A FRAMEWORK AND COMMON DATA ENVIRONMENT FOR THE DEVELOPMENT AND MANAGEMENT OF ASSET INFORMATION MODELS

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DECLARATION

I declare that this thesis represents my own work, except where due acknowledgement is made, and that it has not previously been included in a thesis, dissertation or report submitted to this University or any other institution for a degree, diploma or any other qualification. Parts of this thesis have been published in conference and journal papers listed in the "List of publications" section.

Signed:____

Date:____

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ABSTRACT

Accurate and valid data is essential for the management of buildings throughout their lifecycle. The development of the Building Information Modelling (BIM) methodology and associated technologies and standards presents a unique opportunity to capture Building Owner and Facilities Management (FM) asset data requirements in a structured manner from the early stages of project development. However, an integrated approach is still needed to enable their use in the development of Asset Information Models (AIMs) - data models that contain all digital data (graphical, non-graphical, and documentary) required to operate an asset or portfolio of assets.

This research combines the Design Science Research Methodology (DSRM) and Grounded Theory Method (GTM) in the design of a framework and Common Data Environment (CDE) to support the development and management of AIMs. The framework defines processes for the: (a) structured definition of requirements for FM and maintenance tasks; (b) validation of project data deliverables against the established requirements; and (c) development, management, and visualisation of building asset data. The framework combines the use of Information Delivery Manual (IDM), Industry Foundation Classes (IFC), Construction Operations Building information exchange (COBie), and Content Management Interoperability Services (CMIS) in the development of AIMs to fulfil the owner's Asset Information Requirements. A bespoke CDE based on the Service Oriented Architecture (SOA) is proposed for the management, integration and visualisation of AIM data.

The proposed framework was successfully demonstrated in a selection of pilot studies through the implementation of a bespoke prototype CDE. The pilot studies demonstrated the framework's processes in the development and visualisation of AIMs, focusing on preventive and reactive maintenance tasks. The application of the GTM for data collection and analysis resulted in a comprehensive list of requirements for the development and management of AIMs, which were used to validate the proposed framework and CDE's capabilities. Results from the validation show that the key capabilities of the proposed framework and CDE have been achieved. The prototype CDE demonstrated the integration of the various asset data

sources in the development and management of AIMs. The visualisation of the AIM data - from different and distributed sources - for maintenance tasks was successfully performed in an interactive virtual environment. The demonstration and validation activities provide key inputs for a future evaluation of the research in practice. Additional requirements for the development and management of AIMs were identified during the validation sessions, which should be considered in future work related to this research.

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List of Abbreviations and Acronyms

ACL – Access Control List

ACR – Asset Criticality Rating

AEC – Architecture Engineering and Construction

AIM – Asset Information Model

AIR – Asset Information Requirements

AM – Asset Management

API – Application Programming Interface

BAS – Building Automation System

BCF – BIM Collaboration Format

BERA – Building Environment Rule and Analysis

BIFM – British Institute for Facilities Management

BIM – Building Information Modelling

BIMRL – BIM Rule Language

BMS – Building Management System

BOT – Building Ontology Topology

BPie – Building Programming information exchange

BPMN – Business Process Modelling and Notation

BR – Business Rules

BS – British Standards

BSI – British Standards Institution

CAFM – Computer Aided Facilities Management

CDE – Common Data Environment

CDP – Compliant Design Procedures

CG – Conceptual Graph

CIBSE – Chartered Institution of Building Services Engineers

CMIS – Content Management Interoperability Services

CMMS – Computerized Maintenance Management System

COBie – Construction-Operations Building information exchange

DL – Description Logic

DSR – Design Science Research

DSRM – Design Science Research Methodology

ECM – Enterprise Content Management

EDMS – Electronic Document Management System

EERM – Enhanced Entity Relationship Models

EIR – Employer Information Requirements

ER – Exchange Requirements

FM – Facilities Management/ Facility Manager

FMC – Facilities Management Classes

FP – Functional Parts

GIS – Geographical Information System

GSL – Government Soft Landings

GT – Grounded Theory

GTM – Grounded Theory Method

H&S – Health & Safety

HVAC – Heating, ventilation, and air conditioning

IDE – Integrated Development Environment

IDEF0 – Icam DEFinition for Function Modeling

IDM – Information Delivery Manual

IEQ – Indoor Environmental Quality

IFC – Industry Foundation Classes

IFCOWL – IFC Web Ontology Language

IFCWOD – IFC Web of Data

ISO – International Standards Organization

IS – Information Systems

IT – Information Technology

IWMS – Integrated Workspace Management System

JSON – JavaScript Object Notation

JVM – Java Virtual Machine

KPI – Key Performance Indicator

LCie – Life Cycle Information Exchange

LOD – Level of Development

M&E – Mechanical and Electrical

MEP – Mechanical, Electrical & Plumbing

MVD – Model View Definition

NBIMS – National BIM Standard

NBS – National Building Specification

NIBS – National Institute of Building Sciences

NLP – Natural Language Processing

NRM – New Rules of Measurement

O&M – Operations and Maintenance

OASIS – Organization for the Advancement of Structured Information Standards

OIR – Organisational Information Requirements

OMG – Object Management Group

OPM - Ontology for Property Management

OWL – Web Ontology Language

PARL – Percentage of Asset Remaining Life

PAS – Publicly Available Specification

PDT – Product Data Template

PM – Preventive Maintenance

RASE – Requirement, Applicability, Selection, Exception

RDF – Resource Description Framework

RDM – Regulatory Document Models

REST – Representational State Transfer

RIBA – Royal Institute of Bristish Architects

RKM – Regulatory Knowledge Model

RKQL – Regulatory Knowledge Query Language

RM – Reactive Maintenance

SLA – Service Level Agreement

SMC – Solibri Model Checker

SOA – Service Oriented Architecture

SOAP – Simple Object Access Protocol

SOSA - Sensor, Observation, Sampler, and Actuator

SPARQL – SPARQL Protocol and RDF Query Language

SPie – Specifiers' Properties information exchange

SPFF – STEP (Standard for the Exchange of Product Model Data) Physical File Format

SPIN – SPARQL Inferencing Notation

SQL – Structured Query Language

SQuaRE – Systems and software Quality Requirements and Evaluation

SSAIM - Smart Sewer Asset Information Model

SSN - Semantic Sensor Network

STEP – Standard for the Exchange of Product Model Data

SWRL – Semantic Web Rule Language

UML – Unified Modeling Language

VCCL – Visual Code Checking Language

W3C – World Wide Web Consortium

WLC – Whole Life Cycle Cost

XML – eXtensible Markup Language

XSD – eXtensible Markup Language Schema Definition

1 INTRODUCTION

1.1 Background and motivation

The operation and maintenance phase of buildings is typically the longest and most costly stage in the building lifecycle, accounting for over half of the total lifecycle costs (Akcamete *et al.*, 2010; Becerik-Gerber *et al.*, 2012; Teicholz, 2013; Kassem *et al.*, 2015).

Building owners and Facility Managers need accurate and reliable data to operate and maintain their buildings efficiently. To this end, they rely on data that is generated throughout the planning, design and construction phases of building projects. Data and information handover is usually left until the completion of the construction phase, and information is typically handed over in unstructured formats in a labour intensive, error-prone process (Gallaher *et al.*, 2004). This introduces significant challenges for owners and facility managers when assessing whether the information they need to manage their buildings is included in the handover data.

The development of the Building Information Modelling (BIM) methodology and associated technologies and standards presents a unique opportunity to efficiently manage building asset data exchanges throughout project development, handover, and during the use phase of buildings. According to the National Institute of Building Sciences (NIBS), BIM can be defined as: "(…) a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition." (NIBS, 2019). BIM provides project stakeholders with the capability of interchanging data and information between different technologies and processes across the whole lifecycle of buildings. BIM implementation at the design and construction stages has provided several benefits, particularly in the management of design, construction schedules and corresponding costs (Eastman *et al.*, 2011; Love *et al.*, 2014). To maximise these benefits, building owners need to be involved in the design and development of building projects (McGraw-Hill, 2014).

The implementation of BIM considering a whole life cycle approach is expected to lead to increased information quality and reduced maintenance costs, as a result of automated transfer of accurate, complete and unambiguous information during the handover stage of projects, and during the transfer of building operation between service providers (BSI, 2014b). It is also expected to improve input for decisions at the operational level, by enabling the measurement of the actual performance of building assets (BSI, 2014b).

The emergence of open BIM standards such as IFC and COBie, and methodologies such as the Soft Landings framework, is expected to enable the handover of digital data and information in a gradual and structured way (BSRIA, 2009). The use of open standards is expected to mitigate interoperability, data transfer and data integrity issues throughout project development and during the handover stage.

Several countries such the United Kingdom and the Scandinavian countries, and large clients such as the General Services Administration (an independent agency of the United States) have prescribed open standards and data specifications as data sources and information exchange formats between the project delivery phases and the use phase of the building (Kassem *et al.*, 2015). According to the "Business Value of BIM for Owners" report, building owners in the United Kingdom (UK), both in the private and public sector are increasingly requiring the use of BIM (McGraw-Hill, 2014). The UK Government has mandated "BIM level 2" (i.e. file-based collaboration and library management) on all centrally procured Government projects. As part of the UK Government's BIM strategy, the BS/PAS 1192 series of UK standards has been developed to assist the industry in transitioning into "BIM level 2". The importance of the UK standards has been internationally recognised, and the BS/PAS 1192 series of standards forms the basis of the new series of ISO 19650 standards (ISO, 2017). As part of this strategy, PAS 1192-3:2014 specifies an information management methodology based on the development of Asset Information Models (AIM) - a data model that contains all digital data required to operate an asset or portfolio of assets (BSI, 2014b). Figure 1.1 provides the definition of the various BIM maturity levels, how they are supported by the use of open standards, and how they relate to the AIM development process.

When considering the myriad of data sources that building owners and FMs need to manage, it becomes apparent that file-based collaboration (i.e. "BIM level 2") will not be sufficient for the development and management of AIMs. While file-based collaboration using federated, disparate data sources could be adopted during the project development stages, it will not be sufficient to ensure the data quality and integrity of the various data sources of the AIM.

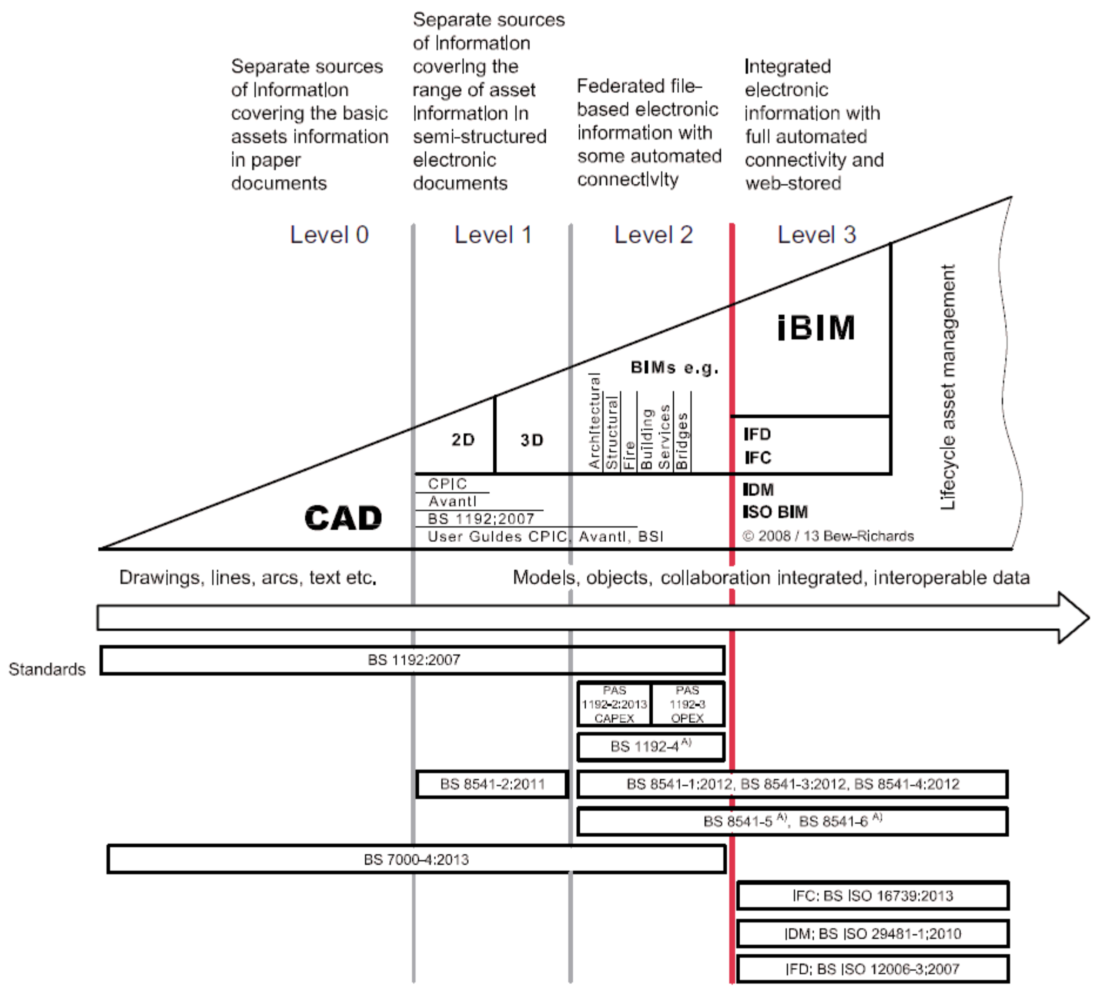

Figure 1.1 – BIM maturity levels extended to asset information management (BSI, 2014b)

Information Technology (IT) solutions based on the Service-Oriented Architecture (SOA) have been regarded as one of the possibilities to address the limitations of file-based collaboration in the development and management of AIMs. SOA-based IT solutions can take advantage of the object oriented nature of BIM in order to enable the integration and synchronisation of the various AIM data sources at object level. The adoption of SOA to enable data interoperability in the AEC/FM industry has been the focus of research for a number of years (Isikdag & Underwood, 2010; Jardim-Goncalves & Grilo, 2010). It is expected that its adoption within the AEC/FM industry will provide the technical support for "BIM Level 3" – Collaboration using web-stored integrated electronic information with fully automated connectivity (BSI, 2014b). Nonetheless, various challenges related to data ownership and versioning must be overcome for SOA-based solutions to become ubiquitous in the industry.

The adoption of data and information management methodologies from the early project development stages can facilitate the validation of the deliverables across the project lifecycle phases, providing accurate AIMs that can be used as a basis for the definition of FM and maintenance tasks. In particular, the structured definition and validation of project deliverables against the data and information requirements of owners and facility managers (e.g. Operations & Maintenance manuals, Health & Safety files and other documents) can improve their handover and support decision making during the operational phase of assets (BSI, 2014b).

This research investigates the current challenges in data management for building owners and facilities management, particularly in the development and management of AIMs. Within this context, this research proposes a framework and Common Data Environment (CDE) for the development and management of AIMs, based on the use of open standards and the SOA. The proposed framework and CDE support the structured definition of data requirements of building owners and facility managers, the validation of project and asset data against such requirements, and the management of the various AIM data sources.

1.2 Research Problem

The unstructured and late delivery of data and information at the handover stage of buildings has been recognised as a key obstacle for the effective development of AIMs. BIM technologies, workflows and standards are providing new possibilities to address these challenges, streamlining the development of AIMs that can be used for Facility Management (FM) and maintenance tasks for both new and existing buildings (Volk *et al.*, 2014). This has been recognised both in recent research efforts, and in the development of standards for the implementation of BIM in the use phase of buildings (BSI, 2012b, 2014b, 2014a, 2015). In particular, an increasing number of case studies have been developed in recent years to showcase and discuss BIM applications in FM and maintenance in these two types of assets - a review is provided in Chapter 3, section 3.2.1.

As a result of this significant body of research, key requirements for the implementation of BIM in FM and maintenance have been identified, to ensure that the development and management of AIMs consider both the owner's intended use for the building, as well as the FM requirements for the management of the building. These include the systematic definition and validation of building owners' requirements, the use of open standards for AIM data sources, and integration of asset data for AIM data management.

A wide range of requirements are developed and validated throughout the lifecycle of buildings. However, problems in addressing and complying with these requirements are still prevalent in the AEC-FM industry, resulting in both projects and assets that underperform compared to the original specifications (Kiviniemi, 2005; Parsanezhad *et al.*, 2016).

The formalisation of building owners' requirements is expected to improve this situation and it is increasingly attracting research interest. An emphasis has been placed on developing frameworks and models that enable both the propagation of client requirements to stakeholders throughout the project lifecycle, and the involvement of clients and facility managers from the early stages of building project development. For example, Kamara *et al.*, (2000) proposed a framework to convey the information in owner requirements to stakeholders in design and construction. Research focusing on the management of building owner requirements in the construction supply chain has highlighted inconsistencies in the interpretation of owner requirements (Nummelin *et al.*, 2011), including the documentation of changes to the requirements (Kiviniemi, 2005). The use of BIM and its underpinning open standards provides the opportunity for structuring these information requirements and supporting their changes and validation throughout the lifecycle of a building. Several approaches have been proposed for the formalisation of the requirements definition based on BIM (Arayici *et al.*, 2005; Kiviniemi, 2005; Teicholz, 2013; Love *et al.*, 2014; Mayo & Issa, 2014; Marchant, 2016; Cavka *et al.*, 2017).

While the current body of research and standardisation efforts such as the PAS1192-3:2014 (BSI, 2014b) recommend the structured definition and consideration of the owner's requirements in the development of AIMs for building and infrastructure projects, a methodology to support the definition and validation of the requirements within the AIM development and management processes is still lacking. Additionally, even though the importance of using open standards and web-based information management and collaboration has been highlighted in PAS 1192 and ISO 16950 standards, both the standards and the existing literature are focusing on the development of AIMs using file-based collaboration approaches (i.e. “BIM level 2”).

A novel approach, including innovative IT solutions based on web-enabled integrated asset data, is needed for the development and management of AIMs, which can be reliably used as a basis for FM and maintenance tasks. To this end, this research proposes the design of a framework and CDE for the development and management of Asset Information Models, considering the definition and validation of building owner and FM requirements, and the use of open standards and open, web-enabled technologies.

From a theoretical viewpoint, this research investigates the requirements that need to be considered in the design of a framework for the development and management of AIMs, in particular the methodologies that can be employed for the structured definition and validation of owner and FM requirements, and the standards that can be used to support the information requirements of AIMs.

From a technical point of view, the research addresses the need for the development of SOA-enabled IT solutions that can support the various development and management processes of AIMs, while providing flexibility and scalability to support specific needs of building owners and FMs, and ensuring the integrity of the various data sources of AIMs.

1.3 Research Scope

This research focuses primarily in the development requirements of AIMs for buildings, in particular to support the handover stage, and the definition of preventive and reactive maintenance tasks. Using the PAS 1192-3 as a starting point, a framework and common data environment based on the SOA are proposed for the development and management of AIMs.

The framework proposes the adoption of open standards for the structured definition of Asset Information Requirements (AIR), considering graphical, non-graphical and documentary data sources, including Information Delivery Manual (IDM), Industry Foundation Classes (IFC), Construction Operations Building information exchange (COBie) and Content Management Interoperability Services (CMIS). The framework defines processes for the structured definition of AIR and validation of asset data sources in the development of AIMs.

A Common Data Environment (CDE) is proposed to demonstrate the development of Asset Information Models (AIMs) following the framework's processes. The CDE demonstrates how existing SOA-based applications can be integrated to provide building owners and FMs with AIMs with accurate information from different sources, which can be used as a basis for various building management tasks, in particular to manage preventive and reactive maintenance tasks. This research does not consider all the different data sources that owners and FMs would need to use for the management of buildings, since these depend on each building owner's specific needs. Instead, the adoption of the SOA methodology is proposed, in order to provide the needed flexibility and scalability for CDEs, which will enable the integration of additional IT systems according to the building owner's specific requirements.

1.4 Research Aim and Objectives

This research aims to provide building owners and facility managers with methods and tools to manage their buildings using Asset Information Models.

The overarching implication from achieving this aim is to ensure the data integrity throughout the AIM development processes, in order to enable the use of AIMs as a reliable basis for the definition of FM and maintenance tasks. To achieve this it is essential to investigate the information standards and technologies that can support the development and management of AIMs, ensuring that they accurately represent the built assets. In order to support the research aim, several objectives have been identified:

1. Investigate the state of the art and identify industry requirements for the development of Asset Information Models (AIMs).
2. Identify existing standards to support the information requirements of AIMs.
3. Identify suitable methods for the validation of AIM data sources against building owner's requirements.

4. Development of a framework to support the validation of AIM data sources, and the development, management and visualisation of AIMs.
5. Development of a prototype CDE to support the validation of AIM data sources, and the development, management and visualisation of AIMs.
6. Demonstration of the proposed framework and CDE through the development of pilot studies.
7. Validation of the proposed framework and CDE through the demonstration of pilot studies to academic and industry experts.

1.5 Structure of the thesis

This thesis is organised into 8 chapters. Figure 1.2 presents the overall structure of the thesis, as well as its relation to the identified research objectives. Chapter 1 describes the background and motivation for the research. The research problem is described, and the scope of the research is identified. Research aims and objectives are identified, which can contribute to answer the research problem.

Chapter 2 describes the research methodology that underpins the thesis. This chapter presents the ontological and epistemological framing of the research, the research approach and rationale, and the research design adopted in the study, including the description of the various research methods employed, the sampling strategy adopted throughout the study, and approaches to ensure the validity and reliability of the research.

Chapter 3 presents the literature review that was carried out in this research. The literature review focuses on three key areas for the development and management of AIMs. Current research on applications of BIM in FM is reviewed initially. Various open data standards and specifications that can be adopted for the development of Asset Information Models are identified and reviewed. Additionally, a review of research focusing on automated compliance checking of digital building data is provided, and various tools and methods are identified for the validation of AIM data.

Chapter 4 presents the provisional requirements model for the development of the proposed framework and CDE. The development of the requirements model consisted in carrying out semi-structured interviews with academic and industry experts, which were analysed using the Grounded Theory Method (GTM). The data analysis complemented findings from the literature review and was used to identify the key requirements for the development of the proposed framework and CDE. Chapters 3 and 4 contribute to achieve objectives 1, 2 and 3, and provide the theoretical and industry background for the development of the proposed framework and CDE.

Chapter 5 focuses on the development of the proposed framework. The key areas of the framework, along with standards, specifications and tools used to support these key areas, were previously identified through the development of the literature review and requirements gathering activities. The proposed framework describes the various processes for the development of AIMs: the structured definition and validation of owner and FM requirements; and the development, management, and visualisation of AIMs. This chapter aims to achieve objective 4.

Chapter 6 presents the development of a CDE for FM, which supports the development and management of AIMs. The architecture and infrastructure of the CDE are defined, and methods for the development, management and visualisation of AIMs are detailed. A prototype CDE is developed based on the defined requirements. This chapter aims to achieve objective 5.

Chapter 7 describes the demonstration and validation activities of the research, which were carried out to provide the technical and theoretical validation of the proposed framework and CDE. The prototype CDE was used to develop pilot studies to showcase the framework's processes in the development of AIMs, focusing on the support of preventive and reactive maintenance tasks. The validation activity consisted of demonstration of the developed pilots to a selection of industry and academic experts, followed by unstructured interviews that were analysed using the GTM, resulting in the updated requirements model for the proposed framework and CDE. The updated requirements model was used for the validation of the proposed framework and CDE and to identify additional requirements to be considered in future research. This chapter aims to achieve objectives 6 and 7.

Chapter 8 summarises the research findings. The limitations of the research and the contribution to knowledge are elicited and recommendations for future work are proposed.

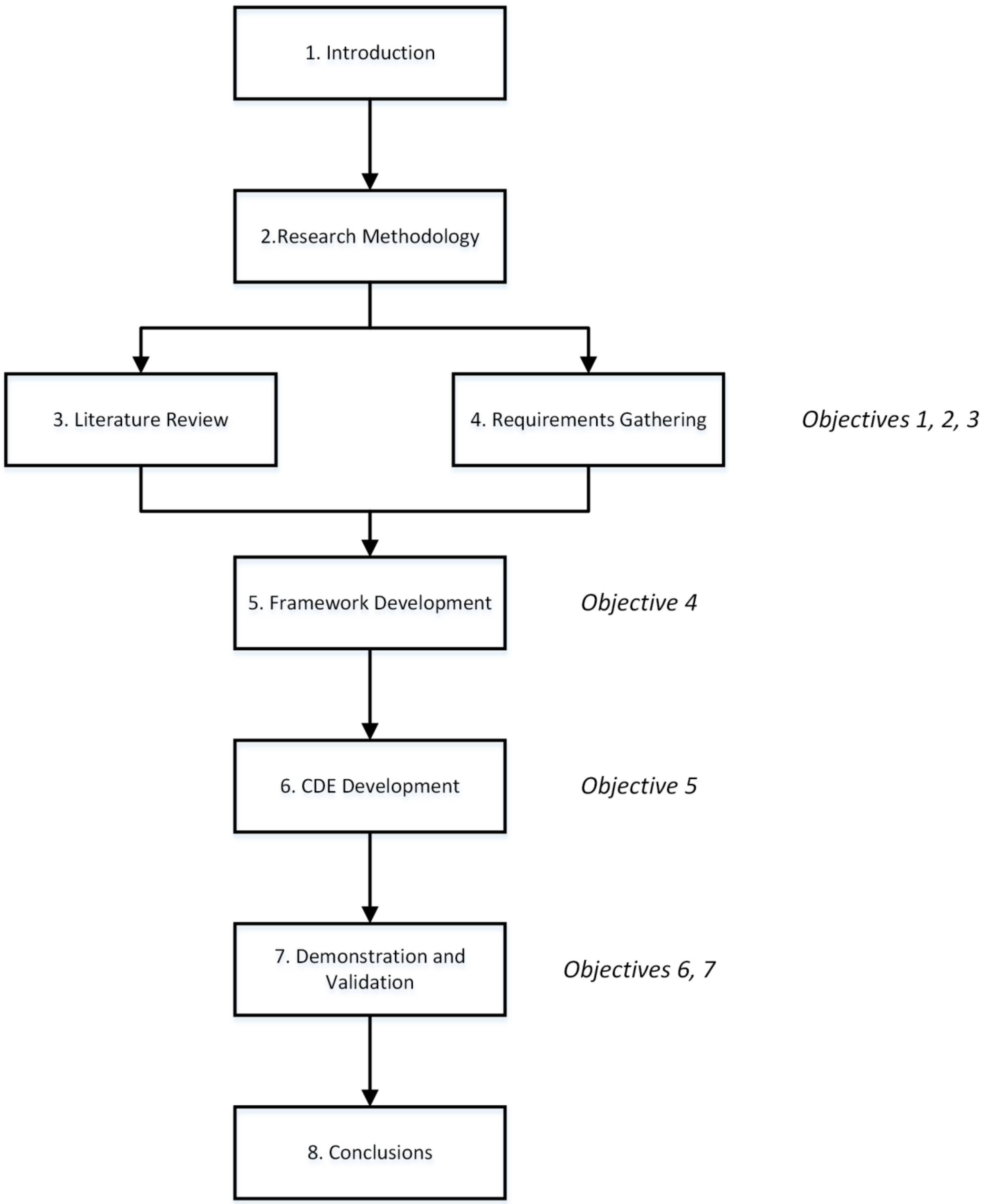

Figure 1.2 – Structure of the thesis

2 Research Methodology

2.1 Introduction

Research can be defined as the search for knowledge, using objective and systematic methods to find a solution for an identified problem (Fellows & Liu, 2008). The purpose of research is to solve problems through the application of scientific procedures (Kothari, 2004).

Research methodology (RM) is a way to systematically conduct research in order to solve the research problem. RM deals with the various steps that a researcher needs to take to investigate the research problem, along with the logic and reasoning behind them (Kothari, 2004). RM encompasses research methods, as well as the rationale and the philosophical assumptions that underlie a particular research study (Dainty, 2008).

Research methods and techniques provide the tools that are used for conducting research. It is fundamental to identify which methods and techniques are relevant to tackle the research problem. By understanding the assumptions underlying the various techniques, researchers can decide if they will be applicable to the research problem. Therefore, the design of the research methodology is a fundamental step within the research process (Kothari, 2004).

This chapter presents the methodological aspects of the study, including the research design and methodology that has been adopted to ensure that its objectives have been achieved. Section 2.2 presents the ontological and epistemological framing of the research. Section 2.3 presents the research approach and rationale adopted in this study. Section 2.4 describes the research strategy, application of research methods, and sampling strategy adopted to fulfil the aim of the research. Section 2.5 describes the measures that were considered to ensure the quality of the research, in terms of research validity and reliability.

Finally, Section 2.5 presents a summary of the research methodology adopted in this research and its underlying assumptions.

2.2 Research Paradigm

Research paradigm can be defined as the theoretical framework by which research is viewed and approached by the researcher (i.e. the research lens adopted by the researcher) (Fellows &

Liu, 2008). The research paradigm can also be described as a structure that is used to create theories. The research methodology is strongly influenced by the theoretical perspectives adopted by the researcher, and by the researcher's epistemological stance (Gray, 2004). The ontological and epistemological position adopted by the researcher has a strong influence on the choice of research methods. Therefore, understanding the research philosophy adopted by the researcher is fundamental to explain the assumptions inherent in the research process, and how they fit in with the adopted research methodology. In fact, the choice of research methods cannot be viewed in isolation from the ontological and epistemological position adopted by the researcher (Dainty, 2008).

Ontology can be defined as the study of what constitutes reality and the nature of existence (Gray, 2004; Dainty, 2008). Two opposing ontological perspectives exist: the ontology of "being" & the ontology of "becoming". The ontology of "being" considers reality as a permanent and unchanging composition of clearly defined entities with identifiable properties. On the other hand, the ontology of "becoming" considers reality as constantly changing, and has an emphasis on formlessness, chaos, interpenetration and absence (Gray, 2004).

Different epistemological positions have emerged from the two different ontological perspectives. Epistemology provides the philosophical background to evaluate the legitimacy and adequacy of the means of obtaining knowledge (Gray, 2004). Epistemological positions that have emerged from the ontology of "being" include: positivism, objectivism, constructivism, and interpretivism. Theoretical perspectives emerging from the ontology of "becoming" include subjectivism and post-modernism.

The objectivist perspective considers that reality exists independently of consciousness, and considers the existence of social phenomena and their meanings independently of social actions (Gray, 2004; Dainty, 2008). Positivism is closely associated with the objectivist perspective. Positivism argues that all knowledge must be based on a set of basic observable facts, and that inquiry should be based on scientific observations, as opposed to philosophical speculation (Gray, 2004).

On the other hand, according to the constructivist perspective, social phenomena are produced through social interaction, and therefore in a constant state of revision (Dainty, 2008). Interpretivism is closely associated with the constructivist perspective as it considers the knowledge of reality as a social construction by a particular person or observer (Gray, 2004). Interpretivism considers understanding as an emergent process, acknowledging that researchers and participants interact and influence each other in a bi-directional way (Kroeze, 2012).

Dainty, (2008) argues that quantitative and qualitative research are rooted in particular ontological and epistemological foundations (i.e. objectivism and constructivism, and positivism and interpretivism respectively). Qualitative research is also often associated with critical theory research, while the pragmatism paradigm has been associated with quantitative, qualitative and mixed methods research (i.e. mixing quantitative and qualitative methods to improve the reliability and validity of the research).

In critical theory research, researchers are called to question current values and assumptions, and challenge conventional social structures. This perspective is not content with interpreting the world (i.e. interpretivism), it also seeks to change it (Gray, 2004).

Pragmatism is concerned with action and change, and the relations between knowledge and action. The pragmatist stance is adequate as a basis for research approaches intervening into the world and not merely observing the world (Creswell, 2009). Pragmatism draws from various research paradigms, having links to positivist, interpretivist, and realist perspectives (Goldkuhl, 2012). This makes pragmatism well suited to investigate both the problems of organisational change (as in action research), and building of artefacts (as in design science) (Goldkuhl, 2012). Pragmatist research often combines different research paradigms in the research design. This makes it equally suitable for mono and mixed methods research (Gray, 2004; Creswell, 2009). Pragmatism is also suitable to carry out qualitative research in the field of information systems (Goldkuhl, 2012).

This research adopts the Design Science Research Methodology (DSRM) through the lens of pragmatism. DSRM is used throughout the research for the development of the proposed framework and CDE. The Grounded Theory Method (GTM), which is closely associated with the interpretivist research paradigm, is used for the qualitative analysis of interviews during the requirements gathering and validation stages of the research. This research combines the pragmatist and interpretive views, however the pragmatist view is the dominant one.

2.3 Research approach and rationale

Research approaches can be classified in three main groups: deductive, inductive and abductive research. Each approach considers a different relationship between theory and research, in particular during the development and testing of theory.

Deductive reasoning can be defined as a method for generating knowledge which proceeds from general to specific: the general theory and knowledge base is first established and the specific knowledge gained from the research process is then tested against it (Kothari, 2004). The deductive approach develops the hypothesis or hypotheses upon a pre-existing theory and then formulates the research approach to test it (Fischer & Gregor, 2011). It is often associated with quantitative research within the positivist approach. The deductive approach requires the definition of measures and indicators against which data is collected. Therefore only observed data is collected and measured, and subjective and intangible evidence is usually ruled out (Gray, 2004).

Inductive reasoning is characterised as a method for generating knowledge which proceeds from specific to general (Lee et al., 2011). In this approach, data collection is the starting point for the researcher, after which the data are analysed to see if there are emerging patterns between variables. The outcome of an inductive approach can be a hypothesis, or a theory. While it can be used for the development of novel theories, the analysed data may also be found to fit into an existing theory (Bryman & Bell, 2011). This approach is strongly associated with qualitative research, where the absence of a theory informing the research process may help in reducing the potential for researcher bias during the data collection stage (Bryman & Bell, 2011). Unlike the deductive approach, the inductive approach does not set out to test a theory or hypothesis. Instead, through a process of gathering data, it attempts to establish patterns, consistencies and meanings (Gray, 2004).

Abductive reasoning has been proposed to overcome the shortcomings of the deductive and inductive research approaches. The deductive approach has been criticised for the lack of clarity in the process of selecting theory to be tested via formulating hypotheses. Inductive approach has also been criticised due to the limitations in theory building based on empirical data (Saunders *et al.*, 2009). Abductive reasoning proposes overcoming these limitations through the adoption of a pragmatist perspective, and focuses on searching for a satisficing solution for a given problem. The purpose of abductive reasoning is not to derive an hypothesis from the existing body of knowledge and test it in a closed system (deductive reasoning), nor inferring a conclusion from observations in an open system (inductive reasoning) (Lee *et al.*, 2011). In abductive reasoning, the research process starts with the existing facts, and is devoted to their explanation (Zikmund, 2010). Facts may emerge when the researcher is faced with empirical phenomena that cannot be explained by the existing range of theories. When following an abductive approach, the researcher considers all possible explanations for the data, forming hypotheses for each possible explanation, checking them empirically by data analysis, and pursuing the most plausible explanation (Charmaz, 2006).

The approach used in this research combines the DSRM and GTM methodologies. DSRM follows deductive reasoning. On the other hand, the theoretical sampling and data analysis processes in GTM combine the inductive and deductive reasoning approaches (Charmaz, 2006). Therefore the research approach adopted in this study combines the inductive and deductive approaches.

2.4 Research Strategy

This study addresses the existing issues in data quality and data management of building asset data, through the design of a framework and CDE for the development and management of AIMs, based on the use of open standards in the context of “BIM level 3” – i.e. Collaboration using web-stored integrated electronic information with fully automated connectivity (BSI, 2014b).

While the technologies enabling “BIM level 3” have been available for several years, their application in the AEC/FM industry is in its infancy. In fact, the majority of collaboration and data management approaches, including the PAS 1192 standard series, are focusing on file-based data exchanges (i.e. “BIM level 2”). This presents a challenge to conduct quantitative analysis of the requirements needed for the development of AIMs to support FM and maintenance processes. For these reasons, this research adopts a qualitative research methodology.

Various research methodologies can be applied in the field of qualitative IS research, and were considered during the development of this study. These include: case studies, action research, design science research methodology, and the grounded theory method.

A case study is an empirical enquiry, which investigates a contemporary phenomenon within its real-life context, especially, when the boundaries between the phenomenon and the context may not be clearly evident (Yin, 2009). This methodology has been extensively applied as a research method to showcase and discuss BIM applications in FM and maintenance in new and existing buildings (a review is provided in Chapter 3, section 3.2.1). This significant body of research has identified key requirements and challenges in the development and management of AIMs, which can provide a starting point for the development of the proposed framework and CDE.

The design science research (DSR) paradigm seeks to extend the boundaries of human and organisational capabilities by creating new and innovative artefacts, including constructs, models, methods, and instantiations (Hevner *et al.*, 2004; Peffers *et al.*, 2007; Hevner & Chatterjee, 2010).

Action Research (AR) is a series of interventionist approaches to the acquisition of scientific knowledge incorporating social research with exploratory action to promote change or development (Given, 2008). Action research assumes an interventionist approach to the acquisition of scientific knowledge which differentiates it from case studies, which are incapable of studying the new or changed methodologies, based on the characteristic constraint of non-interventionism (Baskerville & Wood-Harper, 1996).

The research interest of DSR is to construct new and innovative ways to solve a class or classes of problems, thus creating new reality. On the other hand, AR is conducted to understand existing reality, such as the complex workings of organisational situations and human behaviour (Iivari & Venable, 2009). A comparison between paradigmatic assumptions of AR and DSR is provided in Table 2.1.

The Grounded Theory Method is a systematic strategy of inquiry involving the construction of theory that explains a process, action or interaction grounded in the views of the participants (Creswell, 2009). The grounded theory method can be incorporated into case studies as a means of handling and interpreting data. Similarly to Action Research, it seeks to develop theoretical elements that are useful to practitioners within the research setting (Gray, 2004).

Table 2.1 Summary of the paradigmatic assumptions of Action Research and Design Science Research (Iivari & Venable, 2009).

Paradigmatic dimension	***Action Research***	***Design Science Research***
Ontology	Anti-realism	Realism or anti-realism
Epistemology	Mainly anti-positivism	Mainly positivism, but also anti-positivism, especially in evaluation
Methodology	Idiographic	Constructive (building) Nomothetic (evaluation) Idiographic (evaluation)
Ethics	Means-end Possibly interpretive Unlikely critical	Means-end Possibly interpretive Possibly critical

This research is concerned with the development of novel approaches and IT tools for the development and management of AIMs. To this end, this research adopts the Design Science Research Methodology in the design of a framework and CDE for the development and management of AIMs.

The research design in this study combines the Design Science Research Methodology (DSRM) and the Grounded Theory Method (GTM). DSRM guides the overall design of the proposed framework and CDE. The Grounded Theory Method (GTM) is used to determine the requirements for the proposed framework and CDE, and to provide the validation of the proposed framework and CDE against the identified requirements.

Sections 2.4.1 and 2.4.2 will outline each of these methods. Section 2.4.3 will detail the research design using the combined approach of DSRM and GTM. Section 2.4.4 will detail the sampling strategy adopted throughout the research.

2.4.1 Design Science Research Methodology (DSRM)

Design science is concerned with the development and evaluation of innovative artefacts (i.e. something that is artificial or constructed by humans, as opposed to something occurring in nature (Hevner & Chatterjee, 2010)) to solve existing problems (Peffers *et al.*, 2007). Artefacts may include constructs, models, methods, and instantiations (Winter, 2008). The design science paradigm is fundamentally a problem-solving paradigm. It supports a pragmatic research paradigm that calls for the creation of innovative artefacts to solve real-world problems. Thus, design science research combines a focus on the development and evaluation processes (i.e. design as a process) in the design of the artefact (i.e. the resulting product), with a focus on its evaluation, considering its relevance in the application domain (Hevner & Chatterjee, 2010; Sonnenberg & Brocke, 2012; Villiers, 2012b).

Design science defines rigorous design and evaluation processes, in order to make significant research contributions and communicate the research results, both to technology-oriented and management-oriented audiences (Peffers *et al.*, 2007; Hevner & Chatterjee, 2010).

Various models currently exist for DSRM (e.g. (Peffers *et al.*, 2007; Baskerville *et al.*, 2009; Hevner & Chatterjee, 2010)). While they use different terminology, the underlying concepts and the iterative nature of the design process are common to all the suggested approaches. Peffers *et al.*, (2007) proposed a process model for Design Science Research Methodology (DSRM) for research in Information Systems (IS), building upon work from previous studies. The proposed methodology consists of the following activities:

1. Problem identification and motivation;
2. Defining the objectives of the solution;
3. Artefact design and development;
4. Demonstration of the use of the artefact;
5. Evaluation of how the artefact supports a solution to the research problem;
6. Communication of the results through research publications.

While the research activities are proposed in sequential order, the author suggests that researchers can start the process from any of the first four phases, depending on the nature of the problem. The author defines four entry points, which correspond to different approaches to investigate the research problem (Peffers *et al.*, 2007):

- Problem-centred approach: This approach starts with activity one and should be adopted if the idea for the research resulted from observation of the problem or from suggested future research from an existing research project.

- Objective-centred solution: This approach starts with activity two, and could be triggered by an industry or research need that can be addressed through the development of an artefact.
- Development-centred approach: This approach starts with activity three. It can consist of identifying functionality and performance requirements for a new artefact to be developed, or evaluating the applicability of an existing artefact from a different research domain to the identified research problem.
- Client-context initiated solution: This approach starts with activity four. It can consist of observing and evaluating a practical solution that solved a particular research problem. This approach can be applied to the development of artefacts in the context of consulting experiences.

Another key aspect of DSRM is its iterative nature, in which artefacts are evaluated regarding their suitability as a solution to the problem, using criteria such as validity, utility, and quality. Validity assesses the internal and external validity of the proposed design, ensuring that the artefact works and does what it is meant to do. Utility assesses whether the achievement of goals has value outside the development environment (Gregor & Hevner, 2013). Quality assesses the degree to which the developed artefacts satisfy the needs of stakeholders, and can be determined using quality models such as Systems and software quality requirements and evaluation (SQuaRE) (ISO/IEC, 2011). Depending on the nature of the problem, evaluation can take different forms. Ex ante evaluation focuses on the design of the artefact and can be useful to select a system or technology before it is acquired and implemented in its real use context. Ex post evaluation focuses on the performance of the artefact in its real use context, after it is acquired or implemented by an organisation (Pries-Heje *et al.*, 2008). Both artificial (e.g. demonstration and experiments with a prototype, benchmarking) and naturalistic (e.g. case studies, field experiments, surveys, expert interviews, action research) evaluation methods can be used to conduct evaluation (Pries-Heje *et al.*, 2008; Sonnenberg & Brocke, 2012). Artificial evaluation methods can provide additional control over the evaluation process at a lower cost than naturalistic methods. On the other hand, naturalistic evaluation methods provide added realism to the evaluation process (Pries-Heje *et al.*, 2008). For example, prototyping can be employed as an ex ante evaluation method by using theoretical data to evaluate the artefact's design, and it can also be used as an ex post evaluation method to assess the performance of the artefact within an organisation by conducting real tasks. Action Research and case studies have been proposed to conduct artefact evaluation in a real use context, i.e. ex post evaluation (Hevner & Chatterjee, 2010). The Grounded Theory Method has also been proposed for artefact evaluation, and can also be used to justify the theoretical contribution to the knowledge base, which goes beyond the local solution of a problem and the implementation of an IT artefact (Gregory, 2010). At the end of the evaluation stage, researchers can decide to iterate back to the design and development stage to improve the effectiveness of the artefact, or to proceed to the communication stage, leaving further developments to subsequent projects, depending on the feasibility of further iterations within the research project (Peffers *et al.*, 2007).

The DSRM methodology is summarised in Figure 2.1.

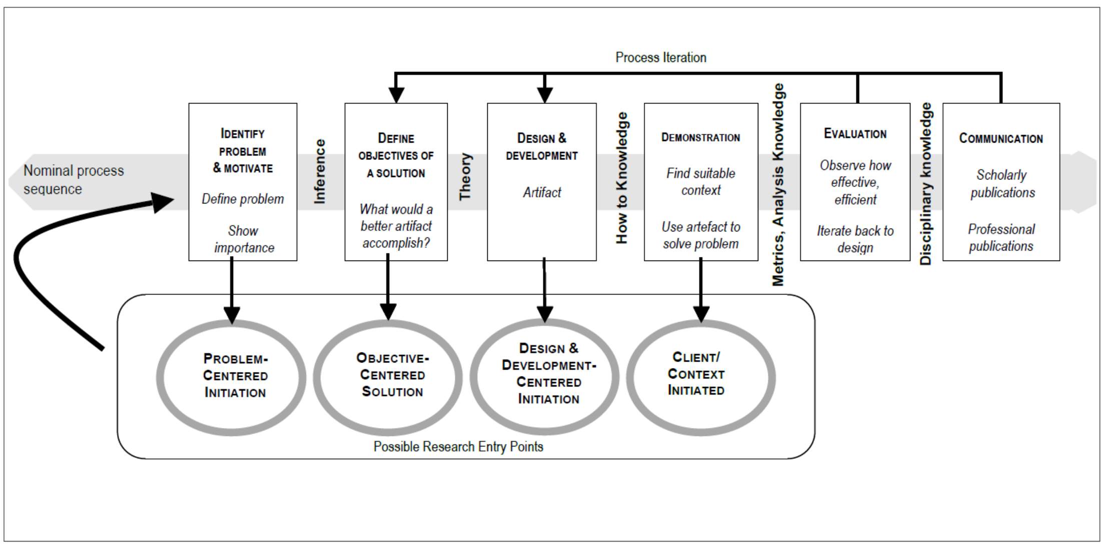

Figure 2.1 - Design Science Research Methodology (DSRM) Process Model (Peffers *et al.*, 2007)

2.4.2 Grounded Theory Method (GTM)

Grounded Theory can be defined as a strategy of inquiry focused on the discovery, or generation of theory from a process, action or interaction grounded in the views of the participants (Urquhart & Fernandez, 2006; Creswell, 2009). In the Grounded Theory (GT) approach, theory and models are generated from a cyclical process of theoretical sampling and data analysis, as themes and patterns emerge (Charmaz, 2006). In Grounded Theory there is continuous interaction between the collection and analysis of data (Glaser & Strauss, 1967; Strauss & Corbin, 1990; Charmaz, 2006; Urquhart & Fernandez, 2006; Villiers, 2012b).

Grounded Theory originated from sociology back in the 1960's as an alternative to research methods based on deductive reasoning, with the objective of shifting the research focus from theory testing to theory generation and discovery (Gregory, 2010). The Grounded Theory Method (GTM) involves systematic collection and analysis of data using multiple stages of data collection and the refinement and interrelationship of categories of information. It prescribes a rigorous analysis procedure which leads to the development of substantive theories (Urquhart & Fernandez, 2006; Creswell, 2009). The theoretical sampling process consists of seeking pertinent data to develop the emerging theory (Charmaz, 2006). To this end, it is essential for the researcher to identify participants who have experienced or are experiencing the phenomenon under study (Thomson, 2011). The GTM is closely associated with the interpretivist research paradigm.

GTM is now prevalent in sociology and health disciplines. Its flexibility as a research method makes it appropriate for researching processes and for developing theory in new areas, such as Information Systems (IS) research, and it has previously been adopted as a research methodology for qualitative research in IS (Baskerville & Pries-Heje, 1999; Urquhart *et al.*, 2010; Joo, 2011).

Urquhart *et al.*, (2010) proposed a framework composed of five guidelines for conducting GT studies in IS. The first three guidelines address ways of achieving adequate conceptualisation for the emerging theory, while the fourth and fifth guidelines establish the scope of the theory in terms of scaling and integration with existing theory:

1. Constant comparison;
2. Iterative conceptualisation;
3. Theoretical sampling;
4. Scaling up; and
5. Theoretical integration.

Based on these guidelines, Villiers, (2012a) proposed a model for the development of Grounded Theory studies in IS (Figure 2.2).

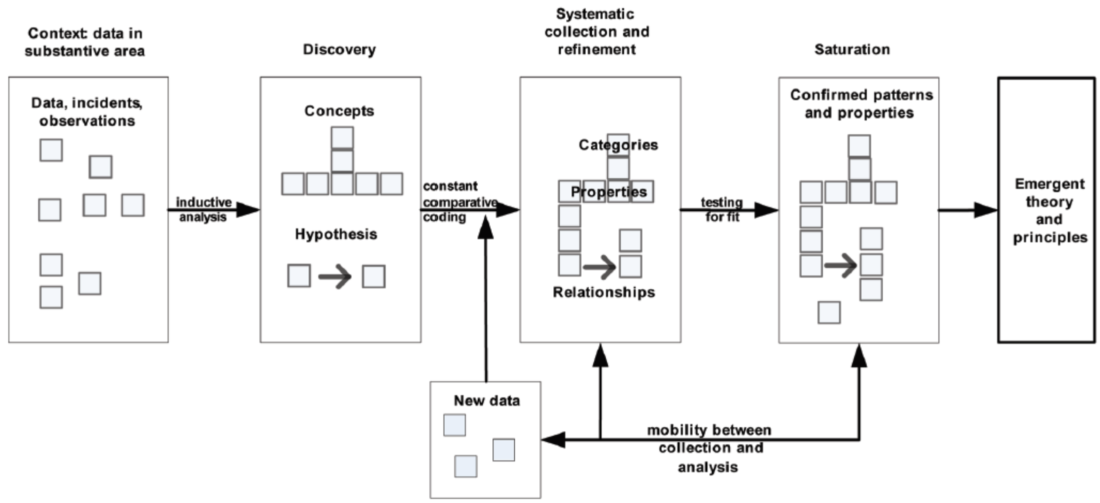

Figure 2.2 – Model for the development of Grounded Theory studies in IS (Villiers, 2012a)

2.4.3 Research Design: Combining DSRM and GTM

Various researchers have highlighted the need to justify the emergent practical knowledge from the application of design theories. The missing link to theory has been identified as one of the main problems of design science research as a IS research approach (Peffers *et al.*, 2007; Hevner & Chatterjee, 2010). Goldkuhl, (2004) states that there is great potential in systematising practical knowledge and grounding it to design theories and proposes an approach for creating and justifying practical knowledge – Multi-grounding of design theories (MGDT).

GTM can be used as an analysis method in conjunction with other research methodologies, such as Action Research (Baskerville & Pries-Heje, 1999; Kock, 2004), Activity Theory (Merwe & Villiers, 2011), and DSRM (Goldkuhl, 2004; Gregory, 2010).

