 'Assets Consume Energy Information Exchange (ACEie)', and the generic description of the MVD. The scope of the MVD is not well defined in the overview description of the MVD, but it is clearly articulated in the MVD diagrams which define the MVD concepts that will be used in the exchange, as well as the structure and relationships between these concepts (MVD deliverables 2 and 3). Also, the scope is defined in the concept implementation guidance specifications which define the IFC entities used to exchange each concept and the implementing agreements that generally reduce the implementation scope that would otherwise be required by the IFC schema (Deliverable 4).

The first step in developing an MVD, using the IfcDoc tool, is to define a new MVD in the baseline file of the selected IFC release in the overview description (IFC 4 ADD2). The baseline IFC file contains the full IFC schema and a set of reusable MVD concept templates and concept use definitions (Figure 8-2). The file is available on the BuildingSMART website.

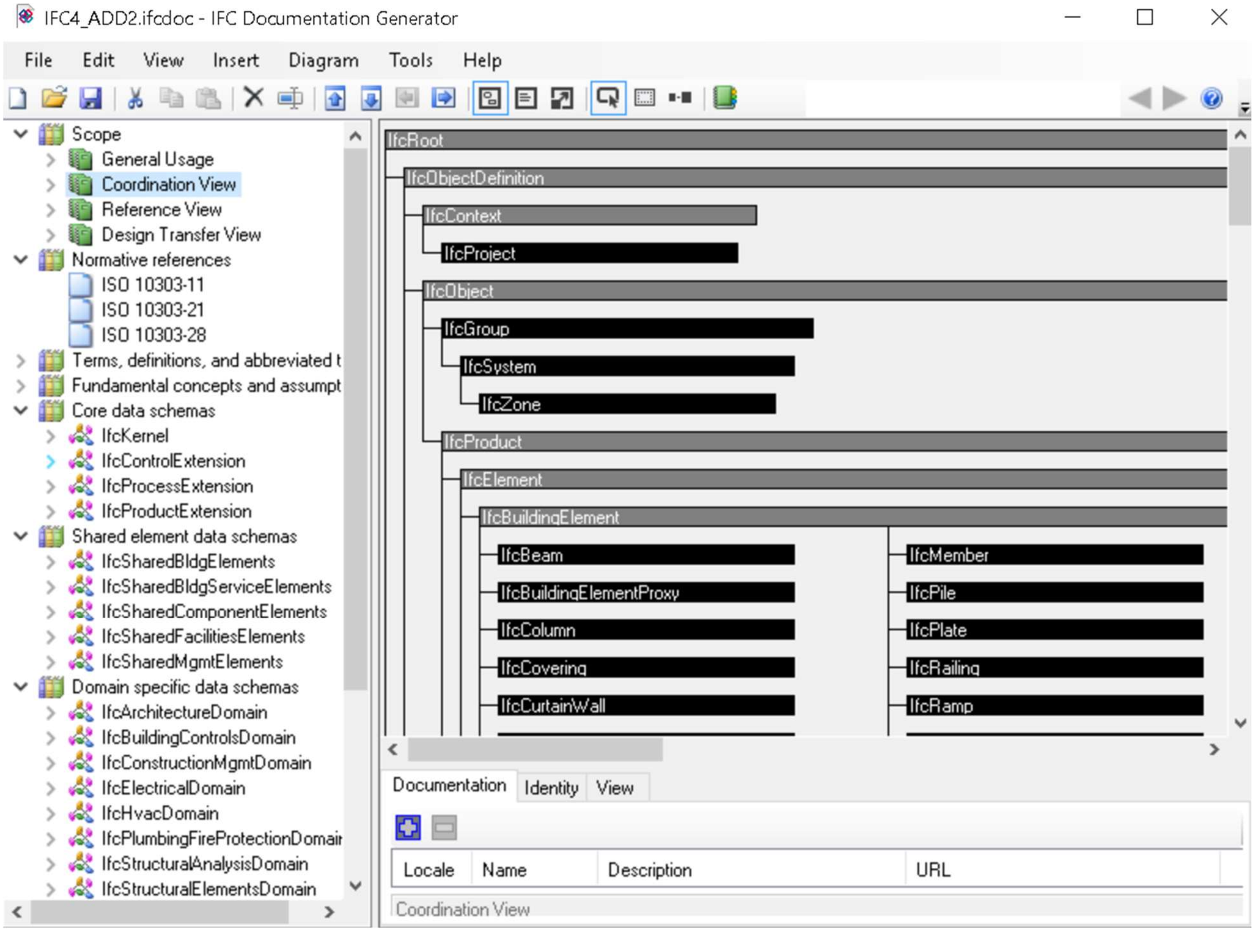


Figure 8-2: Screenshot from IfcDoc tool representing the IFC4 and its associated MVDs

A new MVD called ACEie is added under the scope’s tree. An MVD is assembled using exchange models, entities, concepts, property sets and properties/attributes (Figure 8-3).

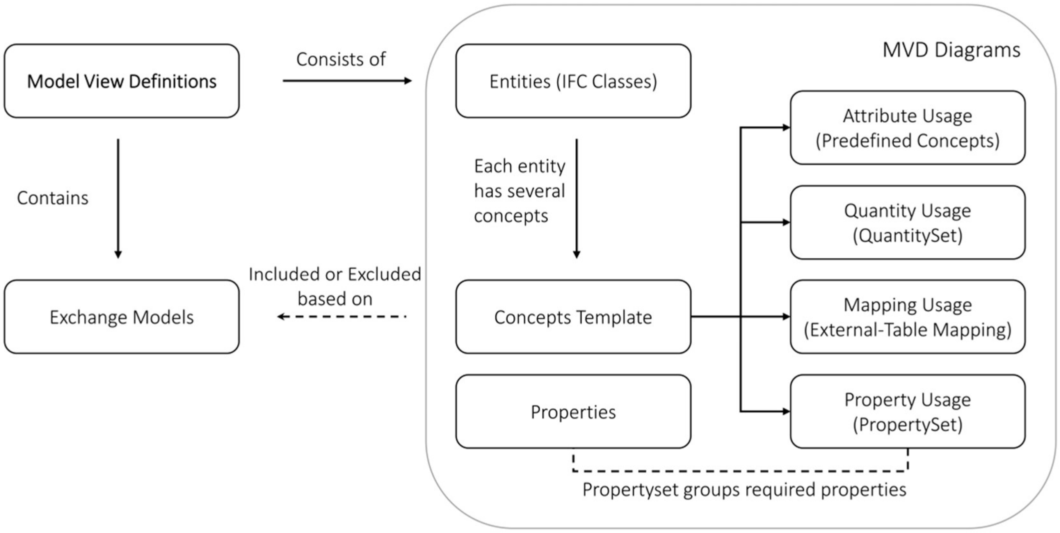


Figure 8-3: MVD components based on IFC schema and IfcDoc structure

Exchange models/definitions (EMs) indicate a particular subset of information to be exchanged in a particular stage of the building lifecycle. For example, COBie V2.4 consists of 28 EMs and their related exchange requirements. The exchange requirements are predefined and formulated by combining the required entities, attributes and their relationships based on the IFC schema. However, the end users can manipulate the entities, attributes, properties and relationship of the predefined concepts in order to achieve the exchange requirements needed for the development of their MVDs. ACEie MVD consists of only four EMs as it only serves the handover stage of existing buildings and their new extensions as predefined in the developed IDM. The four EMs are ACEie_Space/Location, ACEie_Classification, ACEie_Capex&Warranty, and ACEie_Maintenance. Each EM has its own process classification: sender and receiver role classification based the OmniClass classification. To achieve the requirements in the IDM, the sender role has been used to indicate the stakeholder responsible for adding the required information to the BIM models, while the receiver role represents the stakeholder responsible for receiving the updated model and working on adding the new required information for the next EM.

More than 800 entities are included in the IFC4 ADDD2 schema. The most abstract and root class for all IFC entities is the IfcRoot. All entities that are sub-types of IfcRoot can be used independently and they are divided into three main sub-types which form the first level of specialisation within the IFC class hierarchy, namely: IfcObjectDefinition, IfcPropertyDefinition and IfcRelationship. The IfcObjectDefinition entity consists of all the semantically related items such as building assets, project and spatial elements. In IfcDoc, abstract classes are represented in grey, while tangible ones are represented in black. For developing the ACEie MVD, 50 IfcObjectDefinition entities, including spatial entities (such as IfcBuilding, IfcSpace), distribution flow entities (such as IfcBoiler) and other entities, have been selected and added to the developed exchange model view. Although the IFC4 schema has enhanced the level of detail of several assets such as boilers, it still lacks additional classifications for some assets instead of using generic classes (Pinheiro et al., 2018). To overcome this limitation, both air handling units and fan cooling units were mapped to IfcAirToAirHeatRecovery and all the kitchen assets were mapped to IfcElectricAppliance. Once all the entities are identified and added to the model view, the required information from each asset will be established using concepts.

Concepts represent a use definition for a particular entity with specific rules to be enforced (Chipman et al., 2012). The concepts generally encompass a series of specifications and implementation agreements of IFC data exchanges required for one or more entities, their relationships and their attributes (Lee et al., 2018a). The different rules of the concepts are defined using one of the classes of the sub-types of IfcRelationship. There are six fundamental relationship types from the second level of specialisation within the IFC class hierarchy under the relationship branch.

The hierarchy of the building spatial elements required in the EM1 is defined using the predefined 'Object composition' concept template. The sub-type 'IfcRelAggregates' is used to form the hierarchical structure between the different instances. Another predefined concept template is used to link between the instance and its relevant type using the sub-type 'IfcRefDefinesByType'. Also, 'IfcRelDefinesByProperties' is used to add all the required property sets. PSD is explicitly explained as it is used in the development of the proposed MVD.

