Development of Asset Information Requirements to support Asset Management

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Declaration

This thesis is the result of my work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my thesis has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. This dissertation contains fewer than 65,000 words including appendices, footnotes, tables and equations and less than 150 figures, but excluding the bibliography.

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Title: Development of Asset Information Requirements to support Asset Management

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Summary

The management of physical assets (asset management) is becoming increasingly important, supported by a shift in mindsets that are seeing maintenance moving from a *"necessary evil"* to a value-adding exercise. This is enforced by the need to achieve greater asset performance within increasing financial constraints, aiming to achieve *"more for less"* while limiting impact on the natural environment. The development of Building Information Modelling (BIM) and the concept of whole-life asset management provided a *"new"* approach to the management of physical assets based on emerging technologies and information management processes.

The adoption of BIM within the design and construction phase has widely been considered successful with a wealth of studies showing an increase in productivity, reduction in cost and improved risk management. Despite this, the adoption of BIM within the Operation and maintenance (O&M) phase has been limited. A lack of understanding of what information should be collected at an organisational level to support the management of assets throughout their life, results in asset-related information not being collected in alignment with an organisational requirement. Often the gap between the development of Organisational Information Requirements (OIR) and the generation of Asset Information Requirements (AIR), is too much of a jump or hurdle. This is partly due to the fact that asset management organisations purely focus on the development of technical information requirements, with little consideration of the wider organisation.

This thesis proposes a solution to address this challenge by presenting an organisational led framework to the development of Asset Information Requirements (AIR).

This thesis presents an Information Requirements framework and Concept Model, introducing the novel concept of Functional Information Requirements (FIR) to bridge

the gap between the OIR and the AIR. The framework was derived through a literature review, industry investigation, and feedback gained through several iterations of partial case studies. The final iteration was tested and validated for its practical application by a case study within a university estate management department. Furthermore, the framework was tested by a third-party partner within the infrastructure sector.

The thesis concludes that the framework aids in the development of AIR. Feedback noted that while the framework is helpful, it is resource intensive and the “value” of BIM within asset management needs to be addressed to gain the required resources. Furthermore, future research should investigate this challenge by considering the possibility of a common set of information requirements to reduce the need for the framework for individual instances of projects, when the projects are of similar purpose. Emerging techniques should be considered for automatic classification of Assets within a BIM model, this would greatly increase efficiency and reduce the resource intensive nature of the framework. Finally, future research should investigate how the proposed framework can support the evolution of the Digital Twin, within the context of the built environment.

Dedications

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1. Introduction

1.1. Research Context

There is a growing trend both within the academic literature and industrial practice to gain greater insight on the operational and maintenance (O&M) requirements of assets. Asset management has emerged as a domain to maximise the value produced by assets throughout their whole life. Value in this context relates to the output of an asset that can be tangible or intangible, financial or non-financial [1]. Asset management aims therefore to transform maintenance from a "necessary evil" to a value-adding exercise [2].

Historically asset management organisations have been reluctant to change, with the adoption of emerging technologies such as Building Information Modelling (BIM) being limited, especially within the O&M phase [3]. BIM has been demonstrated to reduce costs, increase productivity and provide greater insight into risk management, but it also introduces complex Information Management Systems (IMS) into an industry that was late to adopt such systems and processes [4]. While BIM adoption has been mostly successful within the design and construction phase, its limited adoption within the O&M phase means that BIM models and associated data (developed with significant financial and human resources) are not utilised within the O&M phase, where the greatest value of the models and data could be realised [4].

One of the fundamental challenges for asset management organisations to adopt BIM is to identify the information required to manage the asset throughout their life. While the BIM for O&M standard [5] states that an organisation *"shall"* develop Asset Information Requirements (AIR), it does not provide any tools, frameworks or methodologies on *"how"* this should be achieved. The challenge of aligning asset management objectives to Organisational Information Requirements (OIR) means that an OIR is rarely created, and if they are, they do not effectively contain the asset management requirements, therefore limiting the value of BIM. Furthermore, the standard states that an OIR should be used to generate the AIR. An industry investigation noted that the jump from OIR to AIR is too much of a leap for asset management organisations, resulting in AIR that are solely from a technical perspective. While there is growing use of BIM models, the transformation of them into an Asset Information Model (AIM) is limited as the BIM model is not *"fit for purpose"* from an asset management perspective and therefore limiting its value.

The annual National Building Specification (NBS) BIM survey noted the main barrier to BIM adoption (65%), was the lack of demand from the client, with BIM being seen as a *“tick box”* exercise that adds little value to the overall O&M requirements [6]. This is reinforced by the fact that in the same survey, only 33% of projects have exchanged information to a client within a structured approach [6]. It can be seen that information is not valued within the asset management and construction industry, this is despite a 2018 report that noted poor information management, cost US asset management organisations over $31.2 US Billion dollars in 2018 alone [7].

Fundamentally there is a lack of a structured approach to the development of information requirements within an asset management organisation that enables the adoption of BIM within the O&M phase, which in turn is hindering the business case for the adoption of BIM.

1.2. Problem Description and Research Motivation

The overall problem statement for this research effort: is that *information requirement developed during the BIM information management processes rarely consider asset management requirements, specifically the operational and maintenance phases*. This raises several problematic issues that include:

- The development of information requirements for use within asset management is a complicated task.
- The asset management industry has been late adopters of information management systems and therefore lack technical skills for there development.
- While there are standards and specifications that state information requirements *"shall"* be developed, there is a lack of tools, frameworks and methodologies to aid in their development.

- Considering the complexity of asset management organisations (such as road or rail operators), it is a challenge to achieve consistency within the information requirements that satisfy all of the stakeholders' requirements. This complexity impacts information management, with stakeholders (such as financial, operational and risk management) traditionally developing their own IT solutions with little consideration to other stakeholders.
- The translation from organisational objectives into OIR is poorly understood, resulting in information requirements that do not align back to the organisational objectives.
- Given the fact that OIR are poorly understood, this also impacts the performance of converting OIR to AIR, which is often done in manual and ad-hoc processes.
- BIM models are not developed from an O&M perspective, despite the O&M phase being the vast majority of an asset's lifecycle.

The first challenge for asset management organisations is the sheer complexity in developing information requirements in an organisation with complex asset systems and sub-systems. As an example, Transport For London (TFL) states within their Strategic Asset Management Plan (SAMP) that they maintain and operate over 2,500 asset systems types of fire, mechanical, electrical, civil, structural and power systems over a wide geographic area with several systems dating back to the 1950s [8]. The task of developing information requirements for each asset system is daunting and therefore, often neglected. Furthermore, it is well noted within the literature that one cannot merely ask managers what information they require, as they operate in specific organisational departments and will give a bias to their requirements [9,10]. Moreover, information requirements within asset management are often considered as developing naturally from a technical perspective or duplicated from similar capital works projects, but much like how the physical construction of a bridge is engineered, so must the information requirements [11]. Additionally, the *"information requirements complexity"* challenge is highlighted in the development of BIM-related standards that put a strong focus on the development of information requirements within BIM information management processes. While the domain of requirements engineering as a branch of software engineering can aid in the development of information requirements, it lacks in addressing the unique aspects of asset management, such as an assets life-cycle, complex organisational structures and the hierarchical nature of assets [12].

The information requirements challenge has led to IMS within asset management being developed as a single function and not cross-functional, therefore limiting their capability [13]. Furthermore, this challenge is emphasised by the lack of interoperability between BIM related data (e.g. 3D models) and existing asset management systems such as Enterprise Resource Management [14–16].

Both the information requirements challenge and the lack of interoperability between different asset management systems, specifically the interoperability with BIM related data, results in manual and ad-hoc processes of using BIM within the O&M phase [17]. Ultimately, these challenges are impacting on the opportunity to demonstrate the value of BIM within asset management and hindering the development of a robust business case.

1.3. Research aim and scope

Given the research problem and motivation discussed in the above section, this research effort has the aim: *"To develop a framework that supports the development of information requirements and enables the use of BIM models within an asset management organisation"*.

The research scope defines the boundary of this thesis. Firstly, this research effort is only focused on the O&M phase of an asset lifecycle. Secondly, the research is only focused on physical assets and not abstract assets, such as human or financial assets. Figure 1-1 illustrates the different aspects of assets, along with the lifecycle of an asset, the red dot highlights the thesis scope.

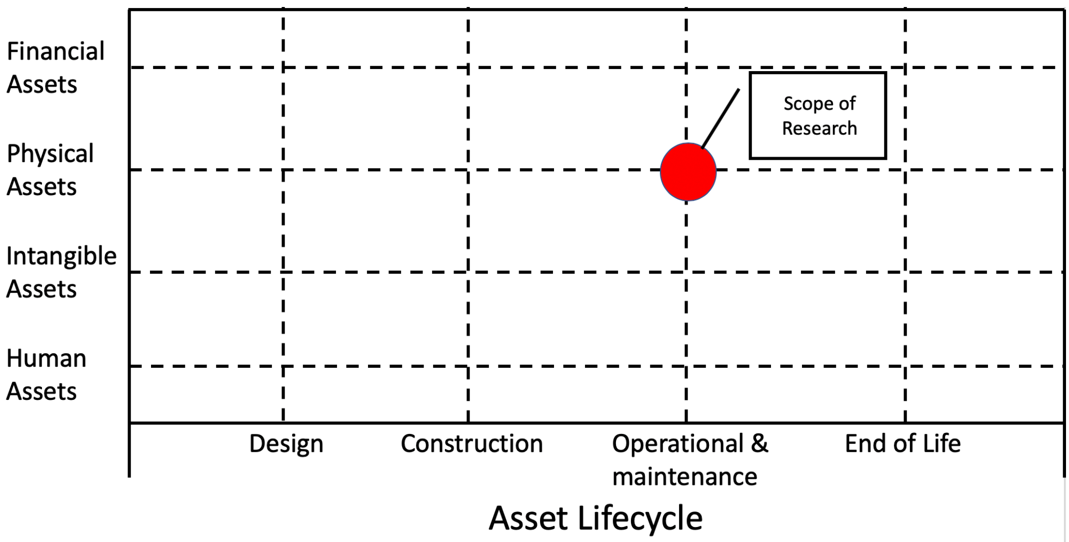

Figure 1-1 Research scope

The BIM standard ISO 19650 defines an information requirement as "specification for what, when, how and for whom information is to be produced" [18]. Within the scope of this thesis, we are only focused on the *"what"* element of an information requirement, this includes within the organisational, functional and asset information requirements.

The design and development of an asset management system as defined within the asset management standards ISO 55000/1/2 [1,19,20] lies outside the scope of this research but is a prerequisite for the case study, specifically the development of asset management objects. Furthermore, while the adoption of BIM is not a prerequisite, an understanding of the BIM principles and an aspiration to adopt BIM is required, as the development of information requirements is ultimately part of the BIM adoption process.

1.4. Research Approach

Information requirements are designed to support the development of digital processes within multiple functions of an organisation. The development of information requirements is articulated within requirements engineering, which is commonly referred to as a branch of software engineering that is concerned with the *"real-world"* wants and requirements for the design, development and implementation of IMS [21]. Unavoidably, this process contains several challenges such as personal bias, challenging the cultural norms and existing organisational structures. As the researcher is the designer and tester of the framework, along with the researchers' industrial experience, undoubtedly the researchers' experience, bias and interest have formed part of the overall research approach. Due to this fact, the interpretive qualitative research methodology was chosen that allows the researcher to measure any phenomena, in contrast to positivism methodology which aims to disregard any thoughts of the researcher altogether [19].

Furthermore, due to the abstract nature and the communication needs for the development of information requirements, a qualitative research approach was adopted, that also aims to address the challenges highlighted within this section. A set of qualitative research tools have been utilised, such as workshops and semi-structured interviews.

Figure 1-2 shows the high-level approach utilised within this thesis which is summarised below:

1. A literature review provide a comprehensive, critical and objective analysis of the current knowledge within the domains of BIM, asset management and requirement engineering. Furthermore, a critical review of current international and UK based standards and specifications within the domains of asset management and BIM is conducted. Finally, an industry investigation was conducted in the form of semi-formal interviews within the asset management industry, with the findings summarised and presented.
2. Using the findings from the review (gaps within the literature, requirements from the standards and current challenges in the industry) a conceptual model was developed that supports the development of the information requirements framework.
3. Utilising the qualitative nature of this research, an approach to the case study was developed. Tools used within the case study development include workshops engagement techniques, stakeholder selection and engagement, interviews (informal and semi-formal), prioritising and negotiation methods.
4. The information requirements framework is tested within an industry case study, and all the data from the case study is documented in a structured approach within predefined templates.

5. Lastly, the outcome of the case study is compared to a set of challenges, validating if the outcome addresses the challenges.

Figure 1-2 High-level Research Approach

1.5. The novelty of the research

From the above objective and research questions along with the literature review and industry investigation, the following points of novelty have been highlighted. This is not an extensive list but a list of the most significant points of novelty.

1. This research for the first time (to the researchers' best knowledge) aims to bring together the domains of BIM, asset management and requirements engineering to provide a framework for the development of information requirements, enabling the use of BIM within asset management.
2. In order to address the challenge of generating the AIR from the OIR, a new set of information requirements is proposed, Functional Information Requirements (FIR). FIR sits in between the development of OIR and AIR, bridging the gap by utilising the aspects of an assets functional output (such as heating or ventilation) to generate information requirements at this new level.
3. While there is an increase in BIM model development, their use within asset management is limited. To address this challenge, an approach to capture an asset management perspective within a BIM model is proposed. Traditionally assets within BIM models are rarely classified and if they are, they will have a single classification. An approach is proposed (see Chapter 7) that enables multiple classifications of a single asset, such as its functional output, asset system and sub-system. Utilising such an approach enables the translation of a BIM model into an AIM, as the BIM model is *"fit for purpose"* by containing an asset management perspective within the asset classification.

1.6. Thesis Structure

The structure of the thesis follows a standard flow which is in line with the research methodology. The thesis consists of nine chapters, including this chapter. Figure 1-3 illustrates this workflow and the rest of the thesis is as follows:

Chapter 2 – provides a detailed background of the research domains of BIM, asset management and requirements engineering. Firstly, a comprehensive academic literature review is conducted within the above domains. Secondly, a review of standards and specifications within the domains of BIM and asset management is conducted. Finally, an industry investigation is completed based on semi-structured interviews with extensive asset management organisations within the UK. Gaps within the literature, lack of processes within the standards and the industry challenges are analysed to provide the research problems and concept model that support the development of the information requirements framework.

Chapter 3 – Introduces the research methodology that aims to address the research problem adequately, the justification for using the chosen research methodology is provided.

Chapter 4 – introduces the information requirements framework, with a summary of the ten steps and discussion of the key assumptions used within the framework development.

Chapter 5 – provides a detailed overview of steps one, two and three within the information requirements framework, focusing on the developing of organisational information requirements.

Chapter 6 – focuses on the development of asset-level information requirements, discussing in detail steps four, five, six and seven of the information requirements framework.

Chapter 7 – discusses the last steps eight, nine and ten of the information requirements framework, enabling the design and development of a BIM model into an AIM.

Chapter 8 – applies the information requirements framework discussed in Chapters four, five, six and seven within an industry case study.

Chapter 9 – summaries the data and feedback from the case study, the conclusion of the overall research effort is presented, along with future research recommendations.

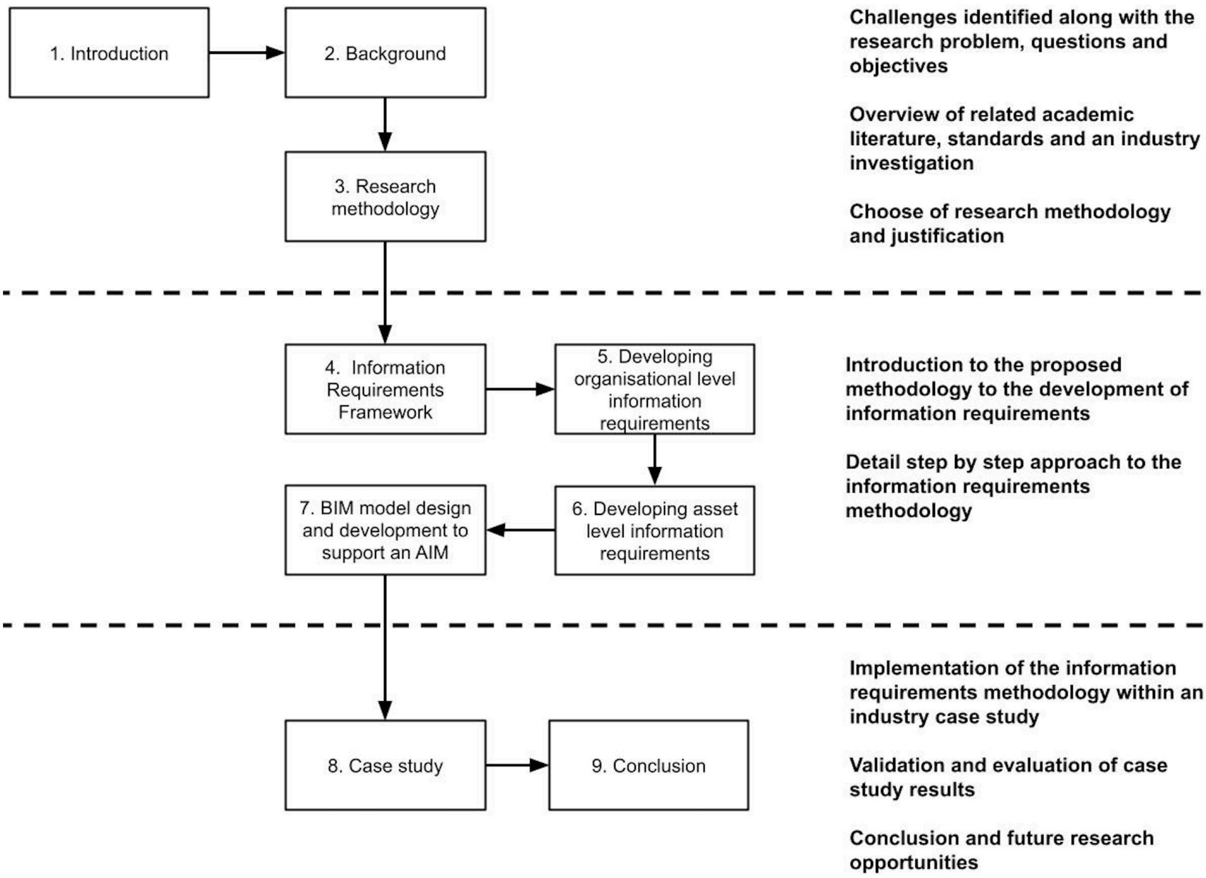

Figure 1-3 Thesis structure

2. Background

2.1. Introduction

This chapter aims to provide a comprehensive review of current approaches, tools and techniques within the domains of Building Information Modelling (BIM), Asset Management and requirements engineering. The review of the above domains will focus on highlighting the information management processes, including information requirements development, development of an Asset Information Model (AIM), whole-life information management and information decisions frameworks.

BIM has grown out of the domains of Product Information Modelling (PIM) within manufacturing, while Asset Management has emerged from the domains of Operational and Maintenance (O&M) and whole-life costing management. Requirements engineering has been developing since the 1960s, growing out of fundamental research within software development, for the need to extract information requirements at both a personnel and organisational levels to support the development of Information Management Systems (IMS). These domains have been chosen as they are the core subjects required to answer the research questions. Furthermore, there are common aspects between the domains that allow for the dissemination of knowledge between them, including the need to develop information requirements, the concept of a lifecycle and information management processes.

Along with the literature review, the domains of BIM and asset management have a set of standards and specifications developed by an array of organisations that aim to provide a standard and structure approach to their adoption within an industrial application. These standards are analysed as they provide the current approaches to BIM and asset management adoption.

An industrial review is conducted in the form of an industry investigation, conducting semi-formal interviews and reviewing of organisational documentation. The case study approach of this research requires an understanding of the *"real world"* approach, which can often differ from the academic literature. Furthermore, while the literature review noted the core challenges, the industry investigation provides a rich context to the challenges, that enables a better understanding of the challenges, including *"real world"* frustration and annoyances. Finally, a summary is provided that highlights the techniques used within the above domains, standards and specification landscape overview along with a set of challenges and requirements from the industry investigation. Furthermore, a concept model derived from this chapter is presented.

Figure 2-1 provides an overview of the framework used to guide this review, with the centre of the Venn diagram being the key elements to extract from each section of the review.

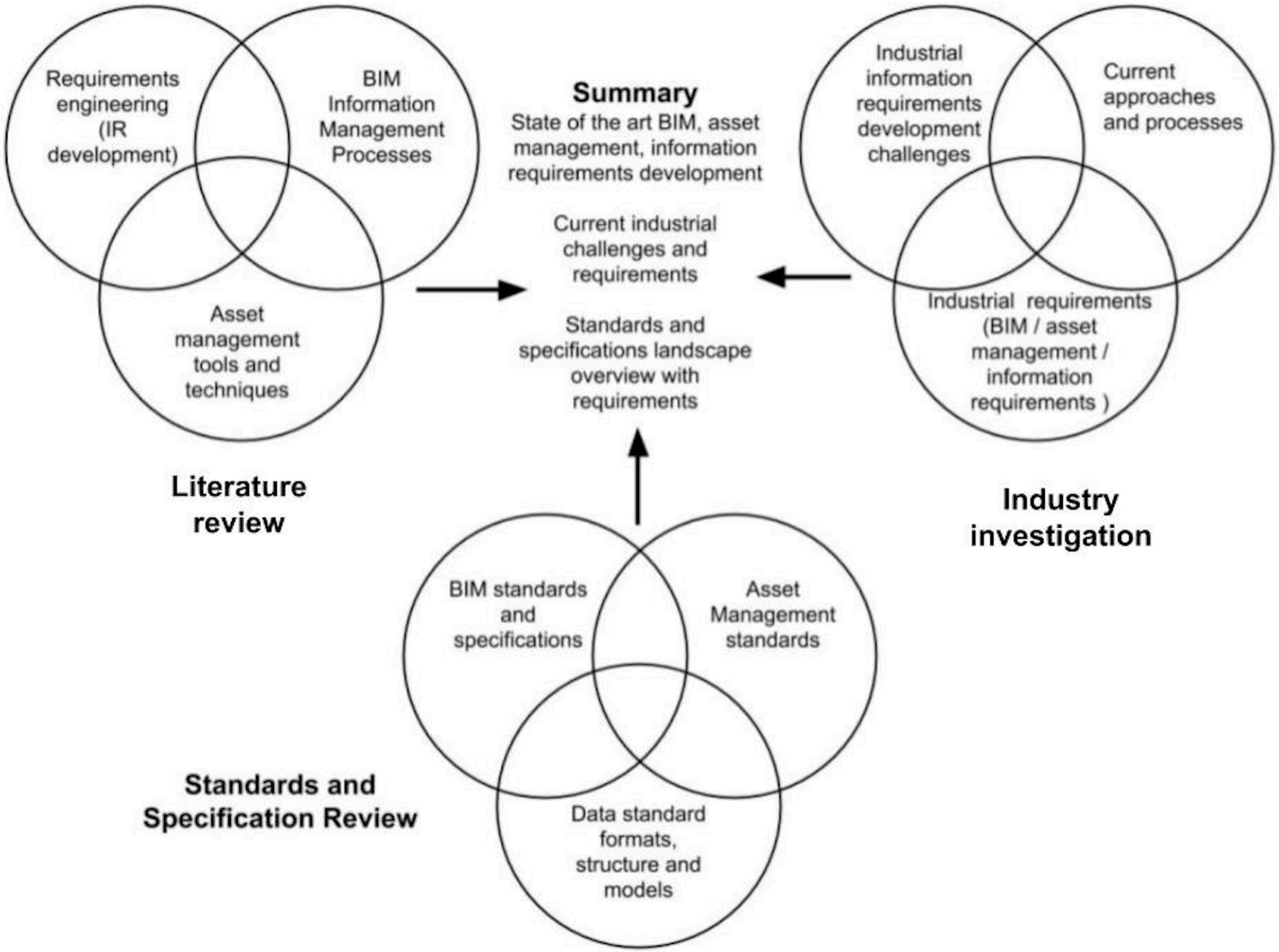

Figure 2-1 background research overview

2.2. Asset Management

Asset management, as defined within the international standard for asset management ISO 55000: *"is the coordinated activities that an organisation performs in order to realise value from their physical assets"* [22]. Furthermore, an asset management system is defined as: *"a set of interrelated or interacting elements to establish asset management policy, asset management objectives and processes to achieve those objectives"* [22]. Finally, an asset within this context is defined as: *"an item, thing or entity that has potential or actual value to an organisation. The value will vary between different organisations and their stakeholders and can be tangible or intangible, financial or non-financial"* [22]. Asset management refers to the management of physical assets (such as a bridge, rail signals or a wall) and not the management of a financial asset, such as a bond. However, the financial and economic aspect of the physical asset is within the scope of asset management.

Furthermore, alongside the definitions in the standards there is a collection of definitions in academic literature, summarised below, Table 2-1.

Source	Definitions
Frolov, Vladimir et al. (2009) [23]	Engineering asset management is a process of organising, planning and controlling the acquisition, use, care, refurbishment, and disposal of physical assets in order to optimise their service delivery potential and to minimise related risks and costs over their entire life.
Godau et al. (1999) [24]	asset management needs to deal with a range of complexities born out of the increasing technological, economic, environmental, political, market and human resources challenges facing this generation and our future generations
Amadi-Echendu et al. (2005) [25]	Physical asset management involves a wide range of disciplines and processes covering the life-cycle stages of creating, establishing, exploiting and divesting a physical asset in a balanced manner to satisfy the continuum of constraints

	imposed by business strategy, economy, ergonomics, technical and operational integrity, and regulatory compliance.
P Clarke (2002) [26]	Asset management is a framework developed through the systematic management of asset life-cycle activities with coordinated planning and execution
Woodhouse (1999) [27]	The best-value whole-life blend of asset development, exploitation & care, including associated risk exposures.
Campbell et al. (2015) [28]	Balanced management over asset performance, risk and cost to reach an optimal result for strategy.
Hasting et al. (2010) [29]	Physical asset management is the set of activities associated with identifying what assets are needed, funding requirements, acquiring assets, providing logistic and maintenance support systems for assets, and disposing or renewing assets.

Table 2-1 summary of definitions for asset management

Asset management literature can be categorised into two domains. Firstly, focusing on technological challenges, specifically focused on asset data management challenges. Secondly, focusing on management processes and the challenges in creating multidiscipline information decision frameworks [30]. Madu [31] noted that technology is critical to the development of an asset management system that can support and monitor the reliability, maintainability and performance of assets. Moreover, there was a move to understanding the strategic dimensions of maintenance management, focused on the organisational commitment to maintenance and reliability management [32]. The strategic shift aided in moving maintenance away from the perspective of a *"necessary evil"* to a multidisciplinary set of strategic activities and decisions that supports value creation [2]. Furthermore, the growing concept of managing assets throughout their whole-life and understanding its value during discrete life-cycle stages was a growing trend that helped to structure asset management as a holistic tool for use within all asset lifecycle stages [33].

The use of advance technology has been gaining pace within the asset management domain. Recent research has focused on the development of Internet of Things (IoT) sensors. IoT has been used on a Metro Rail project as a means of creating an integrated cloud-platform, providing real-time asset performance data [34]. Additional research has focused on IoT in creating data-driven decision making processes [35], predictive asset monitoring [36] and frameworks for real-time benefits realisation to all stakeholders, beyond the traditional O&M stakeholders [37]. Beyond IoT, advance analytics, Machine Learning (ML) and Artificial Intelligence (AI) have been growing in volume within the asset management domain. Such examples include, the automatic detection of road damage based on laser scanning deep neural networks modelling [38], advance planning techniques for complex supply networks [39] and maintenance knowledge management ontologies for Case Base Reasoning [40].

When considering management processes, the state-of-the-art literature is focused on requirements development (specifically technology needs), emerging frameworks and data-driven decision making processes. Data and information are having a major impact on management processes, one such example is a framework for the use of big data within a railway project, which is creating fundamental change in how data is used to both manage the asset and inform the wider organisation [41]. Furthermore, the increase in data is allowing for multi-criteria risk management, moving away from traditional cost-benefits analytics to multi-dimension analytics [42]. Moreover, there are emerging frameworks that focus on sustainability [43] and social aspects [44], that are impacting management processes and priorities.

A key barrier to adopting asset management is the alignment of decision-makers within different organisational departments and various management levels to achieving a consensus of the required value for a given asset [45]. This consensus is complicated to achieve within the traditional managerial top-down approach, as the value of the asset is often misunderstood or not well articulated [46].

Furthermore, the challenge in data quality and information management, including the creation, exploitation and exchange of information throughout an asset whole-life and integration into multiple asset management systems such as Enterprise Resource Management (ERM), maintenance scheduling and budgeting has emerged as a critical barrier to asset management system adoption [47].

This section discussed the evolution of maintenance from a *"necessary evil"* into a set of strategic activities within an asset management system. Asset management itself has transformed from purely a cost focused exercise of assert performance verse cost into a broad aspect of defining and measuring the “value” of an asset, such as operational, environmental and financial. The following sections discuss these challenges, including information management, data quality, management techniques and an asset management standard review.

2.2.1. Data and Information Management within Asset Management

The challenges in the integration of traditional maintenance management tools and information management process often result in manual and ad-hoc approaches to data and information management [3]. Standard asset management tools include ERM, Enterprise Asset Management (EAM), Computer-Aided Design (CAD) and Computerised Maintenance Management Systems (CMMS). While these tools provide a computerised approach to asset information capture and retrieval, they are limited in their integration capabilities, including data analytics. This challenge is born from the complexity of attempting to manage an asset's data throughout its whole-life, which results in a large volume of structured, semi-structured and unstructured data [48]. One of the key requirements for meeting this challenge and gaining the most value out of implementing the above tools is for an organisation to perceive data as its most valuable asset [49]. However, a recent survey shows that only 30% to 50% of data-centric change management projects are successful in delivering the proposed value [50].

Furthermore, while industries such as finance and manufacturing have a comprehensive understanding of the value generated by their data, the asset management industry is lacking this fundamental understanding [30]. In a recent survey of construction and asset management organisations, 61% believe they are behind the curve or industry lagging when considering data management adoption, with only 5% of organisations believing they are at the "*cutting edge"* [51]. Furthermore, only 48% of organisations have developed a data/digital strategy or roadmap, with 30% of organisations stating they have no intentions to develop one shortly [51]. Finally, a massive 76% of organisations believe it will take five or more years to fully embrace data management processes within the industry [51].

It is clear to see that data and information is not valued within asset management, while information management is considered non-value adding. To maximise the value of asset management and enable the adoption of BIM within asset management, information management must become a business-critical activity and considered as value-adding.

Directly related to the lack of information management process, is the lack of data quality processes and frameworks that emphasises the non-value adding perspective of information management, this challenge is discussed within the following section.

2.2.2. Asset Management data quality frameworks

It is well acknowledged that the lack of quality data is a critical issue within asset management [52]. This lack of quality data and therefore *"trust"* within the data often leads to decisions being made by a *"gut feeling"*, received knowledge or a bias judgement and not a data-driven decision [53]. As an example, the advancement of condition-based monitoring is generating a large amount of data, but with little thought given on the quality of such data [54]. Furthermore, there is a lack of knowledge within the asset management literature to support the design, development and management of an asset data quality framework.

The measurement and definition of data quality have been the goal of numerous research efforts, with data quality traditionally being described and measured by the perspective of accuracy [55,56]. However, more recently, there has been an effort not just to measure accuracy but a set of dimensions that when considered within a framework, can provide a comprehensive measure of data quality. This is specifically important when considering the use of data outside of its traditional domains and stakeholders. The four most discussed data quality dimensions within the literature include accuracy, timeliness, completeness and consistency [57]. While most stakeholders accept the dimensions as importance, they will have a bias to the importance of each dimension for their requirements and concerns.

Asset management is predominantly supported by engineering data [57]. Engineering data has a unique set of complex characteristics that are needed to support a long-sophisticated process throughout different life-cycle stages.

Furthermore, a large variety of specialised technical, operational and administrative data supports the management of assets throughout their whole life.

There are several data quality and TDQM frameworks that have been developed within the literature to support data management processes within asset management. M Z Ouertani et al. [58] proposes that data quality should be encompassed within an asset information strategy, for an organisation to select an asset information strategy, they need to examine two perspectives:

1. Top-down perspective, to understand the high-level organisational requirements Including objectives, Key Performance Indicators (KPIs), data requirements and information management system requirements.
2. Bottom-up perspective investigates the information that is required by the assets themselves, this includes asset classification, specific asset characteristics, data requirements and asset information system requirements.

J Goa et al. [53] attempts to align conventional organisational and asset management processes to elements of a data quality framework within the categories of business, stakeholders, information systems and data.

The above frameworks aim to link asset management process to a data quality element, while this is important, ultimately data quality in asset management is limited due to the lack of a structured approach to the development of information requirements [12]. The following section discusses this challenge in the context of adopting management techniques within asset management to support the development of information requirements.

2.2.3. Management techniques within asset management

Developing an asset management system follows a standard set of approaches that every organisation does, including developing a vision, objectives, strategies, plans to achieve the objectives and performance evaluation [59], with this in mind there are several examples in the literature that aims to adopt conventional organisational techniques within asset management.

Critical Success Factors (CSF) were developed to aid organisations in understanding what factors are essential in meeting their objectives [60]. As an example, a CSF for an asset management organisation might include 95% operational run time, prompt reply to customer engagements, reduction in operational costs and less reactive maintenance. W, Yeoh et al. [61] conducted a series of interviews and workshops to investigate a standard set of CSF within asset management organisations, that included cross-functional teams, tight project scopes, well-established business cases, commitment from leadership and high-quality data. Unlike traditional operational requirements within asset management such as asset performance, these frameworks allow for the broader requirements of asset management by including the organisational culture, social perspective and technology as factors to measure.

S Tywoniak et al. [62] proposed that a Balance Scorecard could be utilised to develop KPIs, taking into account the multiple measures of performance and objectives that are natural within asset management, with particular consideration needed regarding the dynamic nature of an assets life-cycle and the need for feedback between individual asset phases.

While the asset management standard ISO 55000 [22] provides an approach to developing an asset management system it does not provide the tool and techniques for doing so; therefore the literature has adopted existing techniques within the management literature domain. The approach of CSF have been adopted within the information requirements framework discussed in chapter 4, as a means to developed information requirements within the context of OIR, see section 5.4.

There is clearly a lack of tools and techniques for the development of an asset management system, especially with the content of information requirements development. The following section provides a comprehensive review of asset management standards, providing the requirements for the adoption of management techniques within asset management.

2.2.4. Asset Management standards review

Asset management standards have been widely developed in the UK by the BSI with industry partnerships.

PAS 55 specification includes the definition of asset management terms, requirements specifications, good practise and guidance on how to implement an asset management system. Furthermore, an integrated approach to meeting conflicting stakeholder demands, value for money and delivering on improved asset performance.

After the successful development and adoption of PAS-55 within the industry, the IAM worked with the BSI to create an international standard, the ISO standards 55000 / 55001 / 55002 were published with a sole focus on asset management.

Table 2-2 provides a summary of both the ISO standards and the PAS 55 specifications.

Title	Description	Reference
Asset management - Overview, principles and terminology	Provides an overview of asset management and asset management systems, providing the contents for ISO 55001 and ISO 55002	ISO 55000 [22]
Asset management - Management systems - Requirements	Provides the specific requirements for establishing, implementing, maintaining and improving an asset management system for asset management	ISO 55001 [19]
Asset management - Management systems - Guidelines for the application of ISO 55001	Guides the application of an asset management system in line with ISO 55001	ISO 55002 [20]
Part 1: Specification for the optimised management of physical assets	A practical overview of the different elements required for the development of an asset management system	PAS 55:1 [63]
Part 2: Guidelines for the application of PAS 55-1	Provides a set of methodologies, frameworks and tools to aid in the development of an asset management system	PAS 55:2 [64]

Table 2-2 Summary of asset management specification and standards

The asset management specifications and standards have been recognised as providing a step-change that bought the performance of assets to the forefront of organisations as a critical measurement of value. From an information management perspective, the standards state that organisations should develop information requirements, but lack in providing any references on how this should be achieved. Furthermore, the standards are strategic and process-focused, supporting the development of strategic management processes and documentation, such as asset management strategies, policies and visions, with little focus from a technical perspective. Due to this fact, asset management concepts and definitions are accepted in industry, but the adoption of asset management is limited due to the lack of technical guidance, specifically in the information management remit.

2.3. Building Information Modelling (BIM)

BIM is the process of designing, constructing or operating a building or infrastructure asset using object-oriented design [5]. This is a step-change from the traditional Computer-Aided Design (CAD) where the designer would have to draw two lines and a hatch to represent a wall, within a BIM authoring software the designer would draw a BIM object of a wall with is associated properties, Figure 2-2 demonstrates this evolution.

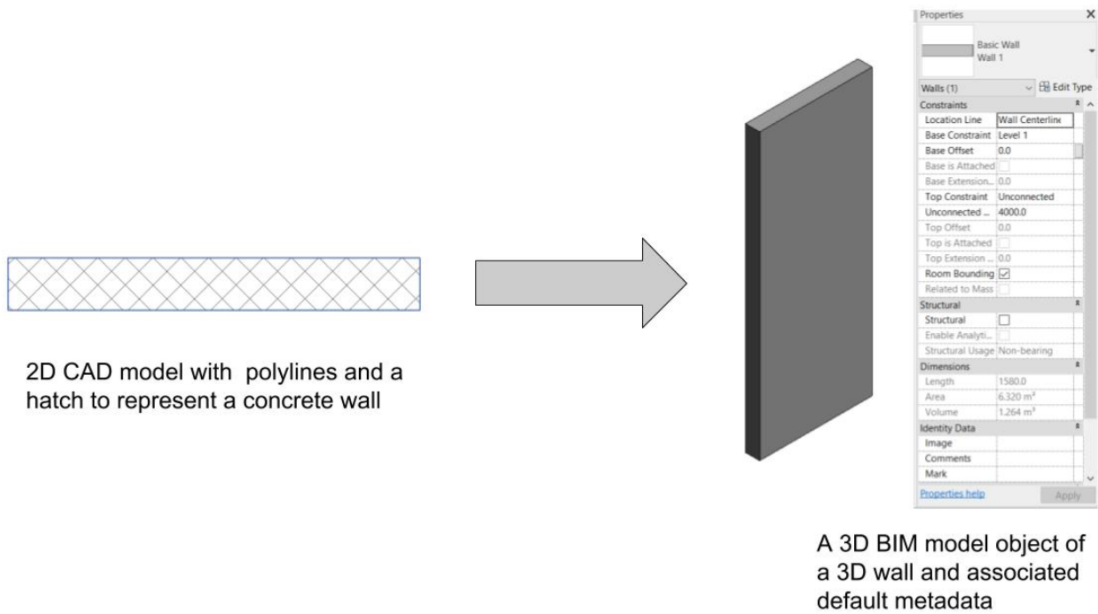

Figure 2-2 From CAD to BIM

Furthermore, The BIM model is a virtual three-dimensional representation of the design (for a new project) or the existing asset (for asset management). Due to the object-oriented approach to BIM model development, it enables the use of metadata that can be attached to an individual object (e.g. instance of a wall) or a group of assets (e.g. all concrete walls) directly within the BIM model. BIM has had the most impact within the design and construction phase, with multiple tools being developed for its use, such as collaborative design [65], visual reputation of the design scheduling (4D) [66], monitoring and visualising the embedded carbon of a given project [67] and visualising health and safety management processes within a BIM model, such as exclusion zones [68]. The adoption of BIM has seen a reduction in the total design and construction cost, increase in productivity and improve risk management processes [69–71]. Despite the success of BIM within the design and construction phase, BIM adoption within the O&M phase has been limited, despite the O&M phase being on average 90% of an assets service life [4].

The following sections discusses BIM use within asset management, including BIM approaches to information requirements development, Asset Information Model, asset data structures and BIM standards.

2.3.1. BIM for Asset Management

Research of BIM within asset management is limited, explicitly considering the large amount of research focused on the design and construction phase, there are a few examples that aim to address this shortage. Love et al. [72] proposes a benefits realisation management BIM framework for asset owners that states BIM should not be implemented as a traditional IT solution, but as a business change program that will impact the organisational value. The framework should be viewed as a learning process that allows the owner to question and measure the benefits of BIM. Furthermore, several KPIs have been developed that measure the success of BIM adoption including quick response to a request for information, reduction in overall cost, reduction in change orders and a reduction in task work duration [73].

Recent literature has focused on the development of frameworks and procedures that aim to enable BIM within asset management, with a strong focus on technology requirements. One such example developed a framework for the specification, production and validation of information that supports the development of a Common Data Environment (CDE) from open standards [74]. Maha Al-Kasasbeh [75] proposes a unified work breakdown structure approach, that proposes a framework where the hierarchy of asset management systems is includes within the hierarchy of an asset system.

A recent survey noted that the cost of software and hardware requirements, along with the lack of skilled professionals is a key barrier to the adoption of BIM within asset management [76]. Several commercial platforms have been developed in recent years that aim to address this challenge and provide an easy to use and economically viable application to support the adoption of BIM within asset management. The platforms focus on an information perspective or on a hybrid information and visualisation perspective. From an information management perspective, platforms such as GliderBIM [77] and the NBS Toolkit [78] provide a structured approach to classifying and validating information, while enabling the exchange of the data within BIM Open formats such as COBie and IFC, little focus is put on the 3D BIM model, but the data and information management processes associated to a BIM project. From a hybrid perspective, 3D Repo [79] provide a cloud based environment, that enable visualisation of the BIM model with a web browser while integrating data enterprise systems and business intelligence applications via API’s, such as PowerBI [80] and Cogital [81]. AssetWise [82] by Bentley System is a similar platform that supports the viewing of BIM models (along with other models such as point clouds) within a cloud environment, with a strong focus on operational analytics, providing tools to analyse and model from multiple data sources.

From a technology perspective, there are several examples of BIM being utilised within asset management processes, this includes the integration of emerging technology such as IoT Sensors, Augmented Reality (AR) and machine learning. IoT sensors and the export of BIM geometry was used within a bespoke platform to monitor the temperature and humidity of specific rooms within a 3D visual interface [83]. 3D geometry from BIM models are used in AR to simulate complex maintenance tasks, such as locating and replacing critical equipment [84]. Finally, Bloch et al. [85] use Machine Learning semantic enrichment to automatically classify BIM objects based on predefined rules. While there is a body of research that supports BIM adoption within asset management, they are developed within bespoke platforms that can rarely be adopted outside of their original research projects. Furthermore, these projects require the development of a BIM model beyond the use of standard modelling tools, requiring advance skills that are beyond most asset management organisations.

The complexity of adopting BIM within asset management is multifaceted, with information management challenges being a vital issue. Common information management challenges highlighted in the literature are summarised below:

- A fundamental lack in understanding on how to demonstrate the value of BIM within the operational requirements. [86].
- Historically, the asset management industry has been hesitant to adopt new and emerging technology processes, resulting in a culture challenge that spans the whole industry. Indeed, the lack of BIM and general data management skills of personnel within the asset management industry strengthens this cultural challenge [3].
- The interoperability between BIM related data (e.g. 3D models) and the existing asset management systems, such as ERM is limited [14–16]. Resulting in often manual and ad-hoc approach of using BIM data that is devaluing the business case for BIM within asset management [17].
- Asset managers are rarely consulted on their requirements for a BIM-enabled project, and this results in a BIM model that is not *"fit for purpose"* [87].

The definition of BIM from an asset owner perspective is poorly understood, and therefore asset owners often consider BIM as a tool for designers and contractors and not a tool for asset management [88], this is despite evidence stating the contrary. Eastman et al. [89] note that *"clients stand to benefit on their construction projects by adopting BIM technologies and workflows to guide their delivery process to higher quality and performance for a whole building life approach".* Eastman et al. [89] describes BIM as a tool for use throughout an assets whole-life, that when adopted, will deliver high-quality data and greater asset performance.

Asset owners often struggle to articulate their requirements in a BIM process, that simply means asset management requirements are not captured [88]. Eadie et al. [90] witnesses that asset owners who consider an asset management approach from the early BIM development stages benefit the most from BIM adoption.

Developing asset management requirements and adopting them within a BIM information management process, is one of the core challenges for adopting BIM within asset management that has not yet been addressed within the current literature. The challenges are multipronged that include poor technology integration between asset management systems and BIM systems, asset management processes are often still manual and not stored in digital formats (such as handwritten condition surveys) and information requirements are simply not developed from an asset management perspective [86].

In summary, this section discussed the use of BIM within asset management from both a managerial and technical perspective, with isolated examples showing the value of BIM within asset management. One of the challenges identified was the need for the development of efficient information requirements, which is discussed within the following section.

2.3.2. Information requirements development

One of the core elements in the BIM-related standards is the development of information requirements. Information requirements are used within BIM to define the Organisational Information Requirements (OIR). Furthermore, it translates the OIR into specific Asset Information Requirements (AIR). Finally, it aims to define the information requirements within capital works projects and how that information should be structured during design/construction for use within the O&M phase. Figure 2-3 provides an overview of the information requirements processes and their relationships, below is a summary of each element.

- **Organisational Information Requirements –** Information required to achieve the organisational requirements.
- **Asset Information Requirements –** Information requirements of the organisation concerning the assets that they are operating and maintaining.

When new construction projects are required, the AIR forms part of the Exchange Information Requirements (EIR).

- **Exchange Information Requirements –** A document that is developed as part of the tendering process for new capital works, that sets out the information to be delivered, the standard at which information should be managed. An EIR is a collective set of AIRs that are bungled together and developed into a contractual document for the tendering and procurement process.
- **Project Information Requirements –** information requirements developed by an owner for when a new capital works project such as a bridge or a building is constructed, defining the information requirements for that new project.
- **Project Information Model –** An information model that is developed during the design and construction phases, comprising of documentation, non-graphical and graphical information and data structures. The PIM acts as a central repository for all project-related information such as design drawings, cost schedule and planning timelines.
- **Asset Information Model –** Data and information that relates to assets to a required level that supports the organisational asset management system.

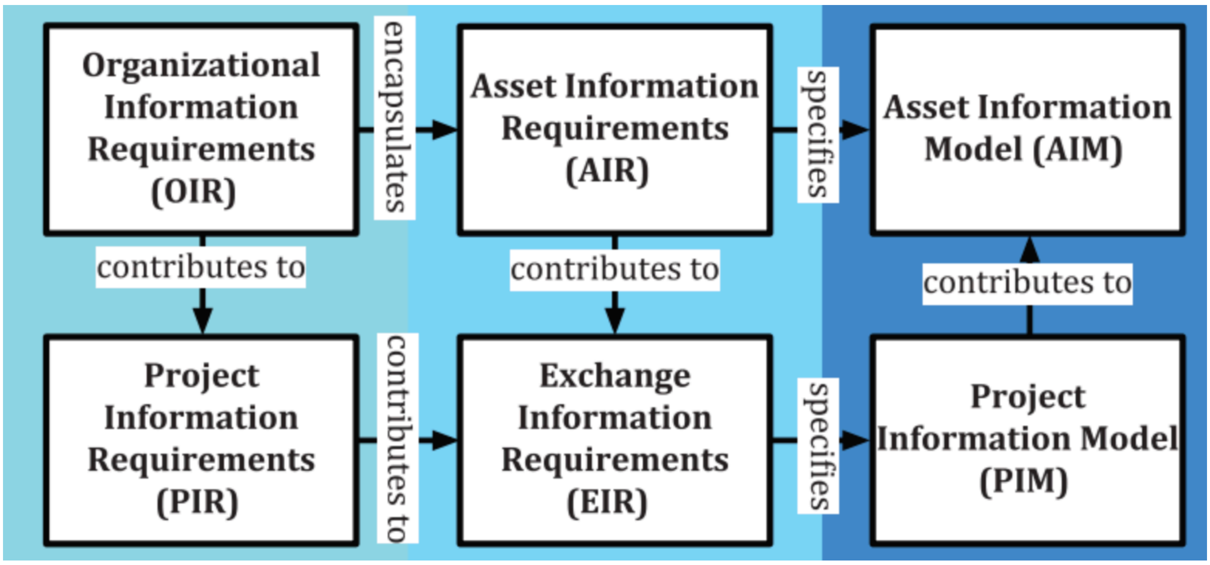

Figure 2-3 Relationship between elements of information management [5]

As stated, the development of information requirements is a critical part of the BIM information management process, specifically when considering BIM within asset management. However, developing these requirements is still a significant challenge. Indeed, asset management requirements in the form of design regulations, operational manuals, technical support and financial management are still often documented in manual and non-digital formats that do not support a BIM process [91]. Despite, a survey of asset owners noting that the digitalisation of requirements being an essential part of utilising the benefits of BIM [71].

Historically asset managers gave little consideration to the importance of information/data management, but BIM is now forcing asset managers to consider the importance of asset-related information. Therefore, information requirements development is often neglected and an afterthought. It is noted that requirements within asset management are often prone to high levels of changes (specifically when considering an asset that is changing throughout the different life cycles). However, these changes are often not documented (specifically in a digital format) and poorly communicated throughout the organisation and the supply chain, making it a challenge to comply with the requirements.

As stated, BIM has brought to the forefront the importance of developing information requirements in alignment to the organisational requirements within asset management. The following section discuss how BIM can aid in the development of information requirements.

2.3.3. A BIM approach to information requirements

The emphasis within the literature aims to develop methodologies and frameworks that enable the translation of high-level organisation requirements to key stakeholders, engaging the asset management team as early as possible within the life cycle stages. [92].

S Ashworth et al. [88] proposes a framework that enables asset management teams to play a leading role in developing a BIM strategy and the EIR, defining what information is required, how it is exchanged and in what format. Ashworth achieved this by having a Facility Manager (FM) representative appointed within the early stages of BIM adoption; he goes on to note: "*an FM is ideally placed to understand the organisations' needs in terms of its culture, corporate strategy, vision, mission and objective".* While no one would argue that FM and asset managers should be consulted during the information requirements development stage, solely focusing on their requirements will lack sight to the broader organisational requirements such as financial, customer engagement and business development.

B Becerik-Gerber et al. [3] provides a detailed discussion on how BIM can provide detailed information requirements for facility management, proposing a standard set of data requirements that should be collected and managed throughout an assets whole-life. Figure 2-4 demonstrates a categorisation of six different facility management-related datasets with the slice of the triangle showing the volume of data within each category. It was noted that a large percentage of the data within these categories could be gained directly from a BIM model, while the categories themselves provide a hierarchical and structured approach to the development of information requirements. Such information can support asset management tasks such as locating building components, visualisation, checking maintainability, space management and condition monitoring. While this framework helps to identify information requirement and categorise them for usability, it fails to address organisational specific information requirements, such as the OIR as mentioned earlier.