Gregory, (2010) performed a comparison between the GTM and DSRM methodologies and concluded that they complement each other well, calling for future research to combine both research strategies. The author proposes the adoption of GTM during the artefact evaluation stage of DSRM in order to justify the theoretical contribution of the research to the knowledge base, which goes beyond the local solution of a problem and the implementation of an IT artefact (Gregory, 2010). Additionally, the inductive nature of the theory development process in GTM could also be used during the problem definition stage of DSRM, in order to develop a systematic understanding of the problem area and identify the requirements for the development of the IT artefact (Gregory, 2010).

The methodology adopted in the research combines the DSRM and GTM. This research aims to address current challenges in data management for building owners and FMs by proposing a framework and CDE for the development and management of AIMs. The proposed framework and CDE constitute the artefacts to be developed. The research follows the structure of the DSRM, while the Grounded Theory Method is used to identify the requirements for the development of the framework and CDE, to provide the validation (in particular the internal validity) of the proposed design, and to justify the proposed framework's theoretical contribution to knowledge. Following the DSRM model proposed by Peffers *et al.*, (2007), the entry point for this study is Stage 1: Problem identification and motivation.

Figure 2.3 presents the research methodology that was adopted to achieve the aim of the research, and highlights the application of the combined DSRM & GTM approach at each stage of the research. Each phase of the research design will now be detailed, including the research methods adopted during each stage of the research.

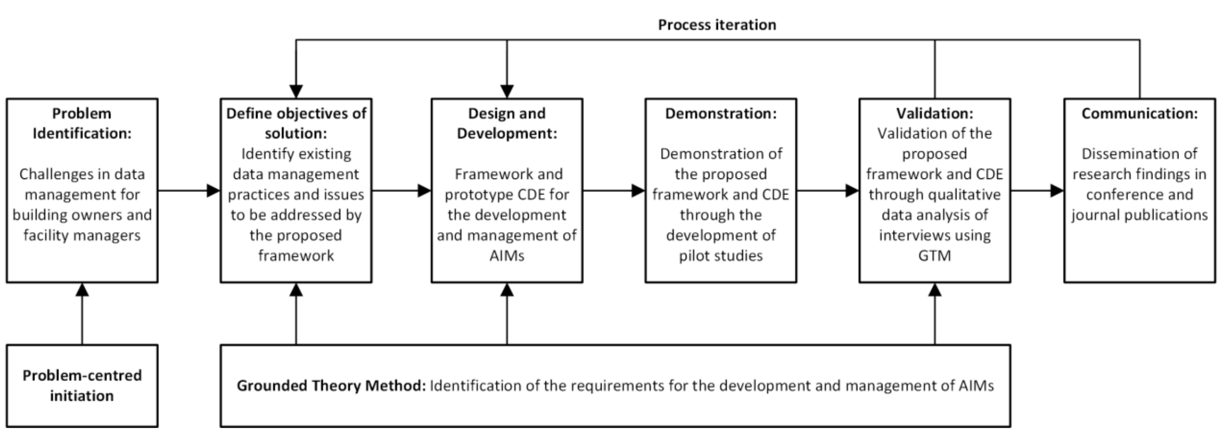

Figure 2.3 – Research methodology flowchart

Identification of the problem and defining objectives for a solution:

The identification of current issues regarding the management of information for the development of AIMs is covered in the Literature Review and Requirements Gathering chapters. A qualitative literature review, and semi-structured interviews carried out with key stakeholders of the research – Designers, Building Owner, and FM – were used to:

- Establish the scope of the existing knowledge in the area of this research, and identify the current practices, existing approaches and issues in the industry;
- Determine the requirements for the development of the proposed framework and prototype CDE.

Qualitative data obtained from the interviews was analysed using the GTM. This research activity provides the basis for the theoretical contribution of the research.

The literature review and requirements gathering activities contributed to achieve objectives 1, 2, and 3 and provided the initial requirements for the development of the proposed framework and prototype CDE:

- Identification of standards and methodologies for the structured definition of building owners and FMs requirements;
- Identification of open data standards to support AIM data requirements;
- Identification of methodologies for the validation of AIM data sources against structured requirements.

Design and development:

A framework is proposed in this research for the development and management of Asset Information Models. The development of the framework is based on the IDM methodology and consists in the definition of various processes using the IDEF0 and BPMN methodologies. Key areas of this framework were identified throughout the literature review and requirements gathering activities, and several processes were defined:

- Definition of structured Asset Information Requirements;
- Identification of Asset Information Model data sources;
- Validation of AIM against AIR;
- Development of a CDE for the management of AIMs;

- Visualisation of AIMs.

The development of the proposed framework fulfils objective 4 of this research.

A prototype CDE is developed for the management of AIMs. Requirements for the CDE were identified in the literature review and interview data analysis. The CDE demonstrates the various processes defined in the proposed framework. The CDE is developed using open standards to store and link the various asset data sources. CDE development consisted of the following activities:

- Definition of the CDE architecture, which is based on the SOA;
- Definition of the CDE infrastructure, through the selection of the various tools and standards which can support the development and management of AIMs;
- Definition of a schema for the AIM, considering the various sources of graphical, non-graphical and documentary data.

The development of the prototype CDE fulfils objective 5 of this research.

Demonstration:

The proposed framework and CDE are demonstrated through the development of pilot studies, consisting of the development of AIMs, and showing how AIM sources of data can be used to streamline the definition of preventive and reactive maintenance tasks. The pilot studies developed during the demonstration activity demonstrate the different domains of the framework and capabilities of the prototype CDE. The demonstration activity in the context of DSRM can be used to provide an initial method of evaluation of the developed artefact (Prat *et al.*, 2014). In this research, the demonstration activity provides the basis for the technical validation of the proposed framework and CDE. Demonstration of the proposed framework fulfils objective 6 of this research.

Validation:

Validation assesses the internal and external validity of the design of the proposed framework and CDE and, together with the demonstration activity, provides the basis for a future evaluation. Validation focused on the demonstration of the proposed framework and CDE capabilities using the developed pilot studies in sessions with a selection of academic and industry experts.

Feedback from the demonstration sessions was gathered in the form of unstructured interviews, and was analysed according to the Grounded Theory method. It provides a qualitative assessment of the framework focusing on its usability and relevance to the industry. The use of the GTM builds upon the initial requirements model resulting from the data analysis performed during the requirements gathering stage.

Following the cyclical nature of the proposed research methodology, two rounds of interviews were undertaken, which revealed additional requirements for the proposed framework and CDE. One development iteration was carried out after the initial round of interviews, to address some of the additional identified requirements for the proposed framework and CDE. The updated requirements model developed as a result of the validation activity is used for the validation of the proposed framework and CDE, and is also used to identify future developments for the research. The validation methodology is detailed in Chapter 7. The validation activity justifies the research's theoretical and technical contributions and fulfils objective 7 of this research.

2.4.4 Sampling strategy

This research uses Grounded Theory as a methodological framework to gather and analyse qualitative data from experts in the form of semi-structured and unstructured interviews. The definition of the sampling strategy is key to ensure that the Grounded Theory method can reveal the patterns, concepts, categories, properties, and dimensions of the given phenomena (Glaser & Strauss, 1967; Strauss & Corbin, 1990; Charmaz, 2006). In particular, it is essential to determine the appropriate sample size to generate sufficient data (Thomson, 2011). Determining the appropriate sample size to conduct interviews using the GTM depends on the concept of 'theoretical saturation'. Theoretical saturation occurs in data collection when (Strauss & Corbin, 1990):

- No new or relevant data emerge regarding a category;
- Categories are well developed in terms of their properties and dimensions;
- The relationships among categories are well established and validated.

There is no set number of interviews for when theoretical saturation occurs (Glaser & Strauss, 1967; Strauss & Corbin, 1990). Therefore, the data collection process continues until the process supplies no new data (Thomson, 2011).

On the other hand, sample size is heavily influenced by the definition and nature of the research problem, as well as the selection of the right participants for the study to facilitate theoretical sampling. By narrowing the focus of the research problem as the point of departure for data collection, or after carrying out initial interviews, the researcher can reduce the number of interviews needed to successfully apply the GTM (Strauss & Corbin, 1990). The theoretical sampling procedure dictates that the researcher selects participants who have experienced, or are experiencing the phenomena under study. The selection of participants is not predetermined and depends on the ongoing data analysis results, i.e., the patterns, categories and dimensions emerging from the data are used to identify relevant participants that can provide a deeper understanding of specific aspects of the research (Thomson, 2011). This process ensures that the researcher has identified experts that can provide the most adequate data for the study (Glaser & Strauss, 1967; Strauss & Corbin, 1990).

In this research, all the identified experts are or have been involved in the implementation and use of BIM-based IT tools, and are or have worked with building owners and facility managers. Experts were identified at three key stages of the research: during the requirements gathering activity, and during both rounds of validation. The second round of validation interviews confirmed the various requirements for the development of CDEs and AIMs identified throughout the various cycle of data gathering and analysis, and ensures that theoretical saturation has been reached. Figure 2.4 provides an overview of the sampling strategy adopted in this research and how it was used to identify and validate the requirements for the proposed framework and CDE.

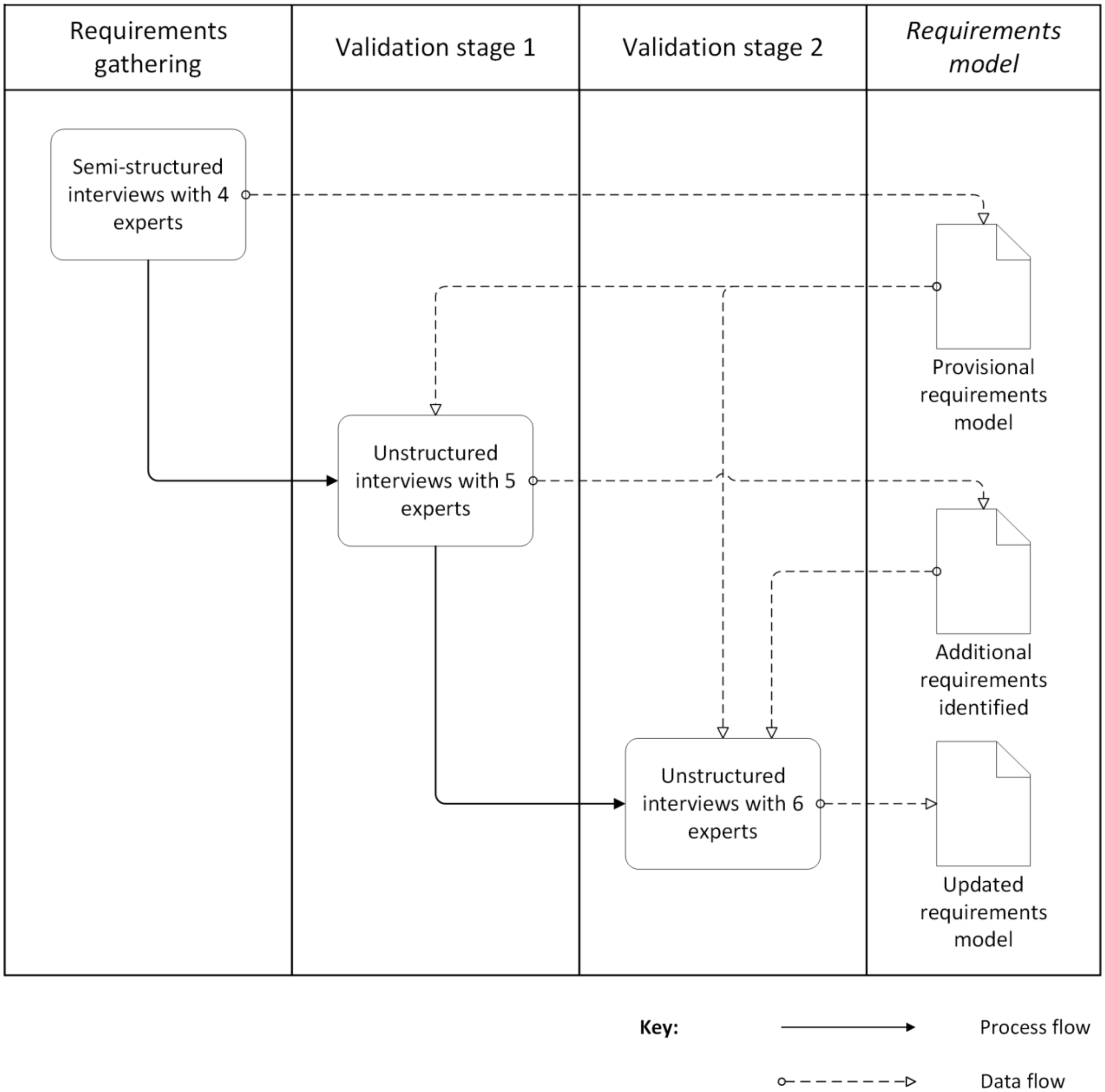

Figure 2.4 – Sampling strategy

2.5 Research quality

Reliability and validity are critical measures to determine the quality of research. This section explains how they were taken into account in the context of this research.

2.5.1 Reliability

Research design should include measures to minimise bias and maximise the reliability of the data collected during research activities (Kothari, 2004).

Reliability focuses on the consistency of research results, i.e., if other researchers would be able to replicate the obtained results (Easterbrook *et al.*, 2008). In qualitative research, reliability is generally weaker than in quantitative research, since different researchers can report varying interpretations of the same phenomena. On the other hand, qualitative research typically provides stronger validity since qualitative researchers' close attention and involvement makes them more likely to ask relevant questions, and less likely to overlook important information, or exclude important data (Kaplan & Maxwell, 2005).

In qualitative research, reliability can be achieved using triangulation approaches. These can consist of (Gray, 2004):

- Data triangulation, where data are gathered using multiple sampling strategies, including the collection of data on the same phenomenon over a period of time, the collection of data from multiple sites, and the collection of data at different levels within a single organisation;
- Researcher triangulation, where more than one observer is used during field data collection, to reduce observer bias;
- Multiple triangulation, consisting of a combination of multiple methods, data types, observers and theories in the same research;
- Methodological triangulation, which can consist in employing different data gathering techniques within the same research method, or where a variety of different research methods are using within the research.

This research used the GTM as the method of data collection and data analysis. Data triangulation was applied by conducting interviews during three different stages of data collection (requirements gathering, and two stages of validation). The analysis of qualitative data obtained in interviews made use of constant comparison, saturation and core relevance GTM concepts, which were used to minimise the influence of researcher bias and subjectivity in the interpretation and conceptualisation processes.

2.5.2 Validity

For research work to be accepted as a contribution to scientific knowledge, the researcher needs to ensure that the conclusions drawn from the study are valid. Validity can be defined as the extent to which inferences and conclusions from research activities are warranted and justified. The validity of the research results depends on how well the research design accounts for the weaknesses of the various research methods employed (Easterbrook *et al.*, 2008).

Internal validity focuses on whether it can be guaranteed that the obtained results during the course of the research follow from the data (Easterbrook *et al.*, 2008). This research follows the GTM during the data gathering and validation stages. Internal validity is ensured by reaching theoretical saturation, that is, when no new concepts emerge from the processes of data collection and data analysis.

External validity is concerned with the generalisability of the research results (Easterbrook *et al.*, 2008). Unlike in quantitative research, where research results can be generalised through statistical inference, results from qualitative research approaches are more difficult to generalise and external validity is ensured by applying the research findings in different contexts (Gray, 2004). In this research, external validity is achieved through the technical demonstration of the proposed framework and CDE. External validity is acquired through the processes of replication and extension by demonstrating the framework and CDE in the development of three pilot studies of increasing technical complexity.

2.6 Summary

This chapter has discussed the research framework applied to this study. An overview of the various elements of research, namely: research paradigm; research approach; and research methodology was presented, and the research was framed within each of these elements. Measures taken to minimise bias and maximise the reliability and validity of the research were described.

This research study proposes a framework to manage the various processes in the development and management of AIMs. The research methodology adopted consists of a combination of the Design Science Research Methodology (DSRM) and the Grounded Theory Method (GTM). The combination of DSRM and GTM in the context of qualitative research in IS has previously been suggested to overcome the shortcomings in highlighting the theoretical contributions in design-based research. The cyclical nature of data gathering and analysis proposed in the GTM is aligned with the cyclical nature of the design process in DSRM.

The research follows the steps of the DSRM for the development of the proposed framework and CDE. The GTM is used throughout the research to gather requirements for the development of the framework and CDE, during the validation of the developed framework and CDE, and to justify the research contribution to the existing theory. The research is qualitative and combines the pragmatist and interpretivist paradigms in the combination of the DSRM and GTM. The research combines inductive and deductive reasoning - DSRM is a deductive process, while GTM employs inductive and deductive reasoning in the theoretical sampling and data analysis processes.

3 Literature Review

3.1 Introduction

This chapter aims to identify and establish the scope of the existing knowledge relevant to this research. A review of current and relevant literature is presented, to establish the theoretical background, and to build an understanding of the current issues in data management related to BIM uses from the perspective of building owners and FMs. A variety of sources were used in the literature review, including textbooks, journal articles, papers from conference proceedings, and research and industry reports.

The literature review is divided in three areas, aligned with the objectives of the research:

- Section 3.2 provides a review of current BIM applications in FM and maintenance, highlighting how building owners and FMs can use BIM to manage building asset data during the use phase of buildings. This task contributes to achieve the first research objective.
- Section 3.3 provides a review of existing standards that can be used to support the various processes of requirement definition, asset data validation and AIM development and management. This task contributes to achieve the second research objective.
- Section 3.4 provides a review of compliance checking methodologies, that can be adopted to ensure the data quality during the development of AIMs. This task contributes to achieve the third research objective.

This chapter introduces the core concepts of the thesis and outlines how the research fits within the context of the relevant literature and knowledge area. The findings from this chapter provide key theoretical inputs in the identification of the requirements for the proposed framework and prototype CDE. Section 3.5 provides an analysis, highlighting the relationship of the outcomes of the chapter to the knowledge gap, aim and objectives of the research. Finally, section 3.6 provides a summary of the chapter’s findings.

3.2 BIM for Building Owners and Facility Managers

BIM can be used by building owners and facilities managers both as an information source and as a repository to support the planning and management of building maintenance activities in both new and existing buildings (Volk *et al.*, 2014). Building owners are the organisations that initiate and finance building projects. Facility managers are the entities typically contracted by building owners to perform various management activities during the use phase of the building in order to maximise its performance, while minimising running costs.

According to ISO 55000, Facilities management (FM) is one of the Asset Management (AM) disciplines, focusing on the management of building and infrastructure assets (ISO, 2014). FM can be defined as an integrated approach to operating, maintaining, improving and adapting building and infrastructure assets in order to support the needs of the occupants, owners and facility managers (Atkin & Brooks, 2009). FM constitutes an extensive field encompassing multidisciplinary and independent disciplines whose overall purpose is to maximise building functions while ensuring occupants wellbeing (Atkin & Brooks, 2009; Becerik-Gerber *et al.*, 2012; Pärn *et al.*, 2017). To this end, the FM discipline requires extensive data and information from various fields and disciplines (Atkin & Brooks, 2009).

BIM can be used as a data source for various FM activities including commissioning and closeout, retro-commissioning, maintenance of warranty and service information, quality control, energy and space management, planning and performing maintenance, emergency management, retrofit planning and deconstruction (Ilter & Ergen, 2015). The use of BIM in a whole lifecycle approach can support the requirements for asset maintenance planning and execution, provided that information is kept in an organised management system (CIC, 2012). The use of BIM has also been proposed to engage professionals in FM and related property management roles in the design process (Wang *et al.*, 2013; Navendren *et al.*, 2015; Tucker & Masuri, 2018). In this way, the use of BIM in FM enables the management of data throughout the lifecycle of building assets (Ilter & Ergen, 2015).

Various factors are hindering the adoption of BIM by building owners and FMs. Becerik-Gerber *et al.*, (2012) have identified and categorised existing factors as “technology and process related” and “organisational”. Traditionally, FM data and information are organised and maintained in dispersed information systems such as Computerised Maintenance Management Systems (CMMS), Electronic Document Management Systems (EDMS), Building Automation Systems (BAS), etc. The information and data required for such systems comes from different sources, is created and manipulated several times during the assets life cycle, and is usually not synchronised between systems, resulting in error-prone processes (Becerik-Gerber *et al.*, 2012). Challenges to ensure the quality of information in the development of BIM models for FM applications have been recognised in recent research, which is focusing on quality assurance approaches for the preparation of FM-BIM data sets (Yang & Ergan, 2017; Zadeh *et al.*, 2017; Motamedi *et al.*, 2018). Building owners and FMs face additional challenges compared to designers when transitioning from current IT systems and ways of working to the BIM approach, considering the amount of already existing data in their current building portfolios (Kiviniemi & Codinhoto, 2014). The limited use of open standards that define the information requirements for specific FM and maintenance tasks is another barrier for improving the information handover to the FM phase, as well as the use of BIM data in the use phase. There is a need for open systems and standardised data libraries that can be utilised by any FM system (BIFM, 2012). The availability of such open standards and data specifications will enable data integration if they are successfully adopted by the industry on new and existing assets.

BIM technologies and open standards are providing opportunities for integrating the FM phase with the upstream project delivery phases. BIM technologies and processes allow the management and integration of the information needed for FM through the asset life cycle phases using open standards while providing a single source of accurate and up-to-date information. The potential use of BIM in FM applications was realised from the early stages of the development of the IFC standard. Studies proposing open BIM data models to enable information sharing among computer applications can be traced back to the early 2000s. An example was the proposal of a data model for FM – Facilities management core model (FMC) – along with mapping between IFC and FMC (Yu *et al.*, 2000). Linking BIM and FM data still remains a challenge since integration approaches have to be flexible in order to support different use cases depending on project and user roles (Kang & Choi, 2013). The use of semantic web approaches has recently been proposed to achieve the integration of BIM and FM. Kim *et al.*, (2018) proposed an ontology to manage BIM-based FM information by linking the BIM-based building elements to historical work records in an FM system database. Other integration approaches for BIM and FM data have been proposed recently, focusing on the integration of MEP data from as-built BIM models with maintenance data to run routine O&M tasks and to effectively respond to MEP-related emergencies (Hu *et al.*, 2018), and to enable the automatic scheduling of facility maintenance work orders (Chen *et al.*, 2018). The development of AIMs using BIM standards has also been applied to infrastructure asset management, including the development of a prototype Smart Sewer Asset Information Model (SSAIM) which integrated IFC models with distributed smart sensors to enable real-time monitoring and reporting of sewer asset performance (Edmondson *et al.*, 2018).

3.2.1 BIM and FM case studies

BIM can support FM functions for both new and existing buildings (Volk *et al.*, 2014). Several case studies aimed to showcase and discuss BIM applications in FM and maintenance in these two types of assets. One of the earliest attempts at using BIM for FM was in the 'ifc-model based Operations and Maintenance of Building' (ifc-mbOMB) project (Nisbet, 2008). This project recreated the design process of a college building using BIM workflows and deliverables which included room-briefing, layout, detailing, environmental analysis, mechanical and electrical equipment requirements, product selection and substitution. During this process, the IFC schema and a model server were used to capture the information needed for asset management. Asset management information was then translated into Maximo facility management format through the mapping of the IFC model to the Maximo data structure (Nisbet, 2008). Outcomes from this project provided the bases for the development of COBie.

One of the main challenges in the implementation of BIM for FM is the handover of data during project closeout, in particular determining the accuracy of as-built BIM models so that they can be used as a basis for the various FM and maintenance tasks. Hamledari *et al.*, (2018) developed an algorithm to automatically update as–built IFC-BIM models by analysing building element semantics and identifying discrepancies between the as-built and as-designed object conditions. Lin *et al.*, (2018) proposed a system for owners to manage as-built BIM model quality assessment and demonstrated their approach in a case study of a selected building in Taiwan.

Several research efforts have focused on the implementation of BIM for the management of existing buildings. A notable example was the development of the Sydney Opera House BIM for FM case study (CRC, 2007). In this project, the Sydney Opera House was modelled specifically for FM purposes using the IFC standard. This project demonstrated the different applications of BIM in FM and highlighted the need for changing current workflows and processes. The project identified the lack of support of the IFC standard by FM tools as a key barrier. Korpela *et al.*, (2015) highlighted the challenges in the integration of several IT systems used for the maintenance of the Center for Properties and Facilities of the University of Helsinki, and how BIM could help address these challenges. The authors proposed that only a subset of BIM data (i.e. a simplified BIM model) is needed for FM and maintenance, and that the definition of such data requirements is essential for the successful integration of various FM and maintenance systems. Carbonari *et al.*, (2015) proposed a simplified remodelling process for existing facilities considering the FM strategy, which could be adopted by FMs. Pishdad-Bozorgi *et al.*, (2018) proposed the development of BIM models containing FM data required for FM tasks such as space analysis, retrofitting, and preventive maintenance, and applied their approach in the context of an existing building in the higher education sector.

The application of BIM for FM in the Manchester Town Hall Complex identified the lack of awareness of the potential of BIM in the FM phase, and the need for clear guidelines for its implementation in FM as key challenges (Kiviniemi & Codinhoto, 2014). The authors highlighted that the lack of interoperability between the existing tools used for FM and building management was a major obstacle during the project. Nonetheless, the BIM-FM implementation resulted in an improvement of the Preventive Maintenance/Reactive Maintenance (PM/RM) ratio. Another case study by (Kelly *et al.*, 2013), using BIM for managing existing university campus buildings, identified the improved accuracy of records of geometric information, and the increased workforce and process efficiencies as two key benefits. The authors also concluded that the lack of: clear requirements for the implementation of BIM in FM; quantifiable key performance indicators; interoperability; clear roles and responsibilities, and contract and liability framework are the main challenges facing BIM in FM applications.

Motawa & Almarshad, (2013) proposed a methodology, which combines the use of BIM and case-based reasoning to capture and manage knowledge in building information models to inform maintenance teams about the history of the building and its components. (Shen *et al.*, 2012) presented an information integration framework that supports software and hardware applications, using agent-based web-services, in providing decision support for facility management and maintenance. Lin *et al.*, (2016) proposed the development of a BIM execution plan to support building owners during the operational phase of buildings. The application of the proposed BIM execution plan in a case study highlighted how BIM can improve the maintenance management procedure.

The visualisation capabilities of BIM and their role in decision making for O&M tasks are receiving an increased attention. Motamedi *et al.*, (2014) integrated Computerised Maintenance Management Systems (CMMS) data with BIM visualisation capabilities to enhance the detection of failure root causes in FM. In this study, IFC model relations were used to capture failure mechanisms and fault tree analysis was used to model and capture knowledge about building system failures.

Rasys *et al.*, (2014) proposed an information integration framework for the management of civil and Oil & Gas facilities in which Web3D technology is used for integrating and visualising assets' 3D components and their linked FM data using class libraries. The use of BIM spatial relations for visualisation and analyses of facilities data were also applied in the planning of maintenance activities and repair works in buildings (Akcamete *et al.*, 2010).

Lin & Su, (2013) developed an information integration system for BIM and FM and maintenance data to enable maintenance workers to access, review 3D BIM models and update their related maintenance records. Shi *et al.*, (2016) developed a multi-user virtual environment based on BIM models to enable communication and collaboration to support FM tasks. Similar approaches have been proposed using a game engine for the integration of BIM models with FM data to enable planning of FM and maintenance tasks (W.-L. Lee *et al.*, 2016; Carreira *et al.*, 2018).

Another area of the built environment that can benefit greatly from the application of BIM to FM is healthcare. Healthcare facilities typically include complex building systems and the planning of maintenance operations is complex due to high occupancy rates. Healthcare facilities have been the focus of development of dedicated facility management models (Featherstone & Baldry, 2000; Lavy & Shohet, 2007; Lucas *et al.*, 2013). In order to support decision-making processes in planning of maintenance operations, Lucas *et al.*, (2013) proposed an object oriented product model based on IFC and COBie, linking facility and clinical information for the mitigation of risks in the planning of maintenance activities.

Another example of a BIM-based maintenance planning effort was the proposal of an asset planning framework to monitor particulate matter in subway stations. The main purpose of this framework is to monitor Indoor Environmental Quality (IEQ) and determine maintenance priority indices for inspected building components (Marzouk & Abdelaty, 2014). Regarding the use phase of buildings, research has also been carried out in the field of structural condition monitoring. In this context, Rio *et al.*, (2013) have proposed a custom IFC property set to support data from structural sensors. Chen *et al.*, (2013) highlight the potential of using facilities management and maintenance data for predictive maintenance methods. The authors proposed an expert system using 3D models as an interface for data access, and maintenance data to provide predictive information using reliability data, subsequently facilitating decision making during maintenance.

This review included a non-exhaustive illustration of BIM for FM studies, and provides evidence of the increased proliferation of studies in this area, and the increased role of BIM technologies and open standards in FM. This increased attention towards BIM for FM studies is also accompanied by remarkable industry wide initiatives in terms of standardisation (IFC and COBie) and mandating BIM uses and standards in FM. Yet studies that systematically investigate such standards as sources of data for FM applications are missing in the literature. Also studies on the workflows required to gradually produce the information needed for FM throughout the project life cycle phases are still limited.

3.3 Standards and specifications for Asset Information Models (AIM)

PAS 1192-2: 2013 and the PAS 1192-3: 2014 respectively specify the information delivery processes and the information exchanges during and between the capital project delivery phases (i.e. planning, design and construction) – Project Information Model (PIM) - and the operational phase – Asset Information Model (AIM). PAS 1192-3:2014 outlines an information management methodology for the operational phase of buildings that considers the use of several different data sources and IT systems. It also introduces the concepts of Asset Information Model (AIM), Asset Information Requirements (AIR), and Organisational Information Requirements (OIR) (BSI, 2014b).

The AIM consists of graphical, non-graphical and documentary data about assets, which can be transferred into asset management systems (BSI, 2014b). PAS 1192-3: 2013 proposes the use of open standards and data specifications (e.g. IFC, COBie) for the definition of Asset Information Models (AIMs) and for the interface between AIMs and existing enterprise systems (BSI, 2014b).

BS 1192-4:2014 supports asset and facility managers in specifying their information needs in the form of an AIM using the COBie specification (BSI, 2014a). The AIM is developed in collaboration between the client and project team (Navendren *et al.*, 2015). Provided that data requirements have been structured from the early stages of project development, data contained in the PIMs can be used for the development of the asset database, which will in turn form the basis for the Asset Information Model (White & Boyne, 2015; Ashworth & Kassem, 2016). The AIM will subsequently require updates during the operational lifecycle of the assets (Talamo & Bonanomi, 2015). The AIM can be managed as a single model, including all the information needed to manage building assets, or as a collection of linked models across information systems (BSI, 2014b; Talamo & Bonanomi, 2015).

Asset Information Requirements (AIR) specify the building owner's data requirements for the Asset Information Model. AIR are generated based on the building owner's Organisational Information Requirements (OIRs). OIR are the data and information requirements required to achieve the building owner's organisational objectives, and can be defined and managed through the definition of an Asset Management Plan (ISO, 2014). Five key areas of AIR have been outlined in the PAS 1192-3:2014: legal, commercial, financial, technical and managerial. Some of the main requirement topics in each of these areas are detailed in Table 3.1.

Table 3.1 – Asset Information Requirements proposed in PAS 1192-3:2014 (BSI, 2014b; Talamo & Bonanomi, 2015)

Legal	***Commercial***	***Financial***	***Technical***	***Managerial***
Ownership	Asset description and function	Original purchase/leasing cost	Design parameters	Identification number
Contractual information	Vendor data	Current replacement costs	Asset dependencies / interdependencies	Asset location
Property boundaries	KPIs		Commissioning dates and data	Spatial data (e.g. room/pavement area)
Work instructions	Condition / performance targets		Performance data	Warranties description and duration
Legal obligations (H&S, etc.)	Criteria of non-conformance			Work schedules and task details
	Spares information			Hazardous content/ waste
				Asset end-of-life data

The use of open standards has been identified as a key requirement for the implementation of BIM in FM, and is especially relevant when considering the long-term storage and management of data, as is typically the case during a building's lifecycle. Open standards can be used to structure data requirements for the development of projects and management of built asset data throughout the lifecycle of assets. Open standards also ensure that the compliance checking procedures will be applicable in the long term, which is of particular interest for building owners and FMs, when considering the lifecycle of buildings. In this section, several open standards are reviewed regarding their support for the information requirements of Asset Information Models – graphical, non-graphical, and documentary data requirements.

Requirements definition and building design activities are both parts of the same process to procure and develop assets according to the owner's requirements (Marchant, 2016). Several standards and specifications - mainly from the ISO 10303 STEP initiative (Pratt, 2005) - have been developed to enable the structured definition of requirements and their representation in building product data. This research adopts the Information Delivery Manual (IDM) methodology for the structured definition of owner and FM requirements (ISO, 2010). The IDM and MVD methodologies are reviewed in sections 3.3.1 and 3.3.2 respectively.

Currently, open BIM standards such as IFC – registered with ISO as ISO16739 (ISO, 2013) – and COBie are continuously being developed by buildingSMART with input from the AEC industry. The overarching aim of these initiatives is to enable information exchange throughout the construction industry business processes and asset life cycle phases. These standards allow models to be structured in a universal way, enabling product data to be exchanged between designers, suppliers, constructors and operators (Atkin & Brooks, 2009). IFC and COBie have also been proposed as data sources for the graphical and non-graphical data requirements of AIM and for the interface between AIM and existing enterprise systems (BSI, 2014b). IFC and COBie are reviewed in sections 3.3.3 and 3.3.4, respectively.

The CMIS standard has been identified to support documentary data requirements. CMIS is an OASIS standard that provides interoperability between CMIS-compliant content repositories (OASIS, 2016). CMIS provides the organisation of unstructured data sources (i.e. documents) through the definition of metadata attributes and folder structures. It is therefore considered a key requirement to manage documents throughout the lifecycle of facilities. The CMIS standard is reviewed in Section 3.3.5.

Semantic web standards can provide an important contribution to support the non-graphical AIM data requirements. Recent developments in semantic web standards for the AEC/FM industry are reviewed in section 3.3.6. Finally, section 3.3.7 provides a summary of this section's findings.

3.3.1 Information Delivery Manual (IDM)

The Information Delivery Manual (IDM) methodology was developed to enable the standardisation of AEC industry processes, specifying the various information exchanges that occur between AEC stakeholders (ISO, 2010). Its main aim is to describe the industry's operational processes, while prescribing the data requirements which support them. Consequently, IDM also aims to capture the knowledge and best practices in the AEC industry (Eastman *et al.*, 2010).

The IDM was developed as an open methodology enabling AEC stakeholders to document business processes and describe the numerous information exchanges that occur between at various stages throughout the lifecycle of buildings. IDMs can be used by AEC stakeholders as general guidance, as well as for the development of software specifications (Berard & Karlshoej, 2012).

Despite having been developed for use with the IFC standard, IDM can be used for the development of other data models and software tools (ISO, 2010), and it can also be used as a process definition methodology independently of data models (Berard & Karlshoej, 2012). The IDM methodology has been used to identify HVAC information requirements in other data models besides the IFC model (Liu *et al.*, 2013).

The Building Programming Information Exchange (BPie) project based on the IDM methodology has been proposed to structure owner requirements for space and briefing definition (East, 2012). An approach using the IDM methodology has also been proposed to enable the use of Product Data Templates (PDTs) by specifying the use of BIM data at different LODs (Gigante-Barrera *et al.*, 2017).

Figure 3.1 highlights the relationships between IDM, MVD, the AEC sector domain experts, end users, and software developers.

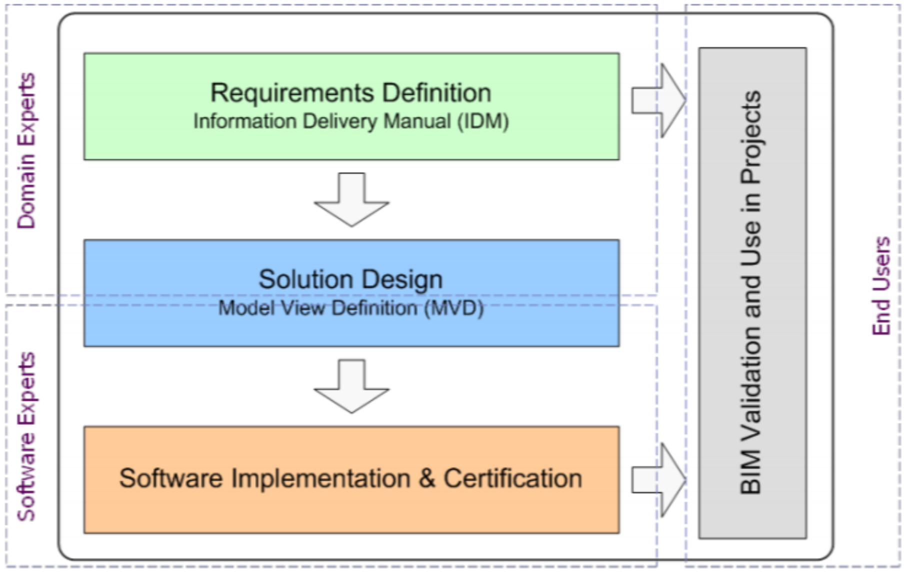

Figure 3.1 – IDM and MVD integrated process (See *et al.*, 2011)

The IDM methodology defines the following main components: Process Maps, Exchange Requirements, Functional Parts, Business Rules, and Verification Tests.

Functional Parts (FPs) are IDM's elemental units of information, and support Exchange Requirements (ERs). Functional Parts can be combined to support exchange requirements and Exchange Requirement Models (ERM). ERMs provide the link between processes and their data requirements, supporting the needs of the industry stakeholders.

The structure of the IDM methodology can be represented according to Figure 3.2 and includes the following components (ISO, 2010):

- Process Map: describes the flow of activities for a given process, including the relevant stakeholders, as well as all associated information and data requirements;
- Exchange Requirements: represent the set of information that is needed to support a particular requirement at a given lifecycle stage. ERs consist of a technical description and a non-technical description to enable the their use by software developers as well as by AEC industry stakeholders;
- Functional Parts: elemental information units used by software developers to support Exchange Requirements, representing individual actions that occur within business processes;

- Business Rules: Constraints that can be applied to data sets used within a specific process. They can be used for compliance checking of BIM data without the need to change its underlying data schema;
- Verification Tests: Software tests to verify their compliance against Exchange Requirements.

The IDM methodology is essentially divided into two phases: process definition and process implementation. Process definition is concerned with the development of Process Maps and Exchange Requirements, which are independent of the platform or product model. Process implementation is concerned with the definition of the platform specific part of the IDM, which is composed by the Exchange Requirements Model (the aggregation of a specific product model's Functional Parts); the definition of Business Rules; and the definition of Verification Tests (to evaluate a software or product model support of the defined Exchange Requirements). After an IDM is defined, it can be used to develop BIM-based applications that support the defined business processes and information exchanges, and may also be used as a tool for process control during project development, construction, and throughout the lifecycle of facilities (Berard & Karlshoej, 2012).

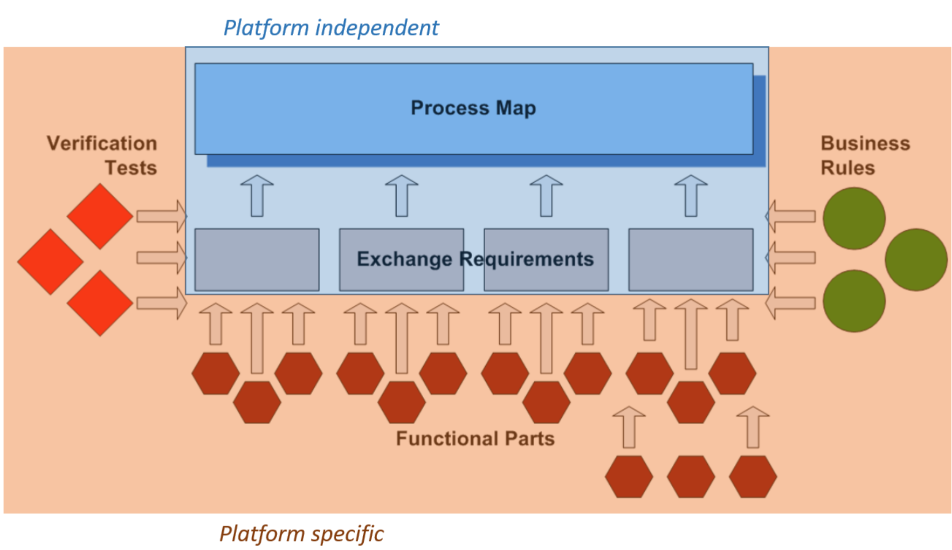

Figure 3.2 – IDM technical architecture - adapted from ISO, (2010)

3.3.2 Model View Definition (MVD)

A Model View Definition (MVD) specifies a subset of the IFC schema that is needed to satisfy one or more Exchange Requirements (buildingSMART, 2019d). The goal of MVD is to provide the implementation of an exchange of IFC data in software applications (See *et al.*, 2011). MVD specifications can be used for the semantic validation of data models (Y.-C. Lee *et al.*, 2015). Validation can be accomplished by attaching business rules defined in the IDM to the concepts defining the required data exchange capabilities. Certification is performed against concepts, while validation is performed against business rules (See *et al.*, 2011). Official MVDs are defined by buildingSMART using the mvdXML format and are used for the certification of BIM software. A summary of the current official MVDs developed by buildingSMART, which are used in software certification is presented in Table 3.2. The IfcDoc tool is used for the definition of the official MVDs, and can also be used for the definition of custom MVDs, as well as for generating the corresponding documentation (Y.-C. Lee *et al.*, 2015; Zhang *et al.*, 2015).

Table 3.2 – List of official IFC Model View Definitions developed by buildingSMART (buildingSMART, 2019d)

Model View Definition	***IFC version***
IFC4 Reference View	IFC4
IFC4 Design Transfer View	IFC4
IFC 2x3 Coordination View 2.0	IFC2x3
IFC 2x3 Coordination View	IFC2x3
IFC 2x3 Structural Analysis View	IFC2x3
IFC 2x3 Basic FM Handover view	IFC2x3

Several limitations of the IDM/MVD approach have been highlighted which have hindered its adoption by the AEC industry. The exhaustive and extremely detailed nature of existing IDMs constitutes a limitation for the use of IDMs by industry stakeholders (Berard & Karlshoej, 2012). Another limitation of the IDM/MVD approach is that due to the descriptive nature of its platform independent components, it is not possible to automate the development of product data models. Currently, MVDs are defined manually using the IfcDoc tool in an error-prone process. Several efforts have been developed to mitigate the aforementioned limitations in the IDM/MVD approach, particularly in terms of reusability of IDM elements. Eastman *et al.,* (2010) proposed an improvement to the definition of Exchange Requirements through the definition of Exchange Models and Exchange Objects. This approach attempted to define information requirements in more detail, so that MVDs could be mapped directly to IDMs, simplifying the iterative mapping procedure. The extended Process to Product Modeling (xPPM) method has been proposed to streamline the development of IDMs and MVDs. xPPM addresses IDM reusability issues by enabling the definition and reuse of a predefined set of ERs and FPs (Lee *et al.*, 2013). To improve and expedite the definition and implementation of MVDs, Zhang *et al.*, (2015) have proposed a framework for an ontology-based concept library as a semantic web-based extension for the IDM-MVD approach.

Despite the limitations in the IDM-MVD approach, it is currently the most adequate approach for the definition of owners and facility managers' requirements in the context of this research. The data requirements for AIM can be conveyed through the application of the IDM-MVD approach. IDM can also be used by domain experts to capture the semantics of building regulations to enable their implementation in rule-checking systems.

3.3.3 Industry Foundation Classes (IFC)

IFC is an open source data model currently developed by buildingSMART. The IFC schema was defined as an EXPRESS schema within STEP to address interoperability challenges within the AEC industry. Currently, IFC schemas are available in EXPRESS, XSD and OWL to allow its representation in STEP Physical File Format (SPFF), eXtensible Markup Language (XML), and the Resource Description Framework (RDF) respectively (Pauwels *et al.*, 2017). The latest version of the IFC schema is currently registered with ISO as ISO16739, in EXPRESS and XSD (ISO, 2013). A JSON schema was recently proposed for IFC, to streamline data exchanges over the web (Afsari *et al.*, 2017). IFC can be used to support the graphical and non-graphical data requirements of Asset Information Models.

IFC aims to support a variety of information domains within the building lifecycle. IFC allows the description of a building in which its objects have a well-defined and interrelated meaning and purpose. The IFC schema operates on a 'ladder process'. Classes can reference other classes at the same (for the Core and Resource layers only) or lower layers, but not in layers at higher levels (Wix & Karlshoej, 2015). Figure 3.3 provides the graphical representation of the IFC data schema architecture including the various layers and domains supported by the schema.

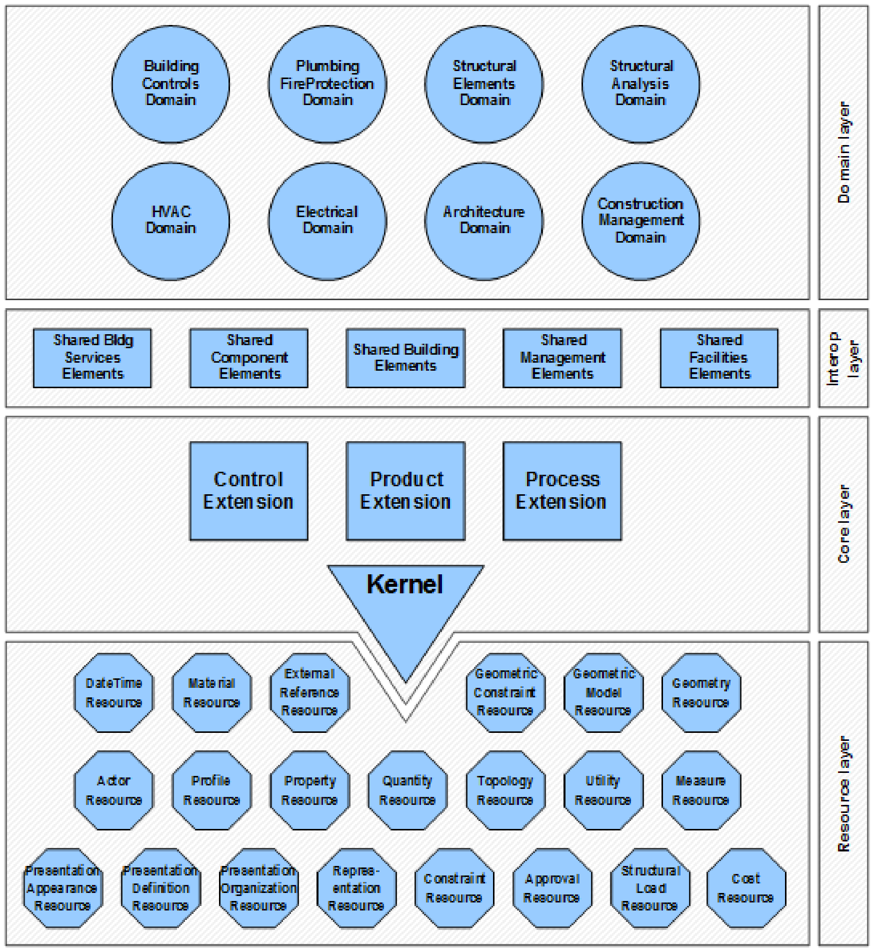

Figure 3.3 – IFC data schema architecture (buildingSMART, 2019a)

While building elements are described in many different ways depending on the software environment, export and import functions should ensure that each BIM environment is able to map its own internal data model to the IFC format, enabling interoperability (Pauwels *et al.*, 2011). To provide specific guidance on the implementation of IFC-related exchanges in specific domains, specialised model views can be defined according to the MVD methodology reviewed in Section 3.3.2. MVDs have also been defined by buildingSMART to evaluate BIM software compliance for specific information exchange scenarios (Table 3.2).

Several limitations in the use of IFC as an interoperable exchange data standard have been highlighted (Pauwels *et al.*, 2011). One of the limitations of IFC is concerned with being restricted to the domains that the schema supports. While IFC can support custom data requirements that are related to the domains it already supports, e.g. through the definition of custom property sets (Rio *et al.*, 2013), this approach is not feasible to support new information domains. This can be a limitation in the design process when e.g. geographical data needs to be integrated with the BIM model. Research has been carried out to address this particular issue by providing the transformation of IFC data to CityGML data (Hijazi *et al.*, 2009), and the integration of BIM and GIS data for FM (Kang & Hong, 2015). Other research is focusing on extending the IFC schema to support infrastructure assets (Koehorst, 2013; buildingSMART, 2019a). Another limitation has been highlighted regarding the breadth of the IFC schema. The MVD effort aims to define specific information exchanges, yet there currently exist only a limited number of official MVDs defined by buildingSMART (Table 3.2). Recent research is addressing this issue through the definition of specific model views and validation of IFC models against these model views (Y.-C. Lee *et al.*, 2015; Zhang *et al.*, 2015; Lee *et al.*, 2017). It has also been highlighted how the IFC schema can be ambiguous in the description of information. For instance, IFC allows the definition of generic objects including their own sets of attributes in the form of ‘IfcBuildingElementProxy’ elements. These elements can be used to support specific data from software tools that is currently unsupported in IFC. While this flexibility might be desirable from users, it requires additional implementation effort by software engineers to enable the interpretation of this information (Pauwels *et al.*, 2011).

3.3.4 Construction Operations Building information exchange (COBie)

The development of COBie began in late 2006 under the NIBS Facility Maintenance and Operations Committee and it is currently specified as a part of the United States National Building Information Model Standard (NBIMS-US V3) (NIBS, 2015; East, 2016). COBie is used to identify and exchange information about facility assets, throughout the lifecycle of facilities (NIBS, 2015). The IFC Facilities Handover model view definition specifies COBie as a subset of IFC data. The NBIMS-US V3 standard describes various COBie use cases, related to data access, reusability, and data validation. The standard defines various business processes and highlights how these benefits can be achieved through the use of COBie (NIBS, 2015). COBie was selected as the format for specifying and handing over data for the use phase of assets in centrally procured UK government projects. The use of standard product data templates through initiatives such as LCie, SPie and industry initiatives such as Product Data Templates (PDTs) can also streamline the delivery of facility asset data (NIBS, 2015; CIBSE, 2016).

The BS 1192-4: 2014 standard was defined to provide guidance on the use of COBie in the UK context, including the transfer of structured information, between project parties, about buildings and infrastructure to fulfil the building owner (or Employer) information requirements (BSI, 2014a). Figure 3.4 provides a representation of the COBie schema according to the BS 1192-4: 2014 standard.