Six property sets have been added to the IfcElectricDomain property sets to represent the required information for the ACEie exchange. The six property sets and their attributes are based on the developed taxonomy; overall, 64 attributes are defined and assigned to the selected objects for the exchange, and the type of IfcValue has been selected for each of them separately based on the attribute measurement. For instance, IfcElecticCurrentMeasure is selected as the primary data type for the 'current' attribute, while IfcLabel is selected for all the different location attributes. In addition to the property sets, quantity sets were defined to provide the essential information related to measured attributes such as asset dimensions. The next step after the development of the MVD is to identify and extract the required data to be exchanged from the building information models. The following sub-section illustrates the development of the API Revit plug-in for this purpose.

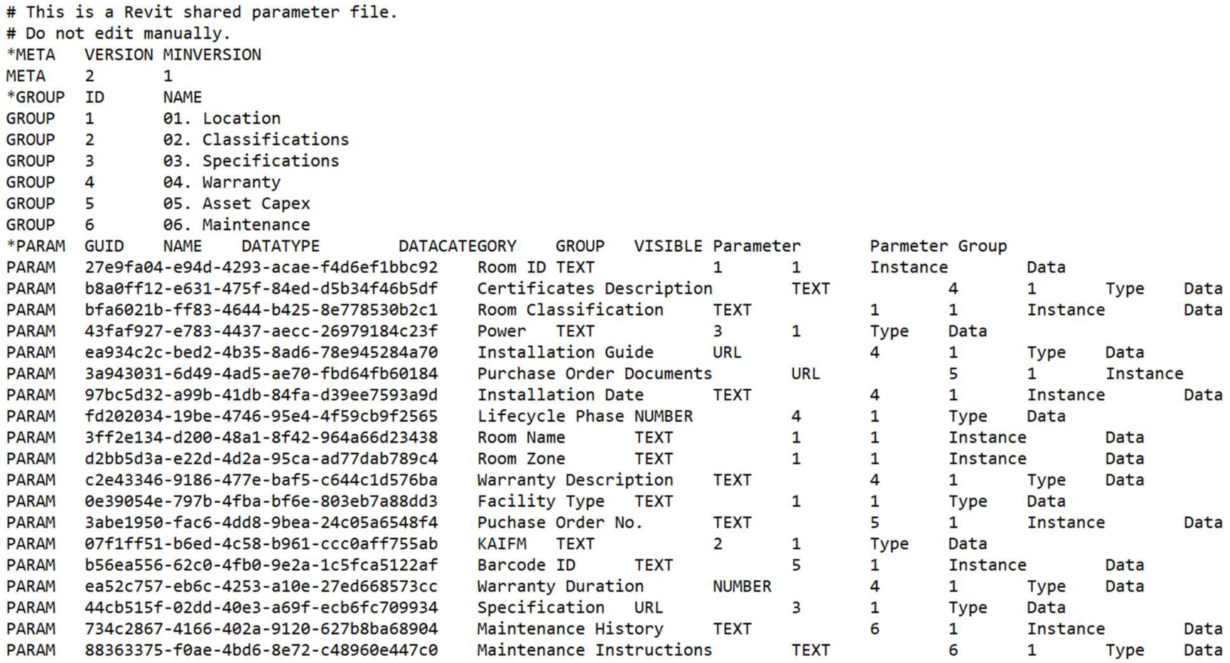
8.4 ACEie Implementation in Revit

The process of adding, connecting and extracting the required information from the building models for the proposed exchange is translated to the developed Revit plug-in. Revit 2019 was selected as it was the latest version at the time of the research and it also contains several enhancements in the IFC export functions. The developed Revit plug-in consists of three primary add-ins. The first add-in supplements the required information – non-graphical information – that is not predefined in the Revit elements. The second add-in function is to fill in some of the information automatically and it consists of three main functions. The third add-in automatically generates six schedules named as the property sets defined in the MVD stage with the parameters hosted in each property set. The three developed add-ins are discussed in detail in the following sub-sections.

8.4.1.1 Adding Information – Add-in

A Revit model consists of object geometry, i.e. graphical information, associated with its predefined properties/parameters, i.e. non-graphical information. However, these existing predefined parameters are not sufficient to cover the information required for AM and therefore further parameters have to be added. Revit provides the functionality for adding user-defined parameters through C# object-oriented programming (OOP) within the .NET Framework environment. This functionality was used to add the required parameters to each Revit object which can be defined as an asset. To create the new model parameters, various parameter properties were considered, including discipline, type of parameter, group parameter under 'value' and categories, based on the Revit Parameter Properties Dialogue Box. The type of parameter (e.g. text, integer, URL) depends on the required information listed in Table 7-1.

All the additional parameters are added in Group parameter under 'Other'. The required parameters are added under specific categories, the selection of which will be defined in the end-user interface as they may differ from one project to another. In order to add user-defined parameters, first, a shared parameter file must be created (Figure 8-4). The shared parameter file stores the definitions and properties of the shared parameters. A shared parameter is an attribute for information that can be used in multiple Revit families or projects. Shared, instead of project, parameters were used in the creation of the new parameters as a shared parameter can be scheduled and made available for multiple projects. The different properties of each parameter were included in the shared parameters text file for standardisation and automation. The first step in the prototyping is creating this shared parameter file. Overall, eight common existing parameters and 39 new parameters (22 type parameters and 17 instance parameters) were identified. Details of the existing and new parameters are illustrated in Table 7-1. Once the default shared parameter file is created, the second step is adding the new parameters and reading from the existing parameters.

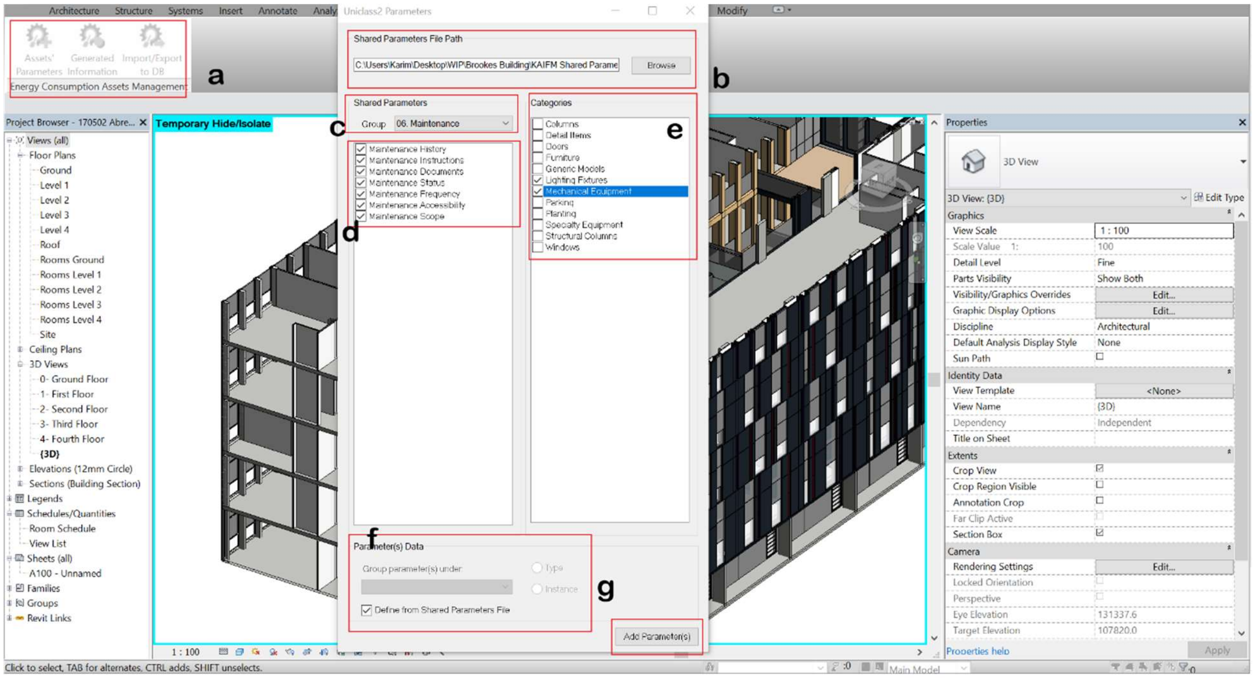


```
# This is a Revit shared parameter file.
# Do not edit manually.
*META   VERSION MINVERSION
META    2       1
*GROUP  ID      NAME
GROUP   1       01. Location
GROUP   2       02. Classifications
GROUP   3       03. Specifications
GROUP   4       04. Warranty
GROUP   5       05. Asset Capex
GROUP   6       06. Maintenance
*PARAM  GUID    NAME    DATATYPE        DATACATEGORY    GROUP   VISIBLE Parameter       Parmeter Group
PARAM   27e9fa04-e94d-4293-acae-f4d6ef1bbc92    Room ID TEXT            1       1       Instance        Data
PARAM   b8a0ff12-e631-475f-84ed-d5b34f46b5df    Certificates Description        TEXT            4       1       Type    Data
PARAM   bfa6021b-ff83-4644-b425-8e778530b2c1    Room Classification     TEXT            1       1       Instance        Data
PARAM   43faf927-e783-4437-aecc-26979184c23f    Power   TEXT            3       1       Type    Data
PARAM   ea934c2c-bed2-4b35-8ad6-78e945284a70    Installation Guide      URL             4       1       Type    Data
PARAM   3a943031-6d49-4ad5-ae70-fbd64fb60184    Purchase Order Documents        URL             5       1       Instance
PARAM   97bc5d32-a99b-41db-84fa-d39ee7593a9d    Installation Date       TEXT            4       1       Instance        Data
PARAM   fd202034-19be-4746-95e4-4f59cb9f2565    Lifecycle Phase NUMBER          4       1       Type    Data
PARAM   3ff2e134-d200-48a1-8f42-964a66d23438    Room Name       TEXT            1       1       Instance        Data
PARAM   d2bb5d3a-e22d-4d2a-95ca-ad77dab789c4    Room Zone       TEXT            1       1       Instance        Data
PARAM   c2e43346-9186-477e-baf5-c644c1d576ba    Warranty Description    TEXT            4       1       Type    Data
PARAM   0e39054e-797b-4fba-bf6e-803eb7a88dd3    Facility Type   TEXT            1       1       Type    Data
PARAM   3abe1950-fac6-4dd8-9bea-24c05a6548f4    Puchase Order No.       TEXT            5       1       Instance        Data
PARAM   07f1ff51-b6ed-4c58-b961-ccc0aff755ab    KAIFM   TEXT            2       1       Type    Data
PARAM   b56ea556-62c0-4fb0-9e2a-1c5fca5122af    Barcode ID      TEXT            5       1       Instance        Data
PARAM   ea52c757-eb6c-4253-a10e-27ed668573cc    Warranty Duration       NUMBER          4       1       Type    Data
PARAM   44cb515f-02dd-40e3-a69f-ecb6fc709934    Specification   URL             3       1       Type    Data
PARAM   734c2867-4166-402a-9120-627b8ba68904    Maintenance History     TEXT            6       1       Instance        Data
PARAM   88363375-f0ae-4bd6-8e72-c48960e447c0    Maintenance Instructions        TEXT            6       1       Type    Data
```