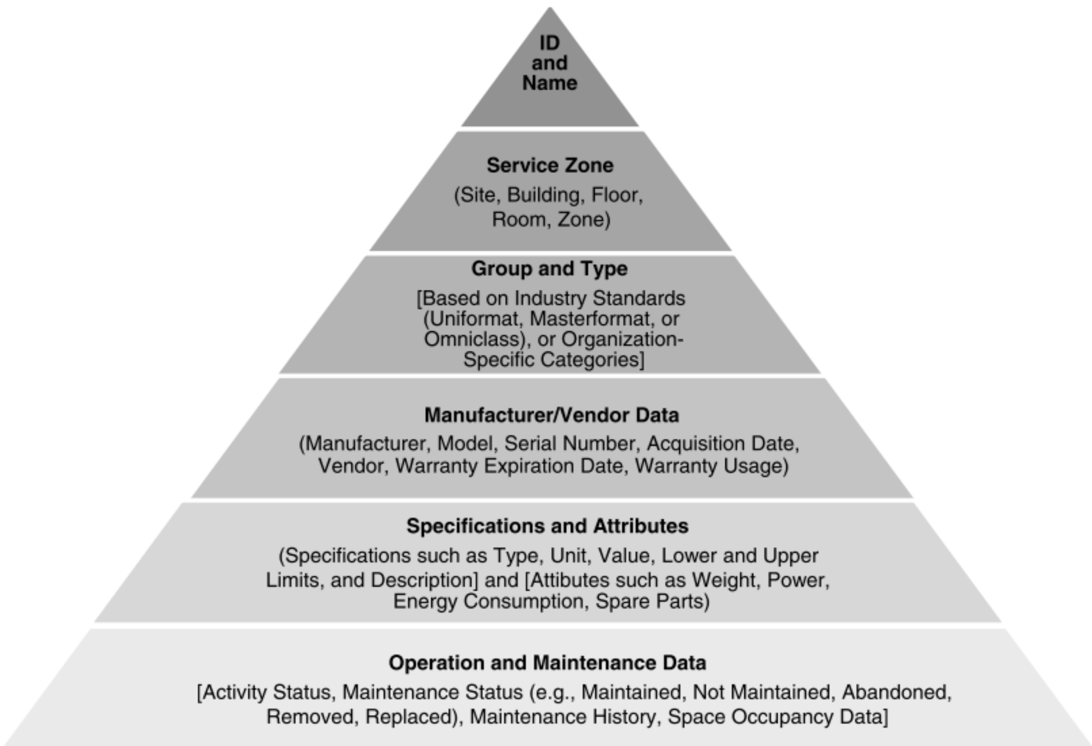

Figure 2-4 Common data structure and requirements [3]

H B Cavha et al. [91] proposes a methodology that takes an organisational perspective, developing owners' information requirements and aligning them to a BIM-enabled approach. This methodology consists of four steps (i) identify sources & collect data, (ii) classify landscape of owner requirements, (iii) identify the required information, and (iv) relate digital information with physical product requirements. While this methodology enabled the ability to extract organisational requirements and embedded them within BIM models, it does not address the complexity in developing the information requirements from the organisational requirements.

To the researchers' best knowledge, there is not a single methodology in its totality that enables the translation of OIR into AIR, which is critical when adopting BIM within asset management.

This section discussed several examples within the literature that utilising BIM in addressing the challenge of developing information requirements, while these examples provide an approach to the development of information requirements, they are limited in addressing the organisational need for the information. Reflexing on this challenge, the following section discusses the development of an Asset Information Model (AIM) within the context of BIM and information requirements.

2.3.4. Asset Information Model

An AIM is defined within PAS 112-3 page 15 as *"data and information that relates to assets to a level required to support an organisation's asset management system"* [5]. AIM can be developed for a single asset (of high value or importance), a system of assets or the whole asset portfolio of an organisation. Furthermore, an AIM is not constricted to a single data type and can include graphical (such as BIM models), non-graphical (such as object metadata), documentation (such as PDF, Excel) and data sources (such as SQL).

An AIM can be developed or updated following three paths within the BIM information management processes, see Figure 2-3. The first path involves an AIM being developed directly from the Project Information Model (PIM), when a capital works project is completed. This involves a handover of information including BIM models and design documentation to the asset management teams and does not involve the integration into asset management systems, resulting in the asset management team having multiple AIM for different projects that have been completed. The second path involves the development of an AIM that is separate to any capital work projects that is developed by the organisation. Projects exchange data within the AIM from the PIM, the PIM itself does not become the AIM, but the required information within the AIM would be populated from the PIM. This path requires an organisation to develop the AIM to the organisational requirements and allow for information to be exchanged as needed, e.g. when projects are completed. The third path involves a combination of both paths. An element of the PIM would be handed directly over, such as the BIM models themselves and other elements such as object metadata would be exchanged from the PIM to the AIM.

An AIM should not intend to replace any of the existing asset management enterprise systems but should enable the integration of them. An AIM pulls down information from multiple systems, aggregating the information and making it available as needed. Systems the AIM can integrate with include purchasing, performance reporting, knowledge management and work scheduling [5].

One of the core goals of an AIM is to address the chronic challenges of interoperability. A well-cited report stresses the importance of interoperability and estimates the cost of inadequate interoperability in asset management to be 15.8 billion US Dollars [93]. Within the context of BIM and Asset Management, interoperability commonly denotes technical interoperability, meaning the exchange of data, information and geometry between different IT systems. Furthermore, the broad nature of asset management makes it a challenge to define the scope of an AIM within an organisation to support its practical development. Finally, defining the AIM information requirements and structure is a daunting task with little supporting frameworks and methodologies that enable the AIM development.

This section discuss the development of an AIM as defined within the BIM standards, the paths to creating an AIM are discussed along with requirements and goals of an AIM development. The following section discusses the technical development of an AIM, including asset data structures, exchange protocol and specific processes.

2.3.5. Asset data structure

In recent years, there have been several methodologies developed to support the development of information exchange requirements and an asset data structure, including graphical data. These methods rely on the creation of an OIR, which is utilised for developing the AIR and the AIM. Furthermore, these methods rely on the use of ISO standards that have been developed by BuildingSMART [94] for the sole purpose of providing greater interoperability within the construction and asset management industry, see Figure 2-5.

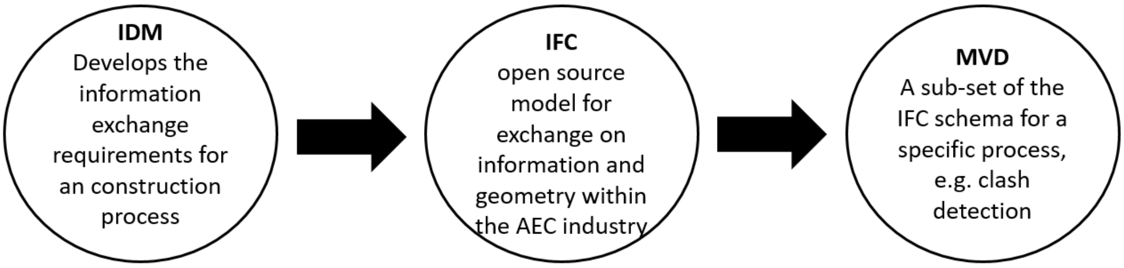

Figure 2-5 Development of an AIM Schema

BuildingSMART developed the Industry Foundation Classes (IFC) open-source file format that allows for interoperability between BIM-enabled applications via the IFC format, based on the EXPRESS specification language (STEP-11) [95].

IFC provides interoperability throughout the life cycle of an asset, including the O&M phase. However, the IFC standard does not specify how what information is required. Information Delivery Manuals (IDM) have also been developed by BuildingSMART and adopted as an ISO standard, ISO 29481 [96]. The IDM standard provides a process map driven methodology that aims to develop a set of information requirements for a specific construction-related activity by documenting and describing them within a structured process. The IDM methodology aims to serve both industry experts and software developers, using fewer technical terms. Domain experts can map out their requirements within the process maps, while the developers can link requirements to IFC classes. Despite this, the IDM is not designed for a direct translation into software development and its “user-friendly” approach makes it limited for facilitating interoperability [97].

A Model View Definition (MVD) defines a subset of the IFC schema for one or more of a given asset [98]. The IFC schema has over a thousand classes related to the

Architectural, Engineering and Construction (AEC) industry and asset management, as such, there is a need to filter and group the required IFC classes. MVDs provide the mechanism for selecting the necessary classes and often works in collaboration with the development of an IDM. MVDs are designed for use by the software development community.

COBie (Construction Operations Building information exchange) is an MVD and aims to provide a common structured approach to the exchange of information from design and construction phase into the O&M phase, including asset systems in buildings and infrastructure. COBie is the exchange format of choice for the UK government and has been developed into the British Standards, BS 1192-4 [99]. COBie is a structured Excel worksheet with pre-populated sheets. A previous study of COBie found that while COBie can fulfil most of the technical information requirements, there are limitations in commercial and financial aspects, including the lack of support for KPIs, financial performance measurements, detailed ownership and environmental factors [100].

There are several attempts within the academic literature to utilise different combinations of the IDM, IFC and MVD standards to aid in the development of information requirements. J Patacas et al. [92] proposes a framework that supports the development and visualisation of an AIM for building owners, that is developed through the BuildingSMART standards. The framework utilises IDM as the means to develop the AIR, IFC is used as a means to export data from the BIM model and convert to COBie, while the geometry from the BIM model is converted to a gaming engine (Unity) for visualisation. The result is a 3D model that is *"explorable"* where the end-user can click on an object and get the COBie associated information, which has been directly exported from the BIM model. While this approach enables the visualisation of data within a 3D model, the asset related information is stored within a static file that cannot be queried by third-party application, it is limited in supporting the interoperability nature of an AIM.

Furthermore, it fails to comprehend the complex issues of the AIR development, with no consideration for the development of an OIR and therefore the translation from OIR to an AIR. J Patacas et al. [92] analyse how IFC and COBie can be used to create an asset register and support service life planning (whole-life management), revealing a lack of support for whole-life management requirements within COBie and the more extensive IFC schema. Furthermore, while both IFC and COBie are extendable from their original schemas, doing so risks creating complex models that are prone to errors and poor interoperability with software solutions, such as IFC viewers. C Kim et al. [97] investigates how an IDM can be converted to a Universal Mark-up language (UML) concept model and converted into a database schema based on that model. This approach meets the interoperability requirements of an AIM but has no direct or indirect link to a BIM model.

In summary, while there is a set of asset data structure and exchange requirements, they are limited to single user cases within the literature with limited scopes. As an example, IFC is a complex format, but the schema is limited in storing O&M related information. While COBie goes some way to address this challenge, it is limited by being stored within a static Excel file and by default it is limited in capturing the rich context of asset information. The following section discuss this challenge within the context of the developed of BIM standards.

2.3.6. Building Information Modelling Standards review

In 2004 the UK Department for Trade and Industry released a report that found the use of Information and Communication Technology (ICT) could be used to improve information quality gathered on a construction site, enable greater collaboration [101]. Some key findings include:

- Up to 80% reduction in the time to find information
- Up to 50% reduction in the time to access and publish tender information
- Up to 85% time saving on manually formatting and editing information

The finds from the report were developed into BS 1192, which is a code of practise for the construction industry when dealing with information management processes [102]. These processes include a file naming convention, development of a Common Data Environment (CDE) and standard data practices.

The first BIM Publicly Available Specification (PAS) 1192-2, focusing on BIM related information management process for assets within the design and construction phases. PAS 1192-2 builds on the collaborative framework proposed in BS 1192, introducing new concepts of BIM within the existing framework.

Moving the focus away from the design and construction phase, PAS 1192-3 was, focusing on the use of BIM within the O&M phase. PAS 1192-3 is a companion document to PAS 1192-2, adopting many of its components but with an O&M focus. BS 1192-4 provides a code of practice for the exchange of BIM related data, utilising COBie (see Section 2.3.5).

More generic BIM-related standards have also been developed that are not focused on a single lifecycle stage. PAS 1192-5 focuses on how to use BIM within a security-minded approach. This includes but is not limited to, who should have specific access to areas of the BIM model, how to securely exchange information within a project and best practise for data management. PAS 1192-6, focuses on health and safety related approaches utilising BIM.

Recent developments have seen the UK BIM standards adopted into ISO standards, both BS 1192 and PAS 1192-2 have been adopted into ISO standards ISO 19650-1 [103] and ISO 19650-2 [104], with further plans to adopt PAS 1192-3.

While not directly related to BIM, ISO 12006-2 provides a methodology for the classification of physical assets for classification within a BIM model [105].

Table 2-3 provides a summary of BIM related standards and specifications.

Title	**Description**	**Lifecycle**	**Reference**
Collaborative production of architectural, engineering and construction information	Provides the framework for the development of a Common Data Environment (CDE), an environment to share design and construction-related data freely. The owner or principal contractor manage the CDE	Design / Construction	BS 1192 [102]
Specification for information management for	Guidance in the management of BIM related data within a CDE. A strong focus on BIM	Design / Construction	PAS 1192-2 [106]

the capital/delivery phase of construction projects using building information modelling	management and required documentation, e.g. BIM Execution Plan		
Specification for information management for the operational phase of assets using building information modelling	proposes the information management framework for the use of BIM within the operational phase, including developing organisational requirements within a BIM-enabled environment	Operational & Maintenance	PAS 1192-3 [5]
Fulfilling employer's information exchange requirements using COBie	UK government requirement for the exchange of information from the project to the end-user/client, in the format of organised spreadsheets	Exchange from Construction to Operational	BS 1192-4 [99]
Specification for security-minded building information modelling, digital built environments and smart asset management	Guidance on how to support BIM processes with security-sensitive information and models.	All	PAS 1192-5 [107]
Specification for collaborative sharing and use of structured Health	Provides a framework for how BIM can be used within the context of health and safety, including risk management by	All	PAS 1102-6 [108]

and Safety information using BIM	utilising the 3D model and information management processes.		
Briefing for design and construction Code of practice for facilities management	Guidance on operational briefing requirements within the design and construction phase	Operational & Maintenance	BS 8536-1 [109]
Building construction — Organization of information about construction works	Defines a framework for classification of construction-related information, e.g. cost, time, models, ETC	Design	ISO 12006-2 [105]
Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries	An opensource information model allowing for the exchange and transfer of 3D geometry, between different enterprise systems	All	ISO 16739 [110]
Building Information Modelling - Information Delivery Manual	A methodology to highlight the exchange of information between different actors for a specific task	All	ISO 29481 [111]
Government soft landings	Guide on how to successfully deliver built asset-related information throughout the lifecycle of an asset	All	GSL [112]

Table 2-3 Summary of BIM standards

The mentioned above standards and specifications provide the foundations for what is required to adopt BIM. Furthermore, it also provides the overall requirements for what it means to be *“doing BIM”*, including information management processes, BIM strategy and policy development, a protocol for information sharing and knowledge/training requirements. Moreover, the standards have been widely acknowledged as enabling BIM adoption, mostly within the design and construction phases. Finally, it is often criticised that the standards state what *“shall”* be done, but lack in practical examples on *“how”* it should be done [71]. For the asset management organisations to gain value out of BIM adoption, there is a clear need to develop a set of methodologies and frameworks, in-line with the above standards

2.4. Requirements Engineering

With the rapid development of computing power in the 1950s and ’60s, organisations found themselves with enormous and promised opportunities to streamline business processes and systems while also gaining greater insight and control. With this rapid development, there was a need to understand the user requirements of these new semi-automated Information Management Systems (IMS) processes. It was quickly realised that you could not ask managers what information they require, as they operate in specific organisational functions and give a bias to their function [10]. It is a mistake to assume that managers know what information they require and that this information will aid them in making better decisions, while evidence demonstrates the contrary [9]. Newly implemented IMS often require significant revisions to meet even the simplest of information requirements to support management decisions [113]. This often has a fiscal impact, with redesigning cost and time being significantly higher than the initial cost, in some cases, as much as 50 to 100 times higher [10]. Information requirements do not arise naturally and therefore have to be engineered, highlighting the need for improving techniques in the development of information requirements to meet this significant challenge [11].

There is a growing set of methodologies, frameworks and tools to address the challenge of developing information requirements. Common information requirements development techniques are summarised in Table 2-4.

Title	Approach	Reference
Business Systems	BSP works first by defending the significant problems encountered within the organisational	Zachman [114]

Planning (BSP)	function, such as low stock or incomplete orders forms. Secondly, solutions are proposed to the problems such as real-time stock checking and order form validation processes. Finally, the critical decisions within the business process are identified. The information requirements are captures for all three processes within the system mapping	
Critical Success Factors (SCF)	The SCP methodology works by first asking the question: what the critical success of your organisational department is? On average most managers will give four to eight responses. This is subsidised with a second question asking what information is needed to ensure the critical success factors are under control?	Rockart [60]
End/Means Analyse (E/M)	The End/Mean analyse works in two parts, firstly identifies the products and services provided by the organisation, what make the product or services effectively to the recipient and what information is needing to validate this effectiveness. Secondly, identify what the critical means (processes) used to provide products or services, what constitutes effective in providing products or services and what information is needed to evaluate this efficiently	Weather [13]

Table 2-4 Summary of Information Requirements Approaches

These techniques were the result of extensive research efforts in the early 1980s and 90s that sought to solve the problems of developing information requirements for IMS.

As IMS became increasingly popular, there has been a shift from process-driven techniques to user-centric design that requires a thorough understanding of the needs and requirements of the users for designing an IMS [115]. The process of developing user requirements has manifested itself as a research domain known as Requirement Engineering (RE).

RE is commonly referred to as a branch of software engineering that is concerned with the real-world wants and requirements for the design, development and implementation of IMS, e.g. software development [21]. The RE process consists of 5 main activities – eliciting requirements, modelling and analysing requirements, communicating/documenting requirements, agreeing on requirement and management of requirements (see Table 2-5) [116]. There are many techniques available for the individual stages to ensure that the requirements are complete, relevant and consistent.

Step	**Approach**	**Techniques**
1. Eliciting requirements (also known as information gathering)	The first step within RE is to between what information is required to support the organisational requirements from an information management system. The primary goal is to capture a comprehensive set of requirements by engaging with stakeholders and capturing their requirements.	Stakeholder Engagement [117] Critical Success Factors [118] Brainstorming [119] Prototyping [120]
2. Modelling and analysing requirements	The second step within RE is to analyse the captured requirements. The main question here to ask here is, to what good is that information for? Furthermore, how will the information be used within the organisation? This process should give assurance that the correct information has been gathered and all gaps have been addressed	Enterprise modelling [121] Joint application development [122] Requirements prioritisation [123]
3. Communicating/documenting requirements	A key element of RE is not merely to identify and capture information requirements, it is also a process of	Requirements traceability [124]

	communicating those requirements with different stakeholder. The way requirements are documented plays a critical role in analysing, validating and managing them.	Storyboards [125]
4. Agreeing / validating requirements	All involved stakeholders should agree to the captured requirements, this is often a challenging task between devious stakeholders with often conflicting goals. Benefits analyse can help to address this by highlight the key benefits for individual bits of information	Guidelines and standards Benefits analyse [126]
5. Management of requirements	Finally, it is natural that the requirements will change over time as the organisation changes. The requirements of the information management system must be captured regularly and updated as and when needed.	Change management [126] Configuration management [127]

Table 2-5 Summary of Requirements Engineering approaches

RE has predominantly been implemented within none asset-centric organisations such as financial, communication and marketing, with limited implementation in asset-heavy industries such as construction and asset management

The asset management industry has been late to adopt IMS, this is partly because the development of information requirements for an asset is complex. While RE goes some way to address this challenge, there are specific challenges within asset management that are not addressed within the common RE frameworks, these include:

- The need to develop information requirements for an asset whole-life; with different requirements for the same asset depending on the life cycle stage, this aspect is not currently captured in RE.

- Assets are not a single element, they are part of systems and sub-systems that support a functional output, this hierarchy nature for the development of information requirements creates a new level of complexity within RE.

For RE to be used within any context of creating OIR and AIR, these challenges will have to be addressed.

2.5. Industry Investigation

As part of this research effort, an extensive industry investigation was conducted in the form of semi-formal interviews with key personnel from major infrastructure and estate management clients within the UK. Furthermore, both BIM and asset management documentation when available where reviewed. The aim of this section can be separated into three segments, as summarised below:

- **Current approaches –** investigate the current approaches to utilising or attempting to utilise BIM within asset management, specifically in the O&M phase. Current approaches to information requirement development, data integration, BIM model design and development and data management processes are reviewed. Furthermore, the approach to the development of asset management processes and the alignment to BIM processes, if any, were discussed.
- **Industry challenges –** while the literature review provides the challenges as defined within the academic literature, this section aims to highlight the challenges from an industrial perspective. Focus is on the “reality” of adopting BIM within asset management with financial constraints and limited resources.
- **Industry requirements –** requirements to enable BIM within asset management can be found within the academic literature, this section focuses specifically on the requirements expressed when conducting the interviews. The requirements aim to capture the tools and frameworks that are needed by industry to enable them to adopt BIM within asset management.

Table 2-6 provides a summary of the organisations that have been included in this research. While not all of these organisations have the same asset types, financial business models or objectives, they do have assets numbering in the thousands in complex systems that require an enormous amount of resources to operate and maintain them.

Company	**Description**	**Category**
Transport for London (TFL)	Many all of London public transport systems (Overground, Underground, Buses and riverboats) and roads within London	Surface rail / underground rail / Buses / Road / boats
Highways England (HE)	Managed all of the highways and A-roads within England	Roads
Network Rail (NR)	Managed all of the surface rails within the UK, only track not rolling stock	Surface rail
University of Cambridge Estate Management (EM)	Manages all of the buildings and selected unities supply within the University of Cambridge, including facility management services	Historical and modern buildings/unities
English Heritage (EH)	Management of historical assets within England including castles, state homes and significant statues	Historical buildings and assets
Crossrail	A new surface and underground rail line being constructed in London from east to west and connecting with existing underground lines	Surface and underground rail
High Speed 2 (HS2)	A new high-speed rail line being constructed to link from London to Manchester via Birmingham with high-speed trains	High-speed surface rail

Table 2-6 Summary of industry interviews

2.5.1. Road to Asset Management

While all of the interviewed asset owners understand the importance of asset management, the approach, current maturity level and resource allocation vary widely.

NR and TFL both lead the way in developing an asset management system, with publicly available asset management policies, strategies and are currently ISO 55000 certified. HE has a three-year process towards ISO 55000 compliance and is hoping to be certified by the end of 2020. On the other end of the spectrum is EH, who due to a pending change in financial funding, have understood the importance of asset management and are at the very early stages of developing an asset management system. While the capital works projects of Crossrail and HS2 do not have any assets currently in operation, they have adopted the asset management fundamentals to achieve asset management within the operational phase.

All of the organisations have set out an asset management framework that is consistent with ISO 55000 [22]. The overarching goal of the individual frameworks is to provide a clear line-of-sight from organisational objectives to the delivery of maintenance and asset management objectives. Figure 2-6 illustrates TFL Asset Management Framework within the Strategic Asset Management Plan (SAMP) that shows this line of sight.

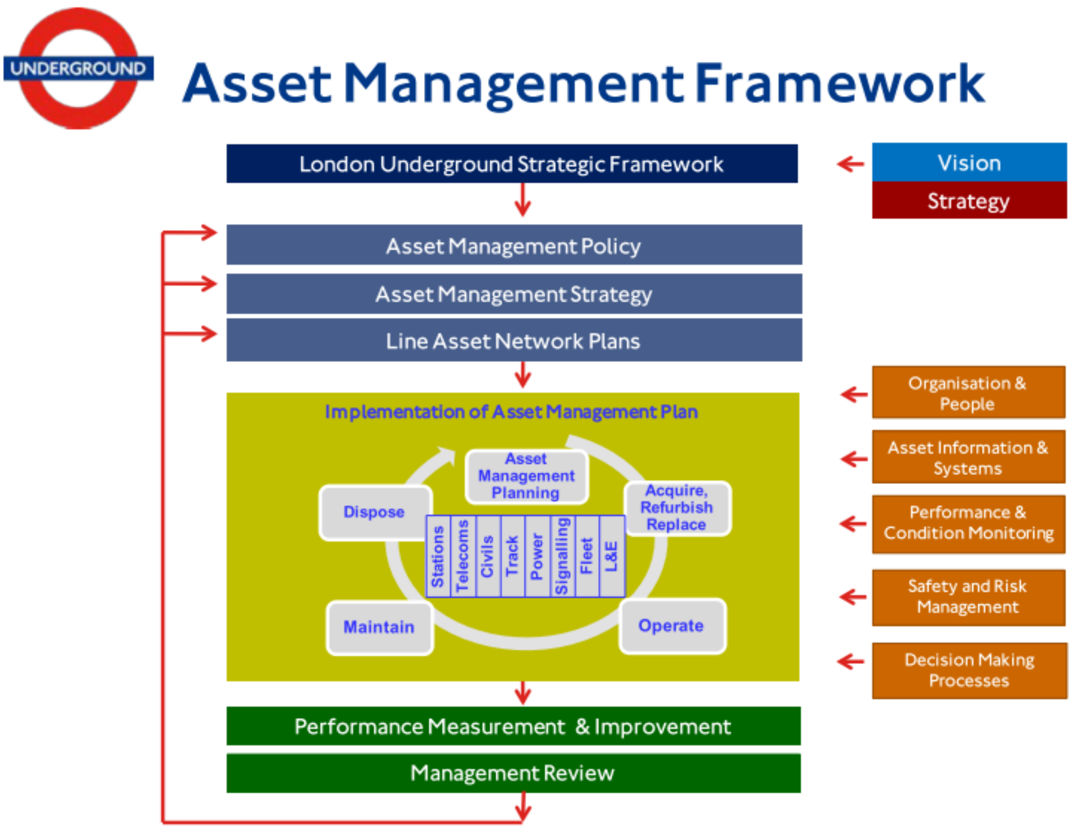

Figure 2-6 TFL asset management framework [128]

Such a framework is essential to cascade the organisations vision into measurable asset management objectives, but the framework itself does not support the achievement of those objectives. Key enablers defined within the asset management strategies help to support the realisation of asset management objectives, key enablers are broadly defined within the asset management strategy and often link to their own strategy. Recurring themes between all the organisations include resource allocation, technology, funding, innovation and asset information. Figure 2-7 shows key enablers and associated documentation from NR asset management strategy.

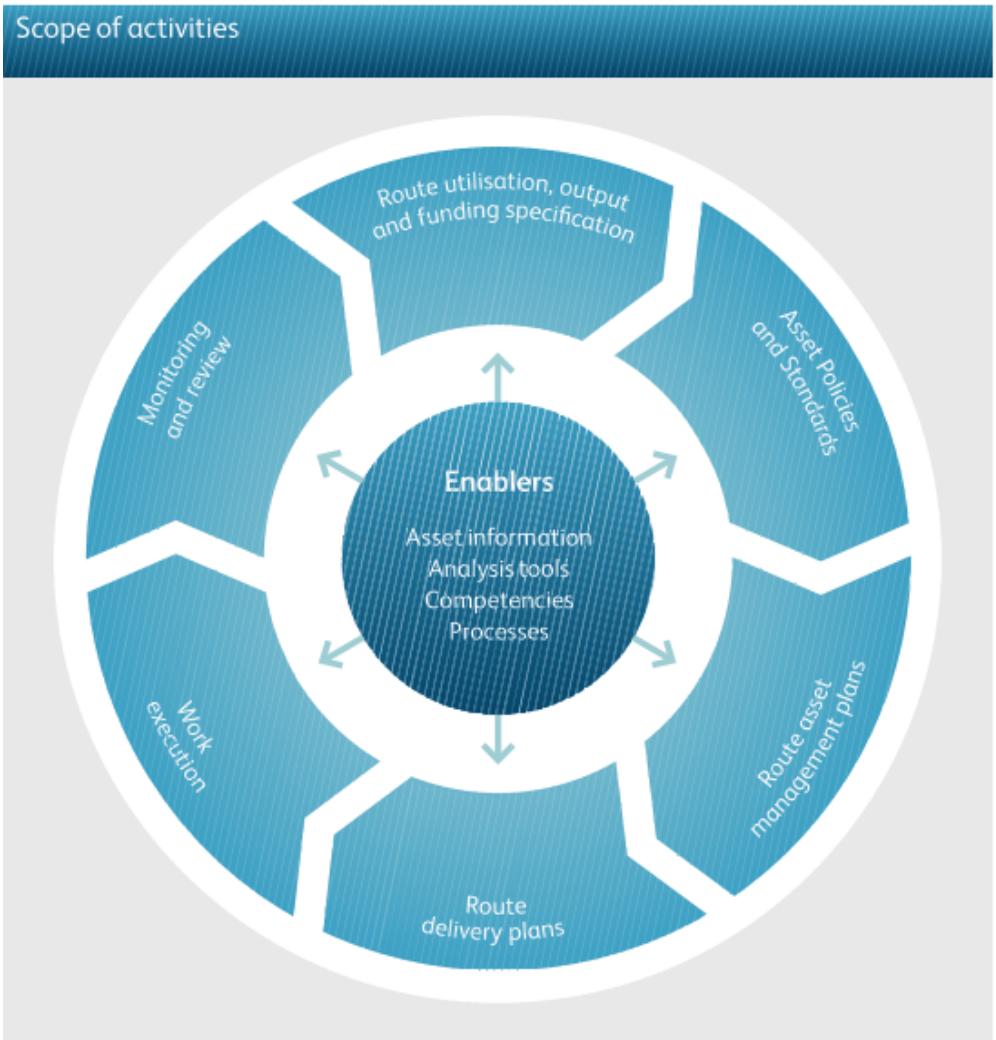

Figure 2-7 NetworkRail asset management enablers [129]

While all the enablers are key to the success of asset management, NR has highlighted the quality of asset information as critical to the maintenance and renewal decision both at the strategic and operational levels. NR scope of asset information is broad, covering all meaningful data related to the assets and asset management itself. Information and therefore, data is seen as an asset within its own right and managed according to ISO 8000 Data Quality Management System [130]. Uniquely, NR is the only organisation (which was interviewed) to specify asset data quality targets that align with the need for decision-making processes.

TFL has a recurring theme of technology, driven by its high-level vision to provide a reliable train service that is supported by emerging and disruptive technologies. The technology theme is carried through to the asset management strategy and underpins the asset management objectives as a key enabler. Technologies that support asset condition monitoring, electric power supply and improved communications (5G data networks) are proposed as key enablers.

Development of asset management documentation is critical to the development of an asset management system, but without an implementation plan, the objectives risk not being realised. A communication plan with internal employees and external stakeholder is a recurring theme within the asset management strategies, it is assumed that this will aid in adoption acceleration. HE has developed a communication plan that includes an associated asset management training and development programme.

2.5.2. Utilising BIM within asset management

While limited, there are a few examples from the interviewed organisations that strive to adopt BIM with an asset management perspective.

Crossrail has established an information and data integration platform that links the virtual and physical world by utilising asset classification within an AIM. Asset tagging allows the on-site operative to scan a QR barcode and link directly to related documentation & drawings. Unfortunately, the assets within the BIM model were not classified during the design phase and could not be used to generate an AIM. Therefore, Crossrail has no direct link between the physical asset and the instance of the asset within the BIM model, it is currently a manual task to connect the associated drawings and documentation to the physical tags.

HS2 has taken some of the lessons learnt from Crossrail and put the AIM as the only model, all functions of the project will operate from the AIM, see Figure 2-8. The 3D geometry itself will be one representation of an asset, e.g. an attribute. Such an approach to BIM within a significant infrastructure project will require extensive integration of complex IMS between an array of stakeholders, software vendors and the supply chain. This method has yet to be proven and deviates from the assumed approach that the PIM generates the AIM. While the development of such an AIM would be a great leap forward, HS2 was unable to demonstrate the core structure of the model or framework to its development.

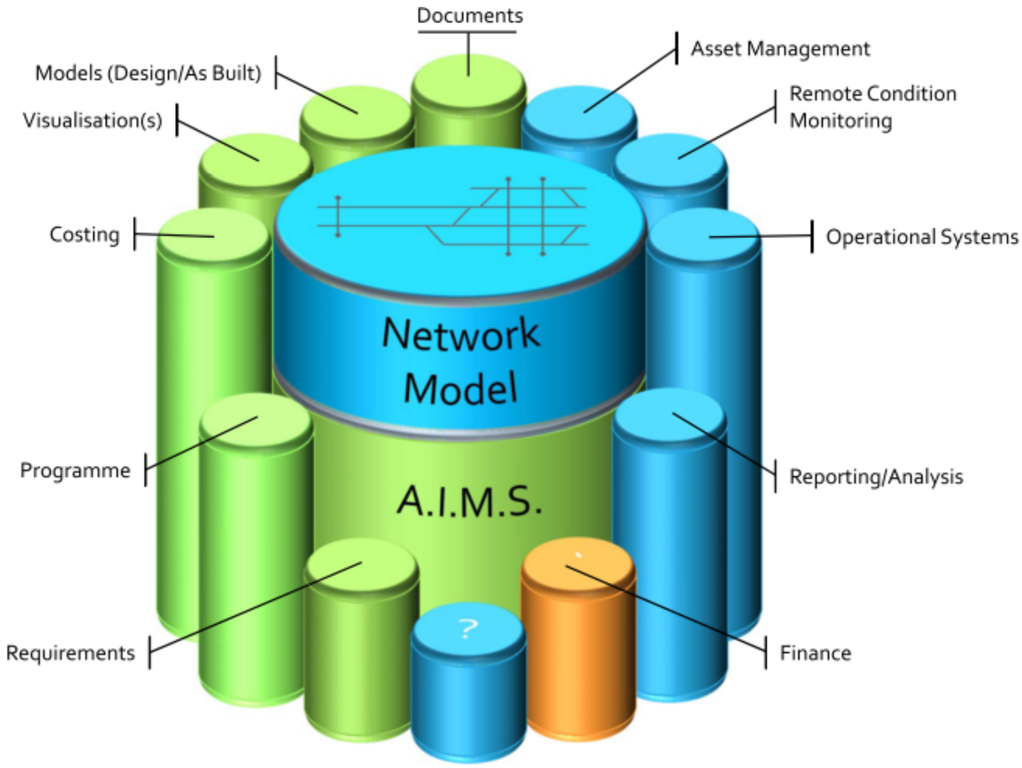

Figure 2-8 High Speed 2 Asset Information Model [sourced from presentation]

While both Crossrail and HS2 have ambitions to develop an AIM, they are capital works projects and do not currently operate any assets, their ability to operate an AIM is limited. In contrast, TFL has an abundance of assets that they operate and maintenance, while developing a broad digital strategy that encompasses BIM, development of an AIM and asset management, see Figure 2-9. The strategy aims to integrate existing enterprise systems such as IBM Maximo [131] for maintenance management, primavera P6 [132] for resource management and SaleForce [133] for supply-chain management. Furthermore, TFL aims to integrate new data sources such as IoT sensors and emerging technologies. Another interesting aspect of the TFL digital strategy is how the information requirements are derived directly from the organisation objectives and informs the Business Data Model / Digital Twin, this requires the development of OIR. Furthermore, the PIM is developed during significant projects and is exchanged with the business data model, demonstrating how BIM is central to the strategy and provides the foundation for all business processes.

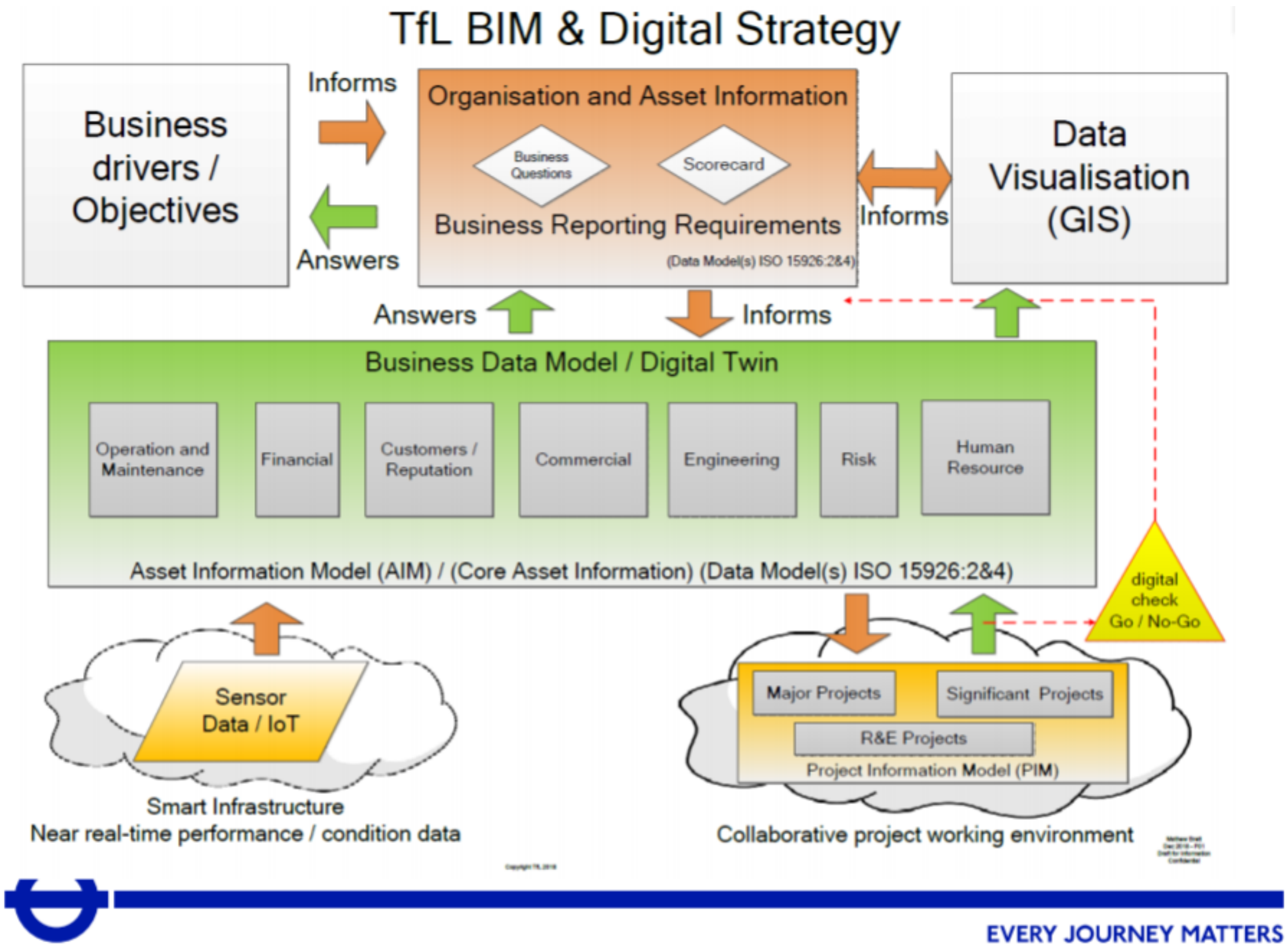

Figure 2-9 TFL BIM & Digital Strategy [sourced from presentation]

2.5.3. An industry approach to the development of information requirements

Both Crossrail and HS2 have spent a significant amount of time and resources in establishing asset information enablers, requirements and tools. Such enablers as Asset Data Dictionary Definition Documents (AD4s) and Asset Information Management Plans (AIMP), provide the foundation for what information is obtained during the design and construction phases.

Crossrail developed individual AD4 for all of its 416 asset classes (systems), this defines the information requirements and at what level of detail to capture such information. The AD4s were slowly developed during multiple informal workshops with an array of stakeholders and chief engineers over a year. Asset Data Collection Spreadsheets (ADCS) were used to collect asset data from contracts, every 40 working days. A set of controls and restrictions within the Excel sheets allowed for data validation at the point of entry. The ADCS contain all the asset codes that have been requested by the contractor from Crossrail. The AD4 plays a significant role in being the master reference file, defining what information should populate the ADCS. Once Crossrail has received the ADCS, it is then imported into the Asset Information Management System (Enterprise Bridge). At this stage, data validation is conducted that validates the data quality as per the AD4 and the Asset Identification Standards.

HS2 made a similar approach to Crossrail, running workshops with stakeholders and chief engineers to develop information requirements. HS2 has also set up an agreement with ProRail from the Netherlands to share object definitions and information requirements, they are currently analysing the similarities and differences. Regarding the data structure for information requirements, HS2 has implemented a cloud-hosted web server, this system allows for machine-readable transfer (XML, JSON and COBie) of information between a website and developed applications, such as a BIM modelling software. While this approach is novel and has the potential to generate significant efficiencies, HS2 does not yet fully understand how such an approach can be cascaded throughout the supply-chain and useable within asset management.

TFL noted that the development of information requirements needs to be flexible and changeable to the customer and client's requirements over a long period. TFL discussed the need for a modelled and structured approach to the development of information requirements that is repeatable, expandable and user-friendly. It was further noted that the current approach to developing information requirements is brainstorming over a long period with asset owners and maintainers, that is time-consuming, inefficient and often lacks in high-quality results.

While not directly related to the development of information requirements, NR in 2014 started on a program of works to change the way in how asset information is collected, stored and utilised to bring substantial benefits to the organisation, this program of works is called ORBIS. ORBIS stands for Offering Rail Better Information Services, the program is still ongoing and aims to finish at the end of 2020, Figure 2-10 provides the big picture and vision of the ORBIS program.

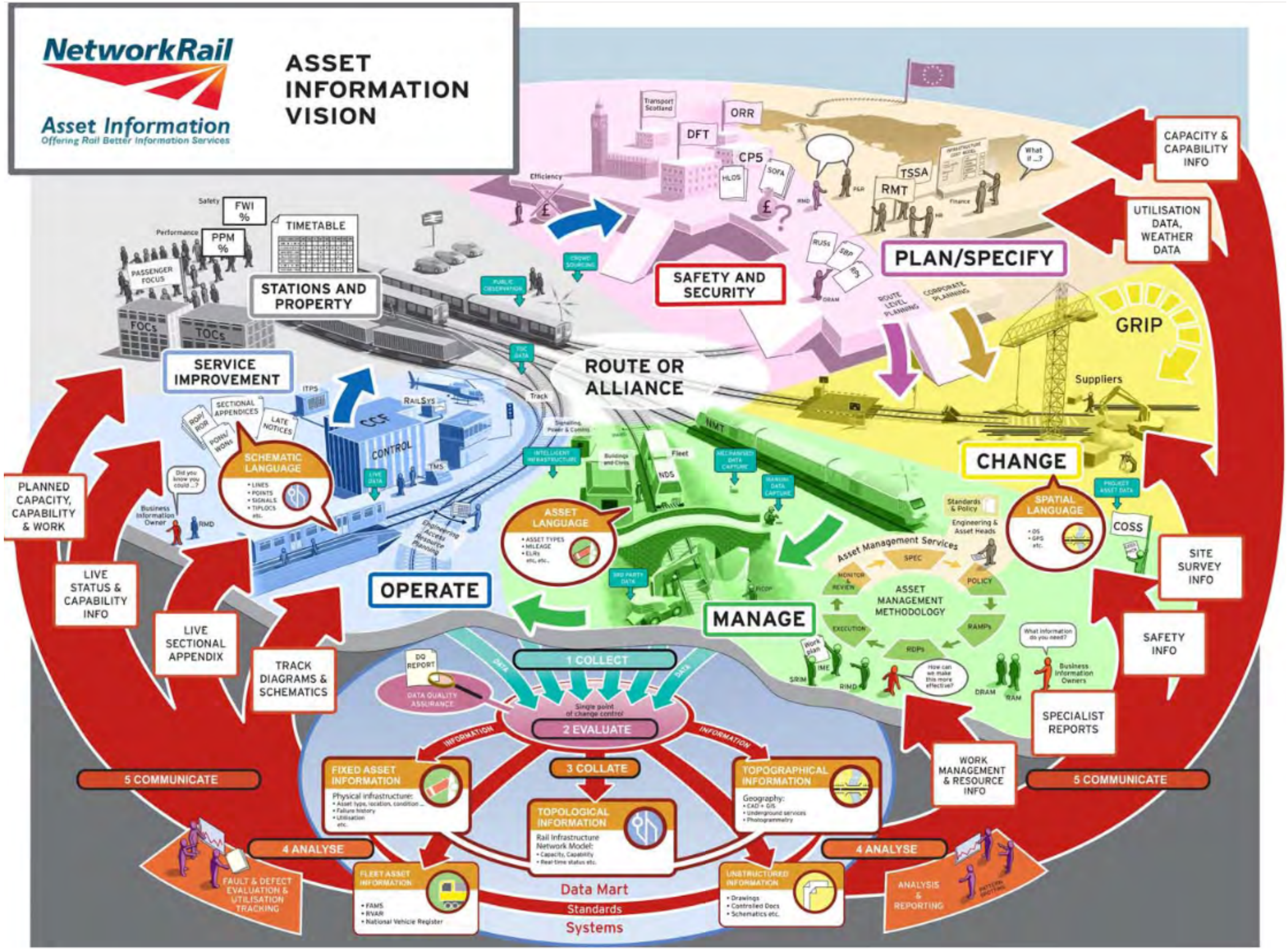

Figure 2-10 NetworkRail Asset Information Vision [134]

During the interview, NR noted that while ORBIS has provided a great vision and foundation for the required organisational culture change, along with providing a high level of quality and assurance of data that is used for organisational decision-making processes, its technical implementation was limited. Furthermore, engagement between the ORBIS team and O&M personnel were limited, and therefore, their requirements were missing from the final products.

2.5.4. Industry investigation summary

It is witnessed that the organisations interviewed have established or are in the process of establishing an asset management system. NR and HE see asset management as a tool to control increase financial pressure, while TFL also sees it as a way to save costs, but also as a tool to integrate its different organisational systems under a single strategy, that meets the organisational requirements. Furthermore, Crossrail and HS2 have used asset management as a tool to make O&M decisions within the design and construction phases.

From a BIM perspective, the organisations stressed that they have adopted the BIM specifications and are developing a set of BIM documentation to guide their BIM adoption journey. NR, TFL and HE have well documented BIM processes and invested heavily within their development. Despite this, it was noted that the full benefits of BIM had not been realised. In contrast, EH as a manager of historical assets, do very little design and construction work and therefore see the benefits of utilising BIM within the O&M phase as a way to preserve and protect assets by utilising digital processes.

Furthermore, as EH is currently going through an organisational change that will see its funding reduced from central government, BIM is also seen as a critical tool for cost savings. Crossrail and HS2 are major capital work projects and therefore have a strong focus on BIM within the design and construction phases, developing processes such as clash detection and design collaboration. Furthermore, both Crossrail and HS2 have developed an extensive process to support the exchange of BIM related data from the design and construction phase into the O&M phase.

An interesting observation is that while all the organisations have some form of BIM and asset management processes, there have been limited attempts to create an alignment between both workstreams. It was noted that the BIM and asset management teams where siloed within the organisations and integration between the teams were rare, despite there being an awareness that BIM can significantly help the objectives of asset management.

The aim of the industry investigation was to validate the challenges identified within the academic literature review are indeed presented within a *"real-world"* environment, along with identifying the current *"state of play"* within industry. The outcomes of the industry investigation are summarised below:

- Indeed, the industry investigation confirmed that the challenge of developing information requirements that is identified within the academic literature is presented within industry. Furthermore, the investigation highlighted the challenge in specifically developing OIR, with none of the interviewed organisations having developed one, noting the lack a form approach, limited resources and a robust business case. Finally, while most of the organisations have developed some form of AIR, they do not align to an OIR and are purely from a technical perspective.
- While All of the organisations understand the value of information requirements, which is presented within their BIM and digital strategies, it was noted that it is considered a *"BIM thing"* and therefore left to the BIM department. This approach is not conducive with developing *"good"* information requirements, as the literature review noted that to achieve efficient information requirements multiple stakeholders from all departments are needed to get a clear consensus.
- A clear disconnect between asset management and BIM was witnessed both within the interviews and reviewing the organisational documentation. In all cases, it was clear that the asset management and BIM departments where isolated from each other, with no real connection between them, despite wanting to use BIM within asset management. While this disconnect is also noted within the literature review, the understanding of how to address this challenge is limited within industry.
- The disconnect between BIM and asset management is also noted from a technology and data perspective, with the development of BIM management systems which have limited integration into asset management systems. The

interviewed organisations noted that this resulted in BIM models developed during the design and construction phase that add little value within the O&M phase. furthermore, BIM information management processes in general were seen as a design and construction tool and not an asset management tool.

The industry investigation confirmed that the challenges identified within academic literature review are presented within the interviewed organisations to a large degree. Furthermore, the investigation noted that real-world challenges developing information requirements and the alignment between BIM and asset management, both from a technical and managerial perspective. There is a clear need for a framework to support the development of information requirements within an asset management organisation, with the aim to enabling BIM within asset management.

2.6. Summary of challenges Identified

The literature review focused on the domains of asset management, BIM, requirements engineering, information requirements development and asset information structure. The review revealed that asset management is the evolution from a traditional maintenance strategy, that was purely focused on maintenance with little consideration to the broader organisation. There is a growing set of asset management literature that generally fits into two domains. Firstly, addressing the data and information management challenges and secondly addressing the organisational managerial challenges. Asset management ISO 55000/1/2 [1,19,20] standards aim to standardise the approach of developing, implementing and maintaining an asset management system. While these standards state what *"shall"* be done, they do not reference any tools or frameworks to aid in achieving them. Correctly, a strong focus is put on developing information requirements to support organisational wide technology adoption. While BIM has been widely cited as a means of addressing the complexity of the information management challenge, it uses within asset management has been limited. BIM has been widely adopted within the design and construction phase, its use within the O&M phase is a natural progression, as the O&M phase is the vast majority of an asset life cycle. While the advantages of utilising BIM within the O&M are highlighted, several challenges are holding back its adoption:

- The industry investigation highlighted the fact that asset management teams and the BIM teams rarely communicate with each other. BIM is often considered as an IT solution that is utilised by capital work projects. Ultimately this disconnect means that BIM models and processes are not designed for the O&M phase and therefore are not fit-for-purpose for the asset management team, generating little overall value.
- The communication disconnect between the asset management team and the BIM team, manifests itself into individual IT solutions, creating data silos that stop information being exchanged between different information systems and asset life cycle stages. While BIM has been cited as a tool to enable this integration, it will have little impact if it is not designed and developed from an asset management perspective.
- Historically, the asset management industry has been hesitant to adopt new and emerging technology, resulting in a culture challenge that spans the whole industry. Indeed, the lack of BIM and data management skills within asset management teams strengthen this cultural challenge.
- The standards and specifications review state what “shall” be done, but there is a lack of tools in achieving the requirements of the standards. This is witnessed when considering PAS 1192-3 [5], which has a requirement to develop information requirements. The literature review highlighted the challenges in defining information requirements, such as the lack of a structured approach to their development. Furthermore, the industry investigation noted the challenges of developing OIR within asset management organisations and the translation from OIR into AIR, this includes developing OIR from often abstract objectives, developing AIR for complex asset systems of systems and gaining consensus between different organisational functions.
- There is a fundamental challenge in understanding how to demonstrate the value of BIM within the O&M phase, this is limiting the development of a robust business case for commercial investment.