COBie data can be delivered as a STEP physical file (ISO 10303-21), as well as through various XML-based formats:

- COBie STEP format – Since COBie is a subset of IFC, it can be represented using the EXPRESS language;
- COBie “Spreadsheet XML 2003” format, which is the format recommended in BS 1192-4 (BSI, 2014a);
- COBielite XML format – a National Information Exchange Model (NIEM) compliant XML specification for COBie (Bogen & East, 2019);
- COBietab XML format – a simplified flat XML schema representation of COBie (East, 2017).

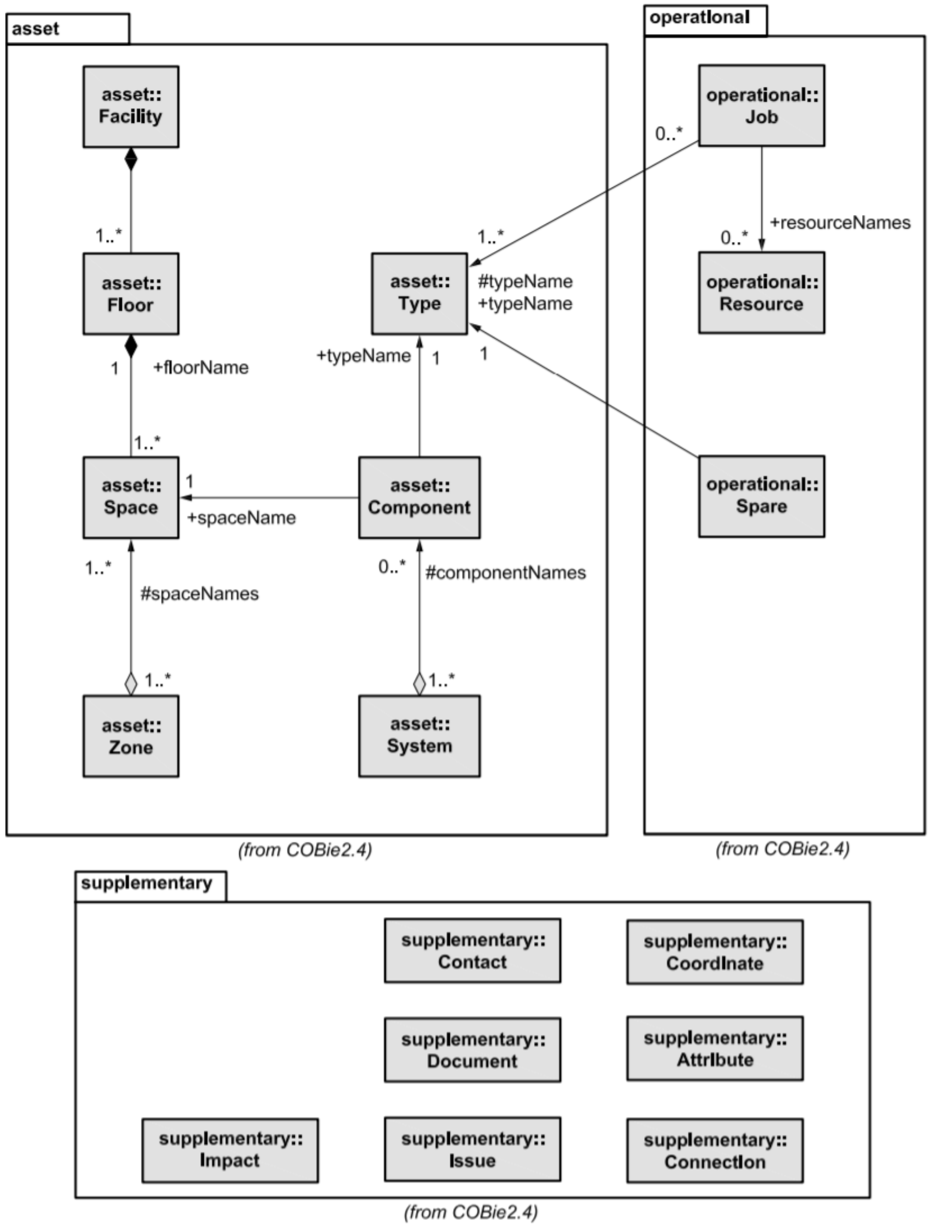

Figure 3.4 – COBie schema (BSI, 2014a)

Different COBie formats can support different workflows. The STEP format is intended to support the exchange of COBie data by software systems that can produce and consume IFC. The “Spreadsheet XML 2003” format, on the other hand, provides a human readable view of facility information.

As outlined in the LCie project, the majority of COBie-based data exchanges do not require the entirety of the COBie schema. Simplified XML schemas for COBie – COBielite and COBietab – have been developed in order to support specific information exchanges using subsets of the COBie schema. Additionally, these data formats omit all the Spreadsheet XML formatting data since they are focused on web-based data exchanges.

To support the use of COBie throughout the lifecycle of buildings, NBIMS v3 part 4 defines various business processes and how COBie can be used to support and validate the information exchanges that occur within these business processes (NIBS, 2015). In the UK, the definition of COBie data drops aimed to capture and validate client's requirements throughout the life cycle of buildings (Cabinet Office, 2012). Data drops specify data requirements during key stages of building life cycle development, and are aligned with RIBA Plan of Work stages (RIBA, 2013). However, further research is needed in order to determine to what level of detail this should be carried out to effectively support client's requirements throughout the lifecycle of the building. For example, agreement is needed to clarify what data is required in the Attribute table and at what level of detail (NBS, 2012). This way it should be possible to consider maintenance requirements for the occupancy and post-occupancy stages from earlier phases of the building lifecycle, supporting a whole lifecycle approach for maintenance (BSRIA, 2009).

3.3.5 Content Management Interoperability Services (CMIS)

The Content Management Interoperability Services (CMIS) standard has been identified to support the AIM document data requirements. CMIS is an OASIS standard that supports content and information sharing between different content management systems (OASIS, 2016). Content repositories manage unstructured data sources including documents, images, videos, etc. CMIS was developed with the objective of managing unstructured data sources through the use of metadata, as well as enabling access and exchange of data between different content repositories. This is achieved by standardising repository access, data storage, retrieval, and search operations. CMIS also provides a SQL-based query language to query content through its metadata (Caruana *et al.*, 2010). Interoperability with CMIS allows the reusability of content models across various content management systems, as well as the integration of content management systems with other systems (OASIS, 2016). Because CMIS is designed using a Service Oriented Architecture (SOA), applications using CMIS do not have to implement the entirety of the CMIS standard to interoperate. Using CMIS, developers can create bespoke software applications and web services for specific use cases that will work across various CMIS-compliant repositories (Müller *et al.*, 2013).

CMIS is language independent and standardisation is defined at protocol level. Standardisation is accomplished through the definition of several specific bindings – RESTful AtomPub binding, SOAP binding for web services, and JSON browser bindings - while data access can be provided through various APIs, such as REST, SOAP, or the OpenCMIS Java API (OASIS, 2012a).

The CMIS domain model is the core of the CMIS standard. It defines the structure of information using metadata, and provides an interface for applications to access a repository and its underlying objects (OASIS, 2012a). The domain model defines the various services, their methods, and the underlying data structures. The main service in the domain model provides access to the repository. Repositories can hold different kinds of data and support different functionalities. Entities managed by CMIS are modelled as typed objects (OASIS, 2012a). Each CMIS object has an object type and properties, including an object ID that uniquely identifies that object (Caruana *et al.*, 2010). The CMIS domain model defines 5 primary base types of objects (OASIS, 2012a) - Document, Folder, Relationship, Policy, and Access Control List (ACL) (Figure 3.5). Due to the heterogeneity of content repository solutions, CMIS does not support all the capabilities of an ECM, instead focusing on key requirements common to all ECMs. Besides document and folder objects, object support is optional.

Given its flexibility, the use of CMIS should be a requirement for the development of a CDE for AIM, both for the structuring of data requirements as metadata, and as a standardised communication protocol between EDMS, FM and other tools in the CDE.

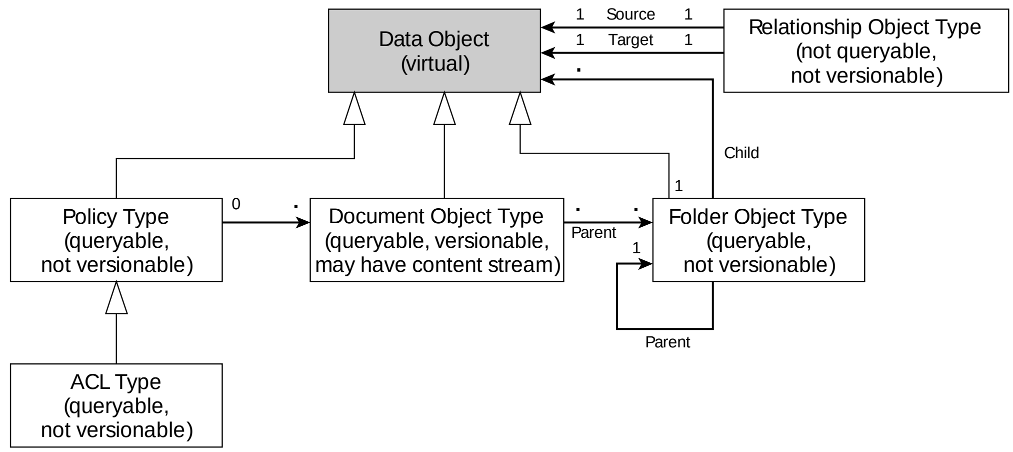

Figure 3.5 – CMIS domain model (Caruana *et al.*, 2010)

3.3.6 Semantic web standards

The adoption of semantic web technologies has been proposed to solve interoperability issues within the AEC/FM industry. Semantic web technologies can be used to support specific data domains outside the scope of the existing open standards for BIM (i.e. IFC and COBie). Semantic web technologies have been applied in research efforts such as the SEMANCO project, which proposed the combined use of census data, land registry data, energy data, building system data, and climate data to create models of urban energy systems to assess the energy performance of an urban area (Sicilia *et al.*, 2014); and in the V-Con project, which focused on improving data exchanges in civil infrastructure using BIM standards (Koehorst, 2013).

The use of semantic web technologies has also been recognised as a possible solution for current issues with IFC, particularly those related to limitations within the EXPRESS language used in the definition of the IFC schema (Beetz *et al.*, 2009; Pauwels *et al.*, 2011; Pauwels & Terkaj, 2016; buildingSMART, 2019c). The use of semantic web representations of IFC also allows linking IFC data with various external data sources. A search engine for building products documentation, developed based on a custom IFC ontology, outperformed traditional keyword-based search methods (Gao *et al.*, 2015). The IFCOWL ontology, which is the semantic data standard equivalent to the IFC EXPRESS schema, is currently being developed by buildingSMART's Linked Data Working Group (buildingSMART, 2019c). However, key challenges remain in obtaining a usable IFC ontology. Pauwels *et al.*, (2017) addressed some of these challenges by proposing the modularisation of IFC data in order to enable the use of subsets of IFC data, as opposed to the entire IFC model, to support given exchange requirements, while optimising the generation of RDF graphs representing BIM projects. The IFC web of data (IfcWoD) model has been proposed as an alternative semantic web representation for IFC. The use of IfcWoD simplifies the process for writing queries, and improves query response time for retrieving building data, when compared to the IfcOWL ontology (de Farias *et al.*, 2015).

As an alternative to the IFC-based semantic web representations, a set ontologies, focusing on specific building data domains, are currently being developed by the W3C: Building Ontology Topology (BOT); Product Ontology; Ontology for Property Management (OPM); Ontology for Property Set Definitions; and, the Sensor, Observation, Sampler, and Actuator (SOSA)/ Semantic Sensor Network (SSN) ontology (Haller *et al.*, 2018; W3C, 2019). Rasmussen *et al.*, (2018) demonstrated the integration of BIM and sensor data using SOSA and BOT datasets to represent a building's overall topology, 2D plan geometry, sensor and actuator observations log and locations. The authors propose an integrated design approach where designers can model sensors and actuators conceptually from the early stages of smart building projects development.

Various efforts in semantic indexing and search have been proposed to improve the capabilities of ECMs. ECMs such as Semantic Media Wiki and Drupal provide manual mechanisms for semantic annotation of content (Gönül & Sinaci, 2012). The use of semantic web standards could complement CMIS classification capabilities by automating the process through the use of taxonomies and ontologies. An automatic semantic indexing and search approach was proposed in the context of the Apache Stanbol project. This approach provided a mechanism for the representation of CMIS compliant ECMs in the RDF format, which can be used for the development of semantic services to provide reasoning facilities to ECMs. It also provided a mechanism for the automatic annotation of documents using semantic data from external sources, thereby establishing an “ontology network”, which can complement CMIS capabilities in the classification and categorisation of documents (Gönül & Sinaci, 2012). A similar semantic web-based approach was used to provide information integration across an array of CMIS-compliant applications. Semantic search and indexing capabilities are provided across a set of IT systems, through CMIS web service interfaces. In this approach, automatic metadata enrichment is achieved using an RDF vocabulary to annotate CMIS metadata (Garshol & Borge, 2013). Another proprietary solution with similar capabilities uses CMIS to connect to content repositories and enhance content using the semantic web (Smartlogic, 2019).

3.3.7 Summary

The increasing adoption of the BIM methodology by the AEC/FM industry could unlock benefits for building owners/FMs during the use phase of buildings, provided that their requirements have been adequately defined and captured (Kiviniemi, 2005; Eastman *et al.*, 2011). The definition of EIR and AIR in the BS/PAS 1192 specifications highlights the importance of adequate methods to capture requirements from the early stages of project development, but does not specify a structured format to enable their automated validation against BIM data sources. Existing owner guides and specifications have not adequately addressed the specific data requirements needed for the implementation of BIM in construction projects (Mayo & Issa, 2014; Cavka *et al.*, 2017). The use of open standards such as the IDM-MVD methodology provides the opportunity for the development of structured owner and FM requirements and ensuring that these are represented in data models.

The IFC, COBie and CMIS standards were identified to support the graphical, non-graphical and documentary data requirements for AIMs. Open standards such as IFC, COBie, and CMIS can contribute to the organisation of information for FM tasks. One key requirement to achieve this is the definition of Model Views. The definition of the IFC FM handover MVD enables the generation of COBie data from IFC models.

Recognising the key role of open standards in supporting building owners and FMs data requirements, several initiatives have been proposed to enable the use of COBie in the industry. The definition of COBie data drops is one such effort. In the UK, the development of the BS 1192-4 standard aimed to provide guidance in the development of COBie according to the building owner (or employer) information requirements.

The asset register is a key element for all FM tasks. In several countries, open BIM standards and data specifications were prescribed as data structures and information exchange formats for the handover of information and data to the operational phase of buildings. Yet, there is a lack of studies investigating the processes for developing and managing asset data complying to open standards during the operational phase. IFC and COBie were evaluated regarding their support of asset register data, according to the BS 8210 standard (BSI, 2012a), and it was found that they support the majority of these data requirements (Appendix C). IFC and COBie can also support custom data requirements, while maintaining compliance to MVDs, through the definition of custom property sets.

The CMIS standard can be used to support documentary data requirements, through the specification of these requirements in the form of metadata, as well as through the specification of document and folder structures that can be used in ECMs. The use of IFC, COBie and CMIS was identified as a key requirement to enable interoperability between the different systems used in the development and management of AIMs, particularly for the identification of a suitable FM environment for this purpose.

Approaches for the development of semantic web models based on the IFC and CMIS standards have been identified in the literature, which could also enable their interoperability with other data sources needed for FM and maintenance purposes within a linked data approach (e.g. BMS, BAS systems, etc.).

3.4 Compliance Checking for Digital Building Data

The implementation of compliance checking methodologies in the AEC sector has been researched for many years. The main focus of this research has been the reformulation of design codes and other statutory documents as computer-based rules operating on specific objects, their properties, and their interrelations within data models that represent the products being validated.

Research into requirements validation and compliance checking methodologies has gathered significant interest in the AEC sector in recent years due to the increasing adoption of BIM by the industry. The semantically rich nature of BIM models, and the availability of the IFC and other open standards have enabled the development of compliance checking tools and systems. A variety of tools and methodologies exist nowadays focusing on providing compliance checking of BIM data against different types of requirements. However, research efforts in this area remain fragmented and a holistic approach to address validation and compliance checking problems in the AEC sector is still lacking (Hjelseth, 2016; Solihin *et al.*, 2017).

Validation of graphical, non-graphical and documentary data sources against AIR can be accomplished through the adoption of querying and rule-checking approaches. In this section, several compliance checking methods and tools that have been developed for the validation of digital data sources will be reviewed. These efforts are organised according to the framework proposed by Solihin *et al.*, (2017) in: Translation methods (Section 3.4.1); Rule computable formats (Section 3.4.2); Rule execution methods (Section 3.4.3), and; Enhanced data models (Section 3.4.4). Finally, Section 3.4.5 provides a summary of the findings of this section.

The outcome of this section is the identification of standards and tools that can support the validation of requirements for AIMs – one of the key components of the framework proposed in this research.

Similarly to the data quality definitions proposed in ISO 8000-8 – i.e. syntactic, semantic and pragmatic quality (ISO, 2015b) - data validation approaches can be divided into three main categories (Solihin & Eastman, 2015; Y.-C. Lee *et al.*, 2015; Hjelseth, 2016):

- Syntactic - validation of data models in terms of conformity to data schemas;
- Semantic - validation of data models suitability to support a given information exchange (e.g. using MVDs);
- Pragmatic - Data content validation according to various requirements including: building regulatory code checking, constructability and other contractor requirements, owner requirements, safety rules, warranty approvals, functional performance, BIM data completeness for handover to FM.

Syntactic validation of data models is concerned with evaluating data compliance against a defined schema. If data models do not satisfy the requirements of their data schemas, syntactic problems may arise, including translations errors, missing or duplicate data, and other issues (Y.-C. Lee *et al.*, 2015).

Semantic validation of data models can be accomplished through the structured definition of model views. Considering the IFC standard, validation can be achieved through compliance evaluation of IFC models against the given model views.

Data requirements (i.e. pragmatic) validation can be more challenging to achieve, especially considering the amount of data exchanges that typically occur during a project's lifecycle. Indeed, buildingSMART's certification assessments only account for limited exchange requirements, and do not consider data round trip, therefore the integrity of the data content cannot be ensured throughout data exchanges (buildingSMART, 2019e). To ensure data integrity in information exchanges that occur throughout the building lifecycle, each information exchange needs specific definition of its contents, including level of detail (Eastman *et al.*, 2010; Y.-C. Lee *et al.*, 2015).

Eastman *et al.*, (2009) have outlined the relationship between these 3 different categories and how they can be applied for compliance checking and data validation of IFC models (Figure 3.6).

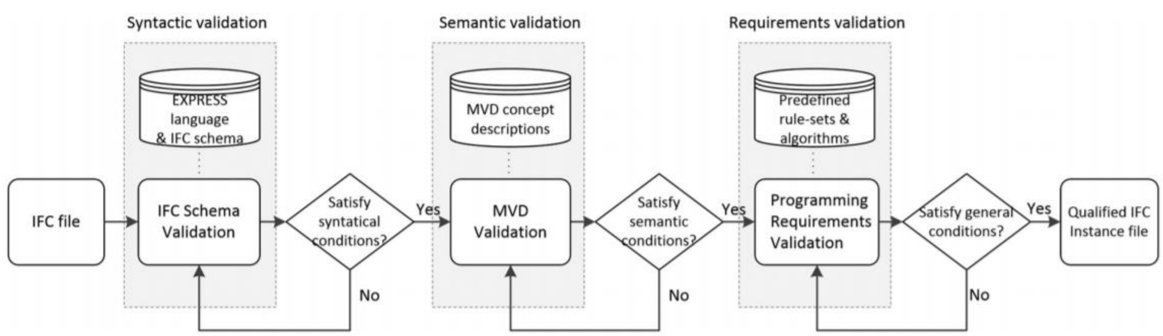

Figure 3.6 – Architecture for IFC-based automated compliance checking (Eastman *et al.*, 2009)

Rule checking approaches for data requirements validation have mostly focused on code checking for building regulations. Several research projects were carried out in this area, including the CORENET project, the HITOS project by Norwegian Statsbygg, the Australian Building Codes Board, and the Smartcodes project from the US International Code Council (Eastman *et al.*, 2009; Nawari, 2012). More specialised compliance checking approaches such as client's requirements validation and requirements for specific building types are also emerging (Solihin & Eastman, 2015).

The general process for rule checking consists of the following steps (Eastman *et al.*, 2009; Pauwels *et al.*, 2011; Solihin & Eastman, 2015):

- Rule interpretation and translation into machine computable format;
- Building model preparation, where the necessary information requirements for compliance checking are specified in the form of a model view;
- Execution of rules against building models;
- Reporting of the rule execution results, including setting up procedures for automatically correcting rule execution failures.

In order to perform the rule checking process it is fundamental to match the coded rules with the properties and structures that are embedded in the building model. Information availability for rule checking can be achieved through two different approaches, or through a combination of these approaches (Eastman *et al.*, 2009):

- Requiring the information provider (e.g. designer) to explicitly provide information in the building model needed for checking;
- Having the rule checking system derive new data, or generate model views that explicitly derive the lacking data from the existing building model data.

These two approaches involve various trade-offs between imposing documentation work on the designer, and providing stronger inference capabilities within the rule checking software. To achieve adequate performance during the rule checking process, a balance must be found between the complexity of the BIM model, and the complexity of the rules to be applied.

It is now fundamental to investigate methods for the validation of data contents against several types of structured requirements, and how these can be used to validate several types of data at various stages during project development, and throughout the lifecycle of facilities.

Recently, (Solihin & Eastman, 2015; Hjelseth, 2016; Solihin *et al.*, 2017) have proposed frameworks for the classification of these research efforts. Data validation and compliance checking methods and tools will be reviewed regarding their suitability to validate owners' and facility managers' information requirements (EIR and AIR) based on the most recent of these efforts, proposed by Solihin *et al.*, (2017). This framework highlights how each of the reviewed methods and tools can support the overall process of automated compliance checking. An overview of the reviewed methods and tools is presented in Table 3.3.

Table 3.3 – Overview of components of automated rule systems – adapted from Solihin *et al.*, (2017)

Translation methods		**Rule computable formats**		**Rule execution environments**		**Enhanced Data Models**
Automatic	NLP	**Meta-languages**	KBIM	**Syntactic requirements**	EDM - Jotne	FORNAX Objects
Manual	RASE	**XML**	LegalDocML		JSDAI	BIMRL
	Conceptual Graph		LegalRuleML	**Semantic requirements**	FORNAX	BERA Object Model
	Ad hoc manual (e.g. CORENET)		BPMN		BIMserver	XML (RASE)
			mvdXML		IfcDoc	ifcOWL
			SmartCodes		Rule engines (e.g. DROOLS)	
		Scripts	BIMRL	**Data requirements**	BIMserver	
			RKM / RKQL		Solibri Model Checker	
			CDP		IfcDoc	
			BERA			
			SPARQL-SPIN			
			SWRL			
			VCCL			

3.4.1 Translation methods

The first step in automated compliance checking methodologies consists in the translation of requirements and regulations into rules that can be interpreted by a computer (Eastman *et al.*, 2009; Pauwels *et al.*, 2011). Several methods have been proposed for the translation of rules and regulations into rule computable formats. These methods can be split into automatic and manual rule translation methods. Currently, the majority of translation methods require large amounts of manual input, with the exception of the NLP approach, which attempts to fully automate rule translation (Solihin *et al.*, 2017; Zhang & El-Gohary, 2017).

The earliest automated compliance checking project in the AEC industry was the Singapore CORENET project, which focused on compliance checking of building regulations.

CORENET supports building code checks on building plans and code compliance checking for building services. Checking of building plans includes rules for accessibility, fire codes, environmental health, household, public housing and vehicle parking. The building service module includes rules for electrical systems, fire alarm systems, fire sprinkler systems, raising main and fire hydrant systems, ventilation, sanitary, plumbing and drainage systems, surface water drainage, gas pipe systems and water services. Rules can be executed against IFC models for validation. In this system, rules are hardcoded and documentation is defined manually (Eastman *et al.*, 2009).

There have been several research efforts using a Requirement, Applicability, Selection, Exception (RASE) methodology, which is a semantic based concept for transforming normative documents into rules. These rules can then be implemented into BIM / IFC based model checking software. This methodology was used in several test cases for the translation of building code clauses into marked up HTML documents (Hjelseth & Nisbet, 2011).

Another translation method that has been developed recently is the Conceptual Graph (CG). CG conforms to First Order Logic - formally defined logic that is expressive and supports automated reasoning (Zhang & El-Gohary, 2017) - and aims to support the unambiguous description of data requirements so that all the participants in implementation efforts can understand the requirements. The conceptual graph methodology aims to remove ambiguities in building codes, which can cause problems when they are translated into rules. The CG is designed to capture both the rules logic and the data model requirements of building objects needed to satisfy the rules. CG provides a standardised way to capture and document data model requirements, as well as the rules logic needed for their validation as their functional requirements. This will allow mapping CG concepts to IFC entities, which can be used for defining MVDs and for software development purposes (Solihin, W; Eastman, 2016).

Zhang & El-Gohary (2017) developed algorithms to automatically extract and transform information using a Natural Language Approach. Their proposed NLP approach uses both syntactic (related to the structure of the text) and semantic (related to the meaning of the text) features. The authors' NLP approach was used to define an Information Representation schema based on First Order Logic, which was used for automated compliance checking of an IFC model (Zhang & El-Gohary, 2017).

The final step in translation methods consists in the transformation of rules into a computable representation that will enable their execution against the data models.

3.4.2 Rule computable formats

The development of dedicated rule languages to represent requirements and regulatory knowledge has been proposed as an alternative to existing rule checking environments, which adopt hard-coded rule-checking approaches to represent rules (Dimyadi *et al.*, 2016). Such approaches are based on an implementation framework consisting of a data-, schema- and rule-agnostic engine that can load data, schema and rules as required depending on specific user queries (Figure 3.7).

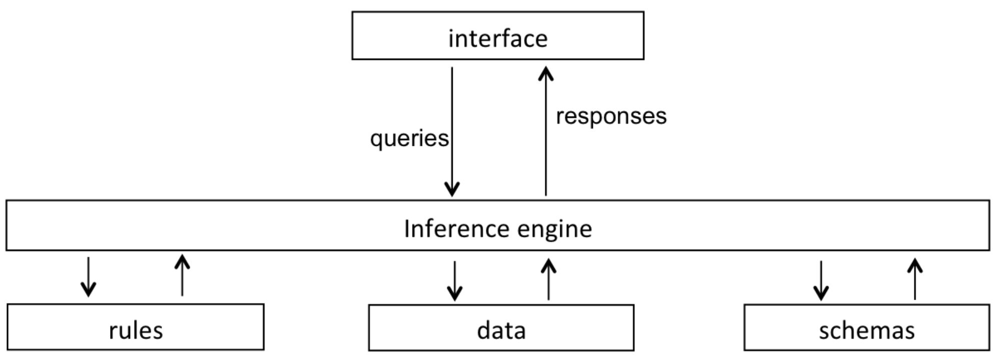

Figure 3.7 – Implementation approach for automated rule checking using a rule engine that is separate from data, schema and rules (Dimyadi *et al.*, 2016)

Various rule computable representations are used in compliance checking methodologies nowadays. These can be classified into XML-based formats, meta-languages and script-based languages (Solihin *et al.*, 2017). Research in the legal domain over the last two decades resulted in various approaches for sharing digital representations of legal documents. Key developments in this area included two XML schemas that are currently being standardised by OASIS: LegalDocML (OASIS, 2017a), based on the Akoma Ntoso - (Architecture for Knowledge-Oriented Management of African Normative Texts using Open Standards and Ontologies) standard (Sartor *et al.*, 2011), and LegalRuleML, based on the RuleML standard

(OASIS, 2017b). LegalDocML can be used to represent the structural, literal content, and presentation aspects of documents, while LegalRuleML can be used to represent the logical content and semantics of documents (Dimyadi *et al.*, 2016).

Dimyadi *et al.*, (2016) proposed the definition of a XSD (XML schema definition) which combined Regulatory Knowledge Models (RKM) - complying with LegalRuleML - with Regulatory Document Models (RDM) - complying with LegalDocML - in order to enable the representation of both regulatory documents and requirement specifications in the same schema. The authors defined RDM and RKM to support the C/VM2 document for fire engineering design in New Zealand. The authors also proposed the definition of Compliant Design Procedures (CDP) workflows based on the BPMN standard (which supports XML) for the evaluation of design compliance. CDP workflows can be executed iteratively for several design options and across multiple projects, automating the manual design compliance audit processes. Finally, the CDP workflow can embed scripts to query both the building model and RKM for compliance checking. The authors demonstrated this capability through the use of the Regulatory Knowledge Query Language (RKQL) developed in their research.

mvdXML is another XML-based approach for the definition of rules. mvdXML, initially developed as a means to document IFC Model View Definitions using a neutral format, can also be used for validation of IFC data against MVDs, or against one or more Exchange Requirements. mvdXML was used in the semantic validation of the Precast Concrete Industry MVD (Y.-C. Lee *et al.*, 2016), and Facilities Management Handover View (COBie) MVD (Lee *et al.*, 2017). mvdXML was also used as a basis for the development of a model checker for validation of IFC models against building regulations and laws (Zhang *et al.*, 2015). In this approach, mvdXML was used for the definition of templates and rules which were executed against the IFC model. The authors provided reporting of the rules execution results using a BCF server.

SmartCodes is an initiative by the International Code Council (ICC) that aims to streamline the process of transforming paper-based codes into machine-interpretable rules. This is achieved through a methodology for marking up electronic copies of building codes using an ontology (Malsane *et al.*, 2015). Building codes can then be mapped into computer-interpretable XML data, which can be used for compliance checking of IFC models (Eastman *et al.*, 2009; Nawari, 2012; Malsane *et al.*, 2015). Currently SmartCodes rules can be executed using other tools such as Solibri Model Checker or XABIO (Malsane *et al.*, 2015).

KBimCode is a domain-specific, standardised, and software independent script language. It can be processed in various formats, such as JSON or XML, and can be used in various BIM assessment tools. KBimCode supports the building permit-related regulations in the Korean Building Act (Park, S; Lee, Y-C; Lee, 2016). The authors demonstrated the translation process from natural language into KBimCode, and how the produced statements can be executed in a BIM assessment tool (KBimAssess-lite) against IFC models.

Standard query or rule languages can also be used as a means to translate requirements and regulations into computable formats that can be executed against building data models. Two recent examples of domain-specific query languages are Building Environment Rule and Analysis language (BERA) (J.-K. Lee *et al.*, 2015), and the BIM Rule Language (BIMRL) (Solihin *et al.*, 2017). BERA deals with building information models in an intuitive way in order to ensure the quality of design and assess the design programming requirements using user-defined rules in the early design phases (J.-K. Lee *et al.*, 2015). BIMRL is a simplified database schema that focuses on improving the performance of validation assessments that involve the geometry of assets (Solihin *et al.*, 2017).

Due to various limitations in the IFC schema when developing automated rule checking systems, recent research approaches are focusing on the use of semantic data models to represent IFC and other building data, as well as the rules needed to perform compliance checking against these data sources. Several query languages can be used to implement rules and query semantic data models. Examples of query languages that have been used by researchers to validate IFC models in semantic representation include N3Logic (Pauwels *et al.*, 2011), SPARQL-SPIN (Zhang & Beetz, 2016), and SWRL (Solihin *et al.*, 2017).

In order to foster the adoption of automated rule checking methodologies by the AEC industry, Preidel, C; Borrmann, (2016) have developed a ‘Visual Code Checking Language’ (VCCL), which uses a graphical notation to represent rules in both a machine and human-readable way.

Traditionally, rule computable formats were closely linked with the rule execution environments, however some of the more recent approaches reviewed (CDP, mvdXML, KBimCode, BIMQL, BERA, N3Logic, SPARQL and SWRL) are independent of a rule execution environment.

3.4.3 Rule execution environments

To support the compliance checking procedure, a number of software applications have been developed to support the execution of rules against data models. Current software applications focusing in the validation of syntactic (Jotne EDM model checker, JSDAI), semantic (IFCDoc, BIMserver, FORNAX), and data requirements (Solibri, BIMserver, IfcDoc) will be reviewed in this section.

Express Data Manager (EDM) is a client-server based-system which supports development of object models, management of model data, application integration, mapping of heterogeneous database structures through the definition of model views, and checking of rules using EXPRESS language. The tool supports object-based validation of IFC and other EXPRESS data models. EDM also allows the user to define additional rules and constraints for the assessment of existing EXPRESS schemas (Nawari, 2012; Y.-C. Lee *et al.*, 2015). However, since the system deploys the internal structure of multifaceted interfaces, and applies a validation process executed by a parameter-driven method, users are limited to use predefined templates for compliance checking (Y.-C. Lee *et al.*, 2015).

JSDAI is a library and a toolkit that supports the development of applications using the STEP standard and tools. The JSDAI API supports reading and writing data sets defined in the EXPRESS language. JSDAI supports the validation of EXPRESS schemas, and conformity tests of the interoperability of STEP Application Protocols (AP) (Y.-C. Lee *et al.*, 2015).

JSDAI provides libraries to handle EXPRESS data in a Java environment to help users read, write, and edit schema files and IFC instance files. The application also supports schema-based rule validation (Y.-C. Lee *et al.*, 2015). Since it is open source, it can be extended with additional functionality. For example, the Semantic NLP approach developed by Zhang & El-Gohary, (2017) was built on top of the JSDAI library. Their validation approach used JSDAI to extract information from IFC models before transforming the information into logic rules.

Another tool that has been used recently for semantic and data requirements checking is IfcDoc. The primary feature of the IfcDoc tool is the development and documentation of IFC MVDs. IfcDoc automatically generates the diagrams, schema definitions, indexes, and contents of MVDs. The IfcDoc tool also supports the validation of IFC files against MVDs defined in the mvdXML format, supporting semantic validation of IFC models (Y.-C. Lee *et al.*, 2015). MVDs defined using the IfcDoc tool have also been used for data content validation (Zhang *et al.*, 2015).

FORNAX was an effort to implement the automated building code compliance checking method defined in the CORENET project. FORNAX is a C++ object library that derives new data and creates extended views of the IFC data model (Nawari, 2012). FORNAX performs the derivation of topological graphs and uses the shortest path algorithm to support rules related to geometric requirements (Solihin & Eastman, 2015). FORNAX is the basis of the ePlanCheck compliance checking tool implementation, which was commissioned by the Singapore government to perform automated conformance checks on digital plans submitted by architects and engineers against building codes and regulations (Solihin & Eastman, 2015). FORNAX has also been applied in Norway by the Selvaag Group to check for fire exit provisions (Nawari, 2012), and in Saudi Arabia as a basis to check for building plans regulatory compliance in municipalities (Solihin & Eastman, 2015).

BIMserver is an open source IFC model server that can be used as a basis for the development of IFC-based applications. BIMserver interprets and stores IFC data as objects in an underlying database. BIMserver provides a variety of features as plugins in an open framework, therefore they can be edited by the user/administrator of the tool. New features can be added to the tool in the form of custom plugins, or custom client-based applications that interact with BIMserver. BIMserver has been used as a basis for IFC-based model checking (Zhang *et al.*, 2015).

Solibri Model Checker (SMC) is a Java-based, standalone platform that performs rule checking against IFC models. SMC converts the IFC model into its own internal data model in order to improve performance. SMC supports the generation of reports and visualisation of compliance checking results can be overlaid onto the corresponding 3D building model. SMC allows customisation of predefined rules, however this feature is limited by the parameters provided by the software's templates. Since the software is not open source it is difficult to customise and extend its code checking capabilities (Y.-C. Lee *et al.*, 2015).

3.4.4 Enhanced data models

Existing product data models based on STEP, such as the IFC, were not explicitly developed with rule checking in mind. To improve the performance of compliance checking approaches against IFC, Pauwels *et al.*, (2011) suggested that the IFC schema should be improved at the logical level. Various research approaches in this area have recognised the shortcomings in STEP-based product models such as IFC in terms of logical representation, and have resorted to the use of intermediate, or enhanced data models to accurately capture the rules needed for semantic and data content validation, simultaneously reducing the burden in the development of designers' specifications.

An early example of this is was the development of FORNAX objects, within the FORNAX tool. FORNAX uses its own internal data model to support the checking of rules involving complex requirements, such as geometric requirements. FORNAX objects were designed to be extensible, which has enabled the application of the FORNAX tool to various countries building codes (Malsane *et al.*, 2015; Solihin & Eastman, 2015). The BIMRL approach also focused on the validation of rules involving geometric relations. In this approach a simplified database schema was proposed to access BIM data and validate geometric requirements. The developed database schema was implemented using relational databases that support 3D geometry. This approach aims to improve the performance of geometry-related rules checking by performing the optimisation of geometry representation at the database level, allowing the rule checking system to focus exclusively on the rules logic (Solihin *et al.*, 2017).

The BERA language, a domain specific language, which focuses on the validation of BIM models against design programming requirements, defines an object model, which is mapped against IFC for rules execution. BERA was implemented using IFC to support building data, Solibri Model Checker (SMC) as an IFC engine, and the Java Virtual Machine (JVM) as a compilation and execution environment (Y.-C. Lee *et al.*, 2015).

To overcome issues related to the logical representation of rules, the use of enhanced data models, based on semantic data standards, has also been proposed for automated compliance checking of BIM data (Yurchyshyna *et al.*, 2007; Beetz *et al.*, 2009; Pauwels *et al.*, 2011; Terkaj & Šojić, 2015; Pauwels & Terkaj, 2016).

Pauwels *et al.*, (2011) investigated the use of semantic information description and rule languages in order to improve building performance checking against IFC models. The authors used RDF to represent IFC data and N3Logic (an extension of the RDF data model to support logic) for the definition of rules. The combination of these two languages enables the creation of a logic-based approach for rule checking. The authors applied this approach to the formalisation of rules for the evaluation of the acoustic performance of building elements. In this approach, two standards were manually translated into a rule ontology in OWL, which described the concepts used within the standards; and a rule set in N3Logic, which described the logic within the standards. A logic inference engine (EYE) was used to evaluate the RDF graph against the defined rules. Finally, the rule checking results are reported in the form of a new RDF graph, which can be used in other information environments for further processing.

Beach *et al.*, (2015) proposed an architecture for automated compliance checking based on a semantic framework, which supports rule extraction from regulations and semantic data mapping to various data formats. The generation of compliance regulations consists in enhancing regulation documents with semantic metadata with input from a regulation expert. Rules are extracted from regulatory documents in the form of XML tags using the RASE methodology (Hjelseth & Nisbet, 2011). Concepts used in the enhanced regulation documents are mapped to a target data format, with input from a data format expert. In this research, the IFCOWL ontology is used to support the semantic mapping of rules to the IFC data format. This approach enables the users to specify the required regulations within the system and verify the compliance of IFC models against these regulations.

One key advantage of the use of semantic data models to represent building data is that this approach can be used to represent several different data schemas which can be queried using the same approach (Pauwels *et al.*, 2011; Zhang & Beetz, 2016). This enables the connection of various data domains, enabling compliance checking approaches involving various different data sources. Considering the variety of data sources and models needed to represent Asset

Information Models, and support FM data requirements, the adoption of semantic data models could enable the development of compliance checking methods and tools specifically for the use phase of building assets. The extensibility capabilities of semantic data standards also make them appropriate for long-term data management approaches, which will be required for the use phase of building assets (Pauwels *et al.*, 2011).

3.4.5 Summary

In this section, several techniques, tools and methods to achieve automated compliance checking were reviewed based on a framework developed by Solihin *et al.*, (2017). Rule checking approaches can be classified in: syntactic, semantic, and data content validation. Rule checking approaches follow the general steps of: interpretation and translation into machine computable format; building model preparation, where the necessary information requirements for checking are specified in the form of a model view; execution of rules against building models; and reporting of the rule checking results.

Numerous approaches have been proposed within the AEC/FM industry to provide compliance checking of digital data sources, but none of these has evolved into a practical solution. Existing efforts remain isolated attempts at providing solutions for automated compliance checking of building data, and highlight the need for standardisation of the compliance checking process (Dimyadi *et al.*, 2016).

Current approaches for validation of building data have mostly focused on the compliance of BIM models against design requirements and regulations during the design development phases of building projects. Indeed, BIM data provides the opportunity for the development of validation approaches due to its structured nature. It should be highlighted that the translation of rules and regulations into machine readable format presents particular challenges, and that even novel methods such as NLP cannot fully automate this process (Solihin *et al.*, 2017; Zhang & El-Gohary, 2017). The applicability and suitability of compliance checking approaches based on BIM data for the definition and validation of FM requirements requires further investigation. This research attempts to address these issues by proposing a methodology for data validation that considers the several data sources that will be used for the development of AIMs.

3.5 Analysis

3.5.1 BIM for building owners and FMs

Objective 1 of this research is concerned with investigating the state of the art and identifying industry requirements for the use of BIM in FM. The qualitative review of applications of BIM for FM and maintenance purposes provided the theoretical background for uses of BIM by building owners and FMs, and revealed current challenges in achieving the integration of BIM and FM.

Several challenges have been identified regarding the implementation of BIM for FM that will need to be addressed in the development of the proposed framework and prototype CDE. It is expected that the use of BIM models will expedite data access and sharing and enable data reusability. However, to enable this, designers must be aware of the FM and maintenance data requirements for the use phase of the building so that they can provide data that will be useful for operations and maintenance. Currently, data is typically not provided in a usable format for FM, resulting in manual input of data into CAFM/CMMS systems. On the other hand, the implementation of BIM by owners and FM reveals itself much more challenging than its implementation during the design and construction stages. Results from existing studies for the implementation of BIM for FM highlight that the involvement of the FM team early in the project development process is crucial to minimise issues during the handover stage, in particular in the process of capturing project information and exchanging it in open data formats that are compatible with FM software applications.

Building owners and FMs face the added challenges of managing BIM data from newer projects along with the already existing data in their current building portfolios (Kiviniemi & Codinhoto, 2014). Building owners and FMs will need to consider the cost-benefit ratio of novel approaches using reality capture to survey existing buildings built before the emergence of BIM, and how to apply such methodologies in order to obtain useful data sets. The use of legacy FM systems presents another challenge since these systems do not support open BIM standards. Building owners and FMs will require a robust business case to integrate their existing systems with new open standards compliant FM systems, as well as all the legacy data from their current building portfolio (Kassem *et al.*, 2015).

There is a need to determine specific data requirements and data quality assessment measures to enable BIM-FM integration for new and existing buildings (Yang & Ergan, 2017; Zadeh *et al.*, 2017; Motamedi *et al.*, 2018). This process needs to consider the input from FMs, as well as lessons learned from the implementation of BIM for FM in the various case studies documented in research in order to determine what data will be required to improve the various management processes during the use phase of buildings.

3.5.2 Standards for AIM

Various standards have been proposed to enable the use of integrated, web-stored electronic information about building assets (i.e. "BIM Level 3") in the development and management of AIMs. This section investigated existing open standards that can be used to fulfil the information requirements of AIMs, in order to achieve objective 2 of the research.

The IDM methodology was identified for the development of structured owner and FM requirements. Its process driven nature can also be used as a basis for the development of the proposed framework.

The IFC schema already supports a substantial amount of information needed for the AEC industry's business processes. However, the IFC schema does not take into account the ways in which information is created and shared by industry practitioners. While the development of IFC model views is an attempt at solving this issue, model views are targeted specifically at software developers for software certification and not at the end users of the software. IDM is proposed as a methodology for secure and reliable information exchange for industry end users. IDM also provides tools for software developers to capture the information flows and data requirements in the IFC development process, so that they can be reused for further developments (ISO, 2010).

The IFC, COBie and CMIS standards were identified to support the graphical, non-graphical and documentary data requirements for AIMs.

While it is possible to support the use of custom data attributes through the IFC and COBie standards, it is not feasible to use such an approach to support entirely disparate information domains, which will need to be considered in the development of AIMs. Recent developments in semantic web standards provide a feasible alternative approach to link data of disparate sources that is outside the scope of the identified standards (IFC, COBie and CMIS). Therefore, the developed framework and prototype CDE will also need to consider the use of linked data sources, in particular to support additional non-graphical data sources outside the scope of the IFC and COBie standards.

3.5.3 Compliance checking

Several rule checking approaches have been proposed in the field of AEC/FM throughout the years. They can be categorised in terms of the types of validation that they support: syntactic, semantic, or data requirements validation. Conventional rule checking systems typically follow a hard-coded implementation approach. In these systems, regulatory knowledge is embedded in the software code, which makes it difficult for domain experts to edit and customise the rules (Dimyadi *et al.*, 2016). Furthermore, since the majority of these systems are proprietary, it is not possible to verify the correctness of the implementation of the rules.

Various approaches have been used in rule systems in order to enable automated compliance checking against building data models, namely IFC. The most recent efforts in this area are focusing on the use of semantic web standards and technologies. There are several advantages in using semantic data models for compliance checking purposes. Semantic web technologies support both the representation of data models, as well as the representation of the rules, which enables the development of logic-based approaches for compliance checking. The logic-based structure of semantic web languages enables their reuse in different rule checking environments, enabling modularity and flexibility in their implementation (Pauwels *et al.*, 2011). Other key advantages of the use of semantic web technologies are that they can be used to represent any data model, and they can be used to validate data from several different sources. This is particularly relevant for this research since they can be used to represent the various data sources that are used in Asset Information Models, and perform automated compliance checking of these data sources.

Objective 3 of this research is concerned with the identification of suitable methods for the validation of asset data against structured owner's requirements throughout the lifecycle of buildings. It was found that the IDM-MVD methodology was adequate both for the definition of data requirements and the definition of rules. Requirements defined in IDM can be represented as mvdXML rules which could be used for content validation of IFC and COBie data. Since IDM requirement definition can be done independent of the data schema, it could also be adopted for the definition of document data requirements, which can be evaluated through the execution of CMIS queries.

One of the key requirements for the validation of AIM is the ability to evaluate disparate data sources, for which open data standards have been identified – IFC, COBie and CMIS.

For these reasons, the use of Semantic Web tools and standards is proposed for the validation of various sources of AIM data, since it can be used both with existing ontologies, such as IFCOWL which can be used to represent IFC and COBie data, as well as with external data sources and systems, through the use of standard web service interfaces.

3.6 Summary

This chapter presented a qualitative literature review, focusing on:

- Current studies on the implementation of BIM for FM, including the expected benefits and challenges of the implementation;
- A review of existing standards that can be used to support the graphical, non-graphical and documentary information requirements of AIMs, including IFC, COBie, CMIS, and additional semantic web standards;
- Existing compliance checking methodologies and tools that can be adopted to ensure the quality of AIMs, according to the building owner's requirements.

Findings from this chapter were evaluated regarding their relevance to answer objectives 1, 2 and 3 of the research. This chapter provides the theoretical foundation for the development of the proposed framework and prototype CDE. Findings from this chapter were combined with the findings from the Requirements Gathering chapter in order to determine the requirements for the development of the proposed framework and prototype CDE.

4 REQUIREMENTS GATHERING

4.1 Introduction

The aim of this chapter is to identify the industry requirements for the development of the proposed framework and CDE. For this purpose, semi-structured interviews were carried out with experts from the AEC/FM industry, with experience in the implementation and use of IT systems to manage FM and building maintenance tasks.

The Grounded Theory Method guides the data collection process, and is used to analyse the qualitative data from the interviews, and elicit the requirements for the development of the proposed framework and CDE. Its application provides further justification to the relevance of the research problem, and the aims and objectives of the research.

Findings from the interviews complement the findings from the literature review and are used as a basis for the development of a requirements model for the proposed framework and CDE. The provisional requirements model results from the implementation of the GTM method, and identifies the key areas and requirements for the proposed framework and CDE for the development and management of AIMs.

4.2 Data collection

This research adopted the GTM in the development of the requirements for the proposed framework and CDE.

Glaser & Strauss (1967) suggest that the process of theoretical sampling should not be influenced by the existing theory, however in practice it is impossible for the researcher not to be influenced by his existing knowledge of the theory. Other grounded theorists propose that the existing theory should be used in conjunction with field data, during the analysis process and development of the emergent theory (Strauss & Corbin, 1990; Charmaz, 2006). For instance, Charmaz (2006) suggests the use of the researcher’s existing knowledge as an additional view of the data in the context of the constant comparative method in GT. In this research, data collection and analysis using the Grounded Theory method occurred in parallel and influenced the development of the literature review. The results of the data analysis are combined with the results from the literature review to identify the initial requirements for the development of the framework and CDE.

Following Glaser and Strauss' technique of theoretical sampling, industry and academic experts were selected considering their common working area (i.e. IT in construction), as well as the differences in their profiles. The key industry stakeholders that have been identified in this research are: Building Owners, Facility Managers, and Designers.

This selection process ensures that the research focuses on a specific area of knowledge, and therefore it is more likely to contribute to the theory in this area of research (Orlikowski, 1993). All the stakeholders are or have been involved in the implementation and use of IT tools for FM. Their different roles allow the identification of different requirements from each of their respective fields.

Semi-structured interviews were chosen as the engagement method since they can provide comparable qualitative data which can be used in the context of GTM to uncover the requirements for the framework and CDE. The use of semi-structured interviews was considered appropriate for this study, since it allowed participants to change the order of the questions, focus on specific questions in which they could provide more insight, and skip questions that were not in their field of expertise. This way, it was possible to focus each interview on the expert's specialty knowledge field in order to identify and capture the requirements for the framework and CDE.

To carry out the interviews, a questionnaire was developed, consisting of 12 questions divided in 4 themes:

- Benefits and challenges of BIM implementation in FM;
- Maintenance and FM data requirements;
- Data validation;
- IT support for building maintenance.

The questionnaire was revised and improved with the experts' input and the final list of questions used for the interviews is presented in Appendix A. Experts A, B and D were interviewed via Skype. The interview with expert C was carried out in person at Teesside University. The interviews were captured using notes and audio recording with consent from the participants. The results from the interviews were transcribed and sent by email to the experts afterwards to ensure that they accurately captured the experts' views. The profiles of interview participants are summarised in Table 4.1.