Figure 8-4: Developed shared parameter file for ACE-IM taxonomy

Figure 8-5 shows a screenshot for the developed ACE-IM Plug-in. The sequence (a-g) shows the steps to execute the plug-in to add the required data for the required assets. Firstly, select the tab assets' parameters. A new window will appear containing all the features for the plug-in. Secondly, browse the computer file system and select the shared parameter created previously. Click on the group drop box where the different categories of the ACE-IM taxonomy appear and their corresponding parameters. Subsequently, select the Revit category required to add the parameters to its properties. For example, select lighting fixtures to add the parameters for all the elements defined under this category. In the defined shared parameter, various parameter properties were considered and predefined for each parameter, including discipline, type of parameter, group parameter under 'value' and categories.

An option was added in the plug-in where the user can either use the properties assigned in the shared parameter or assign customised properties for each parameter. Finally, select 'Add parameter(s)'. Once all the steps are performed, the selected Revit elements will contain the blank parameters that need to be filled for AM. For the developed plug-in, a validation study was conducted. The results of the validation showed that the ACE-IM parameters are added to the elements correctly based on the predefined properties in the shared file.



Shared Parameters File Path: C:\Users\Karim\Desktop\WIP\Brookes Building\KAIFM Shared Parame

Shared Parameters — Group: 06. Maintenance

- ☑ Maintenance History
- ☑ Maintenance Instructions
- ☑ Maintenance Documents
- ☑ Maintenance Status
- ☑ Maintenance Frequency
- ☑ Maintenance Accessibility
- ☑ Maintenance Scope

Categories

- ☐ Columns
- ☐ Detail Items
- ☐ Doors
- ☐ Furniture
- ☐ Generic Models
- ☑ Lighting Fixtures
- ☑ Mechanical Equipment
- ☐ Parking
- ☐ Planting
- ☐ Specialty Equipment
- ☐ Structural Columns
- ☐ Windows

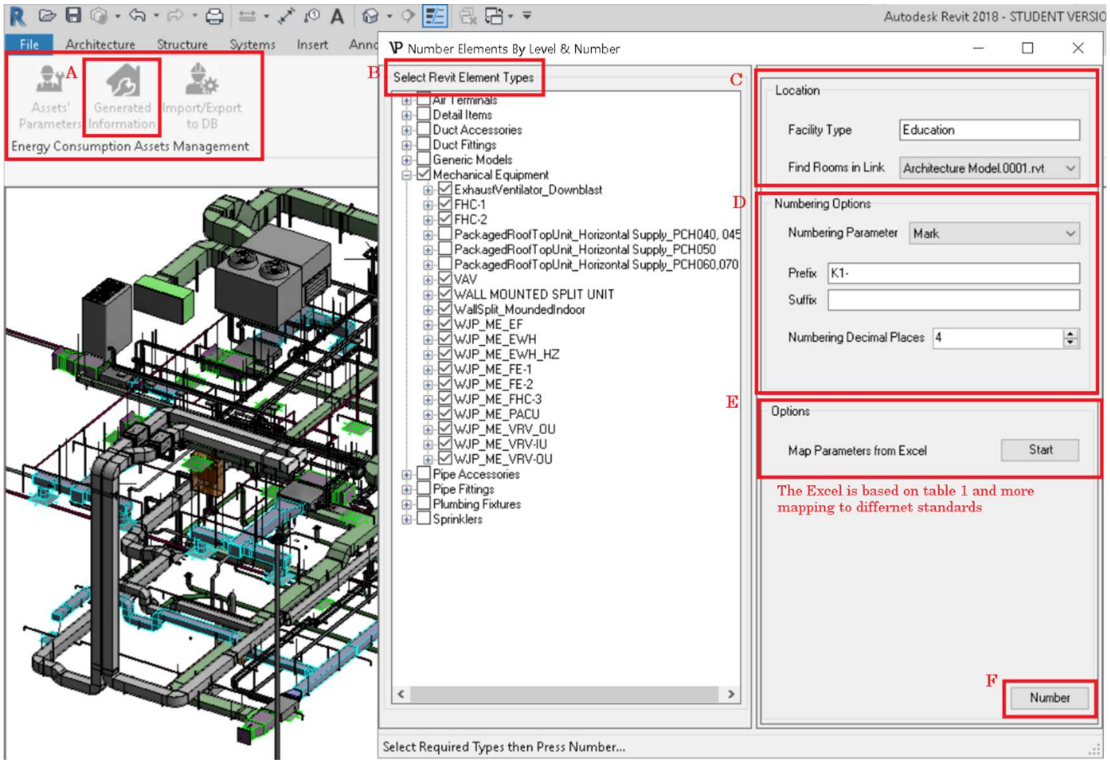
Parameter(s) Data — Group parameter(s) under: ○ Type ○ Instance ☑ Define from Shared Parameters File

3D View: {3D}	
Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Fine
Parts Visibility	Show Both
Visibility/Graphics Overrides	Edit...
Graphic Display Options	Edit...
Discipline	Architectural
Default Analysis Display Style	None
Sun Path	☐
Identity Data	
View Template	<None>
View Name	{3D}
Dependency	Independent
Title on Sheet	
Extents	
Crop View	☑
Crop Region Visible	☐
Annotation Crop	☐
Far Clip Active	☐
Section Box	☑
Camera	
Rendering Settings	Edit...
Locked Orientation	☐
Perspective	☐
Eye Elevation	131337.6
Target Elevation	107820.0

Figure 8-5: First Add-in in the ACEie plug-in

8.4.1.2 Connecting Information – Add-in

As mentioned previously, the connecting add-in consists of three main functions (Figure 8-6). The first function reads from the linked architecture model, recognises the room space that hosts the asset, and, finally, fills in all the parameters related to location and spaces as defined in the architecture rooms. The second function numbers the assets of the same type in the same room to easily identify them. The numbering starts with 1 from the furthermost north in the defined room/space. The third and last function of the second add-in is filling the classification parameters based on the developed cross-linking mapping of the different ontological sources. A predefined spreadsheet contains the 46 assets and their relevant IFC class, IFC class type, NRM1, NRM3 and SFG20. Once the spreadsheet is loaded, the related parameters are automatically filled based on their defined asset classification.



Select Revit Element Types

- ☐ Air Terminals
- ☐ Detail Items
- ☐ Duct Accessories
- ☐ Duct Fittings
- ☐ Generic Models
- ☑ Mechanical Equipment
  - ☑ ExhaustVentilator_Downblast
  - ☑ FHC-1
  - ☑ FHC-2
  - ☐ PackagedRoofTopUnit_Horizontal Supply_PCH040, 045
  - ☐ PackagedRoofTopUnit_Horizontal Supply_PCH050
  - ☐ PackagedRoofTopUnit_Horizontal Supply_PCH060,070
  - ☑ VAV
  - ☑ WALL MOUNTED SPLIT UNIT
  - ☑ WallSplit_MoundedIndoor
  - ☑ WJP_ME_EF
  - ☑ WJP_ME_EWH
  - ☑ WJP_ME_EWH_HZ
  - ☑ WJP_ME_FE-1
  - ☑ WJP_ME_FE-2
  - ☑ WJP_ME_FHC-3
  - ☑ WJP_ME_PACU
  - ☑ WJP_ME_VRV_OU
  - ☑ WJP_ME_VRV-IU
  - ☑ WJP_ME_VRV-OU
- ☐ Pipe Accessories
- ☐ Pipe Fittings
- ☐ Plumbing Fixtures
- ☐ Sprinklers

Location

Facility Type: Education

Find Rooms in Link: Architecture Model.0001.rvt

Numbering Options

Numbering Parameter: Mark

Prefix: K1-

Suffix:

Numbering Decimal Places: 4

Options

Map Parameters from Excel: Start

The Excel is based on table 1 and more mapping to differnet standards

Figure 8-6: Screen shot for the second developed Add-in

8.4.1.3 Extracting Information – Add-in

The third and last add-in is developed to ensure the exportation of the properties in the correct property sets as defined in the MVD. Starting from Revit 2017, an advanced IFC export settings tab is added and one of the added functions is the export of property sets. There are several options for property-set exportation, such as export IFC common property sets, export base quantities, and export schedules as property sets. During the focus group, it was observed that the BIM engineers are not very familiar with IFC property sets and they would prefer that all of the requirements were generated in the Revit environment. Therefore, the selected approach for exportation is using the schedules in Revit as property sets. After extracting the required building assets and the associated required information, it is time to validate the extracted building information model against the developed MVD using the IfcDoc tool.