The literature review highlighted the fact that RE is a research domain that has grown out of software engineering, born for the need to capture user requirements for the emergence of IMS within the 1960s. It was quickly realised that you could not merely ask what information people require, as it will often be wrong and have a bias; therefore, a structured approach was required. The asset management industry and specifically the O&M phase has been late to adopt IMS, this is partly due to the complexity of developing information requirements. Feedback from the industry investigation noted that while RE goes some way to address the challenges, there are specific challenges within asset management that are not addressed within the common RE frameworks, these include:

- Assets are not single elements, they are hierarchical that consists of multiple systems of systems within sub-systems that can be vastly complex. The hierarchical nature of asset within asset management organisations create new levels of complexity, that is not addressed within the common RE frameworks.
- The nature of an asset means it goes through several different life cycle stages, there is a need to develop information requirements for an assets whole-life and these requirements will change as the same asset moves in and out of a specific life cycle stage, this life cycle approach is not currently captured within RE frameworks.

Both the literature and the standards review demonstrated the attempt to standardise asset-related information, IFC being the most advanced which is adopted into an ISO standard. IFC aims to standardise the exchange of information between different BIM authoring software and life cycle stages, including both the 3D geometry and associated metadata. The current version of IFC (version 4) schema has limited use within the O&M phase since the requirements built into the schema lack O&M requirements, such as whole-life costing and risk management. Furthermore, COBie as a sub-set of IFC is a simplified exchange protocol for exchanging information from design models into the O&M phase, which disconnects the information from the 3D geometry, therefore, limiting the 3D model overall use.

It can be witnessed in this chapter that there is a clear need for a framework that supports the development of information requirements in an asset management organisation, the lack of a specific RE framework that supports the complex challenges within asset management reinforces this fact. Furthermore, the historical lack of adopting digital processes and technology within the asset management industry has created a cultural challenge where information management is not considered as a value-adding exercise. BIM has been cited as a key enabler to support technology adoption. Specifically, PAS 1192-3 provides an approach to information requirements development, stating that organisations should develop a set of OIR and AIR. The industry investigation noted that this approach is too simplistic and does not address the complex requirements within asset management, specifically lacking in guidance on how to develop an OIR and how the AIR should be generated from the OIR.

The literature review found that BIM has been widely adopted within the design and construction phase, with limited adoption within the O&M phase. This is partly because BIM models are not designed and developed from an O&M perspective and therefore generate little value. While COBie has been developed as a way to exchange information from design and construction into the O&M phase, it uses an Excel template that limits its technical implementation. While the proposed approaches aim to support the exchange of data into the O&M phase from a BIM model, they do not specifically aid in developing a BIM model for the O&M phase. It can be seen that there is a clear need for a framework to support the design and development of a BIM model to enables its use within asset management, including the development of information requirements.

2.6.1. Identifying the research gaps

The primary gap discovered out of the literature and standards reviews and the industry investigation found that there is currently no framework to aid in the development of information requirements for an asset management organisation.

It can be witnessed within the industry investigation, that there has been an enormous amount of effort devoted to the development of asset management and BIM. While in isolation, these efforts have generated value, they are limited by the fact that they are developed in isolation. It is clear that from an information requirements perspective, the current approach of developing BIM and asset management in isolation is inefficient with the need to develop information requirements.

BIM models are not created from the aspects of asset management, specifically the O&M phase, this is witnessed both within the literature review and industry investigation. The current ad-hoc and unstructured approach to information management means that data from the BIM model and the BIM model itself are not used within the O&M phase. BIM models are often contractually handed over to the asset management team in native formats with little standard structure to them and with limited training on how to utilise them. Furthermore, the BIM models poorly integrate into current asset management processes and IT solutions. This current approach is inefficient and is limiting the use of BIM within asset management.

As stated within the above section, RE is an efficient tool for the development of information requirements, but as asset management organisations have specific complex challenges (e.g. assets hierarchical nature), its common frameworks are limited. BIM has been cited as an enabler to the development of information requirements, but lacking a structured approach means they are often developed in ad-hoc and inefficient processes, if at all.

In summary, research gaps are developed to support the review of the research questions and provide guidance to target a research methodology. Developing and testing a framework for the development of information requirements to enabled BIM within asset management is a clear research gap. Give the research questions, the overall objective of this research effort is to address this research gap by providing a workable set of information requirements. However, the overall objective is to address this research gap as a whole by providing a reusable framework, not specifically developing individual information requirements.

3. Research Methodology

This chapter explains the research methodology utilised to develop the answers to the research questions, presented in Chapter 1 and is structured as follows. Firstly, investigating the structure of the research objective, along with a discussion on the different research methods and overall approach. Secondly, an introduction to the case study design with a discussion on the different tools and frameworks used. Finally, an approach to maintain research rigorously is proposed, along with the chapter conclusion.

3.1. Structure of the research objective

The research objective for this thesis is: "*to develop a methodology that supports the development of information requirements and enables the use of BIM models within an asset management organisation".* As noted within the Research Scope (Section 1.3) the information requirements within the context of this research effort is only focused on the *"What"* aspect and does aim to answer the how, when and for whom. The objective is achieved by answering two research questions.

The first research question: RQ1 "***How can an asset management organisation develop Asset Information Requirements that align to their asset management objectives?"*** is answered by the concept model presented in Section **Error! Reference source not found.** and the information requirements framework presented in Chapter 4. The concept model provides an approach to *"structuring something"* with predefined rules and approach that cannot be changed. While the information requirements framework provides an approach to *"doing something"*, it allows for flexibility in how it should be done, which is critical within an industrial environment that allows for the nuances of the *"real world"*, especially when considering the complexity of asset management organisations.
The second research question: RQ2 "***How should a BIM model be enriched for use within asset management?",*** is answered via the development of an Asset Information Model (AIM) derived from asset metadata that is embedded within a Building Information Model (BIM) (see Chapter 7).

3.2. Selection of research methods

The selection of a research method requires the understanding of what *"research"* means and how different approaches will impact the outcome of the research. Leedy and Orman [135] stated that *"Research is the process of collecting, analysing and interpreting data in order to understand a phenomenon*", reinforcing the fact that research is a structured approach that defines an objective, manages data and communicates the findings. It is also noted that research starts with one or more research questions, to aid the researcher in focusing on the phenomena of interest.

Within the literature, there are two main approaches to research: deductive and inductive. A deductive approach is when the researcher develops a hypothesis, which is tested and the outcomes examined to establish a theory. The hypothesis is developed from none or little existing knowledge. In contrast, inductive uses existing research data and knowledge as a means to build a theory. This is generally considered building on existing research. While the two approaches are different, they can efficiently be used together [136] and will have several advantages when considering the scope of this thesis. The deductive approach lends itself to the information and systems management processes within BIM, as the theories are well documented with a wealth of knowledge within the academic domain. In contrast, the use of BIM within asset management is not well understood. The literature review noted that the value of BIM in asset management is not well defined with limited examples. Therefore, the theory that BIM can support asset management organisations and enable greater efficiencies aligns itself to an inductive approach.

In light of this approach, the philosophical stance chosen is interpretivism, meaning that subjectivity should be considered when conducting the research. This approach is distinctly different from positivism, that states that the world is fixed and stable, so therefore, it should be observed and explained objectively, which emphasises the importance of empirical results. Given the researchers' industry knowledge and the subjectivity of developing information requirements, interpretivism is the most appropriate choice.

In addition, qualitative research is commonly the research method of choice for research in the operational domains of risk management, human resource, marketing and business strategy [137]. As the development of information requirements is an operational need, there is a consensus that qualitative research is the best approach for developing information requirements, such as requirements engineering (see Section 2.4).

Along with the use of inductive, the philosophical stance of interpretivism and the use of a qualitative research approach, Design Science methodology has been adopted as the research methodology [138]. Design science has been used widely within qualitative research, providing a structed approach to the development of a solution to a problem which is design, developed, demonstrated and evaluated [139]. Furthermore, the methodology complements a case study research approach, as it allows for feedback from the evaluation stages into the design and development of the solution, therefore enabling incremental improvements.

3.3. Research Approach

The research steps within Design Science methodology consists of six steps, including: 1) identify the problem, 2) design a solution, 3) design and development, 4) case study, 5) evaluation and 6) communication.

The research approach has adopted the six steps in total and grouped them into three research phases, which are demonstrated in Figure 3-1.

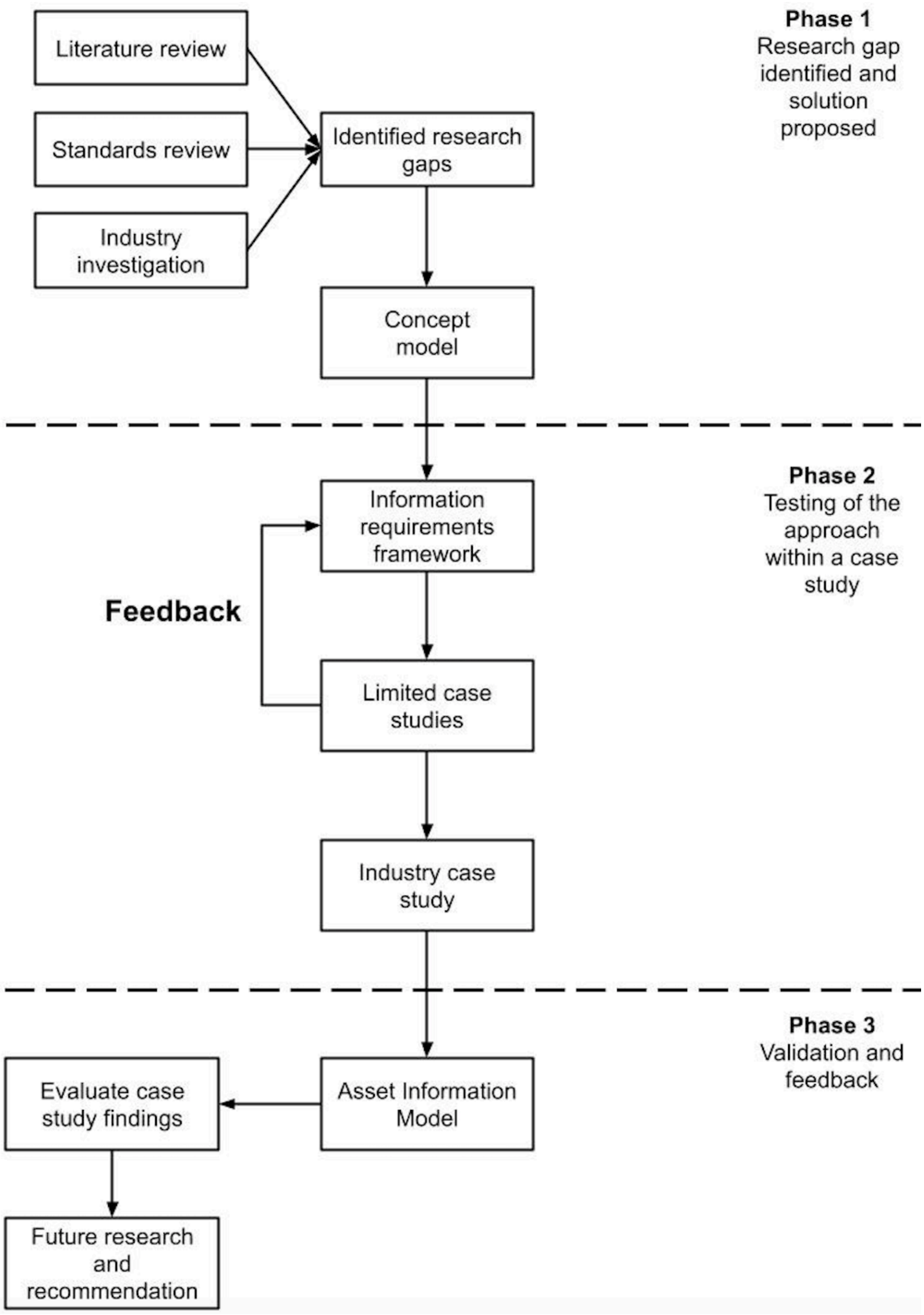

Figure 3-1 Research approach

The first phase highlights the research gaps and identifies the key problems that the research is addressing from the literature review, standards review and industry investigation. Along with the research gaps, a concept model is developed that aims to provide a solution to the identified problem of developing information requirements for asset management.

the second phase includes the development, case studies and evaluation steps. The solution within the concept model was used to design and develop the information requirements framework, that went through several iterations as feedback came from a number of case studies. A single large scale case study was conducted on the final version of the information requirements framework.

the third and final phase, is the valuation of the industry case study, along with future research recommendations. The final solution itself is communicated internally within the case study partners and externally within several journal publications.

3.3.1. Selected research methods

Given the nature of the research questions, objective and the complexity of the research area, a mix of research methods are best placed to provide in-depth results, the below research methods have been utilised.

The below mix of methods are commonly used within qualitative research. Furthermore, the methods directly align to Design Science methodology, with the literature review, interviews and direct observations support the identifying the problem, defining a solution and development steps. While the Joint Design Application and Action Research workshops support the case studies and evaluation of results.

- **Systematic literature review –** is a structured approach to a literature review that defines the collection, critically reviewing research studies and synthesising the findings [140]. A systematic review is formulated around the development of research questions that narrow and guides the review process. The systematic review approach was chosen consists of 5 steps, defining a question(s), research of relevant literature, the grouping of relevant literature, assessing the quality of the literature and analysing, reporting and summarising on the key aspects of the literature [141]. The concept model presented within Section **Error! Reference source not found.** and **Error! Reference source not found.** is a result of the systematic literature review.

- **Interviews –** an interview is described as a meaningful conversation where one person askes predefined questions within an informal or formal manner, and another person answers them [142]. Interviews are a popular qualitative research method that aims to develop research findings from social interactions, to understand the meaning of what the respondents says.
- **Direct observation –** is the process of directly or indirectly observing a subject within their natural environment and documenting the process observed [143]. This process aims to collect qualitative data, with validation and thoughts from the researcher.
- **Joint Design Application (JDA)** – is a generic term that describes a set of tools and methods for conducting a workshop that aligns the requirements of users and the technical development for an Information Management System, such as planning, defining requirements and user interface [144]. Due to the complexity of asset management organisations, a JDA workshop is an appropriate tool to align the requirements of non-technical personnel with technical requirements.
- **Action research workshops –** is a workshop approach where the researcher is not only observing but is also facilitating to gain insight to the research complements aspects of a JDA workshop as described above.

3.4. Case study design

A case study is a powerful tool for validating the framework and is a well-used technique, but is not without its limitations such as resource management, bias and poor-quality data capture. Therefore, the design and development of the case study are critical to the validity of the research.

3.4.1. Case study criteria

Building theories through case study research, requires the development of cases, the process in which the cases are selected, is as important as the techniques used within them [145]. The case study selection is based on the following criteria:

- The organisation should be considered an asset-intensive organisation (such as asset management) that operates and maintains a wide variety of complex asset systems. The organisations assets should provide a function or a service, such as a railway network.
- The organisation has an asset management system in-line with the ISO standard 55000 [22]. It is appreciated that the design, development and implementation of an asset management system is a gradual and ongoing task. As a minimum asset management objectives, vision and plans should be developed and documented in such a way that the researcher can review them.
- Similar to asset management, the organisation is on a journey to adopting BIM information management processes in-line with the PAS 1192-3 specification [5]. While different organisations can be at different levels of BIM maturity, the organisation must have strong leadership that supports BIM adoption.
- The organisation can share asset-related information, such as design parameters, performance and failures, along with asset management documentation such as Strategic Asset Management Plan (SAMP) and objectives within a secure digital environment that does not limit the researchers ability to perform the case study.
- Access to senior and technical stakeholders within the organisation for interviews and engaging in workshops is critical for the case study success. Resource management techniques are used to ensure efficient use of stakeholders time.

3.4.2. case study tools and activities

Figure 3-2 illustrates the case study steps. Firstly, an initial introduction by the researcher is conducted, along with interviews with key personnel within the organisation to get their "*buy-in"* into the case study. Furthermore, an introduction is provided to the researcher by the organisation about the different asset management systems in use, such as BIM, costing, planning, health & safety, maintenance records and asset performance. Secondly, a workshop is conducted in line with the information requirements framework. Thirdly, the results of the information requirements framework are developed into an AIM. Finally, feedback is provided on the process and outcome of the case study providing recommendations and future research opportunities.

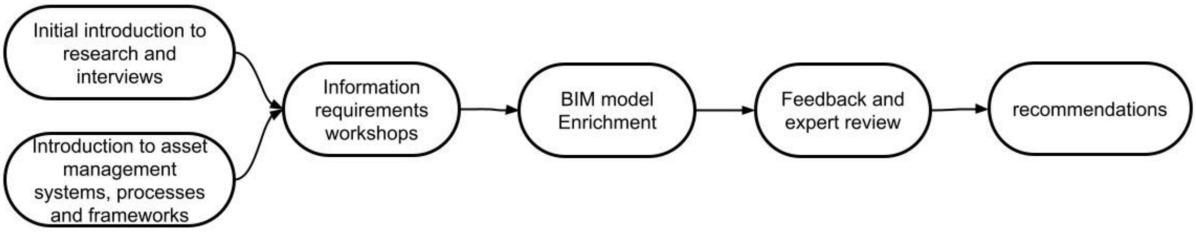

Figure 3-2 Case study tools and activities

A case study approach requires the need for *“real world”* feedback to support iterative learning, enabling the framework to evolve. A feedback loop, simply sometimes called feedback, occurs when an output of a system is routed back into the input of the system. There are two types of feedback, positive and negative. There are several examples of the development of a positive feedback loop related to the asset management industry, safety knowledge feedback [146], quality management [147] and performance enhancement within the construction and design phase [148].

A positive feedback loop has been adopted as a means to provide feedback from the output of the case study to support iterative learning, along with findings and recommendation for future research opportunities.

3.5. Conclusion

This chapter discussed the research methodology, tools and methods that are used within this thesis. The structure and approach to the development of the research objective and research questions are discussed, along with research methods. An overall research approach is provided within Figure 3-1, with selection criteria, tools and methods used within the case study. Overview of the case study approach and tools used is presented in Figure 3-2. Finally, a brief discussion of the research validity assures that the research is conducted in a structured approach that gives weight to the findings.

4. Information requirements Framework

4.1. Introduction

This chapter discusses the development of the information requirements framework. The framework adopts concepts from requirements engineering and information requirements development from Building Information Modelling (BIM), including the development of Organisational Information Requirements (OIR) and Asset Information Requirements (AIR). The framework is the results of the literature review and has gone through several iterations from a set of case studies providing feedback into the frameworks development, this chapter discusses the frameworks development evolution.

There are two core activities required to develop information requirements: (1) to understand the requirements of an organisation and (2) what information is required to achieve the requirements.

Along with the framework, a concept model is also presented, enabling the alignment of asset management within BIM via the development of information requirements, the concept model provides the solution to the problem, while the information requirements framework is designed and developed to address the solution.

4.2. Assumptions

This section outlines assumptions used within the development of the Information Requirements framework, categorised as asset management and BIM assumptions.

4.2.1. Asset Management assumptions

The below assumptions are related to the development of an asset management system:

- The organisations asset management system is compliant to ISO 55000 [22] and derived from the overall business strategy perspective, such as mission statements, visions and objectives.

- The asset management system is stable, with little changes throughout the case study, along with a high level of understanding of the basic concepts of asset management.

4.2.2. BIM assumptions

The below assumptions are related to the adoption of BIM and the development of BIM models:

- The organisation has a comprehensive understanding of BIM as defined within the PAS 1192 [5,99,102,106–108] and ISO 19650 [103,104] standards.
- While it is not required for an organisation to have *"fully"* adopted BIM, they will have basic BIM concepts in place, including a Common Data Environment (CDE), and the use of BIM-related documentation such as BIM execution plans, Information Delivery Manuals (IDMs) and Master Information Delivery Plan (MIDP).
- It is assumed that the organisation uses object-orientated 3D models in the design and construction phase, which are identified as Project Information Models (PIM) within the standard PAS 1192-2 [106]. Ideally, the models will be developed to a standard data structure that includes the classification of objects within the model, but it is accepted that this is not always possible due to the current lack of guidance.

4.3. Concept model

As discussed within the background chapter, there is a fundamental disconnect between BIM and asset management, both within the academic literature and within industrial applications. Furthermore, it was noted within the industry investigation that the need for the OIR to generate the AIR, is too much of a jump for most organisations, which results in poorly developed AIR that is not derived from the OIR. To support the OIR generating the AIR, a concept model has been developed that provides the foundations for the development of the information requirements framework. Specifically, the central aspect of the model is to align documents used within the development of an asset management system to the BIM information requirement approach, to support the development of OIR and AIR. See **Error! Reference source not found.**.

The left-hand side illustrates the documents created when developing an asset management system, while the right-hand side illustrates the BIM information requirements development. The arrows demonstrate the relationships between asset management documentation and BIM information requirements. The dotted lines from the AIM to the Functional Information Requirements (FIR) and the OIR indicate a validation process. The individual grey squares indicate the creation of a document or a set of documents, the squares within the Capital Work Project section highlight the information and model requirements needed for a new asset being constructed and therefore, the information needed for the design and construction phase.

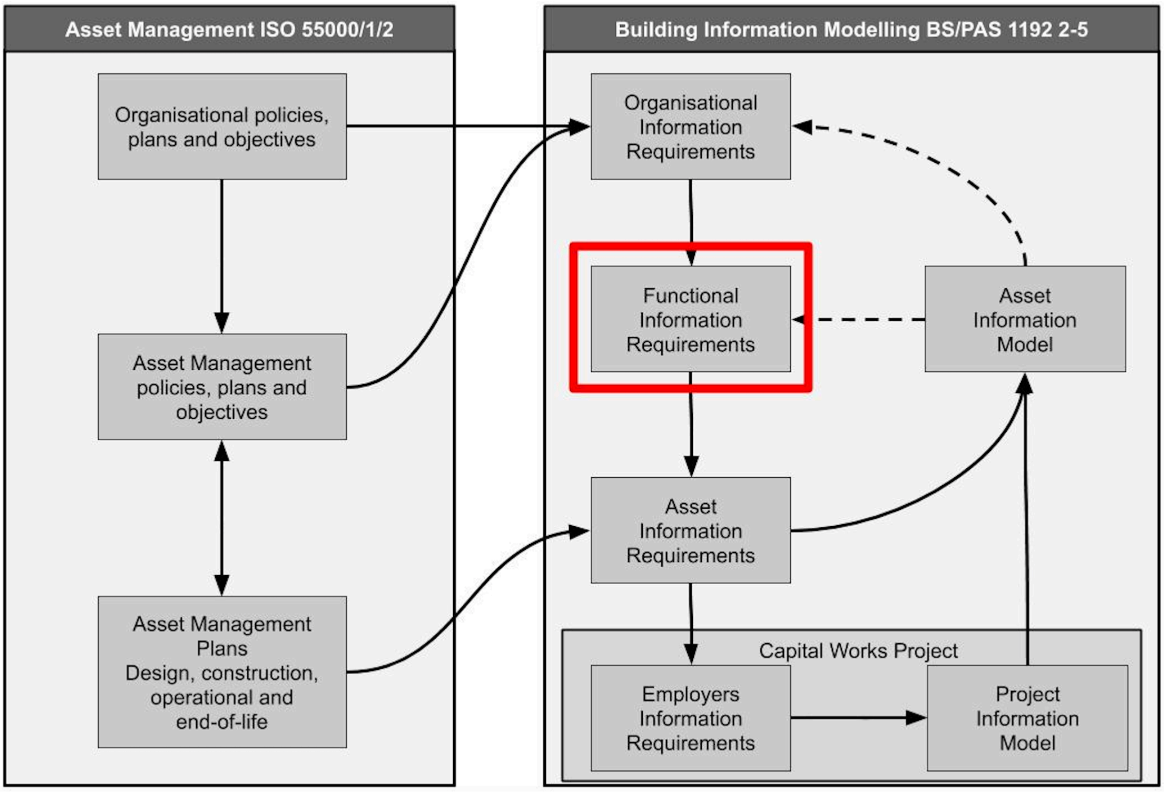

Figure 4-1 concept model for aligning asset management to BIM

The red rectangle within **Error! Reference source not found.** highlights a new set of information requirements that have been developed to aid in bridging the gap between the OIR and the AIR, Functional Information Requirements (FIR), which form a vital part of the information requirements framework and are discussed in detail within Section 6.2.

The concept model provides a mechanism that enables alignment between the concepts of asset management and BIM and supports the development of the information requirements framework presented in detail below.

4.4. Information Requirements Frameworks Evolution

This section discusses the evolution of the information requirements framework. Following the Design Science methodology approach the framework has been developed to address the proposed solution presented within the concept model. The framework has gone through several design and development, case studies and evaluation phases, with feedback being looped back into the framework development, for the point of clarity only the major iterations are discussed.

4.4.1. Initial Framework

The initial framework was derived from the literature review and industry investigation, as a tool to aid in achieving the solution proposed within the concept model, see Figure 4-2. The framework consisted of six steps in total that include:

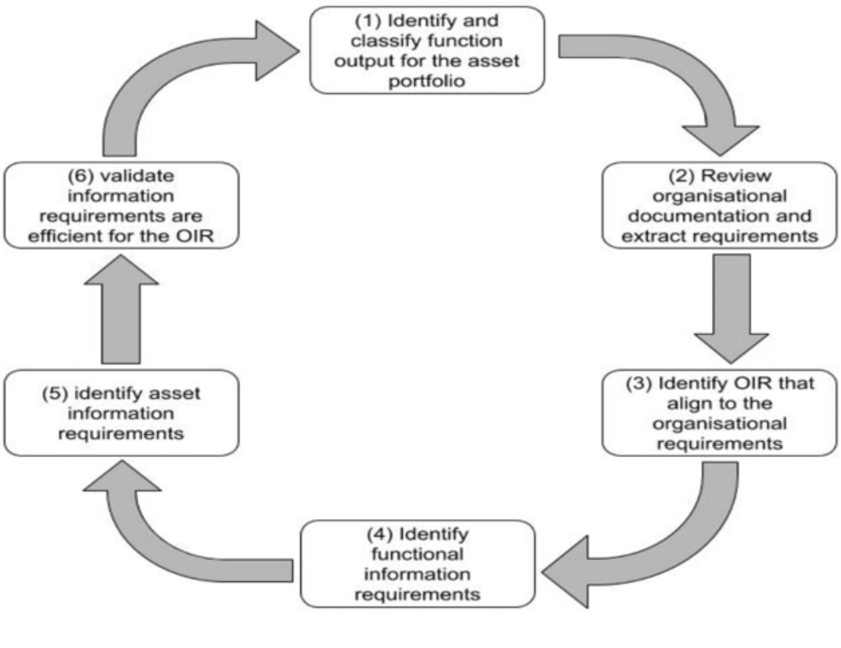

Figure 4-2 Initial information requirements framework

1. Development of an asset classification system that captures an assets functional output, asset system and sub-system, supporting the development of the FIR and alignment to the AIR.
2. The capture of organisational requirements within a single source document. Supporting the need to have a single source of access for organisational requirements, for alignment to the OIR.
3. Development of OIR. The OIR were captured within an information requirement matrix, that aimed to capture the information requirements within the fundamental asset management categories of value, alignment, leadership and assurance as defined in the asset management standards ISO 55000 [1].
4. Development of FIR, a new set of information requirements that aims to align the OIR to the AIR, addressing the challenge of often non-technical requirements within the OIR generating AIR.
5. Development of AIR, forms part of the BIM requirements, utilising the same information requirements matrix as it the development of OIR and FIR.
6. Validation of information requirements, the OIR, FIR and AIR are validated in a collaborative workshop, where the individual information requirements are validated against their need for the organisational requirements.

The framework was tested within an industry case study with English Heritage (EH). The case study consisted of several workshops with key stakeholders. While it was noted that the framework supported the development of OIR, FIR and AIR that aligned to the organisation requirements, its value was limited as it was not clear how EH could use them within their current asset management systems. Furthermore, it was noted that in step two the extraction of organisational requirements was vague, with the lack of a definition of a requirement. Moreover, the categories within the information requirements matrix are abstract in nature, while they help within the OIR step, they provided little value within the FIR and AIR steps. Finally, it was noted that there was not a clear end to the framework, as the arrows showed a continues flow and the information requirements themselves where not documented for the wider organisational use.

The initial framework development and case study results were published within a conference paper [149].

4.4.2. Revised Framework

Using feedback gained from the initial case study, a revise framework where developed, which consists of two individual frameworks (information requirements framework and the BIM model enrichment framework) that work together to support the development of the information requirements and the development of an AIM. The revised information requirements framework uses the same six steps from the initial framework, but with an additional seventh step that aimed to document and communicate the information requirements, see Figure 4-3. Given the feedback from the EH case study, several modifications where adopted:

- Steps one and two have been swapped, with the capture of the organisation requirements coming before the development of an asset classification system. Furthermore, the requirements has been defined as asset management objectives as stated in ISO 55000 [1], removing the vagueness of what is a requirement. Moreover, a set of categories for grouping the asset management objective were used, this was derived from feedback to provide a *"structure"* in identifying and documenting the requirements. The categories are derived from reviewing objectives documented within the case studies and include financial, operational and Environmental.
- Given the fact that step one is now the capture of asset management objectives, there is a prerequisite need for the developed of an asset management system before using the framework, this has been captured within the framework as a *"pre-step"* before step one.
- Feedback noted that the information requirements matrix use of the asset management fundamental where abstract in nature and did little to support the development of the information requirements, therefore they have been replaced by the categories of managerial, technical and financial. The categories were adopted from BIM standards PAS 1192-3 [5] and with feedback from the EH case study.

- A feedback loop was added from the validation process (step 6) back to the AIR development process (step 5), this enabled feedback from the validation step into the information requirements development.
- There is now a definitive end to the framework, with the additional step seven documenting the information requirements, asset management objectives and asset classification within a structured approach enabling the dissemination of the output for both internal and external stakeholders.

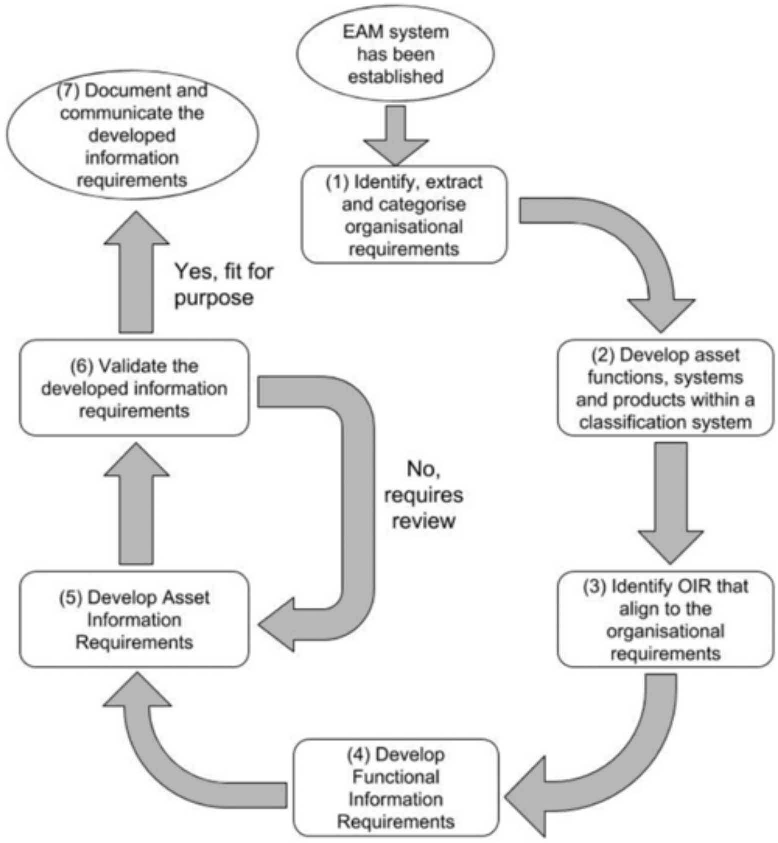

Figure 4-3 Revised information requirements framework

Addressing feedback on how to utilise the newly developed information requirements within a BIM context, a new framework was developed that aided to address this challenge, see Figure 4-4. While this framework is separate to the information requirements framework, it utilises the asset classification developed in step two as a means to support the development of an AIM, that captures the OIR, FIR and AIR.

The framework was used in parallel to the information requirements framework, the steps of the framework are as follows:

1. Step one is the development of an asset classification system that is identical to the asset classification system developed within step two of the information requirements framework, this step should utilise the same classification system to minimise duplication of work and ensure alignment to the information requirements (OIR, FIR and AIR).
2. Step two utilises the asset classification developed in step one to classify all the assets (objects) within a BIM model. As the same classification system is used to develop the information requirements, this creates the alignment between the requirements and the BIM model. This step includes a sub-step, which is the development of custom IFC parameters to store the asset classification codes directly within the instances of the assets within the BIM model.
3. Step three is the development of an AIM database, which is a relational database that is derived from the asset classification system. The OIR, FIR and AIR form the Metadata for the database tables.
4. The final step is the need to populate the AIM database with the assets classified within the BIM model, this is achieved by the development of an extraction platform that imports an IFC export of the BIM model, reads the asset classification and inserts the assets metadata into the corresponding database table.

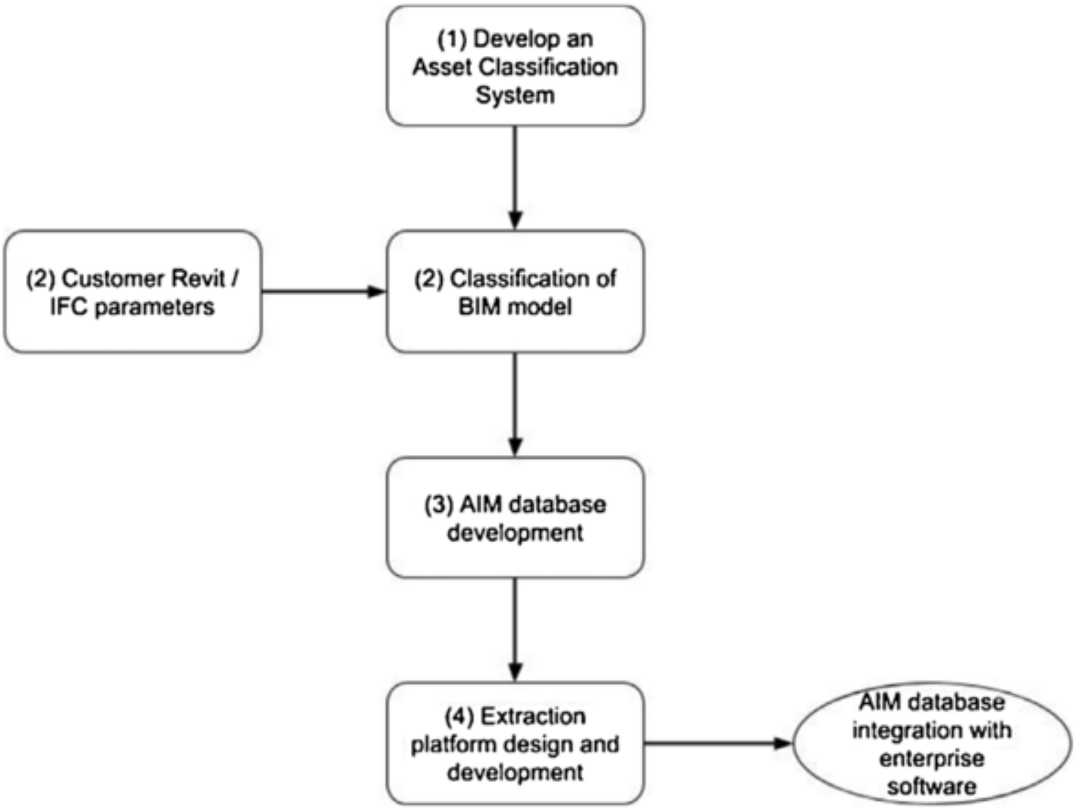

Figure 4-4 BIM model enrichment framework

The revised information management framework and the BIM model enrichment framework were tested within an industry case study at Transport for London (TfL). Similar to the EH case study, feedback noted that the framework was a powerful tool for the development of information requirements and that the use of FIR allowed them to directly link OIR to AIR, which has been a continues challenge. Furthermore, it was noted that running the BIM model enrichment framework in parallel to the information requirements framework gave a line-of-sight between the information requirements and the BIM models. Moreover, it was noted that the framework supported the exchange of BIM models from the design and construction phase into the operational and maintenance phase, creating an asset register like feature with all of the required OIR and AIR.

But the frameworks where not without its limitations. Having both frameworks working in parallel was confusing and often distracted the more technical stakeholders from the information requirements development process. Furthermore, it was not explicitly stated what where the dependencies between the frameworks, such as the development of the AIM can only be done when the OIR, FIR and AIR was completed, this was not realised until sometime into the case study. Secondly, it was noted that the sub-step of step 3 of the BIM model enrichment framework "*Custom Revit / IFC Parameters"* was confusing as this is done within the modelling software itself and forms a requirement for classification of the BIM model and therefore doesn't need its own step within the framework. Finally, it was noted that while the framework provided incremental value to the organisation throughout utilising it, it was not explicitly stated when this value was realised, such as what are the required steps to generating an OIR and does the whole framework need to be completed to realise the value.

4.4.3. Final Framework

Using feedback from the case studies, workshops and industry experts the final framework iteration was developed with the following modifications:

- Both the information requirements and the BIM model enrichment framework have been merged into one framework, resulting in a single ten-step framework.
- The sub-step of step 2 of the BIM model enrichment framework "*Custom Revit / IFC Parameters*" has been removed, as it forms a requirement of the BIM model classification step.
- The output of the framework is more specifically stated, being the development of an AIM and not an AIM that integrated into enterprise systems, as this is out of scope of the framework.
- The framework has been group into three parts, with each part having their own specific outcomes.

The final framework consists of ten steps, divided into three parts: (1) organisational level information requirements (2) asset level information requirements and (3) Asset Information Model (AIM) design and development, see Figure 4-5.

The framework is discussed in detail below, within the three parts.

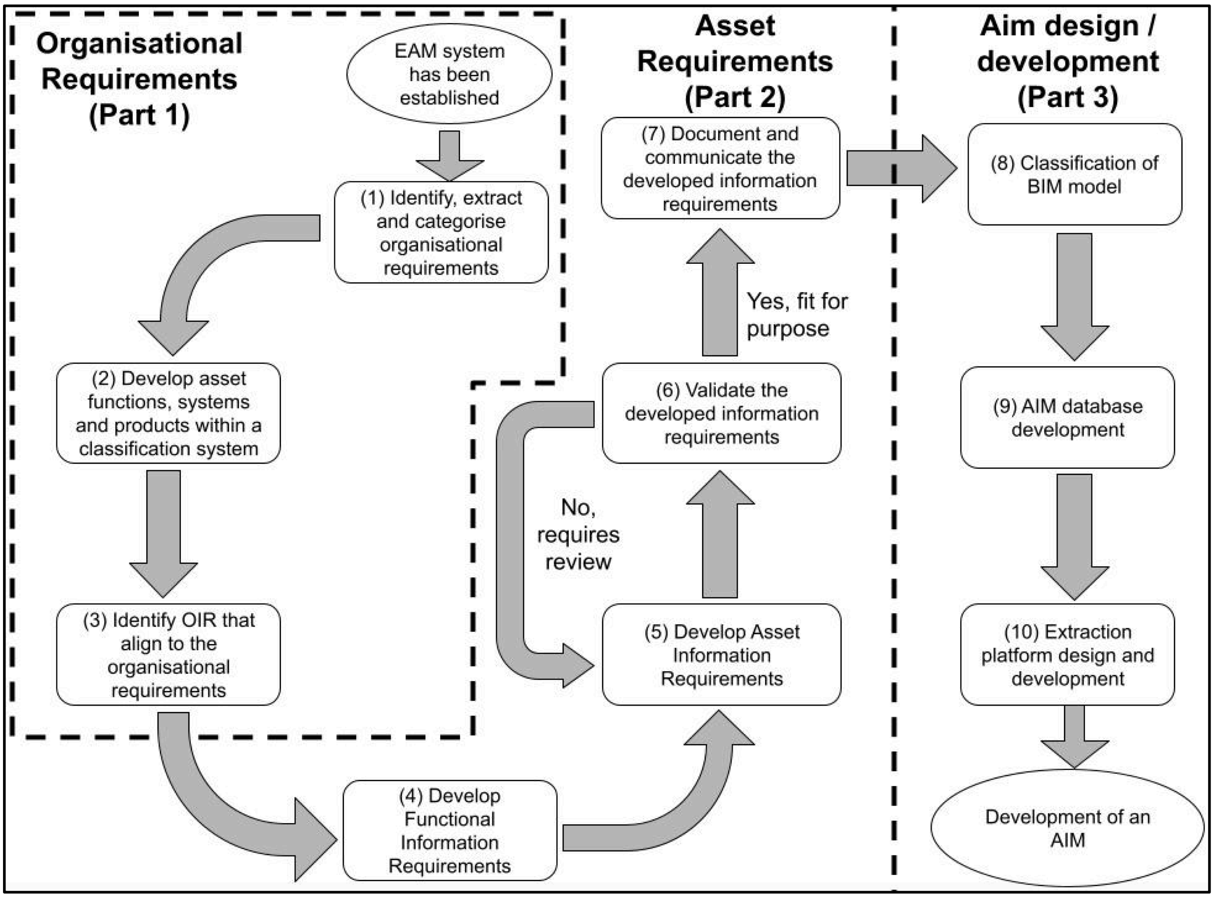

Figure 4-5 information requirements framework overview

Part one – developing organisational level information requirements

Part one is focused on the development of OIR and includes steps one, two and three of the information requirements framework.

Step one is a technical and managerial review of asset management related documentation to identify, extract and categorize asset management objectives into a single document. Step two is the development of an asset classification system that aligns to ISO 12006-2 [105] and supports the classification of an assets functional output, asset system and asset sub-system. Finally, step three is the development of the OIR, adopting techniques from requirements engineering and BIM to support the alignment between OIR and the asset management objectives identified within step one.

The outcome is a collection of asset management objectives that enabled the development of OIR. Furthermore, an asset classification system is developed that supports the development of FIR and AIR within part two and the AIM within part three. Figure 4-6 illustrates the three steps taken within part one and the outcomes on the right-hand side.

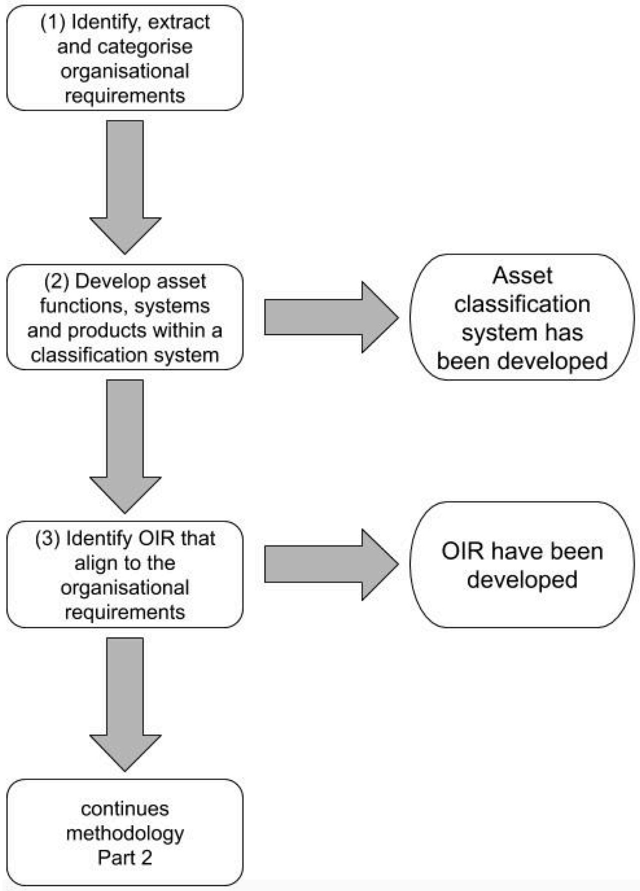

Figure 4-6 Part one steps and outcomes

Part two – developing asset level information requirements

part two is focused on the development of both FIR and AIR, along with the validation, documentation and communication of the newly developed information requirements, including steps four, five, six, and seven of the information requirements framework.

Step four is the development of FIR, a new set of information requirements that have been developed to aid in the challenge of OIR generating the AIR, based on an assets functional output. Step five develops AIR, requirements engineering tools are adopted to support their development. Step six validates the OIR, FIR and AIR, this includes a negotiating approach. Step seven documents and communicates the information requirements within a standard format.

The outcome of part two is a set of documents that capture the information requirements at both the asset functional output level (FIR) and the asset system and sub-system level (AIR). Furthermore, the documents are individually validated and documented. Figure 4-7 illustrates the four steps taken with Part two and the outcomes of the right-hand side.

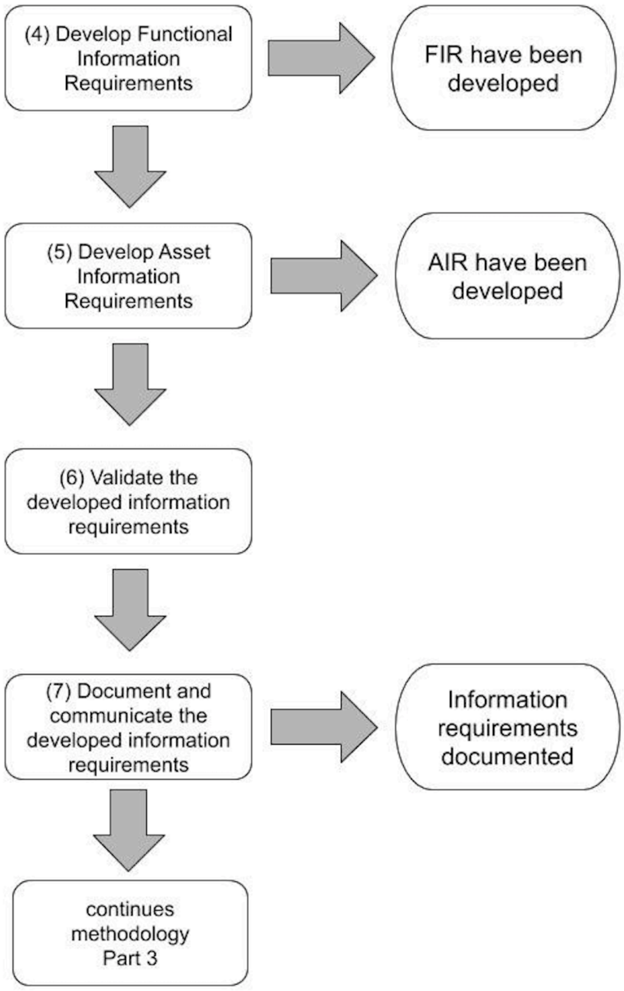

Figure 4-7 Part two steps and outcomes

Part three – design and development of an Asset Information Model

Part three is focused on the development of the AIM database that is derived from the asset classification developed within step two. Including steps eight, nine and ten of the information requirements framework.

Step eight develops a new set of metadata requirements that enables the asset classification to be attached to the associated assets within the BIM model. Step nine utilises the asset classification UML diagrams, as the means to develop the AIM database. Step ten is the development of a platform that enables the extraction of BIM related data from a BIM model into the AIM database.

The outcome of part three is an AIM, including a 3D model and a database that is derived from the asset classification within Part one and the information requirements (FIR and AIR) developed within Part two. Figure 4-8 illustrates the three steps taken with part three, with the AIM and AIM database as an outcome.

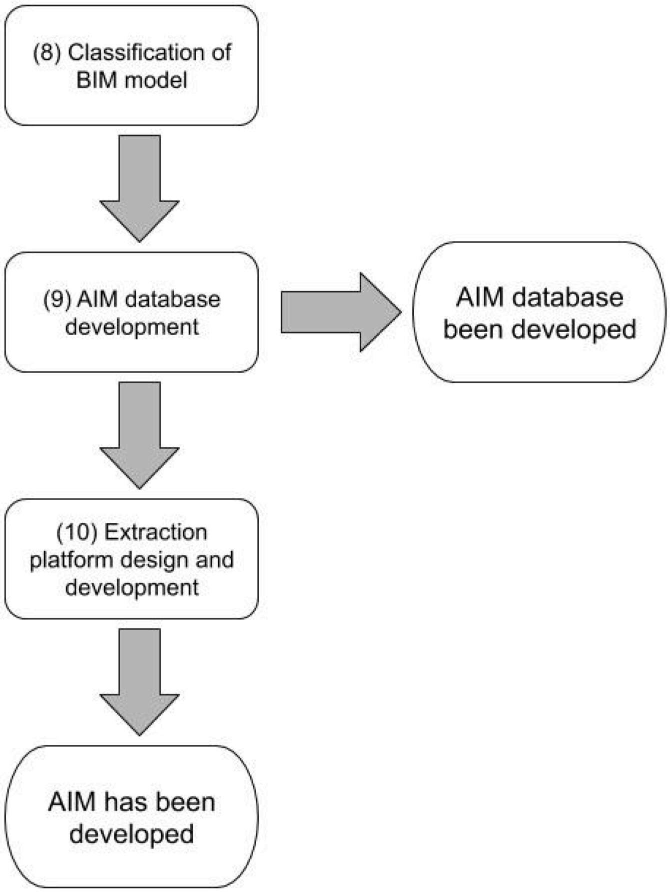

Figure 4-8 Part three steps and outcomes

4.5. Conclusion

This chapter discussed the design, development and evolution of the information requirements framework, along with the concept model.

Reflecting of the chosen research methodology of Design Science, the concept model provides a solution to the problem, which aims to bridge the gap between asset management and BIM via a structured approach to aligning both concepts and the use of FIR. While the Concept Model provides the solution, it was not address how to achieve the solution, the information requirements framework provides a process for achieving the solution, within Design Science this is called the Design and Development stage.

The framework was initially developed from the literature review, standards analytics and industry investigation. The initial framework was tested and evaluated within a case study, with feedback developed a revised framework. The revised framework was also tested and evaluated within a case study, with feedback developed the final version of the framework with is tested within a detailed case study presented in Chapter 8.

The three parts and ten steps of the information requirements framework are discussed, with the outcomes of each part summarised, along with the approach taken within the individual steps. A detailed discussion of the individual steps is provided in the following Chapters 5, 6 and 7, with a case study in Chapter 8.

5. Developing organisational level information requirements

5.1. Introduction

This Chapter focuses on the development of organisational level information requirements, encompassing steps one, two and three of the information requirements framework, see Figure 5-1.