Table 4.1 – Profiles of interview participants

Expert Code	*Profile*	*Institution*	*Experience (Years)*
A	Building Owner/FM	The Inner Temple	12
B	Director in a BIM consultancy/Designer/FM expert	BIMAcademy	10
C	Designer	Atkins	12
D	FM expert/researcher	Zurich University of Applied Sciences (ZHAW)	16

4.3 Data analysis

In this research, three rounds of data gathering were carried out, using semi-structured and unstructured interviews with experts from industry and academia. The interviews were transcribed and analysed using the Grounded Theory (GT) approach proposed by Strauss & Corbin, (1990). Coding is the core process in Grounded Theory. It provides the conceptualisation of data by clarifying the link between data and theory. Codes are not predefined, instead they emerge from the analysis of the qualitative data and provide an abstract view of the data (Charmaz, 2006; Holton, 2007).

In Grounded Theory, coding is a continuous, iterative process, which happens in parallel with theoretical sampling and data analysis. Codes become elements of an emerging theory, which explains the data and directs additional data gathering (Charmaz, 2006). Coding of data occurs simultaneously with data analysis through a process of "conceptual memoing", in which analytical memos are developed to capture the relations between codes and highlight the relevant categories in the emergent theory (Charmaz, 2006; Holton, 2007).

The coding process was adopted to analyse the interview transcripts during requirements gathering, and during the validation stage of the research, and consisted of the following stages:

- Open coding
- Axial coding
- Selective coding

This chapter provides the analysis of the first round of interviews for the requirements gathering activity.

4.3.1 Open coding

The open coding process followed the approach proposed by Charmaz, (2006). In this approach there are two coding stages: initial coding, and focused coding. Initial coding should reflect the process behind the data, and usually consists of line-by-line or incident-by-incident coding (Charmaz, 2006). The application of the initial coding process resulted in 62 codes from the interview transcripts. At this stage, many of the obtained codes were “in vivo”, i.e., they came directly from the experts, not requiring interpretation by the researcher since they already provide additional description of the context (O’Connor, 2012).

The second phase of open coding is focused coding. Focused coding provides more conceptual codes when compared with initial coding. Initial codes are analysed regarding their ability to categorise the data accurately (Charmaz, 2006), and may be used as a category, or merged with other similar codes. In this process, the initial codes were aggregated into 14 focused codes. Table 4.2 provides an example of the development of the focused code “Standards” from the initial codes. Table 4.3 provides the list of focused codes and their frequency, i.e., the relation between the focused codes and the number of supporting quotes extracted from the primary data. In this process, the key concepts relevant to the development of the proposed framework and CDE are revealed. Appendix E provides the list of initial, focused, and axial codes, as well as the relationships between the codes.

Table 4.2 – Development of focused code "Standards": Relation between focused code, initial codes, and supporting quotes

Initial code	***Supporting quote***	***Expert code***
Using standards for PPM and H&S	"Some of the critical standards for maintenance management are: SFG20, H&S compliance standards (asbestos register, legionella, etc…)"	B
Issues from the use of different local standards	"Each country will have their own system. I've been working with the Swiss BIM library where we've been looking at how they could manage FM criteria for the assets and they've looked at COBie/ IFC, the norms for Austria, the DIN specs from Germany and they're so different that it's not feasible to define all the criteria for a BIM object."	D
FM engagement from start of projects	"If you're writing a contract with a BIM methodology in mind, you should make sure to refer to BS 8536, which helps to ensure that the FMs are thoroughly engaged at the beginning of a project."	D
Using standards as AIM integration framework	"The question about non-BIM vs. BIM projects is you tend to get documents as PDFs and drawings mainly and excel spreadsheets. With BIM you get 3D and if the COBie data is formulated properly, you should be able to do your COBie data drops and be able to export and import to your CAFM, if the whole process has been mapped properly. "	D
COBie / IFC compatibility with CAFM	"One of the key questions to ask at the beginning of the BIM process is – have they already got an existing system established, and if they have, can it accept COBie /IFC."	D

Table 4.3 – Relation between focused codes and supporting quotes

Focused codes	*Expert codes*				*Frequency*
	A	**B**	**C**	**D**	
Challenges in BIM for FM	x	x	x		5
Classification		x		x	2
Data integrity		x		x	3
Data management		x		x	8
Expected benefits of BIM for FM		x	x	x	8
FM & maintenance requirements	x	x	x	x	15
Handover			x	x	4
Interoperability	x	x		x	3
IT tools requirements	x	x	x	x	22
Owner requirements management	x	x	x	x	17
Standards	x	x		x	6
Uses of BIM data in FM	x	x	x	x	18
Validation		x		x	3
Visualisation		x	x	x	6

4.3.2 Axial coding

Axial Coding is used to find the relationships between the identified categories during the Focused Coding, and describe the categories by specifying their properties and dimensions. Axial Coding provides the initial steps in defining the major categories in the study (Strauss & Corbin, 1990; Charmaz, 2006).

In this research, Axial Coding was carried out by: a) exploring the relations between the identified categories through analytical memo writing, where descriptions are developed for each category, based on primary data from the interviews, and; b) through the development of a network diagram between the codes, to clarify how codes are linked together, revealing the density (i.e. the number of links to each code) of the codes. In this process, the codes identified during the open coding stage are grouped together under higher order codes (O'Connor, 2012). The usage of analytical memos provides means to describe and justify the choices of categories.

4.3.2.1 Analytical Memo writing

Analytical Memo writing consists of writing informal analytic notes about the data. Analytical memo writing is a key stage in the process of generating grounded theory. Writing memos throughout the research process can be used to highlight the relationships between codes, and help raise codes to conceptual categories (Charmaz, 2006; Holton, 2007). Memos are key in guiding the next steps in further data collection, coding, and analysis. In this research, memos were used in the process to identify the axial codes, which provide the key requirements for the proposed framework and CDE. The identified axial codes are:

- Owner's requirements
- Common Data Environment
- Data quality
- Expected benefits and current challenges in BIM for FM

Tables 4.4 to 4.7 provide the relationships between the axial codes and identified categories from focused codes, as well as description of the categories resulting from the analytical memo writing process for each of the codes, based on the primary data from the interviews. Category descriptions refer to the experts through the expert codes defined in Table 4.1.

Table 4.4 – Axial coding – Owner's requirements

category	***description***
Classification	Use of a classification system is essential to manage the wide variety of data needed for the AIM (D).
	Existing CAFM/IMMS tools already use a classification system, the owner should specify this as a requirement in the EIR (B).
Handover	BIM is not being used to its full potential at the handover phase, currently its application is mostly focused on the design and construction phases (C,D).
	The use of BIM object libraries compliant with local building regulations could improve the handover of data to CAFM/IWMS systems, and improve the maintenance planning process (C,D).
	There are data management challenges in handover of non-BIM data because the handover process varies from project to project, according to what's defined in the project specification requirements (D).
FM & maintenance requirements	There are currently several challenges regarding the availability of data needed for maintenance purposes. Current CAFM/IWMS tools already support the data requirements for FM and maintenance (B). FM data can be used as an input for new build and refurbishment/renewal projects.
	As a result of inexistent or inadequate data, most maintenance contracts end up focusing on reactive maintenance approaches. While information needed for FM and maintenance tasks is typically available, it is usually provided in unstructured format (D). It is up to the owners and facility managers to define the format and content of the data that they require using a methodology such as the EIR. This way it will be possible to manage the data using e.g. CAFM/IWMS tools, since these tools already support this data (B,D).
Owner requirements management	EIR should be used to specify data handover requirements, i.e., when and how the client's asset data is delivered (D). During the use phase, SLAs should specify ownership of the data (B,D). Well defined client requirements will be able to support the client's business strategy (D).
	FM and maintenance data is typically available but not organised (B,D). Key requirements for the development and management of AIMs include: • Considering FM requirements from the early project development stage, including how BIM objects can be used to capture them (A,B,C,D); • Defining the information requirements for use of BIM data in CAFM systems (B); • Considering sustainability requirements (D); • Development and management of AIMs should be flexible to support changes in SLAs during the life of the building (D). • Development of an AIM schema considering the client's needs (B).

Table 4.5 – Axial coding – Common Data Environment (CDE)

category	*description*
IT tools requirements	Currently, CAFM/IWMS and BMS are the most commonly used tools for building maintenance and FM. The selection of the CAFM/IWMS tool provider should be specified by the client at the start of the project in the EIR (A,B,C).
	BIM tools such as Ecodomus are focusing on enabling the link between BIM models and a CAFM system using COBie data (B).
	The customisation of CAFM/IWMS tools is difficult and expensive (B).
	CAFM/IWMS tools should support the definition of a custom AIM schema (B).
	CAFM tools should provide or be integrated with Business Analytics systems to provide data analysis functions (D)
	Filtering out unneeded IFC data before importing it to CAFM/IWMS systems using tools such as SimpleBIM, in order to enable its use for maintenance purposes (B, C).
	Client should evaluate which CAFM/IWMS system will be used during the early stages of project development, including support for IFC/COBie import and the existence of standardised tools and templates to facilitate the import and mapping of data (B, D). The CAFM/IWMS supplier should be involved in the process to evaluate how the BIM data will be transferred and used within the tool (D). Use of a classification system such as NRM, SFG20, Uniclass, Omniclass, should be required in order to achieve the integration of BIM with CAFM/IWMS systems in the development of AIMs (B).
Visualisation	Use of BIM geometry to provide “heat maps” for asset condition and work orders (B)
	Using the BIM model for way finding to improve maintenance planning (B, C, D).
Uses of BIM data in FM	BIM data can be used to improve the retrieval of information about assets to support FM tasks (B). It should enable the client to perform cross estate queries on their assets (B,D).
	FM data can be integrated with BIM to inform the development of new projects (B).
	BIM objects can be used to aggregate or link to data regarding H&S plan; O&M manuals; statutory maintenance (A, D).
	BIM can be integrated with BMS systems to optimise energy use (A, B)
	BIM can be used to support smart building functions such as fire prevention systems and security systems (A)
	CAFM/IWMS tools can be used to link the various data sources needed for the AIM (B)
	BIM data can be used in the development of asset registers (A)
	BIM data can be used for elaboration of reports within CAFM/IWMS tools. CAFM/IWMS systems need major improvements in their reporting capabilities to benefit from the use of BIM data throughout the lifecycle of assets (D).
	BIM can support accessibility planning during maintenance tasks. The relations within the BIM model (e.g. spatial containment) could be incorporated into CAFM/IWMS systems to facilitate assets location, and allow FMs / asset managers to find patterns in reactive maintenance tasks (e.g. analysing if there is a correlation between an asset failure and its location, time of the year, or other factors) (C).
	Annual maintenance costs of assets are frequently missing. The availability of such data along with asset replacement cost data and remaining service life of assets could be used to produce accurate lifecycle cost models (D).

Table 4.6 – Axial coding – Data quality

category	***description***
Data integrity	Current IT tools provide a repository of information and already support FM and maintenance requirements, the issues lie in maintaining the data accurate and up to date (B). A cost effective strategy is needed to ensure that data in CAFM systems is kept accurate and up to date (D).
	FM systems could provide useful data for new and repair/refurbish projects if the data is synchronised (B,D).
Interoperability	Not all CMMS/CAFM systems support the import of BIM data (COBie/IFC), many still rely on manually overlaying polygons in drawings to define spaces/obtain dimensions (B).
	Mapping BIM to CAFM data can be challenging due to the differences in data schemas and data requirements (D). RIBA plan of works could be used as a framework to integrate BIM tools with CAFM/IWMS systems (A).
Validation	In non-BIM projects data is delivered in non-standardised formats (e.g. hard copies, CDs, etc.), which results in time-consuming and error-prone validation exercises, since validation cannot be automated (D).
	The client should specify how they are going to validate the BIM models that are provided to them (D).
	Current industry initiatives such as Product Data Templates (PDTs) and existing tools are not ready to be used for the automated validation of BIM data (B).
Data management	Defining procedures to ensure that data is kept up to date throughout the use phase of buildings is essential, and should be done periodically, depending on the criticality of assets (D).
	The client should own the building data, or at least have continuous access to it (D). If clients own the building data, more accurate data can be provided to new owners when change of ownership occurs (B).
	Currently building data is inaccurate and of poor quality. Maintaining accurate data about a building currently relies on the execution of expensive surveys. It is expected that BIM can improve this process regarding the evaluation of data quality (B). Accurate data is expected to improve maintenance response times (Reactive maintenance) (B, C).
	Data handed over in non-BIM projects is not standardised and hard to manage and validate. These data sources are difficult to use by FM (B, C, D).
	Assessment of existing data is a key requirement of the PAS 1192-2 and PAS 1192-3 specifications for the development of new build and refurbishment/renewal projects (D). Designers would benefit largely from access to existing FM data, but this is typically not provided (B).
Standards	BIM can be used as a basis to streamline the handover process if BIM models are produced using open standards such as IFC and COBie. It is fundamental to define this process from the early stages of project development using e.g. EIR. This will ensure a smooth transition to operations, since data will be ready to be imported or linked directly to CAFM/IWMS systems (B,D).
	FM standards such as SFG20 can be used to streamline the transition of BIM to FM (B).
	Local standards make it difficult to standardise properties for BIM objects (D).
	Standards such as BS 8536 can help ensure that FM are involved from the beginning of the project (D).
	Selection of CAFM systems should consider compatibility with BIM systems such as IFC and COBie (B,D).

Table 4.7 – Axial coding – Expected benefits and current challenges in BIM for FM

category	***description***
Expected benefits of BIM for FM	The ability to retrieve relevant information from the BIM model for FM and maintenance purposes was a key aspect in the development of BIM-FM case studies (B,C).
	BIM could be used to retrieve assets' location for maintenance planning purposes, and to provide access to the information needed for maintenance tasks, including statutory compliance (B,C,D).
	Access to accurate data could lead to a reduction of response times in maintenance tasks and could also enable strategic planning of maintenance tasks. (B,C).
	BIM could be used as a basis for the integration of disparate systems and tools currently used by FM (B).
Challenges in BIM for FM	In order to obtain BIM models that can be used by owners and FM, it is fundamental to specify data requirements in a structured format using e.g. EIR (C). This process should have the input from designers, contractors and FM (B,C).
	It is challenging to prove the benefits of BIM to the client as well as supporting the client with the technology, which might explain current lack of adoption by clients (A).
	The need to change current processes in the FM and property management industry introduced by BIM is a barrier for clients and FM to use BIM (A,B).
	Integration of BIM data from new projects with existing non-BIM data from existing projects in the facility portfolio presents technology challenges (C).
	Making owner aware of the value of data ownership (B,C).
	Current practices in the industry regarding data availability, data quality and data management do not allow BIM to be implemented to its full potential from the client's perspective (A).

4.3.2.2 Network diagram

During the development of axial codes, focused codes are grouped together, based on the analytical memos, through the development of a mind map, or network diagram. In this process, codes were analysed and organised between categories and properties using relations between the codes. This process reveals the key categories that need to be considered in the research, as well as gaps in the grounding of key concepts that will need to be addressed during the validation stage of the study. Figure 4.1 provides the network graph that was used as a basis to organise categories and properties in the development of axial codes.

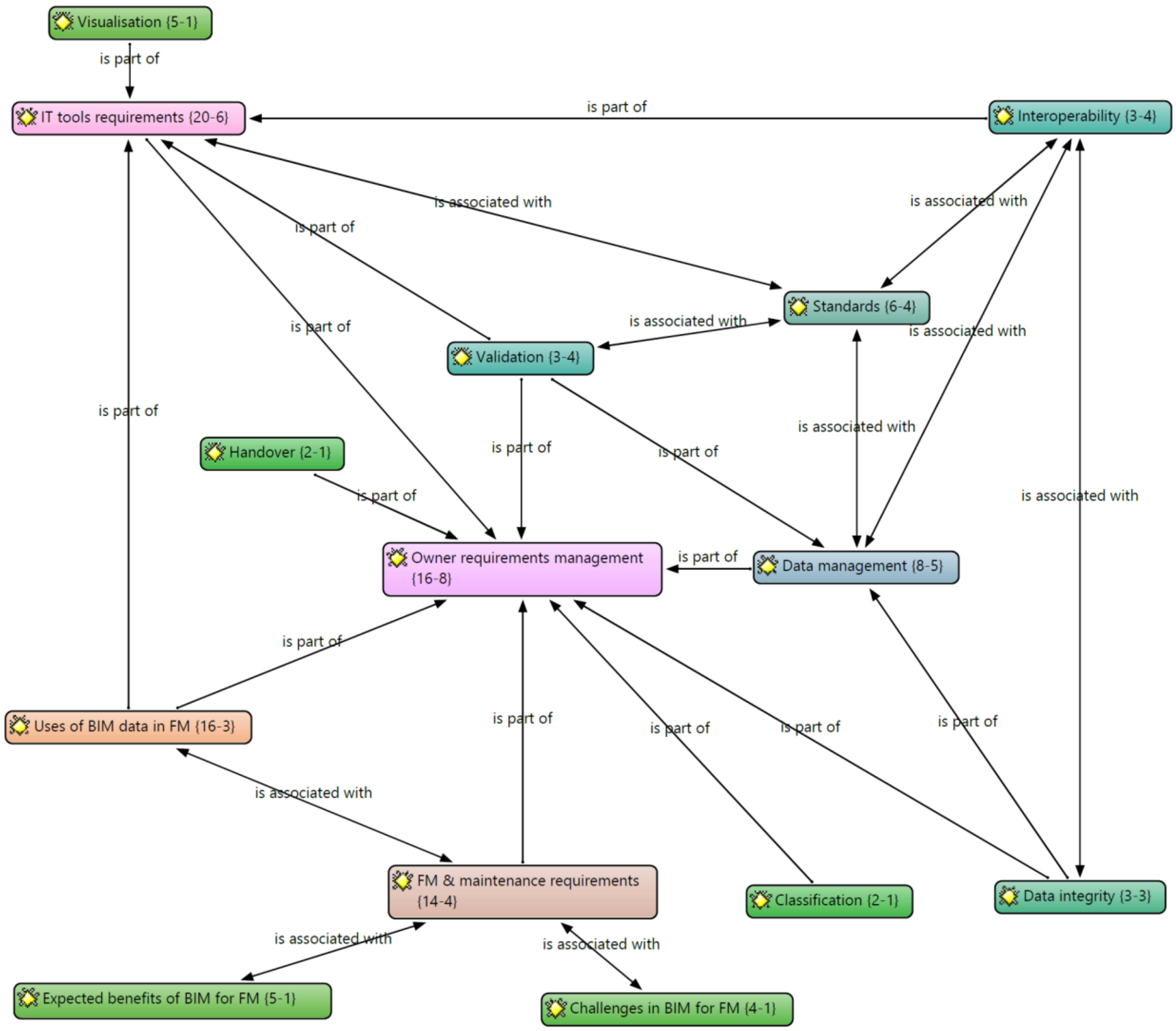

Figure 4.1 – Network diagram of Axial Code categories

4.3.3 Selective coding

The final coding process adopted in the data analysis is selective coding. Selective coding consists in identifying the core category that emerges from the collected data, and systematically relating it to other categories (O'Connor, 2012).

Throughout the data analysis, several requirements have been identified in order to support building owners and FMs in the management of their buildings, using digital technologies. The AIM is central to this process, and is considered the core category in this research.

Various key requirements have been identified for the development of the AIM, which aims to provide an accurate digital copy of the physical building or facility, so that it can be used as a basis for the various decisions and tasks that are performed during the use phase of the building.

The importance of the owner's role in the definition of requirements for the use phase of the building was mentioned as a key requirement in the development of AIMs. The experts mentioned the importance of data validation, and highlighted the differences and challenges in this process regarding the use of non-BIM vs. BIM data. The definition of structured requirements is fundamental for this purpose, and in the case of BIM data could be used as a basis for automated compliance checking. Current tools and methods used by the industry (e.g. PDTs) are not adequate for the validation of BIM data. The use of a standardised method such as EIR was proposed for structured requirements definition, however, the current definition of EIR needs further development in order to engage owners in the requirements definition process. This should include specification of CAFM/CMMS tools for the use phase, the data validation approach used, the use of open standards for data management, and clear definition of data ownership.

The experts mentioned how current CAFM/CMMS tools already support the majority of FM and maintenance data requirements, making them suitable to manage AIMs, but the difficulties lie in obtaining and organising the required data. The selection of these tools should consider how BIM data would be supported, particularly through the use of templates to import the required IFC/COBie data. Mechanisms for filtering the various data sources of the AIM are needed, since not all the data in as-built models will be required for FM and maintenance purposes. The use of classification systems could streamline this process, since they are already supported in CAFM/CMMS tools and current BIM models and tools. The handover process could also be improved if BIM object libraries provide information about BIM objects compliance to local building regulations.

The visualisation capabilities of BIM could be used to provide a visualisation of asset condition and maintenance work orders status. Related research has already been carried out in this area focusing on the visualisation of assets condition (Akcamete *et al.*, 2010; Motamedi *et al.*, 2014). BIM models could also be used for way finding purposes using e.g. game engines to support the planning of maintenance tasks. Relations within the BIM models (e.g. spatial containment relations) could be used to find patterns in reactive maintenance tasks to support failure root cause analyses. BIM data could also provide key inputs for reporting modules in CAFM/CMMS tools, but currently the majority of these tools only support limited import of BIM data, and need further development to leverage the use of BIM data for the whole lifecycle of facilities.

Figure 4.2 outlines a provisional requirements model that will be used as a basis for the development of the proposed framework and CDE. The model outlines the relationship between the core category and the other 4 main identified categories: Owner requirements definition; Owner requirements validation; CDE; Benefits and challenges of BIM implementation in FM.

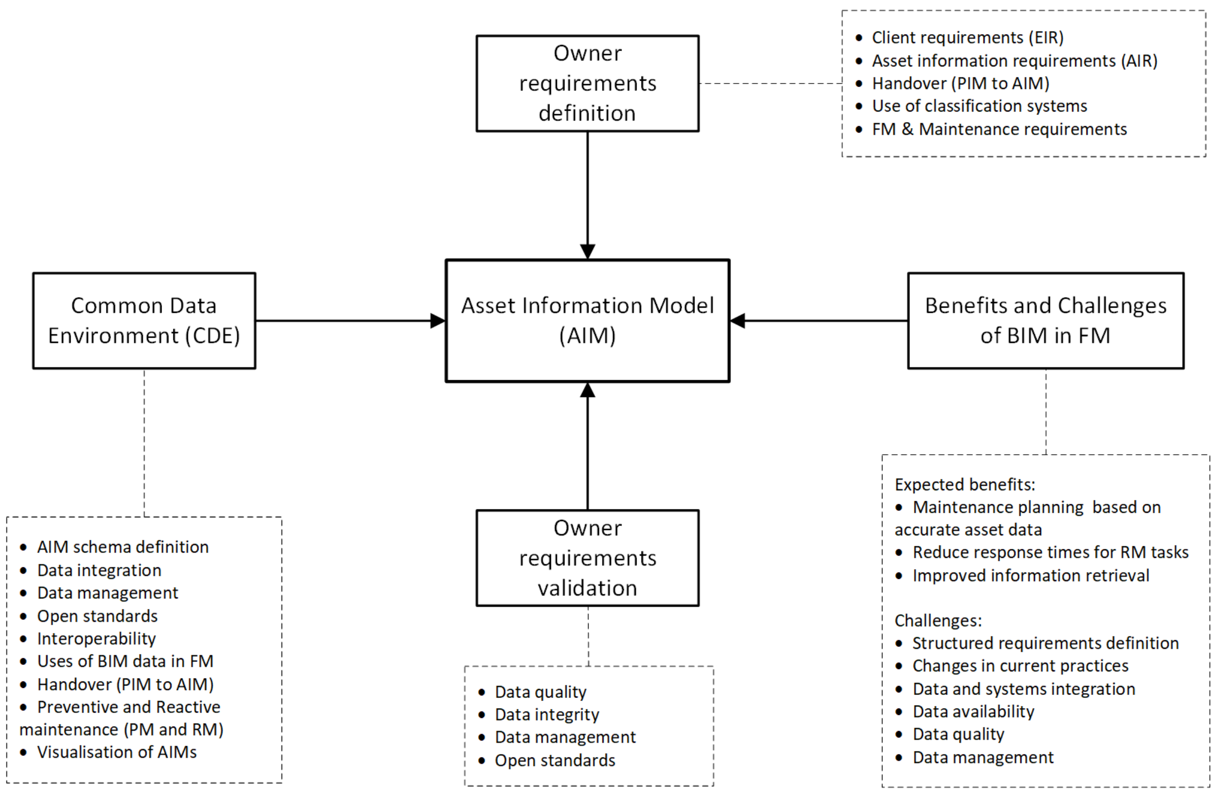

Figure 4.2 – Provisional requirements model for the development of the framework and CDE

4.4 Framework and CDE requirements

The results from the data analysis reveal that there should be a focus in supporting the owner in the definition of requirements, and the management and validation of the data sources in order to obtain AIMs that can be used effectively for the management of buildings during their use phase. The structured definition of requirements for the use phase of facilities, considering input from the designers, FM, and building owner, has been recognised as key in maximising the facilities performance according to the owner and occupants needs. The use of open standards such as IFC and COBie can contribute to the organisation of information for FM tasks, however their use is still limited.

The following requirements have been identified for the development of the proposed framework:

- Structured requirements definition considering the designers, FM and owner's input, using structured methodologies such as EIR/AIR;
- Automated validation of BIM and other structured data sources for AIMs to streamline the handover process (PIM to AIM) and the development of AIMs;

The following requirements have been identified for the development of a CDE to manage AIMs:

- Ability to define a custom AIM schema according to the owner's data requirements (AIR);
- Integration of various data sources to support graphical, non-graphical and documentary data requirements of the AIM, based on open standards;
- Support the definition of preventive (PM) and reactive (RM) maintenance tasks using the AIM data sources;
- Visualisation of AIM data sources to support various FM and maintenance processes.

4.5 Summary

This chapter presented the implementation of the Grounded Theory method in the requirements gathering activity of the research. Interviews were undertaken with stakeholders from the industry and the Grounded Theory method was used to analyse the resulting qualitative data and develop a provisional requirements model for the development of the framework and CDE.

Results from the literature review and interview data analysis show that there is an increasing interest and adoption of BIM-based IT for FM and maintenance tasks, but many of the expected benefits from BIM implementation are yet to be realised. Through the application of the GTM, several key issues have been identified, in particular regarding issues with data quality in projects, and challenges in the validation of the owner’s requirements and the development and management of AIMs. The interviews also revealed potential uses of BIM data for FM and maintenance purposes, including improving the management of RM and PM tasks, as well as visualisation based on BIM models to support maintenance workers in locating and maintaining building assets.

This chapter provides the initial implementation of the Grounded Theory method in the context of this research. The provisional requirements model developed in this chapter provides the foundation for the proposed framework and CDE (Figure 4.2). This model will be improved during the validation stage of the research through further data collection and analysis, in order to provide additional grounding to the proposed framework, and to elicit the proposed framework’s contribution to theory.

5 Framework Development

5.1 Introduction

Throughout the development of this research, various standards and specifications have been identified which could streamline the development of AIMs, through the structured development of owner and facility managers' requirements, and their validation against various data sources. The PAS 1192 series specifications are an important contribution to achieve this goal. In particular, PAS 1192-3 sets out key requirements for information management during the operational phase of facilities, considering the use of several different data sources and IT systems. To accomplish this, several key concepts such as the Asset Information Model (AIM) and Asset Information Requirements (AIR) are introduced. However, the definition and development of standards, tools and implementation details needed for the development and management of AIMs are out of scope of the specification.

In this chapter, a framework is proposed for the development and management of AIMs. The framework provides processes for the definition of structured requirements, validation of various sources of asset data throughout facilities lifecycle (project development and throughout the use phase of facilities), and for the development of a web-based CDE for FM, to manage the various data sources of the AIM. The key requirements for the framework have been identified in the literature review and requirements gathering stage and are summarised in Table 5.1.

Table 5.1 – Key capabilities of the proposed framework

Structured requirements definition and asset data validation throughout buildings' lifecycle	Structured definition of owner and facilities management requirements in the form of Asset Information Requirements (AIR)
	Identification of data standards and specifications for Asset Information Models (AIM)
	Validation of various Asset data sources against Asset Information Requirements
Development of a CDE to manage Asset Information Models	AIM definition
	Information integration
	AIM visualisation

Figure 5.1 highlights the proposed framework in the context of the RIBA 2013 plan of work facility lifecycle stages (RIBA, 2013). The development of the framework was informed by the requirements model developed in the requirements gathering activity (Chapter 4), along with the various standards and specifications which can support structured requirements definition for AIMs, and methods for automated compliance checking that can be used to validate the various asset data sources against structured AIR, reviewed in Chapter 3.

The methodology used to describe the framework processes is detailed in section 5.2. In section 5.3 an overview of the framework is provided. Sections 5.4 to 5.6 provide the specification of the framework and its processes. Finally section 5.7 provides a summary of this chapter.

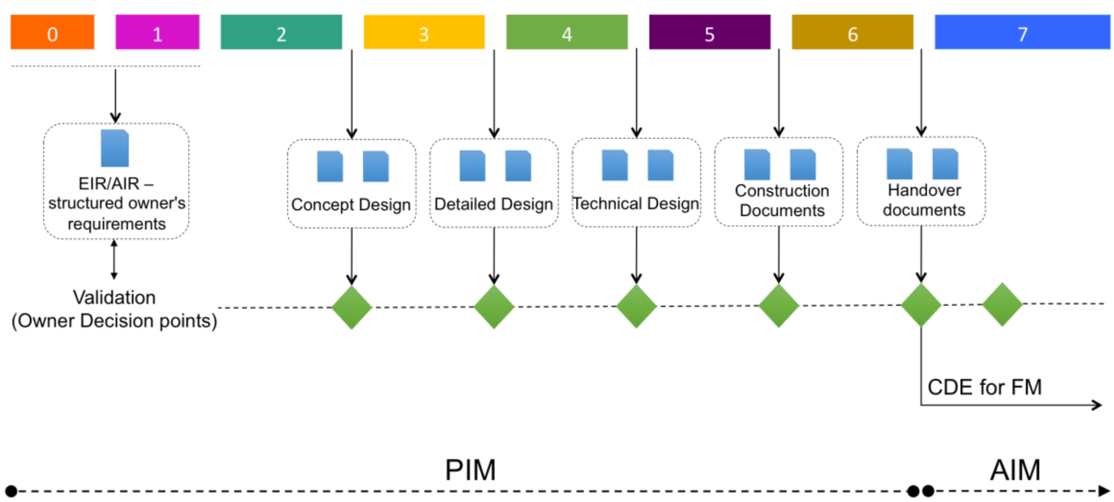

Figure 5.1 – Proposed framework in context of the RIBA Plan of Work (RIBA, 2013)

5.2 Framework Methodology

The IDM methodology was adopted for the development of the proposed framework, using two process modelling methods: IDEF0 and BPMN. IDEF0 is a modelling method used for the development of structured graphical representations of processes or complex systems, including their actions, activities and decisions (Razali *et al.*, 2010). It is part of the IDEF family of modelling standards and has been widely adopted in the development, analysis and integration of IS. IDEF0 was adopted as a Federal Information Processing Standard (FIPS) in 1993 and is currently maintained by the US National Institute of Standards and Technology (NIST) (DAU, 2000). IDEF0 was chosen as the main modelling methodology for the proposed framework due to its capabilities in the description of a sequence and hierarchy of processes, and specification of information and data requirements in the forms of ‘Inputs’, ‘Outputs’, ‘Controls’ and ‘Mechanisms’. IDEF0’s capabilities were used to capture and describe the proposed framework’s processes and data and information requirements. IDEF0 supports the hierarchical definition of functions, whereby each function can be detailed in a separate diagram. ‘Functions’ are represented as boxes. ‘Inputs’ are consumed by the function. ‘Outputs’ are the results of the function. ‘Control’ specifies the conditions required by the function to produce the right ‘Output’. ‘Mechanism’ identifies the means that support the function. While IDEF0 was regarded as appropriate for the representation of the majority of the framework’s processes, Business Process Modelling and Notation (BPMN) was also used since it provides a clearer representation for the collaboration between stakeholders in processes, through the clear definition of the role of each actor involved in the data exchanges. BPMN is a standard proposed by the Object Management Group (OMG, 2019). In this framework, IDM is used in the definition of AIR, including the specification of data requirements to support AIMs. IDM is currently used for IFC development, but can also be used to specify requirements of different data models; therefore it is adopted in this research to specify the requirements of the various data sources used in the AIMs. An overview of the IDEF0 and BPMN methodologies is provided in Figure 5.2.

The development of the AIM is based on various open data standards and specifications. IFC, COBie and CMIS have been identified to support the graphical, non-graphical and documentary data requirements, respectively. The various tools and standards proposed in this framework are identified within the process maps.

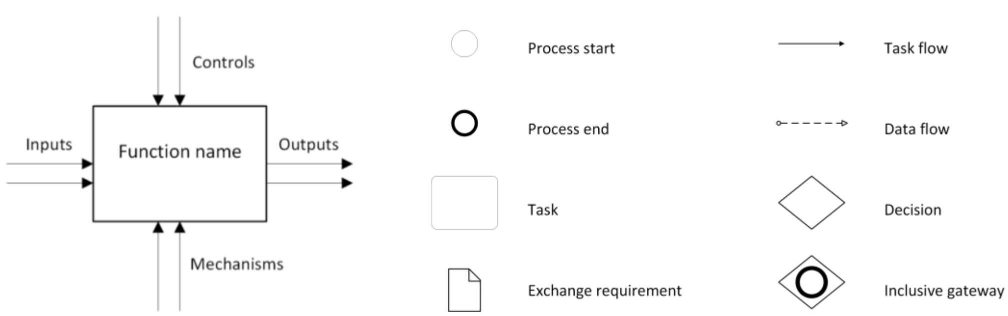

Figure 5.2 – Basic concepts of IDEF0 / Basic concepts of BPMN

5.3 Overview of the proposed framework

The availability of reliable and up-to-date information and data about assets is essential to enable effective asset management (Shetty *et al.*, 2014). Currently, building asset management data is typically stored in paper documents, and disparate, unconnected IT systems, making it difficult to access the relevant data needed to carry out FM and maintenance tasks. The implementation of BIM processes including the creation, collation and exchange of digital information about assets is expected to improve asset management. However, to unlock this opportunity, BIM tools, workflows and deliverables should address the whole life cycle of building assets (Shetty *et al.*, 2014).

In this research, a framework is proposed to support the development of AIMs, in particular the processes of definition of structured AIR, and the validation of AIM data sources. The definition of AIR and the validation of AIM data sources rely on the use of open standards and open technologies in order to allow their implementation throughout the lifecycle of the building and ensure their continued use in future. The proposed framework consists of four key domains to support the development and continuous update of the AIM throughout the lifecycle of the building. Each of these domains are underpinned by the development of a Common Data Environment.

5.3.1 Asset Information Requirements definition

In the literature review, IDM was identified as the most adequate methodology to develop structured requirements, considering the interactions between various stakeholders. The IDM methodology is used for the structured definition of AIR to ensure that these can be represented in the supporting graphical, non-graphical, and documentary data sources of AIMs, to allow their validation throughout the lifecycle of facilities. This will ensure that at the handover stage, the client can compile the AIM data and continuously update it throughout the building lifecycle to support various FM and maintenance tasks. The inputs from the design team and facility managers are taken into account in the definition of AIR.

5.3.2 Identification of Asset Information Model data sources

Data needed for facility management and maintenance tasks can be found in several different sources, systems and formats. Due to the amount and variety of such data (e.g. building drawings/models, O&M manuals, BMS data, H&S file, FM data, etc.), the adoption and use of a single central model or database is unattainable. In chapter 3, several suitable open data standards and tools have been identified to support the development of the AIM using data from disparate models and databases, enabling the use of such data in maintenance planning and execution tasks during the use phase of buildings. Building project data is provided through the use of IFC and COBie. Digital documents including O&M data such as H&S files and O&M manuals can be provided through the use of a CMIS compliant EDMS. FM data is managed in a CDE consisting of several connected repositories enabled by web-service standards such as SOAP and REST. Additional data sources can be integrated if they are available via standard web service interfaces.

5.3.3 Validation of Asset data sources against Asset Information Requirements

The framework supports the definition of the processes for the validation of AIR against the various AIM data sources throughout the lifecycle of buildings. The IDM methodology is used for process definition specifying the flow of activities, and the supporting data and information requirements that need to be fulfilled to perform the specified processes. Exchange requirements (ERs) are used to define specific asset information requirements.

Semantic web tools and standards can be used to represent the various sources of graphical, non-graphical, and documentary AIM data. The use of Semantic Web tools is proposed to achieve the translation of AIR into business rules, and to perform compliance checking of the various data sources of the AIM. The proposed validation approach enables checking requirements at building element property level considering data from several disparate systems (e.g. BIM, FM, and EDMS data). This process is used to validate the various data sources that need to be included in the AIM.

5.3.4 Development of the Common Data Environment (CDE)

The Common Data Environment proposed in this research provides access to data distributed across various applications and provides methods for the visualisation of the various sources of data.

The CDE proposed in this research is based on the Service Oriented Architecture (SOA). The CDE supports the development, management and visualisation of the AIM throughout the use phase of facilities. For this purpose, the CDE provides access to several distributed data sources (graphical, non-graphical and documents) by various client applications (e.g. web browser, Unity application, etc.). Dedicated repositories were identified for each data source and were linked through REST, SOAP and CMIS web-service interfaces. The use of standard web-service protocols ensures that additional systems and data sources can be integrated with the CDE in order to support specific owner and FM requirements.

Two approaches were considered in this framework to provide the visualisation of AIM data from various sources. The first approach consists in the visualisation of IFC models and their associated documents directly from the FM environment. The second approach consists in the use of a game engine for the development of virtual environments where graphical, non-graphical and documentary AIM data can be accessed to support FM and maintenance tasks. It is expected that both approaches can improve the planning of maintenance tasks as a result of their capabilities in accessing maintenance data and information from the disparate data sources. Notably, the virtual environment developed using a game engine also enables the evaluation of accessibility to carry out maintenance tasks.

An IDEF0 diagram representing the relations between these different domains is presented in Figure 5.3 and a node chart is provided in Table 5.2. Each of the framework's domains is detailed in sections 5.4 to 5.6.

Table 5.2 – IDEF0 and BPMN model diagrams for the proposed framework

Model number	*Modelling standard*	*Title*
1	IDEF0	Proposed framework
A0	BPMN	AIR definition
A1	IDEF0	Identification of AIM data sources
A2	IDEF0	Asset data validation
A3	IDEF0	CDE development

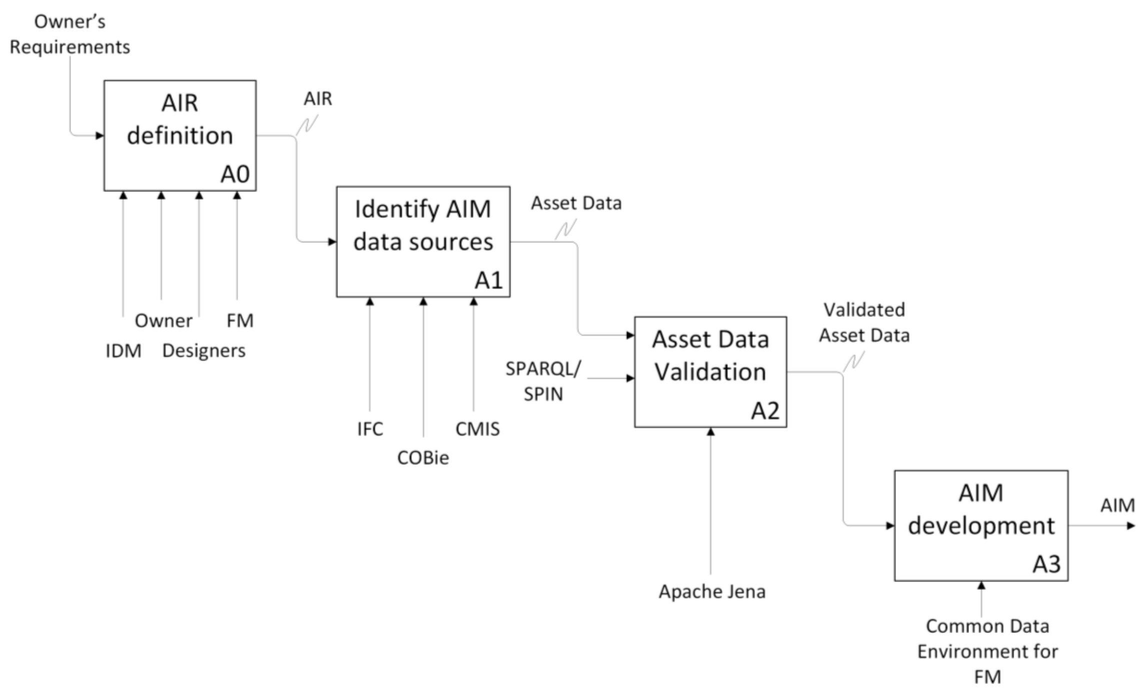

Figure 5.3 – IDEF0 diagram of the proposed framework

5.4 AIR Definition

The definition of AIR is of utmost importance to the owner, since it specifies requirements for all the disciplines involved in the development of the project, and the management of the building until the end of its lifecycle. Well-defined AIR are essential to control the information-centric tasks of processes across the design, construction, operations and demolition of a building.

The IDM methodology is used for the structured definition of AIR. In this framework, IDM is used to define specific data requirements for validation of project data (IFC, COBie, and other documents), ensuring that the data is provided in a suitable format for the development of the AIM, according to the needs of the building owner. The AIR should be continuously updated whenever there is a change in data requirements needed for FM and maintenance operations. Process maps are defined using the Business Process Modelling Notation (BPMN), specifying the flow of activities and supporting data and information requirements that need to be fulfilled to perform the activities (ISO, 2010). Exchange requirements are defined by specifying data and information requirements to support the data exchanges that occur in the defined processes. Functional Parts, which are reusable units of information that specify IFC Entities, Property sets and other Functional parts, are grouped together to support Exchange requirements in the form of Exchange requirement models. Process maps and Exchange requirements are independent from the project and data schema to enable their reuse in different contexts and across different data models (i.e. not just IFC/COBie). This way it will be possible to support the data needed for the AIM that is out of scope of IFC/COBie, such as documentary and other FM data sources.

The design of built assets must fulfil the AIR, including support for the functions that have been defined by the owner, and requirements in building standards and other relevant legislation. For the use phase of buildings, a maintenance policy should be established, including the definition of a preventive maintenance schedule, and strategy to manage reactive maintenance tasks. To this end, AIR definition should take into account the input from designers and facility managers from the early stages of project development, and throughout the lifecycle of the building. Professionals from these fields can help determine: a) what are the assets and b) what is the intended use of handover data, so that if the required data and information is validated, it can be used by the owner for FM and maintenance purposes. The collaborative process for the definition of AIR is proposed in Figure 5.4. This process requires input from the Design Team and Facilities Managers, which is coordinated and approved by the Owner. It is a recurring process, as changes to the requirements throughout the lifecycle of assets need to be accommodated.

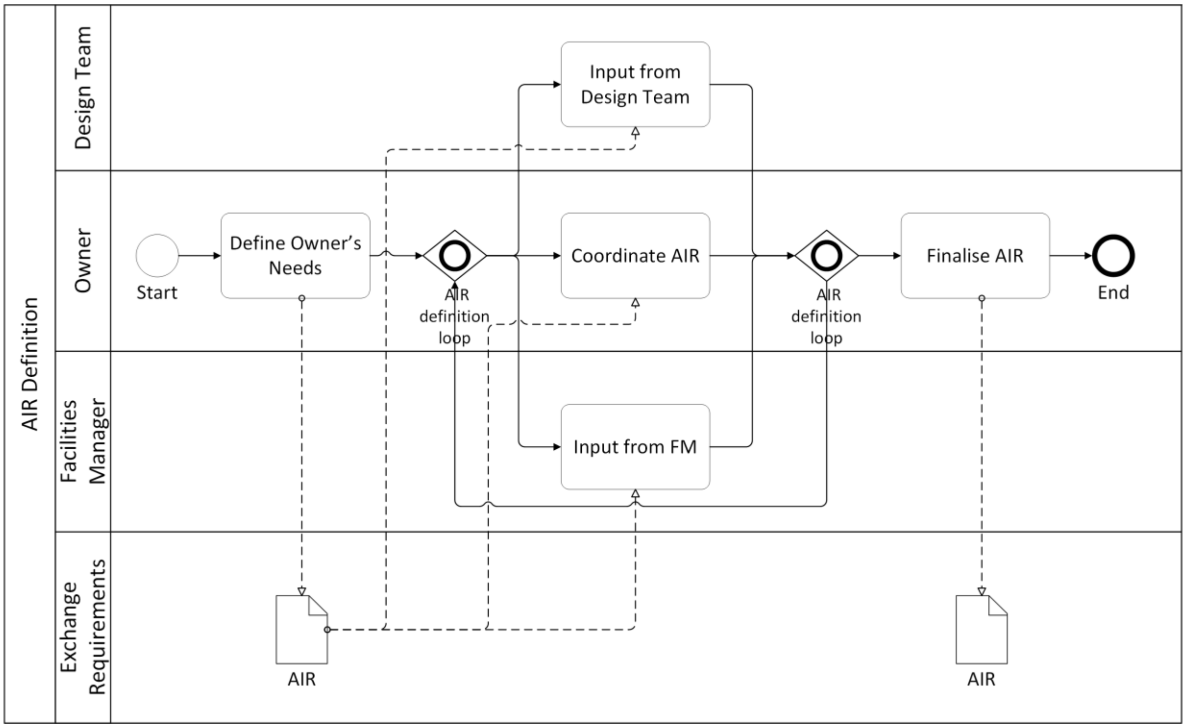

Figure 5.4 – Process map to support the collaborative definition of AIR

5.5 Identification of AIM data sources

The AIM includes graphical, non-graphical, documentary, and other FM data, and should fulfil the AIR defined by the owner with the input from designers and facility managers. IFC, COBie and CMIS have been identified as the open standards that can be used to support graphical, non-graphical and documentary data requirements, respectively.

IFC and COBie can support the graphical and non-graphical asset information requirements for the AIM. Specific IFC entities and Property Sets can be specified via IDM's Functional Parts. While not all data requirements for the AIM are directly supported by the default IFC and COBie entities and property sets, the extensible nature of the IFC schema allows the definition of custom entities and property sets to support additional data requirements. BIMserver has been adopted in this framework for the management of IFC and COBie data. BIMserver supports the storage and management of IFC models in an underlying database structure, and provides several web service interfaces and capabilities such as data querying and filtering for interaction with the stored models (BIMserver, 2018).

The Content Management Interoperability Services (CMIS) standard has been identified to support document data requirements. CMIS is an open standard that supports interoperability between different content management systems. It allows the definition of folder structures for documents and the definition of specific properties of documents and folders as metadata. CMIS support of interoperability allows the reusability of content models across various content management systems (OASIS, 2016). The CMIS-compliant Alfresco EDMS has been adopted in this framework to support the AIM documentary data requirements.

To allow the planning of maintenance tasks considering the different data sources from the AIM, the open source Openmaint FM software is used in this framework. IFC models hosted in a BIMserver instance can be visualised in the Openmaint model viewer, and relevant FM data contained in the IFC and COBie models can be imported into the FM database, using the REST and SOAP web service interfaces. Similarly it is possible to upload documents to the Alfresco EDMS through the CMIS service interface and attach these documents to maintenance tasks in Openmaint. The process for the identification of AIM data sources is summarised in Figure 5.5. The implementation of the Common Data Environment that supports this integration approach will be further detailed in Chapter 6.

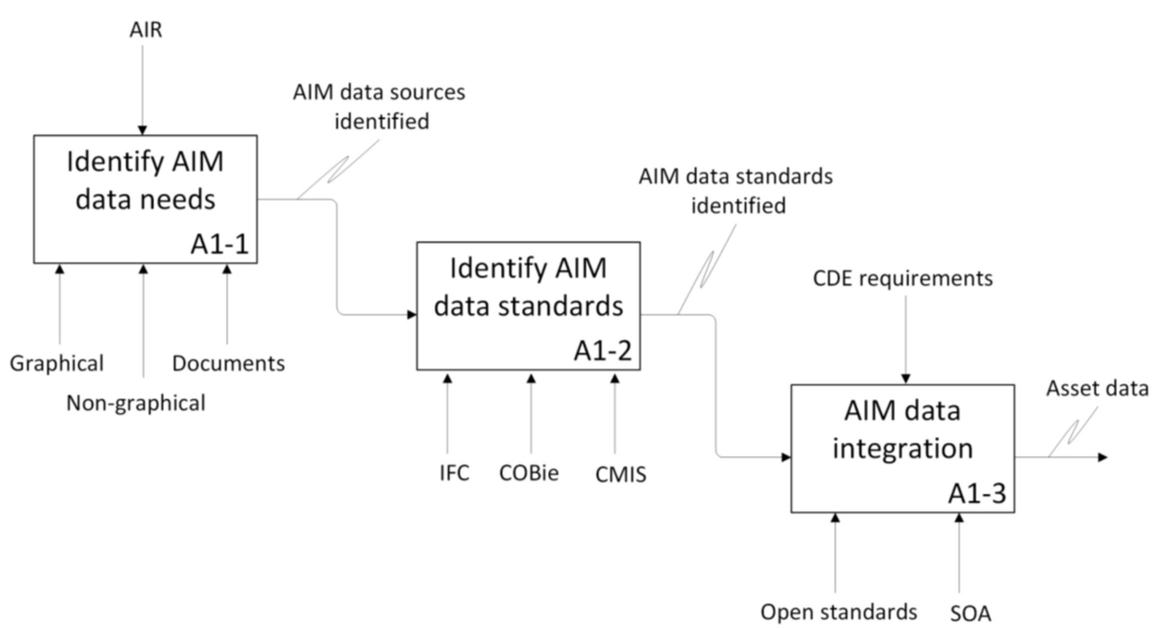

Figure 5.5 – Process map to support the identification of AIM data sources

5.6 Validation of owner's requirements

The validation of owner's requirements is central to the proposed framework. This process follows the general rule checking sequence previously described in Chapter 3 and consists of:

- Interpretation and translation of rules into machine computable format;
- Building model preparation, through the specification of model views;
- Execution of rules against building data from several sources;
- Reporting of the rule checking results.

In the proposed framework, the IDM methodology is adopted in the definition of AIR, and translation of AIR into rule executable format, and semantic web query approaches are adopted for the execution of rules against graphical, non-graphical, and documentary data sources of the AIM.

Business Rules from the IDM methodology have been adopted for the definition of rules. Business Rules allow the definition of specific rules to support specific AIR defined in Exchange Requirements and Exchange Requirement Models. Exchange Requirements, which are schema-independent, can be used to support AIR in FM, EDMS, and other systems, and are used as the basis for the definition of Exchange Requirement Models.