8.5 ACEie Case Study Validation

As mentioned in Chapter 6, the validation feature embedded in the IfcDoc tool is selected for validation of the building information models against the developed MVD. The embedded feature allows users to import an IFC instance file and evaluate it according to the MVD. The selected IFC file is exported from the BIM model using the plug-in created in sub-section 8.4. The model represents an as-built new expansion for a university (Figure 8-7).

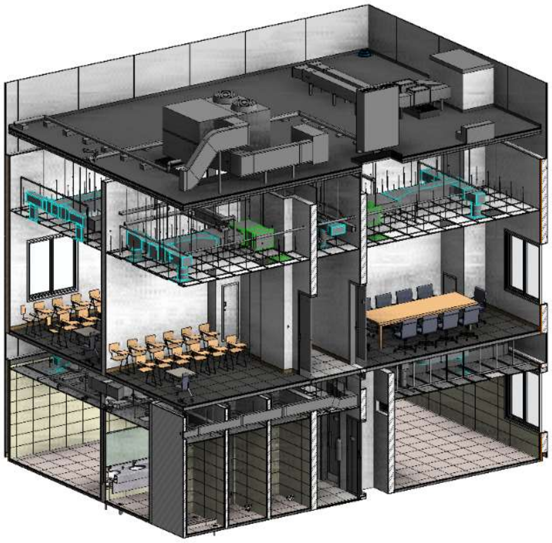


Figure 8-7: BIM model for the selected case study

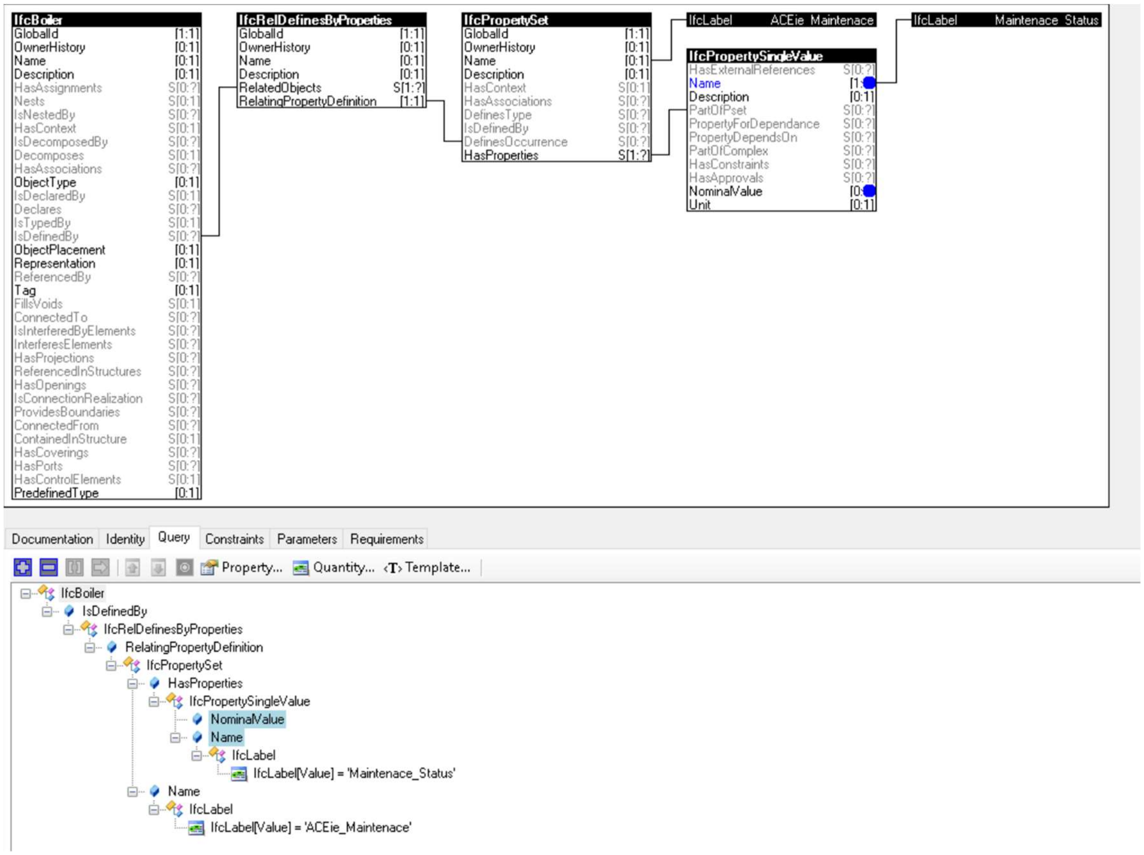
The architecture model includes all the different required spaces and spatial requirements, such as classrooms, toilets, corridors and locker rooms. The mechanical and electrical model includes all the different assets that consume energy and other assets such as sockets, switches, ducts and other mechanical equipment. The sockets ID are added as a parameter to the asset consuming energy through that socket. In addition, required parameters were added and filled using the developed plug-in. On the other hand, the MVD selected is the MVD developed for assets that consume energy and Exchange Model 4 (ACEie_Maintenance) is selected for the IFC instance file validation. Several rule types and logic were designed in order to validate several relationships and attributes of the entities in the developed model view. Each rule type was coded and identified in the ACEie MVD and added through the IfcDoc tool. The logical expressions in IfcDoc, which includes several types and different composition order of rules, were used to develop the five required rule types of the developed MVD. The rule types and logic are:

- Verification of the presence of an attribute.
- Verification of the presence of an element.
- Verification of data accuracy.
- Verification of the cardinality of an element.
- Verification of the presence of a property set and its required properties.

The IfcDoc tool validates the selected IFC model against the model view based on the coded and assigned rule types to the pertinent concepts. It provides two output formats for the validation results: the interactive user interface colour-coded validation report and the HTML format. The colour-coding differentiates the validation outcomes: Pass, Fail, No Instance and Not Applicable. Entities and attributes that satisfy the concept rules are represented in green, while the invalid ones are represented in red. Moreover, the entities that do not have relations or attributes are not coloured.

The first two verification are related to the existence of elements and specific attributes are not in the property sets. The highlighting of these absence reduce effort and time in debugging (Lee et al., 2018b). The third and fourth rules are related to the data accuracy and sematic building elements' requirements.

For example, this model view defines that every building element must be connected to its type of building element (ifcboiler and ifcboilertype). Figure 8-8 represents the validation rule types of the property set checking. Since six property sets were assigned to all the entities that consume energy, a test has to be performed on each property set individually based on the name IfcPropertySet. It is mandatory that the name of the schedule in the Revit which contains the required properties is exactly the same as the predefined IfcPropertySet.



```
IfcBoiler
  IsDefinedBy
    IfcRelDefinesByProperties
      RelatingPropertyDefinition
        IfcPropertySet
          HasProperties
            IfcPropertySingleValue
              NominalValue
              Name
                IfcLabel
                  IfcLabel[Value] = 'Maintenace_Status'
          Name
            IfcLabel
              IfcLabel[Value] = 'ACEie_Maintenace'
```

Figure 8-8: Evaluation coded rule for the property sets using IfcDoc tool

8.6 Chapter Summary

This chapter utilised the mvdXML approach to translate the information required for AM from the building information models into a computer-understandable language using the IFC Express Schema. The chapter opened by identifying the overall requirements specification for data exchange through the engagement of experts with a background in BIM and AM. The context was defined through two main deliverables, process maps and exchange requirements, which together form the IDM. Consequently, an MVD was developed through mapping the different concepts obtained from the Exchange Requirement Models (ERM) diagrams with the IFC schema. MVD development is much more technical work which requires experience in MVD software development tools, standards and practices such as IfcDoc, IFC schema, construction industry and data modelling. Then, a Revit Plug-in was developed to add, connect and extract the required data from the building information models. Finally, several rule types and logic were designed in order to address several relationships, and attributes of the entities in the developed model view, and to validate the exported IFC models against the developed MVD. The following chapter revisits the research objectives taking into consideration the reflection of the semantic and syntactic interoperability findings from this chapter and the previous chapter.

Chapter 9 Research Findings and Discussion

9.1 Introduction

This discussion chapter opens by revisiting the main research objectives, which is followed by a critical reflection on the observations and findings from the previous chapters. The revisit restates and offers a concluding discussion for each of the research objectives in turn, and discusses the pertinent work conducted, evidence produced, and main findings related to each objective. The final section identifies areas for further research in the field of BIM implementation within the Asset Management domain.

9.2 Revisiting the Research Objectives

To present the research findings contributing to the BIM-AM interoperability knowledge, the six research objectives are discussed separately in the following sub-sections. The first two objectives provide the answer to what are the requirements for effective integration between BIM and AM data. While, objectives 3 & 4 come up with an approach to adapt Linked Data and Ontologies to improve the integration between BIM and AM data and objectives 5 & 6 lay out the process to extract, check, share and integrate the required BIM data for AM.

To recapitulate, the six objectives of this research are:

1) Evaluate the theory and practice of BIM implementation for enhancing AM.

2) Develop a conceptual framework of the semantic and syntactic interoperability aspects for BIM implementation in AM.
3) Identify the required information to be exchanged from building information models for AM during the handover stage.
4) Establish a cross-mapping amongst all the different AECO standards and guidelines using ontology and Linked Data.
5) Develop a syntactic interoperability solution to exchange data from BIM to AM platform.
6) Demonstrate and evaluate the usage of the developed semantic and syntactic interoperability solutions through a real-world case study.