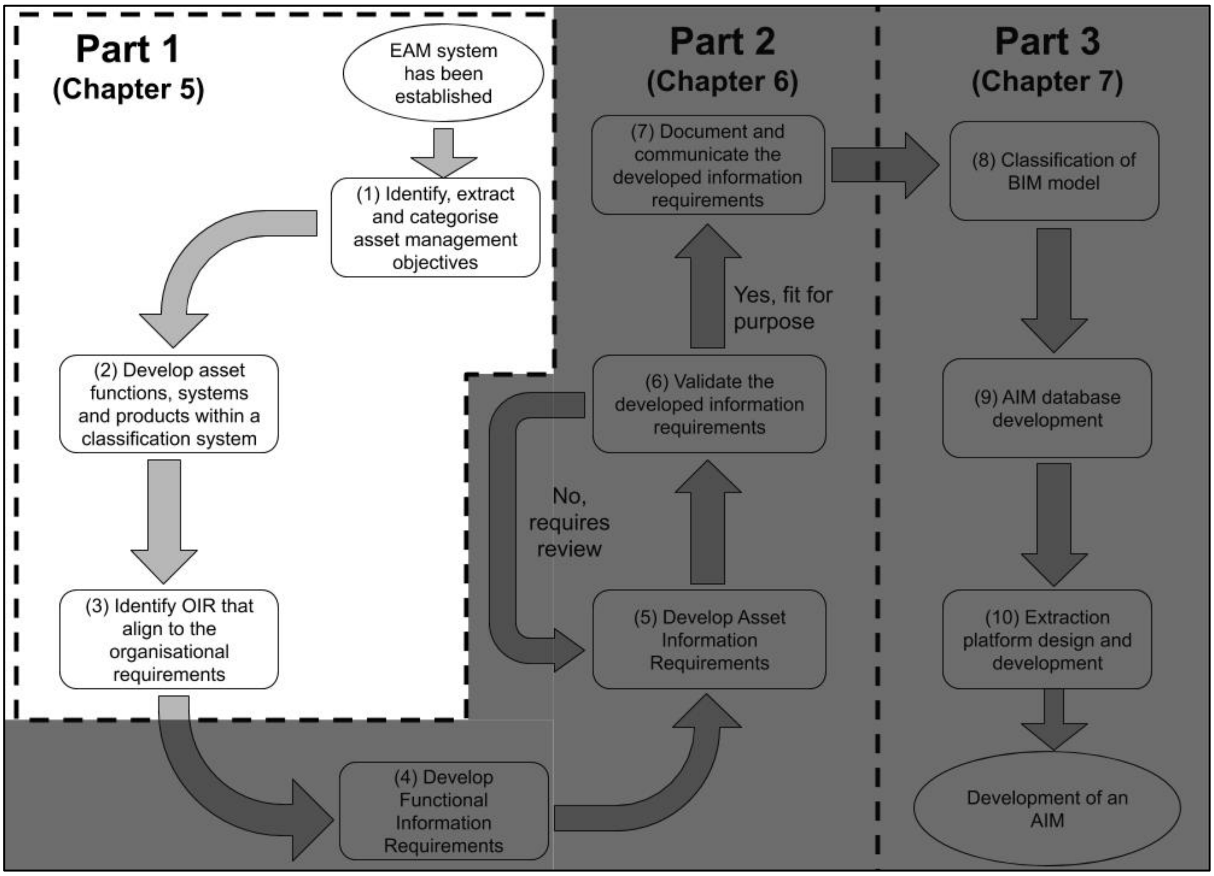

Figure 5-1 the scope of chapter four highlighted within the information requirements framework

This chapter aims to address the challenges of developing Organisational Information Requirements (OIR), the lack of a structured approach to their development is limiting the adoption of Building Information Modelling (BIM) within asset management.

Step one demonstrates how asset management objectives are identified, extracted and categorised. Step two develops an asset classification system that conforms to

ISO 12006-2 [105], and step three supports the development of OIR, utilising the asset management objectives developed in step one.

The outcome of this chapter is the development of OIR, derived from a single source of asset management objectives. Furthermore, an asset classification system is developed that supports the creation of Functional Information Requirements (FIR) and Asset Information Requirements (AIR) in part two (Chapter 6) and the development of an Asset Information Model (AIM) in part three (Chapter 7).

5.2. Identify, extract and categories asset management objectives

The aim of this section (step one) is to document a set of asset management objectives, which is divided into three sub-steps, as seen in Figure 5-2.

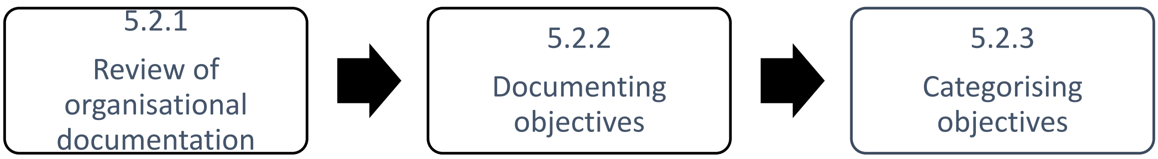

Figure 5-2 sub-steps within step one

Step one is reviewing documentation to identify the objectives, step two is documenting the objectives single accessible document and step three is grouping the objectives into categories.

5.2.1. Review of organisational documentation

This step is a review of organisational documents to identify asset management objectives, which are often in a collection of documents developed within individual organisational departments. Table 5-1 provides an overview of organisational, asset management and BIM-related documents that are a potential source of objectives, the SAMP and BIM Execution Plan where idented within the standards review and the remaining documents were identified within reviewing organisational documentation within the industry investigation.

Source of objectives	Description
Strategic Asset Management Plan (SAMP)	Strategic documentation developed as part of adopting ISO 55000, containing asset management objectives, goals and plans that align with organisational objectives.
Environmental Strategy	An organisational environmental framework and objectives to limit the impact of the organisations actions on the natural environment.
Customer Engagement Strategy	Provides a framework and objectives for engagement with customers and end-users, often containing engagement targets and customer satisfaction targets.
Financial Growth Strategy (Business Plan)	A strategic document that outlines the organisation financial growth plans and objectives.
Information/Technology Strategy BIM	Provides a framework and objectives for the implementation of technology and information management systems.
BIM Execution Plan	BIM-related requirements and objectives, most notably for the design and construction phase but could be utilised within the operational phase.

Table 5-1 source of objectives

The Mayfield Handbook of Technical and Scientific Writing notes that there are four common types of document reviewing techniques, peer reviews, technical reviews, editorial reviews and managerial reviews [150]. Peer review is the process of getting one or more people to review a document that you have personally written, which is not the case for this step as we are reviewing organisational documentation. An editorial review is the process of reviewing a document for spelling mistakes, formatting errors and presentation style. The managerial and technical review both analyse the context of the document from a managerial and technical perspective, therefore a combination of both these approaches have been adopted and are discussed in detail below.

A technical review is a comprehensive analysis that aims to find objectives within the documents. The technical review process finds objectives that are clearly labelled as objectives, that have a clear purpose and conform to the rules of a SMART (Specific, Measurable, Achievable, Realistic and Time-bound) objective [22]. In contrast, a managerial review is a comprehensive review of the text within the document, which aims to find objectives that are within the text but not explicitly labelled as an objective. As an example, an objective found through a managerial review could be to: "*Put in place an asset risk management approach and methodology that integrates with asset management processes"*. This it is clearly an objective but is missing the components of a SMART objective. If the purpose of the objective is not clear, an interview with the document authors should be conducted to ensure it is a valid objective.

The outcome of this step is a list of asset management objectives that have been extracted from asset management, BIM and organisational documentation, using technical and managerial document review approaches.

5.2.2. Documenting Objectives

The second step involves documenting the identified objectives from the multiple documents into a single accessible document, accessible in this context means a document that is easily human and machine-readable. Such document types include Microsoft Excel, Common Separated Value (CSV) or Structured Query Language (SQL) database tables. A single document for objectives has several advantages. Firstly, a *"one source of truth"* that can be cascaded throughout the organisation. Secondly, it is not required to read multiple documents to find the objectives and finally, a single source of objectives for the development of OIR.

The document aims to summarise objectives within a single table format that captures the below information:

ID – Captured against each objective and follows a standard approach. An ID allows for tracking the objective throughout the information requirement development process.

Objective- States the objective itself.

Timeline – The start and target date of the objective should be captured, allowing for analytics on how long is left to achieve the objective and validate that it has been achieved within the stated timeline.

Document – Highlights the document from which the objective has been extracted. This aids in analysing where the objectives are created in an organisation and defining the business owner.

Figure 5-3 provides an example of a Table created in Excel with an individual objective.

ID	Objective	Timeline	Documentation
AMO1	Reduce environmental impact of operational estate assets for BMF projects & the EM vehicle fleet by 6%	Finish_date=2020	SAMP

Figure 5-3 Objectives capture template

The outcome of this step is a single accessible document that contains all of the asset management objectives extract within Section 5.2.1.

5.2.3. Classifying objectives

The third step involves classifying the objectives. The literature review (see Chapter 2) noted that asset management objectives fall into one of three categories: (1) *financial*, the aim to increase revenue while controlling costs, (2) *operational*, increase or optimise operational performance and (3) *customer*, the need to meet the customer requirements. Furthermore, the industry investigation noted an additional three categories: (1) *environmental*, focusing on minimising the organisations impact on the natural environment, (2) health and safety (H&S), focuses on H&S related issues to both the workforce and customers and (3) reputation, dealing with public reputation of the organisation, including Marketing. Table 5-2 provides a definition of the objective category along with examples, for a point of clarity an objective is defined as: *"A result to be achieved within a given purpose"* [1].

Objective category	Description
Financial	Focuses on the financial aspect of the organisation, including such objectives as a reduction in operational cost or requirements for whole-life costing.
Environmental	Objectives fall into this category when they focus on an aspect of environmental impact. Such objectives include the need to reduce CO_2 emissions or preventing landfill waste.
Operational	Operational objectives focus on the specific operational performance of the assets, including maintenance. Such

	objectives include the need to increase the performance of an asset system or a reduction in reactive maintenance.
(H&S)	Any objective focused on the aspect of H&S both from a customer or a workforce point-of-view. Including such objectives as a reduction in employees' sick days or a reduction in customer injuries within a station platform.
Customer	Focuses specifically on the customer and not the performance of the asset that might impact the customers. Such examples would include an increase in customers satisfaction rating or a required number of customer engagement events within a given timeframe.
Reputational	Reputational objectives focus on the reputational value of an organisation. Such examples include customer feedback on marketing or branding.

Table 5-2 Objectives categories

Categorising objectives is especially important for the following reasons:

- Large organisations could have over one hundred objectives, and analysing these objectives is made simpler by categorising them.
- Categorising objectives can aid in identify where there is a lack of objectives within a given category, while also Identifying conflicting or duplicated objectives.
- Helps to identify a baseline of universal information requirements that are required for different organisational objectives within the same category, therefore reducing duplication of work.

The outcome of step one is a set of objectives that have been identified from organisational and asset management documentation, extracted into a single document and categorised as per their usage, providing the foundation for a clear set of OIR.

5.3. Develop assets functional output, systems and sub-systems within a classification system

The aim of this section (step two) is to develop an asset classification system, which is divided into three sub-steps, see Figure 5-4.

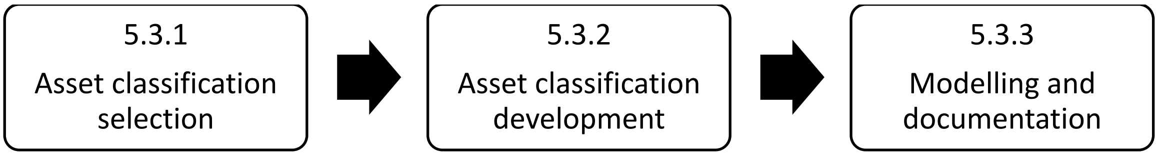

Figure 5-4 sub-steps of step two

Step one is choosing an asset classification structure and type for adoption. Step two is the development of an asset classification system based on the asset systems that the organisation maintains and operate, and step three is documenting the newly developed asset classification system within UML diagrams.

5.3.1. Asset aggregation and classification selection

This section firstly discusses the aggregation of an asset, meaning the parent-child relationship between an assets functional output, asset systems and sub-systems that support it. Secondly, it discusses the classification of the given aggregation.

It should be noted that one of the novel aspects of this research is the development of FIR, as noted within the concept model, therefore the chosen asset classification type must support the classification of an assets functional output. Furthermore, the hierarchical nature of the information requirements within the concept model (see **Error! Reference source not found.**) should also be supported by the asset classification type.

The literature review noted that ISO standards 12006-2 describes two types of asset aggregation. Type-of aggregation is when assets are grouped via a common property of interest. Initially, a generalised common property must be determined that represents all of the assets, subsequent assets are subdivided into specific sub-assets based on different properties. There is no limit as to how many assets or sub-assets can be created. The left-hand side of Figure 5-5 demonstrates the asset class of a wall, roof and floor as a sub-asset of the element. As an example, a wall could be further classified into internal and external walls and further again into wood walls, concrete walls and stud walls.

Part-of Aggregation is derived from the same principles but considers assets as being objects that are part of a system. Multiple assets can be grouped as a sub-system under a single system, and there can be an unlimited number of sub-systems. Systems and sub-systems can be classified from different aspects, as an example, a supply air ventilation system can be classified as supporting the functional output of ventilation or the need to provide a *"comfortable"* environment. The right-hand side of Figure 5-5 demonstrates a ventilation system having the sub-system of a fan. As an example, a ventilation system could have multiple asset systems such as natural ventilation and mechanical ventilation; within this example, the ventilation system could be classified as the functional output of ventilation.

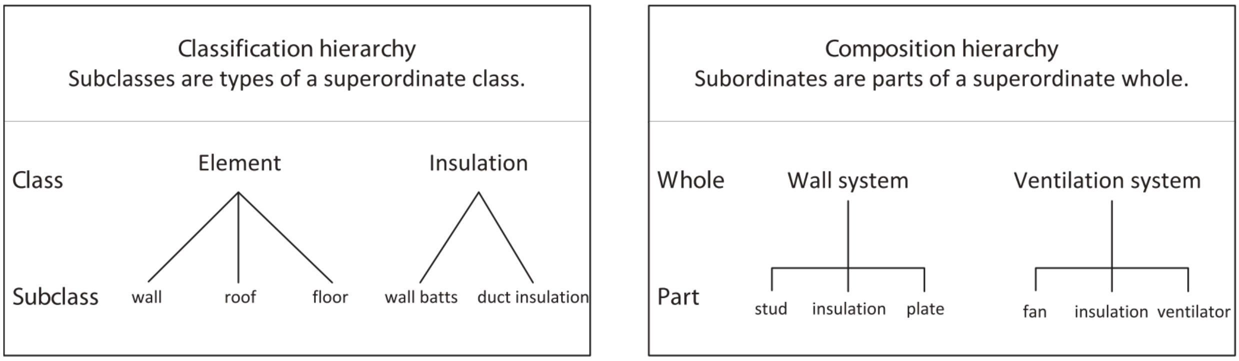

Figure 5-5 Type-of classification and part-of classification [105]

Both aggregations support a parent-child relationship, an asset can have both a *"type-of"* property and be *"part-of"* a system, as such there is no need to enforce the use of a given aggregation. Furthermore, both aggregations support the adoption of an asset classification system that supports the development of FIR and AIR.

While the aggregation provides the structure of a given asset, the structure itself does not provide a classification. Standard ISO 12006-2 provides a structured approach to the development of a classification system that is specifically designed for the classification of assets. There are two significant open-source adoptions of these ISO 12006-2. UNIClass [151] developed by the National Building Specification (NBS) in the UK and OmniClass [152] developed by Construction Specification Institute (CSI) in the United States.

This section discussed the different kind of assets aggregations for asset management, the type-of and part-of aggregations are not inclusive of each other and importantly they support the adoption of an asset classification system. BIM Standard ISO 12006-2 proposed an approach to developing an asset classification system for both type-of and part-of aggregations, while UNIClass and OmniClass are example classification systems, built especially for the construction and asset management industries.

5.3.2. Asset classification development

The development of an asset classification system is a complex task, especially when considering sizeable multidisciplined asset management organisations such as public transport providers and university campus estate management. The literature review noted that asset management organisations traditionally classify their assets at the product level, such as CCTV cameras or a ventilation unit, with little consideration to the overall asset system or functional output. This can be a daunting task, as even small organisations can have different individual assets that number in the thousands. Furthermore, there is a risk in alienating departments of the organisation that do not focus on the performance of individual assets but the functional output that they support, such as the financial or customer engagement department.

It is proposed that when implementing an asset classification system that the organisation classify the functional output of their assets. A functional output is defined as: "the function in which single or multiple asset systems supports its functional output". As an example, a gas radiator heating system or an electric heating system would support the functional output of heating, while an air supply system would support the functional output of ventilation. UNIClass Table EF provides a database of 76 functions that offers a comprehensive set of functional outputs covering infrastructure, buildings and civil works [153].

The key benefit of classifying functional outputs is that it supports the development of FIR, by providing a level at which information requirements can be developed for an asset. Furthermore, it provides a starting point for asset classification that is understood by different organisational departments. As an example, the customer relationship department within an estate management company will not have expert knowledge on asset system or sub-systems that support the functional output of heating, but they will understand the performance requirements (e.g. temperature) that the tenants require. Classifying an assets functional output enables the alignment of the functional output to the asset systems and sub-systems that support them, creating a direct line-of-sight from the functional output to its supporting systems.

It is also required to classify asset systems that support the functional output. Similar to the requirements for FIR, it supports the development of AIR. UNIClass provides a table for asset systems, Table Ss within UNIClass provides the classification of 2085 asset systems and sub-systems [154]. Only asset systems and sub-systems that support a functional output should be classified. Finally, the lowest level of asset classification is products. Similar to the functional output and asset systems, UNIClass has classified 6870 products within Table PR [155]. A product is an individual object within a given asset system. As an example, a thermostat or a radiator in a heating system could be classified as an individual product within the system. Care should be taken when classifying products, as classifying all the products within the asset systems can be a lengthy and expensive task. As an example, it would not often be justified to classify the product of a door system, such as the handle, hinges, glass panels or the frame since it is not be necessary to hold information at that level. When developing a classification at the product level, there should be a strong justification, such as a legal requirement. The AIR captures the information requirements at the asset system and sub-system level, therefore asset systems must be classified. Figure 5-6 demonstrates the relationships between the asset classification and the information requirements development.

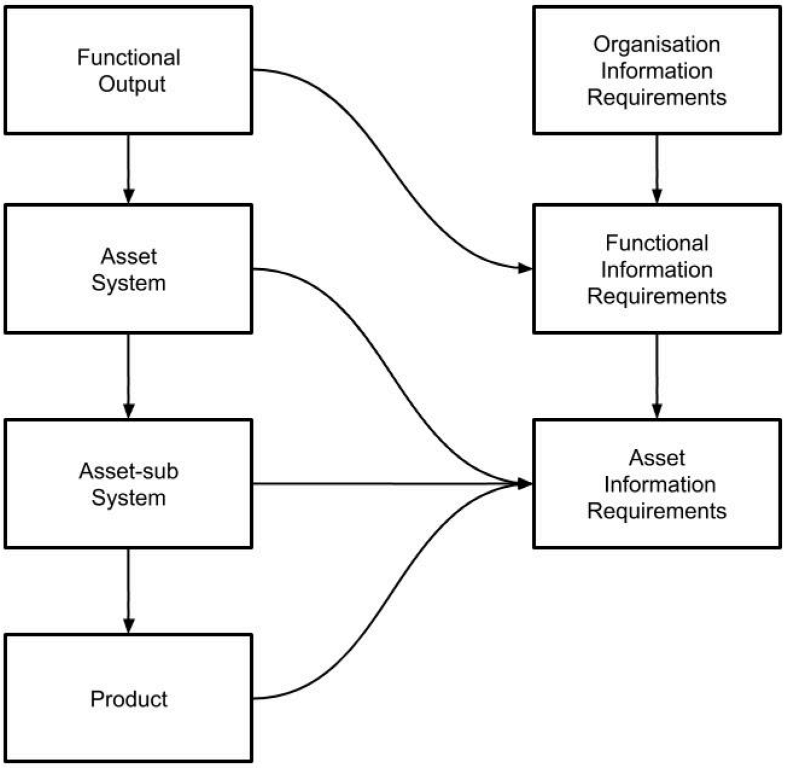

Figure 5-6 relationship between asset classification and information requirements development

The outcome of this step is an asset classification system that represented the organisational assets, including functional outputs, asset system, sub-system and if required products. While UNIClass examples are used, any classification system that supports a parent-child classification and conforms to ISO 12006-2 can be adopted, such as OmniClass [152].

5.3.3. Modelling and documentation

The final requirement is the need to document the newly developed asset classification system when considering the documentation process, there are several requirements, including:

- Accessible and readable by both technical and non-technical personnel.
- Any documented asset classification should be easily converted into a machine-readable format with minimal effort, while not impacting on the human readability requirement.
- The asset classification should be visualised within a diagram, that shows the relationship between the functional output and the supporting asset systems and sub-systems.

While the initial development can be handwritten, which would be common within workshops, the final version must be in a digital format. Furthermore, the format should allow for metadata to be attached to the assets within the diagram to support the future development of an Asset Information Model (AIM).

Simple diagrams in Microsoft Word or Google Drawings provide convenient access and easy to read diagrams but are limited in their use for future database development and lack the ability to capture metadata. Process mapping tools such as Visio [156], Xmap [157] and Coogle [158], are highly accessible via web sharing platforms and can capture metadata within the diagrams, but have limited capability in exporting the diagrams for future database development. A limited number of process mapping software allows for the export of an XML schema that represents the visual diagram, supporting the machine-readable requirement but is limited within database development, especially when considering complex diagrams.

When considering the requirements and the limitations in the above process mapping tools, the development of Universal Mark-up Language (UML) diagrams is an appropriate tool to document the asset classification. UML is a standardised development modelling language that is intended to provide an approach to the visualisation of a system, computer architecture or database schema. UML is a mark-up language that uses two diagrams types to visualise the relationships within a given system, structural (or static) and behavioural (or dynamic). Structural diagrams emphasise the static elements of a system, meaning objects within a system that does not regularly change over time. Behavioural diagrams focus on the dynamic nature of a system, such as a user's interaction within a given system. UML diagrams allow for a high level of flexibility within their development. Firstly, basic diagrams can be developed that illustrates the parent-child relationship between an assets functional output and the supporting asset systems. Secondly, assets modelled within the diagrams can have metadata attached to them that represents information requirements such as material, installation day and warranty status. Finally, the diagrams can be developed into a database schema, providing the constrains and datatypes are modelled.

It is proposed that a static UML diagram is developed per an assets functional output. The diagrams can be in any style, with emphasis put on the readability requirement, while maintaining the required level of detail. The description of the functional output and asset systems should be used to name the assets within the diagrams and not the associated classification code (e.g. UNIClass), this ensures that non-technical personnel can understand the diagrams. Figure 5-7 provides an example of a static UML diagram for the functional output of heating, with associated asset systems and sub-systems.

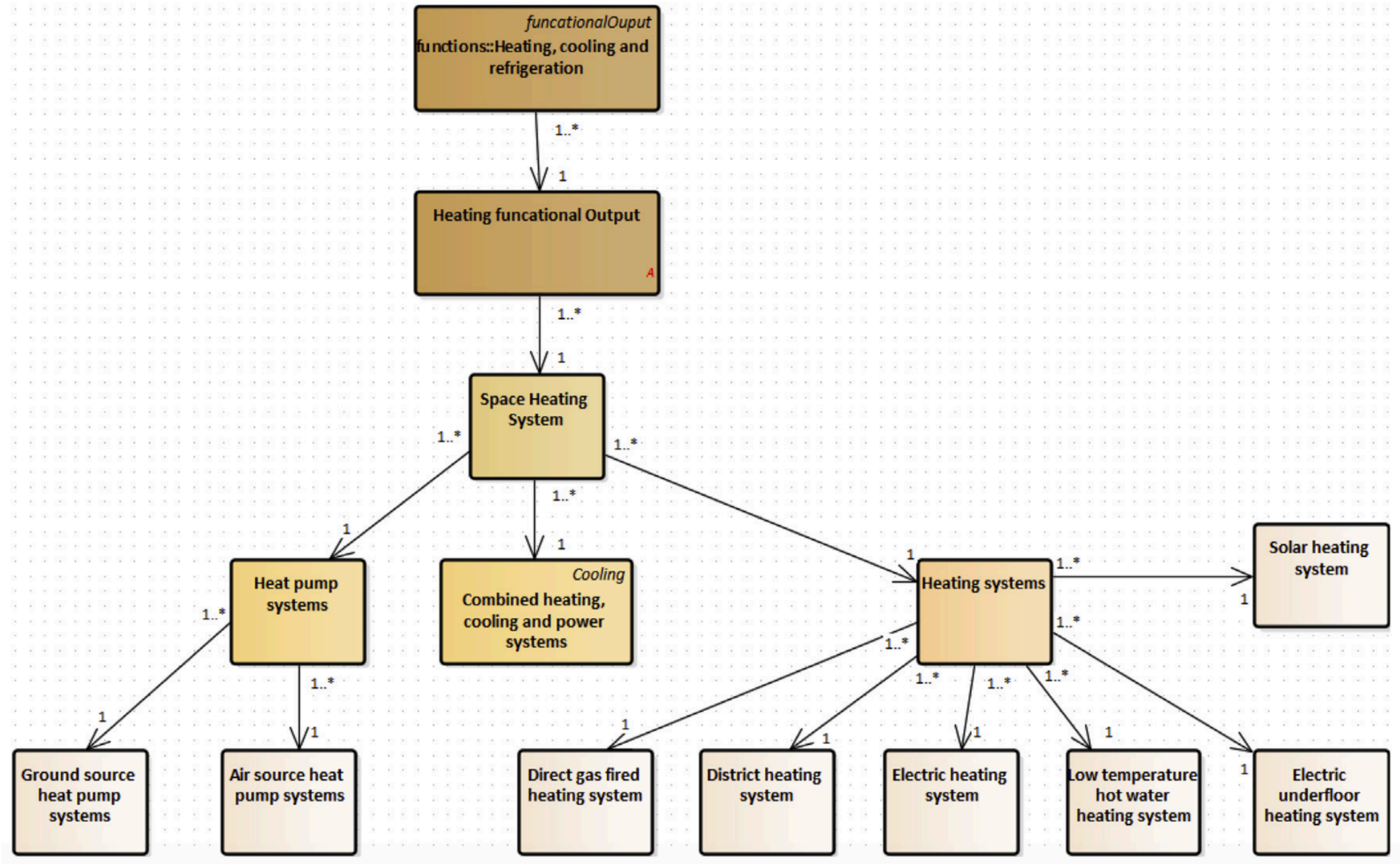

Figure 5-7 UML structured diagram of the functional out for heating

There are many UML modelling software products, such as Enterprise Architecture [159]. Many of the programs have drag and drop functionality to develop the diagrams, allowing non-technical personnel to develop them.

The outcome of this step is a set of UML diagrams that represent the asset classification development within Section 5.3.2. A single UML diagram represents an assets functional output, with the assonated asset systems and sub-systems.

5.4. Developing Organisational Information Requirements (OIR)

This section (step three) discusses the steps taken for the development of OIR, which is divided into three sub-steps, see Figure 5-8.

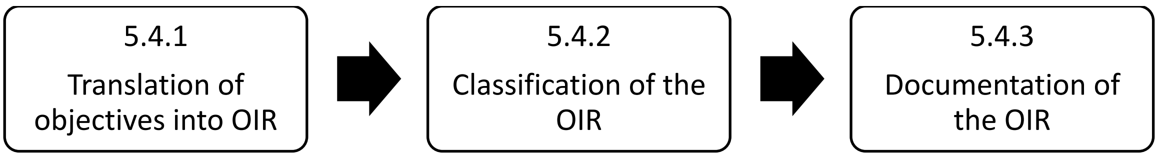

Figure 5-8 sub-steps of step three

Step one is the translation of the objectives identified in Section 5.2 into a set of OIR. Step two is classifying the information requirements within a given category, including data types and step three is documenting the newly developed OIR.

The primary goal of developing an OIR is to provide the information that is required to inform the achievement (or not) of the objectives identified. The development of an OIR can be a daunting and complicated task due to its broad and cross-disciplinary nature. Furthermore, as witnessed within the industry investigation (see Section 2.5), the development of OIR within asset management organisations is often an ad-hoc and a manual process, if done at all. Therefore, there is a clear need for a structured and organisational lead approach to the development of OIR.

5.4.1. Translation of objectives into OIR

The literature review noted that several tools from the domains of BIM and requirements engineering have been developed to aid in the creation of information requirements, such as Business system Planning (BSP), the Ends to the Means approach (E/M), Critical Success Factors (CSF) and Plain Language Questions (PLQ) [10]. BSP is a three step process to gain the required information, firstly you identify the problem, then the solution and the decisions needed to address the solution, with all three steps generating a set of information requirements [114]. While BSP is efficient in developing information requirements, it requires the need for the decisions to a set of problems to be defined and well-articulated, which the industry investigation noted is not the case. The E/M approach is a two-step process, the first step looks at the *"ends"* ,meaning what is success at the end and what information is needed to evaluate the effectiveness of reaching the ends [113]. The second step looks at the *"means",* meaning what are the key means or processes to meet the ends and determining what information is need for efficiency operate the means. Similar to BSP, while E/M aids in the development of information requirements, it is a complex task that requires alignment between different organisational departments to efficiently develop the ends and means, which is currently lacking within asset management organisations. CSF is a simple approach of determining what factors are needed to succeed, while PLQ are simple questions that are asked to determine what information is required, as a combination together they are a powerful but simple tool to aid in information requirements development. Specifically, CSF aids asset management organisations by providing a single point of alignment between the asset management department and the wider organisation, being a success factor. Furthermore, PLQ combined with the CSF provides an easy approach to extracting information requirements from non-technical stakeholders.

Supporting the translation of objectives into OIR, the two concepts of CSF and PLQ have been adopted. Firstly, Critical Success Factors (CSF) are developed that provide the scope and guidance to the development of Plain Language Questions (PLQ). The development of CSF and their role in supporting the creation of PLQ is discussed in detail below.

Critical Success Factors

A CSF is defined as: *"a critical factor or activity required for ensuring the success of an organisation",* within the context of an OIR, a CSF is used to highlight the critical factors required to ensure the success of achieving an asset management objective.

CSF have been widely adopted within the software engineering industry to highlight the customer and end-user requirements for the development of information management systems (IMS). Developing CSF involves asking senior management or department leads, what are the critical factors that determine the success of the business department they manage? Moreover, what information is required to ensure that the CSF is acceptably managed? This approach is slightly modified to move the focus away from individual organisational departments to the objectives by changing the question to: *"what are the Critical Factors that ensure success in achieving this objective?".* CSF are developed within a workshop environment, where participants are encouraged to identify around four to six factors that are important for them. Table 5-3 provides an example of CSF for the objective, *"Reduce the total controllable costs by 5%".*

Number	**Critical Success Factors**
1	Prompt response to maintenance requirements
2	Reduction in operational costs
3	Reduction in maintenance costs
4	Less reactive maintenance and more planned maintenance
5	Have the correct tools and materials
6	Whole-life cost management

Table 5-3 Examples of critical success factors

The outcome of this step a set of simple and understandable set of CSFs per objective that guides the development of PLQ.

Plain Language Questions (PLQ)

A PLQ is defined within PAS 1192-3 as: *"questions asked of the supply chain by the employer to inform decision-making at key stages of an asset life cycle or project"* [5]. In the context of OIR, PLQ is an approach for stakeholders to ask a set of questions regarding their assets. As the definition highlights, PLQ have been developed as a means for an asset owner to extract information from their supply chain, predominantly during the design and construction phase. The industry investigation in section 2.5 noted that they have rarely been used, despite them being included within the BIM standards.

PLQ has been adopted for the development of OIR as they are a simple but powerful approach that enables the extraction of information requirements from a complex organisation. Firstly, it involves the development of *"plain"* questions. In this content, a plain question means it is easily understood by all stakeholders encompass all of the OIR for the given objective. Secondly, it involves developing the answer to the PLQ. The answers should be in the form of a single statement or reference to a document or database. As an example, the PLQ: "*what is my total operational cost per week?"* Could be answered by the total operational cost, which is "*two million pounds per week"*. While a more specific question such as: "*how do you intend to implement BIM within this project?"* could be answered by a reference to the BIM execution plan. Furthermore, the answers need to be formatted to a specific requirement, this then forms the OIR. As an example, the answer to the above question "*total operation cost"*, would be formatted to total_operational_cost, the spaces within the answer are replaced with an underline dash, as is a requirement for the future development of the AIM, see Section 7.3.

Table 5-4 provides an example of PLQs grouped under a CSF along with the information requirement.

Critical Success Factor	**Plain Language Question**	**Information requirement**
prompt response to maintenance requirements	What is the current response time to maintenance request?	currently_maintenance _responce_time
	What is the required response time to maintenance request?	required_maintenance _responce_time
	Who is responsible for planning maintenance?	maintenance_owner
	What is the cost savings to a prompt response to maintenance requests?	cost_saving_prompt _maintenance
less reactive maintenance and more planned maintenance	What is the total planned maintenance to date?	total_planned_maintenance _to_date

	What is the acceptable level of reactive maintenance?	reactive_maintenance_allowed
	What is the total completed reactive maintenance to date?	Total_reactive_maintenance_to_date
	What is the difference between reactive and planned maintenance?	difference_between_reactive_planned_maintenance
whole-life cost management	who is responsible for whole-life management?	whole-life_management_owner
	How does my O&M cost compare to my capital investment?	O&M_cost_compared_new_build
	What is the planned capital investment?	total_planned_capital_investment

Table 5-4 Examples of PLQ aligned to CSF

The outcome of this step is a set of PLQ that align to CSF, with the answer to the PLQ forming the information requirements. A set of CSF, PLQ and information requirements are developed per objective documented within Section 5.2.

5.4.2. Classification of the OIR

Categorising the OIR is critical, as it supports future development into the AIM and a structured way to store, extract and maintain the OIR. Firstly, the information requirements are categorised based on their standard usage and secondly, on their data type.

Information requirements categories

The information requirement categories of financial, managerial and technical are adopted from both the asset management ISO 55000 standard [22] and the BIM PAS 1192-3 standard (Appendix A page 21) [5], where they are mentioned as common information requirements categories that are used within the Operational and Maintenance (O&M) phase of an asset. Furthermore, the categories were also a common theme within the industry investigation (see Section 2.5) where multiple reviewed documents mentioned the categories.

categorising of information requirements has several advantages. Firstly, it allows a quick review of the OIR to ensure that there is not a bias to one kind of category. As an example, having all financial related information requirements and no managerial would result in a poorly functioning OIR. Secondly, it provides a structured approach to the development of the information requirements themselves, ensuring that only relevant information requirements are developed. Finally, it enables the filtering and extracting of information requirements based on the category, as an example, extracting all related technical information for a given OIR or objective.

As the aspects of financial, managerial and technical are common themes with different definitions within different industries, there is a need to provide a standard definition within the context of an asset management organisation. Table 5-5 describes the information requirements categories from an asset management perspective.

Information requirement category	**Description**
Financial information requirements	Financial information requirements capture financial information. Supporting the monitoring and validation of financial related performance, and support such functions as whole-life costing, capital investment plans and strategic financial decision-making processes. Examples of financial information include operational cost, maintenance cost and initial cost.
Managerial information requirements	Managerial information requirements capture managerial information that an organisation requires to maintain and operate their assets, including legal and commercial elements. Examples of managerial information include ownership, asset location and warranty/ insurance information.
Technical information requirements	Technical information requirements capture information that an organisation requires to evaluate the design, operational and maintenance

	performance of their assets. Examples of technical information include operational performance data, design parameters and dependencies and interdependencies

Table 5-5 information requirements categories

Data types

Classification of the data type enables the future development of an AIM and also ensures that the information requirement is appropriate to answer the PLQ.

A data type is a single property that tells a compiler (used to compile software code into a program) how the program intends to use the data. While there are complex data types such as composite, functions and geometry, there are a set of *"primitive"* data types that a common among all programming languages that include string, integer, Boolean and date/time. Furthermore, the data types also play an important role in maintaining a high-level of quality data, by only allowing the correct datatype to be inserted into the correct field.

One of the requirements for OIR development is the need for non-technical stakeholders to develop and maintain it, as such, the data types should be easily understandable. It is proposed only to utilise the primitive data types as they provide all of the requirements for the future development of an AIM, while still relatable to non-technical stakeholders. Furthermore, they also cover all of the information requirements data type needs. As an example, functions and geometry data types cannot be derived from a PLQ, Table 5-6 provides an overview of the data types along with a description.

Data Type	**Description**
String	Contains only normal, special (symbols such as &,^,@) characters and spaces.
Integer	Containing only numbers and not special characters such as dollar/pound symbols or percentage symbol.

Boolean	Has one of two possible, that should if the value is true or false, presented in any way, such as 0 = false and 1 = true or negative and positive.
Date/Time	Stores a set of characters, symbols and numbers, ISO dates/time formats can be adopted.

Table 5-6 information requirements data types

The outcome of this step is a set of OIR, with the individual information requirements been classified within an information requirements category and a data type.

5.4.3. Documentation of the OIR

The final step of the OIR development is the need to document it. Similar to the documentation of asset management objectives, the OIR should be stored in a human and machine-readable format such as Excel, CSV or SQL tables.

The OIR should be structured within a table style format that contains the following columns as described below, with the rows containing the individual CSF, PLQ and information requirement.

- **CSF ID** – individual CSF have a unique ID that should be documented next to the CSF. CSF aid in developing PLQ, the CSF ID will be duplicated for every row that is associated with the CSF. Data rules within Excel, indexing within SQL or similar should be adopted to support automatic ID generation.
- **CSF –** contains the CSF itself. Similar to the CSF ID, the CSF will be duplicated for every PLQ that is grouped within the CSF.
- **Category –** is where the information requirements category is stated. As this column can only contain one of the three values, it should be restricted to only allowing these values. As an example, a list can be created in excel or a relationship in SQL to enable only the allowed values.
- **PLQ –** contains the PLQ itself. There should be no duplication of a PLQ, each PLQ should be unique within a given OIR.
- **PLQ ID –** each unique PLQ should have a PLQ ID, throughout the whole OIR document. As an example, the same question used multiple times within different OIR's but within the same OIR document, will have the same PLQ

ID. Similar to the CSF ID, data rules and relationships should be adopted to enable the automatic development and management of PLQ IDs.

- **Information requirement –** is where the developed information requirement (answer to the PLQ) is stored. Formatting rules and conditions should be utilised to automate the formatting requirement.
- **Data type –** is where the data type of the information requirement is noted. As this column only contains one of four values, it should be restricted to only display one of those allowed values.

The first row within a given OIR should be the objective that the OIR is being developed for, this row should reference the asset management objectives document developed in Section 5.2. Furthermore, the objective ID, timeline and category should also be referenced into the individual OIRs. Within Excel, this could be linked directly to the OIR table or within SQL constraint relationships, such as a primary key.

Figure 5-9 provides an example OIR template completed within Excel, the objective covers the whole top row of the table with a single PLQ per row.

The outcome of this step is a set of OIR, documented within a structured approach with the above columns. Each OIR should be its own table/sheet within a single OIR document.

Reduce total business impact of Estate Facilities' controllable costs by 5%							
OB_ID	**ID**	**Critical Success Factor**	**Category**	**Question**	**Question ID**	**Information_Requirement**	**Data_Type**
AM05	CSF1	prompt response to maintenance requirements	**Managerial**	What is the current response time to maintainince request?	MQ5	current_maintaince_responce_time	Integer
AM05	CSF1	prompt response to maintenance requirements	**Managerial**	what is the planned response time to maintaince request?	MQ6	planned_maintaince_responce_time	Integer
AM05	CSF1	prompt response tomaintenance requirements	**Managerial**	what is the different between the planned response time and the current?	MQ7	current_vs_planned_responce_time	Integer
AM05	CSF1	prompt response to maintenance requirements	**Financial**	What is the cost savings to a prompt response to maintanince requests?	FQ2	maintanince_cost_savings	Integer
AM05	CSF1	prompt response to maintenance requirements	**Managerial**	who is responable for planning maintanince?	MQ8	maintanince_owner	String
AM05	CSF2	reduction in operational cost	**Financial**	What is the current total operational cost?	FQ3	total_operational_cost	Integer

Figure 5-9 OIR template example

5.5. Summary

This section summaries the below steps of the information requirements framework:

1. **Extract, identify and categorise asset management objectives**
2. **Develop an asset classification system including functional output, asset systems, sub-systems and products**
3. **Develop OIR aligned to the asset management objectives**

Step one discusses the review of organisational documents with the aim of sourcing asset management objectives, several example documents for review are provided in Table 5-1. It was highlighted that objectives could be identified via both a managerial review and technical review or a combination of both. Once the objectives have been sourced, they are categories and documented, the information requirements categories are provided in Table 5-2.

Step two discusses the development of an asset classification system from an assets functional output. Firstly, the asset classification systems of type-of and part-of are discussed in detailed and justification for choosing part-of as it supports the classification of an assets functional output is discussed. Secondly, the development of a parent-child asset classification system that proposes the novel aspect of classifying the assets functional output, along with assets systems and sub-systems, is proposed. Finally documenting the asset classification system, both within a human and machine-readable format is discussed. Human readable aspects of the documentation should be easily understood by non-technical stakeholders and accessible to all, while machine-readable should be easily understood by standard program compilers, it is proposed that UML diagrams would meet both requirements.

Step three is the development of the OIR, utilising the asset management objectives sourced within step one (see Section 5.2), adopting CSF from the domain of requirements engineering and PLQ from the domain of BIM. The newly developed OIR should be documented within both human and machine-readable formats, such as Excel, CSV or SQL / Access database tables.

This section addressed the challenges of an organisation developing OIR by creating an alignment between the asset management objectives and the OIR itself. Furthermore, the asset classification system developed within step two (see Section 5.3) enables the developed of FIR and AIR within part two of the information requirements framework(Chapter 6) along with the AIM within part three of the information requirements framework (Chapter 7).

6. Developing asset level information requirements

6.1. Introduction

This chapter discusses part two on the information requirements framework, focusing on the development of Functional Information Requirements (FIR) and Asset Information Requirements (AIR), along with validating, documenting and communicating the newly developed information requirements. Part two includes steps four, five, six and seven, see Figure 6-1 for the scope of this chapter.

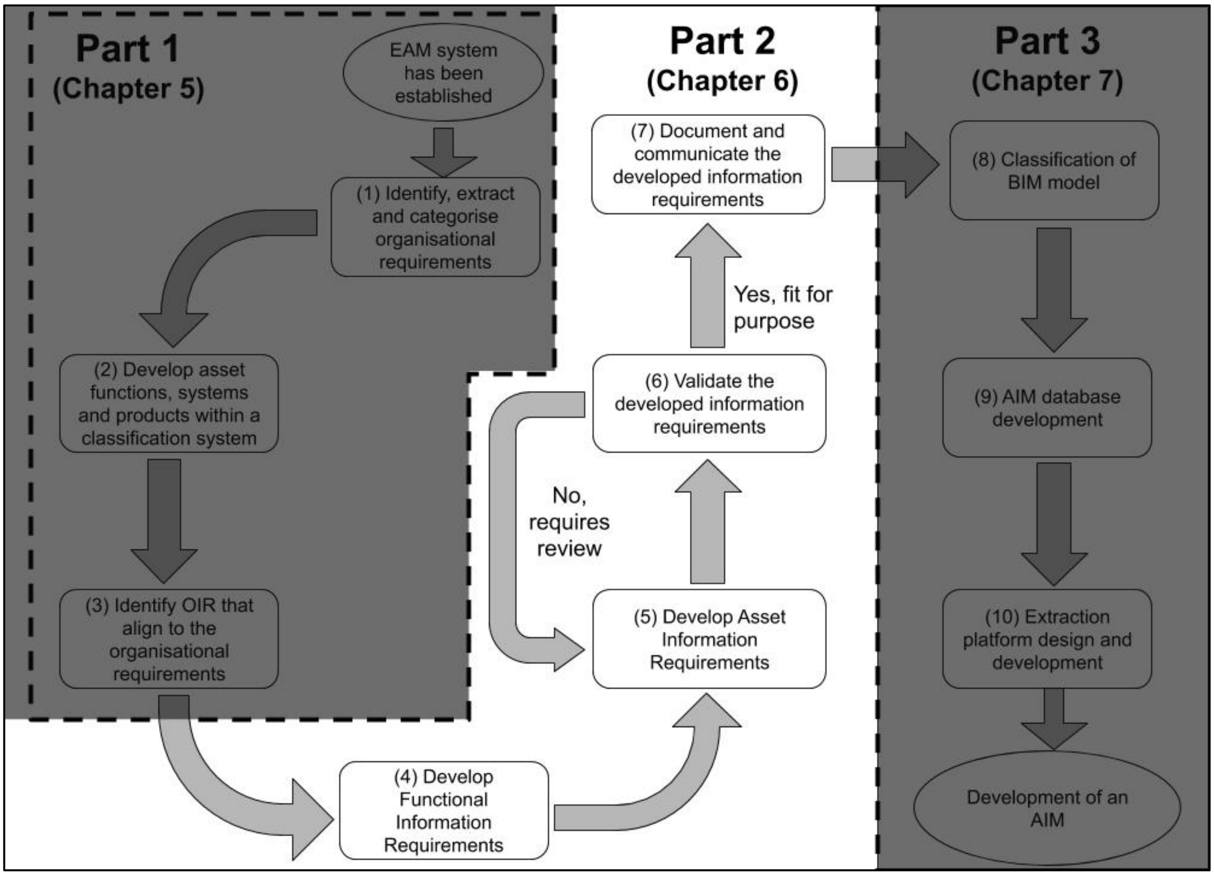

Figure 6-1 Scope of Chapter 6 within the information requirements framework

The industry investigation (see Section 2.5) noted the challenges that asset management organisations have with developing an OIR, and the OIR generating the AIR, with the jump from OIR to AIR being considered too much of a leap for most organisations. This chapter aims to address this challenge with FIR, as a means to bridge the gap between OIR and AIR, therefore addressing this challenge.

Step four involves the development of FIR. FIR is a new set of information requirements developed within this research effort as a means to bridge the gap between the OIR and the AIR. As the researcher developed the concept of FIR, there is a need to provide a definition, as per below:

“Information requirements developed at an asset's functional output level of an organisations asset classification system.”

As an example, the functional output of heating can be supported by multiple asset systems types such as gas heating, electric heating and solar heating, the capture of information at this level has several advantages. Firstly, it allows for greater engagement with stakeholders from non-technical backgrounds. Secondly, it addresses the challenge of the AIR being generated from the OIR, an asset management organisation will have sufficiently less asset functional outputs then asset systems, therefore the development of information requirements at the assets functional output level is less resource intensive.

Step five adopts the development of AIR from the BIM standards, with a definition provided in PAS 1192-3. Step six is the process of validating the developed information requirements. Finally, step seven is aggregating all of the information requirements (OIR, FIR and AIR), storing and documenting them within a structured process, while developing a communication plan for communicating the new information requirements with all stakeholders.

6.2. Develop Functional Information Requirements (FIR)

When developing FIR, it is essential not to consider the asset systems or sub-systems, as is common within asset management organisations. Care should be taken to enforce the fact that a FIR aims to capture the impact of the assets functional output on the objectives. As an example, to answer the PLQ of *“what is our total operational cost?”,* which is aligned to the objective of *“reducing operational cost by 5%”,* it is essential to understand how the functional output of heating will impact this objective and what specific information is required from the functional output of heating to answer the PLQ. Examples FIR properties could include, remaining service life, power consumption and running time of the HVAC system of the building.

The advantages of classifying assets by their functional output is ensuring alignment between the organisation and the assets they operate and maintain, the information captured within the FIR will aid in this alignment.

FIR are developed within three sub-steps, see Figure 6-2. Step one stakeholder selection, selecting key personnel to contribute to a workshop. Step two design and development of a Joint Design Application (JDA) workshop and step three documenting the FIR. A JDA workshop is a generic term that describes a set of tools and methods for conducting a workshop that aligns the requirements of users and the technical development for an Information Management System, such as planning, defining requirements and user interface [144]. Due to the complexity of asset management organisations, a JDA workshop is an appropriate tool to align the requirements of non-technical personnel with technical requirements.

Figure 6-2 sub-step of step four

6.2.1. Stakeholder selection

Stakeholders' selection should focus on highlighting key personnel required for the JDA workshop, the process involves engaging personnel at all management levels of the organisation to gain insight on their specific knowledge related to asset management. The FIR is vital in aligning the organisation with its assets, as such, the key personnel should understand the organisational management frameworks, Table 6-1 provides a summary of key stakeholders. The below stakeholders have been selected as they are noted as key decision makers within the literature review and influential stakeholders within the industry investigation. Furthermore, the stakeholders also aligned to the BIM standards as owners of asset management activities such as life-cycle costing, asset optimisation, change management, IT systems and customer satisfaction reporting.

Stakeholders	Description
Finance director/manager	Care should be taken to ensure that finance personnel do not have a bias to a specific project or organisational departments. Finance personnel with a whole organisational perspective should be selected.
Risk manager	The organisational wide risk manager should be selected. The risk manager should know corporate, financial and compliance risk, not just risk related to the management of assets.
Asset manager	The most senior person that has the organisational responsibility to asset management should be selected. They will provide clarity to the asset management objectives and provide a leadership perspective.
Customer Engagement Manager (CEM)	Should provide a customer perspective on assets. This person should have a strong understanding of what assets are customer facing and how best to have those assets should perform, including appearance.
Information Technology (IT) director	Provide insight on the decisions related to the design, development and management IT-related systems such as enterprise resource management, scheduling/jobs allocation and building management systems.

Table 6-1 FIR stakeholders selection categories

The outcome of this step is a list of personnel from the above stakeholder categories that are best placed to participate within a information requirements workshop, based on their industry knowledge and seniority.

6.2.2. Design and development of an information requirements workshop

The literature review noted that elicitation of information requirements is a core step of developing information requirements, which is also a resource intensive activity that takes over 50% of the total time [160]. Several workshop approaches have been proposed to aid in the development of information requirements including Quality Function Deployment (QFD), collaborative approach to requirements development and Joint Design Application (JDA). QFD is the process of using facilitated group techniques to aid in the development of information requirements, which includes using task simulations with domain experts to simulate the information exchange process [161]. A novel approach is proposed in the form of a collaborative framework that aims to collectively develop requirements from the narrative of a set of case studies developed with domain experts [162]. While both QFD and the collaborative framework are efficient processes for developing information requirements, they are constraint to a single approach which doesn't support the requored alignment between stakeholder while limiting the facilitators involvement within the workshops.

A JDA workshop is a logical choice for the FIR workshop development as it enables the facilitator to participate in the workshop, which is significant due to the researchers' industry experience [144]. Furthermore, due to the multidiscipline nature of asset management and the different stakeholders required for the development of FIR, JDA can provide the flexibility in tools and techniques that can meet the stakeholders requirements.

While there is no hard structure for the development of JDA workshops, there are some fundamental building blocks at include facilitation, agenda-setting/structure, documentation and group dynamics.

A JDA workshop should be facilitated by a single person who leads the activities and ensures that it is completed within the given timeline and scope. It is expected that facilitators are actively involved within the workshop, they should have knowledge of the organisational structure and requirements.

Similar to other workshop developments, a JDA workshop should have a predefined agenda with a loose structure. The agenda sets out the scope of the workshop by highlighting the specific activities and documentations to be developed within the workshop.