The definition of Exchange Requirement Models provides a structured approach that is particularly suited for the validation of IFC and COBie models. In this research, Semantic Web tools can be used for the validation of various asset data sources against structured AIR. Using the Apache Jena framework, it is possible to execute SPARQL queries against several asset data sources in RDF format hosted in a triple store, and it is also possible to connect to external non-RDF repositories via web service interfaces, and validate additional data sources.

The proposed validation process should be carried out at key stages during project development, at the handover stage, and during the use phase of facilities, according to the EIR (Figure 5.1). For example, it can be carried out at specified COBie data drops, and to validate key information exchanges defined in the AIR (BSI, 2014b). This process is summarised in Figure 5.6. Table 5.3 summarises the data models and validation methods for the AIM within the proposed framework.

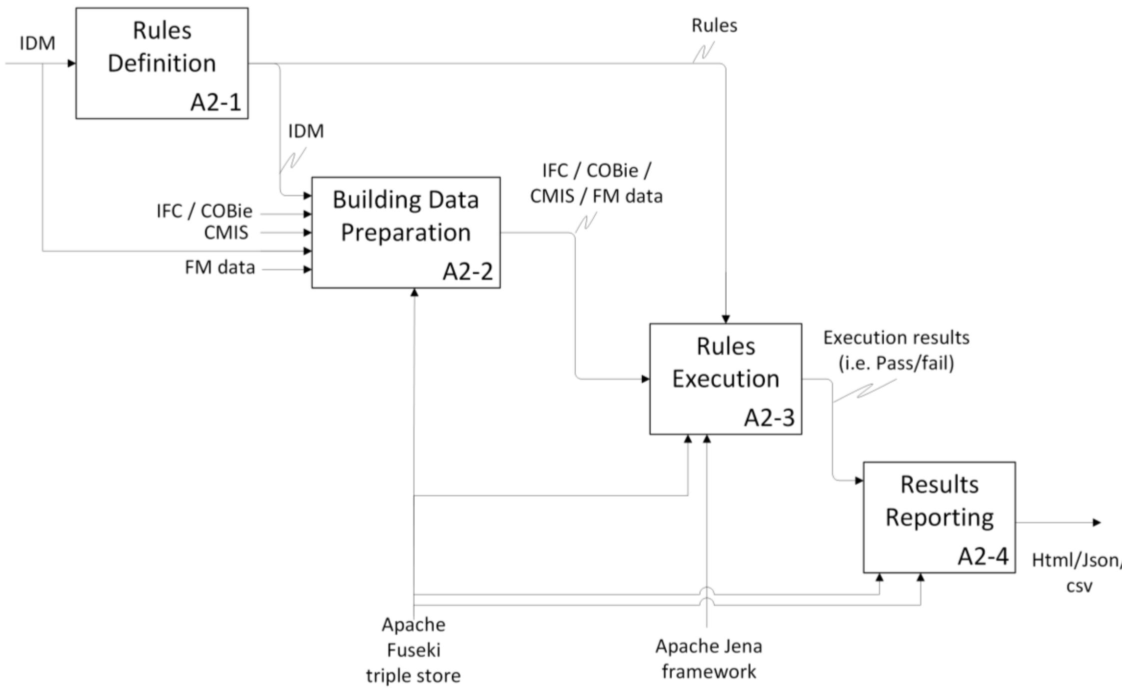

Figure 5.6 – IDEF0 diagram for AIM validation

5.7 Summary

In this section, a framework was proposed for the structured definition and validation of Owner and FM asset requirements, and for the development and management of Asset Information Models. The framework was developed in context with the Asset Information Management processes defined in ISO 19650 and PAS 1192-3, providing methods to implement the generic processes defined in both specifications. The IDM standard was previously identified in this research as the most adequate methodology for the structured definition of owner and FM requirements. The IDM methodology is used for the structured definition of AIR, specifying data requirements for the various identified AIM data sources. The framework's processes were defined using the IDEF0 and BPMN process modelling languages. IFC, COBie and CMIS standards support the graphical, non-graphical, and documentary data requirements of the AIM, respectively. The proposed validation method follows the key steps identified in the literature and is according to the data quality definition proposed in ISO 8000-8 (ISO, 2015b).

Table 5.3 provides a summary of the various open standards, validation methods, and tools that have been identified for the validation, development, management, and visualisation of Asset Information Models (AIM) within the proposed framework. The following chapter will describe the development of the CDE, which implements the framework processes in the development of a SOA-based FM environment. The development of the CDE demonstrates the use of the various identified asset data sources and the integration of the identified IT tools.

Table 5.3 – Summary of open standards and tools used in the validation of asset data, development and visualisation of the AIM

AIM data sources	Supporting standards and specifications	Supporting tools		
		Asset data Validation	**AIM Development**	**Visualisation**
Graphical Model	IFC	Apache Jena (Semantic Web)	BIMserver	Unity (game engine) Openmaint
Non-graphical data	IFC and COBie	Apache Jena (Semantic Web)	BIMserver	
	PostgreSQL database (FM data)		Openmaint	
Documents	CMIS	Apache Jena (Semantic Web)	Alfresco	

6 Common Data Environment Development

6.1 Introduction

The development of a CDE was identified in the proposed framework as a key requirement for the development, management and visualisation of AIMs. The CDE concept defined ISO 19650-1 and PAS 1192-3 was used as a basis for the development of the CDE for FM proposed in this research (BSI, 2014b; ISO, 2017). According to ISO 19650-1 and PAS 1192-3, a CDE is defined as "a single source of information for any given project or asset, used to collect, manage and disseminate all relevant approved files, documents and data for multi-disciplinary teams in a managed process". The CDE provides collaborative access to information and provides different levels of access to information at different stages of development (Figure 6.1). In essence, the CDE is used for the development and management of the AIM. However, both PAS 1192-3 and ISO 19650-1 do not specify how to obtain or manage this information.

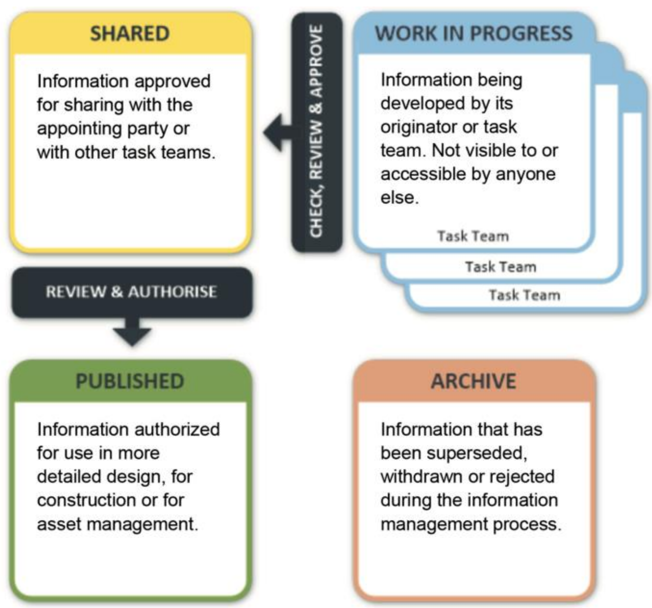

Figure 6.1 – Common Data Environment concept (ISO, 2017)

PAS 1192-3 proposes the use of the same CDE process to manage project (PIM) and asset (AIM) data, despite the differences in business processes and data requirements during the project development stages and the use phase of facilities. While the use of federated, disparate data sources could be adopted during the project development stages (i.e. PIM development), Owners and FM will need to know how each source of data is related (i.e. graphical, non-graphical, and documentary data) to effectively support various maintenance and FM tasks throughout the use phase of facilities. The CDE requirements specified in the PAS 1192 and ISO 19650 series are not sufficient to support changes in asset data requirements throughout the lifecycle of facilities, but they can be used as a starting point for the development of a CDE for the use phase of facilities. In this research, a Service-Oriented Architecture (SOA) based on the use of standardised web-service protocols and open data standards is proposed for the development of a web-based CDE for FM. The proposed approach aims to provide access to data from various sources according to the Owner and FM requirements. The proposed approach also supports changes in data requirements and data sources, which can occur throughout the lifecycle of buildings.

The development of the CDE consists of 5 main tasks, which are detailed in the following sections:

- The definition of the CDE architecture (Section 6.2);
- The definition of the CDE technical infrastructure (Section 6.3);
- The definition of a data schema for the AIM according to the identified data standards and specific owner's data requirements (Section 6.4);
- Development of the AIM through the integration of the various data sources (Section 6.5);
- Visualisation of AIM data to support FM and maintenance tasks (Section 6.6).

An overview of the process is provided in Figure 6.2.

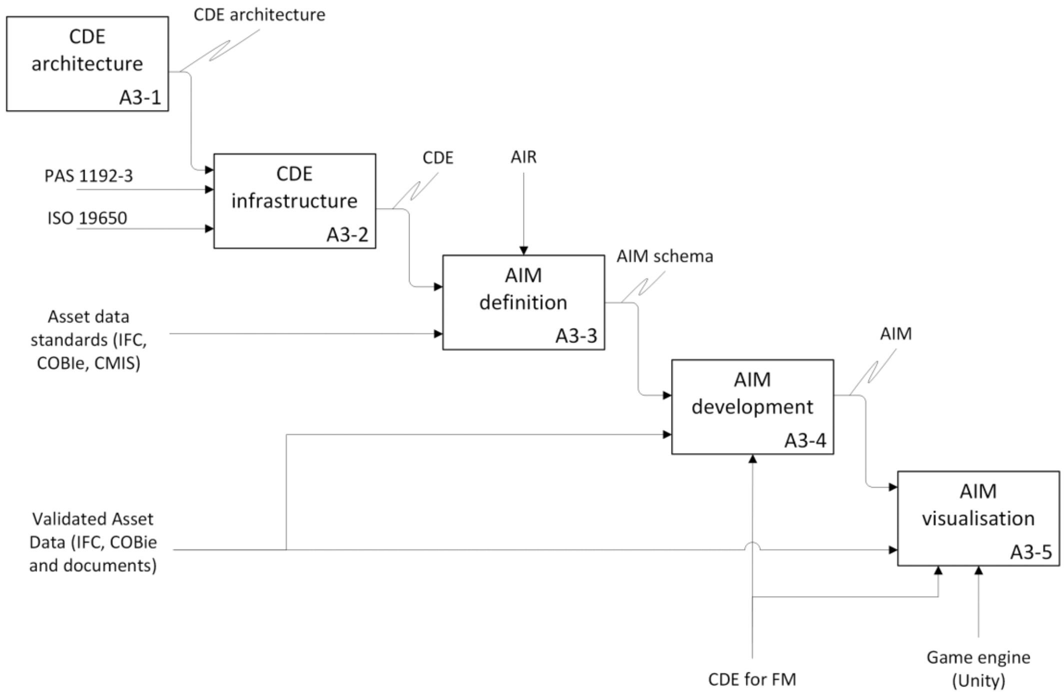

Figure 6.2 – CDE development process

6.2 CDE Architecture

Owners and FM need continuous access to various sources of data about their building portfolios, and they also need to provide different levels of access to these data sources to external stakeholders when they outsource FM services, or when changes in building ownership occur. The FM discipline is characterised by providing several services, which can occur at various points during the use phase of facilities. Traditionally, the data needed to support these tasks is not synchronised across the various systems, which hinders its accessibility and usability for various processes both within the Owner/FM organisation, and between the Owner/FM organisation and external entities. Asset data requirements often change throughout the lifecycle of facilities, requiring the introduction of new IT systems that must be integrated with existing ones. Various stakeholders within Owner and FM organisations also have different data requirements depending on their roles. Examples of roles might include Building Systems Engineers, Maintenance Experts, etc. IT solutions for FM must support the myriad of collaboration processes that can occur within the Owner/FM organisation, and between the Owner/FM organisation and external organisations. In order to support these fundamental requirements, this research proposes the adoption of an SOA for the development of a CDE for FM. According to the OASIS reference model, “Service-oriented architecture (SOA) is a paradigm for organising and utilising distributed capabilities that may be under the control of different ownership domains.” (OASIS, 2012b).

Service-orientation consists in the development of independent and reusable logic units (i.e. services) that can be collectively and repeatedly utilised in the support of specific industrial and business requirements (Erl, 2009). Services are independent reusable blocks that collectively represent an application environment. Services typically represent a given domain that can support a specific business process, and they communicate with each other through standard communications protocols (Erl, 2004). One key application of the SOA methodology has been its use within the software industry to enable interoperability over web services. Web services expose application functionality through a network, and allow other services and applications to interact with the application’s methods. Communications are provided by standardised protocols such as SOAP and REST, thereby providing independence from the underlying application platform and technologies.

The technology architecture of a SOA implementation typically consists of a combination of technologies, products, APIs, supporting infrastructure extensions, and various other parts which contribute to achieve an organisation’s business processes (Erl, 2009). To successfully implement SOA technology architecture, Erl (2009) highlighted four key characteristics that any form of SOA should provide: Business Driven, Vendor Neutral, Enterprise Centric and Composition Centric. These characteristics are relevant for Owner and FM organisations due to the non-linear nature of business processes, the changes in data and business requirements and the long term support of assets which is a key requirement for Owner and FM organisations. The development of reusable services, which can be composed in different configurations, depending on the business process, can be used to support a wide range of FM services along with changes in owner and FM requirements over time. Table 6.1 highlights how these four key characteristics can support Owner and FM business processes.

The technology architecture for the proposed CDE environment is provided in Figure 6.3. In this example, several applications are identified (BIM, FM, EDMS, GIS) and can be integrated using standard web service communication protocols. Different users will have specific access rights to each application through the definition of different service compositions. Additional applications or services can be added to the CDE depending on the Owner/FM organisation's business requirements. An example of application integration between a BIM and FM environment using web-services is provided in Figure 6.4.

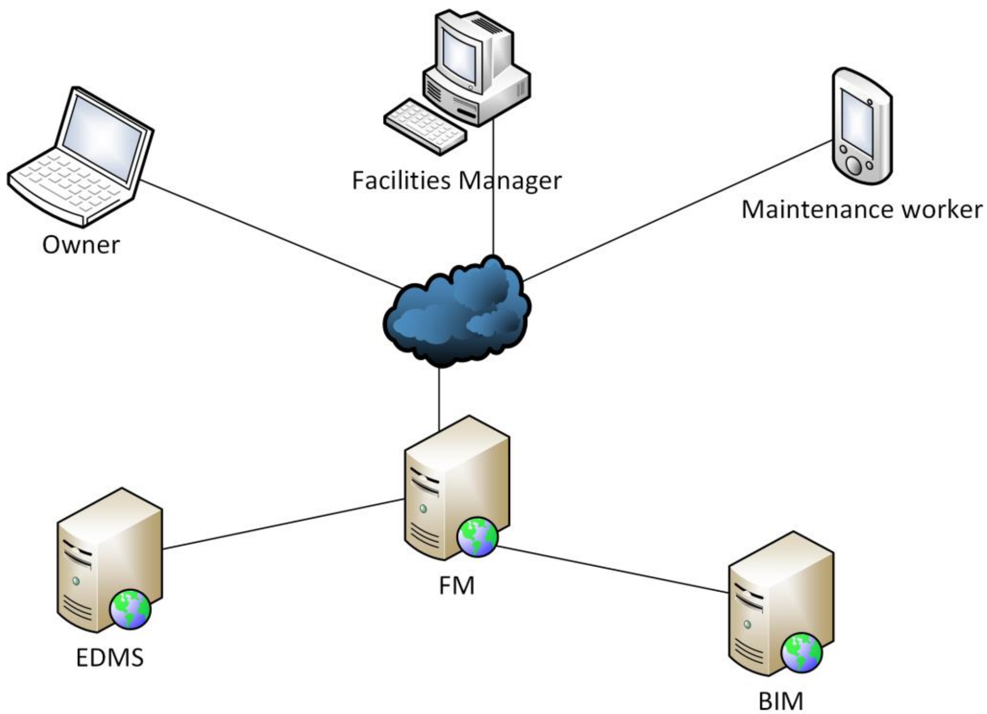

Figure 6.3 – CDE technology architecture overview

Table 6.1 – Key SOA capabilities and their relevance to Owners and FM – adapted from Erl, (2009)

Characteristic	***Description***	***Relevance to Owners and FM***
Business-Driven	SOA allows close alignment between the technology architecture and the current business architecture. This context is then constantly maintained so that the technology architecture evolves in tandem with the business over time.	Owners and FM need an IT infrastructure that will be used for a long period of time, and which is flexible to support a wide range of FM services which can change according to the Owner's requirements.
Vendor-Neutral	The architectural model is not based solely on a proprietary vendor platform, allowing different vendor technologies to be combined or replaced over time in order to support business processes on an on-going basis.	Owners and FM need to use different open and proprietary IT systems to manage various data sources, at different stages of facility lifecycle and possibly for different projects.
Enterprise-Centric	The scope of the architecture represents a meaningful segment of the enterprise, allowing for the reuse and composition of services and enabling service-oriented solutions to span traditional application silos.	Capabilities of the various IT systems used by Owners and FM often need to be combined and reused to support FM services and changes in owner requirements over time.
Composition-Centric	The architecture inherently supports the mechanics of repeated service aggregation, allowing it to accommodate constant change via the agile assembly of service compositions.	

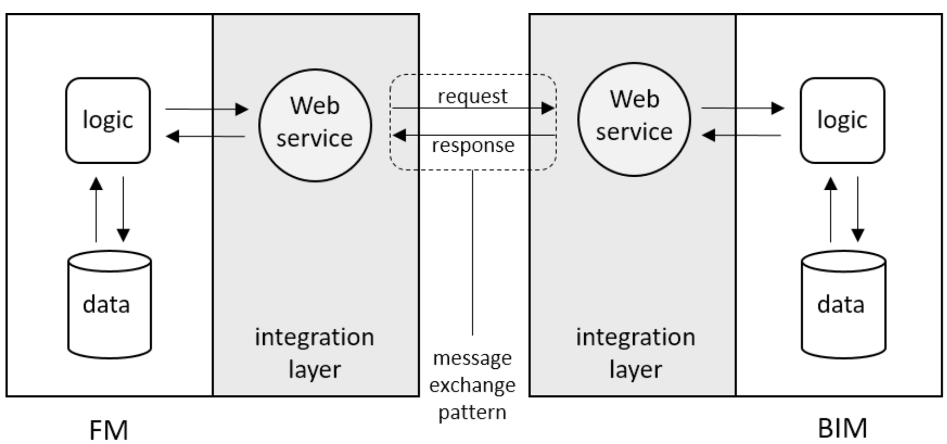

Figure 6.4 – Service-oriented integration of BIM and FM data using the request and response message exchange pattern – adapted from Erl, (2004)

6.3 CDE Infrastructure

Having identified the technology architecture requirements for the CDE, it is now possible to define its technology infrastructure, i.e. the specific software and hardware that can support the technology architecture (Erl, 2009).

The platform independent, web-based CDE is developed using existing SOA-based technologies and standard web-service protocols to provide access to various sources of graphical, non-graphical, and documentation data to different stakeholders at different stages of buildings' lifecycle. Each of the CDE's applications can be deployed on a single server, or in various distributed servers, and can support the proposed framework's various capabilities through web-based interfaces. Communication is established using standard web service protocols, as well as WebSockets. The web socket protocol was initially developed to provide browser-based applications with two-way communication with servers, without the need to open multiple HTTP connections (IETF, 2011). Stakeholders have different levels of access to each application's functionality depending on their role, since access is provided through composition of services from the different applications according to the business process. The CDE proposed in this research focuses on two key processes during the development and management of the AIM (Figure 6.5):

- Validation of data of various sources at various stages of the facilities lifecycle;
- Development of the AIM from the PIM following handover of data at the end of the project stages;

An overview of the data access requirements of the Project Information manager and Asset Information manager to the project and asset CDEs to support the processes exemplified in Figure 6.5 is provided in Table 6.2. Although it is suggested that the Project Information Manager uses an IFC model server as his CDE to manage project data through a web-service interface, it is only required that the data is sent and received in IFC and COBie format, and validated against the owner's requirements.

Table 6.2 – Project Information Manager and Asset Information Manager data access during PIM and AIM development

	Project Information Manager	*Asset Information Manager*
PIM	Work In Progress	
	Shared	Shared
	Published	Published
	Archive	Archive
AIM		Work In Progress
	Shared	Shared
	Published	Published
	Archive	Archive

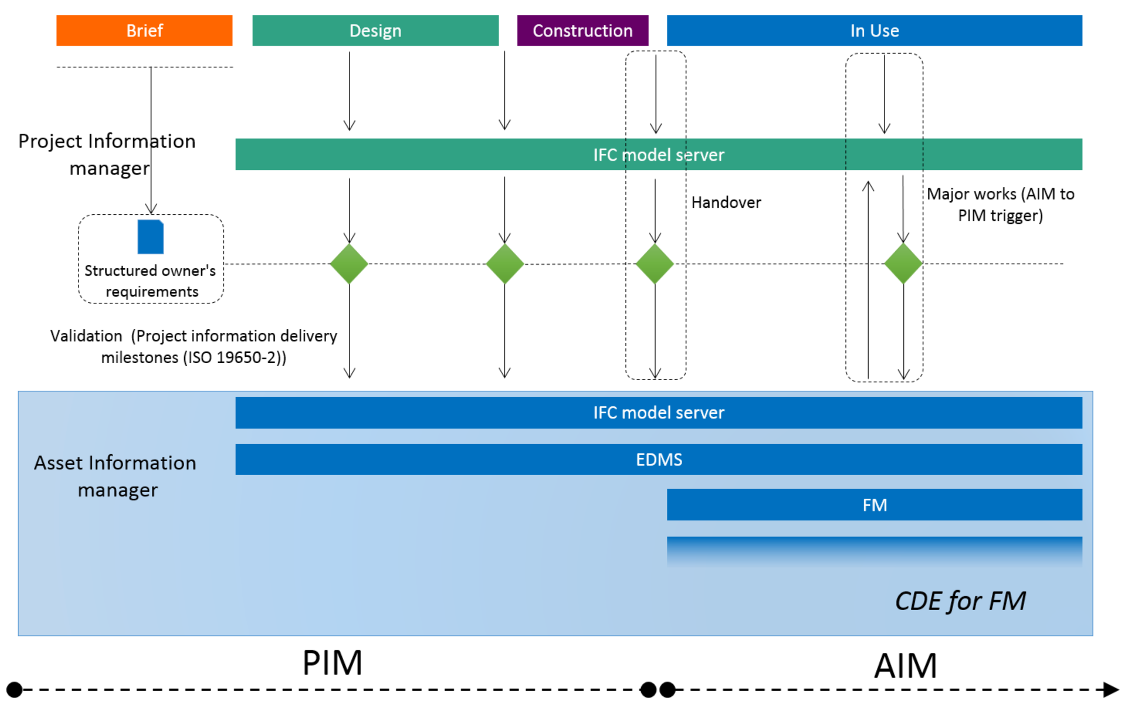

Figure 6.5 – Examples of information exchanges between project team and Owner/FM organisation throughout facilities lifecycle

The technology infrastructure of the CDE for FM consists of an IFC model server, a web-based FM software, a CMIS compliant EDMS, and a triple store to host IFC and COBie data in RDF format, to support the validation processes. Support for BIM data (graphical and non-graphical) is provided through the use of the BIMserver IFC model server. Support for documents is provided through the Alfresco CMIS-compliant EDMS. FM data is supported by the Openmaint open source FM environment. The Openmaint FM environment was identified as the most suitable to provide a CDE for the development of AIMs due to its support of IFC/COBie and CMIS standards, and ability to integrate other systems via standardised web service interfaces (Tecnoteca, 2019). IFC and COBie data is hosted in the Apache Jena Fuseki triple store in RDF format.

Visualisation of AIM data is provided using: a) IFC viewer within Openmaint; and, b) game engine (Unity). The technology infrastructure that supports the proposed AIM data validation and integration approaches is represented in Figure 6.6 and Figure 6.7. An overview of each application's service inventory is provided in Table 6.3.

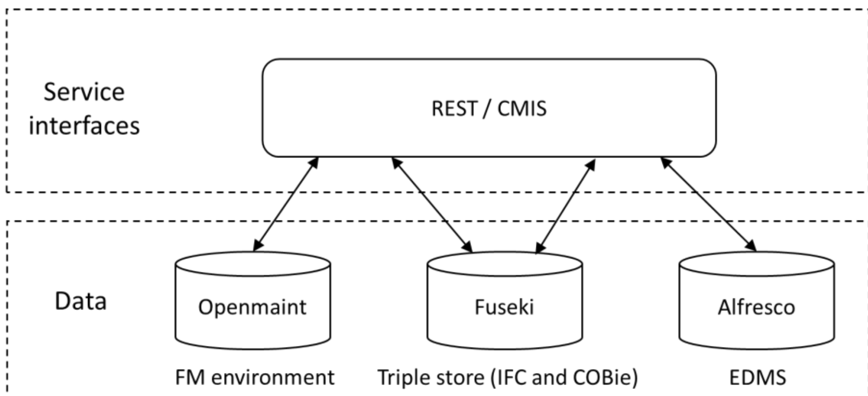

Figure 6.6 – AIM data validation – technology infrastructure

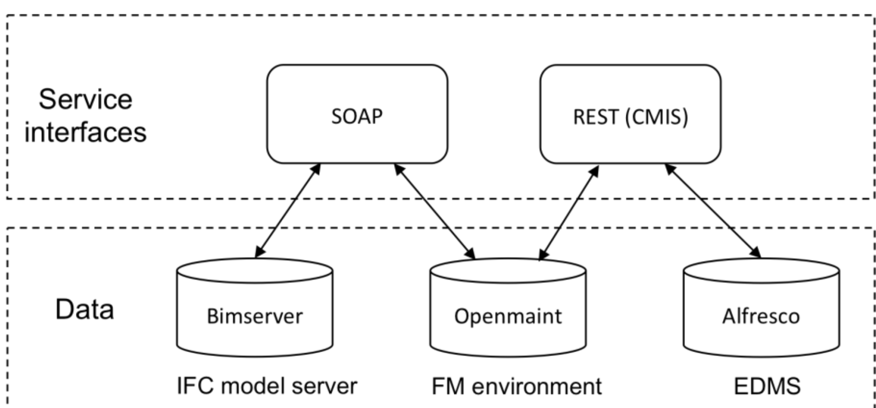

Figure 6.7 – AIM data integration – technology infrastructure

Table 6.3 – Service inventories for Openmaint, Alfresco, BIMserver, and Fuseki

Openmaint	*Alfresco (through CMIS)*	*BIMserver*	*Fuseki*
Card management (CRUD operations)	Repository	Administration	Query
Lookup heading management (CRUD operations)	Navigation	Authentication	Update
Relations management (CRUD operations)	Object	Metadata	Protocol
Workflow management (Start and update workflows)	Multi-filing	Plugin management	Graph Store HTTP Protocol
Document management using CMIS (Upload, Download, Delete, Update)	Discovery	Service Interface	
	Change	Settings	
	Versioning	Low Level Interface	
	Relationship	Notification Interface	
	Policy		
	ACL		

A Linux virtual machine was used for the implementation of the server side systems of the prototype CDE. The operating system used was Ubuntu 16.04 64bit and 8GB RAM was assigned to the virtual machine. Openmaint, Alfresco and BIMserver were deployed in separate Apache Tomcat instances, while Fuseki is accessed using its default HTTP server. All applications can be accessed through a web interface. Considering scalability issues resulting from the management of larger building portfolios, each component could be implemented in similar fashion in separate physical servers. Figure 6.8 provides an overview of the CDE implementation including the interaction between two ‘clients’ (web browser and Unity application) and the server side applications. The Openmaint FM application, accessible via a web browser, is the main point of access for the various stakeholders during the use phase of the building, and the other applications’ functionality is accessed through their web-service interfaces. The building owner can access all the tools using a web browser. The Unity game engine is used to provide visualisation of AIMs. Virtual environments can be defined in Unity and provide real time access to graphical, non-graphical and documentary data via web services and Socket.IO. The AIM visualisation method will be detailed in Section 6.6. Table

6.4 provides details of the CDE implementation. This prototype CDE was implemented and used for the development of the pilot studies documented in Chapter 7.

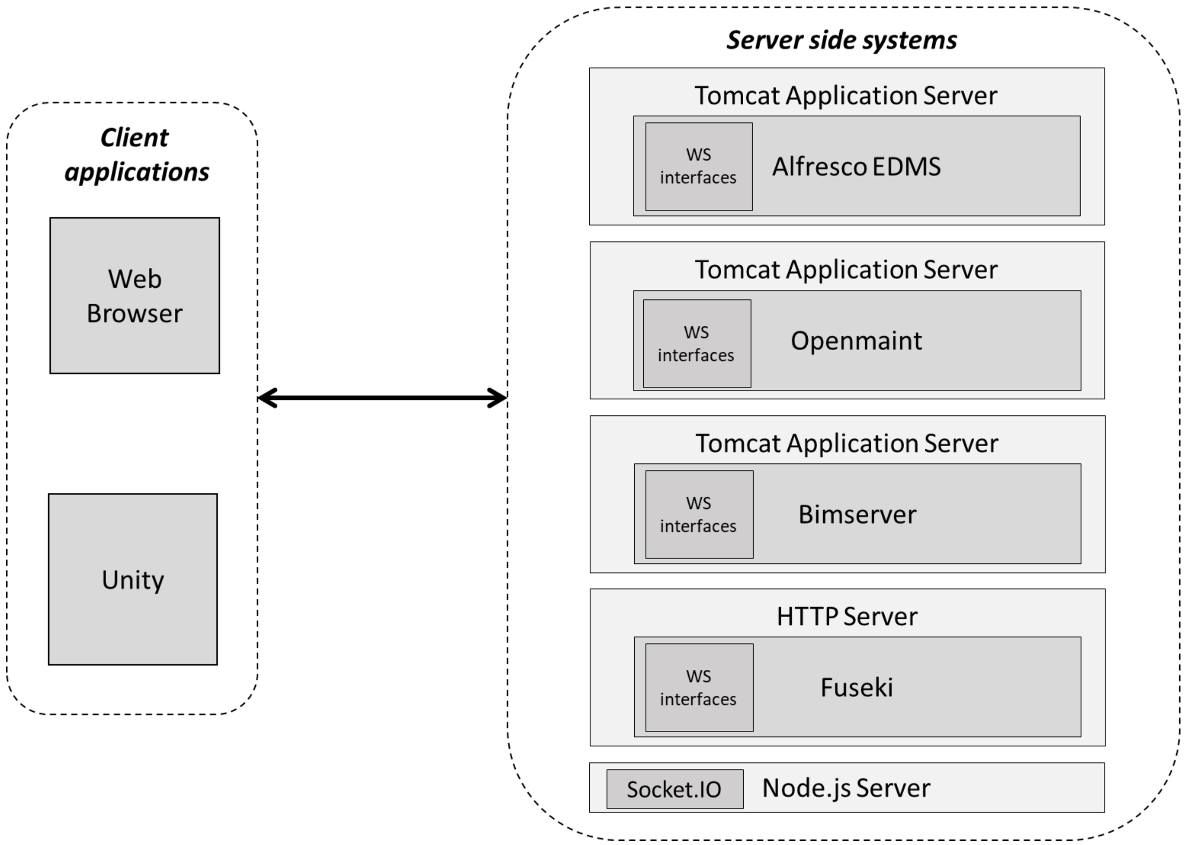

Figure 6.8 – Implementation of the CDE for FM

Table 6.4 – CDE configuration details

	Openmaint	*Alfresco*	*BIMserver*	*Fuseki*	*Node.js*
Software version	1.1 (CMDbuild 2.5.0)	5.2.0 Community	1.5.81	3.8.0	10.11.0
JDK	1.8	1.8	1.8	-	-
Apache Tomcat version	8.5	7.0	7.0	-	-

6.4 AIM definition

The next step in the development of the CDE is the definition of the AIM schema, which will enable importing and linking data from several sources into the FM environment. The Openmaint FM environment, which is based on an object-relational database model, has been adopted for this task, since it provides complete customisation in the development of its underlying database schema. This is a key requirement for the AIM since maintenance and FM data requirements will vary depending on the facility, which can result in changes to the AIM schema. The PostgreSQL object-relational database is adopted for the development of the AIM schema, since it supports some object-oriented concepts such as inheritance, allowing the representation of relationships within IFC and COBie data (e.g. an Asset is included in a Space). Spatial data is supported through the use of the PostGIS extension. The default PostgreSQL database schema provided in Openmaint already supports some of the needed requirements for the information integration of BIM data sources and documents into the FM environment. The generalisation and specialisation mechanisms can be used in the development of new database tables to support various data requirements, including BIM and GIS data requirements.

The default Openmaint database schema defines the ‘Class’ superclass with key attributes such as ‘Id’, ‘Code’ and ‘Description’, which are inherited to all the subclasses in the data model through specialisation. When a given object is classified (e.g. Building), a set of attributes is added to it based on this definition.

Several requirements were identified that were not supported by the default schema, which resulted in the configuration of an additional table for Zones and several custom attributes. In order to support COBie and IFC data requirements in the FM database and establish links between the IFC models, documents and FM data, several tables were defined in Openmaint and relationships were established between the following tables: ‘Building’, ‘Floor’, ‘Room’, ‘System’, ‘Zone’, ‘Asset’, ‘Maintenance Manual’ and ‘Maintenance Group’. The definition of these relationships was based on the IFC and COBie schemas and is a key requirement for linking BIM models into the database, as well as for the definition of preventive and reactive maintenance tasks. It also allows filtering assets by ‘Room’, ‘Floor’, ‘Zone’, ‘System’, 'Building', as well as for the definition of Maintenance Manuals enabling the organisation of documents by IFC element type, through the definition of Maintenance Groups. The aforementioned tables, along with their relations are described in Figure 6.9 in the form of an Enhanced Entity Relationship Model (EERM). Figure 6.10 highlights how inheritance was used in the specialisation of the *Class* table for the description of properties and relations between the 'Room' and 'Asset' tables. Inherited attributes are omitted in subclasses. The 'IsInRoom' attribute, inherited from the 'InventoryItem' table specifies in which 'Room' the 'Asset' is included.

One of the key features of the CDE is the customisation capability in the definition of its underlying database schema. It is possible to edit the database schema at any time in order to accommodate requirement changes for new or existing projects. This can be achieved by editing the underlying PostgreSQL database directly, or through Openmaint's administration interface. Figure 6.11 shows the definition of the custom 'Asset Criticality Rating' (ACR) attribute using Openmaint's administration interface.

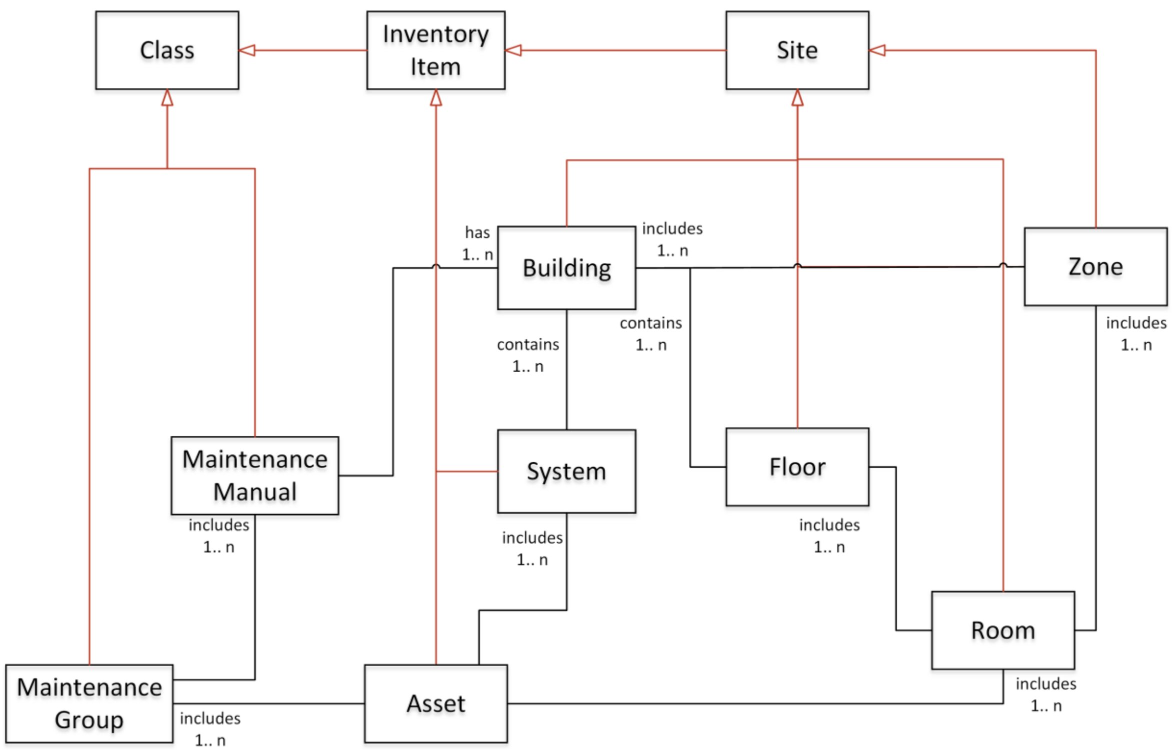

Figure 6.9 – Overview of Openmaint database tables used in the development of the AIM schema

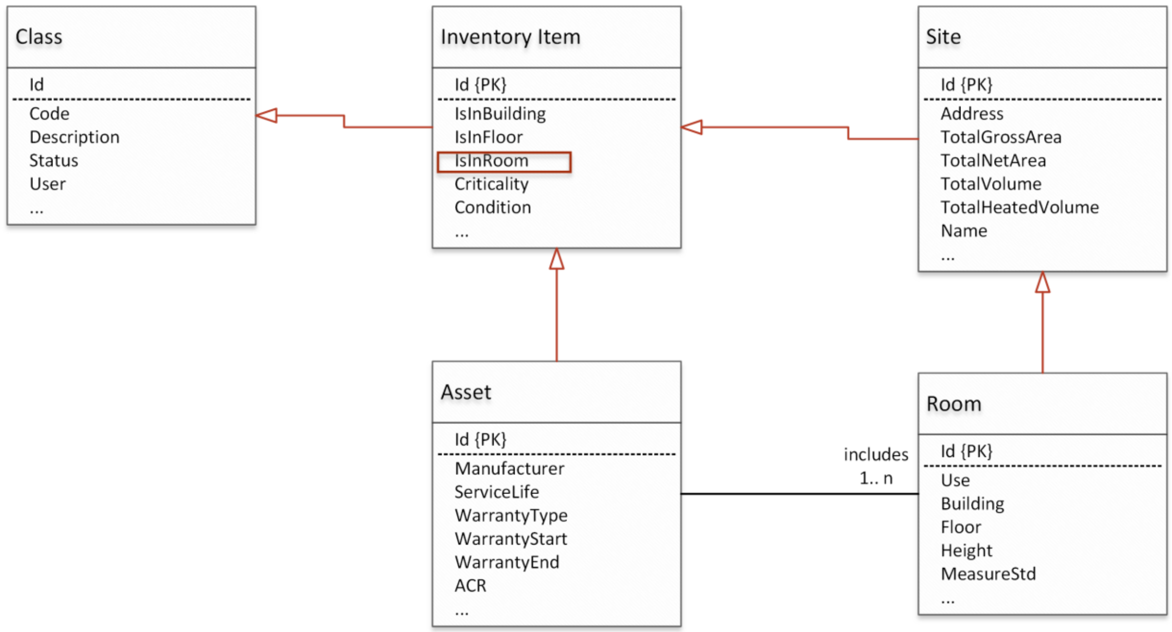

Figure 6.10 – EERM model highlighting relationship between 'Asset' and 'Room' tables in AIM schema

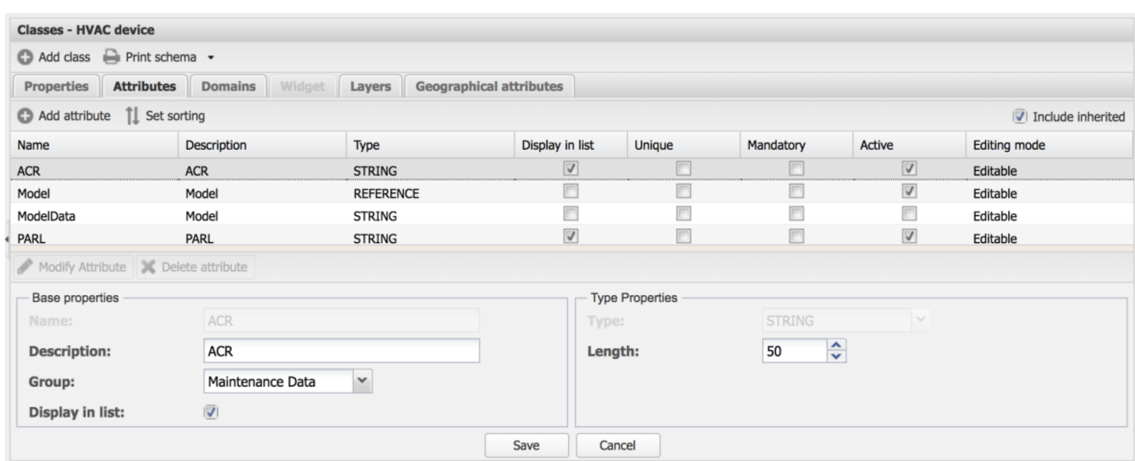

Figure 6.11 – Definition of custom attribute 'Asset Criticality Rating (ACR)' for the HVAC device Table in Openmaint administration interface

6.5 AIM development

Once the AIM schema has been defined, it is possible to import COBie and IFC data into the FM database and link external data sources through the Openmaint web service interfaces. This section outlines the methods used to link external BIM data and documents.

6.5.1 BIM

IFC and COBie can support the graphical and non-graphical asset information requirements for the AIM. Specific IFC entities and Property Sets can be specified via IDM's Functional Parts. While not all data requirements for the AIM are directly supported by the default IFC and COBie entities and property sets, the extensible nature of the IFC schema allows the definition of custom entities and property sets to support additional data requirements. In this research, 'asset criticality' data, defined according to BS 8544:2013 (BSI, 2013), was added to an IFC model in the form of a custom IFC property set, and was used to: 1) demonstrate the proposed AIR validation methodology, 2) assess the criticality of assets as a basis for the automated generation of reactive maintenance tasks, and 3) provide the display of data in the virtual environment. BIMserver has been adopted as the IFC model server in this framework to manage IFC and COBie data. BIMserver provides the storage and management of IFC models in an underlying database structure, and provides several interfaces and capabilities such as data querying and filtering for interaction with the stored models (BIMserver, 2018). BIMserver's functionalities are accessible through its web services (Table 6.3) as well as client and server Java APIs. BIMserver also stores information about projects, revisions, users, checkouts, and history in its underlying database. BIMserver provides IFC data versioning on a per-object basis.

IFC models can be uploaded to BIMserver and linked to Openmaint. IFC data relevant to FM can be imported into the database. To this end, a mapping is defined and inserted into the underlying PostgreSQL database to allow the import of the desired IFC element data from BIMserver into the Openmaint environment. Table 6.5 provides examples of the mapping between IFC entities and Openmaint tables.

Table 6.5 – Example mapping between IFC entities and Openmaint database tables

IFC Entity	***Openmaint Table***
IfcBuilding	Building
IfcBuildingStorey	Floor
IfcSpace	Room
IfcZone	Zone
IfcSystem	System
IfcEnergyConversionDevice	GenericHvacDevice
IfcFurnishingElement	GenericFurnishingElement

6.5.2 Documents

To address the AIM documentary data requirements, a content model was defined in a CMIS compliant content repository, Alfresco Community Enterprise Content Management. Alfresco provides an implementation of the CMIS bindings, including the mapping of the Alfresco content metamodel to the CMIS domain model. This allows content models defined in Alfresco to be exposed and manipulated via CMIS web services (Table 6.3). Alfresco content models are defined as XML documents, which must comply with the content metamodel XSD schema provided by the Alfresco content repository (Alfresco, 2019).

The content model metadata was defined based on generic requirements identified in Product Data Templates (PDTs) (CIBSE, 2016) and deployed into the Alfresco EDMS using the bootstrap approach. The IFC Building Name and Type properties were included in the content model to support validation of documentary data requirements against IFC/COBie data. The Alfresco content model schema is represented in Figure 6.12. The definition of custom properties to support the AIR is described in Table 6.6.

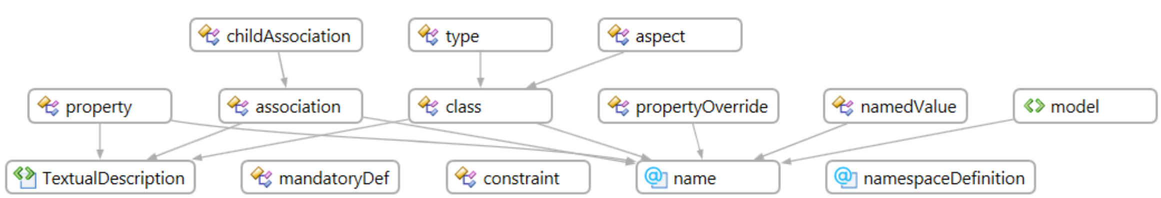

Figure 6.12 – Alfresco content model XML schema definition (XSD) (Alfresco, 2019)

Table 6.6 – Alfresco content model properties for the Asset Information Model

Property	CMIS property name	CMIS Property Type
Building Name	bim:BuildingName	Text
IFC Type	bim:IFCType	Text
Manufacturer name	bim:Manufacturer	Text
Manufacturer website	bim:ManufacturerWebsite	Text
O&M Manual	bim:OMManual	Text

6.6 AIM visualisation

Two approaches were considered to provide the visualisation of AIM data from various sources. The first approach consisted in the visualisation of IFC models within the Openmaint FM environment. While this allows the visualisation of BIM models along with linked documents and FM data, such as associated maintenance manuals, several performance issues were found, especially in larger models using complex geometry. The second approach consisted in the use of a game engine to provide the visualisation of the various AIM data sources, and provide the evaluation of accessibility to carry out maintenance tasks. The method used for the visualisation of integrated AIM data consisted of a series of steps, which are summarised in Figure 6.13, and described in Table 6.7.

The Unity game engine was used for the visualisation of AIM data in an integrated virtual environment, however the proposed approach is generic and could be used with a different game engine or visualisation library. A method was developed to allow linking geometric, non-geometric, documentary and FM data from the different sources of the CDE to display AIM data in a unified interface. The method requires importing geometric data into the Unity game engine, and attaching non-geometric and documentary data to the corresponding game objects as metadata.

An initial scene can be defined in Unity, and the geometric model can be imported in Collada format through the BIMserver web service interface. Geometry errors, which can arise due to the use of complex geometry, can be fixed within the Unity editor, or using external applications. The geometry model can then be prepared through the assignment of textures and materials, and the definition of colliders, to enable its navigation and interaction capabilities. Non-geometric data from BIMserver can be retrieved in real time when interacting with the assets through the BIMserver web service interface. This is achieved through the use of the Bimconnect Unity package, which provides an implementation of BIMserver's web services for Unity (TRC, 2015).

CMIS metadata and FM data are accessed in real time using WebSockets using the Socket.IO library. Socket.IO is a JavaScript library that enables real time, bi-directional communication between web clients and servers (Socket.IO, 2019). Socket.IO was used since it eliminates some of the overhead used by web services, improving the performance of the game. In this framework, the Socket.IO extension for Unity is used to establish the connection between Unity and a Node.js server. The Node.js server retrieves CMIS metadata and FM data, which is displayed in the virtual environment. The proposed visualisation methodology allows the Owner/FM to provide the game to stakeholders external to their organisation, such as external maintenance service providers, or to prospective new owners of the building, during a change of ownership process. The combined use of web services and WebSocket technologies within the game engine ensures that the virtual environment is always synchronised with the data in the CDE. This approach can be extended to provide data from other data sources of the Owner/ FM's CDE.

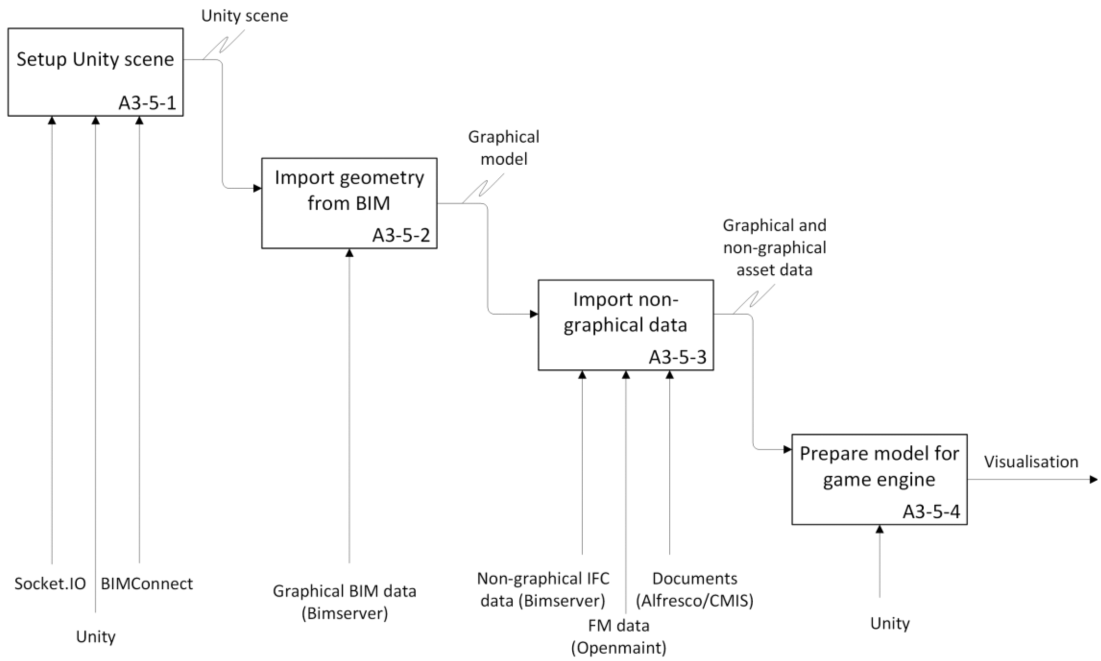

Figure 6.13 – IDEF0 diagram for AIM visualisation

Table 6.7 – Activity description for AIM visualisation process

Task code	*Description*
A3-5-1	Set up a new scene in the Unity game engine including the Socket.IO and BIMconnect Unity packages.
A3-5-2	Import the geometry from the BIM model in Collada format through BIMserver's service interface. Fix geometry errors within the Unity editor or using an external design tool.
A3-5-3	Configure access to non-graphical data and documents of the AIM. Non-graphical BIM data is retrieved through BIMserver web service interface; FM and Documentary data is retrieved using the Socket.IO library.
A3-5-4	To enable navigation and interaction with the model, it is possible to assign mesh colliders to the model's game objects. Depending on the size of the model, individual colliders might have to be simplified to improve performance. Attach non-graphical data and documents to game objects as metadata through the definition of scripts in Unity.