Objective 1

The heterogenetic characteristics of AM data present opportunities for encapsulating rich semantic data within BIM. Research and prototype systems have already been developed to improve the interoperability between BIM and AM systems (Kang and Hong, 2015). Different approaches were developed and suggested using one of five methods or combinations of some or all of these methods (methods are discussed in detail in Chapter 2). The four main approaches are manual or iterative spreadsheet-based, Industry Foundation Classes (IFC), Construction Operation Building Information Exchange (COBie) and Proprietary Middleware (

Table 9-1).

Table 9-1: BIM-AM linking approaches and the corresponding methods to achieve the approach

Approach	Methods
Manual and Spreadsheets:	Extract, Transform & Load (ETL) and Data Warehouse (DW).
Industry Foundation Classes:	BIM-based neutral file format.
Construction Operation Building Information Exchange (COBie):	BIM-based neutral file format. Design Pattern and application programming interface (API). Extract, Transform & Load (ETL) and Data Warehouse (DW).
Proprietary Middleware:	BIM-based neutral file format. Design Pattern and application programming interface (API). Web service. Extract, Transform & Load (ETL) and Data Warehouse (DW). Information Delivery Manual (IDM) and Model View Definition (MVD).

Manual and Spreadsheets

In this approach, facility managers update a CMMS or CAFM system by the information required from the BIM data and paper documents either manually or using customised spreadsheets compatible with the FM systems (Arayici, 2015). With the manual spreadsheet-based approach, inputting, verifying and updating the information in the FM systems is a costly and time-consuming process and, furthermore, there is no objective validation of the quality or the strength of the data entered. The principal advantage of this contextual ‘mend and make do’ approach is that the facilities team can operate it without making changes or revisions to their existing work processes, such as they may be.

Industry Foundation Classes (IFC)

The IFC-based approach is an open, vendor-neutral BIM data repository, specified and developed by BuildingSMART, for the semantic information of building objects, including geometry, associated properties and relationships. The IFC approach can facilitate cross-discipline coordination of building information models, including architecture, structural and building services, data sharing and exchange across IFC-compliant applications, and handover and reuse of data for analysis and other downstream tasks (Thein, 2011). IFC is an object-oriented database of information that enables data sharing via ifcXML and aecXML. This is especially effective for interoperability among BIM authoring applications, such as analysis applications to calculate quantities and costs, heat loss, cooling loads, lighting requirements, etc., or to handover data to FM applications for O&M. When IFC is imported, the applications must interpret and transform imported objects to their native objects as best as possible; consequently, data loss occurs. Additionally, there are some software applications which are still not compatible, directly or indirectly, with IFC (Arayici et al., 2018). As the IFC schema has a rich and vast data model that can contain the required data for different applications, construction professionals and software developers have worked on developing processes for the IFC sub-schemas (MVD) for each discipline to improve the implementation of IFC.

Construction Operation Building Information Exchange (COBie)

The COBie-based approach is to enter the structured data as it is created during the design, construction and commissioning stages (Messner, 2013). Designers provide floor, space and equipment layouts. Contractors provide model and serial numbers of installed equipment. Much of the data provided by contractors comes directly from product manufacturers, who also participate in COBie. At the early stages of design, the vertical and horizontal spaces that are necessary to fulfil the local building regulation requirements for the building, facility or infrastructure project are defined. Within these buildings, facilities or infrastructure projects there are also specifications for the different types of systems that will be required, which might include mains grid power distribution, renewable energy, energy conservation installations (e.g. solar panels and ground source heat pumps), backup generators e.g. (for teaching hospital operating theatres), energy-efficient lighting systems, telecommunications and computer networking systems, heating, ventilation and air conditioning (HVAC), district heating or combined heat and power systems, natural ventilation as a function of building design, potable water, wastewater, vertical transport systems (e.g. elevators and escalators), fire protection, intrusion detection and alarms, and other systems.

Overall, the COBie approach looks promising as regards creating an interoperability bridge between the design and construction phases and the operation and maintenance stage. However, the COBie approach has yet to mature successfully into a robust system suitable for industry-wide implementation. The main problem with COBie implementation stems from its reliance on spreadsheets instead of an xml-based information exchange, and this arises from the fact that it was developed in silos; it does not assist software firms and guideline organisations to better integrate with systems and classifications, and undefined outputs from COBie demanding organisations (John, 2013).

Proprietary Middleware

Proprietary middleware is computer software that is designed by a single company which provides services to software applications beyond those available from the operating systems. This approach finds a link between the BM and FM systems, sometimes a bi-directional link, using programming languages and API, design pattern, web services, and BIM-based neutral file formats such as open data standard

(IFC) and data structure specifications (COBie). The benefits of this approach are that middleware enables two separate systems (BIM and FM) to interact, providing a single source of information, reducing the human errors, and updating the information dynamically. However, it has high cost, and is a complex process, and the implementation is fixed during programming in the proprietary middleware approach (Kang and Choi, 2015). One of the most successful proprietary middleware packages for BIM-FM integration on the open market is Ecodomus.

Data Transfer Workflows

The workflow of these different approaches often includes a COBie format spreadsheet as the exchange format for the BIM data to the AM systems (Ibrahim et al., 2016). That is because most of the CMMS systems such as the AiM system accept the COBie format spreadsheet as the primary format. The Manual or semi-automatic Spreadsheets approach can be utilised by extracting the required information for AM from the BIM model using BIMLink or Dynamo to a spreadsheet, then the information in the spreadsheet is manually mapped onto a COBie format spreadsheet. In the IFC approach, practitioners utilise Solibri, one of the leading BIM platforms for quality control purposes, to verify and validate the COBie information within the IFC model and then export it in a COBie spreadsheet format. Also, the COBie extensions for Revit released by Autodesk and Ecodomus both automatically generate the required data in a COBie format.

Although the entire information-capturing process from the BIM models, by any of the available approaches, seems to go smoothly, unexpected errors usually occur when importing the COBie spreadsheet into the AM systems (Pishdad-Bozorgi et al., 2018). Most of the errors are related to semantic interoperability, such as models contain superfluous information, or there is missing information, absence of mapping predefined parameters and incompatible value types. Therefore, researchers should concentrate on scoping the computable information requirements for better semantic interoperability rather than concentrating on developing technology-driven functions and applications to overcome the syntactic interoperability barrier.

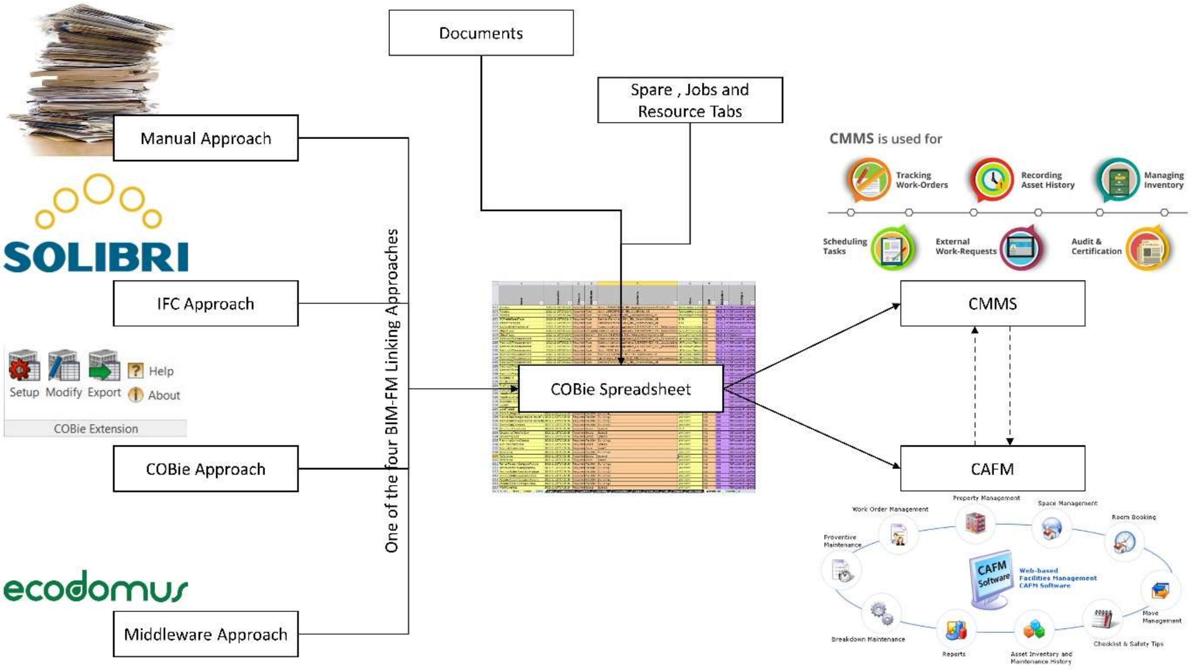


Figure 9-1: BIM-AM workflows for capturing and exchanging asset information

Objective 2

Strategic planning is the key for an effective implementation of BIM in the AM sector (Chunduri et al., 2013). In other words, a well-executed plan for exchanging data from BIM platforms to AM systems is crucial for achieving the required interoperability between the two systems. The developed framework of this research can also be presented as an interoperability plan for exchanging the data from the BIM tools to the AM systems. Figure 9-2 shows the five aspects of the ACEie framework as a process for an effective capture and exchange of required AM data from the BIM tools. The developed process is compared to the proposed FM-enabled BIM framework by Pishdad-Bozorgi et al. (2018).