Group Dynamics

One of the aspects of a JDA workshop is the use of dynamic group activities. Such activities can be adopted from the domain of requirements engineering and include brainstorming, mind mapping and prototyping.

Brainstorming is a group creativity technique that aims to find a dynamic conclusion to a set of problems. There are several different kinds of brainstorming approaches, including directed, guided, individual and question. Table 6-2 provides a summary of brainstorming techniques.

Brainstorming techniques	**Description**
Directed	Is used when the set of criteria for evaluating a good idea is already known. Participants within a directed brainstorming session are often given a single or set of brainstorming questions that focus their creative development.
Guided	A brainstorming session that is focused on a particular subject and constraint under a perspective and a set amount of time. Participants are encouraged to adopted different mindsets for a period of time while contributing to a central mind map of ideas.
Individual	Is the process of completing a brainstorming exercise in solitary. Often used by authors to support creative writing exercise. Such techniques include freewriting, word association and mind mapping.
Question	This brainstorming is focused on developing questions, rather than coming up with the initial answers and short-term solutions, which is common in traditional brainstorming types. The developed questions form part of a future action plan.

Table 6-2 brainstorming types

Both directed and guided brainstorming techniques complement the FIR development.

A directed approach is used when the criteria for a *"good idea"* is already known and is well understood, the Critical Success Factors (CSF) developed as part of the OIR are used as the criteria. Furthermore, the Plain Language Questions (PLQ) also developed within the OIR step, provide the "*brainstorming questions"* that need to be answered. The aim of the directed brainstorming exercise is to get answers to the questions developed within OIR. As an example, the CSF to *"reduce whole-life costing"* and the related PLQ "*what is our total operational cost?"* are used to elicit requirements from the participants.

The adoption of different mindsets within the guided brainstorming session enables a creative approach to the development of FIR. This is specifically important when considering asset management organisations, which are historically siloed within their departments and not prone to change.

Mind mapping is a common exercise and often used within a brainstorming session. A mind map is a diagram that aims to visualise and organise information. Mind maps are commonly used within organisations to generate, visualise, structure and classify ideas to support problem-solving and decision-making processes. Mind maps can be used within the brainstorming exercise to support the visualisation, structure and classification of the developed information requirements around a given PLQ.

The outcome of this step is a JDA workshop that is designed for the development of information requirements, adopting elements of directed and guided brainstorming techniques.

6.2.3. Documenting the FIR

When documenting FIR, there are two elements of consideration. Firstly, the documentation of the information requirements themselves developed during the workshop. Secondly, similar to documenting OIR, the FIR needs to be stored within a human and machine-readable format to support the development of the AIM (see Section 7.3).

The final requirement of a JDA workshop is to document the outcome of the workshop, in this context, the FIR. To support the capture of the information requirements developed during the workshop, an Information Requirements Matrix has been developed (see Figure 6-3).

The matrix can be populated by two means. (1) the researcher acting as the facilitator would load the matrix on a projector/television and populate it live within the workshop, as the activity is taking place. Furthermore, the researcher might take notes and make observations during the workshop to populate the matrix at a later date. (2) the matrix is printed then handed out to participants to populate as an individual or a group, with the matrixes then being shared and discussed.

The matrix aims to support a structured approach to the capture of information requirements, the sections of the matrix are described in detail below.

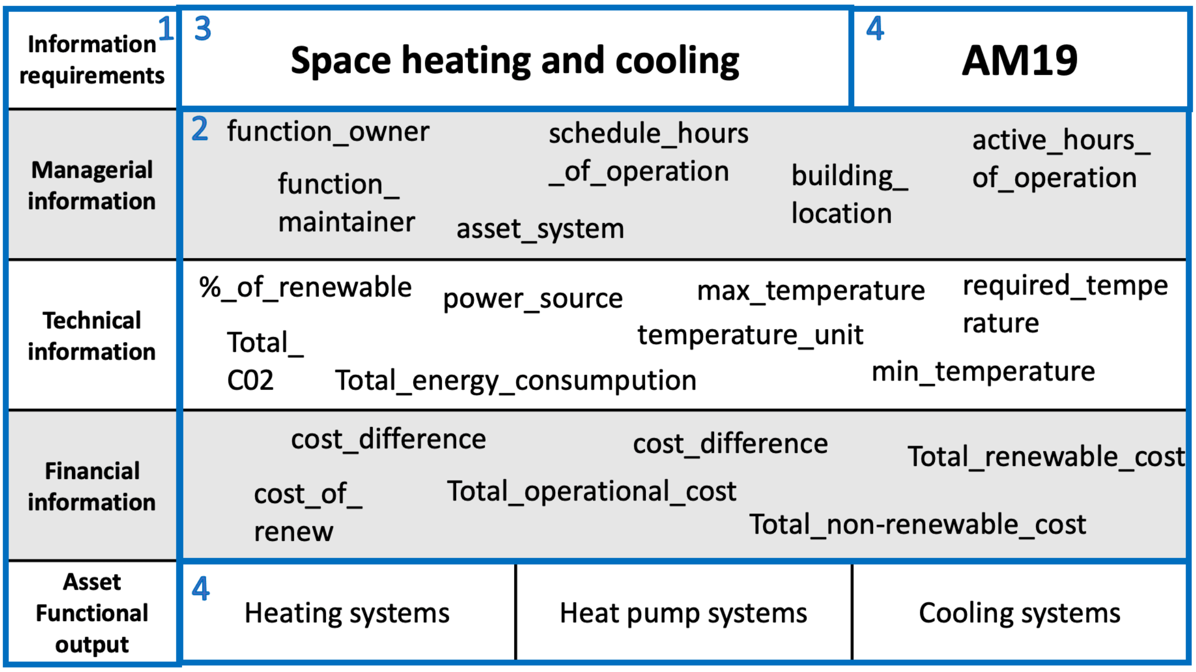

Figure 6-3 information requirements matrix

Section 1 - Adopts the use of the information requirements categories that are utilised within the development of OIR (see Section 5.4) and classification of asset management objectives, see Section 5.2.3. Utilising the information requirements categories has several advantages. Firstly, it aids in the development of information requirements themselves by providing a structured approach as to what *"kind"* of information should be captured. Secondly, as the information requirements categories are used within the development of OIR and in classifying asset management objectives, it creates consistency throughout the framework and supporting a direct line-of-sight from the OIR to the FIR.

Section 2 - Is the central part of the matrix where the information requirements are documented.

Section 3 - Is where the assets functional output that the information requirements are being developed for is written. As an example, a FIR created for the assets functional output of heating, which would be titled as *"functional heating output"*. The functional outputs are derived from the asset classification system developed in Section 5.3.

Section 4 - Captures the objective ID that the FIR is referencing, providing a direct line-of-sight from the FIR and the OIR, as the documentation of the OIR has the objective ID. Furthermore, if required, the category of the objective can be written next to the objective, this can aid in directing the FIR development process. As an example, if an FIR is being developed for an environmental-related objective, having the category of the objective written down can aid in keeping the participants focused on developing environmental-related information requirements.

Section 5 - Is where the asset systems that support the assets functional output are written, only asset systems that have been identified within the asset classification system should be written within this section. Asset sub-systems should not be included, as they are discussed within the development of AIR, see Section 6.3.

The outcome of this step is a set of information requirements matrices that have been completed as part of a JDA workshop. An information requirements matrix should be completed per functional output. There is a further need to aggregate all of the captured information requirements into a single source document, this process is discussed below.

Documentation of the FIR outside of the JDA workshop, is similar to the documentation of the OIR and asset management objectives, the FIR should be stored in a human and machine-readable format such as Excel, CSV or SQL tables.

FIR documentation should be in the style of a table, such as a table within Excel or SQL database, with the columns below:

Asset functional output – contains the name of the assets functional output that the FIR is being developed for, linked to the asset classification developed within Section 5.3. In excel this could be a data link to create a drop-down box or in SQL a primary key link to an asset classification table.

Asset classification – states the given asset classification code for the functional output, automatically populated and changes when the functional asset output is changed. The classification should be extracted from the asset classification system.

Objective ID – similar to the information requirements matrix, the objective ID references back to the original objective that the FIR is addressing. The objective ID should be extracted from the asset management objective documentation (see section 5.2.2), this can be achieved by data linking tools in Excel or table linking in SQL databases.

Information requirements categories – is where the information requirements are documented within their given category. A single cell within the table is used to document a single information requirement, following the same formatting structure as the OIR (see Section 5.4.3).

The outcome of the FIR documentation step is a set of documented FIR, with a single document containing all of the information requirements, in both a human and machine-readable format.

6.3. Develop Asset Information Requirements (AIR)

This section (step five) describes in detail the development of AIR and can be divided into two sub-steps, see Figure 6-4.

Figure 6-4 sub-steps of step five

Step one is the development of AIR which are generated from the FIR, the AIR includes both asset systems and sub-systems information requirements and step two is the documentation of the AIR themselves.

6.3.1. AIR development

Much like the development of FIR, the development of AIR is best achieved in a multi-discipline collaborative workshop environment. The workshop should utilise the same methodologies such as stakeholders selection, brainstorming and JDA workshops.

While the development of both the OIR and FIR focused on non-technical stakeholders, the development of AIR is focused on the technical aspects of assets, therefore the stakeholders involved within an AIR workshop should be from a technical perspective. Furthermore, the engagement with personnel for the AIR workshop is not focused on the *"authority"* the stakeholder has within the organisation but the knowledge and insight they can provide to the workshop. Table 6-3 provides a summary of key stakeholders that should be considered within an AIR workshop.

Stakeholders	**Description**
O&M engineers	O&M engineers are a board stakeholder that can include specific engineers such as heating and cooling specialists and more generic engineers such as civil and mechanical engineers. O&M engineers should be engaged to aid in the development of specific O&M related information requirements. Several O&M engineers might be needed depending on the unique requirements.
Planning/schedule technician	Focus on the scheduling and planning of jobs, both reactive and proactive. Furthermore, scheduling technicians have a detailed understanding of legal and statutory maintenance requirements. Scheduling technicians should be engaged to understand the technical requirements of scheduling and what information it requires.
Quantity Surveyors (QS)	Acts as a financial management stakeholder at an asset system or sub-system level. QSs can provide granular asset financial information requirements. A QS should be engaged when detail financial information requirements are needed.
Spares/material manager	Maintains the organisations' spares and material requirements, such as thermostats, piping and electrical switches. Spares manager can provide great insight into what produces, and materials are

	needed within a specific asset lifecycle and provide detailed information requirements.

Table 6-3 summary of stakeholders involved within an AIR workshop

The AIR workshops follow the same group dynamic exercises within the FIR workshop, including direct and guided brainstorming.

Similar to the FIR brainstorming exercise, the CSF are used as an overall guidance for what *“good looks like”*, providing a goal for what the AIR should aim to address. While the PLQ are answered within the FIR, they will gain that information from the AIR, therefore the PLQ should also be referenced to ensure that the AIR are answering the questions. Furthermore, the information requirements themselves (the answers to the PLQ) are used as a means to ensure the alignment between the FIR and the AIR. Participants are asked a question similar *to “reflecting on the CSF and PLQ, what information is required from the specific asset systems and sub-systems to address this requirement?”.* As an example, to address the FIR of “total_operational_cost”, the participants would use the related CSF of “*reduction in whole-life cost” and the PLQ “what is the total operational cost?”,* to develop a set of AIR for the asset system of electric heating, such as, hours_of_operation, power_consumption, performance_rating and power_source.

Other tasks within the brainstorming exercise include task simulation, where the participants are encouraged to discuss in detail the task they regular perform such as reactive / planned maintenance and inspections, to gain insight into specific information on asset systems.

This section discussed the use of brainstorming techniques within the development of AIR.

6.3.2. Documenting AIR

This section discusses the documentation of the information requirements developed from the AIR workshop, this includes both from the JDA workshop itself and documentation outside of the workshop.

The JDA workshop uses the same information requirements matrix within the FIR development to document the developed information requirements. Section three of the matrix will state the asset system or sub-system that the matrix is being completed for. While section four will highlight any sub-systems that are within the given asset system.

Figure 6-5 provides an example of the information requirements captures within a matrix for the asset system of Heating and the sub-system of Electric Heating, which is under the functional output of Space Heating and Cooling. Figure 6-3 provides an example of information requirements for the functional output of Space Heating and Cooling.

Information requirements	Heating systems		AM19
Managerial information	Location_zone _level, Asset_type, total_planned_maintenance, asset_system_owner, totating _heating _M2, scheduled_planned_ maintenance, total_reactive_maintenance		
Technical information	performance_ rating, min_temperature, total_energy_ consumption, target_C02, max_temperature, required_temperature, asset_system_C02		
Financial information	active_operational _cost, unit_ cost, planned_maintenance_cost, active_maintenance_cost, planned_investment, planned_operational _cost		
Asset Systems	Electric heating systems	Solar heating systems	Low-temperature heating systems

Information requirements	Electric heating systems		AM19
Managerial information	criticality, asset_sub_system_owner, location_room, supporting _activity, detailed _location, planned_maintenance, next_maintenance _schedule, maintenance_histroy, reactive_maintenance		
Technical information	voltage, outputs, service_life, running_total_C02, Remaining_life, C02_per _outlet, sections, C02_reduction _level, running_ time, %_of_renewable, sensor_rating, %_of_none_renewable		
Financial information	CO2_cost_Saving, cost_per_CO2 _output, cost_of_CO2_ saving		
Asset Functional output			

Figure 6-5 AIR matrix

Considering documentation outside of the JDA workshop, the AIR documentation adopts the same table used within the FIR development. The top row highlights the given asset system that is being documented, with the asset classification directly under it.

The outcome of the AIR documentation step is a single document that contains all of the information requirements. Furthermore, AIRs should be documented in such a way that allows for both human and machine-readable aspects to be addressed.

6.4. Validating information requirements

This section aims to validate that the OIR, FIR and AIR are complete, comprehensive and fit for purpose. Furthermore, this step also confirms that the information requirements captured are the correct ones needed, and an adequate quantity has been developed to address the information requirements needs for the given objective.

The literature review (See Section 2.4) noted that within the domain of requirements engineering, validation of information requirements is a critical but complex step. Firstly, it requires diverse stakeholders with often conflicting goals to reach an agreement [163]. Secondly, validation of the information requirements can only be achieved within their *"real world"* usage, which is often an expensive and timely task.

Addressing the first challenge, it is required to resolve the conflicts between the different stakeholders. Robison and Volko [164] propose a negotiation project lifecycle model that incorporates the organisational point-of-view by first setting out their goals and objectives in the early stages of the negotiation. The overarching theme is a level and common playing field where all participants are working towards a single set of goals and objectives. The advantage of using this approach is two-fold. Firstly, as part of the information requirements framework, asset management objectives have been captured within step one (see Section 5.2), which can be used as the overarching goals. Secondly, one of the key challenges within asset management is its multifunctional aspect that is often neglected within information requirement development. The level playing field approach with common goals and objectives support the collaborative framework that enables the required cross-functional negotiation process.

Addressing the second challenge, small scale prototyping enables the simulation of the developed information requirements, within the *"real"* world. As noted, asset management organisations are complex and adopting new information requirements within their business processes is a lengthy and expensive task. The focus should be on the small-scale aspects of prototyping, as an example, focusing on a single asset management objective or asset functional output. Prototyping can be technical and non-technical. Technical prototyping means developing the newly developed information requirements into machine-readable formats and implementing them within asset management systems. While technical prototyping provides a broad validation approach, it is an expensive and time-consuming exercise that involves a large amount of technology and data development skills that are not commonly found within asset management organisation, and therefore have to be outsourced.

Non-technical prototyping requires the documentation of information requirements, as an example, in an Excel worksheet or an SQL database table, but no technology solutions are developed or directly implemented within asset management systems. Non-technical prototyping should aim to simulate asset management processes with the new information requirements. As an example, process maps can be used within a collaborative workshop environment to simulate events within asset management and witness if the newly developed information requirements support asset management decision making processes. Furthermore, non-technical prototyping can include interviewing and direct observation to gain insight into the new requirements.

The outcome of this step is a set of OIR, FIR and AIR that have been negotiated and validated. As a minimum requirement, a consensus should be established between all stakeholders that the information requirements are fit for purpose and aid the organisation in making informed decisions around their asset management objectives. For larger organisations, technical and non-technical prototyping can aid in gaining the consensus between stakeholders with often conflicting requirements, goals and constraints.

6.5. Communicate and documenting asset management objectives and information requirements

This section discusses the documentation and communication of the asset management objectives and information requirements, including OIR, FIR and AIR, which consists of two sub-steps, see Figure 6-6.

Figure 6-6 sub steps of step seven

6.5.1. Documentation

Documentation in the context of this step is the process of aggregating, sorting and storing the developed information requirements, asset management objectives and asset classification system.

The documentation of information requirements is discussed in detail within the individual steps. Care should be taken when collecting information requirements from all of the steps, to ensure that the structured approach to their development is maintained. A large number of information requirements will be developed, specifically in large asset management organisations that maintain complex assets, there is a need to manage the documentation in a structured approach. Firstly, a standard approach to a folder structure and naming convention should be adopted, the BIM standard BS 1192 [102] provides such an approach for BIM related documentation and should be adopted for the documentation of information requirements. Secondly, view, edit and delete permissions should be managed by a Common Data Environment (CDE) such as ProjectWise [165] or OneDrive [166] that supports user permissions management, ensuring that documents cannot be moved, edited or deleted without the correct permissions.

Similar to the document the information requirements documentation, asset management objectives is discussed in detailed within Section 5.2.2. Asset management objectives should be stored within a single document that is both human and machine-readable, such as Excel, CSV or SQL tables. Similar to the information requirements, the documents should be managed within a CDE.

Finally, documentation of the asset classification system is discussed in detail in Section 5.3.3. As multiple documents are developed during the asset classification development, such as UML diagrams, care should be taken to ensure that the documents that are correctly structured in folders and sub-folders, with a standard naming convention, such as in BS 1192 [102].

6.5.2. Communication

This section focuses on the communication of the developed information requirements and the asset classification system.

The organisation should consider the communication requirements for both internal and external stakeholders. As an example, an external stakeholder might need to know specific information requirements related to a fire door inspection but would not require the asset classification for that given asset. Furthermore, any security / safety-related issues should be considered when communicating with external stakeholders. Internal communication should be limited to only communicating the information and assets classification that is relevant to the given stakeholders, ensuring that personnel are not overloaded with information.

A communication plan should be developed that builds awareness of the new information and asset classification requirements, an understanding on how the new requirements will impact existing stakeholders and engaging with personnel that have not been involved within the development process. The communication plan should include the following aspects:

1. Highlight the benefits of the new requirements and how they are expected to impact specific stakeholders.
2. Schedule to implementing the new requirements within the asset management systems, including key milestones that have been set.
3. Any specific events, workshops or leadership meetings that are best suited to deliver the communication needs.
4. Define the unique requirements of specific external stakeholders and how best to communicate the new requirements within contracts and legal terms.

5. A formal process for providing feedback and reporting.

The outcome of this step is a well-defined communication plan that highlights the needs of internal and external stakeholders. Furthermore, it provides the foundation for communicating the benefits of the new requirements and stakeholder's engagement needs.

6.6. Summary

This chapter saw the discussion of part two of the information requirements framework that is focused on the development of FIR and AIR, along with validation, documentation and communication of the information requirements, this includes steps four, five, six and seven.

Step four sees the development of FIR, as FIR are a new concept developed within this research effort, a definition is provided within the introduction section. JDA workshops are introduced as a means to aid in the development of information requirements, including the use of directed and guided brainstorming exercises, as a means to encourage collaborative working within a workshop environment. Furthermore, an information requirements matrix is developed (see Figure 6-3) as a structured means to capture information requirements within the workshop. The final task is to document the FIR, similar to the OIR documentation, it is required to document them both within human and machine-readable formats.

Step five sees the development of AIR, AIR our adopted from the BIM standards and a definition is provided within the standard PAS 1192-3, which is utilised for this step. The AIR development follows much of the same activities within the FIR development, such as stakeholder selection, JDA workshops and brainstorming activities. An AIR aims to capture information at the asset system or sub-system level.

Step six aims to provide a process for validating the information requirements within a negotiation life cycle and prototyping. A negotiation project life cycle is proposed that uses a common goal as a means to support *"win-win"* and *"give and take"* negotiation approach, within this context the asset management objectives are used as the common goal.

Finally, step seven highlights the need for documenting and communicating the newly developed information requirements. While documenting the FIR and AIR are discussed within their individual steps, this step focuses on storing the documents within a structured approach, a document control workflow is adopted from the BIM standards. The communication section discusses the need for developing a communication plan that highlights key benefits, timeline to implementing the new information requirements and a means to provide feedback to senior management and the broader asset management department.

This section addresses the challenge of an OIR generating an AIR, that was highlighted within the academic literature and industry investigation, by developing a new set of information requirements (FIR) that aims to bridge this gap. Furthermore, a structured approach to the development of AIR is proposed, along with a process of documenting, validating and communicating the newly developing information requirements.

The outcome of this chapter, being the AIR and FIR are used within the following chapter to support the development of an Asset Information Model, along with the asset classification developed in Section 5.3

7. BIM Model Design and Development to Support an AIM

7.1. Introduction

This section discusses in detail the last three remaining steps, eight, nine and ten of the information requirements framework, see Figure 7-1.

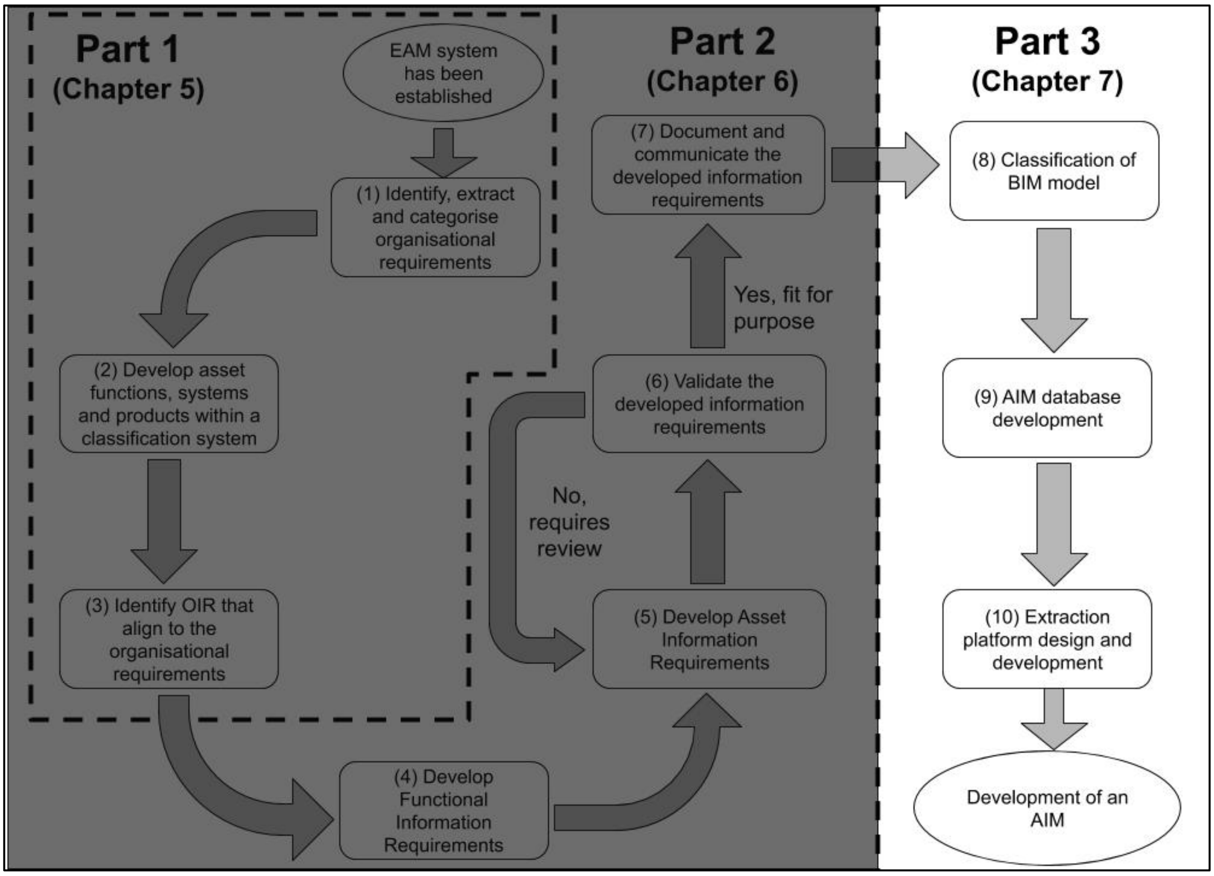

Figure 7-1 scope of Chapter six within the information requirements framework

Chapters 5 and 6 focused on the development of information requirements to enable Building Information Modelling (BIM) within asset management. This chapter focuses on the design and development of a BIM model to enable its use within asset management. As a point of clarity, a BIM model within this context is a 3D object-orientated model.

Current limitations of the Industry Foundation Classes (IFC) schema is limiting the adoption of BIM models within asset management, as it only allows for a single classification of an object and not the multiple aspects of an asset classification system, such as an assets functional output, system and sub-system. This limitation means that a BIM model is not structured from the perspective of an asset management organisation, who maintain and operate assets functional outputs.

This chapter proposes an approach to the development of custom metadata requirements that are developed within a BIM model, therefore allowing multiple classification of the same object. Furthermore, a mapping between the custom parameters and IFC property classes is proposed, allowing for the export of the asset classification within an IFC model. Moreover, a structured approach to the development of an Asset Information Model (AIM) database is proposed, along with an extraction platform for populating the database with the IFC model.

Step eight utilises the asset classification system developed in Section 5.2, to classify objects within the BIM model, custom parameters are created within the BIM model authoring software for export into an IFC model. Step nine is the development of an AIM database, which is derived from the asset classification UML diagrams. Furthermore, this steps also utilises the Organisational Information Requirements (see section 5.4), Functional Information Requirements (see section 6.2) and Asset Information Requirements (see section 6.3) as columns within the AIM database. Finally, step ten is the development of an extraction platform for extracting asset-related data from a BIM model. Furthermore, an AIM database is derived from the asset classification system and an extraction platform is developed to extract data from a classified BIM model into the AIM database.

The literature review (see Chapter 2) noted that the definition of an AIM is poorly defined, with conflicting definitions. As a point of clarity, the below definition from PAS 1192-3 is adopted:

"data and information that relates to assets to a level required to support an organisation's asset management system" [5] *page 3.*

7.2. Classification of the BIM model

This section discusses the classification of a BIM model, including the development of custom metadata requirements that are mapped into an IFC export. This step is critical in the development of an AIM, as it provides an approach that allows a BIM model to be extracted and inserted into the AIM database, see Section 7.4.

To support the classification of the BIM model, the process has been derived into three steps (see Figure 7-2). Step one, the creation of custom metadata that enables the storage of the asset classification developed within step two of the information requirements framework, this enables the assets within the BIM models to be aligned direct to the FIR and AIR, as they utilise the asset classification to support their development. Step two is the classification of the BIM models itself, by populating the metadata created in the previous step, this provides a structure to the BIM model that aligns to the information requirements (FIR and AIR) for populating an AIM. Finally, step three, is mapping the custom metadata within the BIM model to IFC classes, this is important by enabling the asset classification to be exported within the IFC open-source format, therefore not limiting the framework to a given BIM enterprise software format.

These three steps where derived from the initial case studies and feedback that support the overall information requirements framework development, See Chapter 4.

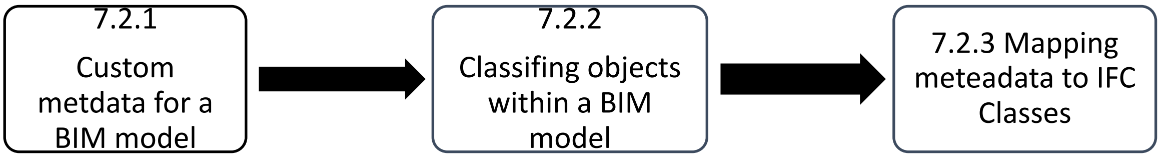

Figure 7-2 sub-steps of step eight

7.2.1. Custom metadata for a BIM model

This step discusses the need for a new set of metadata requirements within a BIM model. The asset classification system developed in Section 5.2 is adopted, enabling the classification of objects within the BIM model.

Figure 7-3 provides an example of the asset classification metadata attached to a BIM object. The left-hand side of Figure 7-3 shows the new metadata requirements that are attached to a fire door, which is part of a BIM model, each object within the model will have the same asset classification metadata.

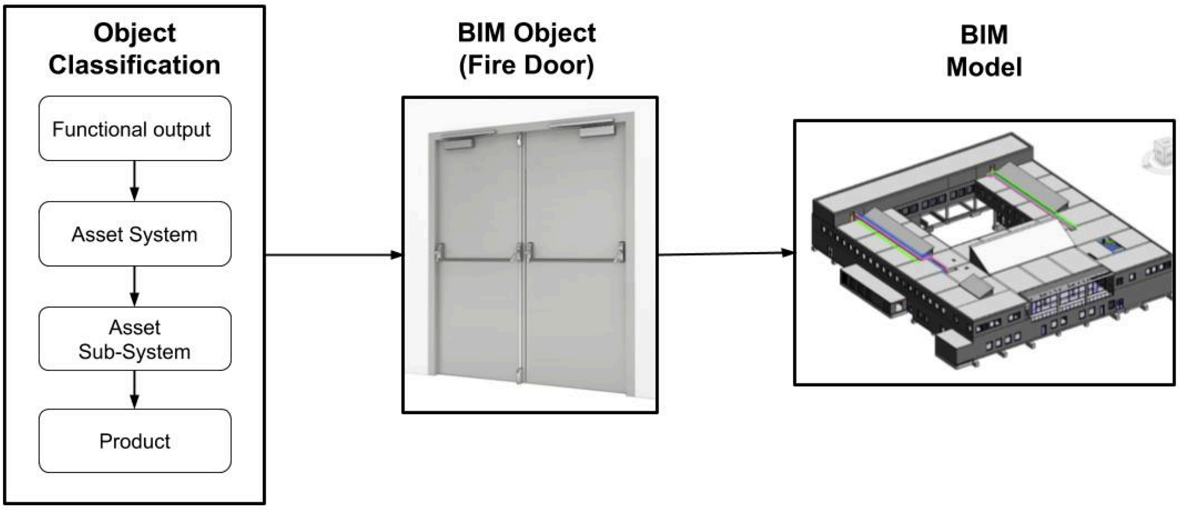

Figure 7-3 BIM model classification process

There are several advantages to implementing the asset classification system within a BIM model:

- The ability to search, filter and extract BIM objects based on their functional output, system and sub-system.
- Provides an approach that enables the structured exchange of information from a BIM model into an AIM model, via the asset classification.
- Direct alignment between the information requirements developed within the information requirements framework (see Chapter 5 and 6) and the BIM model.

Most established BIM authoring software such as Autodesk Revit [167], Bentley System MicroStation [168] and Graphisoft ArchiCAD [169], allow for the development of custom metadata requirements for use within BIM models. As an example, Revit allows for the development of custom parameters, while MicroStation and ArchiCAD allow for the development of additional attributes that act as custom metadata requirements. The outcome of creating custom metadata is a TXT or XML file that is loaded into the BIM authoring software which associates the metadata with the objects in the BIM model. It is proposed to use this feature as a means to attach the required asset classification to a given object. Using this approach has several advantages over attaching the metadata directly within the BIM objects themselves:

- Metadata requirements only have to be developed once and not per the individual BIM objects.
- Can be used for multiple BIM models, providing a consistent and structured approach.
- One source for asset classification related metadata requirements. If the requirements change, this could be reflected within all of the BIM models that use the asset classification metadata.

Table 7-1 provides a summary of the asset aggregation metadata requirements, along with UNIClass examples.

Metadata name	**Description**
FuncationalClassification	Is the functional output of the BIM object. As an example, heating, lighting or ventilation. An example UNIClass classification for functional is EF_40_60 (ventilation).
SystemClassification	Is the asset system that the given BIM object is within. As an example, gas heating, water chiller or commercial lighting. An example UNIClass classification for asset system is Ss_65_40_32 (Hot Water Unit)
SubSystemClassification	if the classification of a given asset sub-system is needed, it should be captured within the metadata. An example of an asset sub-system is a Low-Temperature Hot Water Unit, that is a sub-system of a hot water unit and has the associated UNIClass code of Ss_65_40_32_66.

Table 7-1 asset aggregation metadata requirements

7.2.2. Classifying BIM objects within a BIM model

This step discusses the process of classifying objects in a BIM model, populating the custom metadata requirements created in Section 7.2.1 with the asset classification developed in Section 5.2.

In order to populate the metadata with the associated asset classification, it is required to select the objects. While it is possible to select objects in a BIM model and classify them manually, this would be a long and complicated task, especially when considering that simple BIM models can easily have over ten thousand objects within them.

There are multiple ways in which a BIM model can be manipulated in order to select objects efficiently for classification. Search filters allow the selection of objects via their disciplines such as architectural, structural and MEP, that are similar to the functional output level of the asset classification. Custom views can be created with both 2D and 3D views of the model. As an example, a view with a 3D section can be used to quickly select multiple assets of the same type, such as a ventilation system. Finally, selection sets can be created based on any number of parameters that automatically selects objects based on a set of rules and constraints that are built into the set. As an example, a selection set could be developed to select only objects that have an airflow, therefore selecting objects related to ventilation, or only selecting doors that are over 1200mm in width, as any door over 1200mm in width is a fire door.

Along with the manual processes discussed above, there are also multiple techniques that can automatically populate the classification metadata. Predefined objects can be use that are already populated with the required classification, the Rapid Engineering Model developed by Highways England is an example of pre-populated objects for inserting into a BIM model. Another example is a proposed framework that automatically checks an IFC model against a set of rules, such a process could be modified to automatically classify objects [170]. As an example, you could classify a fire door by stating that if a door is over 1500mm wide, it is classified as a fire door.

Not all objects in a BIM model have a functional output and therefore do not need to be classified. For example, Zones and spaces are 3D objects that state the name of the location (such as an office or a hallway) and provide parameters of that space, such as width, length, height, area and volume. A site is a 3D object that is generally developed from a survey showing contours, heights and special features on the site. Furthermore, features of a site such as ponds, trees and shrubs are individual BIM objects, but as they might not have a functional output, they need not be classified, along with the above BIM objects. While such objects don’t have a functional output, it does not mean that they are not important, as an example, space information is important when conducting cost per area analytics, such objects will still be converted into the AIM database and federated model.

The outcome of this step is a BIM model, with all objects in the BIM model that have a functional output are classified as per the asset classification system developed in Section 5.2.

7.2.3. Mapping custom parameters to IFC property classes

This step discusses the mapping of the custom metadata that was populated with the asset classification in Section 7.2.2 to IFC property classes, for export into an IFC model.

While different BIM authoring software have different approaches to mapping custom metadata to IFC properties, there are some common themes. Firstly, they all use simple text-based configuration files for the mapping process. Secondly, a custom IFC property set has to be created, which is a container that contains all of the property related to the given set, the name of the property set should start with “Pset_” and relate to the properties within it. Thirdly, a direct mapping is made between the custom metadata within the BIM model and the IFC property set that will be exported within the IFC model. Finally, a datatype for the given IFC property within a property set is defined, such as text, integer or date/time.

Figure 7-4 provides an example of IFC mapping from the asset classification metadata to IFC properties. The left-hand column is the name of the custom parameters developed within the BIM model. The middle column is the data type within the IFC schema. The right-hand column is the name of which the custom parameter will be mapped to within the IFC schema. Finally, the IFC properties are stored within an IFC property set called *“Pset_classification”*, which is located above the three columns.

```
#
# user defined PropertySet Definition File
#
 Format:
        PropertySet:    Pset_classification
        FuncationalClassification       Text    FunClassification
        SystemCalssficiation            Text    SysClassification
        SubSystemClassification         Text    SubSysClassification
        ProductClassification           Text    ProClassification
```

Figure 7-4 Example IFC mapping file

The outcome of this step is a TXT or XML file that maps the custom metadata developed within Section 7.2.1 to IFC property sets, this ensures that the custom metadata is exported within an IFC model, see Section 7.4.1.

7.3. AIM Database Development

This section discusses the development of an AIM relational database. The AIM database acts as a storage solution for data that is extracted from a BIM model, see Section 7.4. Furthermore, the AIM database forms an integral part of the overall AIM development, see Section 8.8.

This section is divided into two steps (see Figure 7-5). Firstly, the development of the AIM database schema, the schema itself is derived from the asset classification UML diagrams which in turn are developed from the asset classification system. Utilising the asset classification system to develop the AIM database schema, creates a direct alignment between the AIM and the FIR / AIR. Step two is *"physically"* building the AIM database, which is an automatic process from the database schema design.

While a database could be manually created, aligning the schema to the asset classification and utilising UML diagrams is an efficient database development process that supports non-technical stakeholders' engagement.

Figure 7-5 sub-steps within step nine

7.3.1. Developing an AIM database schema

This step focuses on converting the developed asset classification UML diagrams into database schema diagrams. Step two (Section 5.2) of the information requirements framework saw a set of UML diagrams developed that represent an asset classification system. The UML diagrams themselves are basic class diagrams that demonstrate the relationship between a functional output, asset systems and sub-systems that support it. While the diagrams are helpful to aid in the development of the asset classification model, they must be further developed to support the development of a database.

As a point of clarity, an example asset classification UML diagram (for lifts) is provided below in Figure 7-6.

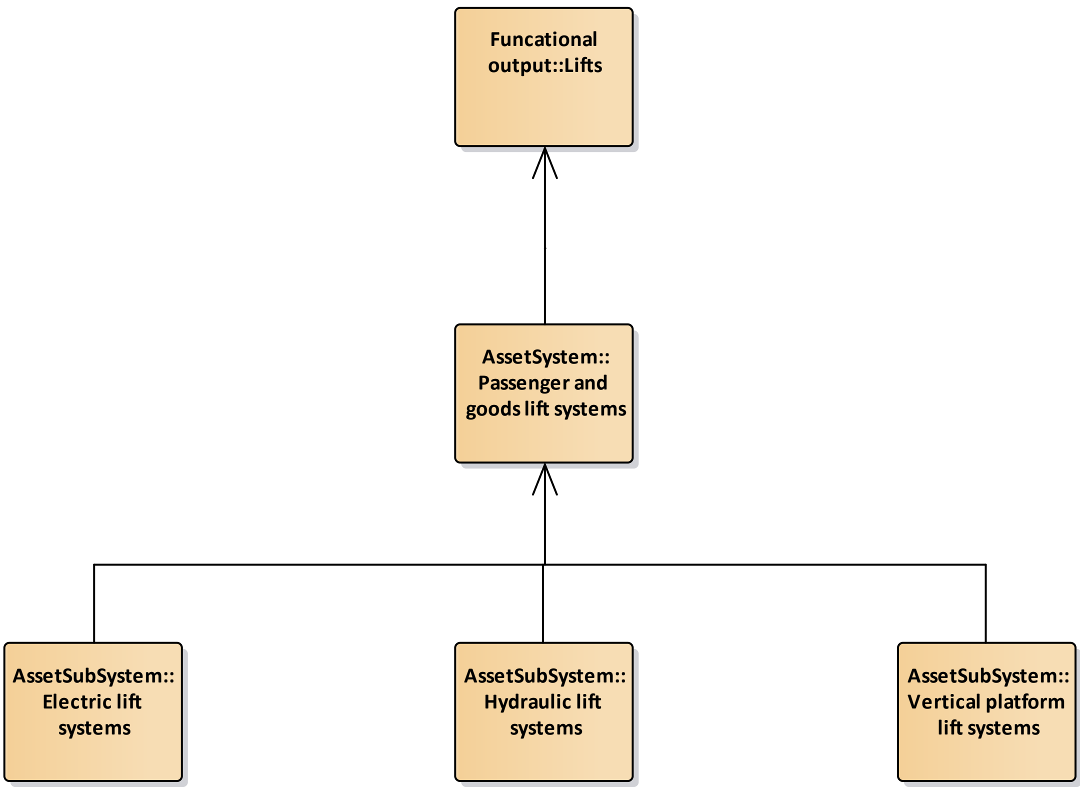

Figure 7-6 Asset classification UML diagram for lifts

Converting UML diagrams into a database schema

A relational database (such as MySQL [171] or Microsoft Access [172]) is a set of formally described tables that can be accessed or reassembled without reorganising the database tables themselves. Each class within the UML diagrams will represent a database table, several aspects have to be built into the diagrams to support the database development. Firstly, while the UML diagrams illustrate the relationship between the different classes with solid arrows (see Figure 7-6), it does not explicitly state how that relationship is created. Within relational databases, the relationship between the tables is established by developing Primary Keys (PK) and Foreign Keys (FK) that act as a cross-reference between tables, with a one to many (1:*) or a one to one (1:1) relationship. As an example, the functional output of heating has a one to many relationships, meaning that many asset systems can have a relationship with heating, but heating cannot have a relationship with any other table. Furthermore, this also ensures consistency within the database by only allowing asset systems to have a relationship with one functional output. As an example, the table for electric heating system cannot have a relationship with both the tables for heating and ventilation. The relationship between the functional output, asset system and sub-system is maintained by utilising the asset classification itself as the primary and foreign keys.

Figure 7-7 illustrates a database schema diagram that is derived from the asset classification UML diagram for lifts in Figure 7-6. The UML classes have been converted to database tables, with the asset classification name replaced within the classification code. Furthermore, the representation of a relationship between the different classes (as seen in Figure 7-6) is converted to a database compatible PK and FK relationship.

Figure 7-7 Database schema diagram for Lifts

The outcome of this step is a set of database schema diagrams that have been derived from the asset classification UML diagrams developed in Section 5.3.3. The diagrams are used within the following step (Section 7.3.2) to *"physically"* build the AIM database.

7.3.2. Building the AIM database

this step discusses the build of the AIM database. While developing the UML diagrams provides the structure for the development of the AIM database, it does not build the database itself. There are two steps required to develop the AIM database from the UML diagrams: (1) An instance of a database must be established and running and (2) the UML diagrams need to be converted into queries that will create the tables and relationships. A query is a command-line statement that enables the manipulation and creation of the database, such as selecting and displaying data, creating and deleting tables and establishing relationships between the tables.

Starting an instance of a database

This step discusses the initiation of a relational database instance. There are multiple ways an instance of a database can be established. Many cloud-based operators provide database tools, such as Amazon Relational Database Service [173] provides a user-friendly workflow for starting a database instance. Furthermore, relational databases can be developed on a local computer network with database server software such as MySQL [171]. The database should be developed with default settings such as network port, host address and charsets requirements.

The outcome of this step is an instance of a relational database that is running on a cloud solution or local server. No tables, relationships or views should be developed at this point.

UML diagrams converted to queries

This step converts the UML database diagrams into queries that are executed on the database instance developed in the previous step.

Common UML diagram development platforms such as Enterprise Architecture [159], Vertabelo [174] and SqlDBM [175] have database development tools that convert UML diagrams into queries.

Figure 7-8 provides an example of the database builder within Enterprise Architecture. The left-hand shows the execution queue where the queries are automatically created and waiting to be executed. The right-hand side shows the statement that is within the query, which is automatically created by the database builder tool.

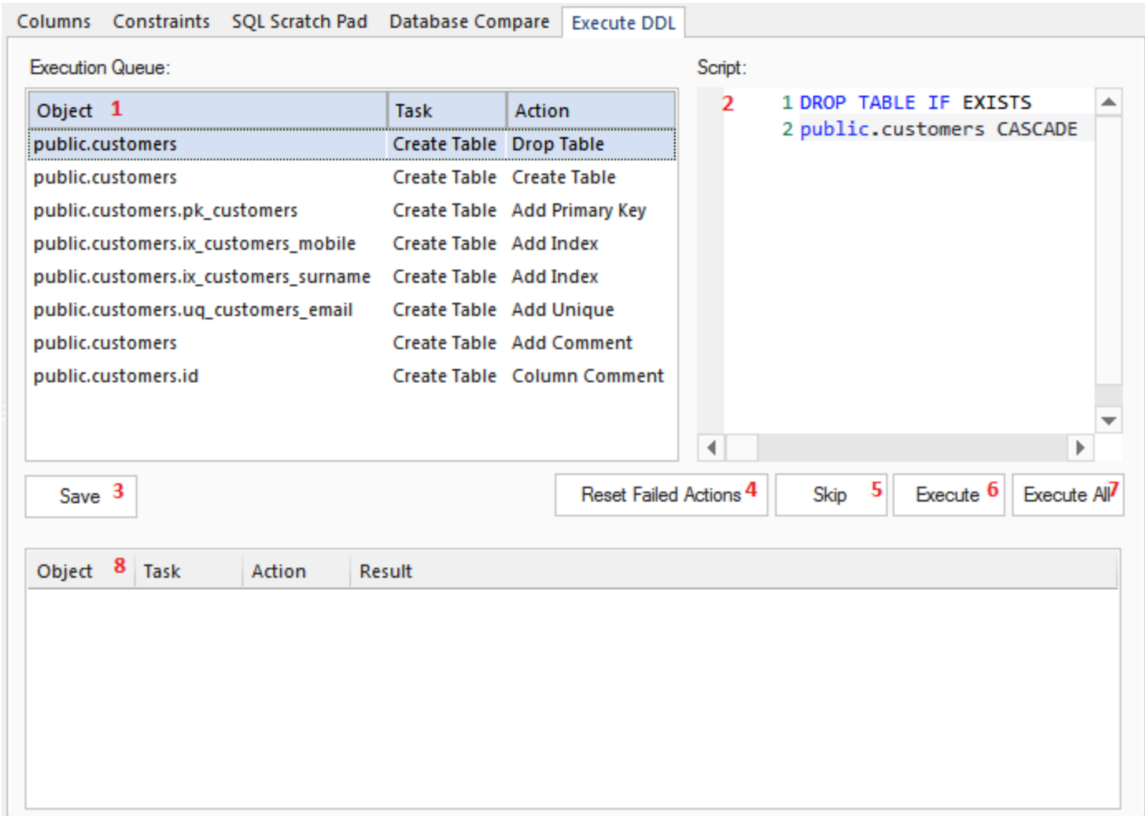

Figure 7-8 Example queries from Enterprise Architecture

Building the database in such a way has several advantages. Firstly, if the UML diagram changes, the database builder will automatically create new queries to execute. Secondly, the non-coding approach addresses the challenge of limited technology-related skills within asset management organisations. Finally, the UML diagrams can be shared with both technical and non-technical stakeholder for review.

The outcome of this step is the AIM relational database, that is built from the UML database schema that in-turn is derived from the asset classification UML diagrams.

It should be noted that this section developed the AIM relational database, it did not populate the database with any data. The database developed within this step is used within the following step (Section 7.4) as a means to store extracted data from a BIM model.

7.4. Extraction platform design and development

This section discusses the development of an extraction platform, which enables the export of objects from a BIM model into the AIM database, based on the objects asset classification.

This section is derived into two steps. Firstly, the export of a BIM model into the IFC format with the populated asset classification metadata. Exporting the model to IFC format ensures that the process is vendor neutral and therefore not limiting the exploitation of the model within non-vendor specific applications. Step two is the development of an application platform that enables the automatic extraction of assets directly from the BIM model into the AIM database.

While there are some commercial applications that allow you to open and edit IFC files, such as usBIM.viewer+ [176], they will not populate a database, as is required to develop an AIM. furthermore, the platform develop utilises the assets classification within the BIM model to efficiently extract the data and populate the AIM database (which is also derived from the asset classification), therefore maintaining the link between the information requirements (OIR, FIR and AIR) and the BIM model.

Figure 7-9 sub-steps of step ten

7.4.1. Exporting a BIM model to IFC

This step discusses the export of an IFC model from BIM authoring software.

Major BIM authoring software enables the export of BIM models into the IFC format, with BIM objects associated to IFC elements. As an example, a BIM object of a door is associated with the IFC element, IFCdoor. Furthermore, common IFC properties are exported with the corresponding BIM object, as an example, a door would have the property of width and height, while a floor would have the property of area and thickness. The BuildingSMART Data Dictionary provides a summary of common IFC properties exported with a given BIM object [177].

There are several standard settings when exporting an IFC model, such as IFC version, additional contents, level of detail and property sets. At the time of writing this thesis, IFC4 is the most recent version and has several performance upgrades from IFC3 and is the export version of choice. Additional contents can be exported with the IFC file such as 2D plans, annotation and 3D zones or spaces. Unless there is a specific requirement, additional content should not be added to the IFC model, this helps in avoiding large and complex models.

Property sets define the metadata that is associated with a given object within the BIM model, Figure 7-10 shows the property set window settings. The user-defined property sets related to the custom metadata developed in Section 7.2.1 and therefore is required to be exported within the IFC model. Furthermore, the common IFC property sets have valuable information that can be used for asset management processes and should also be exported.

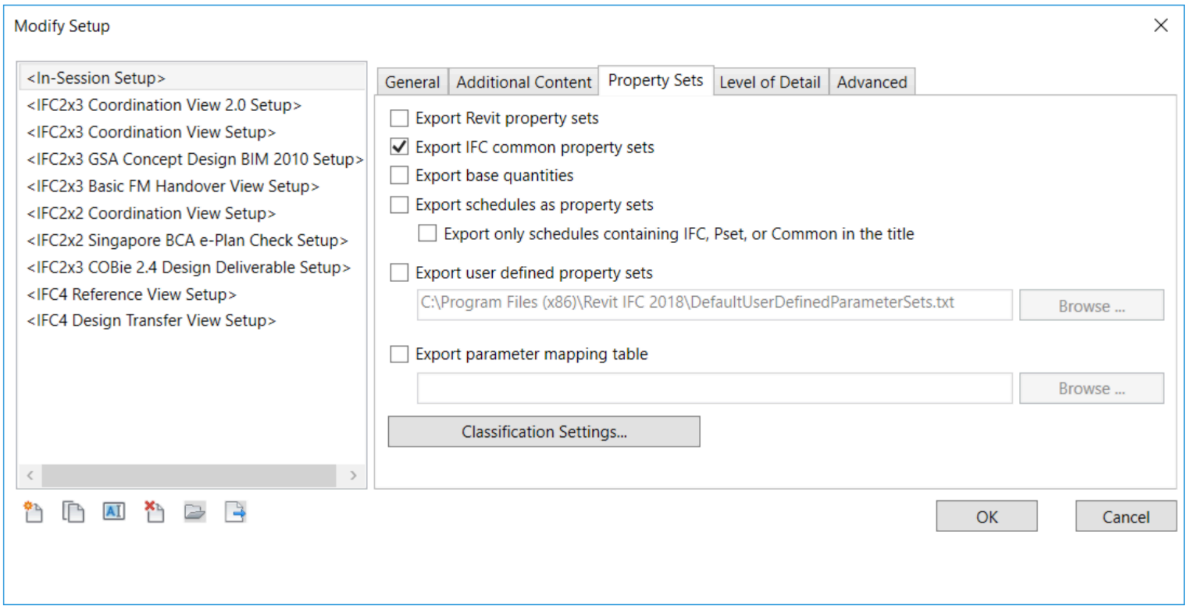

Figure 7-10 IFC export settings in Autodesk Revit

The outcome of this step is a BIM model that has been exported into an IFC model, along with the user-defined and common property sets. Furthermore, the model should be the latest IFC version (IFC4), low level of geometry detail and without any additional contents.