6.7 Summary

In this chapter, a CDE for FM was proposed based on the SOA to provide real time access to the various asset data sources for the development and management of AIMs. The various processes that support the development of the CDE and AIM were described:

- The definition of the CDE architecture;
- The definition of the CDE technical infrastructure;
- The definition of a data schema for the AIM according to the identified data standards and specific owner's data requirements;
- Development of the AIM through the integration of the various data sources;
- Visualisation of AIM data to support FM and maintenance tasks.

Key outcomes of this chapter are the development of a prototype CDE, and the proposed methodologies for the development and visualisation of AIMs. As part of the demonstration activity (Chapter 7), the prototype CDE will be used for the development of various pilot studies, which showcase the framework's capabilities in the structured definition of requirements, the validation of asset data, and the development, management and visualisation of AIMs for preventive and reactive maintenance tasks.

7 DEMONSTRATION AND VALIDATION

7.1 Introduction

This chapter presents the demonstration and validation of the proposed framework and CDE. The framework and prototype CDE are demonstrated through the development of pilot studies, showcasing the development process for an AIM. The development of the pilot studies validates the technical feasibility of the proposed framework and CDE. AIM development includes the definition of maintenance requirements, their validation, and its usage for the automated generation of Reactive and Preventive maintenance (RM and PM) tasks.

The validation activity consisted of demonstrating the prototype CDE's capabilities to a series of industry experts, using the developed pilot studies, and collecting feedback from unstructured interviews with the experts. Qualitative data from the interviews was analysed using the Grounded Theory method, building upon the initial requirements gathering analysis undertaken in Chapter 4. The data analysis provides a qualitative validation of the proposed framework and CDE against the various requirements for the development and management of AIMs.

Section 7.2 describes the development of the pilot studies, including the definition and validation of maintenance requirements, the development of the AIM including the integration of the various data sources, and their use in the definition of PM and RM activities, and the visualisation of the AIM, considering its various data sources. Section 7.3 presents the results from the validation activity carried out with academic and industry experts focusing on the proposed asset data validation approaches, and the AIM development, management and visualisation capabilities of the CDE. Finally, section 7.4 provides a summary of the findings of this chapter.

7.2 Demonstration

This section presents the technical validation of the research. The proposed framework and prototype CDE were used in the development of 3 pilot studies. The 'Project 1. Duplex Apartment' and the 'Project 3. Medical Clinic' model were was chosen since they are both thoroughly documented data sets, including Revit, IFC, COBie and handover documentation data, including operation and maintenance manuals (East, 2019). A BIM model for the Teesside University Centre House building was provided in Revit format by Teesside University Estates Department and was also used as a pilot study. An overview of the building models is provided in Figure 7.1 and Figure 7.2.

This section will detail the development of the AIM for the ‘Clinic’ project, since it is the most complex of the three data sets. This project is based on a medical and dental clinic building at a location in the South-West United States. The pilot study describes the development of the AIM, and how it can be used to automate the definition of PM and RM tasks within an existing SOA-enabled FM software. The pilot study demonstrates the various capabilities of the proposed framework and CDE:

- Definition of structured maintenance requirements and their validation against AIM data sources (documents, maintenance plans, etc.) (Section 7.2.1);
- The development of the AIM using various data sources, including BIM models and documents, and its use to automatically generate PM and RM maintenance tasks in an existing FM environment (Section 7.2.2);
- Visualisation of the AIM in a virtual environment, including its associated non-graphical and documentary data (Sections 7.2.3).

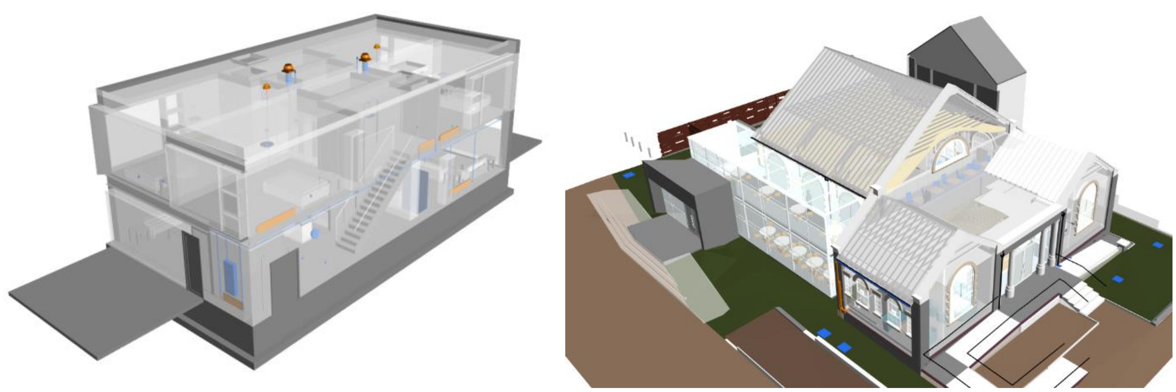

Figure 7.1 – Duplex (left) and Centre House (right) IFC building models rendered using Bimserver 1.5.81 (combined architectural, structural and MEP models)

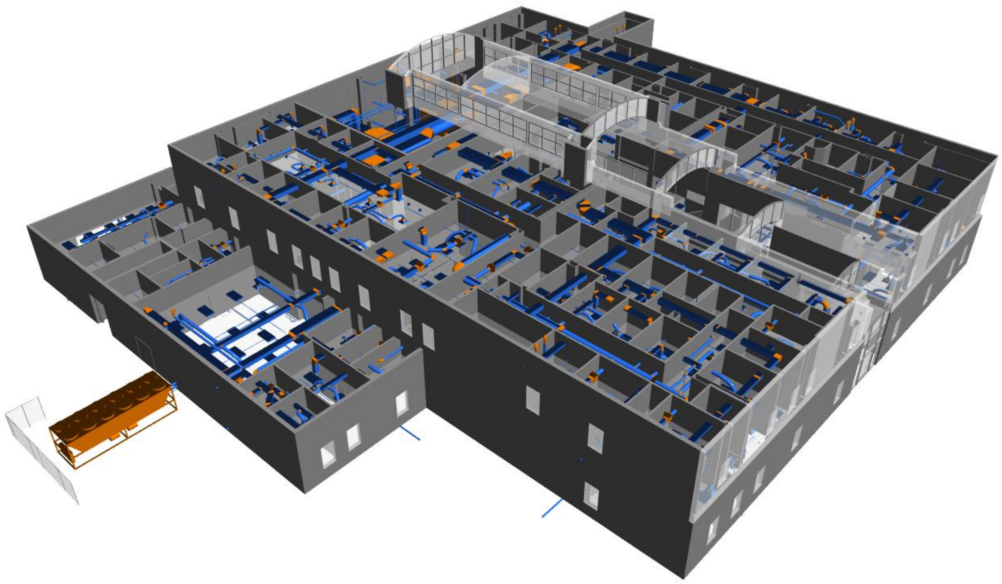

Figure 7.2 – Clinic IFC building model rendered using Bimserver 1.5.81 (combined architectural, structural and MEP models)

7.2.1 Definition and validation of maintenance requirements

Accurate and reliable data is an essential requirement for building owners and FMs to manage their facilities effectively. The definition and validation of maintenance requirements is a prerequisite for the development of an AIM, which accurately represents the building and can be used as a basis for maintenance planning and other FM tasks. This process starts with the definition of AIR, involving the owner, designers and FMs, and has been defined previously in the Framework Development chapter (Section 5.4). AIR documents can be stored in digital format in the owner's EDMS system as part of the CDE. During the construction stage, the Design-Build Team/Contractor will contact manufacturers to obtain specific building products. Building product data should be provided according to Product Data Templates (PDTs) and can be supported through the definition of a CMIS content model, which was previously detailed in section 6.5.2. This ensures that this data is according to the AIR, and can be referenced in IFC/COBie data drops. The Design-Build Team/Contractor uses the Product Data Sheets (PDS) provided by manufacturers to input data into the IFC/COBie deliverables according to the AIR. Finally, IFC/COBie deliverables are handed over to the owner who accepts or rejects them based on the results of the compliance checking process. A process map, describing the sequence of tasks and information exchanges that occur during the compliance checking process is provided in Figure 7.3.

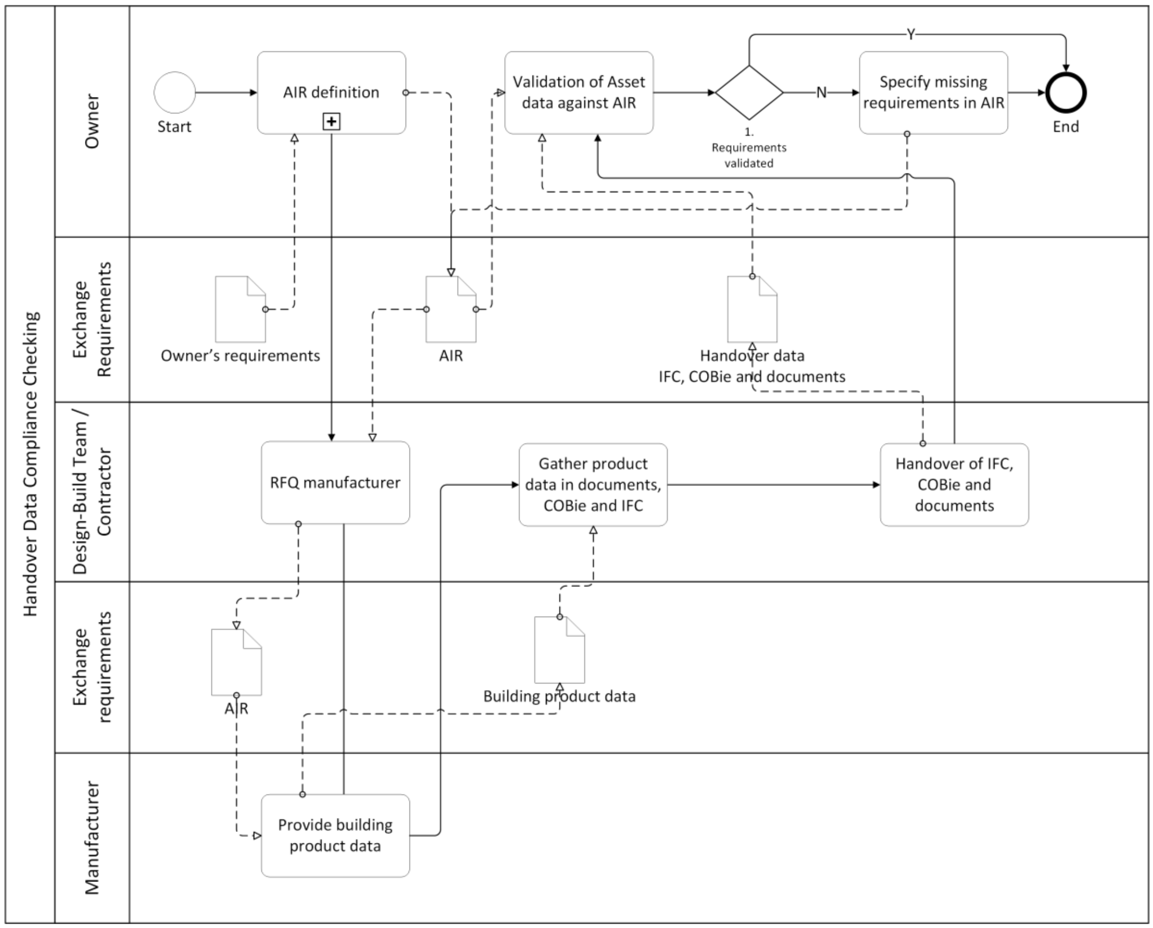

Figure 7.3 – Process map for compliance checking of AIM data sources at the handover stage

In Chapter 3, several compliance checking approaches were identified, which could be adopted for the validation of asset data from graphical, non-graphical and documentary sources against structured Owner and FM requirements. This research adopts the use of semantic web technologies, since they can be used to represent and perform compliance checking of the various data sources that are used in Asset Information Models.

The compliance checking approach consists of the following steps:

- Definition of structured maintenance requirements (AIR);
- Requirements interpretation and translation into machine computable formats (i.e. rules);
- Execution of rules against AIM data sources;
- Reporting of the rule checking results.

7.2.1.1 AIR definition

The primary goal of this pilot study is to demonstrate how an AIM defined using the proposed framework and CDE can be used to streamline the development of PM and RM tasks. To this end, various maintenance data requirements were identified, which should be validated during the handover stage, in order to enable the development of the AIM. These requirements can be classified as ‘pragmatic’ data requirements (ISO, 2015b), or in the ‘requirements validation’ category, according to Eastman (2009) and are summarised in Table 7.1.

IFC and COBie allow the specification of the various operation and maintenance documents that are needed for the operation of the building. These documents are a key prerequisite for successful operation of the building, and are needed for the definition and execution of PM and RM tasks. These documents should be specified in IFC/COBie deliverables at handover, along with the documentary metadata requirements that have been previously identified in section 6.5.2.

IFC and COBie also enable the specification of the PM tasks for the building, using IfcTask entities and the COBie Job tab. If PM tasks are specified in this manner, the building owner/FM can import this information into their CAFM/CMMS system.

Finally, ‘Asset Renewal’ is a maintenance requirement for building mechanical and electrical (M&E) systems. In this study, the asset criticality methodology proposed in BS 8544:2013 is adopted for the classification of critical assets (BSI, 2013). The ‘Asset Renewal’ maintenance requirement is defined as a custom IFC property set. Its properties are ‘Asset Criticality Ranking’ (ACR), which can be critical, or non-critical; ‘Percentage of Asset Remaining Life’ (PARL), which is given by equation (1) (BSI, 2013); and ‘Asset Renewal’. This requirement states that, for critical assets, if PARL is less than or equal to 20%, the asset must be renewed. In this research, this requirement is used to demonstrate how to automatically trigger Asset renewal work orders for the affected assets using a CAFM/CMMS system.

Table 7.1 – Overview of maintenance data requirements

Requirement name	***Rule Description***	***Data sources***
Handover Documents	At handover, operation and maintenance documents specified in COBie Documents tab must be available in a document repository.	IFC/COBie and CMIS
Preventive Maintenance data	At handover, Preventive maintenance activity data must be specified in IFC/COBie format in the form of IfcTask entities, and available in the COBie Job tab.	IFC/COBie
Asset Renewal	Determination of PARL is mandatory for critical assets. If PARL is less or equal than 20%, asset must be renewed.	IFC/COBie

$$PARL\ (\%) = \frac{Current\ Age}{Remaining\ Service\ Life} \times 100 \qquad (1)$$

The first step of compliance checking methodologies is the definition of requirements in a structured, machine interpretable way. The definition of maintenance requirements follows the IDM methodology, including the definition of AIR Exchange Requirements (ER) and Exchange Requirement Models (ERM). ER and ERM definition for the various requirements can be found in Appendix D. The maintenance data requirements identified in Table 7.1 focus on the handover of validated asset data to the Owner, however the validation methodology can be applied at any stage of the building lifecycle.

7.2.1.2 AIR validation

Following ER and ERM definition, Business Rules were defined to check if the maintenance requirements specified by the owner have been fulfilled in the submitted data drops. Business rules are defined using SPARQL queries that are executed against various data sources expressed in RDF triples. The SPARQL Protocol and RDF Query Language (SPARQL) is a

W3C standard for querying RDF data. SPARQL can be used to query RDF triples locally, or through SPARQL endpoints that expose RDF data via standardised interfaces using the HTTP protocol (W3C, 2008). The Apache Jena framework is used to convert of IFC and COBie data to RDF format, and for execution of SPARQL queries against IFC and COBie data stored in the Apache Fuseki Server triple store, which hosts IFC and COBie data of the Clinic model in RDF format. An overview of the process and tools used for the validation of asset data using Semantic Web tools and standards is provided in Figure 7.4.

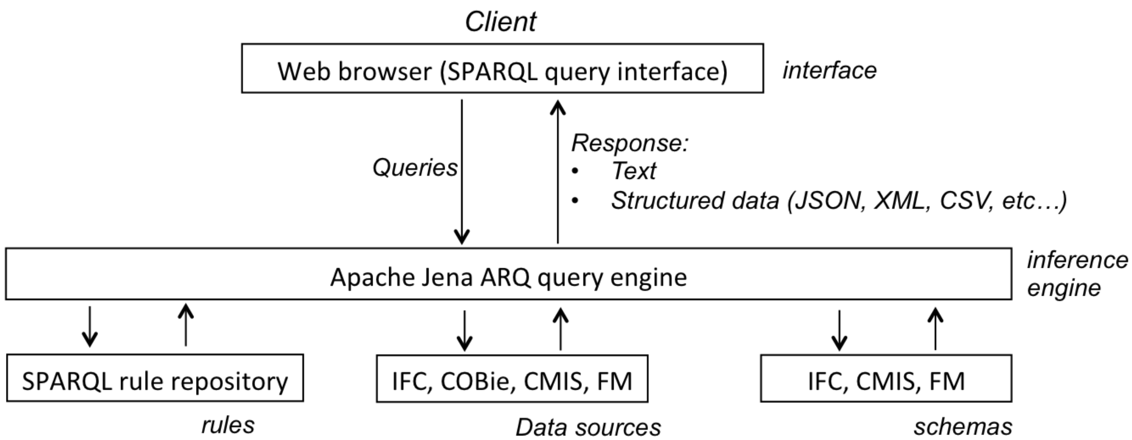

Figure 7.4 – Overview of the validation process and tools using Semantic web tools

Handover documents

To check if the handover documents specified in the COBie documents sheet have been submitted to a CMIS compliant repository, a Java application was defined using the Apache Jena framework. The application connects to Alfresco through the CMIS REST (AtomPub 1.1) service interface and retrieves the documents name through the ‘cmis:name‘ property. The SPARQL query in Table 10.2 was defined in the Java application to query the COBie data stored in the Fuseki triple store using the REST web service interface, and return the document names from the ‘IfcDocumentReference’ entities that match document names in the Alfresco repository. The application returns the list of documents defined in COBie and whether they were found in the repository or not. Figure 7.5 shows an excerpt of the results of the execution of the application using the Eclipse IDE. This example shows how the compliance checking methodology adopted in this research uses Semantic Web tools and standards for the validation of disparate data sources, i.e. BIM data in COBie format and documents stored in a CMIS-compliant EDMS.

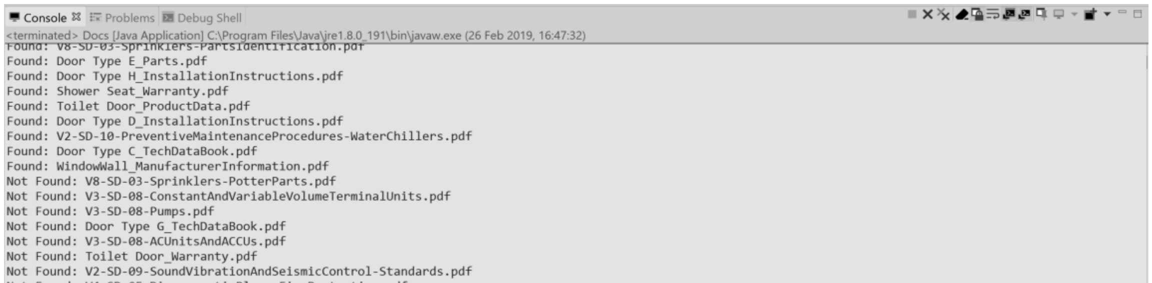

Figure 7.5 – Execution results for ‘Handover Documents’: Java application within the Eclipse IDE

Preventive Maintenance data

Checking if the preventive maintenance data has been specified in the COBie job sheet can be achieved through the definition and execution of a SPARQL query against the COBie data stored in the Fuseki triple store. The SPARQL queries defined in Table 10.9 and Table 10.10 were used to retrieve the list of ‘IfcTask’ entities defined in the COBie handover data and the required attributes according to the AIR. Figure 7.6 shows an excerpt of the PM data defined in COBie obtained from the query execution.

	taskname	description	tasktype	status	ismilestone
1	"Air Handler Lockout"	"1. Turn off power at the control panel. 2. Shut down all auxillary power to the unit. 3. Check power readings to insure total shut down. 4. Remove safety pin from the panel.5. Kill power to the device. 6. Wait until all moving parts have been STOPPED. 7. Complete task."	"Safety"	"Not Yet Started"	"true"^^xsd:boolean
2	"Boiler Lock Out"	"2. Place placard on door."	"Safety"	"Not Yet Started"	"true"^^xsd:boolean

	taskname	propertyname	propertyvalue
1	"Air Handler Lockout"	"TaskDuration"	"30."^^xsd:double
2	"Air Handler Lockout"	"TaskInterval"	"1."^^xsd:double
3	"Boiler Lock Out"	"TaskDuration"	"2."^^xsd:double

Figure 7.6 – SPARQL query execution results for ‘Preventive Maintenance data’

Asset Renewal

The RDF model of the IFC MEP Clinic project, stored in the Fuseki triple store, was used to validate the Asset Renewal maintenance requirement. The SPARQL query defined in Table 10.11 was used to retrieve the custom property set data defined to support the Asset Renewal maintenance requirements. Figure 7.7 shows the query execution results, where 'value' provides the URI link to the corresponding IFC Element.

	ifcboiler	name	value
1	<http://linkedbuildingdata.net/ifc/resources20171026_160536/IfcBoilerType_99557>	"PARL"	<http://linkedbuildingdata.net/ifc/resources20171026_160536/IfcReal_157900>
2	<http://linkedbuildingdata.net/ifc/resources20171026_160536/IfcBoilerType_99557>	"ACR"	<http://linkedbuildingdata.net/ifc/resources20171026_160536/IfcText_242391>
3	<http://linkedbuildingdata.net/ifc/resources20171026_160536/IfcBoilerType_99557>	"AR"	<http://linkedbuildingdata.net/ifc/resources20171026_160536/IfcText_242393>

Figure 7.7 – SPARQL query execution results for 'Asset Renewal'

7.2.2 AIM development

Once the various sources of asset data have been validated against the owner's requirements at the handover of the project, it is possible to use them for the development of the AIM. This section will describe the various activities that were undertaken in the development of the AIM for the Clinic pilot project. The development of the AIM uses the validated sources of asset data (i.e. graphical, non-graphical, and documentary data sources) in order to support the previously identified maintenance requirements, and demonstrates its use for the development of PM and RM tasks:

- Integration of BIM and FM data;
- Integration of BIM and documents;
- Automated definition of Preventive Maintenance tasks;
- Definition of Reactive Maintenance tasks.

The sequence of activities and interactions between various actors and components of the system in the use cases is described through the use of UML sequence diagrams and BPMN diagrams.

7.2.2.1 Integration of BIM and FM data

Once the various asset data sources have been validated against the maintenance requirements, they can be uploaded into their dedicated repositories. Since the CDE is based on the Service Oriented Architecture, the Owner/FM is able to upload distinct sources of data (i.e. graphical, non-graphical and documentary data) from a single user interface (i.e. Openmaint). To achieve this, the Owner/FM starts by defining a new BIM project in Openmaint's administration interface. IFC files are uploaded to a BIMserver instance through Openmaint's administration interface, via BIMserver's SOAP web service interface. In order to link IFC models to the FM database and import the required BIM data according to the previously defined maintenance requirements, an XML script is defined and inserted into the 'public._BimProject' table for the corresponding BIM project in Openmaint. In Table 7.2 an excerpt of the XML mapping used to import data from IfcBoiler instances is shown. Additional SQL scripts were defined to retrieve and map the 'IfcRelContains' spatial containment relationships to the FM database according to the AIM schema defined in Section 6.5.

To ensure that the BIM data has been successfully imported according to the AIR, it is important to check the validity of the imported data against the original IFC data. This can be achieved by checking the data in the FM database against the IFC data stored in the Fuseki triple store, according to the AIR defined by the owner. Using the D2RQ platform it is possible to access local and remote databases as RDF graphs and perform SPARQL queries against them (Cyganiak, 2019). The Apache Jena Framework was used to check the "Asset Renewal" and "Preventive maintenance" data requirements in the FM database against the values in the IFC and COBie models using SPARQL queries. The D2RQ mapping language was used to retrieve the 'Asset' and 'MaintenanceActivity' tables from Openmaint's PostgreSQL database and generate the RDF schema and mapping files. The SPARQL queries used to retrieve asset and preventive maintenance data from the FM database are defined in Table 10.12 and Table 10.13 respectively.

Finally it is possible to view the IFC model from the FM interface and access its related FM data stored in Openmaint (Figure 7.8). This process enables the Owner/FM to selectively import BIM data into the FM environment according to their requirements and access it through the IFC model viewer from the FM web interface, while ensuring the quality of the data and its compliance to the AIR. Figure 7.9 provides an overview of the interaction between the Owner/FM and the Openmaint and BIMserver applications that underpins this process.

Table 7.2 – Excerpt of xml import mapping configuration in 'ImportMapping' column of 'public._BimProject' table

```xml
<bim-conf>
  <entity ifcType="IfcEnergyConversionDevice" cmClass="GenericHvacDevice">
    <attributes>
      <attribute type="simple" ifcName="ifcRoot_Name" cmName="Code" />
      <attribute type="simple" ifcName="ifcRoot_Description" cmName="Description" />
      …
    </attributes>
    …
  </entity>
</bim-conf>
```

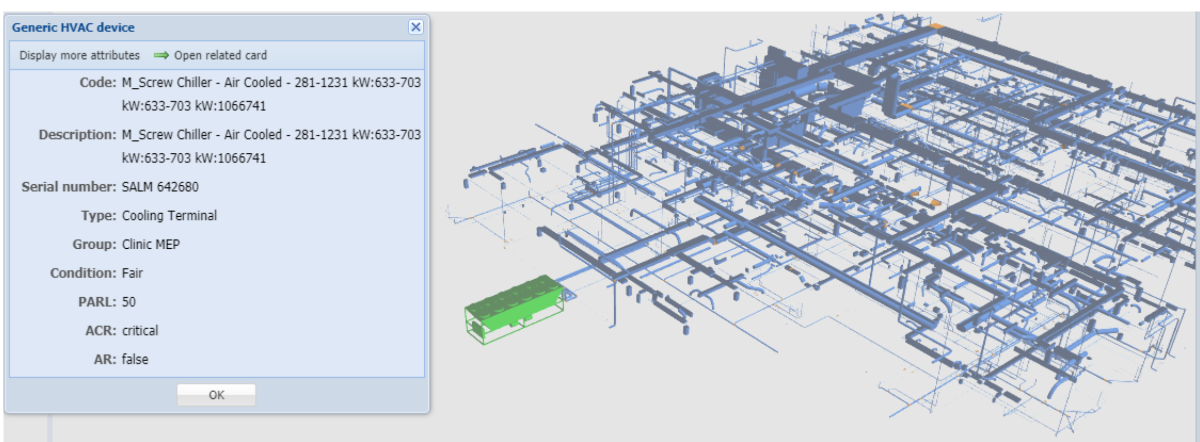

Figure 7.8 – Link between BIM model and FM database – accessing FM data from the IFC model viewer for the Clinic MEP model

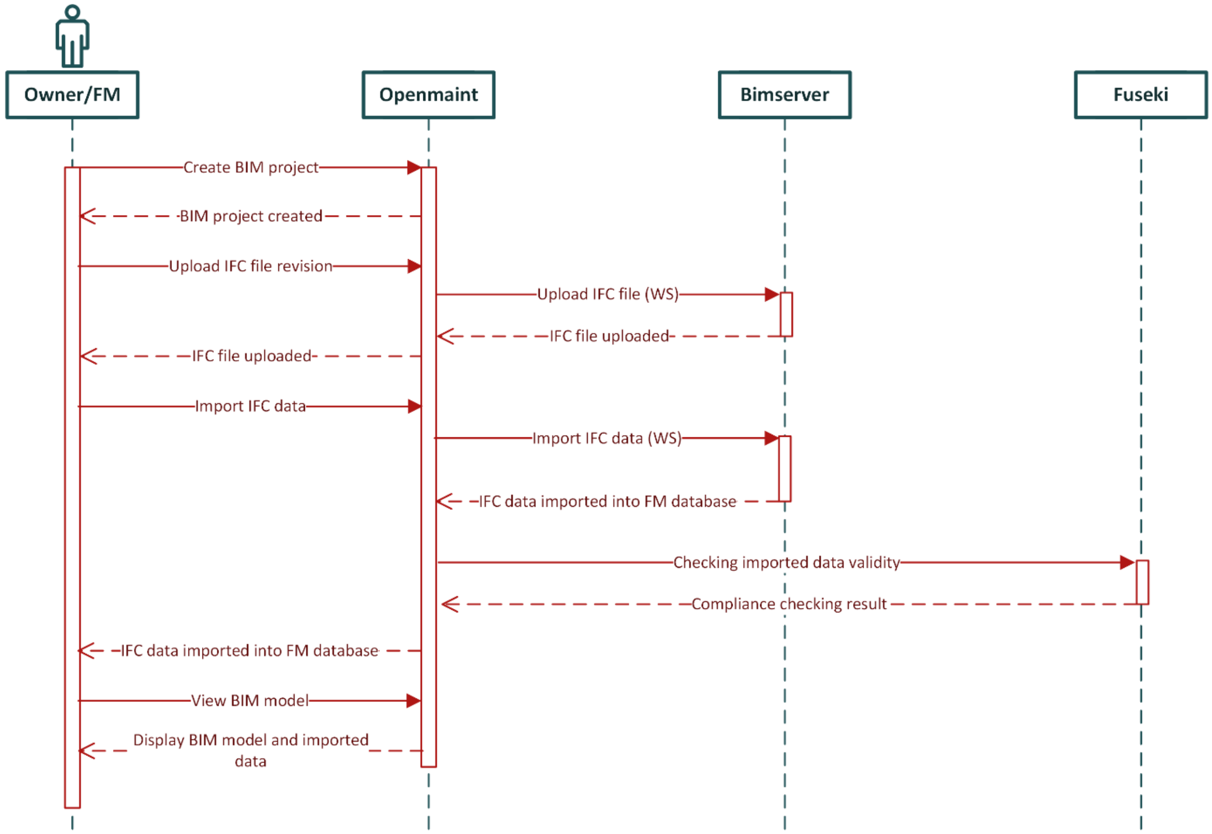

Figure 7.9 – UML sequence diagram for the integration of BIM and FM data

7.2.2.2 Integration of BIM and documents

The integration of operation and maintenance documents with their corresponding building elements is a prerequisite for the definition of PM and RM tasks within the prototype CDE. After BIM models have been linked to Openmaint and maintenance data has been imported into the FM database according to the Owner/ FM requirements, a Maintenance Manual can be defined by uploading the various operation and maintenance documents defined in COBie to the CMIS-compliant EDMS and linking them to building assets. Similarly to the process used to link BIM models to the FM database, documents can be uploaded to a CMIS-compliant repository via the CMIS REST web service interface and accessed through Openmaint. To automate this task, a Java client application was developed to upload all the documents referenced in an IFC model through the ‘IfcDocumentReference’ entity. The client application connects to Openmaint using its web service interface and defines a new

'Maintenance Manual' entity for the building. 'Maintenance Group' and 'Maintenance Item' entities are defined based on the IFC Element Type classification (e.g. Uniclass 2015, Omniclass, etc). Finally, the application connects to Alfresco through the CMIS REST web service interface to upload the documents and associate them with the building's assets by classification. This process can be used throughout the use phase of the building, whenever there is a new COBie data drop with associated documentary data. The Owner/FM can also upload and access additional documents manually through Openmaint and Alfresco web interfaces. The 'Handover Documents' AIR developed in Section 7.2.1 is used to validate this process by verifying if the documents uploaded to the EDMS are according to the Owner's requirements. Figure 7.10 provides an overview of the process. Figure 7.11 highlights how documents are associated to specific 'Maintenance Groups' using the Omniclass category defined in the Clinic model.

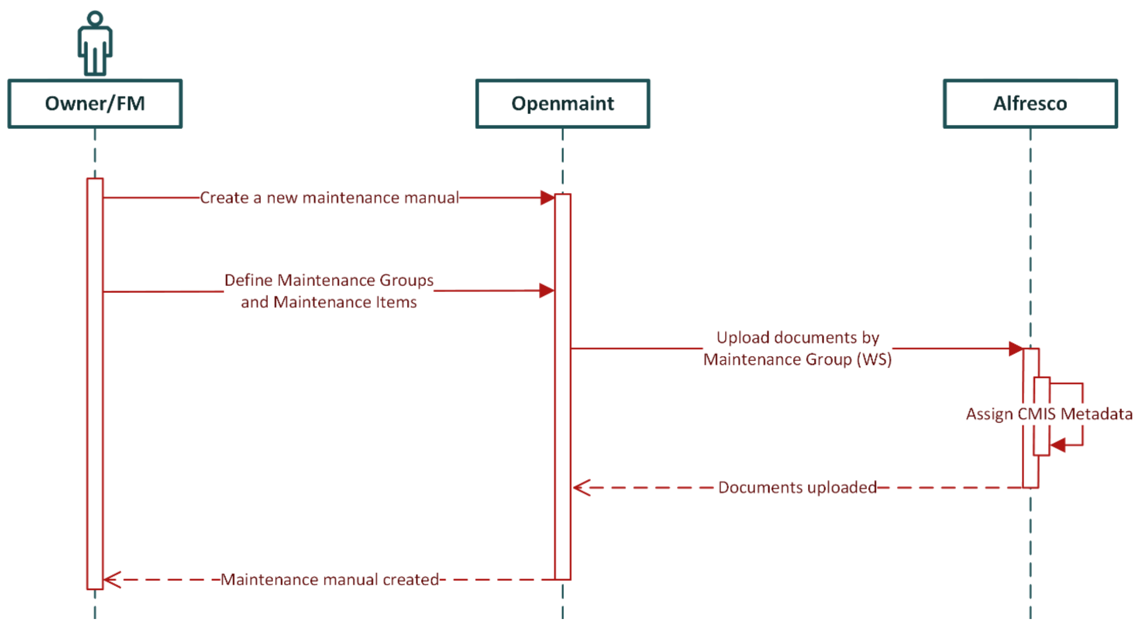

Figure 7.10 – UML sequence diagram for the definition of the 'Building Maintenance Manual'

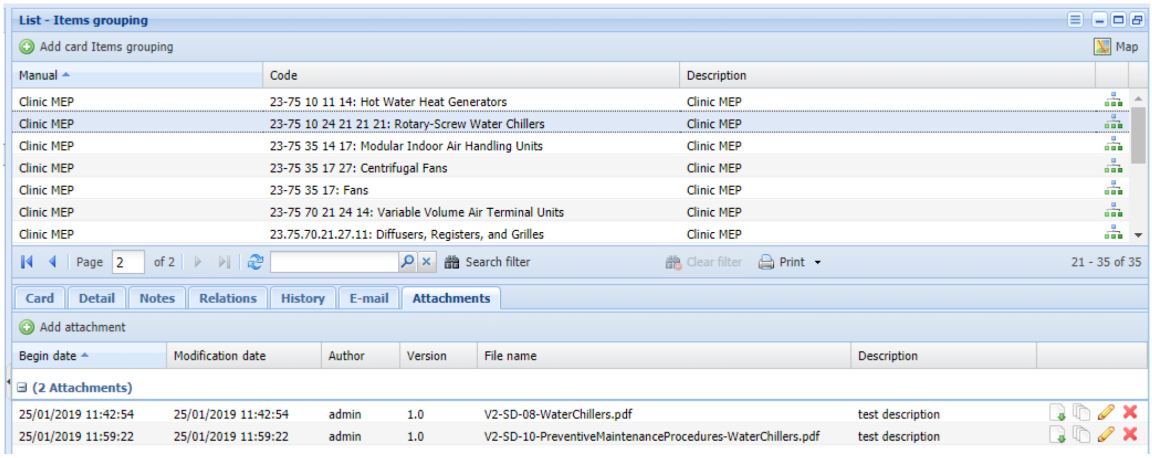

Figure 7.11 – Maintenance Manual and associated handover documents for the Clinic model

7.2.2.3 Automated definition of Preventive Maintenance tasks

After importing BIM data, including preventive maintenance tasks data, and linking documents into the AIM, it is now possible to define a Preventive Maintenance Calendar using Openmaint. This can be achieved through the execution of predefined workflows - ‘Maintenance Calendar generation’ and ‘Workorder generation’ - using the Enhydra Shark workflow server (version 4.4.1).

After PM activities have been imported, a maintenance calendar can be generated for a given time interval through the execution of the ‘Maintenance Calendar generation’ workflow. A list of work orders are automatically generated for a given maintenance calendar through the execution of the ‘Workorder generation’ workflow and their associated data is stored in pdf format in a CMIS-compliant EDMS. The list of work orders and their requirements will be emailed to the ‘Team’ associated with the PM activity. Figure 7.12 provides an UML sequence diagram that summarises this process.

Figure 7.13 provides an example of a generated Preventive Maintenance Activity, highlighting the database relationships. Figure 7.14 provides an example of a Maintenance Calendar generated for the ‘Clinic’ model using this method.

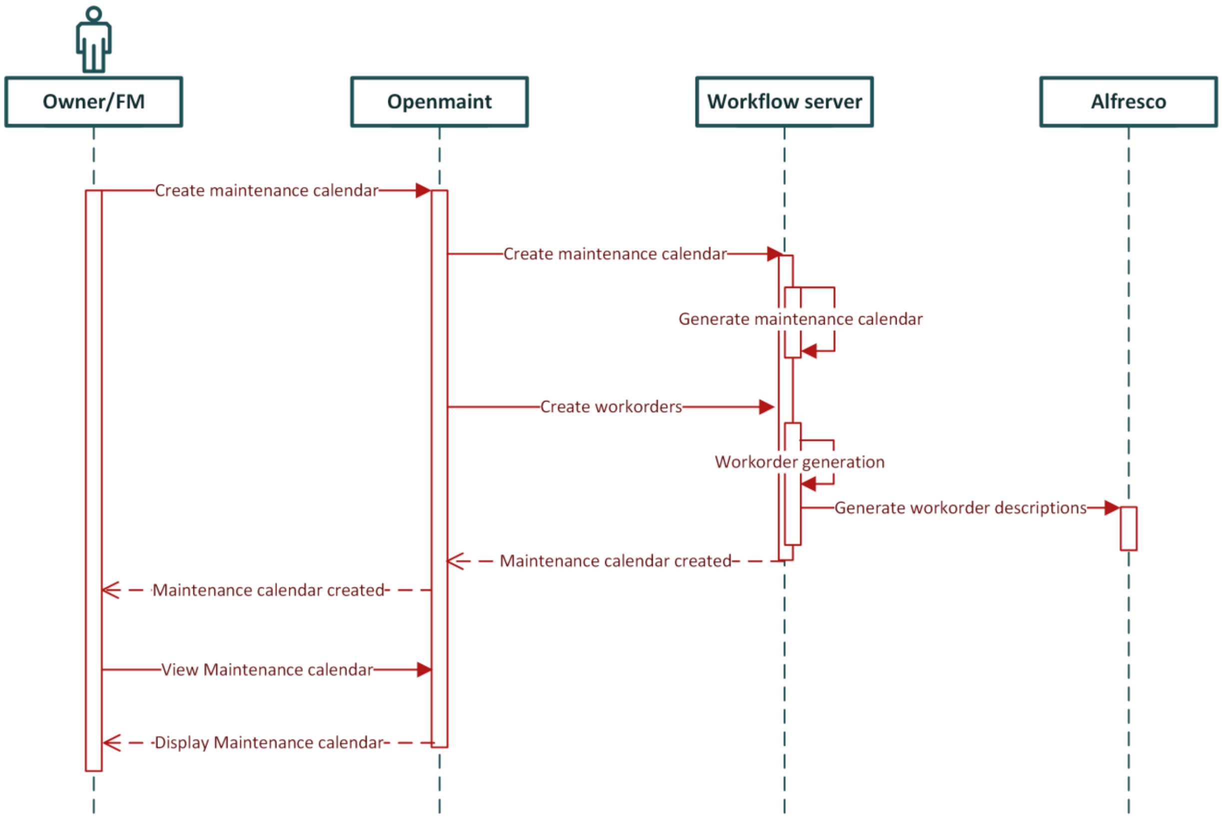

Figure 7.12 – UML sequence diagram for the automated definition of Preventive Maintenance tasks

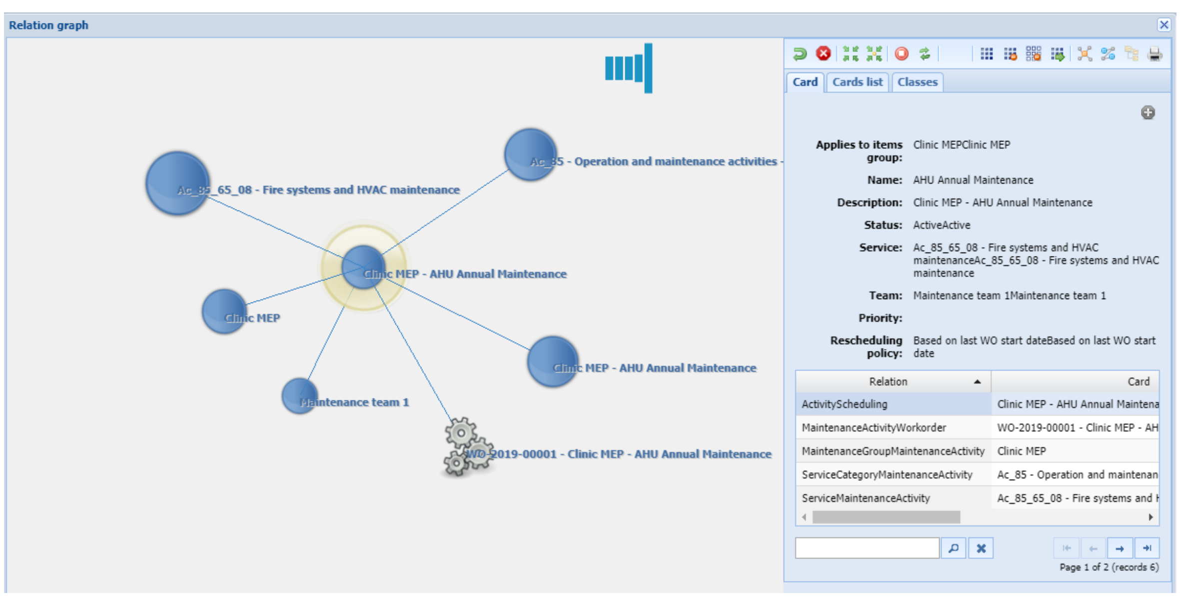

Figure 7.13 – Preventive maintenance activity and related entities in Openmaint

List - Maintenance calendar

Add card Maintenance calendar — Map

Appointed team	Workorder objects	Description	Scheduled start	Activity	Workorder started
Maintenance team 1	Clinic MEP	Clinic MEP - AHU Annual Maintenance	28/01/2019 00:00:00	Clinic MEP - AHU Annual Maintenance	Yes
Maintenance team 1	Clinic MEP	Clinic MEP - Boiler Lock Out	28/01/2019 00:00:00	Clinic MEP - Boiler Lock Out	Yes
Maintenance team 1	Clinic MEP	Clinic MEP - Boiler Annual Maintenance	28/01/2019 00:00:00	Clinic MEP - Boiler Annual Maintenance	Yes
Maintenance team 1	Clinic MEP	Clinic MEP - Sprinkler Head Semi-Annual Maintenance	28/01/2019 00:00:00	Clinic MEP - Sprinkler Head Semi-An...	Yes
Maintenance team 1	Clinic MEP	Clinic MEP - Sprinkler Head Semi-Annual Maintenance	28/07/2019 00:00:00	Clinic MEP - Sprinkler Head Semi-An...	No
Maintenance team 1	Clinic MEP	Clinic MEP - AHU Annual Maintenance	28/01/2020 00:00:00	Clinic MEP - AHU Annual Maintenance	No
Maintenance team 1	Clinic MEP	Clinic MEP - Boiler Lock Out	28/01/2020 00:00:00	Clinic MEP - Boiler Lock Out	No
Maintenance team 1	Clinic MEP	Clinic MEP - Boiler Annual Maintenance	28/01/2020 00:00:00	Clinic MEP - Boiler Annual Maintenance	No
Maintenance team 1	Clinic MEP	Clinic MEP - Sprinkler Head Semi-Annual Maintenance	28/01/2020 00:00:00	Clinic MEP - Sprinkler Head Semi-An...	No
Maintenance team 1	Clinic MEP	Clinic MEP - Sprinkler Head Semi-Annual Maintenance	28/07/2020 00:00:00	Clinic MEP - Sprinkler Head Semi-An...	No
Maintenance team 1	Clinic MEP	Clinic MEP - AHU Annual Maintenance	28/01/2021 00:00:00	Clinic MEP - AHU Annual Maintenance	No
Maintenance team 1	Clinic MEP	Clinic MEP - Boiler Lock Out	28/01/2021 00:00:00	Clinic MEP - Boiler Lock Out	No
Maintenance team 1	Clinic MEP	Clinic MEP - Boiler Annual Maintenance	28/01/2021 00:00:00	Clinic MEP - Boiler Annual Maintenance	No
Maintenance team 1	Clinic MEP	Clinic MEP - Sprinkler Head Semi-Annual Maintenance	28/01/2021 00:00:00	Clinic MEP - Sprinkler Head Semi-An...	No
Maintenance team 1	Clinic MEP	Clinic MEP - Sprinkler Head Semi-Annual Maintenance	28/07/2021 00:00:00	Clinic MEP - Sprinkler Head Semi-An...	No
Maintenance team 1	Clinic MEP	Clinic MEP - AHU Annual Maintenance	28/01/2022 00:00:00	Clinic MEP - AHU Annual Maintenance	No
Maintenance team 1	Clinic MEP	Clinic MEP - Boiler Lock Out	28/01/2022 00:00:00	Clinic MEP - Boiler Lock Out	No
Maintenance team 1	Clinic MEP	Clinic MEP - Boiler Annual Maintenance	28/01/2022 00:00:00	Clinic MEP - Boiler Annual Maintenance	No

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Figure 7.14 – Preventive Maintenance Calendar generated in Openmaint

7.2.2.4 Definition of Reactive Maintenance tasks

The definition of reactive maintenance tasks is also supported by the ‘Workorder Generation’ workflow. Maintenance requests can be generated manually by the user through the Openmaint web interface, or automatically, using the Openmaint REST web service interface.

Building users can initiate maintenance requests to log a fault in the building. The user can select which assets or locations are affected by the fault by selecting a related ‘Asset’, ‘Room’, ‘Floor’, ‘Zone’, or ‘Building’. Maintenance requests are forwarded to a ‘Helpdesk’ which evaluates the fault. If the activity is approved, the ‘Helpdesk’ user can generate one or more work orders - including the work order priority and due date - which will be issued to the appropriate ‘Team’. After the ‘Team’ receives the work order notification, they schedule the activity to be executed. The ‘Team’ can also create additional maintenance requests related to the work order. Finally the ‘Team’ can assign an outcome for the work order, which will be communicated back to the Helpdesk. The Helpdesk evaluates the final outcome of the activity and closes the ‘Maintenance Request’. A BPMN interaction diagram is provided in Figure 7.15 outlining the manual Reactive Maintenance process.

The ‘Asset Renewal’ AIR can be used as a basis for automated generation of reactive maintenance tasks. To demonstrate this, a Java client application was developed, which checks the 'Asset Renewal' AIR requirements for MEP assets, and generates a Renewal work order for assets where the 'Asset Renewal' parameter is critical. Figure 7.16 provides an UML sequence diagram that summarises this process. An example definition of a Reactive Maintenance work order is provided in Figure 7.17.