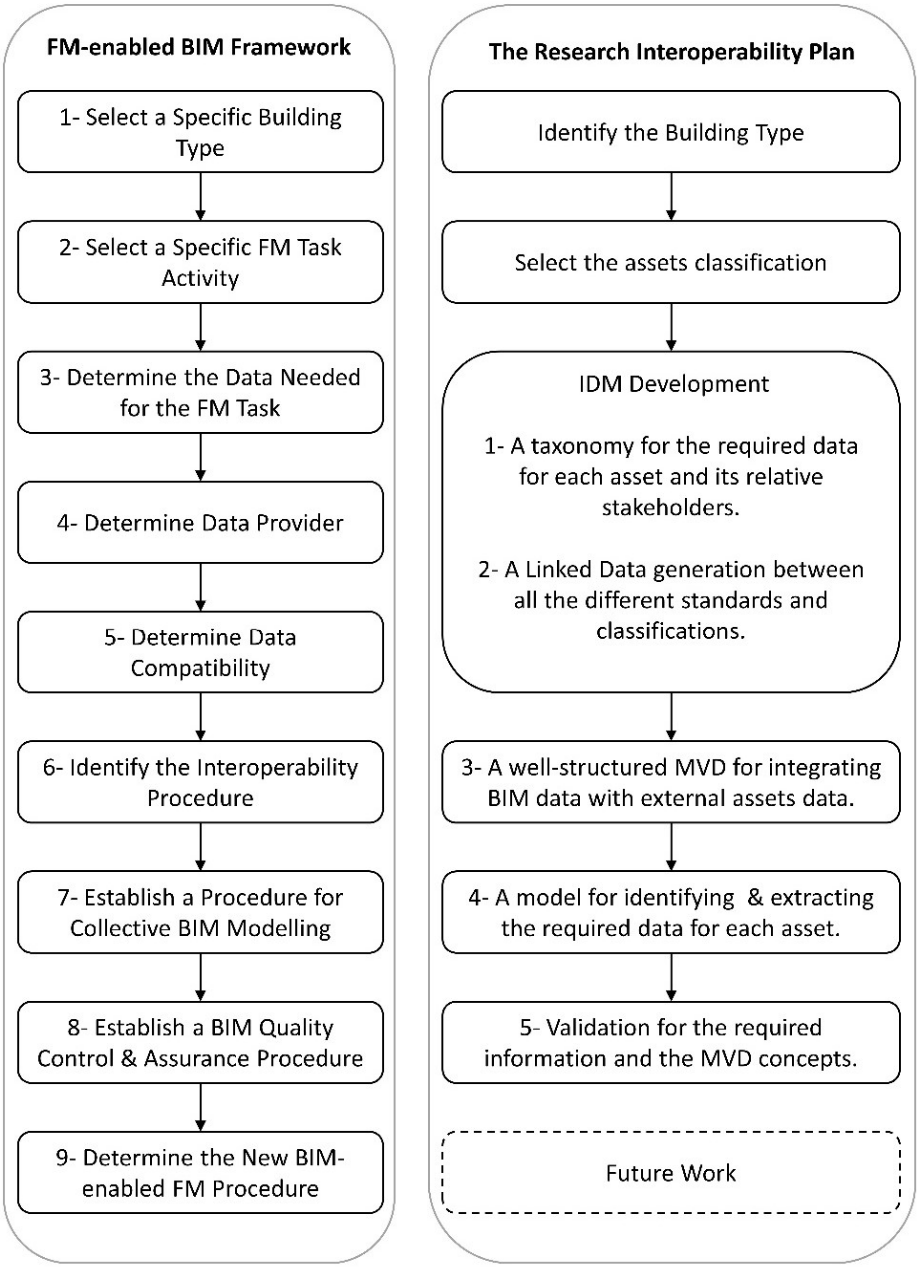


Figure 9-2: The developed process plan for FM-enabled BIM framework proposed by Pishdad-Bozorgi et al. (2018) Vs the developed process in this research

Select a Specific Building Type

ISO 55000 - Asset management — Overview, principles and terminology (2014) stated that a building maintenance strategy is one of the main aspects in the management of building operation and maintenance processes. There are four main building maintenance strategies that can be utilised during the in-use phase: reactive maintenance (breakdown maintenance), preventative maintenance (scheduled), predictive maintenance (PdM) and reliability-centred maintenance (RCM). Each strategy requires different information to be effectively adopted, while the selection of the strategy is based on the importance, size and type of the building and assets. Therefore, it is vital to identify the building type at the commencement of any BIM implementation as the building, asset or infrastructure project type will determine the information requirements for the BIM model significantly. Most of the available research into BIM implementation in FM (Thabet et al., 2016, Cavka et al., 2017, Kiviniemi and Codinhoto, 2014, Teicholz, 2013) has been conducted on buildings used in the education sector. That is because these buildings usually consist of several spaces, systems and equipment, which provides a range of opportunities for realising the benefits of using BIM for maintenance planning. This research study also concentrates on a university building for its case study.

Select a Specific FM Task Activity

Due to the heterogeneity of the assets, the required information cannot be generalised for all FM activities or for all assets or even by the asset system (Cavka et al., 2017). However, the main required information taxonomy can be generalised for assets based on their functionality and the associated FM task activity (Farghaly et al., 2018). Due to the increasing emphasis on providing a sustainable performance during a building's lifecycle, this research concentrates on assets which consume energy as buildings consume enormous amounts of energy; for example, it is estimated that they consume an average of 41% of the world's energy use during the operation phase (Boss Controls, 2016). The framework is developed for assisting maintenance personnel to enhance building maintenance operational efficiency and quality.

All the other aspects are discussed in detail in the responses to the three further questions. Question 3 discusses the data required from the building information models for the maintenance and operation of the assets that consume energy in buildings used in the education sector. Also, the data format required for each attribute is presented and the different stakeholders responsible for providing and using the data are mentioned. Question 4 shows how Linked Data and ontologies can improve the exchange of data between the BIM and AM systems. Finally, the process to collect, extract and validate the BIM data is discussed in Question 5, while the determination of the new BIM-enabled FM procedure is discussed in the sub-section on future works.

Objective 3

The identification of the information required from the building information models for AM is a necessary and critical step for the implementation of BIM in AM. The absence of that information would have a negative impact on the building performance, as it would be the reason for workflow variabilities (Arashpour and Arashpour, 2015). Variability can be reduced by defining the owner's requirements, illustrating the appropriate workflows and assigning the new jobs related to the BIM data in an early stage of the project. The information required from the building information models varies depending on the facility team's mission and goals, and also the assets and building characteristics. The required information should be presented in a taxonomical structure, as developing a taxonomy of the objects of a knowledge field can provide a common terminology that eases the sharing of knowledge and supports decision-making.

Chapter 6 presented a domain taxonomy of the data required for assets that consume energy, which has been created in order to facilitate the successful implementation of BIM in AM. The taxonomy also represents the primary stakeholders associated with the process of collecting, adding and extracting the data from the BIM models. Despite the heterogeneity of the assets and the information that has to be managed, the top level of the taxonomy can be generalised for all the required information in BIM for AM. The top level is classified into six main branches/classes: location/space, classifications, specifications, warranty, asset capex, and maintenance.

1. The location/space class hosts all the information related to the spatial location of the assets, and the facility and building descriptions. This information can be identified and captured from the architectural models during the design stage.
2. The classifications class holds the information which represents the assets as predefined in several AECO vocabularies and standards.
3. The specifications class holds the information which describes and specifies the assets from the manufacturing point of view.
4. The warranty class hosts all the information related to warranty, starting dates and test reports.
5. The asset capex class holds the information related to the asset cost and identification.
6. Finally, the maintenance class represents the information related to the O&M stage.

In Chapter 6, a taxonomy of the required information for assets that consume energy was presented using the proposed classes. Apart from information needs, there are several other important factors that need to be considered in offering a knowledge resource for asset management, such as: available, reliable and valid knowledge sources are required, and relations between the different data sources need to be considered. Therefore, cross-domain integration is required with the clear definition of required information to systematically manage activities for asset operation and maintenance.

Objective 4

The IFC format has been utilised as the format for providing information exchange between BIM and AM; however, it still presents many challenges. Although the IFC schema is a rich and vast data model that can contain the required data for different applications and needs in the AECO domain, facilities managers do not normally use it, since IFC models either do not contain the required information or they contain superfluous information which makes it difficult to extract the required information. BIM already has been moving in the direction of knowledge processing, with the development of IfcOWL, thus being able to leverage web Linked Data as a tool to extend interoperability to other knowledge domains which were not previously considered.

Ontologies excel at integrating data and resources from different knowledge domains and perspectives such as sensors, asset databases and building information models. Additionally, ontology reasoning capabilities offer new creative ways to interpret data, information and knowledge, and allow a more realistic representation of human behaviour and design knowledge than conventional tools. However, the practical application of ontology-based systems requires extensive knowledge of the domains involved and their correct definitions, and also a well-defined process for the development and publishing of ontologies and Linked Data. In addition to that, it was shown in Chapter 7 that an ontology representation of models allows a retrieval of contextual information for several AECO standards due to a rich semantic environment. Chapter 7 demonstrated that Linked Data can provide cross-mapping between the ontological sources such as Uniclass2, NRM1, NRM3, SFG20 and IFC.

Objective 5 & 6

Successful implementation of BIM in AM requires a well-executed syntactic interoperability plan for exchanging data from the BIM tools to the AM systems. The data exchange consists of four main steps: extraction, validation, sharing and integration. There are different approaches for extracting the required data from the BIM tools (discussed in Question 1). Most of the available projects use COBie as the data exchange format for extracting and sharing the required building information models with the AM systems, since the COBie spreadsheet format is compatible with several AM systems such as AiM. However, the COBie extension toolkit and similar tools only comply with open standards such as COBie 2.4; they do not comply with CMMS systems. Consequently, the use of COBie as the exchange format leads to errors related to the semantic quality of the BIM data and lack of integration due to the difference in naming conventions between the two systems. In Chapter 7, the developed Revit plug-in provides a podium to add and extract the data from the BIM models based on the identified specification in the developed taxonomy ontologies. Once the data is extracted in the IFC format, it should be validated against the developed MVD. One of the methods for validating data in the IFC model is to check the elements in the BIM authorising tool; however, that approach is labour intensive, inefficient and prone to errors (Pishdad-Bozorgi et al., 2018). Two different approaches are adopted for the validation of IFC models, which are using IfcDoc (MVDXML checker) and Semantic Web Rules Languages (SWRL).