7.4.2. Platform development

This step discusses the development of an application that aims to extract structured data from an IFC model, the application must meet several requirements, including:

- Capable of reading complex IFC models with over ten thousand BIM objects, including all IFC elements and property sets within IFC version 4.
- Able to extract properties from IFC elements and filter, group and sort via those properties. As an example, group all objects that have the classification for heating, such as UNIClass code EF_65.
- The application itself will insert data directly into the AIM database. This includes automatically creating queries that will insert data into the tables created in Section 7.3.
- The application should aim to have the least hard coding (such as C++ or C#) as possible, in order to maintain useability within an asset management organisation.
- Repeatability is a critical element. Providing the IFC file is in a similar structure and the user-defined property sets (for the asset classification) have been created in the same format, the application should work with any IFC file.
- Work on all model discipline types including structural, architectural, engineering, civil and infrastructure.

Application development can be split into three steps. Step one, importing an IFC model into the application. Step two, extracting, filtering, transposing and merging data from the IFC model as per the asset classification. Furthermore, this step also prepares the data for inserting into the AIM database, such as syntax and formatting. Finally, step three is creating and executing the queries that insert the data into the AIM database.

There are multiple ways to work with the IFC format. Firstly, hard coding an application with programming languages such as Python, C++ or C#. Secondly, using an Extract, Transform, Load (ETL) application [178] as a means of developing a workflow for importing, manipulating and exporting the data. ETL is the preferred choice for platform developed, due to its non-coding approach and its ability to read and write into many different formats, including IFC.

Extract, Transform, Load (ETL)

ETL is a category of applications that enable the extraction, transformation and loading of data between different datasets, including databases such as SQL and file formats such as CSV and JSON. ETL applications are considered more user-friendly and maintainable as they do not require any hard coding skills, with many ETL applications able to import over three hundred different databases and file formats. ETL applications are based on developing a workflow that transforms the data as it moves along the workflow, this is generally done by dragging and dropping *"transformers"* into a canvas workplace and connecting them to transform the data. Figure 7-11 shows an example ETL workflow in FME Desktop [179], with the imported data in pink on the left-hand side and the exported data in green on the right-hand side. The blue boxes are *"transformers"* that manipulate the data along the workflow, enabling the extracting, filtering and transformation of data.

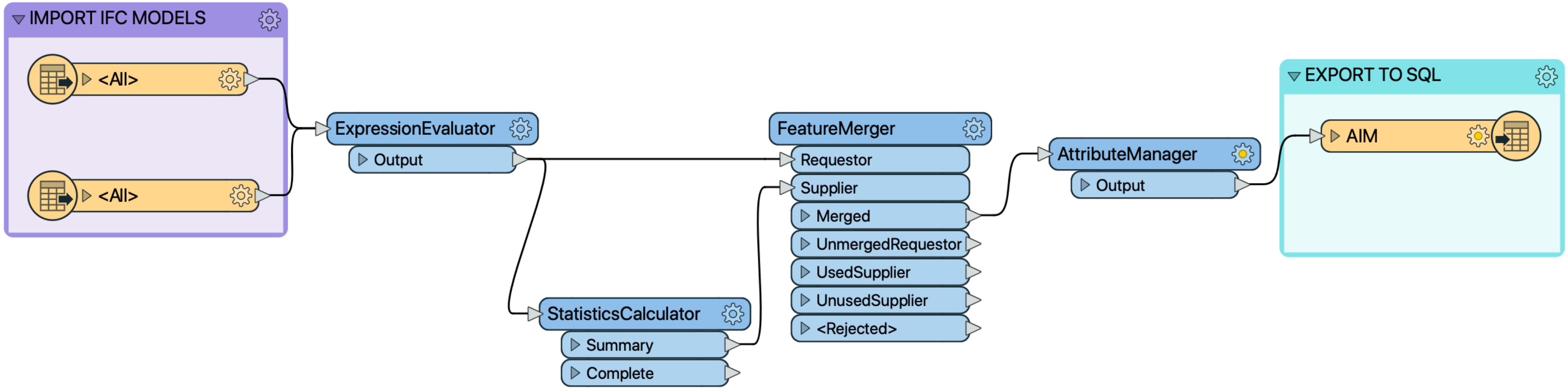

Figure 7-11 Example of an FME desktop canvas

The use of an ETL application for platform development has several advantages over the use of hard coding. Firstly, the non-coding approach to developing the workflow addresses the lack of technical programming skills within an asset management organisation. While it is noted that there is still a learning curve and a need for technical understanding while developing a workflow within an ETL application, it is significantly less compared to hard-coding [180]. Secondly, ETL applications have a pre-built user interface, meaning the end-user only changes the input and output settings and never sees the workflow. As an example, when a new IFC model is issued, it can be selected without having to edit the workflow, meeting the repeatability and user-ability requirements for non-technical stakeholders. Thirdly, a single workflow within an ETL application is far easier to manage and maintain than a collection of code, packages and libraries, which is important when considering asset management organisations do not commonly have code management skills in-house.

This step discussed the development of an ETL platform that is capable of reading an IFC model, then filtering, grouping and transforming the data before inserting into the AIM database (see Section 7.3). The platform development itself is discussed in detail within an industry case study, see Section 0.

7.5. Summary

This section summarises steps eight, nine and ten within the information requirements framework. The three steps presented shows how a BIM model should be designed and structured for use within an AIM.

The steps discussed addresses the challenge of adopting BIM within asset management, providing an approach that enables a structured exchange of BIM objects within a BIM model into an AIM database.

Step eight is the classification of the BIM model, meaning to attached new metadata to objects within the BIM model with the asset classification developed in Section 5.3. This involved creating a set of asset classification custom metadata requirements, mapping the new requirements to IFC property sets and the classification of the BIM model itself.

Step nine is the development of the AIM relational database. The AIM database is derived from the asset classification UML diagrams developed in Section 5.3.3, which are developed into database schema diagrams. The database schema diagrams are converted to database queries and executed on a database instance to create the tables and constraints and therefore, the AIM database.

Step ten is the design and development of an extraction platform for populating the AIM database with the IFC model. The first step is exporting an IFC model from the BIM authoring software, including the custom metadata requirements developed in Section 7.2. The second step is the development of the platform itself, it is proposed to use an ETL application as it supports the user-ability requirement within an asset management organisation and natively supports the import of IFC models.

The outcome of this chapter is a BIM model that has been designed from an asset management perspective by developing a new set of metadata requirements that enables multiple classification of the same object. Furthermore, an AIM database is derived from the developed asset classification system (see Section 5.3) and an ETL platform that enables the extraction of data from an IFC model into the AIM database.

The steps discussed in this chapter, along with the steps discussed in Chapter 5 and 6 are implemented within an industry case study within the following chapter.

8. Case Study

8.1. Introduction

This chapter presents the findings from an industry case study. The aims of the case study is to demonstrate the practical application of the information requirements framework discussed in Chapters 5, 6 and 7. Firstly, the case study approach is presented in detail, along with defining the organisational challenges. Secondly, the specific details of the case study are presented along with the tools and techniques used within the framework. Lastly, the Asset Information Model (AIM) itself is developed, as the outcome of adopting the framework.

The case study was carried out within an asset management department of a significant research and teaching university based in the UK, with over 400 buildings to maintain and operate over a large geographical location. Furthermore, the university is currently in a growth stage, with new buildings and major refurbishments being commissioned within the next five years. The department has around 100 employees, both technical (such as maintenance engineers) and non-technical (such as administrative).

Due to the size of the university, a specific campus was chosen that is part of the broader university estate within the same city and is a growing focus for the university. The campus consists of 20 buildings, some dating back to 1955 and the most recent commissioned building in 2019, with the vast majority being commissioned within the past 20 years. The use of this specific campus area has several advantages. Firstly, the researcher has acquired a large number of datasets within the campus area, including Building Information Modelling (BIM) models, utility models, point cloud and drone flyover photos. Secondly, as it is a growth area for the asset management department, they are keen to show the campus as a state-of-the-art example, therefore making resources available to the researcher. Finally, compared to the rest of the university estate, the buildings are significantly newer, making access to relevant documentation easier to source.

For reference, the case study follows the same steps within the information requirements framework, see Chapter 4 and Figure 4-5, starting from Section 8.5 to Section 8.7.

8.2. Case study approach

When considering the approach for a case study, there are three primary types: key cases, outlier cases and local knowledge cases. Key cases are case studies that are chosen because the researcher has a particular interest within the subject. Outlier cases are case studies where a specific event, organisation or person standout from what is considered the norm and the difference is considered of interest to the researcher. Finally, the local knowledge case study is where the researcher has amassed an amount of knowledge about a given point and is well placed to conduct a case study.

Within the above primary case types, a case study can take four different approaches, as noted within Table 8-1.

Case study approach	**Description**
Illustrative case study	Are descriptive and aim to *"shed light"* on a specific event or situation, highlighting the relationships and processes that are embedded within them. Particularly helpfully for providing insight on a topic which most people are not aware of.
Exploratory / Pilot case study	Are typically used during the early stages of the research progress when the researcher wants to identify research questions and methodologies for a larger and generally more complex study. They help provide structure to the research process and ensuring that the research addresses a compelling challenge.
Cumulative case study	Is when a researcher will collect and analyse a set of already completed case studies. Used to gain a generalisation and shared understanding of what research has already been completed within a given domain.

Critical instance case study	Are conducted when the researcher wants to understand what happens with a unique event or wants to challenge a commonly held assumption that might be faulty due to a lack of critical knowledge.

Table 8-1 Case study summary adopted from [1]

Crossman [181] notes that before a case study approach is chosen, there is a need to identify the purpose and goal for the case study. The purpose of this case study is to evaluate the performance of the information requirements framework(see Chapter 4) being adopted within a *"real world"* setting. The goal is to demonstrate how a structured approach to the development of information requirements would enable the development of Organisational Information Requirements (OIR) and address the challenge of developing Asset Information Requirements (AIR).

Reflecting on the purpose and the goal, this case study falls into two primary case study types, key and local knowledge case studies, justified by the researchers' specific interest and prior industrial experiences within the domain. Local knowledge is gained from being embedded with the industry partner during the research effort and prior informal interviews and conversations before conducting the case study. Given that this case study aims to address a specific and well-defined challenge, the most applicable approach is the critical instances case study approach. The critical instance approach enables the challenging of the assumptions of BIM adoption within asset management, as highlighted within Chapter 2. Furthermore, such an approach also supports the creation of new knowledge and therefore enables the evaluation of the proposed framework.

8.3. Developing a challenges matrix

Chapter 2 highlighted the challenges of adopting BIM within asset management and this section aims to identify the challenges within the case study organisation.

It was decided that a matrix approach (compare to a linear approach) was the most appropriate way to capture the challenges. A linear approach captures challenges within one category, such as horizontally. While, a matrix approach allows for two categories, horizontally and vertically. Asset management is a multidiscipline approach with many stakeholders managing the assets throughout multiple different lifecycle stages. Given this aspect of asset management, a matrix that addresses the different challenges of the stakeholders within a given asset lifecycle stage was developed.

Reviewing the asset management standards and literature (see Section 2.2), it was noted that there are four high-level activities that asset management organisations perform: 1) operate and maintain assets, 2) inspect assets, 3) reporting on assets performance and 4) design and construct new assets. The activities are used within the horizontal axis of the matrix, see Table 8-2 for a description.

Asset management activities	**Description**
Operate and Maintain (O&M)	The physical activity of operating and maintaining an asset or a system of assets. As an example, for a railway network, this would include the operating of rolling stock or signals. For a university campus asset management team, this could include operating and maintaining a buildings ventilation system or maintaining lab equipment.
Inspect	The activity of inspecting an asset, meaning that no physical work is done on the asset, it is merely inspected. This can include legally required inspects such as fire doors or performance and conditions-based inspections, such as inspecting the performance of an HVAC unit.
Report	The aspects of reporting on an asset's performance, performance can be both financial and non-financial. As an example, the cost of operating an asset could be reported against the revenue generated from the asset, such as advertising boards. From a non-financial aspect, environmental impact or customers satisfaction are standard reporting requirements.
Design and Construct	The activity of assets being designed and built, including the refurbishment of assets when the activity of design and construct is required. Including the need to build a

	new asset to support an increase in performance or to support a new service, such as a new railway line or new equipment for emerging research.

Table 8-2 Asset management activities

The industry investigation in section 2.5 noted a common set of challenges in asset management organisations: 1) developing information requirements, 2) organisational data management, 3) asset data management and 4) the organisational culture. These challenges form the vertical axis of the matrix, see Table 8-3 for a description.

Asset management challenges	**Description**
Information Requirements challenge	defines the key challenges that organisations have in the development of information requirements. Including stakeholder engagement, poorly defined of organisational requirements (e.g. asset management objectives) and the lack of a formal process to the development of information requirements.
Organisational data management challenge	defines the critical organisational data management challenges, this includes the management of asset data from an organisational perspective. Furthermore, this also includes data governance and management frameworks that provide the foundation for data management within an organisation. Such processes include developing a Data Quality Framework (DQF), planning schedules, financial management and risk management.
Asset data management challenge	focuses on the unique challenges within the management of asset data itself from a technical and managerial perspective. From a technical perspective, this includes such examples as the capture, exchange and storage of asset performance-related data. From a managerial perspective, this includes such examples as

	asset classification, uniformed asset data structures and standard unique asset ID association.
Organisational culture challenge	focuses on the unique organisational culture within asset management organisation and the challenges it puts on the development of information requirements. Including such examples as an industry that is generally hesitant to change specifically when involving technology, a lack of digital and data management skills within the industry and poor adoption within the leadership team to champion BIM and digital processes.

Table 8-3 Asset management challenges

8.3.1. Case study organisational challenges matrix

Bringing together both the asset management activities and challenges as described within Table 8-2 and Table 8-3, a matrix was developed with the asset management activities on the horizontal axis and challenges on the vertical axis. The matrix was populated through several informal conversations with the asset management team, see Table 8-4.

Category	O&M	Inspection	Reporting	Design & Construction
Information Requirements	technical / service information is not captured no standard approach to the development of information requirements	lack of technical / service & performance information	lack of information to report on (managerial, financial, environmental , operational) lack in understanding what	lack of what information should be captured at a project level for the AM team

			information is required for reporting	
organisational data management	the use of manual and non-digital processes poor access to historical maintenance records poor data integration between ERM, BIM, scheduling and spares management lack of a data quality process for maintenance	poor access to historical inspections limited integration of monitoring software such as BMS & SAP poor data integration means that inspections are often done in isolation to other AM tasks the use of manual and non-digital processes	lack of guidance on what to report on poor data integration between enterprise systems, result in manual and ad-hoc report creation no process for translating organisational requirements into reporting requirements (e.g. KPIs)	BIM models developed during the design and construction phase are not developed from AM team requirements (O&M phase) lack of understanding on how the AM team define their requirements for the BIM model BIM models are developed in different formats that are not accessible to the AM team

		lack of a data quality process for inspections		
asset data management	lack of a standard asset classification system from a maintenance perspective no standard asset data structure asset information is stored in different file formats and databases	no standard approach to asset location information lack of an asset classification system for inspections	lack of an assets classification system for reporting lack of a standard process for unique ID's	no standard approach on how new assets information should be captured no standard approach on how asset information should be exchange from the project into the AM systems no standard approach on how assets within the BIM model should be organised (e.g. classification / IFC)

Organisational challenges	lack of digital, technology and BIM training within the AM team the challenge in developing a business case for BIM / digital investment	lack of digital, technology and BIM training within the AM team	lack of digital, technology and BIM training within the AM team	the contractual handover of information is poorly documented data itself is often undervalued as an essential resource

Table 8-4 Case study challenges

The challenges are used within the conclusion as a point of validate for the framework.

8.4. Data sources used within the case study

This section discusses the data sources that are used within the development of the AIM (see section 8.8). BIM standard PAS 1192-3 [5] describes an AIM as having three categories of data sources, geometry, databases and files. The specific datasets used within the case study are summarised below.

8.4.1. Geometry

This section discusses the geometry used in the development of the AIM.

BIM models

In total, three BIM models were utilised within the case study.

- **BIM model A** - an existing building constructed in 2009
- **BIM model B** - a building completed in 2019 and is currently occupied
- **BIM model C** - a building that is currently under construction, due for commission in 2022.

The parameters and aspects of the models are discussed in detail below.

BIM model A

BIM model A is an existing building that was commissioned in 2009, the model was developed by the researcher in Autodesk Revit 2019. The researcher obtained Computer-Aided Design (CAD) drawing from the asset management department. The building has gone through several internal redesigns, such as merging of office spaces, unfortunately, these changes where rarely captured on the CAD files. Where possible, the researcher did visual observation to compare the accuracy of the CAD drawings to the physical building. Where MEP assets cannot be easily observed, such as pipes hidden within floors and under drop ceilings, assumptions were made as to how such assets are designed. Table 8-5 provides an overview of the BIM model parameters.

BIM model parameters	**Value**
Estimate length (meters)	50.5
Estimate width (meters)	57.6
Estimate height (meters)	16
Area (M2)	2938
Floors	2

Table 8-5 BIM A parameters

Figure 8-1 illustrates a 3D view of BIM model A. The left-hand-side is an external view of the building with architectural and structural assets, while the right-hand side is a 3D section, showing MEP assets.

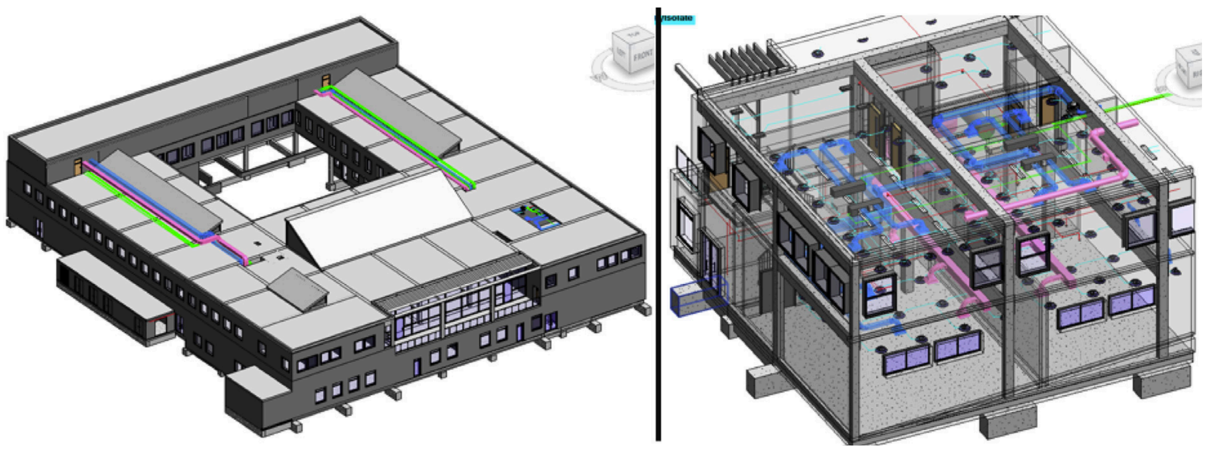

Figure 8-1 Overview of BIM model A

BIM model B

BIM model B is of a newly constructed building that was provided to the researcher by the asset management team, that received the model from the lead-contractor as part of the handover of the building. The BIM model does not 100% represent the physical building, due to an ongoing snagging list and small changes to office configuration after occupation. Table 8-6 provides an overview of BIM model B parameters.

BIM model parameters	**Value**
Estimate length (meters)	58.2
Estimate width (meters)	30.1m
Estimate height (meters)	14.2
Area (M2)	1522
Floors	2

Table 8-6 BIM B parameters

Figure 8-2 illustrates BIM model B, the left-hand shows an overview of the model and the right-hand is a cross-section throughout the model, showing MEP and structural assets.

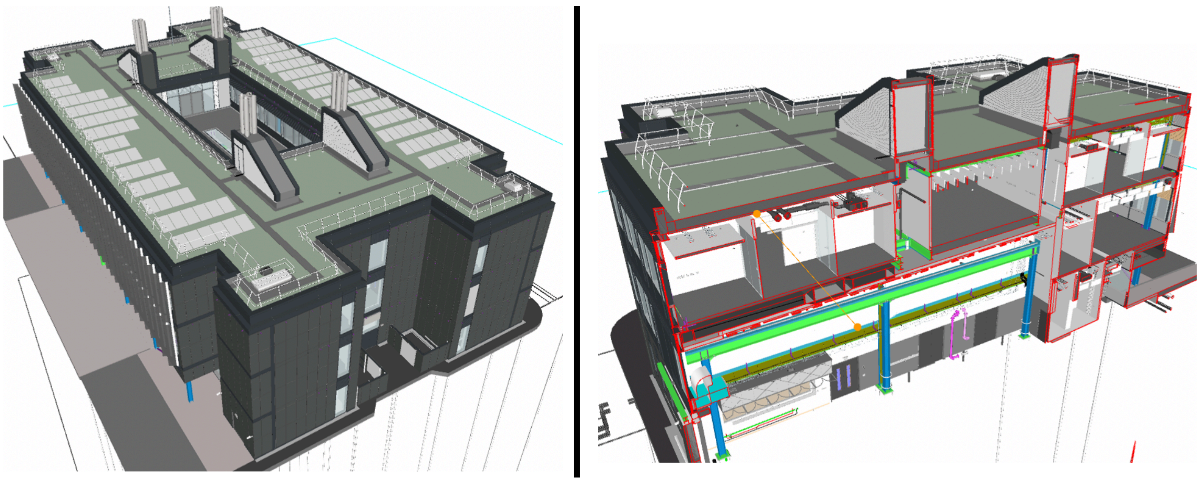

Figure 8-2 Overview of BIM model B

BIM model C

BIM model C is of a building currently under construction within the campus area, the researcher obtained the model from the asset management team, who receives a monthly update of the model from the lead-contractor. Sections of the building are still under design, it is estimated that the model is 80% complete, with MEP aspects of the modelling being the least developed. While the model is not complete, it still forms part of the case study, as it enables the developed of the BIM model into the AIM. Table 8-7 provides an overview of BIM model C parameters at the time of receiving it.

BIM model parameters	**Value**
Estimate length (meters)	168
Estimate width (meters)	97
Estimate height (meters)	16
Area (M2)	12386
Floors	3

Table 8-7 BIM C parameters

Figure 8-3 shows BIM model C, with an overview on the left-hand side and a 3D cross-section on the right-hand side. As this model is still under development, little MEP assets can be seen within the building, but architectural and structural assets are presented.

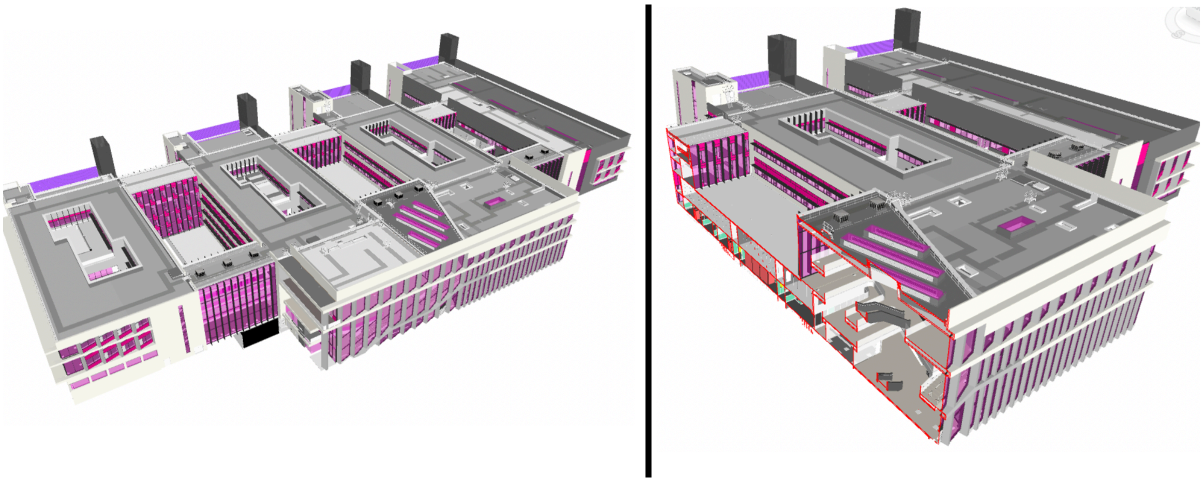

Figure 8-3 Overview of BIM model C

Point cloud

A point-cloud scan of the campus site has been conducted, involving the use of a LIDAR scanner mounted on top of a van as it drove around the campus site several times to capture a point-cloud mesh.

A raw export of the data was provided in LAS (LIDAR Data Exchange file) to the researcher, which in total was 36.6 GIG worth of data. LAS files are similar to a Common Separator Value (CSV) file, where every point captured within a single row contains, a unique ID, location of a point within a given coordinate system such as latitude, longitude and altitude and a colour value of the point, such as Red Green Blue (RGB).

To make the raw LAS file manageable and useable within an AIM, the researcher processed the file within Autodesk Recap into a ReCap Project (RCP) file, that significantly reduced the file size and made it accessible to BIM modelling software such as Autodesk Navisworks.

Figure 8-4 provides an overview of the point cloud data within the AIM model. The model is a one to one scale of the real-world, the data captured in total is 980 meters long and 485 meters wide. Furthermore, the data is geolocated, meaning it is placed correctly into the model, as it is in the real world. Due to the nature of this survey data, the accuracy is plus or minus 10cm.

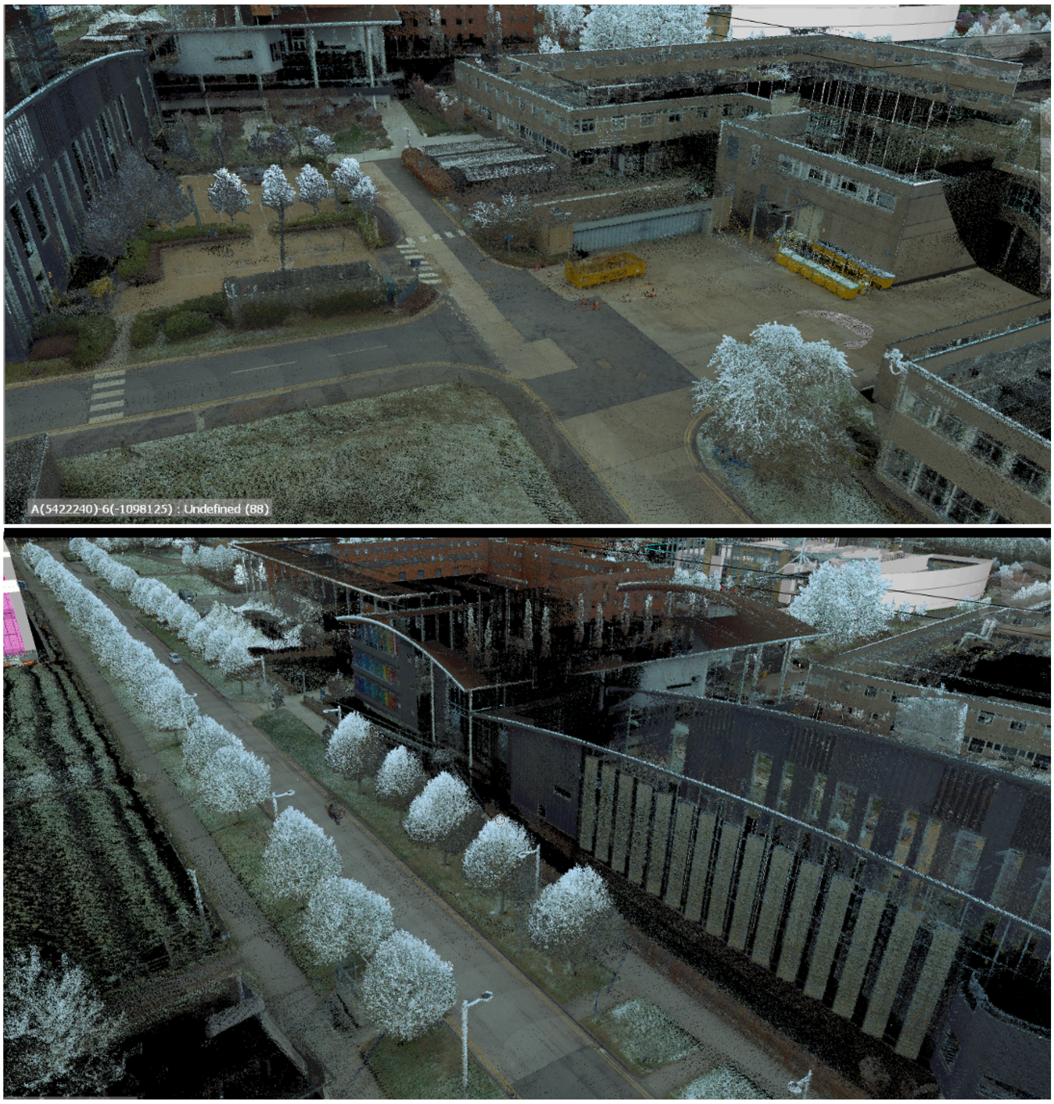

Figure 8-4 Overview of Point-cloud data

In addition to the researcher’s development of an AIM relational database, a database storing Internet of Things (IoT) related data such as temperature and humidity has been developed as part of a broader research effort.

The IoT database is hosted internally within the universities IT systems. Due to the complexity and permission requirements of working within a real-time database solution, an export was provided. The database contains time-series, environmental-related data of specific zones in BIM model A.

Such data can enable the asset management team to develop trends and analytics.

8.4.2. File storage (EDMS)

In the context of this case study, an Electric Document Management System (EDMS) is a single location to store documents within a structured approach, such as PDFs, drawings, Excel and word documents. It was noted earlier that using the asset management departments current EDMS solution would be complicated, due to permission issues and the current complexity in the different enterprise solutions in use. It was decided that the researcher should develop an EDMS for the case study and not integrate into the current systems within the asset management department. OneDrive within Microsoft 365 was chosen as it is cloud-hosted and provides flexibility within its structure.

Figure 8-5 demonstrates the file structure within the EDMS.

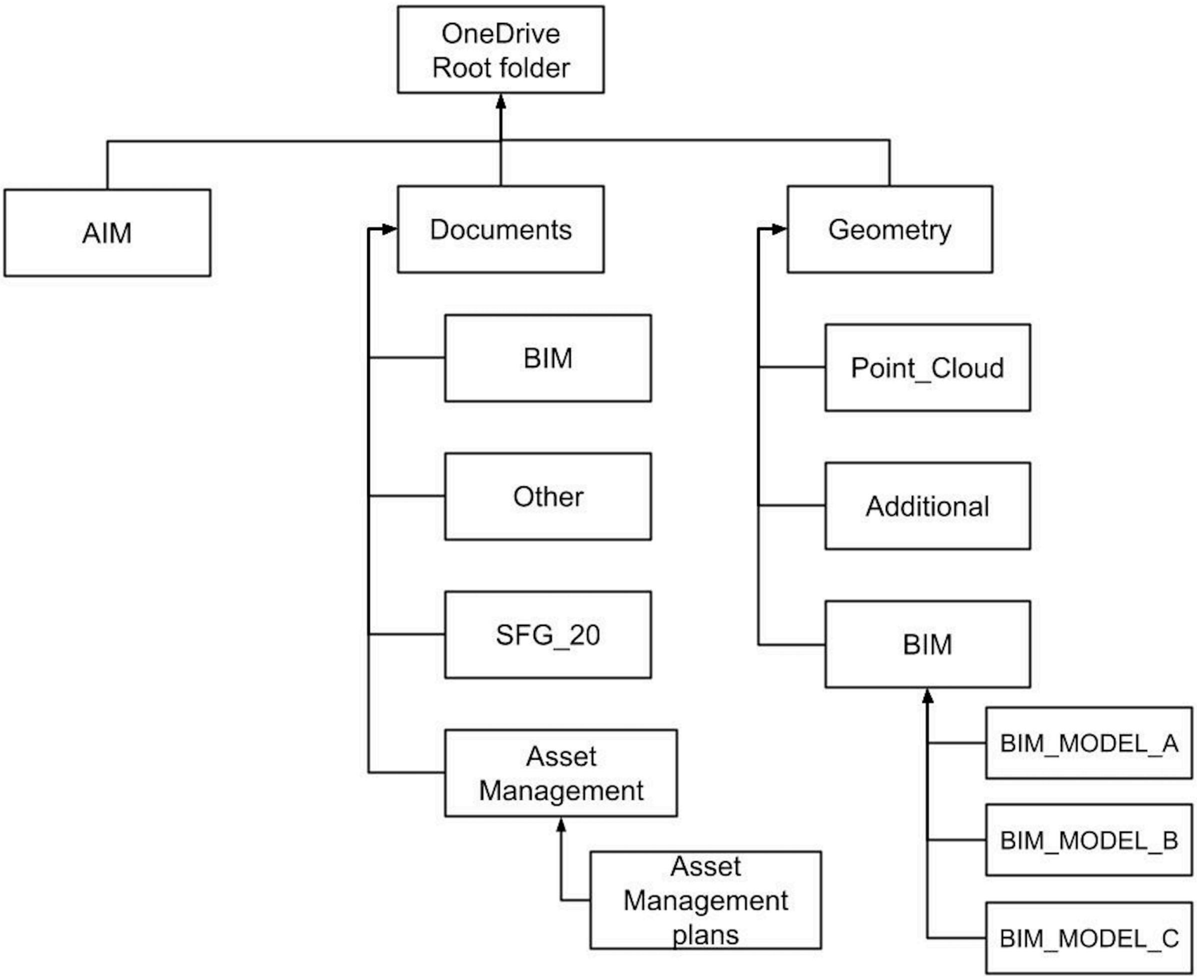

Figure 8-5 Folder structure within the EDMS

8.5. Developing organisational level information requirement

This section discusses part one of the information requirements framework (see Figure 4-5), that incudes steps one, two and three, Figure 8-6 provides an overview of this section.

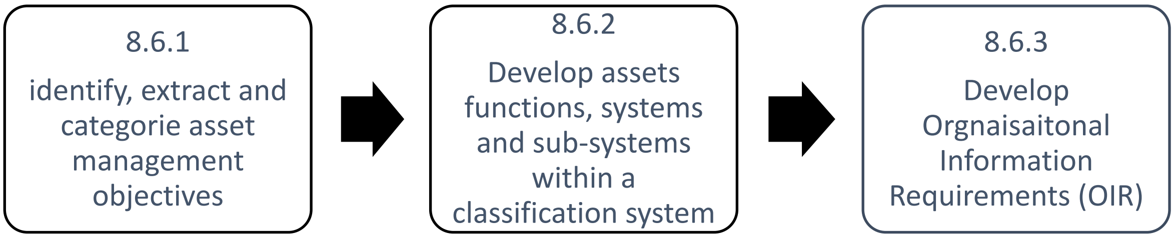

Figure 8-6 sub-steps of Section 8.6

The outcome of this section is a set of OIR that align with the asset management objectives that are documented in step one. Furthermore, an asset classification system is developed that supports the future development of Functional Information Requirements (FIR) and AIR.

8.5.1. Identify, extract and categories asset management objectives

Step one is the need to identify, extract and group asset management objectives, which is broken down into the steps of sourcing documents for review, reviewing documents, validating and documenting the objectives.

Insourcing documents for review, the researcher was put in touch with personnel within the asset management leadership team. The researcher contacted them over the phone, email and in-person to introduce the case study and request the required documents. Table 8-8 provides an overview of the documents that were reviewed.

Document title	**Source**
Strategic Asset Management Plan (SAMP)	Asset Management, strategy development team
A set of asset management plans	Asset Management, strategy development team

2017 / 2018 annual report (estate management)	Asset Management, strategy development team
Strategic Framework (estate management)	Asset Management, strategy development team
BIM Execution Plan	Projects and improvement team
Employers Information Requirements (EIR)	Projects and improvement team
Common Data Environment (CDE) guide	Projects and improvement team
Climate Change impact strategy	Environmental management

Table 8-8 documents related to sourcing objectives

The strategy development team, being a leadership function within the asset management department provided strategic documentation, including the SAMP. The project and improvement team manage the use of BIM and technology within the asset management department, such as Geospatial Information Systems (GIS), data analytics and CDE adoption. The team provided a set of documents that outline technology adoption, with a strong focus on BIM and GIS. The newly developed environmental management team that aims to lead the university within the sustainable policy provided the Climate Change Impact Strategy (CCIS) for review, which was a valuable source for environmental-related objectives.

Documentation review

The document review consisted of a technical and managerial review, which is discussed below.

A technical review in this context is not reviewing for technical accuracies, such as engineering calculations but looking for technical aspects that relate to an objective, such as objectives that conform to the SMART acronym. SMART objectives are discussed in detail in Section 2.2 for reference, it stands for Specific, Measurable, Achievable, Relevant and Time-bound. Furthermore, a technical review will capture objectives that are documented within a structured and distinct approach, such as under the heading objectives, requirements, goals, aims or similar.

In total, 15 objectives were extracted within the technical document review within eight documents. The vast majority of objectives in this review were sourced from the SAMP, all objectives are listed in Table 8-9.

A managerial review in this context aims to extract objectives from the text that are not explicitly worded as objectives but have aspects of an objective. A managerial review is suited to this kind of document review as it allows the researcher to interpret the text and make a critical review of its context. The objectives captured within this process are generally within the text of the document, with an element of validation needed to ensure that it is an objective and not an aspiration or similar. Validation is achieved by reviewing the objectives with asset management personnel, the objectives were modified in-line with recommendations from the asset management leadership team.

In total 5 objectives were extracted within the managerial review within eight documents, all objectives are listed in Table 8-9.

Documenting objectives

The format of choice for documentation is CSV, as it meets both the human and machine-readable requirements. Firstly, the format can be open within Microsoft Excel, which is heavily used within the organisation. Secondly, most common programming languages have packages for integrating CSV files, while database management systems allow for the importing of CSV files. To support the structured approach to documenting the objectives, the following columns where used:

- **ID** – As a means to give an objective a unique ID to an objective
- **Objective** – Capturing the objective itself in full.
- **Timeline** – Date at which the objective should have been reacted, this can be in a year, month, day or a combination of all three.
- **Category** – The category of the objective, as discussed in Section 5.2.3.

A full list of the objectives are provided below in Table 8-9.

ID	Objective	Timeline	Category

AMO1	Reduce environmental impact of operational estate assets for BMF projects & the EM vehicle fleet by 6%	2020	Environmental
AMO2	Reduce benchmark costs of delivering FM services	2020	Financial
AMO3	Improve asset information system	2023	Operational
AMO4	Develop and deliver asset performance measures	2019	Operational
AMO5	Reduce total business impact of Estate Facilities' controllable costs by 5%	2023	Financial
AMO6	Improve handover procedure for new assets to enable efficient ongoing management by EF	2019	Operational
AMO7	Improve specification of new construction, and ensure conformance with estate drivers and goals	2018	Operational
AMO8	Improve all asset management processes; document and put relevant controls in place to manage the delivery of all AM objectives efficiently and effectively	2021	Operational
AMO9	Identify competency requirements and develop competencies to match needs of EF to deliver AM plans and objectives	2021	Operational
AM10	Put in place optimised 10-year AM plans consistent with this SAMP to support sustainability, resource planning and management of long-term risk	2020	Operational
AM11	Make effective use of Planet (or successor IT) system for scheduling, delivering and recording planned maintenance.	2020	Operational
AM12	Put in place asset risk management approach and methodology and integrate into asset management processes	2021	Operational

AM13	10-year asset management plans supported by resources	2020	Operational
AM14	Develop and implement prioritised programme of lifecycle strategies for key assets that represent high impact on costs and/or risks	2020	Operational
AM15	Unplanned maintenance requirements identified, supported by auditable review of asset health and evidence.	2019	Operational
AM16	Life cycle costing methodology in place and used to support business cases for capital projects	2020	Financial
AM17	Develop standardised contract for services that ensures effective, cost effective and sustainable delivery of services, improves asset information and reduces EF overheads.	2020	Operational
AM18	Review and refine condition assessment surveys	2020	Operational
AM19	To reduce carbon emissions from energy use by 34% by 2020 against a 2005 baseline.	2020	Environmental
AM20	To reduce water consumption by 20% by 2020 against a 20% 2005 baseline.	2020	Environmental

Table 8-9 Asset management objectives

8.5.2. Develop assets functions, systems and sub-systems within a classification system

This section discusses the development of an asset classification system, which is step two of the information requirements framework, see Figure 4-5. Within the case study, this is adopted in five tasks; (1) adopting an asset classification structure (2) asset classification document review (3) asset classification workshop (4) documenting the asset classification system and (5) asset classification system validation.

Adopting an asset classification system

Section 5.3.1 discussed the use of a part-of approach to the development of an asset classification system that conforms to ISO 12006-2 [105], providing a structured approach to the development of an asset classification system. However, it does not provide the classification system itself, only the approach.

The literature and standards review (see Chapter 2) noted that there are several attempts to develop an asset classification system that conforms to ISO 12006-2 and follows a part-of approach, most notably UNIClass and OmniClass. The researcher adopted UNIClass, as it provides a classification of an assets functional output, which is a crucial requirement within the development of FIR (see section 6.2). Furthermore, UNIClass is developed by the National Building Specification (NBS) in the UK and as this case study is focused on a UK university, it was a logical choice. Figure 8-7 provides an example of a UNIClass structure for a heating system.

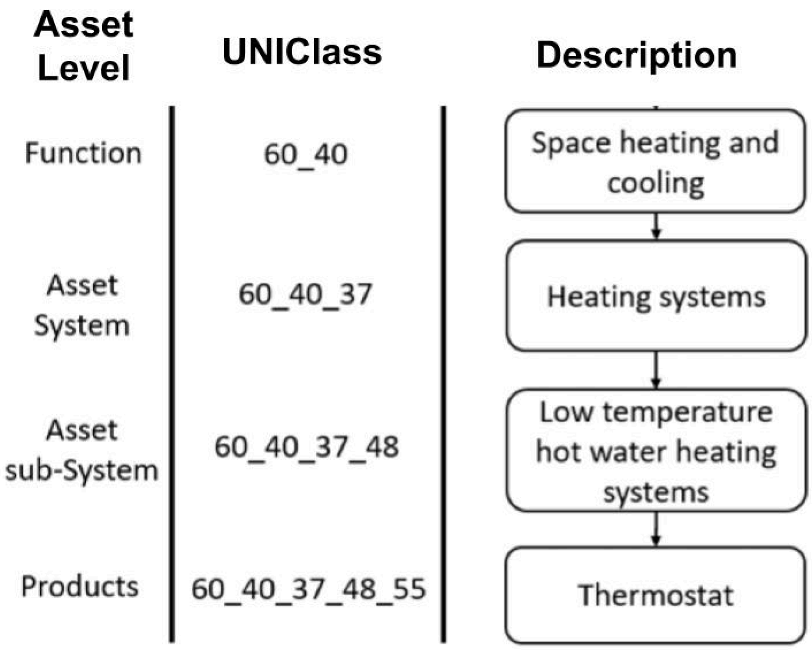

Figure 8-7 asset classification structure example

Asset classification document review

The document review process is a technical review, where assets names, descriptions and abbreviations are analysed and associated with UNIClass codes.

The document review process consists of two document types, an export of the asset register from the asset management maintenance scheduling system and a Construction Operations Building information exchange (COBie).

The review consists of identifying the functional asset output, asset system and asset sub-system within the documents.

As the University is currently within a significant expansion and re-development stage, which is mostly being done in BIM, there is a COBie document of BIM model B available for review. COBie is discussed in detail within Section 2.3.6, simply put is an exchange format that is exported from a BIM model and provides a default set of information about all BIM objects within the model, including floors, zones and spaces. Discussions with the asset management team noted that while specialised asset systems will change between the different departments, such as the need for biological waste removal systems within the veterinary school, the vast majority will stay similar, such as ventilation, heating, fire doors and lighting, therefore COBie is a suitable document for review.

A COBie file consists of several tables and columns, that is documented within the BIM standard BS 1192-4 [99]. For this review, the research focused on the sheets (tabs) of system, type and component. There are several columns within these sheets, including ExtIdentifier, ExtObject and ExtSystem that provide unique ID's and reference the software that the COBie is developed from, in this case, Autodesk Revit. The columns that the researcher focused on were name, category and description, between these three columns, the researcher was able to filter between asset systems and sub-systems, then determine the appropriate functional output. Figure 8-8 provides an example of the data within the COBie file of BIM model B.

Name	TypeName	Description
RHP_Sink_Laboratory_450x365mm_714	RHP_Sink_Laboratory_450x365mm	Sink Laboratory_450x365mm
RHP_Sink_Laboratory_450x365mm_718	RHP_Sink_Laboratory_450x365mm	Sink Laboratory_450x365mm
RHP_Sink_Laboratory_450x365mm_719	RHP_Sink_Laboratory_450x365mm	Sink Laboratory_450x365mm
RHP_Sink-Circular_260mm_RHP_Sink-Circular_260mm_SK3_720	RHP_Sink-Circular_260mm_RHP_Sink-Circular_260mm_SK3	Sink Circular
RHP_Sink_Laboratory_450x365mm_730	RHP_Sink_Laboratory_450x365mm	Sink Laboratory_450x365mm
RHP_Sink_Laboratory_450x365mm_731	RHP_Sink_Laboratory_450x365mm	Sink Laboratory_450x365mm
RHP_Plumbing_Contour21_S3056_STANDARD WC_908	RHP_Plumbing_Contour21_S3056_STANDARD WC	Standard WC
RHP_Plumbing_Contour21_S4066_S406601_913	RHP_Plumbing_Contour21_S4066_S406601	Standard toilet seat without cover
RHP_Plumbing_ASH_ConcealaMultiproduct_S363667_REFER TO N15 SFF01_91	CISTERN_ArmitageShanks_Conceala2-AllVariants	Push button flush controllers
RHP_Plumbing_Flushplate_S4399AA_915	RHP_Plumbing_Flushplate_S4399AA	Push button flush controller
RHP_Plumbing_Contour21_S3056_STANDARD WC_909	RHP_Plumbing_Contour21_S3056_STANDARD WC	Standard WC
RHP_Plumbing_Contour21_S4066_S406601_916	RHP_Plumbing_Contour21_S4066_S406601	Standard toilet seat without cover
RHP_Plumbing_ASH_ConcealaMultiproduct_S363667_REFER TO N15 SFF01_91	CISTERN_ArmitageShanks_Conceala2-AllVariants	Push button flush controllers
RHP_Plumbing_Flushplate_S4399AA_918	RHP_Plumbing_Flushplate_S4399AA	Push button flush controller
RHP_Plumbing_Contour21_S3056_STANDARD WC_910	RHP_Plumbing_Contour21_S3056_STANDARD WC	Standard WC
RHP_Plumbing_Contour21_S4066_S406601_919	RHP_Plumbing_Contour21_S4066_S406601	Standard toilet seat without cover
RHP_Plumbing_ASH_ConcealaMultiproduct_S363667_REFER TO N15 SFF01_92	CISTERN_ArmitageShanks_Conceala2-AllVariants	Push button flush controllers
RHP_Plumbing_Flushplate_S4399AA_921	RHP_Plumbing_Flushplate_S4399AA	Push button flush controller
ASH_Contour21_S6967_BIM_GB_S6967AC - Contour 21 Close coupled Doc M pa	ASH_Contour21_S6967_BIM_GB_S6967AC - Contour 21 Close	Disabled WC Package
RHP_Plumbing_Contour21_S3056_STANDARD WC_1089	RHP_Plumbing_Contour21_S3056_STANDARD WC	Standard WC
RHP_Plumbing_Contour21_S4066_S406601_1097	RHP_Plumbing_Contour21_S4066_S406601	Standard toilet seat without cover
RHP_Plumbing_ASH_ConcealaMultiproduct_S363667_REFER TO N15 SFF01_10	CISTERN_ArmitageShanks_Conceala2-AllVariants	Push button flush controllers
RHP_Plumbing_Flushplate_S4399AA_1099	RHP_Plumbing_Flushplate_S4399AA	Push button flush controller
WC Suite_1102	WC Suite	RHP_Plumbing_Contour21_S6960_S6960AC
RHP_Plumbing_Contour21_S6360_3DPL_S636001_1103	RHP_Plumbing_Contour21_S6360_3DPL_S636001	Handrail
RHP_Plumbing_Contour21_S6360_3DPL_S636001_1104	RHP_Plumbing_Contour21_S6360_3DPL_S636001	Handrail

Figure 8-8 Example of COBie data file

An asset register was exported from the maintenance scheduling system, meaning that all assets that have a maintenance record (reactive or proactive) will be exported. As an example, assets such as fire extinguishers, boilers and air handling units are well documented as they have scheduled maintenance requirements, which is often a legal requirement. In contrast, such assets as windows, walls and doors (non-fire) that do not have recurring maintenance schedule are poorly documented, if at all.

From a data quality perspective, the data itself is of poor quality. There is no asset classification or a standard structure to the assets name, location or description, this is partly due to the limitations of the maintenance scheduling software and lack of controlled data capture techniques, such as drop-down boxes to select an assets name.

Despite the data quality concerns and lack of an asset system structure, the review of the asset register, while time-consuming, did provide insight to the bulk of assets that the department maintains, such as lifts and fire doors.

Asset classification workshop

Along with the document review, a workshop was conducted after the researcher had reviewed the documentation, gaining an understanding of the universities assets portfolio. The workshop followed the loose agenda structure of introduction, discussion of document review, discussion of missed or amended asset systems, feedback and review of outcomes.

The researcher noted while the loose and informal approached to the workshop risk poor resource management and not getting the *"required data"*, it was appropriate to enable the attendees the freewill to discuss their thoughts to gain a consensus for the outcome. Furthermore, the attendees had not attempted to develop an asset classification system before. Therefore, a flexible approach was required to ensure that knowledge sharing was encouraged.

Asset classification system documentation

The asset classification system documentation process consists of two parts, firstly documenting the outcomes of the document review and workshop and secondly documenting the asset classification system in UML diagrams.

For documenting the outcomes of the document review and the workshop, a CSV file format was chosen. A single sheet within the CSV file contains the columns of Funcational_output, Asset_system and Asset_sub-system. Table 8-10 provides an example of the CSV format, the functional output classification is repeated for each asset system and sub-system that is within that functional output. Furthermore, Table 8-10 shows that the functional output of EF_60_40 has three asset systems and seven asset sub-systems, the asset system of heating has four sub-systems, while the asset system of cooling has one sub-system.

Funcational_output	Asset_system	Asset_sub-system
EF_60_40 **Space heating and cooling**	Ss_60_40_15 Combined heating, cooling and power systems	Ss_60_40_15_40 Combined heat and power systems
	Ss_60_40_17 Cooling systems	Ss_60_40_17_12 Chilled water systems
	Ss_60_40_37 Heating	Ss_60_40_37_26 Electric heating
		Ss_60_40_37_21 Direct gas-fired heating systems
		Ss_60_40_37_22 District heating systems
		Ss_60_40_37_48 Low-temperature hot water heating systems
		Ss_60_40_37_85 Steam heating systems

Table 8-10 examples of the CSV structure

A full list of the developed asset classification is provided in Appendix A. In total 24 functional outputs, 71 asset systems and 134 asset sub-systems have been classified.