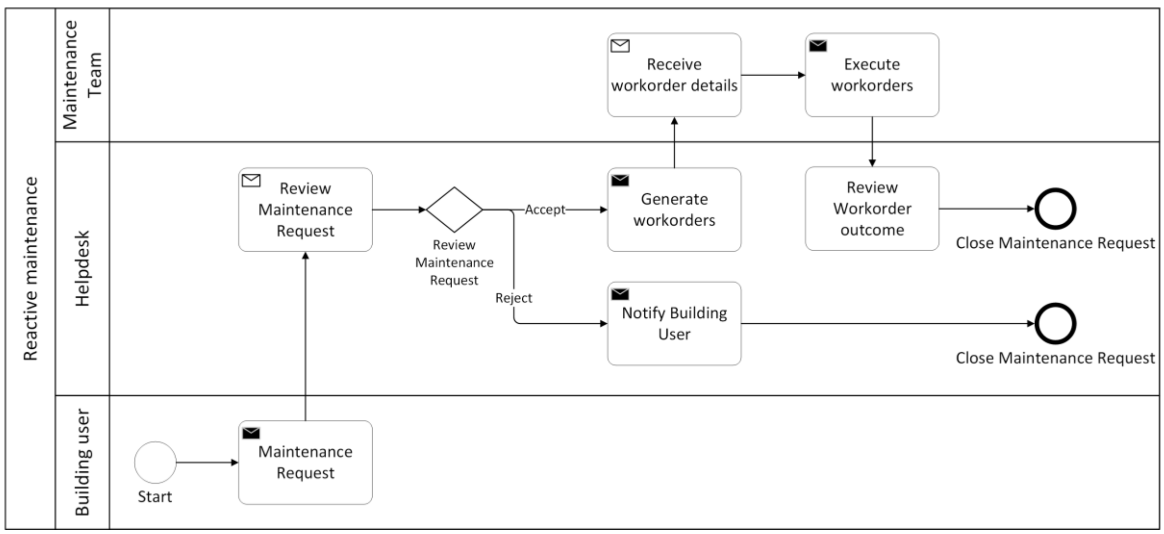

Figure 7.15 – Process map for the manual definition of a Reactive Maintenance request

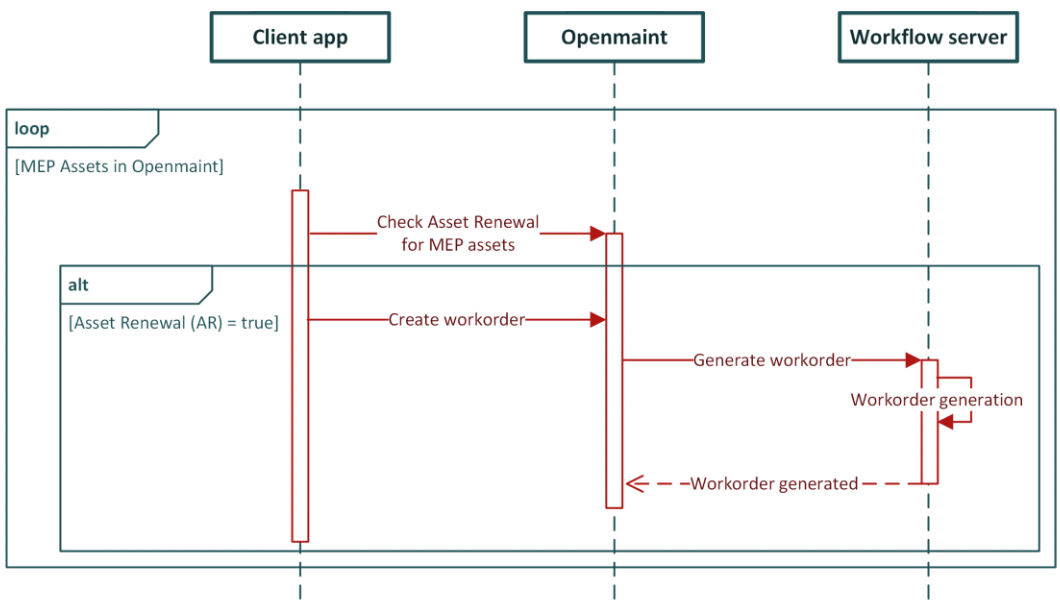

Figure 7.16 – UML sequence diagram for the automated definition of Reactive Maintenance tasks

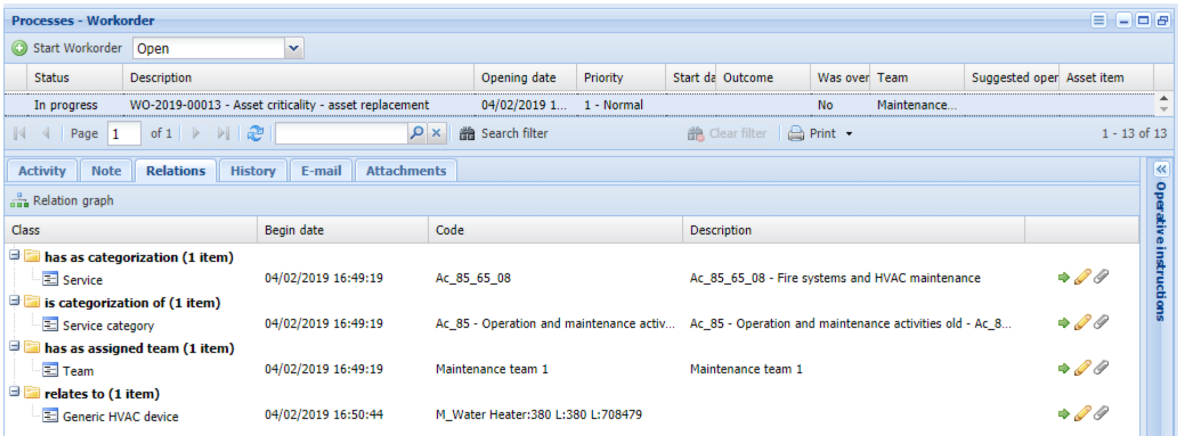

Figure 7.17 – Work order details for Reactive Maintenance task

7.2.3 AIM visualisation

Once the AIM for a building has been defined, it is possible to visualise its BIM model along with the associated FM, maintenance data and documentary metadata. Two approaches were explored in this research to provide the visualisation of AIMs. Openmaint includes an IFC viewer which can be used to interact with models hosted in a BIMserver instance, providing links to the various sources of AIM data stored in the underlying FM database and document repositories. Visualisation of AIMs using this method can be achieved after the AIM model has been defined and links have been established between the various sources of asset data. An example was provided earlier in Figure 7.8.

While it was possible to access the AIM data from Openmaint's IFC viewer, several issues were found. The main issue was that Openmaint failed to render a large number of IFC instances, which can be seen in Table 7.3 and Figure 7.18. Additionally, Openmaint's IFC viewer is not suitable to quickly locate assets and evaluate their accessibility onsite, which becomes apparent when considering the complexity of the 'Clinic' model. For this reason, the use of the Unity game engine is proposed as an alternative to provide the visualisation of the AIM. The use of a virtual environment developed using Unity also enables the evaluation of accessibility to carry out maintenance tasks.

Table 7.3 – Comparison of IFC entities rendered in Openmaint and Bimserver 1.5 for the Clinic MEP model

	Number of entities rendered	
IFC Entity	**bimvie.ws (Bimserver)**	**Openmaint**
IfcBuilding	1	1
IfcBuildingStorey	4	4
IfcSpace	526	526
IfcFlowSegment	5952	5952
IfcFlowFitting	6693	2231
IfcFlowController	173	118
IfcFlowTerminal	3053	34
IfcFlowMovingDevice	137	1
IfcEnergyConversionDevice	3	1

Figure 7.18 – Visual comparison of Clinic MEP model rendered in bimvie.ws Bimserver 1.5 plugin (left) and Openmaint (right)

The visualisation of the AIM within a virtual environment was performed according to the process described in Section 6.6. An empty scene was set up in Unity, where the AIM geometric model stored in BIMserver was imported through its web service interface.

Non-geometric data from IFC and COBie models is accessed in real time BIMservice's web service interface. To display on-screen information about the building, scripts were defined to react to users' interactions with the game objects. This functionality can be achieved through the definition of colliders and their association with the game objects (Figure 7.20). This allows the information to appear on-screen when the user walks through a Space defined in IFC, or when the user clicks on a game object that contains IFC data. For this purpose, it is important to identify the key assets (critical assets), which require the display of their data and information. In this research, the asset criticality methodology proposed in BS 8544:2013 is adopted for this purpose.

Documentary metadata and FM data is retrieved using the Socket.IO library. To achieve this, the Socket.IO extension for Unity was imported into the project and used to establish the connection between Unity and a Node.js server. The Node.js server then connects to Openmaint via its REST web service interface, and to Alfresco via CMIS ATOM web service interface to retrieve the AIM data.

The First Person Controller package was imported into the project and added to the scene to enable navigation through the model. When the game is initialised, information about existing work orders is retrieved from the CDE and displayed on screen. Figure 7.19 shows how maintenance data can be retrieved from the CDE and displayed in the virtual environment. By clicking on the game objects the user can access the asset's IFC, FM and CMIS metadata, and the attached documents through a link to the Alfresco repository. Figure 7.20 shows the collider definitions for the display of data. Figure 7.21 shows COBie space data displayed when the user walks through a space with a defined collider and the asset data that is retrieved from the CDE when the user clicks on a critical asset. The user can also open the related web page for a given 'Room' based on his current location.

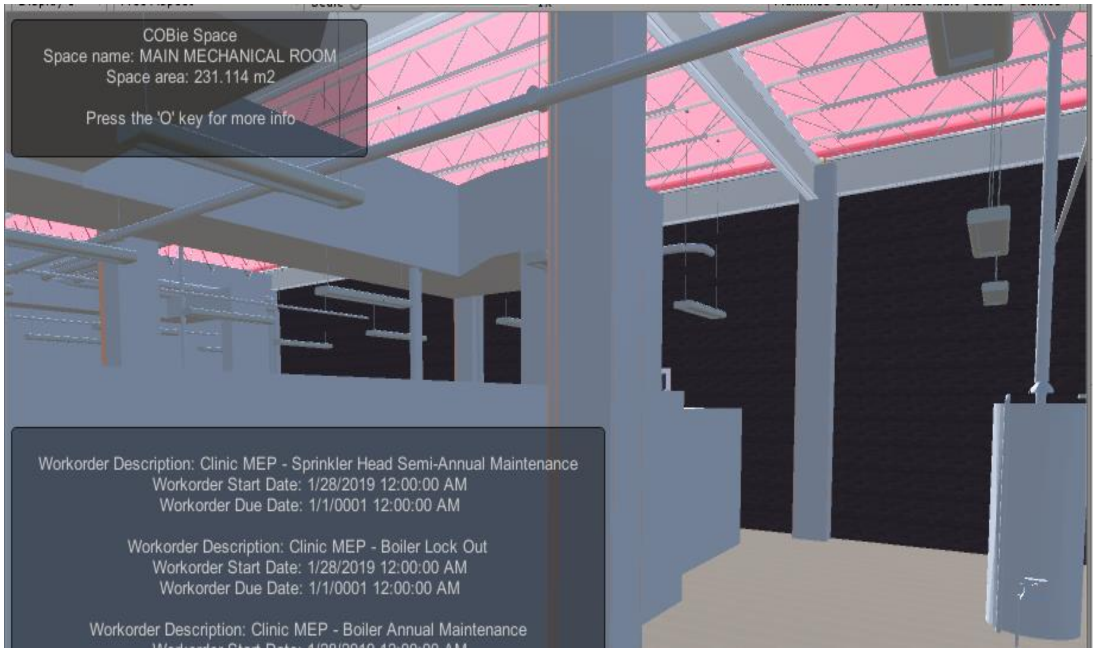

Figure 7.19 – Displaying maintenance work order data in Unity

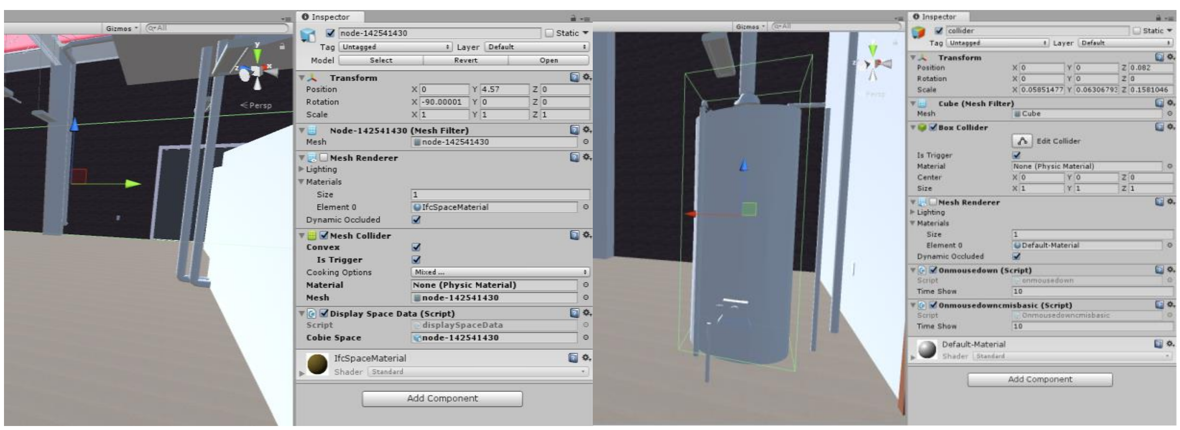

Figure 7.20 – Definition of colliders in Unity from IfcSpace entity to allow the display of space data (left) and COBie and documentary asset data (right)

Figure 7.21 – Displaying COBie space data and COBie documentary asset data in Unity

7.3 Validation

7.3.1 Methodology for validation

Validation in this research consisted in carrying out live demonstrations of the prototype CDE with a variety of industry and academic experts using the pilot studies developed in section 7.2 of this chapter, followed by discussions regarding the usability and functionalities of the proposed framework and prototype CDE. The objective of the validation activity is to provide the internal validity of the research, and elicit its theoretical contribution, thus complementing the technical contribution of the research, which resulted from the development of the demonstration activity.

The combined DSRM and GTM research design adopted in this study relies on the co-evolution of the requirements model and developed solution through an iterative process. During the validation stage, two rounds of unstructured interviews were undertaken to identify the positive and negative feedback, which is used to build upon the initially identified requirements for the proposed framework and CDE. One development iteration was undertaken considering feedback from the first round of interviews, to improve existing functionalities in the CDE, which are demonstrated in the final form of the pilot studies.

Data analysis is performed using the GTM, and considers the feedback from the interviews in the development of the updated requirements for the proposed framework and CDE. In this way, the data analysis approach is used to identify how the requirements have been fulfilled, and also to identify future research activities to be developed.

7.3.2 Data collection

To provide validation of the proposed framework and CDE, unstructured interviews were carried out with industry and academic experts. The selection process considered the common working area of the experts (i.e. IT in construction and related areas), and their relation with building/facility owners and facility managers, as well as the differences in their profiles. Unstructured open-ended interviews were chosen as the engagement method in order to guide the discussions according to each participant’s field of expertise and to obtain specific feedback on each of the framework and CDE functionalities. Two rounds of interviews were undertaken. All the interviews were conducted in person, except for the interviews with Experts G, N, and O, which were conducted via Skype. All experts were interviewed individually, except for experts J and K, and experts L and M, which were interviewed together at the respective companies’ premises. The interviews were captured using notes and audio recording with consent from the participants. The results from the interviews were transcribed and sent by email to the experts afterwards to ensure that they accurately captured the experts’ views. Table 7.4 provides details about the panel of experts. The list of questions used in these interviews was revised and improved using the experts’ input and the final list of questions used for the interviews is presented in Appendix B.

Table 7.4 – Profiles of interview participants

Expert Code	Profile	Company/Institution	Experience (Years)
First round of validation interviews			
E	Director in a BIM consultancy	BIM Strategy Ltd.	10
F	Software Developer and Completions Coordinator for Oil and Gas projects	Unasys Ltd.	12
G	Expert in Linked Data applications for BIM	Ghent University	12
H	Senior Lecturer in BIM & Energy Reduction in Built Environment	Teesside University	10
I	Lecturer in Construction management	Teesside University	8
Second round of validation interviews			
J	Director in an Engineering consultancy company	TGA	20
K	BIM manager/specialist	TGA	18
L	Director in a BIM consultancy	BIMacademy	10
M	Computer scientist	BIMacademy	3
N	BIM manager	WSP	13
O	Digital Construction Specialist	BAM Nuttall	12

7.3.3 Data analysis

The methodology adopted for data analysis of the interviews with experts is the same as in the Requirements Gathering chapter, and follows the Grounded Theory (GT) approach proposed by Strauss & Corbin, (1990). Interviews were transcribed and analysed using the Grounded Theory coding approach as its core process. Grounded Theory considers the coding process as a continuous, iterative process, which happens in parallel with theoretical sampling and data analysis. Therefore the analysis of the validation interviews builds upon the concepts identified during the Requirements Gathering research activity to provide the updated requirements model and validate the proposed framework and CDE. Figure 7.22 provides an overview of the data analysis results in the context of the sampling strategy framework defined for this research.

The coding process adopted to analyse the interview transcripts during the validation stage of the research consisted of the following stages:

- Open coding
- Axial coding
- Selective coding

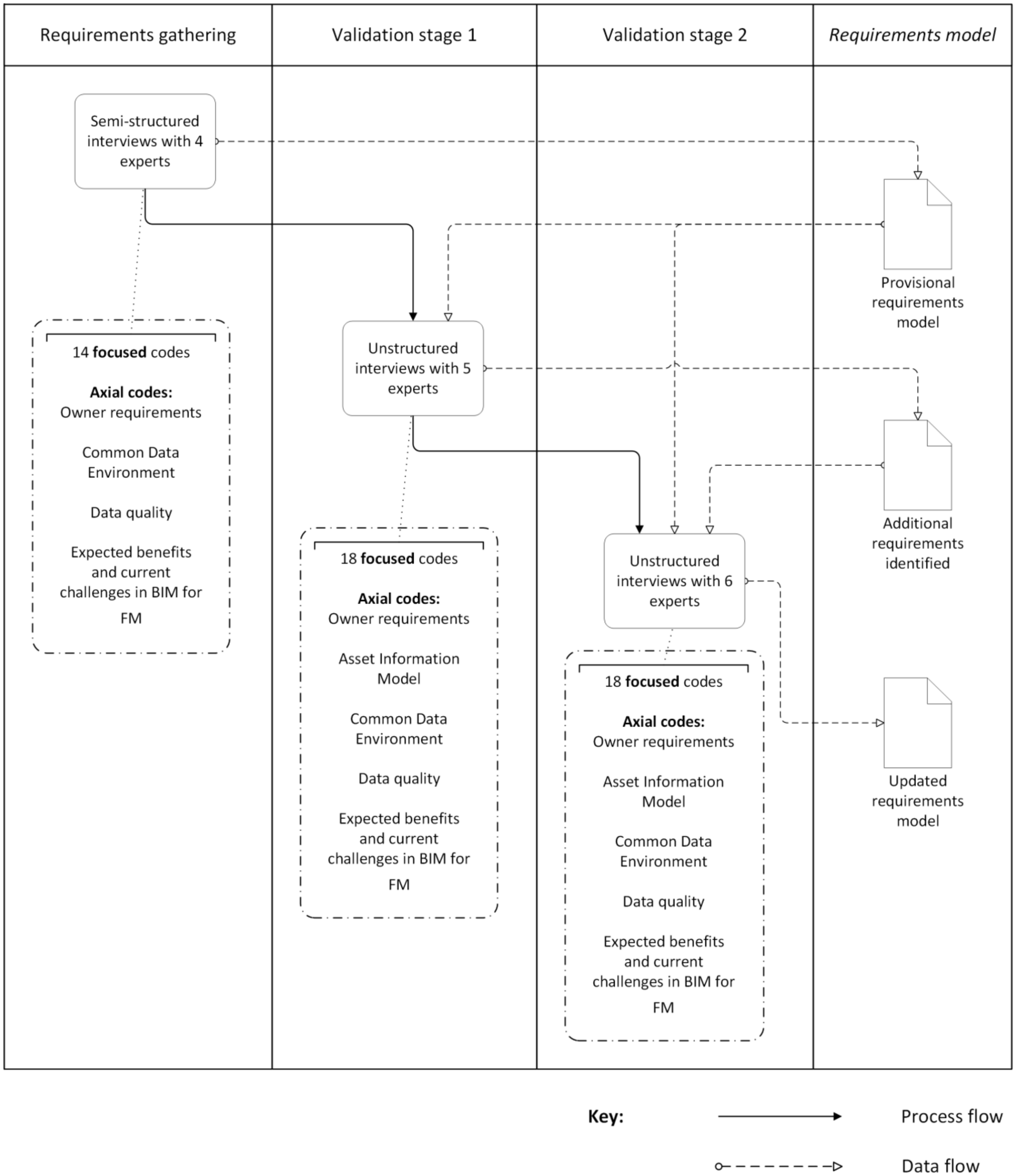

Figure 7.22 – Overview of data analysis results

7.3.3.1 Open coding

The open coding process followed the approach proposed by Charmaz, (2006) and was split into two stages: initial coding, and focused coding. The initial coding process revealed a total of 103 unique codes. The data analysis at this stage of the research builds upon the initial data analysis developed in the Requirements gathering stage. It was found that many of these codes were directly related to the previously identified codes, and that they could provide additional grounding to the focused codes identified previously. Table 7.5 provides the list of focused codes and their frequency, i.e., the relation between the focused codes and the number of supporting statements extracted from the primary data. Appendix F provides the list of initial, focused, and axial codes, as well as the relationships between the codes. Table 7.6 provides an example of the development of the focused code "Data quality" from the initial codes and supporting quotes.

Table 7.5 – Open coding – relation between initial codes and focused codes

Focused codes	***Expert codes***															***Frequency***
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	
AIM development					x			x		x	x	x	x	x	x	19
CDE requirements	x	x	x	x	x	x		x		x		x	x	x		50
Challenges in BIM for owners and FM	x	x	x		x					x	x			x	x	25
Challenges in BIM implementation														x	x	14
Challenges in the prototype CDE					x			x				x	x			7
Classification		x		x	x					x	x	x		x		16
Data integration strategy					x		x		x			x				26
Data integrity		x		x				x	x			x	x			13
Data management		x		x	x	x			x		x	x	x	x		21
Data quality		x		x	x					x		x	x			10
Expected benefits of BIM for FM		x	x	x										x		11
FM & maintenance requirements	x	x	x	x	x		x	x		x	x			x	x	36
Handover			x	x	x							x			x	8
Owner requirements definition	x	x	x	x	x	x	x			x	x	x		x	x	33
Owner requirements validation		x		x	x		x				x	x		x		10
Standards	x	x		x	x	x		x		x	x			x	x	23
Uses of BIM data in FM	x	x	x	x	x			x		x	x			x	x	29
Visualisation		x	x	x	x			x	x		x			x		16

Table 7.6 - Development of focused code "Data quality": Relation between focused code, initial codes, and supporting quotes

Expert	*Focused code*	*Supporting quote*
B	Issues with non-BIM data	"In Non-BIM projects data is handed over in the form of drawings, pdf files, DVDs with information collated about all the assets. The data is often hard to use or of no use to the FM team."
D	Quality of existing data	"If you look at the PAS 1192-2 model, on the right-hand side, before you look at the EIR is a bit that says "assess existing information". If you're doing a refurb project, you could have very good quality information, or very bad quality information. It's an important thing to think about."
D	Impact of accurate data in FM outsourcing	"If the data is open and transparent, it should mean that the client can say to the client provider "I can give you total transparency about the assets that are in the building", this should make the FM provider more comfortable in pricing their service in a way that they're not including lots of extras for risk, because they have access to the information."
E	Data quality issues in IFC viewer	"The (Openmaint IFC) viewer is not great but it's actually opened the "Duplex" model which a lot of viewers don't. (…) It does seem to have dropped off the IfcProxy elements but with a proper modelling standard you shouldn't use IfcProxy elements anyway. It's impossible to map the proxy class, since it's the left over elements, so what do you map it to? That's a challenge but probably not one that you need to take on. "
J	Importance of classification in data quality	"Classification is one of the key things to have that model developed properly. One of the key things that we find regularly is a lack of modelling standard, including classification. That is something that stops us doing what we need."
L	Impact of accurate data in building/ facility value	"If building owners own the data (…), more accurate data can be provided to new owners when change of ownership occurs. Currently the process consists in performing surveys every 5 years or so because there is no data, or the data available is inaccurate/wrong (e.g. mismatch when aligning plans and elevation drawings)."
M	Role of COBie in providing accurate data	"From my point of view I would put a lot of focus on the actual data side because that's generally how it's being used. I think at the minute the industry is sitting behind 3D models for FM. (…) Whereas with the data, the data has a serious use, and if you can get that data in and out really quick, that's when it becomes really valuable because that's where the industry is lagging. There's very few FM systems out there where you can just take some BIM data and just feed it straight into FM and start working really quick. That's where you'll start to see a lot of value. To be able to just have a COBie file and within a day being able to create work orders and process that information that's where there is a key. "

7.3.3.2 Axial coding

Axial coding was used to identify the focused codes which are relevant for the validation of the framework and prototype CDE. The axial coding process clarifies the relationships between the identified categories during the Focused Coding process, specifying the properties and dimensions of the categories. For this purpose, the analytical memo writing process is used to describe each of the identified categories based on primary data from the interviews and demonstration sessions. This process provides further justification for the choices of categories. The identified axial codes for the purpose of the validation of the framework and prototype CDE are:

- Owner requirements
- Asset Information Model
- Common Data Environment
- Data quality
- Expected benefits and current challenges in BIM for FM

As part of the axial code development process, a network diagram was developed to clarify the relations between the different identified categories. Figure 7.23 provides the network graph that was used as a basis to identify the various categories in the development of axial codes.

Tables 7.7 to 7.11 provide the relationships between the axial codes and identified categories from focused codes, as well as description of the categories resulting from the analytical memo writing process for each of the codes, based on the primary data from the interviews. Category descriptions refer to the experts through the expert codes defined in Table 7.4.

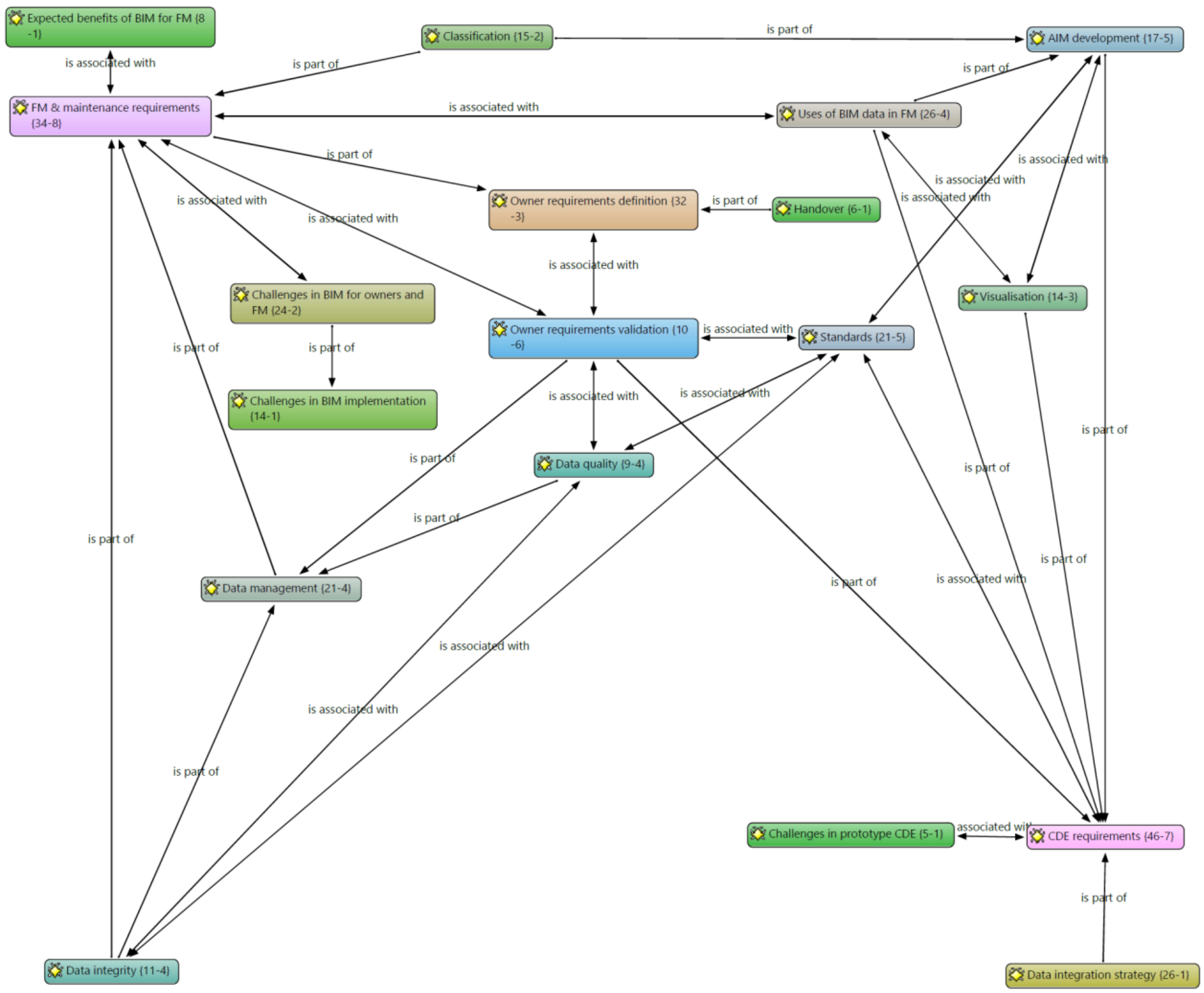

Figure 7.23 - Network diagram of Axial Code categories

Table 7.7 - Axial coding – Owner requirements

category	***description***
Classification	Classification is a key requirement for the development of the AIM (E, J, K, L, N). The adoption of classification systems provides a common content structure which is crucial in the development of e.g. asset registers. It also enables users to perform cross-estate queries (E). However, current classification systems are not finished, ambiguous, and hard to navigate, and as a result end up not being used (J, K). Another issue, which is highlighted in the example models, is the use of multiple classification systems, which hinders some of the benefits (e.g. cross-estate queries) (L, N). This highlights that the building owner should specify the classification system at the beginning of the project.
Handover	Despite the introduction of standards and approaches such as the PAS 1192 series and GSL/Soft Landings approach, the handover process still presents major challenges. As shown in the pilot projects, the use of COBie as a data transfer solution from BIM into FM could improve this process (E, L, O). However it is fundamental that the data required by the building owner has been specified in advance and that an auditing process throughout the design and construction phases is used to check if the data is being delivered according to the requirements (L, O).
FM & maintenance requirements	The presented models highlight the potential that well defined BIM data holds for an improved transition into the use phase of buildings, by partially automating the development of preventive and reactive maintenance tasks (E, H, J, K, N). This could be used in the future as a basis for providing more accurate budgeting for maintenance tasks (O). It is also important to specify the graphical requirements of the AIM, since not all the assets will need to be modelled to the same LOD. It is also important to consider how the proposed framework and CDE can be applied to existing buildings where there is no BIM data available (G, J, N). The proposed framework could be used to define the strategy for reality capture of existing buildings, including the specification of what elements and attributes to focus on (E, O).
Owner requirements definition	All the industry experts expressed their difficulties in obtaining requirements from building owners that can be checked against building data. The proposed method to structure requirements using IDM can be adopted by building owners if they have external help in defining the requirements. Expert E mentioned an ongoing project which is using a similar approach through the definition of a COBie requirements matrix as part of the EIR, which is being used to verify the compliance of the COBie data drops.
Owner requirements validation	Experts E, K, L, N, highlighted that the proposed validation methods could be used for the validation of building owner requirements defined in PDT and AIR templates to support the 'BIM Level 2' process. Experts G, E, highlighted the relevance of the proposed linked data approach for the validation of building owner and FM requirements, since it can be used to express the identified data sets, and other relevant data sets for FM and maintenance, as well as the definition of the rules based on the requirements defined through the IDM methodology.

Table 7.8 - Axial coding – Asset Information Model

category	***description***
AIM development	The development of the AIM and related processes of customising and maintaining it highlight its potential uses as a central part of the AM/FM strategy, as opposed as serving as a static reference only (E). This process shows how the building owner can define their AIM from a well-defined PIM according to the PAS standards (O). The proposed CDE improves one of the major issues during the handover stage, which is relating disparate sources of data, enabling their use as a basis for the definition of preventive and reactive maintenance tasks (E,H,O). The use of BIM information in the system, in particular object relations, provides owners and FM with a theoretical model of the building (E). In this instance, the use of a 3D model is not always essential, as these relations can be captured using formats such as COBie (J,K,L,M). The support for COBie data in the CDE, and the possibility to import the relations defined in the model is a key aspect of the prototype (J,K,L,M).
	Additional aspects that should be considered in the AIM include how onsite data can be captured into the AIM, as well as considering how the AIM data can be used for the planning of new projects (O, N)
Uses of BIM data in FM	The presented models highlight the potential that well-defined BIM data holds for an improved transition into the use phase of buildings, by partially automating the development of preventive and reactive maintenance tasks. This could be used in the future as a basis for providing more accurate budgeting for maintenance tasks (H, L, O). It is also important to specify the graphical requirements of the AIM, since not all the assets will need to be modelled to the same LOD. It is also important to consider how the proposed framework and CDE can be applied to existing buildings where there is no BIM data available. The proposed framework could be used to define the strategy for reality capture of existing buildings, including the specification of what elements and attributes to focus on (E).
Visualisation	One of the advantages of the proposed visualisation methodologies is the possibility of incorporating external sources of data (E,H,I). Expert H mentioned how the proposed visualisation method highlights one of the key capabilities of the proposed system, i.e. the ability to retrieve real time asset data from a building from multiple systems through different ‘client’ applications (web browser, and Unity application). Experts E, H, I, acknowledged the relevance of this approach since it supports the addition and removal of IT systems to the CDE to include additional data sources, depending on the building owner and FM requirements.
	The experts highlighted the limitations in the Openmaint IFC viewer, including missing objects (E), as well as lack of useful interaction with the model for maintenance planning. It was acknowledged that the alternative visualisation methodology using the Unity game engine addressed these issues. Proposed improvements included the addition of section boxes, and dedicated views for MEP assets (i.e. dedicated room/space views, views behind dropped ceilings) (H, K, N).

Table 7.9 – Axial coding – Common Data Environment (CDE)

category	*description*
CDE requirements	Development of AIM should support the integration of 3D model with documents and non-graphical data sources (E,F).
	Ability to manage all the buildings/facilities from the same user interface, and filter assets by various parameters, including physical (e.g. building, floor, space, system) and across the facility portfolio, using e.g. classification (E, H, F, L, M, N).
	Ability to define customised workflows to support various FM and maintenance processes (F).
	Customisation of the AIM schema and user interface for various types of users (i.e. building owner, building manager, FM, building users, designers, contractors, etc.)
	Ability to automatically import and define maintenance schedules using common classification standards such as Uniclass or SFG20 (L, M).
	Ability to use the CDE when there is no graphical model (e.g. for older facilities) through the definition of an AIM based on COBie (L, M).
	Ability to easily update and maintain the various sources of AIM data ensuring consistency of the data (L, M).
	Ability to locate 3D assets from a list of maintenance work orders defined in the FM system (L, M).
	Ability to share maintenance work order information with subcontractors and internal maintenance team onsite through the use of mobile devices (H, L, M, N).
	Currently, CAFM/IWMS and BMS are the most commonly used tools for building maintenance and FM. The selection of the CAFM/IWMS tool provider should be specified by the client at the start of the project in the EIR (A,B,C).
	The processes in the proposed framework can be applied to existing commercial tools, e.g. Ecodomus, to link COBie information and documents to 3D models (N).
Data integration strategy	The proposed data integration approach using SOA and Linked data sources is particularly relevant for the development and management of AIMs, since it allows the use of a variety of graphical and non-graphical data sources, which can change according to the owner's requirements (E, G, I, L). The prototype CDE shows how legacy FM tools can be integrated with BIM and other data sources, showing how existing tools can be used for web-based data exchanges using open standards in the context of FM and maintenance (E, G, I, L). The proposed approach can be improved in the future through the integration of semantic web data, which can be supported through the use of the triple store that is already used for the validation of requirements (E, G, I).
Challenges in prototype CDE	While the proposed validation methodology is an important contribution of the proposed framework to ensure the validity of the data, building owners and FMs cannot easily use the method since rule definition will need the input of technical experts (E, H, L).
	The proposed CDE uses the Openmaint GUI as its main graphical interface which is not very user friendly. BIM integration, in particularly the visualisation of IFC models is limited and makes it hard to interact with the 3D models (H, L, M).
	The proposed visualisation approach using the Unity game engine addresses the visualisation issues present in the Openmaint IFC viewer, however it introduces additional complexity in managing the system, particularly in ensuring that the sources of data used across the various components are reliable and up to date (H, L, M).

Table 7.10 – Axial coding – Data quality

category	***description***
Data integrity	Various experts highlighted some issues related to data integrity in the prototype CDE, in particular related to the process to import BIM data into the FM system (H, I, L, M). This is a key challenge in the industry, since this is typically how FM systems operate. The experts highlighted the need to ensure that the data in the FM system is aligned with the data in Bimserver to ensure its reliability. In the future this can be achieved by automating the import operation whenever there is a new revision of the model in Bimserver.
Data management	The experts highlighted the data management capabilities in the CDE, in particular the customisation and relations views which clarify the hierarchy of the AIM and how the various data sources are related. Some aspects that need further consideration include automating the proposed management of the AIM data throughout the lifecycle of the building, to ensure that the AIM provides an accurate digital representation of the building, and identifying who should be responsible for this task (I, E, F, K, L, M, N).
	Regarding the data import process during the development of the AIM, the experts highlighted that it will be challenging to manage the various data sources involved in the process, and ensure their integrity, and that this process could be streamlined using the proposed CDE as an example (L,M).
Data quality	The experts highlighted some of the issues related to IFC modelling requirements, in particular regarding the use of IfcProxy classes in the pilot models (E, J, M). Since an IfcProxy element can represent anything, it can't be used accurately when mapping elements to the FM database. This is an issue that occurs frequently in the industry since IFC is not always a key deliverable in projects, and the development process for IFC models is overlooked. This highlights the relevance of the proposed methodology for defining and validating requirements using IDM, since it can be applied in the verification of IFC modelling requirements during the project development stages.
	Experts J and M mentioned that frequently BIM models do not present sufficient detail to be used for operational tasks, and that an approach based on non-graphical data using COBie should be possible.
Standards	The prototype CDE showcases how an AIM can be developed through the integration of various sources of data using open standards. Expert N mentioned that there is a challenge to highlight the advantages of open standards to the industry, despite the fact that standards such as IFC and COBie can be used as legacy formats, as opposed to the use of proprietary models which might not be supported in 5 or 10 years.
	Various experts highlighted the relevance of using COBie as a basis to specify requirements and for the transfer of information into the FM system. COBie can provide a baseline structure for the AIM, and simplify the process of transitioning from PIM to AIM (E, J, K, N, O).
	Some experts mentioned that the PAS standards are referenced in projects, including the definition of EIR, but they end up not being used because of a lack of understanding about their purpose (E, N, O).

Table 7.11 – Axial coding – Expected benefits and current challenges in BIM for FM

category	***description***
Challenges in BIM implementation	Several challenges with the implementation of "BIM level 2" were raised by the experts, in particular, its implementation in civil engineering and infrastructure processes (N, O). The "BIM level 2" mandate is not sufficient to ensure the development of AIMs with synchronised data sources (E, N, O).
Expected benefits of BIM for FM	The ability to retrieve relevant information from the BIM model for FM and maintenance purposes was a key aspect in the development of BIM-FM case studies (B,C).
	BIM could be used to retrieve assets' location for maintenance planning purposes, and to provide access to the information needed for maintenance tasks, including statutory compliance (B,C,D).
	Access to accurate data could lead to a reduction of response times in maintenance tasks and could also enable strategic planning of maintenance tasks (B,C).
	BIM could be used as a basis for the integration of disparate systems and tools currently used by FM (B).
	Universities and health facilities can benefit the most from the implementation of BIM in FM since they typically deal with more than one FM provider, and need an efficient way to manage the data and transition of the data between providers (N).
Challenges in BIM for FM	In order to obtain BIM models that can be used by owners and FM, it is fundamental to specify data requirements in a structured format using e.g. EIR (C). This process should have the input from designers, contractors and FM (B,C).
	It is challenging to prove the benefits of BIM to the client and FM as well as supporting the client and FM with the technology, which might explain current lack of adoption by clients and FM (A, E).
	The need to change current processes in the FM and property management industry introduced by BIM is a barrier for clients and FM to use BIM (A,B).
	Integration of BIM data from new projects with existing non-BIM data from existing projects in the facility portfolio presents technology challenges (C).
	Making owner aware of the value of data ownership (B,C).
	Current practices in the industry regarding data availability, data quality and data management do not allow BIM to be implemented to its full potential from the client's perspective (A).
	Current contracts are not flexible enough for the use of distributed data sources during project development (E).

7.3.3.3 Selective coding: Updated framework and CDE requirements

The final coding process adopted in this research is Selective coding. The core category of the research has been identified as the AIM in the Requirements Gathering chapter. The demonstration sessions with experts and subsequent discussions provided the validation of the proposed framework and CDE, regarding its capabilities in the development, management and visualisation of AIMs, in the context of preventive and reactive maintenance tasks. Additionally, new requirements emerged from the discussions, which should be considered during further development iterations of the research.

The main requirements of the proposed framework and CDE have been fulfilled. The main areas that need improvement are concerned with the usability of the prototype CDE, as well as streamlining the processes of requirements definition and validation, and data management of the AIM. Several additional features were proposed during the latter stages of data capture, including improved integration between the AIM data and the visualisation of the 3D model, the development of a mobile interface to enable access to the CDE on site, and support of additional data sources.

Figure 7.24 provides a summary of the identified requirements for the proposed framework and CDE. The updated list of requirements for the proposed framework and CDE, and how they have been fulfilled at this stage, is provided in Tables 7.12 to 7.14.

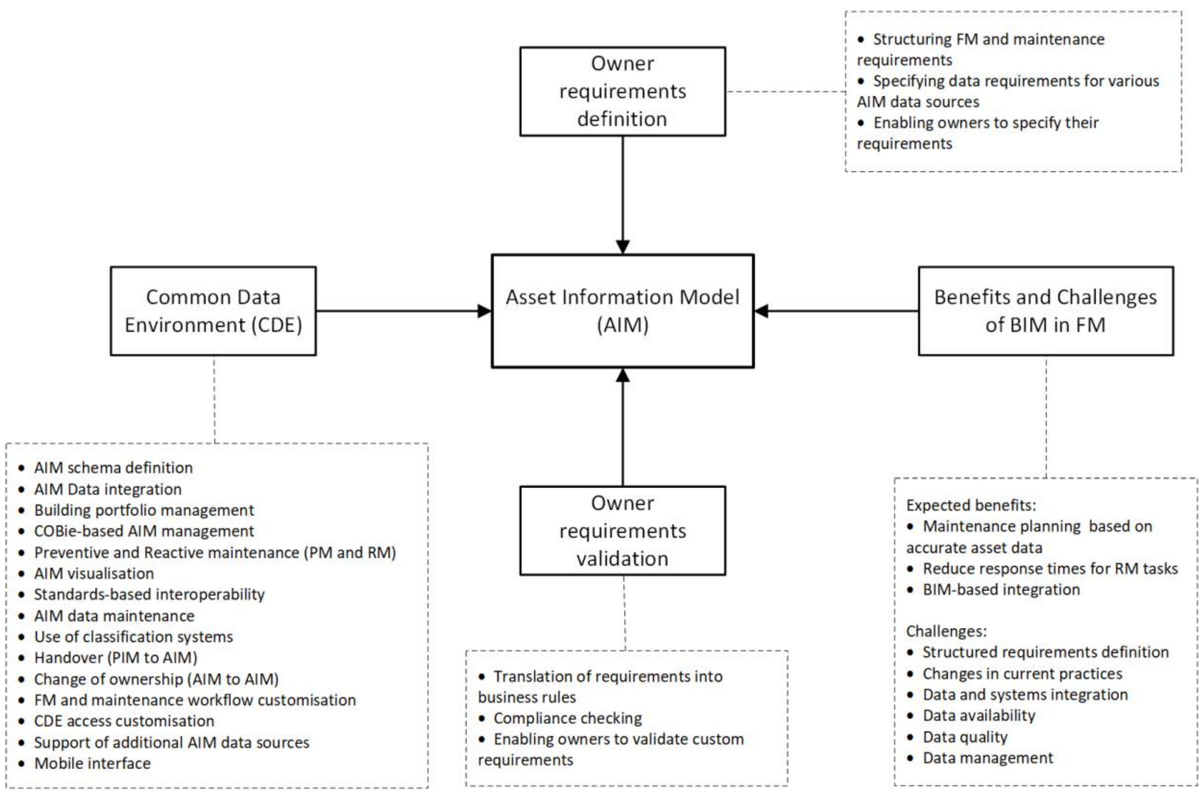

Figure 7.24 - Updated requirements model for the proposed framework and CDE

Table 7.12 – Validation of framework requirements: CDE & AIM

CDE & AIM requirements	***Achieved***	***Details***
AIM schema definition	Yes	It is possible to fully customise the AIM schema using the administration tools in Openmaint.
AIM data integration	Yes	Integration of graphical, non-graphical and documentary data sources for the AIM using IFC, COBie and CMIS standards.
Building portfolio management	Yes	The Openmaint FM software allows building owners and FMs to manage various buildings within the same interface.
COBie-based AIM management	Yes	It is possible to develop an AIM using the proposed CDE using solely non-graphical data and documents based on the COBie standard.
PM and RM tasks definition	Yes	The prototype CDE enables importing PM task information from COBie, and automatic definition of RM tasks based on key parameters (e.g. Asset Criticality Rating).
AIM visualisation: Interaction with 3D model to retrieve AIM data from various sources	Yes	Through the use of the Unity game engine it is possible to navigate and interact with the 3D model of the AIM, and retrieve its associated maintenance and other FM data.
AIM visualisation: Retrieve associated maintenance data from the FM environment	No	Improvements to the IFC viewer in Openmaint could be used to provide this functionality.
Standards-based Interoperability	Yes	Standards-based interoperability using IFC, COBie and CMIS.
AIM data maintenance	Partially	Currently, the processes for importing and managing the AIM data are not completely automated. These processes can be automated in the future, using the CDE's web service inventory to ensure that all the AIM data sources are relevant and up to date.
Use of classification systems	Yes	The CDE requires the use of classification systems for the definition of maintenance tasks. The owner will need to use the same classification system across his building portfolio to enable cross estate queries based on classification.
Handover (PIM to AIM)	Yes	Demonstrated through the development of the pilot studies.
Change of ownership (AIM to AIM)	No	Further developments are needed to support this process within the prototype CDE. The use of open standards and the proposed structured definition and validation of requirements will play a fundamental role in the process.
FM and maintenance workflow customisation	Partially	It is possible to define custom workflows using Openmaint however the owner will need technical support to achieve this.
CDE access customisation	Yes	Access rights to the AIM data can be configured for different users through the Openmaint administration tool.
Supporting additional AIM data sources	No	Semantic web data sources can be hosted and managed in the Fuseki triple store. Their integration along with other external data sources can be achieved using web services.
Mobile interface	No	Since the proposed CDE is composed of web-based systems, a dedicated mobile interface can be developed to achieve this requirement.

Table 7.13 – Validation of framework requirements: Owner requirements definition

Owner requirements definition	*Achieved*	*Details*
Structuring FM and maintenance requirements	Yes	The owner's requirements, including FM and maintenance requirements are structured using the IDM methodology
Specifying data requirements for various AIM data sources (graphical, non-graphical and documentary)	Yes	While the IDM methodology was defined to specify requirements using IFC, it can be used to specify requirements in other data sources, including future data sources to be identified (e.g. semantic web data sources)
Enabling building owners to specify their requirements	Partially	Building owners will need the input from an expert to translate their requirements into IDM, or other structured formats

Table 7.14 – Validation of framework requirements: Owner requirements validation

Owner requirements validation	*Achieved*	*Details*
Translation of Owner requirements into Business rules	Yes	The requirements defined using IDM are translated into SPARQL queries, which are used to validate the various sources of AIM data.
Compliance checking of owner requirements against the AIM data sources	Yes	A triple store is used to store the IFC and COBie data in RDF format. The Apache Jena framework is used to verify the owner's requirements against the AIM data sources stored across the CDE components, ensuring the validity of the AIM during its development and management processes.
Enabling building owners to validate their requirements	Partially	Further developments are needed to simplify, or abstract the query development and execution process for non-technical users.

7.4 Summary

This chapter presented the Demonstration and Validation of the research. The demonstration activity validates the technical feasibility of the proposed framework and CDE. The demonstration activity consisted of the development of pilot studies which demonstrated each of the proposed framework's capabilities in the development of AIMs:

- The structured definition and validation of various maintenance requirements, considering various asset data sources (graphical, non-graphical and documentary);
- The development of the AIM using various data sources, including BIM models and documents, and how they can be used to automate the definition of PM and RM maintenance tasks within a SOA-based FM environment;
- Visualisation of Asset Information Models and their associated data sources (graphical, non-graphical and documentary).

The pilot studies demonstrated the suitability of the proposed Semantic Web approach for the validation of different data sources against structured requirements, through the translation of structured requirements into business rules using SPARQL queries, and through the validation of different sources of data, including semantic (RDF) representations of IFC and COBie data, and external sources of data (i.e. documents).

The development of AIMs consisted in linking various sources of graphical, non-graphical and documentary asset data, and was used as a basis for the definition of preventive and reactive maintenance tasks. The development of the AIM demonstrated how IFC and COBie standards can be used to automatically import preventive maintenance data, and trigger reactive maintenance tasks in a FM environment.

The proposed method for the visualisation of the AIM enables maintenance personnel to locate assets and their associated data and documents before reaching the intervention space. This can also contribute to decrease the downtime of the building while work is being performed on assets. The interactive visualisation, including the possibility of retrieving up to date asset data from various distributed systems, provided an enhanced and tailored approach compared to those of design applications.

The validation activity consisted of demonstrating the prototype CDE to various industry experts, through the developed pilot studies, and collecting feedback using unstructured interviews. Qualitative data from the interviews was analysed using the GTM method, building upon the requirements identified initially, to provide an updated set of requirements for the proposed framework and CDE. In this process, the capabilities of the framework were validated against the various requirements, and additional requirements for future developments have been identified. The data analysis provides a qualitative validation of the proposed framework and CDE against the various requirements identified throughout the research, and provides the basis for the theoretical contribution of the research, by identifying a set of requirements for the identification and/or development of CDEs, and the development and management of AIMs.

The demonstration and validation activities provide key inputs for the evaluation of the research. The proposed demonstration activities can be applied to real tasks to evaluate the framework and CDE using quantitative metrics (e.g. using the SQuaRE methodology (ISO/IEC, 2011)). The proposed validation methodology can be applied to the evaluation of the framework and CDE in a real world context on the basis of qualitative data (e.g. using the GTM to analyse qualitative data from a case study).

8 CONCLUSIONS

8.1 Overview

Accurate and reliable data is fundamental for the management of buildings throughout their lifecycle. The development of the BIM methodology and associated technologies and standards presents a unique opportunity to efficiently manage building asset data exchanges throughout project development, handover, and during the use phase of buildings. Previous studies have highlighted various issues in the development and management of AIMs that are preventing the effective management of buildings using reliable data. This research addresses these challenges through the design of a framework and CDE for the development, management and visualisation of AIMs based on SOA and open standards.

This research combined the design science research methodology (DSRM) and the grounded theory method (GTM) in the development of the proposed framework and CDE. The research design followed the steps in the DSRM methodology, whereas the GTM was used at two key stages: during the requirements gathering stage, to identify requirements from the industry; and during the validation stage, where it was used to justify the theoretical contribution of the research, following the validation of the proposed framework and CDE.

A literature review was carried out to identify requirements for the development and management of AIMs. The results of the literature review were combined with the results from the initial requirements gathering activity, and several key requirements were identified for the development of the proposed framework and CDE.

The proposed framework describes the processes for the development and management of AIMs, including structured requirements definition, and the validation of a variety of graphical, non-graphical and documentary data sources to ensure the data quality of the AIM across data exchanges that occur during the building's lifecycle. A prototype CDE, consisting of several data repositories linked through web services was developed to demonstrate the framework's processes in the development, management and visualisation of AIMs.

As part of the DSRM methodology, a demonstration activity was carried out with the objective of providing the technical validation of the research. Demonstration consisted of the development of 3 pilot studies using existing building data sets of increasing complexity, which showcase the various steps in the development of the AIM, and how the AIM enables the definition of preventive and reactive maintenance tasks.