Each approach has its own advantages and disadvantages and the selection of the approach is based on the requirements of the research project.

The requirements for syntactic interoperability can be summarised into the following: 1) the facility managers and the AM system specialist should be involved at an early stage of the project to specify the data-formatting requirements compatible with the selected AM system; 2) the BIM models should be developed using one of the BIM tools and the assets should be represented using parametric elements which can be associated with several parameters, and also the elements should be mapped to the relevant IfcClass in the latest IFC schema; 3) continuous validation should be conducted on the building information models against the developed MVDs and the facility manager's specifications; and 4) An early pilot study has to be conducted to guarantee smooth data integration between the two systems.

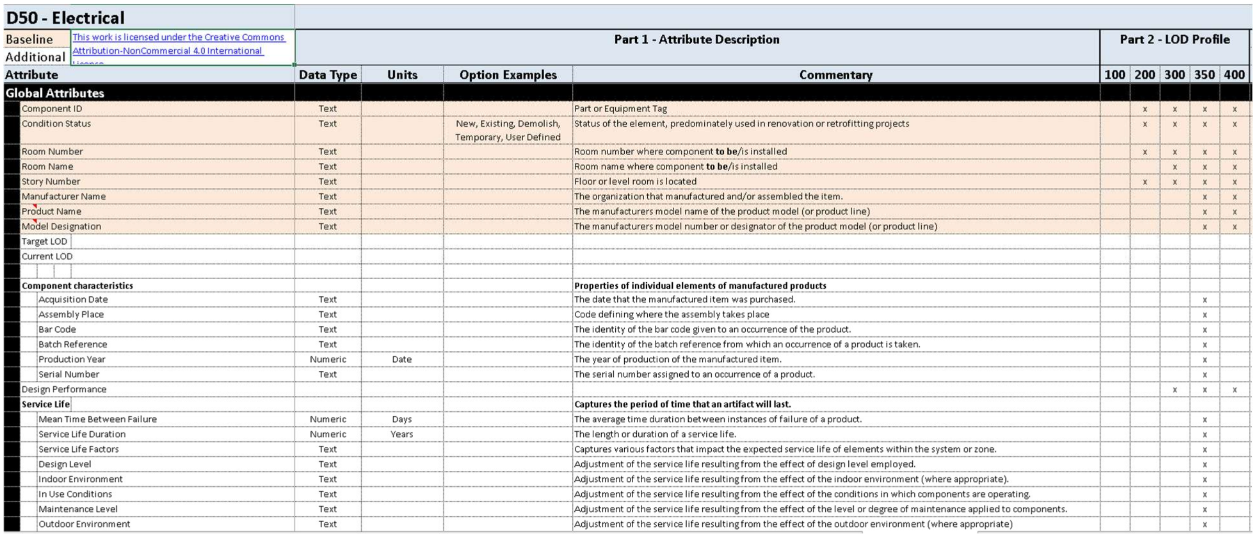
9.3 Future Research Topics

9.3.1 Post-occupancy Evaluation Approach for Information Exchanges

Although COBie is seen as the international standard for the publication of a subset of building information models focused on delivering asset data, several experts and researchers have critiqued the COBie schema and templates as providing a maze of ambiguous field names, and many of its attributes are confusing (John, 2013, Yalcinkaya and Singh, 2019). Therefore, it is time to evaluate COBie post-implementation and investigate its practical applications in supporting the FM activities. As far as this researcher is aware, all the COBie evaluation studies have been undertaken at the implementation stage in order to verify the extraction and integration process; however, none of these studies discuss either the business value of implementing COBie or raise the errors which come to light post-implementation. This study aims to help modify the current data flows to make them more efficient and effective. It also aims to enhance the COBie specifications so they might reach the desired level of maturity.

9.3.2 Development of MVD Using the 2016 xl Table

In November 2017, the BIMForum, the US chapter of BuildingSMART, released a spreadsheet for the level of details (LOD) specifications. The spreadsheet represents each system in a separate sheet and the related non-graphical attributes required in each LOD stage (Figure 9-3). The attributes are divided into three main categories: Baseline, Additional and Item Specific. Baseline attributes are the ones populated when no other requirements are specified in the EIR document. The additional ones are the possible attributes that would be required for a specific purpose, such as asset maintenance. The item-specific attributes are the attributes related to a specific item from the system, such as the number of sockets. This attribute is only related to the outlet element. The future research suggestion here is to develop an MVD for the identified attributes in the LOD specification and verify it using several case studies.



D50 - Electrical

Baseline
Additional

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	Part 1 - Attribute Description				Part 2 - LOD Profile				
Attribute	**Data Type**	**Units**	**Option Examples**	**Commentary**	**100**	**200**	**300**	**350**	**400**
Global Attributes									
Component ID	Text			Part or Equipment Tag		x	x	x	x
Condition Status	Text		New, Existing, Demolish, Temporary, User Defined	Status of the element, predominately used in renovation or retrofitting projects		x	x	x	x
Room Number	Text			Room number where component **to be**/is installed		x	x	x	x
Room Name	Text			Room name where component **to be**/is installed			x	x	x
Story Number	Text			Floor or level room is located		x	x	x	x
Manufacturer Name	Text			The organization that manufactured and/or assembled the item.				x	x
Product Name	Text			The manufacturers model name of the product model (or product line)				x	x
Model Designation	Text			The manufacturers model number or designator of the product model (or product line)				x	x
Target LOD									
Current LOD									
Component characteristics				**Properties of individual elements of manufactured products**					
Acquisition Date	Text			The date that the manufactured item was purchased.				x	
Assembly Place	Text			Code defining where the assembly takes place				x	
Bar Code	Text			The identity of the bar code given to an occurrence of the product.				x	
Batch Reference	Text			The identity of the batch reference from which an occurrence of a product is taken.				x	
Production Year	Numeric	Date		The year of production of the manufactured item.				x	
Serial Number	Text			The serial number assigned to an occurrence of a product.				x	
Design Performance							x	x	x
Service Life				**Captures the period of time that an artifact will last.**					
Mean Time Between Failure	Numeric	Days		The average time duration between instances of failure of a product.				x	
Service Life Duration	Numeric	Years		The length or duration of a service life.				x	
Service Life Factors	Text			Captures various factors that impact the expected service life of elements within the system or zone.				x	
Design Level	Text			Adjustment of the service life resulting from the effect of design level employed.				x	
Indoor Environment	Text			Adjustment of the service life resulting from the effect of the indoor environment (where appropriate).				x	
In Use Conditions	Text			Adjustment of the service life resulting from the effect of the conditions in which components are operating.				x	
Maintenance Level	Text			Adjustment of the service life resulting from the effect of the level or degree of maintenance applied to components.				x	
Outdoor Environment	Text			Adjustment of the service life resulting from the effect of the outdoor environment (where appropriate)				x	

Figure 9-3: Attribute table anatomy for electrical assets - level of development specifications

9.3.3 Development of IamOwl

Generally, it is a good idea to include as many information sources as are available in order to enhance the level of detail of the building assets' topologies and relations to each other. Unfortunately, manual and semi-automatic maintained pools of information tend to become outdated rapidly and may be incomplete and/or superfluous, which would result in a degradation of quality regarding asset management. The implementation of ontology engineering for the creation and use of ontologies in environments of disparate information sources has shown great success in several research fields. The proposed research topic is the development of an ontology (IamOWL – Information for Asset Management) which would represent all the classes and individuals utilised in AM platforms such as Maximo and AiM. Also, the proposed ontology for development should take into consideration the PAS 55-2 standard during the development of the classes and slots. The resulting ontology and instantiations of its concepts and roles can be split along semantically meaningful borders to improve queries and reasoning tasks, and for its reuse in different contexts. Also, it would significantly improve the interoperability between the CMMS databases and other technologies such as BIM, IoT and also sensors databases. A crucial contribution would be cross-linking the IfcOWL and IamOWL.

Chapter 10 General Conclusions

10.1 Introduction

This concluding chapter opens with a summary of the key findings. Next, it highlights the contribution to knowledge generated by this study. This is done with reference to the chosen research methods and as evidenced in the four main research outcomes. Finally, the limitations of the work are presented and recommendations for further study are proposed.

10.2 Summary of Key Findings

Despite the potentially transformational competencies of BIM which are presented in Chapter 2, which in essence facilitate the effective management and operation of building assets, the implementation of BIM in AM still faces several obstacles. One of the main obstacles is achieving interoperability between BIM and AM platforms. Several information-exchange specifications such as COBie and SPARKie have been developed to achieve interoperability. However, it has been argued that these information-exchange specifications alone are not sufficient as they are either generalised for all assets or for specific asset systems. Also, these specifications focus only on developing technology-driven functions and applications to overcome the syntactic interoperability barriers and they neglect the development of computable information requirements for better semantic interoperability.

Therefore, the aim of this thesis has been to enhance the BIM-AM exchange process by focusing on improving both semantic and syntactic interoperability for the data exchange of assets that consume energy from the BIM tools to the AM systems during the handover stage. This was fulfilled by achieving the objectives stated in Chapter 1 and by addressing the three formulated research questions in 1.2. To recapitulate, the key objectives of the research were to:

1) Evaluate the theory and practice of BIM implementation for enhancing AM.
2) Develop a conceptual framework of the semantic and syntactic interoperability aspects for BIM implementation in AM.
3) Identify the required information to be exchanged from building information models for AM during the handover stage.
4) Establish a cross-mapping amongst all the different AECO standards and guidelines using ontology and Linked Data.
5) Develop a syntactic interoperability solution to exchange data from BIM to AM platform.
6) Demonstrate and evaluate the usage of the developed semantic and syntactic interoperability solutions through a real-world case study.