Along with documenting the outcomes of the document review and workshop, there is also the need to document the asset classification system itself, including the hierarchy relationships. Furthermore, the documentation also needs to support the human and machine-readable requirements, to achieve this, UML diagrams were used to model the asset classification system. As discussed in Section 5.3, UML is a standardised approach to developing diagrams that visualise the relationships of a system, such as an asset classification system.

Enterprise Architecture (EA) was chosen as the development tool, as it provides a user-friendly interface and advance tools for database development. A single UML conceptual diagram is developed for each asset functional output, the name of the diagram reflects the functional output that is represented within the diagram, such as heating, ventilation or lighting. Secondly, a class is created for each asset functional output, system and sub-system, a class in this context is simply an object that represents part of the classification system. The name of the class is the name of the asset classification, such as Solar Heating System, an alias is provided for each class that represents the classification code, such as Ss_60_40_37_81, which is used within the AIM database development, see Section Appendix J.

Once the classes and diagrams are created, it is then required to populate the diagrams, by dragging and dropping the classes into the diagrams. A relationship between the classes is created within the diagrams by drawing an association arrow between the classes, representing the asset hierarchy in UNIClass.

Figure 8-9 illustrates a UML conceptual diagram for the functional output of heating, the yellow squares and rectangles are classes within the diagram, with the arrows representing the asset classification hierarchy.

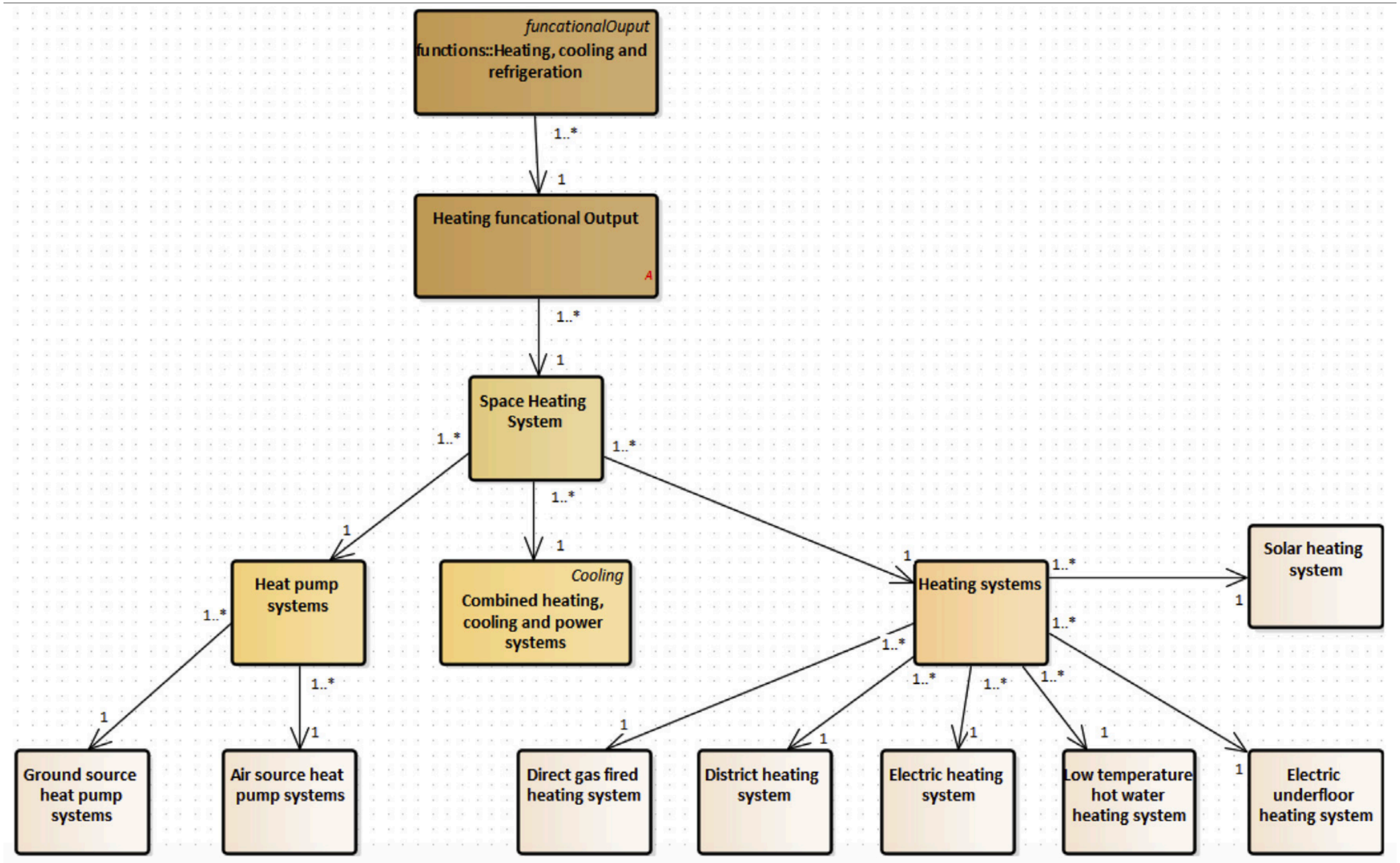

Figure 8-9 UML conceptual model diagram for the functional output of heating

In total 24 diagrams where created, that contains the 24 functional outputs, 71 asset systems and 134 asset sub-systems, a sample set of diagrams are provided in Appendix B.

8.5.3. Developing organisation Information Requirements (OIR)

This section discusses the development and documentation of OIR, which is step three of the information requirements framework, see Figure 4-5. The OIR development requires the translation of asset management objectives into information requirements, this is achieved via the development of Critical Success Factors (CSF) guiding the development of Plain Language Questions (PLQ) and the information requirements themselves. Finally, the OIR is documented.

Critical Success Factors (CSF)

CSF is a crucial element of OIR creation and supports the development of PLQ. A CSF is derived by asking the participants *“what are the Critical Success Factors of achieving this objective?”* on an objective by objective basis. The CSF, are written down as part of an OIR development within an informal workshop setting with stakeholders from the asset management department.

The CSF developed for the OIR are provided below in Table 8-11.

CSF related to a financial objective	**CSF related to an environmental objective**	**CSF related to an operational objective**
prompt response to maintenance requirements	reduction in energy usage	define critical assets
reduction in operational cost	optimisation of assets operational performance	identify risks
reduction in maintenance costs	efficient assets operational hours	analyse the risks
less reactive maintenance and more planned maintenance	increase in renewable operational energy	identify ways to reduce the identified risks

have the correct tools and materials	understanding assets portfolio environmental impact	
whole-life cost management		

Table 8-11 Critical Success Factors

Plain Language Questions (PLQ)

PLQ form part of the BIM standards and are discussed in detail in section 5.4, for reference PLQ is a simple and easily understandable question that aids in developing information requirements.

Similar to the CSF, a large number of PLQ was developed in the OIR workshop. While there is little in the literature on how many PLQ should be developed, it should be considered that *"less is more"* to prevent information overload, while still providing the required level of information.

The PLQ developed for the above CSFs are provided in Table 8-12

Managerial PLQ	Technical PLQ	Financial PLQ
PLQ related to a financial objective		
What is the current response time to maintenance request?	what is the total reactive maintenance requests to date?	What is the cost savings to a prompt response to maintenance requests?
what is the planned response time to maintenance request?	what is the total planned maintenance to date?	What is the current total operational cost?
what is the different between the planned response time and the current?	what is the different between reactive and planned maintenance?	what is the planned operational costs?
who is reasonable for planning maintenance?	what is the total completed planned maintenance to date?	what is the different between the planned operational cost and the current?

who is reasonable for the operational cost?	what is the acceptable level of reactive maintenance?	what is the total maintenance cost?
who is reasonable for the maintenance cost?	what is the current inventory level?	what is the planned maintenance costs?
does the inventory level meet the currently planned maintenance requirements?		what is the different between the planned maintenance cost and the current?
what is the current time lost due to low inventory levels?		what is the cost to date for maintain the inventory level?
who is reasonable for the inventory levels?		what is the total cost of operating the business?
who is reasonable for whole-life management?		what is the planned capital investment?
		how does my O&M cost compare to my capital investment?
PLQ related to environmental objective		
how is the business owner for reducing energy usage?	how much energy is currented used within the estate?	what is the cost saving benefits of reducing my energy?
what activity is supported by the functions?	what is the required energy usage to support the energy reduction?	How much cost is renewable energy?
what are the scheduled operational hours of the function?	what are the most energy consumption functional output?	How much cost is non-renewable energy?
what are the active operational hours of the function?	what is the least energy consumption function?	What is the cost difference between renewable and non-renewable energy?

are the functions operational requirements time based?	what is the measurement of energy consumption?	what is the financial cost of measuring and decreasing environmental impact by 35%?
are the functions operations sensor based?	how is energy consumption measured?	
how much energy is sourced from no non-renewables?	what is the min performance requirements?	
how much energy is sourced from renewables?	what is the max performance requirements?	
what is the target for % of renewable energy?	what is the optimise performance?	
what is the highest populating function?	how much energy is produced locally or from the grid?	
what is the required C02 output for a 6% reduction?	what is the % difference between renewable and non-renewable?	
what is the amount of hazardous waste going to landfill, if any?	what is the current C02 operational output?	
	what is the measure of water consumption to operate the function, if any?	
PLQs related to an operational objective		
what activities does my functions support?	what asset systems / sub-systems support the function?	what is the financial cost of asset failure?

how critical is the activity to Estate Management?	what is the severity of impact in the risk occurring?	Cost of developing the risk rating?
what is the vulnerability of the identified risk on the asset function / system?	what is the likelihood of the risk occurring?	
what is the operational risk of asset failure?	what is the allowable amount of risk per asset function?	
what is the reputational risk of asset failure?	can asset performance be optimised to support the reduction of risk?	
what object-based risks have been identified?		
what scenario-based risks have been identified?		
what are the common risks associated to each asset function / system?		
what is the classification of the risks?		
how will the risk be monitor and validated?		
has a risk management plan been developed?		
can the identified risk be avoided?		
can the risk be transfer (e.g. outsourced / insurance)?		
if the risk is small and gains are high, is it		

possible to accept the risk?		

Table 8-12 Plain Language Questions

Information requirements

The information requirement themselves are the answer to the PLQ. The information requirements should be simple and easily understood, that aim to answer the question in full.

In total 74 individual information requirements within the OIR where developed for three objectives, which are listed in Table 8-13.

Objective	Information Requirement	Category	Data type
AM05	current_maintaince_responce_time	Managerial	Integer
	planned_maintaince_responce_time	Managerial	integer
Reduce total business impact of Estate Facilities' controllable costs by 5% by 2025	current_vs_planned_responce_time	Managerial	Integer
	maintanince_cost_savings	Financial	Integer
	maintanince_owner	Managerial	String
	total_operational_cost	Financial	Integer
	planned_operational_cost	Financial	Integer
	current_vs_planned_operational_cost	Financial	Integer
	operational_financial_owner	Managerial	String
	current_maintaince_cost	Financial	Integer
	planned_maintaince_cost	Financial	Integer
	current_vs_planned_maintaince_cost	Financial	Integer
	maintaince_financial_owner	Managerial	String
	total_reactive_maintaince	Technical	Integer
	total_planned_maintaince	Technical	integer
	reactive_vs_planned_maintaince	Technical	String
	completed_planned_maintaince	Technical	String
	reactive_maintaince_levels	Technical	Integer
	inventry_level	Technical	Integer
	inventry_planned_maintaince	Managerial	Integer
	time_lost_inventry	Managerial	Integer

	inventry_cost	Financial	Integer
	inventry_owner	Managerial	String
	total_business_cost	Financial	Integer
	total_capital_investment	Financial	Integer
	O&M_vs_capital_investment	Financial	Integer
	wholelife_owner	Managerial	String
	Objective_start_date	Managerial	Date
	Objective_finish_date	Managerial	Date
	Objective_on_target	Managerial	boolean
AM19 **Reduce carbon emissions from energy usage by 34% by 2030 against a 2005 baseline**	energy_useage_level	Technical	Integer
	required_energy_level	Technical	Integer
	highest_energy_function	Technical	String
	lowest_energy_function	Technical	String
	measure_energy_consumption	Technical	String
	measurement_enegry_useage	Technical	Integer
	cost_saving_enegry_useage	Financial	Integer
	energy_useage_owner	Managerial	String
	min_performance_req	Technical	Integer
	max_performance_req	Technical	Integer
	op_performance	Technical	Integer
	activity	Managerial	String
	scheduled_op_hours	Technical	Integer
	active_op_hours	Technical	Integer
	operational_time_based	Technical	Boolean
	operational_sensor_based	Technical	Boolean
	non-renewable_energy	Technical	Integer
	renewable_energy	Technical	Integer
	energy_produced_local/grid	Technical	Boolean
	%_different_energy	Technical	Integer
	total_%_renewable	Managerial	Integer
	highest_populting_function	Managerial	String
	C02_operational_output	Technical	Integer

	target_C02_operational_output	Technical	Integer
	target_C02_financial_cost	Financial	Integer
	water_consumption	Technical	Boolean
	hazardous_water_landfill	Technical	Boolean
	Objective_start_date	Managerial	Date
	Objective_finish_date	Managerial	Date
	Objective_on_target	Managerial	boolean
AM12 **Put in place asset risk management approach and methodology for individual risk ratings per asset by 2021**	function_activity_support	Managerial	String
	activity_criticality	Managerial	Integer
	supporting_systems	Technical	String
	risk_on_function	Managerial	String
	cost_asset_failure	Financial	Integer
	Total_risk_budget	Financial	Integer
	Cost_of_development	Financial	Integer
	operational_asset_failure	Managerial	String
	reputational_asset_failure	Managerial	integer
	object_risks	Managerial	integer
	scenario_risks	Managerial	integer
	common_risks	Managerial	integer
	risk_classification	Managerial	integer
	severity_of_risk	Technical	Integer
	likelihood_of_risk	Technical	Integer
	allowable_risk	Technical	Integer
	risk_monitoring	Managerial	String
	risk_management_plan	Managerial	String
	aviod_risk	Managerial	String
	optemised_risk_asset_performance	Managerial	Integer
	risk_transferd	Managerial	String
	accepted_risk	Managerial	String
	Objective_start_date	Managerial	Date
	Objective_finish_date	Managerial	Date
	Objective_on_target	Managerial	boolean

Table 8-13 Organisational Information Requirements

Documenting OIR

Once the CSF, PLQ and information requirements are developed, it is then required to document the outcome. The researcher developed a template within Microsoft Excel as it meets the human readability requirement by providing an easy to read formatted table, and the machine readability requirement as it can be exported as a CSV format.

Figure 8-10 illustrates the OIR template, the first row displays the objective that the OIR is being developed for, the columns have the CSF, PLQ and information requirements as discussed above, along with objective ID, category, question ID and data type. Documenting the OIR is discussed in detail within Section 5.4.3.

Reduce total business impact of Estate Facilities' controllable costs by 5%							
OB_ID	ID	Critical Success Factor	Category	Question	Question ID	Information_Requirement	Data_Type
AM05	CSF1	prompt response to maintenance requirements	**Managerial**	What is the current response time to maintainince request?	MQ5	current_maintaince_responce_time	Integer
AM05	CSF1	prompt response to maintenance requirements	**Managerial**	what is the planned response time to maintaince request?	MQ6	planned_maintaince_responce_time	Integer
AM05	CSF1	prompt response tomaintenance requirements	**Managerial**	what is the different between the planned response time and the current?	MQ7	current_vs_planned_responce_time	Integer
AM05	CSF1	prompt response to maintenance requirements	**Financial**	What is the cost savings to a prompt response to maintanince requests?	FQ2	maintanince_cost_savings	Integer
AM05	CSF1	prompt response to maintenance requirements	**Managerial**	who is responable for planning maintanince?	MQ8	maintanince_owner	String
AM05	CSF2	reduction in operational cost	**Financial**	What is the current total operational cost?	FQ3	total_operational_cost	Integer

Figure 8-10 OIR Documentation

As both the category and data_type columns have a pre-defined set of values, they are developed as lists so only the allowed values can be selected. Furthermore, as the columns of OB_ID, ID and Question_ID are unique values they are automatically generated by the use of formatting rules within Excel, this ensures that no ID's are repeated.

The documented OIR are provided in Appendix C.

8.5.4. Summary

It was noted within the literature review and industry investigation that the development of OIR is a challenging task that requires a deep understanding of the organisational needs and requirements that is often neglected. This section aimed to address this challenge by providing a structured approach to the development of OIR.

Reflecting on the challenges, step one (see Section 8.5.1) was to identify the asset management objectives by reviewing asset-related documentation to extract a set of objectives, a summary of the documents required is provided in Table 8-8. The objectives where validated within an informal workshop and documented within a CSV table format.

Step two (see Section 8.5.2) was the development of an asset classification system that supports the future development of FIR, AIR and an AIM. Firstly, the document review was conducted, reviewing a COBie and asset register export, with a large number of asset systems and sub-systems sourced. Secondly, an informal workshop was conducted with management stakeholders to capture the assets that were not found within the document review. The workshop highlighted the functional outputs that the asset system support and unique asset systems not within the documents such as medical and veterinary related assets. Furthermore, the asset classification system was documented within a collection of UML diagrams

The third and last step within this part (see Section 8.5.3) is the development of the OIR. Utilising the asset management objectives that were extracted and documented within step one, an OIR contains a collection of CSF, PLQ and the individual information requirements, which is the answer to the PLQ.

8.6. Developing asset information requirements

This section discusses Part two of the information requirements framework (see Figure 4-1) discussing steps four, five, six and seven, Figure 8-11 provides an overview of this section. The asset classification developed within step two (see section 5.3) provides the structure for developing both the FIR and the AIR, while also adopting techniques from BIM and requirements engineering. A negotiation process is adopted to validate the individual information requirements. Finally, the documentation and communication step aggerates the OIR, FIR and AIR into a single source document and provide a structured approach to communicating the new requirements to both internal and external stakeholders.

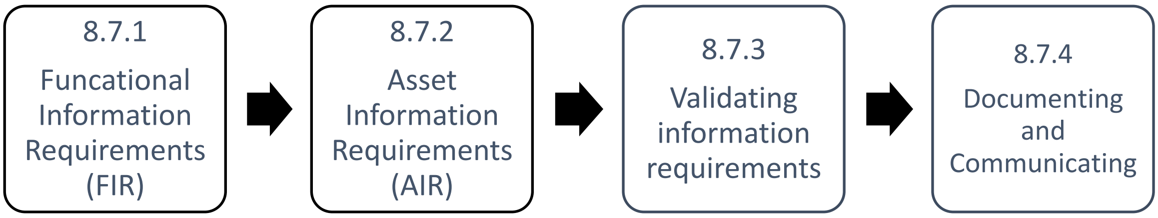

Figure 8-11 sub-steps of Section 8.7

The outcome of this section is the development of FIR and AIR, which are validated, documented and communicated.

8.6.1. Functional Information Requirements (FIR)

This section discusses the development and documentation of FIR, which is step four of the information requirement framework. FIR is developed within three steps: (1) Joint Design Application (JDA) workshop, (2) document review and (3) documenting the FIR.

FIR Joint Design Application (JDA) Workshop

This section discusses the development and implementation of a JDA workshop, including Participant selection and group dynamics.

Participant selection

Participant selection is the process of selecting participants from different stakeholders' categories to participate within the FIR workshop, a full list of stakeholders categories can be found in Table 6-1 and Section 6.2.1. The researcher executed the participant selection with support from a key contact within the asset management department, the contact provided one to two names within each stakeholder category. The researcher contacted each individual over emails and phone calls to gain an understanding of their role within the organisation, their asset management and BIM knowledge level and their seniority within the organisation. The ideal participant will have some technical knowledge related to the assets functional output, but not be focused on the day to day running of them, such as in managerial roles. A limited understanding of the value of asset management and BIM is a requirement so that they can be fully engaged within the conversation.

Group Dynamics

The group activates are an essential part of a JDA workshop. As such the activity of brainstorming has been adopted within the workshop, precisely a combination of directed and guided brainstorming types, a full list of brainstorming types and descriptions can be found in Table 6-2. Asset management objectives are used as a means to provide a common goal and also scopes the workshop, while the assets functional output that the FIR is being developed for guides the brainstorming activity.

The information requirements matrix was developed as a means to enable the collaborative engagement of the stakeholders within the brainstorming exercise, the matrix is discussed in detail in section 6.2.3, including the individual features of the matrix. The matrix was populated within the workshop by one of two means. (1) the researcher acting as the facilitator would load the matrix on a projector/television and populate it live within the workshop, as the activity is taking place. (2) the matrix is printed then handed out to participants to populate as an individual or a group, with the matrixes then being shared and discussed.

Within most of the workshops, a combination of both approaches where used. The participants populating their matrix was a creative exercise and provided a meaningful discussion that resulted in information requirements that would not have been captured without the group activity. In comparison, the facilitator populating approach provided a structured means to populating the matrix and enabled the participants to articulate their thoughts into a statement, with the facilitator converts into an information requirement. Feedback from the participants noted that this approach supported collaboration, as it focused them on discussing their thoughts while populating the matrix as an individual or as a group did not support the same level of discussion. Furthermore, the researcher also noted that when the whole group is populating the matrix, one or two participants would dominate over the other participants, hindering the group activity.

Figure 8-12 shows an example of information requirements matrix that has been populated, with the information requirements within the central section.

Information requirements	**Heating**		**AM05**
Managerial information	Location_site, Function_owner, Asset_system, sched_planned_maintenance, Location_building, Function_maintainer, Asset_sub_system, Location_room, Function_operator, reactive_maintenance		
Technical information	performance_rating, running_time, service_life, Remaining_life, min_temperature, max_temperature, required_temperature, running_time		
Financial information	active_operational_cost, unit_cost, planned_maintenance_cost, active_maintenance_cost, planned_operational_cost, planned_investment		
Asset Systems	Electric heating systems	Solar heating systems	Low-temperature heating systems

Figure 8-12 an example of a populated information requirements matrix

In total 17 information requirements matrix where developed, examples are provided in Appendix D.

FIR document review

This section discusses the review of SFG-20 which is a comprehensive set of documents that sets out the planned maintenance tasks and schedules for over 900 individual asset systems. The asset management department uses SFG-20 for guidance on how to perform maintenance tasks, prioritising maintenance tasks from a legal perspective and scheduling requirement.

Among the many features of SFG-20, it provides a step by step guide for the tasks on a given asset that has to be completed to maintain and operate them efficiently, therefore it is a de-facto industry standard for maintenance tasks.

SFG-20 uses a basic hierarchy for categorising the estimated 900 asset systems it documents. At the first level, it has the two categories of (1) Specialise Services that include maintenance plans related to workshop equipment, access equipment and surveillance system and (2) Core Functions that include such categories as Ventilation, Lighting and Air Handling Units, within the core functions categorise is individual asset systems.

While SFG-20 does not adopt UNIClass, the core functions categories are similar to the assets functional output classification within UNIClass, this alignment enabled the researcher to review the asset maintenance plans and documented a set of information requirement. As an example, when reviewing the maintenance plans for ventilation, it was noted that an asset systems performance is measured within airflow per second, while lighting is measured within the power output of kilowatts per hour. It is important when considering the OIR for *"Total_oprational_cost"* or similar, as this will have different FIR based on the assets functional output measurements.

Documenting FIR

Once the workshops and document review have been completed, there is a need to capture the output (e.g. information requirements) within a single document. The document must be both machine and human-readable, the machine-readable requirement supports the development of the AIM database in Section Appendix J, similar to the OIR, the file format of CSV was chosen.

In total 195 individual information requirements where developed, Appendix E provides a full list within the CSV table format.

8.6.2. Asset Information Requirements (AIR)

This section discusses the development and documentation of AIR, which is step five within the information requirements methodology, see Figure 4-5. The AIR development follows the same three steps as the FIR, (1) JDA workshop, (2) document review and (3) Documenting the newly developed AIR.

AIR Join Design Application (JDA) Workshop

This section discusses the development and implementation of a JDA workshop, including participant selection and group dynamics.

similar to the FIR participant selection, the researcher along with a key contact at the asset management department provided the contact of one or two personnel within each stakeholder category (see Table 6-1) for who should be attending the workshop. The researcher contacted each of the personnel to ask for their participation in the workshop.

In contrast to the FIR participant selection process, the AIR participant selection focuses on technical stakeholders', that have day to day running knowledge of the asset systems. Stakeholders within the workshop included, O&M engineers, quantity surveyors, planning technicians and asset managers.

Group dynamics in AIR workshop uses the directed and guided brainstorming approaches to populate the information requirements matrix, from an asset systems perspective and not an assets functional output perspective. The same CSF and PLQ as per the FIR are used to support the development of AIR. furthermore, the information requirements themselves (answers to the PLQ) are used as a guidance to the kind of information that is required to address the requirement.

Task simulation was also commonly used as a means to simulate common tasks that the organisations complete and reflect on the information used within those tasks that would support the given objective.

The information requirements matrix was used to support this data capture, examples are provided in Appendix F.

Documents review

Similar to the review of SFG-20 within the FIR development, it is also reviewed to support the development of AIR. While the asset systems within the core functions of SFG-20 do not directly relate to the asset systems in UNIClass, they are similar to the point that the review of the asset management plans provides a source of information requirements. Figure 8-13 provides an example of the asset systems under the core functions for lighting in SFG-20, it can be seen that the asset systems such as emergency lighting, external lighting and internal lighting relate to asset systems in UNIClass.

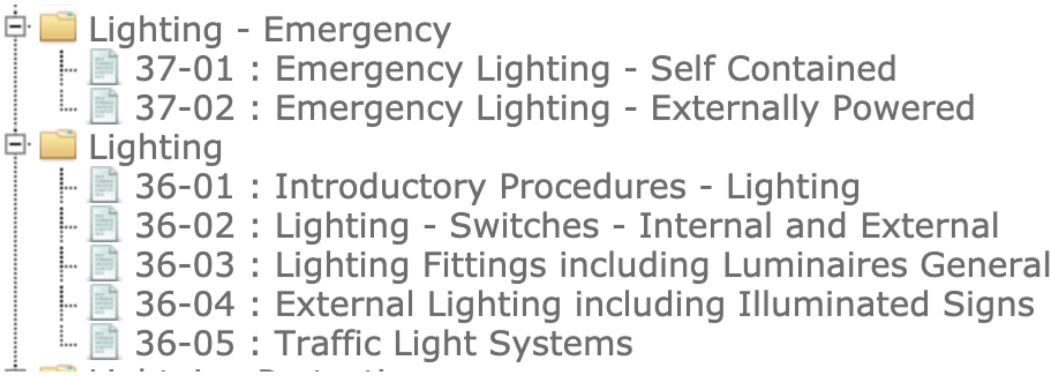

Figure 8-13 lists of schedules within SFG-20

Following the same processes within the FIR document review, the asset management plans where reviewed to gain information requirements explicitly related to the individual asset systems. As an example, reviewing the maintenance plans for emergency lighting provides the maintenance schedule which has a direct impact on the OIR for *"Total_maintenance_cost"*.

Similar to the FIR, the AIR is also populated within the human and machine-readable format of CSV, the machine-readable aspect supports the development of the AIR into the AIM database, see Section Appendix J.

In total 347 individual information requirements where developed, 168 asset systems and 189 asset sub system, a full list is provided in Appendix G in the CSV table format.

8.6.3. Validating information requirements

This section discusses the validation of the OIR, AIR and FIR, which is achieved using a negotiation to gain consensus. Further validation is achieved by reviewing outcomes of the case study, as the information requirements are implemented into an AIM, this is discussed in Section 8.9.

The negotiation step takes the form of a workshop with senior stakeholders, adopting a negotiation project lifecycle model that incorporates the organisational point-of-view. In this case, the asset management objective documented within step one (see Section 8.5) are used for this purpose, as they have already been validated. The overarching goal for the negotiation is for a *"common playing field"* on which the participants are working together without the organisational seniority structure. Figure 8-14 illustrates the negotiation approach, with the participants within the stakeholders at the top of the figure, focusing on one objective at a time, the left-hand side shows the information requirements in the OIR, AIR and FIR for the objective. Each information requirement is discussed, and a consensus is made to reject or approve it.

When considering the FIR and AIR, technical support should be gained to ensure the information requirement is relevant to the functional output for the asset-system.

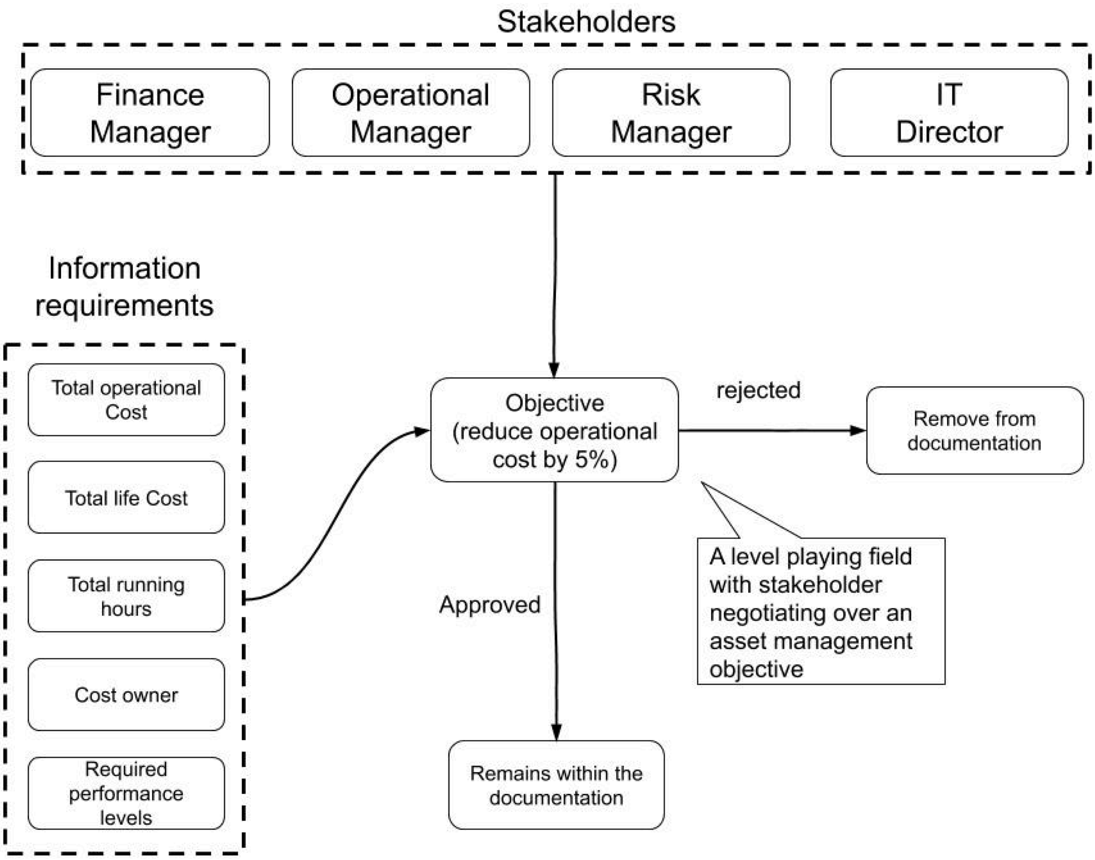

Figure 8-14 negotiating model

8.6.4. Document and communicate information requirements

This section discusses the documentation and communication of the information requirements, communication includes both internal and external stakeholders.

Documenting information requirements

The individual information requirements of OIR, FIR and AIR are documented within their own steps, this step is focused on the collection, structure and storage of all the information requirements.

The documents related to the information requirements are stored in OneDrive within the developed EDMS folders (see Figure 8-5). While not adopted within this case study, an approval workflow, such as Work in Progress, Shared and approval workflow as seen within the BIM Common Data Environment (CDE) cloud be used for extensive scale information requirements development.

Communicating information requirements

Communication of the information requirements consists of two tasks: (1) developing a communication plan that aids the case study partner in communicating the new information requirements and (2) the researcher participated in several workshops and industry meetings, communicating the case study output.

A communication plan template was developed in collaboration between the researcher and key stakeholders, with several meetings taking place to develop and approve the plan. The communication plan template was developed in-line with ISO 55000 but modified to specifically focus on information requirements, containing benefits of implementing the information requirements, understanding why communication is essential and feedback reporting processes.

The communication plan template aims to enable the case study organisation to efficiently communicate the advantages of the new information requirements to a broad set of stakeholders. This is specifically important if they continue the framework throughout the asset portfolio with a coordinated effort, communication being a critical aspect.

Along with the communication plan, the researcher also attended several meetings and workshops to help communicate the newly developed information requirements. Furthermore, a PowerPoint presentation was developed and shared with the case study partner for future presentations.

This communication exercise focused explicitly on stakeholders that were not involved in the information requirements process, attempting to get their *"buy-in"* into the benefits of the new information requirements.

8.6.5. Summary

The BIM for O&M standard (PAS 1192-3) discusses the fact that an OIR should generate an AIR, the literature review noted the complex challenges of an OIR generating asset level information requirements, while the industry investigation also noted the challenges. The outcome of the background section was a concept model (see Section 2.5.2 and figure 2-16) that addressed this challenge by developing a new set of information requirements that sits in between the OIR and the AIR, FIR. This section discussed the development of FIR in an industry case study, along with the AIR and an approach to communicating and validating the newly developed information requirements. Being step four, five, six and seven of the information requirements framework see Figure 4-1.

Step four (see Section 8.6.1) provides a structured approach to the development of FIR by utilising an information requirements matrix, JDA workshop and document review. The information requirements matrix (see Figure 8-12) was developed as a means to capture information requirements as an outcome of the JDA workshop. Feedback noted that the matrix was a valuable tool to not only document the requirements but also provide guidance on the kind of information requirements that should be developed. The JDA workshop produced a lot of managerial and financial related information requirements, but a limited amount of technical information requirements, due to the broad nature of an assets functional output and the participants selection process, selecting mostly senior management stakeholders. In contrast, the document review of SFG-20 provided a high level of technical information requirements.

Step five (See Section 8.6.2) uses similar approaches to the FIR, including JDA workshops, document review and the information requirements matrix. The JDA workshops were more detailed with assets requirements compared to the FIR and produced more technical information requirements. This is due to the fact of focusing on the asset system and sub-system level, allows for a greater understanding of the asset, producing technical information requirement, along with managerial and financial requirements. The document review of SFG-20 also produced a large number of technical information requirements.

Step six (see Section 8.6.3) is the validation of the newly developed information requirements in the form of negotiation lifecycle approach that saw information requirement negotiated over a common goal, which in this case is the asset management objectives. This process was successful in providing a consensus between the participants and reduced the overall information requirements by consolidating similar information requirements.

Finally, step seven (see Section 8.6.4) is the documentation and communication of the information requirements. OIR, FIR and AIR are documented within the individual steps on which they are developed, the documents are stored within a document structure folder on a OneDrive location. A communication plan is developed for both internal and external stakeholders, which is adopted from the asset management standard (ISO 55000). Furthermore, the researcher attended several internal and external presentations to highlight the process and promote the newly developed information requirements.

The outcome of this section is a set of FIR and AIR information requirements that are validated, documented and communicated. The development of the FIR aims to bridge the gap between the OIR and the AIR.

8.7. BIM model design and development to support an AIM

Part three of the information requirements framework (see Figure 4-1) focuses on the development of an AIM, exploiting the UML diagrams developed as part of the asset classification system (see Section 8.5.2) to classify assets within a BIM model and develop the AIM database. Furthermore, a platform is developed that enables the population of the AIM database from the BIM model.

Figure 8-15 sub-steps of section 8.7

The outcome of this section is an AIM relational database that is derived from the asset classification UML database diagrams and populated by the objects in BIM model A, via the extraction platform.

8.7.1. Classification of a BIM model

This section discusses the classification of a BIM model, which is step eight of the information requirements framework. This section includes three steps: (1)

developing custom metadata parameters (2) classification of BIM objects within a BIM model and (3) exporting an Industry Foundation Class (IFC) model.

While multiple BIM models are used within the AIM, (see section 8.4), only BIM model A is classified in this case study.

Developing custom metadata parameters

BIM models A, B and C are developed in the BIM authoring software, Autodesk Revit. One key advantage of having all of the BIM models developed by the same BIM modelling software is that a set of shared custom metadata requirements can be developed once and used multiple times. As a reminder, the custom parameters are used to store the asset classification codes from the asset classification system developed in Section 8.5.2. To create a set of custom metadata parameters, it is created within one BIM model project, then shared with the other BIM models.

Figure 8-16 shows the shared parameter settings within Autodesk Revit.

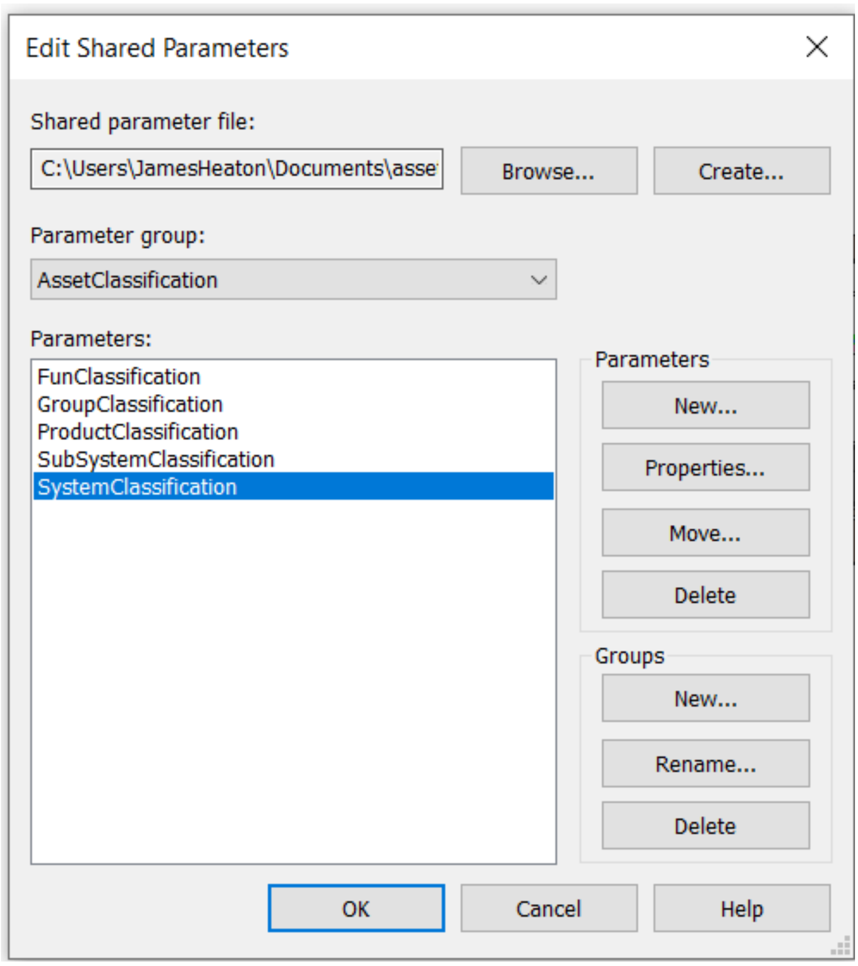

Figure 8-16 Shared parameters settings windows

Firstly, the shared parameter file itself is created at the top of Figure 8-16. Secondly, a parameter group is created to group all of the individual parameters and lastly, a new parameter was created for each level of the asset classification.

As the share parameters were created within BIM model A, they are automatically associated with all BIM objects in the model. Figure 8-17 illustrates the TXT file that is created by Autodesk Revit for the share parameters, it shows a single group called "*AssetClassification"* was created, along with five parameters with a GUID, name and associated data type. This file can be loaded into BIM model B and C to get the same custom parameters as BIM model A.

```
# This is a Revit shared parameter file.
# Do not edit manually.
*META	VERSION	MINVERSION
META	2	1
*GROUP	ID	NAME
GROUP	1	AssetClassification
*PARAM	GUID	NAME	DATATYPE
PARAM	7807c318-a237-4fc3-8fb8-2cf01b803b39	GroupClassification	TEXT
PARAM	b9007324-9f39-4870-ae35-9780aa49c646	SubSystemClassification	TEXT
PARAM	452bfce8-42ad-4c73-8174-dc465d1756f4	FunClassification	TEXT
PARAM	8f05dff1-675f-44a4-bb35-7b33b29bf166	ProductClassification	TEXT
PARAM	393a95ff-584b-4bb6-88ae-24842efc10a2	SystemClassification	TEXT
```

Figure 8-17 Share parameters TXT file

The outcome of this step is a set of custom parameters that enable the capture of multiple asset classification codes within an individual BIM object. The share parameter tool means this only had to be developed once but can be loaded into multiple models.

Classification of BIM model A

This section discusses the classification of the BIM objects in BIM model A. While the above section demonstrates how to develop custom parameters for the capture of the asset classification codes, it does not classify the BIM objects themselves. To classify an object, it must be selected by itself or as a group with the properties window open. The property window will change depending on the kind of objects that are selected and if they are select individually or as a group, but the asset classification parameters remain consistent.

Figure 8-18 provides an example of a single BIM object, in this case, a duct fitting being selected in BIM model A and the parameters for that given object. The red square highlights the asset classification parameters that were created within the above section.

BIM model A has over 7,985 BIM objects, it is not practical to select every BIM object and classify them individually. Several tools were used to manipulate the BIM model to select groups of BIM objects efficiently. Including custom filters, BIM object filters, model categories and 3D views or sections.

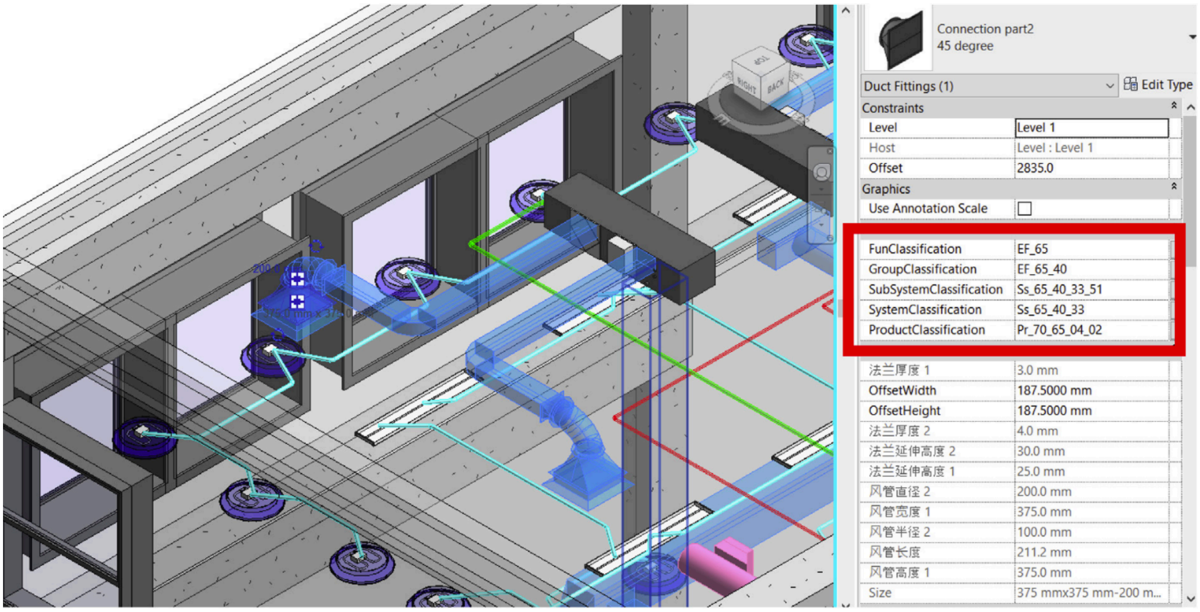

Figure 8-18 Parameters of a BIM object selected within BIM model A

Custom Filters

Custom filters are a user-defined filter that filters objects in the BIM model by a set of rules, enabling the researcher to change the visibility of objects within a view. As an example, a supply air filter was created that displayed only the objects that have the parameters *"supply of air",* therefore only showing objects related to ventilation, in total eight custom filters where developed. Making the custom filters visible one by one, enabled the researcher to select multiple objects at the same time and classify them as per their functional output, asset system or sub-system. The Researcher noted that custom filters were an efficient way to select objects, providing a highly flexible approach to filtering objects on a specific parameter or rule. Figure 8-19 provides an overview of the custom filters' settings, the left-hand side shows the filters that have been created, while the right-hand side illustrates the visualisation of just ventilation related objects within a 3D view.

In total eight custom filters where created, that aided in classifying a total of 4,322 instances of assets and took an approximate one hour, including the creation of the filters and classifying the objects themselves.

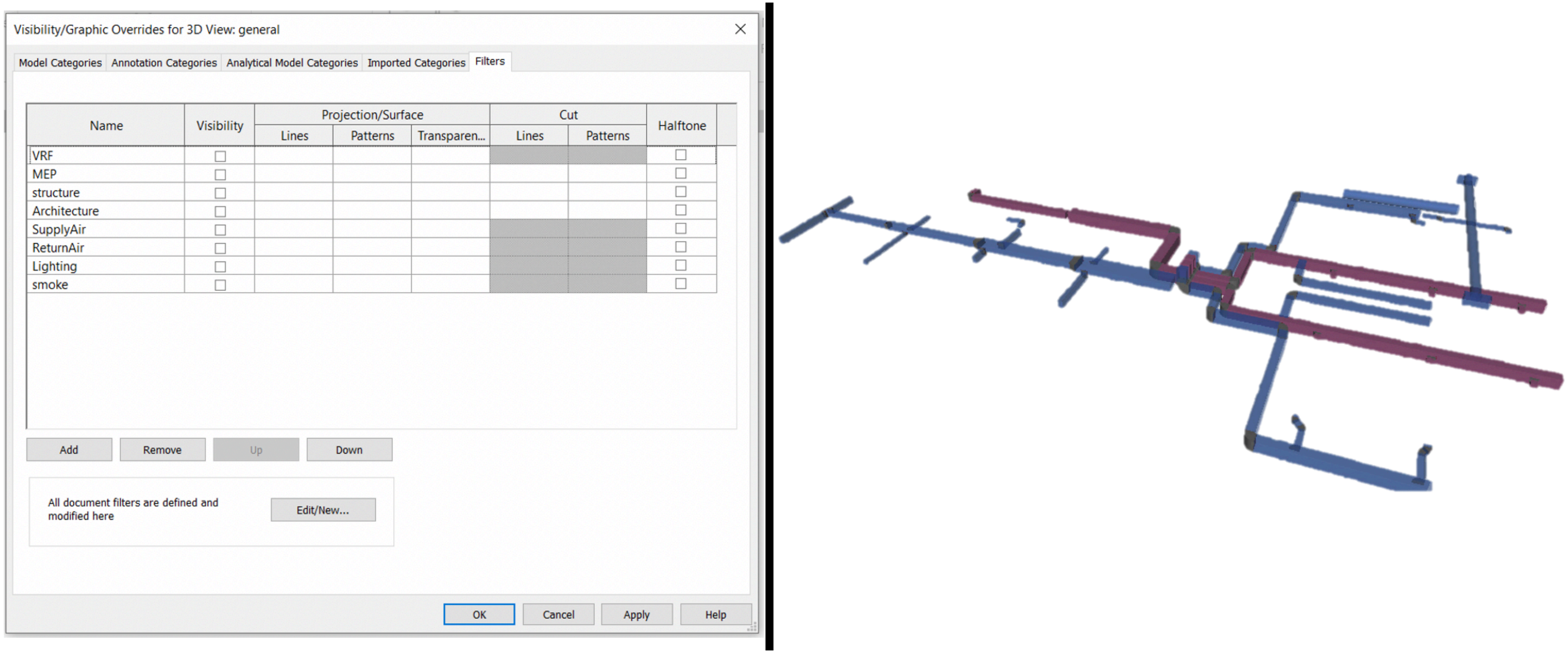

Figure 8-19 Overview of custom filters

Default Filters

Along with custom filters that are developed by the researcher, there is a default set of filters, see Figure 8-20. These filters provide a basic set of filtering options, such as stairs, windows or doors, it does not filter by specific object parameters. As an example, the pipes or pipe fittings filter would contain objects relating to ventilation, water supply, sewer and electricity, as they all contain the same objects.

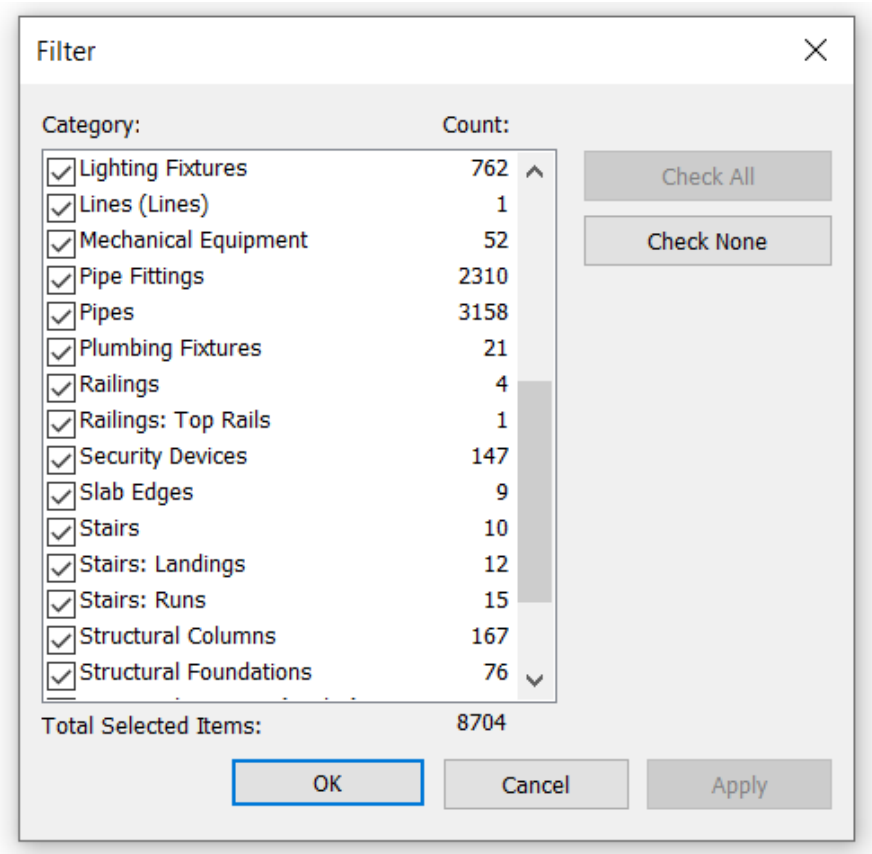

Figure 8-20 BIM object filters

The researcher used these basic filters as a means to filter objects where the functional output of the object is clear, such as doors, windows and walls, as there is no subjectivity as to what classification is required for those objects. Even with these basic filters, care should be taken to ensure that objects are correctly classified. As an example, while filtering doors, will only show the objects related to doors, it will not distinguish between an internal door or a fire door, which require two different classification codes. In this example, custom filters would be best suited to filter only doors on a specific width, that represents a fire door.