The validation of the research consisted in the demonstration of the pilot studies and subsequent discussions with academic and industry experts. The GTM was used at this stage to elicit the theoretical contribution of the research. Analysis of the primary data gathered in these sessions built upon the initially identified requirements, resulting in a comprehensive list of requirements for the development and management of AIMs, which was used to validate the proposed framework and CDE's capabilities. Results from the validation indicate that the key capabilities of the proposed framework and CDE have been achieved. The framework provides capabilities to ensure that owners and FMs can obtain and manage accurate data from various sources in the development of AIMs. The prototype CDE highlights how AIMs can be developed and managed using disparate data sources that can be integrated and synchronised via standard communication protocols such as web service interfaces. The proposed data integration approach can be adopted to achieve the integration of additional data sources for AIMs, according to the building owner's needs. The demonstration and validation activities provide key inputs for a future evaluation of the research in practice. Additional requirements for the development and management of AIMs were identified during the validation sessions, which should be considered in future work related to this research.

8.2 Discussion of findings against aim and objectives

This section summarises the conclusions of the research according to each of the research objectives, and demonstrates how the research has contributed to achieve the aim of the project.

8.2.1 Conclusions on objective 1

Investigate the state of the art and identify industry requirements for the development of Asset Information Models (AIMs):

The literature review and initial stakeholder interviews focused on identifying the requirements for the development and management of AIMs. Building owners and Facility Managers need accurate and reliable data about their assets in order to manage their buildings. The BIM methodology and associated standards and tools can be used to provide building data according to owner and FM requirements. However, key challenges remain in the transition of projects from handover into the operations stage, and also in the transition of building owners' existing assets into BIM-based AIMs. In recent years, an increasing number of standards and specifications have been developed in order to support owners and FM in the specification of their asset data requirements. The implementation of specifications such as the PAS 1192 series is expected to streamline the delivery of asset information and ensure that asset data is according to the owner's requirements. The increasing adoption of open standards by the AEC industry (i.e. IFC and COBie) and the use of modelling standards and classification systems are expected to facilitate the validation of asset data against building owner requirements.

The literature review revealed an increasing research interest in adoption of BIM technologies for FM, however the use of open standards is still limited, especially for non-graphical and documentary asset data sources. The literature review and analysis of the interviews highlighted key requirements for the proposed framework and CDE, namely, the importance in the definition of structured, verifiable owner requirements for asset data, as well as for the IT systems that will be used for the development and management of AIMs.

8.2.2 Conclusions on objective 2

Identify existing standards to support the information requirements of AIMs:

One of the key requirements to obtain accurate data in the development of AIMs is the definition of structured and verifiable asset data requirements. It has been recognised that existing owner guides and specifications have not adequately addressed the specific data requirements of building owners and facility managers (Mayo & Issa, 2014; Cavka *et al.*, 2017). In this research, the IDM methodology was adopted for the structured definition of Asset Information Requirements. Despite IDM's limitations, it was concluded that it is adequate for the development of structured maintenance and FM requirements, since it can be used to specify data requirements for any data standard.

The IFC, COBie and CMIS standards were identified to support the graphical, non-graphical and documentary data requirements of AIMs. The standards can support custom asset data requirements, which can be used to specify document metadata requirements, and preventive maintenance requirements, and can be used at handover as an input for the AIM. IFC, COBie and CMIS enable interoperability between the different systems used in the development and management of AIMs, and are a key requirement in the identification, or development of a suitable CDE which can be used for the development and management of AIMs.

8.2.3 Conclusions on objective 3

Identify suitable methods for the validation of AIM data sources against owner's requirements:

Several tools, techniques and methods for automated compliance checking were reviewed in Chapter 3. The majority of existing approaches for the validation of building data have focused on checking the compliance of BIM models against design requirements and regulations during the design stages of building projects. Studies focused on the validation of maintenance and FM requirements for the use phase of buildings, considering various sources of asset data are lacking. In this research, several methods were identified that could be applied for the definition and validation of maintenance and FM requirements against graphical, non-graphical and documentary asset data sources.

The use of Semantic Web tools and standards was identified as the most adequate methodology to achieve this objective. Semantic Web tools and standards allow the translation of structured requirements defined using the IDM methodology into business rules, and the validation of various sources of data, including semantic (RDF) representations of IFC and COBie data, and external sources of data (i.e. documents).

8.2.4 Conclusions on objective 4

Development of a framework to support the validation of AIM data sources, and the development, management and visualisation of AIMs:

In Chapter 5, a framework was proposed for the development and management of AIMs. The requirements for the development of the framework were identified through the literature review and requirements gathering activities, resulting in a provisional requirements model. The proposed framework enables:

- The definition of owner’s requirements in the form of structured AIR;
- The validation of AIM data sources against the AIR;
- The development and management of AIMs through the development of a SOA-based CDE;
- The integrated and interactive visualisation of the AIM including graphical, non-graphical and documentary data sources stored in disparate sources, using open standards and open technologies.

The proposed framework ensures that the building owner can obtain and use AIMs that are adequate for the use phase of buildings (e.g. maintenance tasks). To this end, a CDE is proposed based on open standards and open SOA enabled tools for the development and management of AIMs. The definition of AIR requires input from the design team and facility managers. The AIR approved by the client guides the validation of data drops and deliverables throughout building project development, and for the development and management of the AIM during the use phase of buildings. The framework combines the use of existing methodologies and open standards - IDM, IFC, COBie and CMIS. This approach enables the reuse of the defined processes and their business rules within the requirements validation processes against AIM data sources.

8.2.5 Conclusions on objective 5

Development of a prototype CDE to support the validation of AIM data sources, and the development, management and visualisation of AIMs:

To demonstrate the applicability of the proposed framework, a prototype CDE was developed based on PAS 1192 and ISO 19650 principles. The requirements for the development of the CDE were identified from the provisional requirements model, established as a result of the requirements gathering activity. A prototype CDE results of the integration of existing SOA-enabled open source tools that are used to manage the various data sources of the AIM, including their validation against structured AIR.

The development of the CDE consisted of a series of tasks:

- The definition of the CDE architecture;
- The definition of the CDE technical infrastructure;
- The definition of a data schema for the AIM according to the identified data standards and specific owner's data requirements;
- Development of the AIM through the integration of the various data sources;
- Visualisation of AIM data to support FM and maintenance tasks.

8.2.6 Conclusions on objective 6

Demonstration of the proposed framework and CDE through the development of pilot studies:

This research objective is concerned with the demonstration activity of the research. Demonstration of the proposed framework and CDE consisted in the development of AIMs for several pilot studies. The pilot studies demonstrated the framework's processes in the validation, development and visualisation of the AIM, considering its various data sources, and also demonstrated how the proposed CDE can be used for the management and visualisation of the AIM to support PM and RM tasks. The demonstration activity validates the technical feasibility of the proposed framework and CDE.

The validation of AIM data was successfully demonstrated within the AIM development process, using the proposed Semantic Web approach for the validation of graphical, non-graphical and documentary data sources as specified in the AIRs. The proposed approach enabled the translation of structured requirements into business rules to achieve the validation of different sources of data, including semantic (RDF) representations of IFC and COBie data, and external sources of data (i.e. documents).

The prototype CDE demonstrated the integration of graphical, non-graphical and documentary asset data, using the IFC, COBie, and CMIS standards in the development of AIMs. The process for the development of the AIM demonstrated the use of standards in the automated definition of preventive and reactive maintenance tasks within the CDE.

The visualisation of the AIM, including its associated non-graphical and documentary data was also successfully performed in a virtual environment using the Unity game engine. The virtual environment provided visualisation of the geometric objects and real-time display of data (non-graphical and documentary) required for the critical assets. Users can interactively navigate the model and access the required information and data about each critical asset.

8.2.7 Conclusions on objective 7

Validation of the proposed framework and CDE through the demonstration of pilot studies to academic and industry experts:

The validation activity consisted of demonstrating the prototype CDE in a series of sessions with industry experts, and collecting feedback using unstructured interviews. Qualitative data from the interviews was analysed using the GTM method, and builds upon the provisional requirements model developed during the requirements gathering stage, to provide an updated set of requirements for the proposed framework and CDE. The experts highlighted the use of standards in the proposed SOA-based approach, due to its flexibility and scalability, which will enable the integration of additional data sources for the AIM.

The data analysis provided a qualitative validation of the proposed framework and CDE, and revealed the theoretical contribution of the research, by identifying a set of requirements for the identification or development of CDEs that will enable the development and management of AIMs in the context of "BIM level 3", i.e. using web-stored integrated electronic information with fully automated connectivity.

The demonstration and validation activities provide important inputs for the evaluation of the proposed framework and CDE. In future work the evaluation of the research will focus on the utility, quality and efficacy of the proposed framework and CDE in practice (Section 8.5.1).

8.3 Contribution to knowledge

This research provides theoretical and technical contributions towards understanding the requirements for the development of AIMs, which can be used as a reliable basis for the management of buildings, in particular regarding operations and maintenance (O&M).

Despite an increasing focus on the use of BIM and other digital technologies for the management of buildings during their use, the requirements for the development and management of AIMs constitute a critical gap in the literature. The adoption of the combined methodological approach in this research provided the basis for its theoretical and technical contributions. The application of the GTM to the requirements gathering stage and validation activities in the research design complements DSRM's iterative approach, providing the necessary theoretical justification for the proposed design, throughout the various steps of problem definition, artefact development, demonstration and validation.

From a theoretical point of view, this research contributed to the existing knowledge by: a) identifying a set of key requirements for the development and management of AIMs that can be used as a basis for FM and maintenance functions, and b) through the design of a framework for the development and management of AIMs considering the identified requirements. Additionally, the research contributes to the CDE process defined in PAS 1192, by identifying requirements that need to be considered for its implementation using web-stored integrated electronic information with fully automated connectivity, i.e. "BIM level 3".

The prototype CDE for the development and management of AIMs, which provides the instantiation of the proposed framework, constitutes the technical contribution of this research. By combining the use of open standards, standard data transfer and communication protocols, and existing tools, the prototype CDE demonstrated the development process of AIMs which can be used as a basis for the definition and execution of preventive and reactive maintenance tasks. Additionally, the consideration of SOA and linked data technologies in the development of the CDE provides flexibility and scalability, which can be used to incorporate the additional requirements that were identified during the validation activities of the research.

The findings from this research contribute to the field of IS research in AEC/FM. The standards-based approach adopted in the proposed framework and CDE contributes to research in technology and standards for digital representation of buildings, and highlights the importance of the use of standards for the representation and data management of AIMs. The proposed approach for the structured definition and validation of structured and unstructured maintenance requirements provides an important contribution to the field of compliance checking of digital building data. It is expected that evaluating the developed artefacts (i.e. framework and CDE) in an organisational context according to the proposed evaluation methodology (Section 8.5.1) will highlight the contribution of this research to the field of management information systems.

8.4 Limitations of the research

The following limitations of this research should be highlighted, and considered in future developments related to this research.

The main limitations regarding the research design are: a) data gathering activities focused on experts input instead of users input, and b) the framework and CDE were not evaluated in practice. At this stage, validation of the design of the proposed framework and CDE was achieved by conducting and analysing interviews with experts according to the GTM, and through the demonstration activities. This presents limitations in internal validity of the research, since the validation was not undertaken within an actual work activity environment with actual users of the framework and CDE. External validity was addressed through the demonstration activity where three pilot studies of increasing technical complexity were developed. The results from the demonstration activity are not statistically significant, and present a threat to the external validity of the research. Evaluation of the design and use of artefacts in their real use context is a key requirement to rigorously proof their relevance for practice and it can address these limitations.

Future research should address these limitations by conducting the evaluation of the proposed framework and CDE in a real use context in order to evaluate the impact in real projects and organisations. The generalisability and repeatability of the research can be improved by carrying out prototyping activities using real project data, while the reliability of the research can be improved via data triangulation (by complementing the data captured from experts with data captured from users), and via methodological triangulation (through the combination of artificial and naturalistic evaluation methods). Considering the organisational context should also address the data gathering limitations in this research and improve the quality and reliability of qualitative data, by complementing experts input obtained throughout the requirements gathering and validation activities with input from actual users of the developed artefacts. Section 8.5.1 provides an outline for future evaluation activities.

There are some technical limitations which should be addressed in the future.

This research focuses on the use of automated methods for the validation of structured requirements against data models. One key requisite for data validation in this research is that requirements must be provided in a structured format in order to be used for compliance checking procedures. Translation of requirements into a structured format that can be used for rule checking is a challenging process that currently requires the input of experts. Additional research should focus on how to enable building owners and FMs to carry out this process independently. Another technical limitation in the development of the prototype CDE was using BIMserver and the Fuseki triple store to host IFC/COBie data. This brings additional challenges in data management and data integrity, to ensure that BIM data in both systems is synchronised. In the future this could be improved by relying on the triple store to manage BIM data within the CDE and provide the integration of BIM data with the other sources of AIM data using semantic web standards. In order to achieve this, a detailed evaluation of the model management capabilities of the triple store must be carried out.

8.5 Recommendations for future work

Several limitations and additional requirements for this research have been identified as a result of the validation of the research. This research identified several requirements for the development of CDEs and AIMs, focusing on the handover and PM and RM tasks definition processes. The importance of the "change of ownership" (AIM to AIM) and "major works" (AIM to PIM) processes outlined in PAS 1192-3 was reiterated by several experts during the validation activity. The proposed framework and CDE should be further developed considering how to support these key processes. This could be achieved by complementing the proposed research design with the development of representative case studies with the industry, in order to identify the CDE and AIM requirements for their development in the context of "BIM level 3", i.e. using web-stored integrated electronic information with fully automated connectivity.

One of the key contributions of this research was demonstrating how various sources of data, linked through the use of web services, can be used in the operational phase of buildings. Future studies should consider the integration of additional external data sources, such as data related to energy management and other FM application areas, detailing the requirements and validation methods to support the handover (PIM to AIM), change of ownership (AIM to AIM) and major works (AIM to PIM) processes. As an improvement to the proposed SOA-based CDE, future developments should also explore the integration of BIM data and external asset data sources using Semantic web standards and Linked Data in the development of the AIM. The use of Semantic Web standards and tools was already demonstrated to be a valid approach for the validation of a variety of data sources against structured building owner and FM requirements. Linked Data approaches should facilitate the integration of a variety of AIM data sources that are needed for different purposes during the use phase of buildings.

8.5.1 Evaluation

One of the limitations of this research which warrants a closer look is its lack of evaluation in practice. While the validation of the design of the proposed framework and CDE was successfully achieved by carrying out the demonstration and validation activities, conducting evaluation is fundamental for organisations to assess the design and suitability of the developed artefacts, as well as their performance in a real use context (Hevner *et al.*, 2004; Venable, 2006; Sonnenberg & Brocke, 2012). In this section, an evaluation framework employing both artificial and naturalistic evaluation methods is proposed to conduct ex ante and ex post evaluation activities of the research (i.e. before and after its implementation in a real world context).

The proposed evaluation activities are: prototyping (using test data, as well as real project data), and conducting a case study. Prototyping can be used as an ex ante evaluation method prior to the implementation of the proposed framework and CDE to assess its usefulness for the organisation. The use of prototyping is also proposed as an ex post evaluation activity to demonstrate how the proposed framework and CDE can be used to perform real tasks, in this case the development of the AIM, and the execution of PM & RM tasks based on AIM data.

The case study aims to demonstrate the implementation of the proposed framework and CDE in a real organisation (e.g. Housing association). Data collection methods for the case study include the AIM data sources which are used for the development of the AIM and can be evaluated for completion & accuracy using the proposed AIM validation methodology, and interviews, which can be analysed using the GTM, building upon the analysis carried out in this research. Case study findings will also contribute to the updated requirements model developed as a result of the Validation activity (Section 7.3). Figure 8.1 outlines the proposed evaluation activities in the context of the research design.

Following Hevner *et al.*'s (2004) guidelines for design evaluation, several activities that can be used to evaluate the utility, quality and efficacy of proposed framework and CDE are proposed in Table 8.1. The activities focus on the development of the CDE, AIM data validity (specifically regarding PM data requirements), and potential time and cost savings in maintenance activities achieved from the implementation of the proposed framework and CDE. Several metrics defined in the SQuaRE methodology (i.e. data quality (ISO, 2015a), system and software product quality (ISO, 2016b), and quality in use (ISO, 2016a)) have been identified to assess the framework and CDE based on the proposed activities (ISO/IEC, 2011). The complete list of identified metrics is provided in Appendix G.

The combination of artificial and naturalistic methods in evaluation can account for the weaknesses in each of these methods while ensuring the reliability of the research via data and methodological triangulation. While artificial methods can provide a lower effort in demonstrating the suitability of an artefact, naturalistic evaluation is fundamental to demonstrate the suitability of artefacts in a real world context (Venable, 2006). Conducting a case study can provide the evaluation of the proposed framework and CDE in a real world context and improve the internal validity of results at the expense of generalisability. On the other hand, the use of quantitative metrics for evaluation improves the external validity of the research, and can be used as a basis to compare the performance of the proposed framework and CDE to other existing systems, both prior to and after their implementation by an organisation.

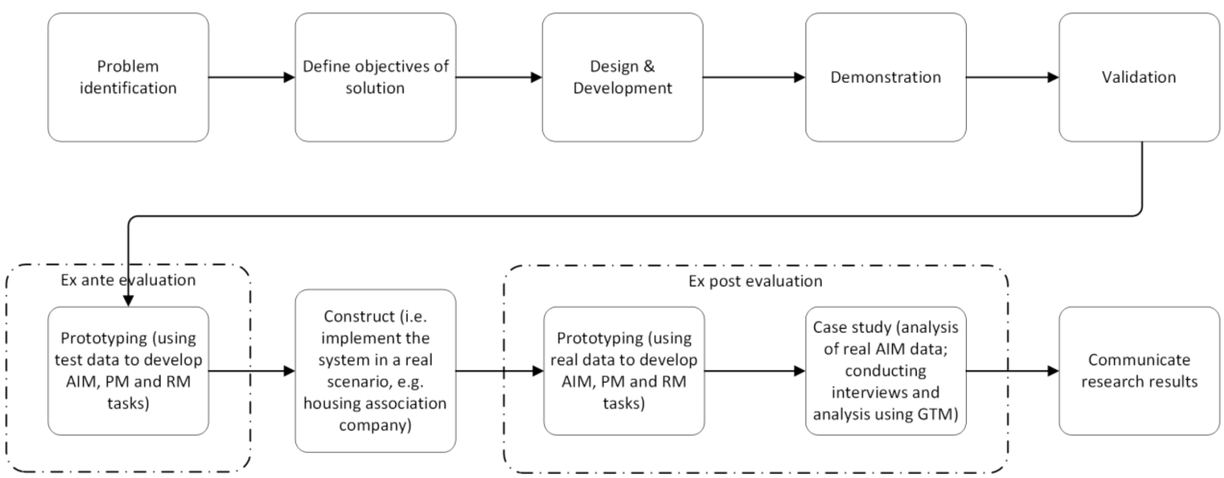

Figure 8.1 - Ex ante and ex post evaluation in the context of the research design

Table 8.1 – Activities and quantitative metrics proposed for future evaluation

Activity	*Description*	*Metrics*
Evaluation of the CDE	Evaluation of the prototype CDE using SQuaRE metrics for Software product quality and Data quality.	Software product quality (Table 10.22): • Functional suitability • Functional appropriateness • Availability Data quality (Table 10.24): • Accessibility • Availability • Recoverability
PM data validation in AIM development	Measure completeness in PM work order data based on accurate and up to date AIM using the AIM requirements definition and validation methodology.	Data quality (Table 10.23): • Accuracy • Completeness • Consistency
Time difference in PM task execution	Calculate time savings by performing PM tasks based on accurate and up to date AIM developed according to the proposed framework and comparing to historical records.	Quality in use (Table 10.21): • Effectiveness • Efficiency
Time difference in RM task response	Calculate time savings resulting from use of virtual environment to eliminate additional trips to the same location to carry out reactive maintenance work orders. Perform comparison with historical RM task response data.	Quality in use (Table 10.21): • Effectiveness • Efficiency
Potential Cost savings	Determine reduction in O&M contracting costs resulting from accurate and up to date equipment inventory in the AIM, on a yearly basis.	Quality in use (Table 10.21): • Economic risks mitigation

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10 APPENDICES

Appendix A – Questionnaire used for Requirements Gathering

The following list of questions was developed and used in the semi-structured interviews as part of the requirements gathering activity (Chapter 4).

General BIM/FM

1. How do you think BIM could improve building maintenance tasks (specific aspects of BIM)?
2. To what extent can existing FM data support new projects / repair and refurbishing projects? How can BIM support this?
3. How can owners account for the lifecycle of the building (e.g. 50 years) when defining Service Level Agreements in FM contracts when these are typically fixed term for the FM service provider (e.g. 5/10 years)?
4. How to deal with change of ownership during the life of the building in the definition of SLAs?
5. To what extent can BIM/ digital asset data help mitigate issues between owner (client) and FM provider?

Maintenance data requirements

6. What are the critical criteria and maintenance management standards (e.g. statutory maintenance, H&S, accessibility etc.) considered when planning maintenance?
7. Is Information/Data needed for planning of maintenance tasks typically available? How can this information can be obtained and organized/kept up to date?

8. Is there data/information needed for maintenance that is currently not used/ not available but could be supported by a BIM / FM database?

Data Verification/Validation

9. How is data handed over in non-BIM vs. BIM projects?
10. How is data currently verified / validated?

IT support for building maintenance

11. Which are the most currently used IT tools in building maintenance and current methods / procedures for using these tools (e.g. templates, classification, standards, etc.)?
12. What are needed functionalities lacking in current building maintenance tools?

Appendix B – Questionnaire used for validation

The following list of questions was developed and used in the unstructured open ended interviews as part of the validation activity (Chapter 7).

- What are your experiences involving BIM projects, and what were the main challenges associated with them?
- What are the main challenges that you encounter when working with building owners and FMs?
- Do you use classification systems in your organisation? What challenges have you encountered regarding the use of classification systems?
- Do you use open BIM standards (e.g. IFC, COBie) in your organisation? What challenges have you come across using these standards?
- What is your experience using PAS 1192 standards, in particular for the definition and use of EIR and AIR?
- What are the main challenges in the implementation of PAS 1192 in your experience?
- What are the key requirements to enable BIM implementation by building owners and FMs?
- What are the main challenges for BIM implementation by building owners and FMs?
- What are the main issues with current BIM-FM integration and to what extent does the proposed CDE address them?
- How can we improve the processes for capturing and validating the building owner requirements in the development of AIMs?
- What are needed functionalities currently lacking in the prototype CDE?
- How can the proposed visualisation methodology be improved?
- How can the reliability of the data in the proposed CDE be improved?
- What additional processes does the framework need to consider to support the needs of building owners and FMs?

Appendix C – Evaluation of COBie and IFC support for asset registers

One of the key requirements for facility information management is the development of an asset register (BSI, 2012b). An asset register is a "collection of records holding information about facility assets in terms of their manufacturer, vendor, make, model, specifications, date of acquisition, initial cost, maintenance cost and requirements, accumulated depreciation and written-down value" (BSI, 2012b). In Table 10.1 an analysis was performed to evaluate the support of asset register information requirements defined in BS 8210 (BSI, 2012a) by IFC/COBie data entities, considering the project phase at which such data becomes available.

The FM data and information requirements of asset registers are based on established standards and were extracted from Section 9.7.4 of BS 8210 (BSI, 2012a). The entities utilised for IFC4 and COBie 2.4 were adopted from the building SMART IFC 4 specifications (buildingSMART, 2019b). The project phases, at which such data and information requirements become available, were adopted from the definition of COBie Data Drops of the UK Cabinet Office's COBie Data Drops document (Cabinet Office, 2012).

Analysis

Table 10.1 shows that several of these requirements are not directly supported in IFC 4 (5 out of 22) and COBie 2.4 (6 out of 22). Most of the non-supported fields are part of data drops generated during for O&M phase of buildings. Gaps that were identified in this analysis include capital information such as costs breakdown, written down value of assets, accumulated depreciation, and sources of components and spare parts. On the other hand, some of the information requirements for O&M can be represented in the COBie.Job worksheet (COBie 2.4), which identifies O&M tasks that need to be carried out to run the facility efficiently, or in IFC 4 through the corresponding IFC entity IfcTask (buildingSMART, 2019b). Such information includes: requirements for access equipment, permit-to-work requirements, replacement cycle, servicing requirements and other maintenance requirements.

These results are in line with related research carried out in this area. Talamo & Bonanomi (2015) analysed the COBie schema against the AIR – as proposed in PAS 1192-3:2014 - and concluded that COBie can fulfil most of these data requirements, although some limitations were found regarding data in the commercial category, including the lack of support of data about the condition and performance targets of assets, key performance indicators (KPIs), and criteria for non-conformance of assets. An analysis of the support of the IFC schema for information and data requirements for the O&M phase also revealed that the current IFC standard does not include all the required properties and relations related to the O&M phase (Motamedi *et al.*, 2014). Examples of such properties include: operational statuses (e.g., decommissioned, broken, inactive), downtime information, failure classes, and physical / operational conditions. While it is possible to include additional information in IFC and COBie files using custom property sets, this could result in models that are heavy, inefficient, and difficult to use. It is therefore necessary to identify and / or define complementary schemas and validation methodologies that are suitable to support the AIM data that is out of the scope of IFC and COBie.

Despite the limitations found in this analysis and related work, it should be noted that in the case of IFC, and due to the flexibility of its schema, FM software providers might be able to indirectly support the non-supported information requirements through *ad-hoc* software functionalities. Also, the possibility of including additional information in IFC and COBie files, using custom property sets, is a valid proposal since it preserves compliance with defined model views, while strengthening the role of these schemas in fulfilling O&M information requirements.

Table 10.1 – Evaluation of IFC and COBie support for asset register requirements as defined in BS 8210 (BSI, 2012a; buildingSMART, 2019b)

Asset register information requirements (BSI, 2012)	*IFC 4*	*COBie 2.4 (Spreadsheet xml)*	*COBie Data drop*
a) identification number or unique reference for the asset;	SerialNumber (Pset_ManufacturerOccurrence)	Component sheet - SerialNumber	4 – as-built
	BarCode (Pset_ManufacturerOccurrence)	Component sheet - BarCode	4 – as-built
		Component sheet - TagNumber	4 – as-built
		Component sheet - AssetIdentifier	4 – as-built
b) make and/or model;	ModelReference (Pset_ManufacturerTypeInformation)	Type sheet - ModelReference	4 – as-built
c) manufacturer;	Manufacturer (Pset_ManufacturerTypeInformation)	Type sheet - Manufacturer	4 – as-built
d) vendor, if different to manufacturer;	Manufacturer (Pset_ManufacturerTypeInformation)	Type sheet - Manufacturer	4 – as-built
e) date of manufacture;	ProductionYear (Pset_ManufacturerTypeInformation)		4 – as-built
f) date of acquisition, installation or completion of construction;	AcquisitionDate (Pset_ManufacturerOccurrence)	Component sheet - InstallationDate	4 – as-built
	WarrantyStartDate (Pset_Warranty)	Component sheet - WarrantyStartDate	4 – as-built
g) location of asset;	IfcSpace	Component sheet - Space	4 – as-built
h) whether or not access equipment is required;	IfcTask	Job sheet	5 – O&M
i) whether or not the asset is subject to a permit-to-work requirement	IfcTask	Job sheet	5 – O&M
j) initial cost;	IfcCostValue		4 – as-built
k) predicted lifetime;	ExpectedLife (Pset_ServiceLife)	Type sheet - Expected Life	4 – as-built
l) specification;		Type sheet - all	4 – as-built
m) replacement cycle;	IfcTask	Job sheet	5 – O&M
n) cost breakdown;			5 – O&M
o) servicing requirements, including type and frequency of service;	IfcTask	Job sheet	5 – O&M
p) other maintenance required;	IfcTask	Job sheet	5 – O&M
q) maintenance costs;	ReplacementCost	Type sheet - ReplacementCost	5 – O&M
r) accumulated depreciation;			5 – O&M
s) written-down value;			5 – O&M
t) source of components and spare parts, where applicable		Type sheet - Manufacturer	5 – O&M
u) energy consumption and, where applicable, energy-efficiency rating;	SustainabilityPerformanceDescription / Environmental (IfcTypeObjectProperty)	Type sheet - SustainabilityPerformance	4 – as-built
v) identification of hazardous or other risks to people or property.	Pset_Risk		4 – as-built

Appendix D – AIR and SPARQL Query definitions for pilot studies

AIR Exchange Requirements and Exchange Requirements Model

Table 10.2 – AIR Exchange Requirement: Handover Documents

Type of Information	*Required information*	*Supplying actor*	*Data type*
Documentary data	Manufacturer ID	Manufacturer	String
	Manufacturer Website	Manufacturer	URL
	O&M Manual	Manufacturer	String

Table 10.3 – AIR Exchange Requirement Model: Handover Documents

Property	*CMIS property name*	*CMIS Property Type*
Building Name	bim:BuildingName	Text
IFC Type	bim:IFCType	Text
Manufacturer name	bim:Manufacturer	Text
Manufacturer website	bim:ManufacturerWebsite	Text
O&M Manual	bim:OMManual	Text

Table 10.4 –AIR Exchange Requirement: Preventive Maintenance data

Type of Information	*Required information*	*Supplying actor*	*Data type*
Documentary data	Task name	Owner/FM	Text
	Task description	Owner/FM	Text
	Task type	Owner/FM	Text
	Task status	Owner/FM	Text
	Is milestone	Owner/FM	Boolean
	Task duration	Manufacturer	Real
	Task frequency	Manufacturer	Real

Table 10.5 – AIR Exchange Requirement Model: Preventive Maintenance data

Exchange requirements			***Functional Parts***
Required information	**Supplying actor**	**Data type**	**Entity/Property set/ Functional part**
Task name	Owner/FM	Text	IfcTask.IfcRoot.Name::IfcText
Task description	Owner/FM	Text	IfcTask.IfcRoot.Description::IfcText
Task type	Owner/FM	Text	IfcTask.IfcObject.IfcObjectType::IfcLabel
Task status	Owner/FM	Text	IfcTask.Status::IfcLabel
Is milestone	Owner/FM	Boolean	IfcTask.isMilestone::IfcBoolean
Task duration	Manufacturer	Real	COBie_Pset_Job.TaskDuration→IFCPropertySingleValue ::IfcReal
Task frequency	Manufacturer	Real	COBie_Pset_Job.TaskInterval→IFCPropertySingleValue:: IfcReal

Table 10.6 – AIR Exchange Requirements: Asset Renewal

Type of Information	***Required information***	***Supplying actor***	***Data type***
Non-graphical BIM data	Asset Criticality Ranking (ACR)	Owner	String
	Percentage Asset Remaining Life (PARL)	Owner	Real
	Asset Renewal	Owner	Boolean

Table 10.7 – AIR Exchange Requirement Model: Asset Renewal

Exchange requirements			***Functional Parts***
Required information	**Supplying actor**	**Data type**	**Entity/Property set/ Functional part**
Asset Criticality Ranking (ACR)	Owner	String	Pset_AIM.ACR→IFCPropertySingleValue::IfcText
Percentage Asset Remaining Life (PARL)	Owner	Real	Pset_AIM.PARL→IFCPropertySingleValue::IfcReal
Asset Renewal	Owner	Boolean	Pset_AIM.AR→IFCPropertySingleValue::IfcBoolean

SPARQL queries used for the validation of AIM data sources

Table 10.8 – Handover Documents: SPARQL query to retrieve the list of document names defined in a IFC/ COBie file

```
PREFIX ifcowl: <http://ifcowl.openbimstandards.org/IFC2X3_TC1#>
PREFIX express:  <https://w3id.org/express#>
SELECT ?name
WHERE {
  ?ifcdoc a ifcowl:IfcDocumentReference.
  ?ifcid a ifcowl:IfcIdentifier.
  ?ifcdoc ifcowl:itemReference_IfcExternalReference ?ifcid.
  ?ifcid express:hasString ?name .
}
```

Table 10.9 – Preventive Maintenance Data: SPARQL query to retrieve the list of maintenance task data in IFC/ COBie according to the Preventive Maintenance data AIR

```
PREFIX ifcowl: <http://ifcowl.openbimstandards.org/IFC2X3_TC1#>
PREFIX express:  <https://w3id.org/express#>
SELECT ?taskname ?description ?tasktype ?status ?ismilestone
WHERE {
   ?ifctask a ifcowl:IfcTask.
   ?ifctask ifcowl:name_IfcRoot ?name.
   ?ifctask ifcowl:description_IfcRoot  ?descr.
   ?ifctask ifcowl:objectType_IfcObject ?objtype.
   ?ifctask ifcowl:status_IfcTask ?taskstatus.
   ?ifctask ifcowl:isMilestone_IfcTask ?milestone.
   ?name express:hasString ?taskname.
   ?descr express:hasString ?description.
   ?objtype express:hasString ?tasktype.
   ?milestone express:hasBoolean ?ismilestone.
   ?taskstatus express:hasString ?status.
}
```

Table 10.10 – Preventive Maintenance Data: SPARQL query to retrieve maintenance task data in IFC/ COBie property sets according to the Preventive Maintenance data AIR

```
PREFIX ifcowl: <http://ifcowl.openbimstandards.org/IFC2X3_TC1#>
PREFIX express:  <https://w3id.org/express#>
SELECT ?taskname ?propertyname ?propertyvalue
WHERE {
   ?ifctask a ifcowl:IfcTask.
   ?rel ifcowl:relatedObjects_IfcRelDefines ?ifctask.
   ?ifctask ifcowl:name_IfcRoot ?ifcnameroot.
   ?ifcnameroot express:hasString ?taskname.
   ?rel a ifcowl:IfcRelDefinesByProperties.
   ?rel ifcowl:relatingPropertyDefinition_IfcRelDefinesByProperties ?propertyset.
   ?propertyset ifcowl:hasProperties_IfcPropertySet ?properties.
   ?properties ifcowl:name_IfcProperty ?property .
   ?property express:hasString ?propertyname.
   ?properties ifcowl:nominalValue_IfcPropertySingleValue ?value.
   ?value express:hasDouble ?propertyvalue.
 }
```

Table 10.11 – Asset Renewal: SPARQL query definition for 'Asset Renewal'

```
PREFIX ifcowl: <http://ifcowl.openbimstandards.org/IFC2X3_TC1#>
PREFIX express:  <https://w3id.org/express#>
SELECT ?ifcboiler ?name ?value
WHERE {
  ?ifcboiler a ifcowl:IfcBoilerType.
  ?ifcboiler ifcowl:hasPropertySets_IfcTypeObject ?propertyset.
  ?propertyset ifcowl:hasProperties_IfcPropertySet ?properties.
  ?properties ifcowl:name_IfcProperty ?property .
  ?property express:hasString ?name.
  ?properties ifcowl:nominalValue_IfcPropertySingleValue ?value.
}
```

Table 10.12 – Integration of BIM and FM data: SPARQL query for 'Asset Renewal' data from Openmaint

```
PREFIX db: <http://example.org/schema/openmaint#>
SELECT ?description ?parl ?acr ?ar WHERE {
  ?asset a db:Asset.
  ?asset db:Asset_Description ?description FILTER ( CONTAINS(?description, "Clinic MEP")).
  ?asset db:Asset_PARL ?parl.
  ?asset db:Asset_ACR ?acr.
  ?asset db:Asset_AR ?ar.
}
```

Table 10.13 – Integration of BIM and FM data: SPARQL query for 'Preventive Maintenance' data from Openmaint

```
PREFIX db: <http://example.org/schema/openmaint#>
select ?name ?instructions ?type ?activitystatus ?milestone ?estimatedtime ?leadtime where {
  ?task a db:MaintenanceActivity.
  ?task db:MaintenanceActivity _Description ?description filter ( contains(?description, "Clinic MEP")) .
  ?task db:MaintenanceActivity ?name.
  ?task db:MaintenanceActivity _Instructions ?intructions.
  ?task db:MaintenanceActivity _Type ?type.
  ?task db:MaintenanceActivity _ActivityStatus ?activitystatus.
  ?task db:MaintenanceActivity _Milestone ?milestone.
  ?task db:MaintenanceActivity _EstimatedTime ?estimatedtime.
```

Appendix E – Grounded Theory Analysis – Requirements gathering

Table 10.14 Requirements gathering – List of initial, focused, and axial codes

Axial codes	***Focused codes***	***Initial codes***
Owner's requirements	Classification	Classification support by CAFM/IWMS tools
		Classification as a key requirement for AIM development and management
	Handover	Handover process is project specific
		Data management challenges in handover of non-BIM data
		Improving the handover process using BIM object libraries
	FM & maintenance requirements	Using FM data for new build/refurbishment projects
		Data provided in unstructured format
		FM & Maintenance data requirements should be defined in the EIR
	Owner requirements management	EIR
		SLAs should specify data ownership
		Importance of the AIM schema to organise FM and maintenance data
		Information requirements for use of BIM data in CAFM systems
		FM input in defining building owner requirements
		AIR definition from early stage of project development
		FM data requirements for BIM objects
		Account for changes in SLA during building lifecycle
		Sustainability requirements

Table 10.15 Requirements gathering – List of initial, focused, and axial codes (cont'd)

Axial codes	***Focused codes***	***Initial codes***
Common Data Environment	IT tools requirements	EIR specifies selection of IT tools
		BIM - CAFM/IWMS integration tools
		Customisation of CAFM/IWMS tools difficult and expensive
		AIM custom schema definition
		Data analysis and reporting functions
		Compliance with open standards
		Compatibility with classification systems
	Visualisation	Wayfinding to improve maintenance planning
		Visual feedback for asset condition and work orders
	Uses of BIM data in FM	Use of BIM models to retrieve related FM data
		Enable cross-estate queries
		Integration of BIM with BMS to optimise energy use
		Development of asset registers
		Improve reporting capabilities in FM tools
		Evaluate accessibility planning for maintenance tasks
		Automated definition of PM and RM tasks
		Development of lifecycle cost models

Table 10.16 Requirements gathering – List of initial, focused, and axial codes (cont'd)

Axial codes	***Focused codes***	***Initial codes***
Data quality	Data integrity	Data synchronisation
		Data integrity
		Strategies to keep the data up to date
	Interoperability	BIM-FM data integration
		Interoperability issues between BIM and FM software
		Mapping BIM data to FM software
	Validation	Building owner/client should define the data validation strategy
		Involving CAFM suppliers in the validation process
		Current tools provide manual validation
	Data management	Data ownership
		Defining data management processes to ensure the AIM is up to date
		AIM data quality
		Assessing the quality of existing data
	Standards	Using standards for PPM and H&S
		Issues from the use of different local standards
		FM engagement from start of projects
		Using standards as AIM integration framework
		COBie / IFC compatibility with CAFM
Expected benefits and current challenges in BIM for FM	Expected benefits of BIM for FM	Improving retrieval of information
		Maintenance planning based on accurate asset data
		Reduced response times for RM tasks
	Challenges in BIM for FM	Current practice in the industry
		Adoption by the building owner/client
		Structured requirements definition
		Data and IT systems integration
		Data availability
		Data quality
		Data management

Appendix F – Grounded Theory Analysis – Validation

Table 10.17 Validation – List of initial, focused, and axial codes

Axial codes	***Focused codes***	***Initial codes***
Owner's requirements	Classification	Classification support by CAFM/IWMS tools
		Classification as a key requirement for AIM development and management
		Current classification systems are not finished
		Challenges in the use of multiple classification systems
		Clients/Building owners requiring the use of a classification system
	Handover	Handover process is project specific
		Data management challenges in handover of non-BIM data
		Improving the handover process using BIM object libraries
		Improving the handover process using BIM standards (e.g. COBie)
		Improving the handover process by providing the validation of BIM data
	FM & maintenance requirements	LOD requirements for AIM graphical model
		Automation of PM and RM tasks definition
		AIM of existing buildings
		Reality capture strategy for existing buildings
		Cost requirements: replacement and current costs of assets
		Statutory maintenance requirements
	Owner requirements definition	EIR
		SLAs should specify data ownership
		Importance of the AIM schema to organise FM and maintenance data
		Information requirements for use of BIM data in CAFM systems
		FM input in defining building owner requirements
		Structured AIR definition from early stage of project development
		Challenges in obtaining requirements from building owners in a usable format for validation
	Owner requirements validation	Translation of requirements into business rules
		Enabling validation of custom requirements
		Use of proposed validation method for requirements in PDT and AIR templates
		Use of linked data approach to validate requirements in different data sources

Table 10.18 Validation – List of initial, focused, and axial codes (cont'd)

Axial codes	***Focused codes***	***Initial codes***
AIM	AIM development	AIM as a central part of asset/facility management strategy
		Development of AIM from PIM using PAS 1192
		Integration of graphical, non-graphical and documentary data sources in AIM development
		Semantic relations in BIM data (COBie, IFC)
		Support AIM / asset register development based on COBie (i.e. no 3D model)
		Capturing on-site data into the AIM
		Using AIM data for new/refurbishment/renewal projects
	Uses of BIM data in FM	Automated definition of PM and RM tasks
		Considering AIM requirements for maintenance
		Considering application of the framework to non-BIM data sets
	Visualisation	Visualisation of various sources of AIM data
		Limitations in the visualisation of IFC models using Openmaint
		Development of dedicated views for MEP assets
Common Data Environment	CDE requirements	EIR specifies selection of IT tools
		BIM - CAFM/IWMS integration tools
		Building portfolio management from a single interface
		AIM custom schema definition
		Workflow customisation for FM and maintenance tasks
		AIM data maintenance
		Locating 3D assets from maintenance work order entries
		Mobile interface
		Compliance with open standards
		Compatibility with classification systems
		Support additional AIM data sources
		CDE access customisation for different users
		AIM visualisation
		Standards-based interoperability
		Support handover process (PIM to AIM)
		Support change of ownership process (AIM to AIM)
		Customisation of CAFM/IWMS tools difficult and expensive
		Application of proposed framework to existing commercial tools
	Data integration strategy	Using SOA and linked data for the development and management of AIMs
		Integration of legacy tools with CDE
		Integration of semantic web data with CDE
	Challenges in prototype CDE	Rule definition needs expert input
		Limitations in visualisation of IFC models within FM interface
		Complexity in managing CDE and ensuring reliability and data integrity

Table 10.19 Validation – List of initial, focused, and axial codes (cont'd)

Axial codes	***Focused codes***	***Initial codes***
Data quality	Data integrity	Issues in data synchronisation across the CDE
		Data integrity
		Strategies to keep the data up to date
	Data quality	Issues with non-BIM data
		Quality of existing data
		Impact of accurate data in FM outsourcing
		Data quality issues in IFC viewer
		Importance of classification in data quality
		Impact of accurate data in building/ facility value
		Role of COBie in providing accurate data
	Data management	Data ownership
		Defining data management processes to ensure the AIM is up to date
		AIM data quality
		Assessing the quality of existing data
		Customisation of the CDE
		Automation of the proposed AIM data management process
	Standards	Using standards for PPM and H&S
		Issues from the use of different local standards
		Issues from lack of understanding of standards (e.g. PAS 1192)
		FM engagement from start of projects
		Using standards as AIM integration framework
		COBie / IFC compatibility with CAFM
		Standards-based interoperability enables integration of AIM data sources
		COBie use as a basis for AIM schema

Table 10.20 Validation – List of initial, focused, and axial codes (cont'd)

Axial codes	***Focused codes***	***Initial codes***
Expected benefits and current challenges in BIM for FM	Challenges in BIM implementation	BIM level 2 implementation issues in infrastructure and civil projects
		Misunderstanding between organisational and project team levels
		BIM level 2 not sufficient to achieve data synchronisation in AIM
	Expected benefits of BIM for FM	Improving retrieval of information
		Maintenance planning based on accurate asset data
		Reduced response times for RM tasks
		Improved data transfer between FM providers (AIM to AIM)
	Challenges in BIM for FM	Current practice in the industry
		Adoption by the building owner/client
		Structured requirements definition
		Data and IT systems integration
		Data availability
		Data quality
		Data management
		Current contractual forms

Appendix G – Evaluation metrics for future research

Table 10.21 – Evaluation metrics: Quality in use (ISO, 2016a)

	Id	Name	Measurement function
Effectiveness	Ef-1-G	Task completion rate	X = A/B A = Number of unique tasks completed B = Total number of unique tasks attempted
	Ef-3-G	Number of errors per task	X = A A = Number of errors made by the user during a task
	Ef-4-G	Tasks with errors	X = A/B A = Number of tasks with errors B = Total number of tasks
	Ef-5-G	Task error intensity	X = A/B A = Number of users making an error B= Total number of users performing the task
Efficiency	Ey-1-G	Time to complete tasks	X = T T = Task time
	Ey-2-G	Time efficiency	X = A/T A = Number of objectives achieved T = Time
	Ey-3-S	Cost-effectiveness	X = A/B A = Total cost of carrying out the task B = Number of objectives achieved
Economic risk mitigation measures	REc-1-G	Return on investment (ROI)	X = (A – B)/B A = Additional benefits obtained B = Invested amount
	REc-2-G	Time to achieve return on investment	X = T T = Time to achieve ROI
	REc-4-G	Benefits of IT Investment	X = Aa/At A = Measure of the benefits of IT investment (a = actual, t = target)
	REc-5-S	Service to customers	X = A/B A = Actual level of service B = Intended level of service

Table 10.22 – Evaluation metrics: Software product quality (ISO, 2016b)

	Id	*Name*	*Measurement function*
Functional suitability	FCp-1-G	Functional coverage	X = 1 – A/B A = Number of functions missing B = Number of functions specified
	FCr-1-G	Functional correctness	X = 1 – A/B A = Number of functions that are incorrect B = Number of functions considered
Functional appropriateness	FAp-1-G	Functional appropriateness of usage objective	X = 1 – A/B A = Number of functions missing or incorrect among those that are required for achieving a specific usage objective B = Number of functions required for achieving a specific usage objective
	FAp-2-G	Functional appropriateness of system	$X = \sum_{i=1 \ to \ n} {A_i}/{n}$ Ai = Appropriateness score for usage objective i, that is, the measured value of FAp-1-G for i-th specific usage objective n = Number of usage objectives
Availability	RAv-1-G	System availability	X = A/B A = System operation time actually provided B = System operation time specified in the operation schedule
	RAv-2-G	Mean down time	X = A/B A = Total down time B = Number of breakdowns observed

Table 10.23 – Evaluation metrics: Data quality (ISO, 2015a)

	Id	*Name*	*Measurement function*
Accuracy	Acc-I-1	Syntactic data accuracy	X=A/B A= number of data items which have related values syntactically accurate B= number of data items for which syntactic accuracy is required
	Acc-I-2	Semantic data accuracy	X=A/B A= number of data values semantically accurate B= number of data values for which semantic accuracy is required
	Acc-I-3	Data accuracy assurance	X=A/B A= number of data items measured for accuracy B= number of data items for which measurement is required for accuracy
Completeness	Com-I-1	Record completeness	X=A/B A= number of data items with associated value not null in a record B= number of data items of the record for which completeness can be measured
	Com-I-2	Attribute completeness	X=A/B A= number of records with associated values not null for a specific data item B= number of records counted
	Com-I-3	Data file completeness	X=A/B A= number of records contained in a data file B= number of records expected
	Com-I-4	Data values completeness	X=A/B A= number of data values for a data item in a data file connected to expected values B= number of data values expected for a data item in a data file

Table 10.24 – Evaluation metrics: Data quality (cont'd) (ISO, 2015a)

	Id	Name	Measurement function
Consistency	Con-I-1	Referential integrity	X=1-A/B A= number of data items not consistent by value B= number of data items for which referential integrity must be defined
	Con-I-2	Data format consistency	X=A/B A= number of data items where the format of all properties is consistent in different data files B= number of data items for which format consistency can be defined
	Con-I-3	Risk of data inconsistency	X=A/B A= Number of data items where exist duplication in value B= Number of data items considered
	Con-I-6	Semantic consistency	X=A/B A=number of data items where values are semantically correct in the data file B=number of data items for which semantic rules are defined
Accessibility	Acs-I-1	User accessibility	X=A/B A= number of data items relevant to the user's task within a specific context of use having values accessible by intended users B= number of data items that are relevant to the user's task within the context of use having values that are required to be accessible in conformance to specification
Availability	Ava-D-1	Data availability ratio	X=A/B A= number of data items available in a specific period of time B= number of data items requested in the same period of time
Recoverability	Rec-D-1	Data recoverability ratio	X=A/B A= number of data items successfully and correctly recovered by the system B= number of data items that are required to be recovered
	Rec-D-2	Periodical backup	X=A/B A=number of data items (or data file) successfully backed up periodically B=number of data items (or data file) to be backed up

Appendix H – List of Publications

Patacas J., Dawood H., and Dawood N. (2017). Reality Capture and Visualisation of 3D Oil & Gas Facility Data for Operations and Decommissioning, *Lean and Computing in Construction Congress (LC3): Volume I, Proceedings of the Joint Conference on Computing in Construction (JC3)*, July 4-7, 2017, Heraklion, Greece, pp. 201-208 http://itc.scix.net/cgi-bin/works/Show?lc3-2017-285

Patacas J., Dawood N., Greenwood D., Kassem M. (2016). Supporting building owners and facility managers in the validation and visualisation of asset information models (AIM) through open standards and open technologies, *ITcon* Vol. 21, Special issue CIB W78 2015 Special track on Compliance Checking, pg. 434-455, http://www.itcon.org/2016/27

Patacas J., Dawood N., Vukovic V., Kassem M. (2015). BIM for facilities management: evaluating BIM standards in asset register creation and service life, *ITcon* Vol. 20, pg. 313-331, http://www.itcon.org/2015/20

Patacas J., Dawood N., Kassem M. (2015). A framework for the development of Asset Information Models to support Asset Information Requirements throughout the lifecycle of buildings, *Proceedings of the CIB W78 conference 2015*, Eindhoven, The Netherlands, October 27th-29th 2015

Patacas J., Dawood N., Kassem M. (2015). A framework to support owner's asset information requirements throughout the lifecycle of buildings, *15th International Conference on Construction Applications of Virtual Reality in Construction*, Banff, Alberta, Canada, October 5-7, 2015

Patacas J., Dawood N., Kassem M. (2014). Evaluation of IFC and COBie as data sources for asset register creation and service life planning, *14th International Conference on Construction Applications of Virtual Reality in Construction and conference on Islamic Architecture*. Sharjah, UAE, 16-18 November, 2014.

Dawood N., Miller G., Patacas J., Kassem M. (2014) Construction health and safety training: the utilisation of 4D enabled serious games, *ITcon* Vol. 19, Special Issue BIM Cloud-Based Technology in the AEC Sector: Present Status and Future Trends, pg. 326-335, http://www.itcon.org/2014/19