Following the application of concurrent mixed methods and methodological triangulation discussed in Chapter 5, the outputs have met these objectives. The outputs of the research can be classified into four main elements:

a) Taxonomy of required information during handover for assets that consume energy.
b) Linked Data between the different AECO standards.
c) API plug-in for Autodesk Revit in order to add, connect and extract the required information.

d) MVD for exchange of assets that consume energy data from building information models to AM systems.

10.2.1 Taxonomy of Required Information

Due to the heterogeneity of assets' characteristics, the developed taxonomy focuses only on the assets consuming energy in educational buildings. The developed taxonomy consists of 60 parameters categorised into six main categories: Space/Location, Classifications, Specifications, Warranty, Asset Capex and Maintenance. Each category contains various parameters which can be instance or type parameters. Each defined parameter is associated with the stakeholders responsible for adding and using the data and the project phase where the data can be added. The developed taxonomy represents the data required for the effective application of BIM for AM. The taxonomy, which is based on international data, could facilitate further academic research, contribute to the relevant on-going works by the AECO industries and provide the underlying foundation for establishing the owner's Asset Information Requirements (AIR).

10.2.2 Linked Data of AECO Standards

Identifying the information required from the BIM models alone is not enough to effectively conduct AM-related activities. Cross-domain integration with a clear definition of the required information would be more effective to systematically manage activities for asset operation and maintenance. This research presented a process map for Linked Data generation for building assets to improve asset management. By providing a detailed description of all the tasks and related tools and technologies in the generation and publication processes, the developed process map can help both owners and facilities mangers to manage the building assets information from different databases with semantically Linked Data.

The different developed ontologies reused terms of widely deployed vocabularies and standards in the AECO industry, such as IFC, NRM1, NRM3, Uniclass2 and SFG20. Vocabularies linking using schema-level constructs of classes and properties provides a shared knowledge representative of a conceptual model. The different classes of the ontologies from the selected standards were object/asset-based linked and mapped. The proposed process map aims to help researchers and practitioners interested in managing and operating building assets without authorisation of BIM platforms and by exploiting Linked Data technologies. Although it is possible to create the same mapping system using traditional SQL-based technology, the usage of the Linked Data approach can provide a foundation for enabling modularity of new technologies and future extensions for the systems.

10.2.3 Revit Plug-in

In this research, the process of adding, mapping and extracting the required information from the building information models for the proposed exchange is translated to the developed Revit plug-in. Revit 2019 was selected as it was the latest version released at the time of the research; it also contains several enhancements in the IFC export functions, and it provides developers with a rich documentation resource in the Software Development Kit.

The developed Revit plug-in consists of three primary add-ins. The first add-in supplements the required non-graphical information that is not predefined within the Revit elements. The second add-in function is to fill in some of the information automatically and it consists of three main sub-functions. The first sub-function reads from the linked architecture model and recognises the room space hosting the asset and, finally, it fills in all the parameters related to location and spaces as defined in the architecture model's rooms. The second sub-function numbers the assets of the same type in the same room to easily identify them. The third and last sub-function of the second add-in is filling the classification parameters based on the cross-mapping developed between the ontological sources. Finally, the third add-in automatically generates six schedules with the parameters hosted in each property set. The generated schedules are named as the property sets defined in the MVD based on the developed taxonomy classification. The generated schedules can easily be exported as an IFC model to be evaluated against the developed MVD.

10.2.4 ACEie MVD

For the development of an MVD, an IDM has to be developed first. An IDM was created by engaging experts in seven semi-structured interviews and two focus groups, which ensured that the final model would be sufficiently semantically meaningful to provide most of the information required for decision-making concerning the operation and maintenance of assets that consume energy. The developed IDM provided a process map for data exchange during the handover stage, a set of information required to be delivered in each exchange model (64 attributes in total) and also a list of the assets to be exchanged. Consequently, an MVD was formed which meets the end-user's needs as defined in the IDM and provides an implementable format for sending and receiving software applications. The MVD was developed based on the latest IFC schema (IFC 4 Add2) using the IfcDoc tool. It consists of four exchange models, 86 entities, 10 different concept templates, and six property sets and their hosted 62 properties. The four EMs are: ACEie_Space/Location, ACEie_Classification, ACEie Capex & Warranty, and ACEie_Maintenance. Each EM indicates a particular subset of information to be exchanged in a particular stage in the handover phase.

10.3 Key Contribution to the Body of Knowledge

This research contributes to knowledge in two different contexts, which are theoretical and practical. Within the theoretical context, there were two main research outcomes, which are related to semantic interoperability. The first outcome/finding was a conceptual taxonomy where the critical information required from BIM models for asset management practice is identified, and workflows, roles and responsibilities to fully integrate these datasets are stated. Moreover, the conceptual taxonomy is polished in the light of the case study evaluation. The second outcome was Linked Data where all the different standards and classifications used in the AEC and O&M domains are linked to each other as ontological sources to enhance the semantic interoperability among BIM and AM systems. The developed process map for the Linked Data development also contributes to the knowledge of managing and operating building assets without the authorisation of BIM platforms and by exploiting Linked Data technologies.

On the other hand, within the practical context, an innovative MVD that would improve the integration between BIM data and other asset databases for better asset management decisions was developed. The developed MVD specifies the appropriate entities required from the IFC schema to maintain and operate the assets which consumes energy in a building. Also, a possible application in a BIM platform to identify and extract the required data based on the proposed taxonomy was developed and demonstrated in a real-world project. The process of adding, connecting and extracting the required information from the building information models for the proposed exchange is translated by the developed Revit plug-in

Meanwhile, this research provided a contribution to knowledge in a broader sense in the following ways:

1- Knowledge has been added from the literature surveys in the fields of BIM, AM, Ontologies and Linked Data, commenting on recent developments, limitations, benefits and the potential for integration between different technologies.

2- The sum of the investigations conducted within the scope of this research, has contributed to the overall knowledge about BIM-AM data integration approaches and associated limitations and challenges. Also, it has outlined how Linked Data can enhance BIM-AM data integration. The proposed process of development and publishing of Linked Data outlined in this research would also be easily replicated for other purposes and further benefitting from Linked Data concepts.

3- The investigation into BIM and AM interoperability has also contributed to knowledge by identifying the main semantic and syntactic interoperability concepts, while commenting on their implementation methods and challenges. Also, it showed that researchers should concentrate their work more on the semantic interoperability concepts rather than the syntactic interoperability concepts, as the BIM-AM integration using the available approaches seemed to go smoothly, but unexpected errors usually occur when importing the COBie spreadsheet into the AM systems. Most of the errors that arise during the exchange of data from building information models to AM systems are related to semantic interoperability, such as: models containing superfluous information, or information is missing, the absence of mapping predefined parameters and incompatible value types.

10.4 Limitations, Future work and Recommendations

10.4.1 Limitations

This research provides a rich understanding of the problematic nature of the interoperability between BIM and AM, and shows that achieving semantic and syntactic interoperability between the required datasets extracted from the building information models and the AM systems is crucial in order to achieve better asset management performance. However, there are some limitations, which future research could address. These limitations can be summarised as follows:

- The developed taxonomy concentrates only on the assets which consume energy, as it is hard to generalise the required information for all the maintainable assets due to their heterogeneity characteristics.
- The developed ontologies from the ontological sources such as NRM1, NRM3, SFG20 and Uniclass2 are currently limited to only a few types of assets (assets which consume energy). That was done to cover only the research focus and also for simplicity.

Once the mapping between the ontological sources has been executed, a case study of an educational building was conducted to evaluate the proposed mapping. The case study had several limitations due to the absence of required information from sensors and other databases to provide information related to other aspects such as the occupant behaviour, room temperature and lecture schedules.

- Despite the case study evaluation for the developed MVD, certification testing has not been performed on the developed MVD by the third parties recommended by BuildingSMART and BLIS.

10.4.2 Future Work

Considering the limitations stated in the previous sub-section, 10.4.1, the following could be addressed in future work:

- The developed taxonomy scope could be extended to cover more assets and compared to the developed LOD specification 2016 where the required information for each asset is individually stated.
- The developed ontologies could be enhanced by adding the other assets' classifications to the ontological sources. Additionally, further investigation could add more SWRL queries and rules, as the developed SWRL rules are currently limited to only a few types of assessment.
- More case studies could be conducted to evaluate the developed Linked Data; the future case studies should include data related to occupant behaviour, room temperature and lecture schedules.
- The developed MVD could be sent to BuildingSMART as an MVD proposal to be evaluated by the community. Also, further work could include the preparation of the software certification, which means specifying test cases and expected quality criteria. The conducted case study could be a starting point for the next stage, with more case studies conducted to verify the developed MVD and Revit plug-in.

10.4.3 Recommendations

Based on the conclusions and research findings of this study the recommendations for the construction industry and suggestions for further research are summarised as follows:

- The AECO industry as a whole must work together to establish a well-structured taxonomy for the required information for all the maintainable assets based on the developed LOD specification 2016 and other developed taxonomies. Also, the taxonomy should be evaluated using multiple real-world projects.
- Clients have to promote and implement a process to add, extract and exchange required information for the effective management of the building assets during the operational stage. Also, this required information and associated tools and methods for collection, extraction and exchange have to be documented in the EIR at an early stage of the building lifecycle.
- As presented in the Discussion chapter, the main challenge during the exchange of data from BIM models to AM systems is the semantic errors that show up once the required data is imported to the AM systems. These semantic errors comprise missing information, the absence of mapping predefined parameters and incompatible value types. Researchers should investigate the development of an ontology for main classes and individuals in asset management systems and the developed ontology should be mapped to the IfcOWL ontology.
- Semantic validation of the information extracted from the building information models is a critical step for effective interoperability. Further research should be undertaken to investigate the use of other applications such as those for evaluating the data extracted from the building information models against the predefined rules.

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