In total ten of the categories were used to classify 2,389 instances of assets and took an approximate time of 1 hours and 45 minutes, due to the need to confirm the asset system types.

Model Categories

Similar to filters, model categories make it possible to hide or show specific BIM objects within a view. The categories follow the same as the list in the filters discussed above but allow for greater control within the filtering aspect. As an example, while the filters allow the filtering of ducts, the model categories allow the researcher to select specific ducts within the duct sub-categories such as an oval, square or circle ducts. This is a clear advantage over the default filters, as it allows the researcher to refine the BIM object selection process. As an example, in BIM model A, a square duct is only used for the functional output of ventilation, while oval duct is for heating, filtering by these categories allows for bulk selection and classification. Figure 8-21 illustrates the model categories settings with the categories and sub-categories, the tick within the visibility column controls the visibility of the given category or sub-category.

The researcher used this ability to select specific asset categories and sub-categories that related to an assets functional output.

In total 6 model categories were used to classify 821 instances of assets and took an approximate one hour

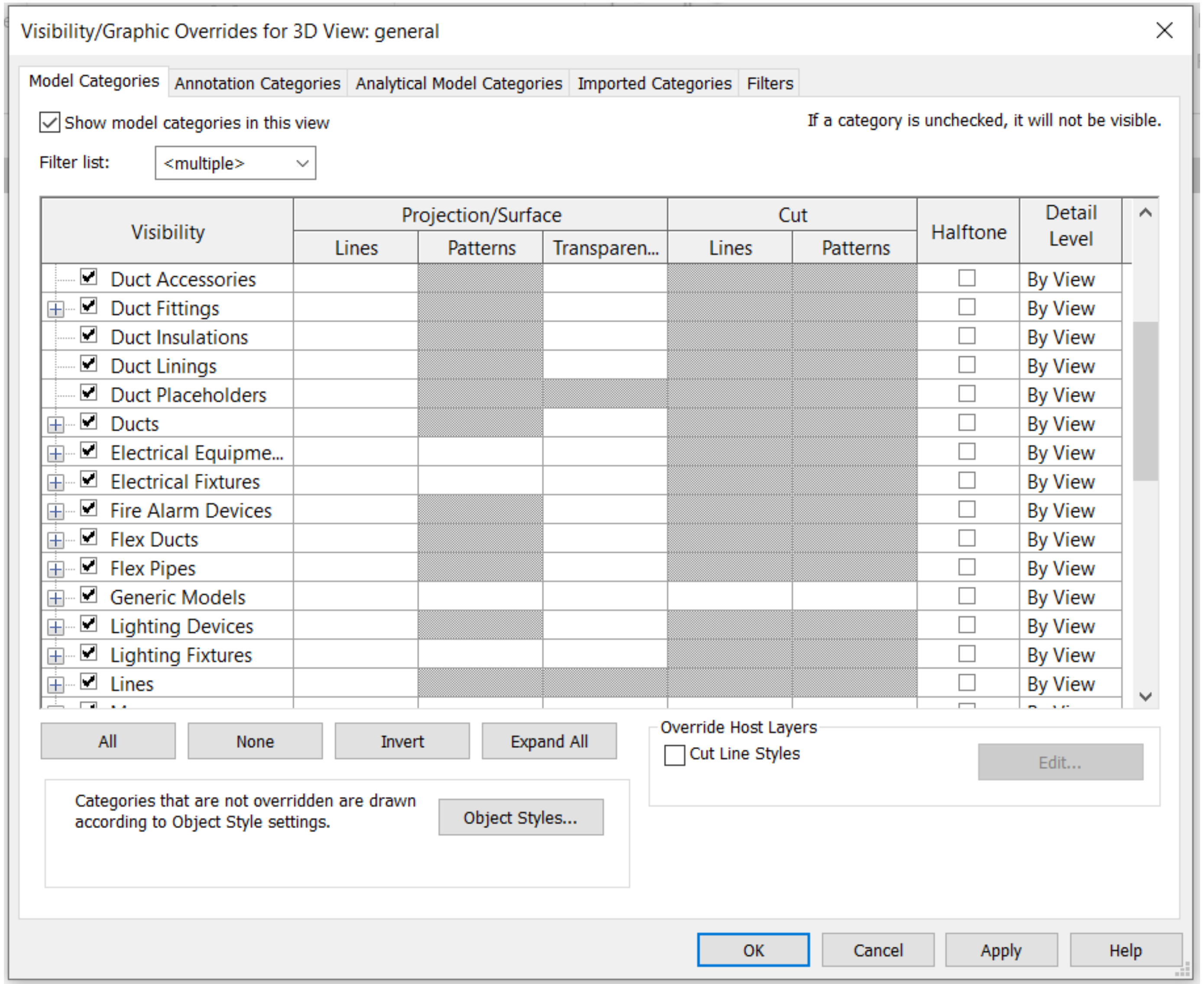

Figure 8-21 BIM object categories

Custom 3D views and sections

The final approach used was developing custom 3D views and sections. A BIM model is a set of 2D and 3D views of the same model, default views include floor plans, site plans, elevations and 3D views. Custom model views can be created, including 3D views; these views can be edited to hide specific objects within the view without impacting other views. As an example, within a custom 3D view, a floor or ceiling could be hidden, making visible objects, such as pipes under a floor. Multiple objects can be selected and hidden within the same view, to make large areas of the model visible for selection. Furthermore, within a 3D view, a section box can be applied that enables a dynamic section of the 3D model, the section box was used to isolate the model into the area of interest, see the right-hand side of Figure 8-1.

This approach was used as a last resort, to select unique and complex objects that cannot be filtered out by the approaches mentioned above, as it is a manual and ad-hoc step which is prone to errors and time-consuming.

In this approach multiple ad-hoc 3D views and sections were created to select the remaining 315 instances of assets, taking an approximately 50 minutes. Utilising all four approaches, in total 7,947 instances of assets were classified within BIM model A, taking a total time of 3 hours and 35 minutes.

Exporting IFC models

The final task is the need to export BIM model A from Autodesk Revit into an IFC model, Figure 8-22 shows the IFC settings window.

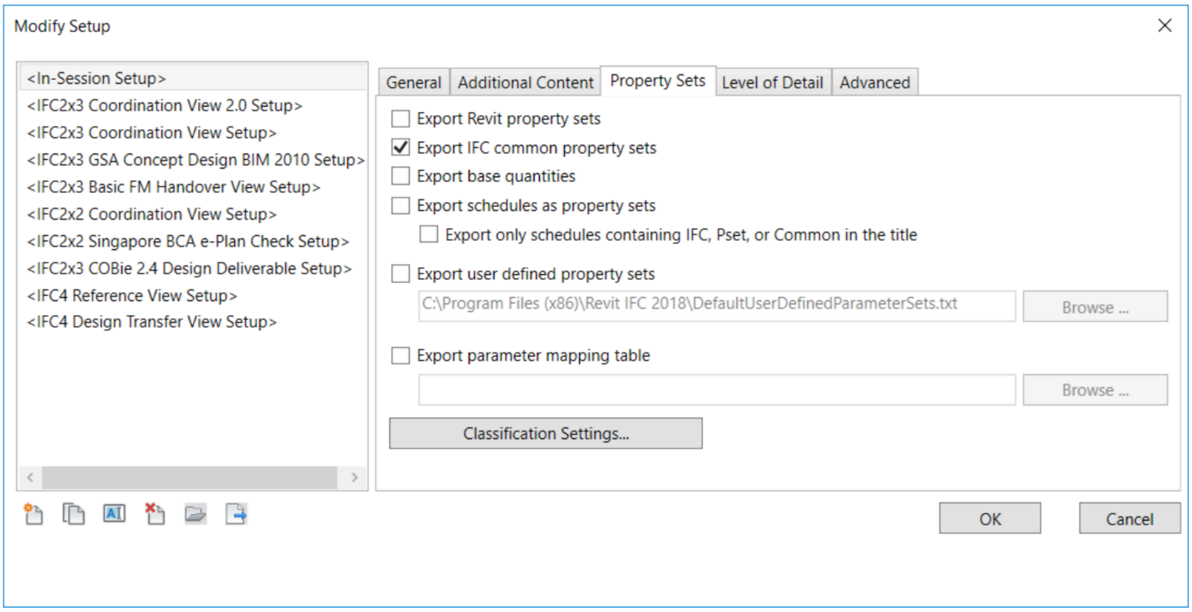

Figure 8-22 IFC export settings in Autodesk Revit

The left-hand side shows the default setup for IFC exports that are developed and certified by BuildingSMART [182], as we are creating a custom IFC export, a new setup is needed, this is done by clicking the button on the far bottom left-hand side and calling it *"AIM export".* IFC4 is selected as the IFC export version, the level of detail tab refers to the level of detail within the 3D geometry, this should be kept low to limit the impact on the file size. The user-defined property sets relate to the shared parameters that were developed at the start of this section, exporting user-defined property sets embeds the asset classification within the IFC export.

The outcome of this section is a BIM model with a set of custom parameters that enabled the researcher to classify the BIM objects in the model with the asset classification system developed in Section 8.5.2. Furthermore, an IFC model is exported from BIM model A, that includes IFC common and user-defined property sets, IFC version four (IFC4) and a low level of 3D geometry detail.

8.8. Developing an Asset Information Model (AIM)

This section discusses the creation of an AIM, including a single source 3D model that integrates BIM model A, B and C, point-cloud model and the AIM / IoT databases. Nuances of the datasets are discussed in Section 8.4. As a point of clarity, an AIM is defined within the BIM standard PAS 1192-3 as *"data and information that relates to assets to a level required to support an organisations asset management system"* [5].

This sections, consist of three steps : (1) AIM structure and format (2) importing BIM models and geometry into the AIM and (3) Connecting databases and documents into the AIM, see Figure 8-23.

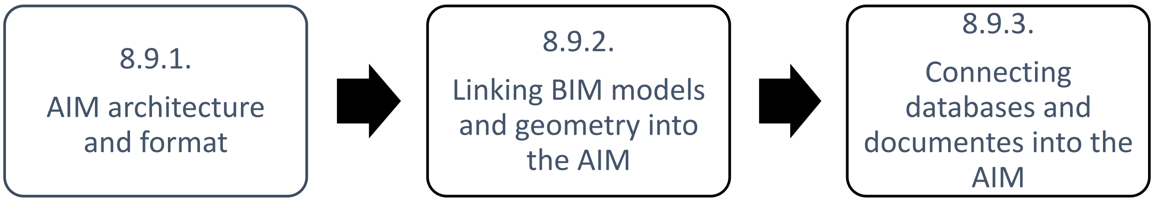

Figure 8-23 sub-steps of Section 8.8

8.8.1. AIM architecture and format

This section discusses the structure and format of the AIM, the goal of the AIM is to integrate the BIM models, additional geometry, asset-related documents and asset-related databases into a single accessible source.

AIM Architecture

Figure 8-24 provides an overview of the AIM architecture.

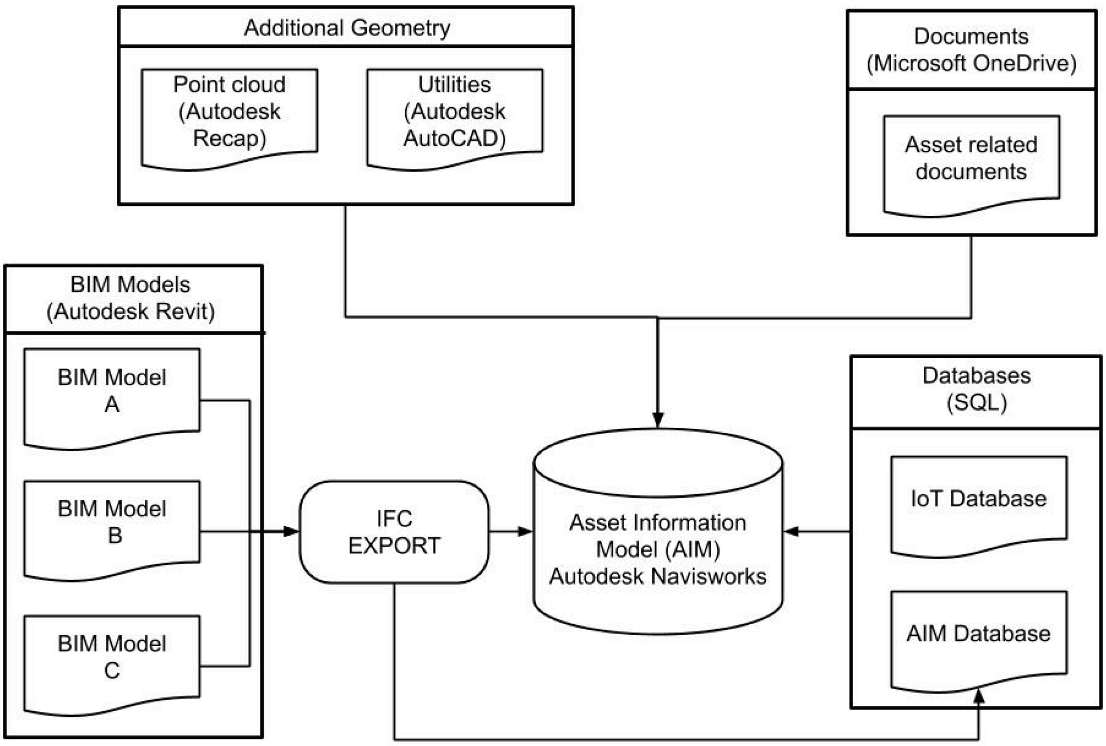

Figure 8-24 AIM architecture overview

The BIM models, additional geometry and documents are stored within OneDrive as per the EDMS structure in Figure 8-5, while the AIM and IoT databases are stored within an instance of MYSQL on a local drive. The important thing to note is that the datasets are not imported into the AIM but linked, creating a federated model with multiple datasets linked into it. This means that if the models or documents change, this will be automatically reflected in the AIM. Furthermore, it means the AIM is easily expandable when new models become available, keeping the file size of the AIM to a minimum.

AIM format

Considering the user-friendly requirements, Autodesk Navisworks was chosen as it has a simple user interface, along with several advantages:

- Ability to import many different geometry formats, including IFC, Autodesk Recap and AutoCAD.
- Natively connects to SQL databases.
- Documents can be displayed both as a link to geometry or as a link within a parameter.
- A free version of the software is available for download and the asset management team has experience of working with Autodesk products.

AIM location

The location for where the AIM and associated data would be stored was chosen, as stated in Section 8.4.2, the AIM will not directly link into existing asset management systems due to the complexity of linking a research project into a live system, including security concerns.

The researcher decided to host the data within a shared folder on the University OneDrive cloud, this ensured that the asset management team could freely access it, while also maintaining the data within the university IT systems. Within the root folder, the folders of BIM models, additional geometry and documents were created, storing the associated data. Within the documents folder, multiple folders were created depending on the document type, such as asset management plans, strategy and schedules. The AIM and IoT databases are stored within a SQL server on the university network.

8.8.2. Linking BIM models and additional geometry into the AIM

This section discusses the linking of BIM models A, B and C within the AIM, along with the additional geometry of a point cloud scan.

Linking BIM models to the AIM

BIM model A, B and C are all created within the same BIM modelling authoring software (Autodesk Revit), therefore linking the three BIM models is the same process.

An IFC model is created for BIM model B and C using the same process that was used for creating the IFC model of BIM model A (see Section 8.7.1). The three IFC models are placed within the BIM models folder on the OneDrive shared folder, then linked into the AIM Navisworks file, as the models are geo-located, they are inserted into the model within reference to their correct location within the campus.

Linking additional geometry

Regarding the point-cloud data, as stated in section 8.4.1, is a raw export of the data was provided in LAS format and processed by the researcher with Autodesk Recap into the format RVT, that Significantly reduces its file size. The .RVT file was placed within the additional geometry folder and linked into the AIM model. Figure 8-25 shows an overview of the point-cloud data within the AIM along with BIM model C and B, while Figure 8-26 shows a close-up view with BIM model A and C.

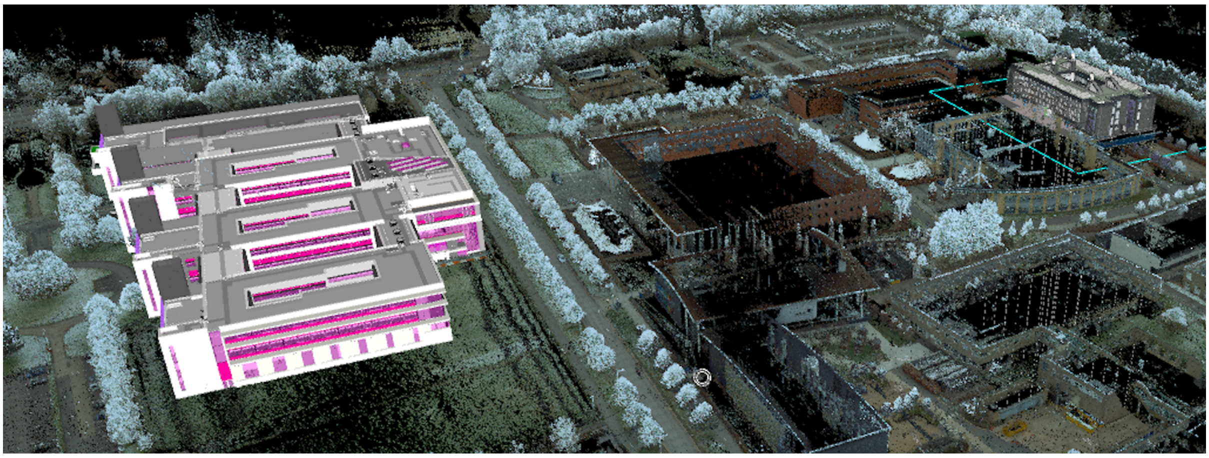

Figure 8-25 an overview of BIM model C, B and point-cloud within the AIM

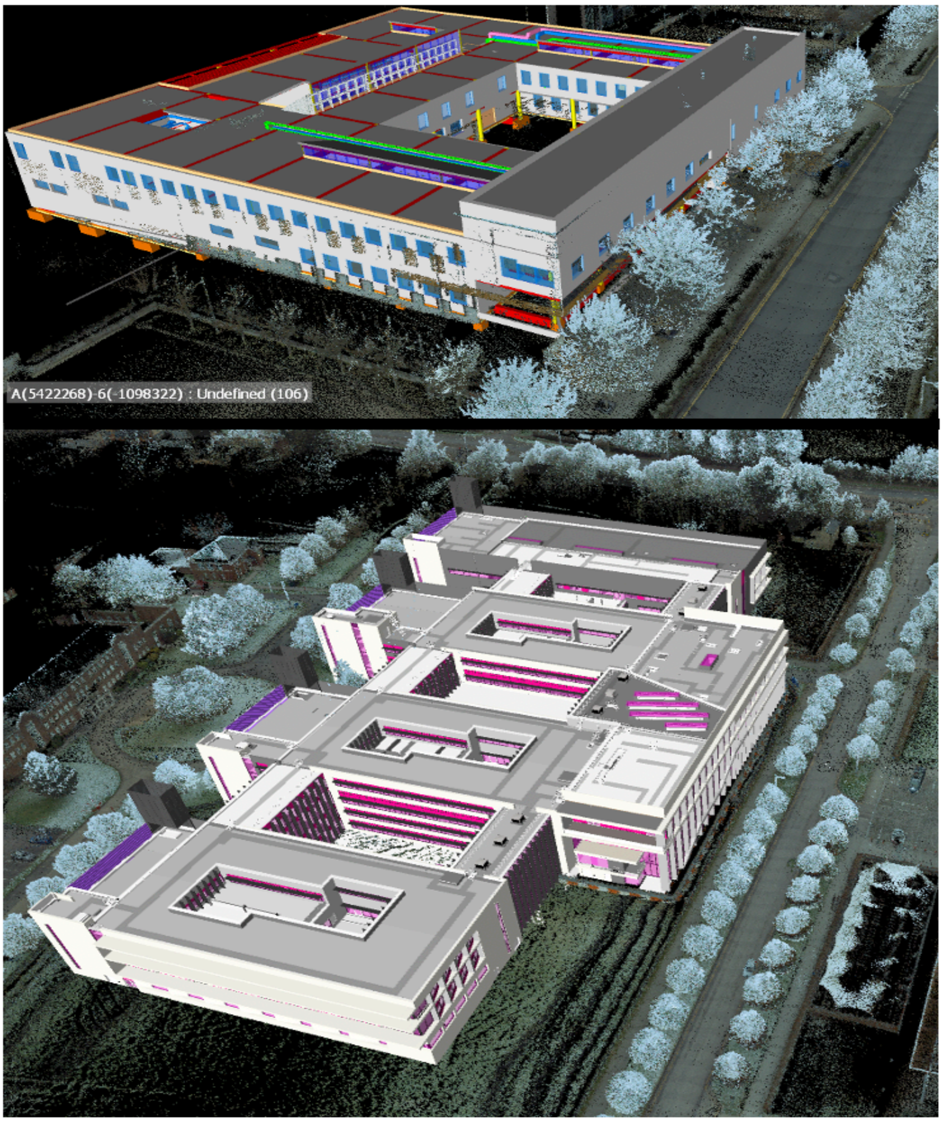

Figure 8-26 BIM model A, C and point-cloud data within the AIM

The outcome of this section is a single Navisworks model that has BIM model A, B and C, along with a point-cloud model linked within it.

8.8.3. Connecting databases and documents into the AIM

This section discusses the linking of both the AIM database and the IoT database into the AIM, along with linking asset-related documents.

AIM Database

This section is focused on linking the AIM database that is developed within Section Appendix J into the AIM model. Navisworks has a set of database tools for connecting into SQL databases and displaying the values on a property panel. The link between the AIM database and the AIM is created via the IFC unique ID that is created when the IFC model is exported. Figure 8-27 provides an overview of the data link settings within Autodesk Navisworks.

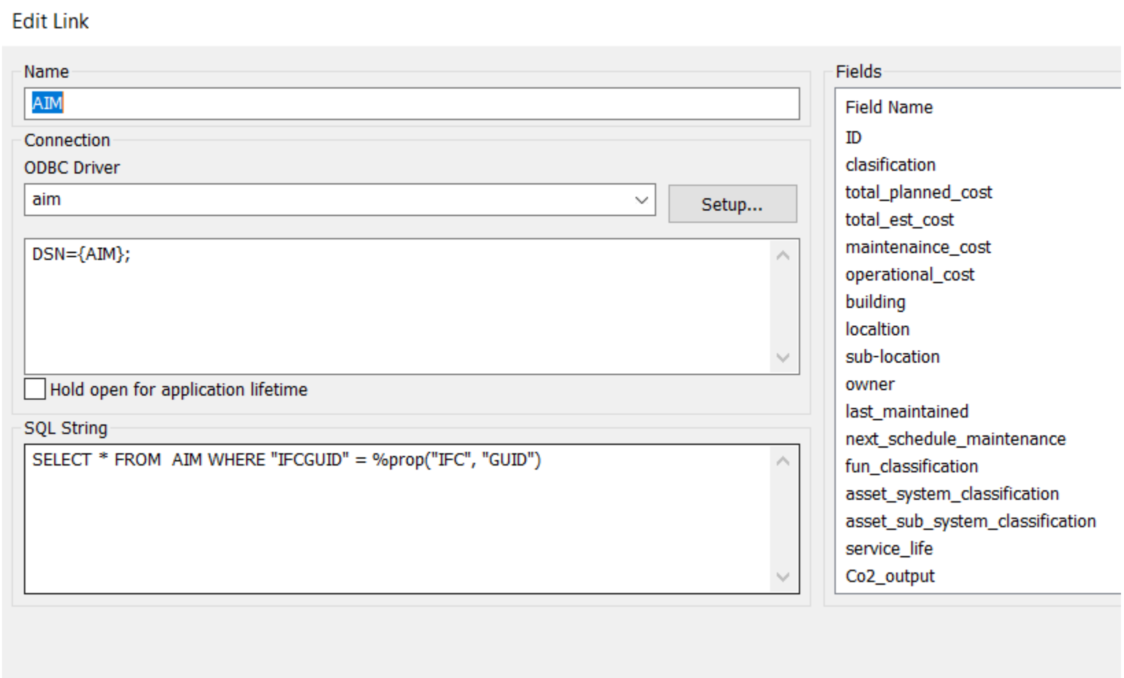

Figure 8-27 data link settings within Autodesk Navisworks

The top left of Figure 8-27 is the name of the datalink profile, as it is linking to the AIM database, it is simply called AIM. The Open Database Connectivity (ODBC) driver connects to a Domain Name Server (DNS), which is linked to the AIM database, the DNS is also called AIM.

The bottom left of Figure 8-27 is the SQL string that is used to extract data from the AIM database and visualise it within the AIM. The query extracts all data from the AIM database where the IFC Global Unique ID (GUID) matches the IFC GUID for the objects within the AIM.

Finally, the right-hand side of Figure 8-27 is where the fields within the AIM database are mapped to the display name in the AIM, in this case, the names have not been changed.

Figure 8-28 shows an example of a ventilation system, on the left-hand shows the asset is being selected within a 3D model, the right-hand side shows the associated data within the AIM database. It is important to note that the data itself is not directly inserted into the model but is queried when the object is selected, this means that the data will refresh and change as the database is edited.

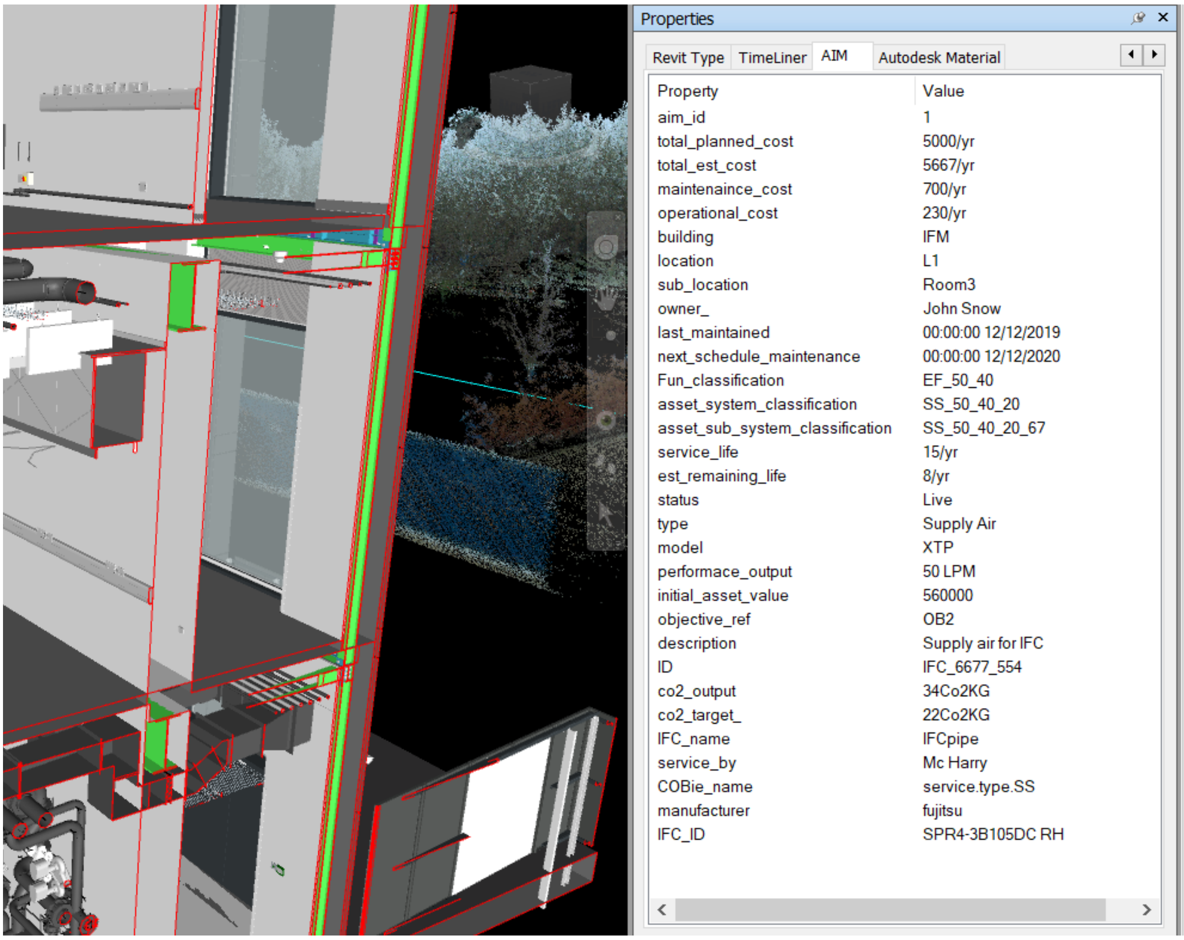

Figure 8-28 AIM database linked to an asset within the AIM

IoT Database

Similar to the AIM database, the IoT database is linked to the AIM using the database tools, see Figure 8-27. The IoT sensors measure temperature, humidity and lighting within several offices, meeting rooms and lecture halls in BIM model A. As the sensors measure environmental aspects and not asset performance (such as flow or voltage) it is not appropriate to link the IoT data to an asset, as what was done in the AIM database link, instead it is linked to a 3D space in the AIM.

Documentation

Documents can be associated with the AIM by *"linking"* the document within Navisworks or a link stored within the AIM database.

A combination of both approaches is used. For example, links to documents primarily related to the assets are built into the AIM database, such as asset management plans, while documents related to general guidance or overview are linked directly into the AIM.

Figure 8-29 shows an example of a link to a safety access documentation for accessing the plant room, that should be read before entering the plant room, the link is attached to the door that goes into the plant room, when clicked it opens the document within OneDrive.

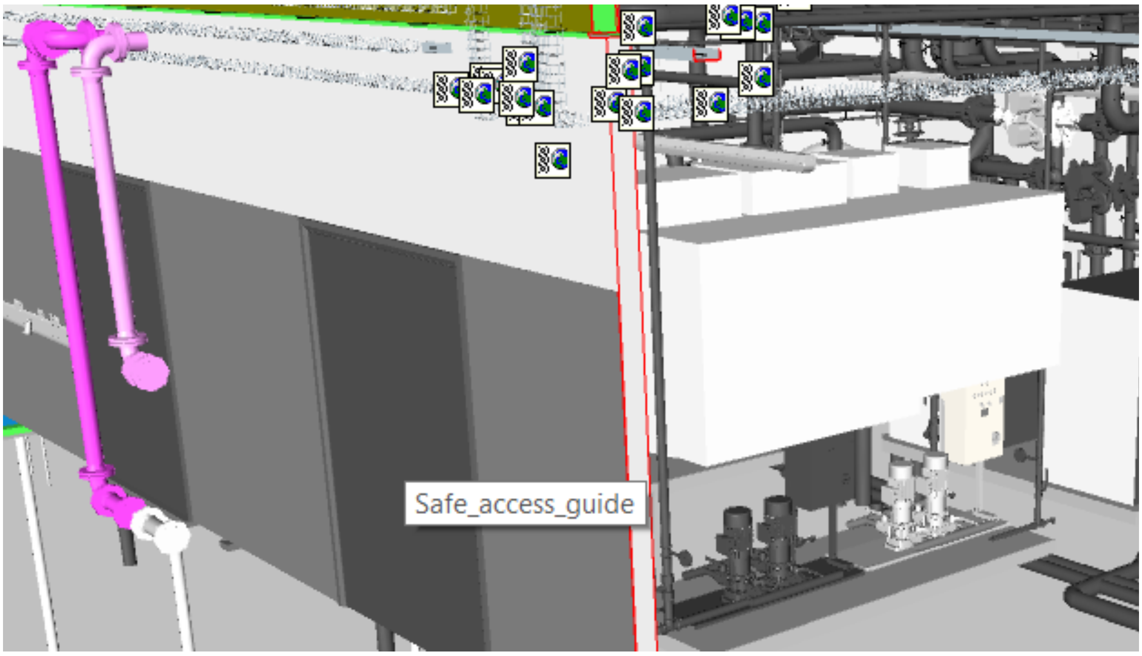

Figure 8-29 documents linked within the AIM model

8.8.4. Summary

While the development of the AIM is not an individual step within the information requirements framework, see Figure 4-1, it is an outcome of implementing the framework.

The development of the AIM itself consists of three steps: (1) developing the AIM architecture and format, (2) linking BIM models and point-cloud data into the AIM and (3) connecting the AIM / IoT databases and documented into the AIM.

Step one (see Section 8.8.1) provides an overview of the AIM architecture, with enforces put on the fact that no datasets are directly inserted into the AIM, but linked into the model, providing a federated AIM that consists of multiple models and 3D geometry. Furthermore, a discussion is provided around the AIM format, which was chosen as Autodesk Navisworks. Finally, the AIM storage location and folder structured is discussed.

Step two (see Section 8.8.2) discusses the linking of BIM model A, B and C, along with the point-cloud data into the AIM. The IFC export was created of BIM model B and C, while the IFC model created of BIM model A created in Section 8.7.1 was reused and imported into the AIM, creating a single federated model with all of the BIM models within it. Secondly, the point-cloud data that was converted from a LAS file into an RVT was inserted into the AIM, providing a more comprehensive view of the campus area and context for the BIM models.

The final step was to link the AIM and IoT databases, along with asset-related documentation into the AIM. The database where liked in by using the data tools feature provided within the AIM, a DNS server was created of the both the AIM and IoT databases and a SQL string created to query the database. In the case of the AIM model, the IFC GUID was used to associate the data with the asset within the model, while for the IoT database, it uses a space/zone ID. Asset related documentation was placed within the EDMS structure (see Figure 8-5) and linked into the model via a link within the attributes or a direct "placement" into the AIM, see Figure 8-29.

The outcome of this section is an AIM that is useable by the case study partners that reflects an asset management perspective and requirements, a reflection of the AIM performance is provided within the Conclusion of this chapter.

8.9. Evaluation of the AIM

The AIM itself is an outcome of the case study, development of the AIM including the integration of the AIM and IoT databases, BIM models, point cloud and documentation is discussed in detail in section 8.8. This section is focused on evaluating the AIM, including case study feedback.

The AIM is a 3D model (can be displayed as 2D) that is a 1:1 scale of the physical world, that enables the user to move or *"fly"* around the model and select individual assets, assets systems or buildings to hide or isolate them, create dynamic 3D sections and the use of measuring tools, among other features. Selecting an asset in the AIM will display the AIM and IoT databases within the properties panel (see Figure 8-28), that is being directly queried from the databases, this data is not stored within the AIM itself.

While displaying the AIM database within a 3D environment is helpful, the AIM data can also be used for analytics within the AIM. As an example, the "*appearance profiler"* feature changes the appearance of an asset-based on a given value, the operational_cost value from the AIM database could be used to visualise the costliest assets in red and the cheapest in green.

Feedback noted that the user-interface of the AIM was significantly more comfortable than trying to navigate the models within the native BIM authoring software. Furthermore, having all of the BIM models within a single federated model with a point-cloud scan provided greater insight into the context of the building with the surrounding infrastructure and buildings, in a single source. Having the AIM and IoT databases integrated into the model, enabled both technical and non-technical stakeholders to easily access the information without having to provide reports or similar. Despite feedback noting the user-friendly aspect of the AIM, which is significant compared to using BIM models within their authoring software, there was still a challenge in getting users to engage with the model, this is part of a wider cultural challenge in addressing technology adoption within the asset management industry.

The AIM developed within this case study was created in isolation to the broader information management systems, due to security and performance issues of integrating into a *"live"* system. Feedback noted that this limited its *"real"* use within decision-making processes, but also noted that it was a significant tool in demonstrating the benefits of an AIM and is currently being used to develop a business case to gain investment for integrating and widening the scope of the AIM.

Further feedback noted that while the visual 3D aspect of the AIM is essential, especially when engaging with senior or external stakeholders, the *"true"* value of the

AIM is the standardised asset and organisational data structure. Having a single source of access for all asset-related data (including technical, financial and managerial), was considered a critical success that has the potential to enable data-driven decisions and analytics that are not currently possible. Furthermore, the export of assets within systems and functional outputs from the BIM model was seen as a clear advantage over a COBie export or the traditional approach of a master asset register. Finally, there was a clear understanding of the value of BIM to the asset management department, when the models are designed and developed to support the creation of an AIM.

In conclusion, the AIM demonstrated that the asset management department could utilise BIM models that are designed and developed from an asset management perspective within the O&M phase. Furthermore, the AIM database acting as a central source of asset-related data, allows for data-driven decision making and analytics that is not currently possible in the current information management systems, due to a lack of interoperability.

8.9.1. Reflecting on the case study challenges matrix

This section reflects the challenges matrix developed in Section 8.3.1. The matrix itself is divided into the categories of information requirements, organisational data management, asset data management and organisational cultural challenges, which are discussed below.

Information requirements challenges

When reviewing Table 8-3, this category highlighted the challenge of developing information requirements themselves, with no standard approach to their development resulting in poor quality information requirements. Furthermore, this hampered the organisations ability to gain insight or report on their asset performance, especially within the context of asset management objectives, such as cost-saving and environmental impact.

The case study directly addressed this challenge by providing a structured approach to the development of information requirements. Furthermore, it also addresses the organisational context within the information requirements development by utilising the assert management objectives as the starting point for the OIR development.

Moreover, the introduction of the FIR enables the reporting of asset performance at the assets functional output level, as an example, reporting on the environmental impact of heating within a given building.

Organisational data management challenges

When reviewing Table 8-3, this category highlighted the challenges of managing organisational data between multiple lifecycles stages and diverse enterprise systems. This includes the use of manual and ad-hoc data management processes that result in poor data quality, enterprise solutions unable to efficiently communicate with each other, data is often duplicated within different systems and BIM models, not design or developed for asset management use cases.

The case study aimed to address these challenges by providing a structured approach to the development of an AIM. While the development of the AIM itself does not directly address the data quality challenges, it does provide the required standardisation to support the adoption of a Data Quality Framework. The AIM database provides an open-source database structure that enables the interoperability between different enterprise systems, therefore reducing the duplication of data and providing *"one source of truth"* related to organisational data. Furthermore, the classification of assets within the BIM models from an assets functional output ensured that the asset management perspective was built into the BIM models.

Asset data management challenges

When reviewing Table 8-3, this category focused on the specific challenges related to the creation and management of asset-related data throughout its whole life. Including a lack of an asset classification system, no standard asset data structure, asset data is within different systems with poor interconnectivity and a lack of clarity on how asset-related information should be exchanged between stakeholders.

Asset themselves are highly diverse and so is the associated data, to address this an asset classification was adopted to associate the developed FIR and AIR onto the given assets functional output or asset systems and sub-systems. The same asset classification system created the AIM database, to provide a standard asset data structure that was used within the information requirements development and the

AIM development. Furthermore, the extraction platform automated the extraction of asset-related information from a BIM model into the AIM database for exploitation by different technology systems and exchange with stakeholders.

Organisational cultural challenges

When reviewing Table 8-3, this category summarised the organisational cultural challenges that are specific to this case study but that the industry investigation (See Section 2.5) noted was common among asset management organisations. This includes, a lack of BIM and general technology skills, the challenge in defining the value for a robust business case to gain investment, lack of leadership buy-in and data (and the management of data) itself is often undervalued and not considered value-adding.

It was a common theme in the case study that the solutions and tools used whereas user-friendly as possible and understood by stakeholders with a limited understanding of technology and digital processes. The use of CSF and PLQ within the OIR developed highlights this fact, while the JDA workshops within the FIR and AIR developed ensured all stakeholders could engage. The case study itself acted as a means to gain leadership buy-in and support the *"digital campus"* strategy, that aims to develop a business case for digital adoption within the university. Furthermore, the transparency of the AIM means that a large group of stakeholders could now see asset-related data, therefore the value and appreciation for the data had increased and changed many mindsets to the importance and value-adding properties of asset data.

8.10. Third-party industry case study

In addition to the case study presented in this Chapter, the information requirements framework was adopted by an industry partner (Jacobs) within a case study on the Transpennine Route Upgrade (TRU) Programme, a major railway enhancement project to improve connectivity between York and Manchester delivered by Network Rail [183].

The researcher supported the industry partner in the initial stages that involved a detailed discussion of the information requirements framework and a detailed literature review, including the researchers' published journal papers. Following this, the industry partner conducted an industry investigation, that included a conversation with colleagues and Network Rail, along with the researchers own industry knowledge.

Following the literature review and industry investigation, several modifications where adopted to the framework:

- Validation of information requirements at the point of data capture, with pre-defined clarification statement to support the required consensus.
- The use of python script to automatically read organisational documentation and extract objectives based off a set of key words.
- Utilisation of a web application to capture CSF and PLQ within a structured approach. Figure 8-30 provides a screenshot of the web application. The objective is selected on at the top, with CSF created on the left-hand side and PLQ on the right-hand side.

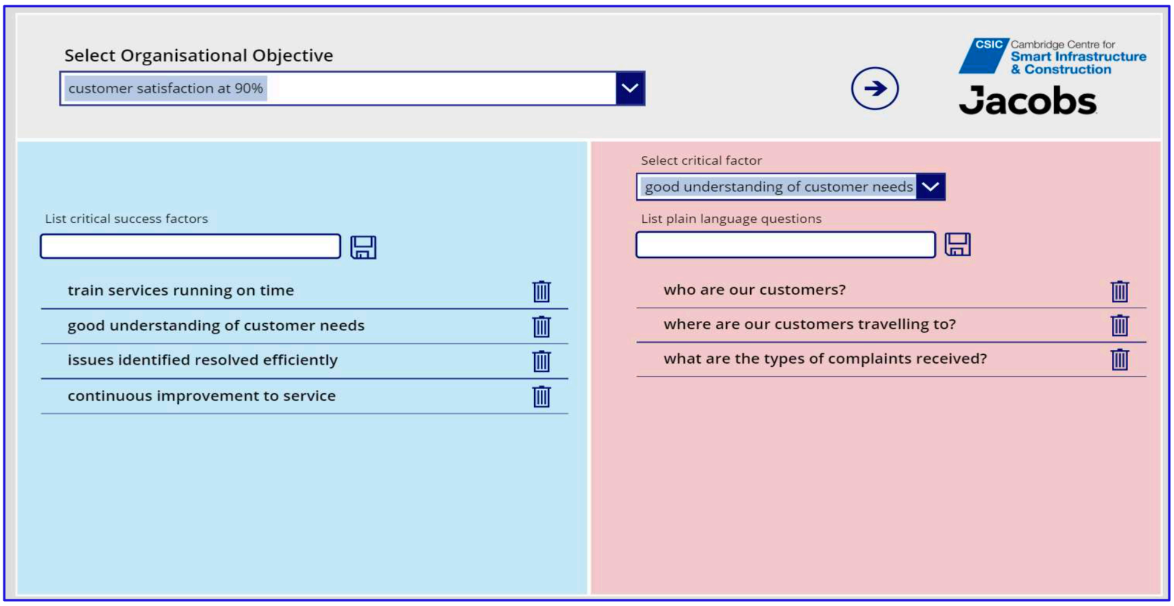

Figure 8-30 screenshot of web application

The outcome of the case study say 60 objectives extracted and the development of 7 CSF, 26 PLQ (and therefore OIR), 15 FIR and 3 AIR for a single objective. The full result can be seen in Appendix I.

The case study proved that third parties could adopt the framework with minimal support from the researcher. Furthermore, it also demonstrated that the framework is not limited to buildings or university campuses but is also applicable to the infrastructure industry. Feedback noted that it was a valuable exercise that should be adopted within all projects but will require a large amount of resource and leadership commitment to be realised.

9. Conclusion

This chapter provides the overall conclusion to this thesis and is divided into five sections. Section one provides a summary of the thesis. Section two reflects on the research questions and provides a detailed response to answering them. Section three provides an overview of the main contributions. Section four notes the limitations of the research and finally, Section five discusses future research opportunities.

9.1. Summary

This thesis presented a concept model and an information requirements framework that supports an asset management organisation to develop Asset Information Requirements (AIR), enabling the adoption of Building Information Modelling (BIM). The design and development of both the concept model and the information requirements framework adopts elements from the domains of requirements engineering, asset management and BIM. The concept model (see Section **Error! Reference source not found.** and **Error! Reference source not found.**) is the main outcome from the background chapter aligning the domains of asset management and BIM. The concept model introduces the concept of Functional Information Requirements (FIR), as a means to bridge the gap and address the challenges of Organisational Information Requirements (OIR) generating AIR.

An information requirements framework was presented, that provides a step-by-step approach to the development of AIR and an Asset Information Model (AIM) that is derived from a BIM model, along with the above-mentioned FIR.

Given the multidisciplinary research within this thesis, the main contribution is not an incremental addition of knowledge within a given domain, but rather linking the domains of BIM and asset management with requirements engineering and therefore broadening those domains with new knowledge.

9.2. Reflections on the research questions

To guide the research progress, two research questions were introduced in Chapter 1, the answers to which are summarised below.

RQ1: How can an asset management organisation develop asset information requirements that align with their asset management objectives? This thesis demonstrated how a structured approach to the development of information requirements, can provide AIR that align with the asset management objectives. Examining the above research question:

… develop asset information requirements… This is demonstrated in Chapters 4, 5 and 6 with the information requirements framework, aiding in the development of OIR and FIR that generates the AIR. Furthermore, the application of the framework in an industry case study (see Chapter 8) demonstrated the development of OIR, FIR and AIR within an industrial application.

… that align with their asset management objectives? The concept model (see **Error! Reference source not found.**) shows how documentation developed as part of an asset management system can provide the required alignment between asset management objectives and the OIR, FIR and AIR. The concept model provided the concepts for the development of the information requirements framework. Furthermore, Chapter 8 demonstrated how this alignment was achieved within an industry case study.

RQ2: How should a BIM model be enriched for use within asset management? This thesis demonstrated how a BIM model is manually enriched with asset information:

How should a BIM model be enriched… Chapter 7 showed how objects (representation of assets) within a BIM model are aggregated and manually enriched with asset classification codes based on their functional output, asset system and sub-system.

…for use within asset management? Chapter 5 and 6, demonstrate the development of FIR and AIR that are modelled within UML database diagrams, supporting the creation of an AIM database. Chapter 7 showed how a classified BIM model could be exported into an IFC model and imported into an extraction platform, where data is extracted from the classified objects in the model and inserted into the AIM database. Section 8.8 demonstrated the creation of a 3D AIM, with the AIM database linked into it. Furthermore, the case study conclusion (see Section 8.9.1) reflected on the case study challenges (see Table 8-3) and highlighted how the AIM addressed those challenges, enabling the use of BIM models within asset management.

9.3. Contributions of this research

This section summarises the contributions of this thesis within an industry application and the academic domain, including a summary of published journal papers. Furthermore, a summary of the key contributions is provided.

9.3.1. Contribution to academic knowledge

Academically, the work presented within this thesis contributes to the fields of asset management, BIM and requirements engineering by:

- Creation of a systematic framework to define AIR
- Defined and created a new concept called FIR to aid in the development of AIR.
- Creation of a concept model that aligns elements of asset management and BIM to support the development of AIR.
- Creation of a systematic framework that supports the design and development of a BIM model to aid asset management.

The following section summaries the journal articles published during the production of this thesis, in order of their contribution significance. Conference papers are not included within this summary as they include findings that are later published within the papers or topics that are not directly related to the thesis objective, see the start of the thesis for a full list of publications.

[12] J. Heaton, A.K. Parlikad, J. Schooling, A Building Information Modelling approach to the alignment of organisational objectives to Asset Information Requirements Automatization in Construction (2019): This paper is the first publication to present a conceptual model that introduces the concept of FIR and a framework to support the development of information requirements within an asset management organisation. The framework is shown to be efficient in developing organisational led information requirements within a case study.

[184] J. Heaton, A.K. Parlikad, J. Schooling, Design and development of BIM models to support operations and maintenance, Computers in Industry (2019): This paper embedded the information requirements framework within the development of an Asset Information Model (AIM). Furthermore, the paper provided an approach to standard asset classification and structure that supported the exchange of BIM model data into a relational database. The framework is tested within a case study and is shown to be an efficient way to exchange BIM model data into an AIM database for use within the O&M phase.

[185] J. Heaton, A.K. Parlikad, A conceptual framework for the alignment of infrastructure assets to citizen requirements within a Smart Cities framework, Cities. 90 (2019): This paper presented a conceptual framework that took components (specifically, classifying an assets functional output) from the information requirements framework and aligned them into a Smart Cities framework within the context of a digital twin. The findings contribute to the evolution of BIM into the domain of digital twins for O&M and highlight future research opportunities.

A. Johnson, J. Heaton, S. Yule, S. Luke, D. Pocock, A.K. Parlikad, J. Schooling, Informing the Information Requirements of a Digital Twin: A Rail Industry Case Study, ICE publishing - Smart Infrastructure and Construction, (submitted, not yet published): This paper discusses a third-party industry case study presented in Section 8.10 that utilised the information requirements framework. It demonstrated the fact that the framework can be adopted with minimal support from the researcher and be applied within the infrastructure industry.

9.3.2. Contribution to industry practice

This thesis contributes to the practical application of a framework that support the development of AIR by:

- Development a step-by-step framework with the use of practical tools and techniques that aid in developing AIR.
- The creation of FIR, aided in bridging the gap between OIR and AIR, therefore allowing the alignment between them.
- A practical approach to the classification of a BIM model to support the creation of an AIM.
- Published results from a case study that can be used as evidence to support a business case for BIM adoption within asset management

The researcher attended several industry events in the UK and USA presenting the research and the case study results to leaders within the asset management and construction industry.

Furthermore, the researcher engaged with several industry experts from Bentley system to aid in the development of a training webinar titled "*Outcome driven OIRs*" that adopted many of the approaches discussed within thesis, including the use of CSF and PLQ to aid in the development of OIR and the use of FIR to bridge the gap between the OIR and AIR.

Moreover, the training material was also used within a workshop for a major new airport project in Poland. Feedback and results from that workshop where recently published within a blog post [186].

Finally, during the researcher effort several quote where gained from industry leaders within the BIM and asset management domains, which are summarised in Table 9-1

Industry leader	**Quote**
Iain miskimmin, Director of Bentley Systems Academy Bentley systems	*"After seeing several presentations that James has done in regard to his work to develop an organisational lead approach to the development of Asset Information Requirements, I contacted James regarding developing an introduction and training module to this research. With James support several training sessions has taken place with great success, along with a workshop in Poland for Warsaw new airport project"*
Chrissie Leonard, Head of Asset Management University Estate Management	*"James has spent a sufficient amount of time and effort with the asset management department, originally using his knowledge in BIM and digital process to aid are adoption to BIM and digital processes within the operational and maintenance phase. As his research progressed, as did the value provided to the asset management team, including an asset classification system, information requirements and a 3D AIM. it is the aim of the asset management team to continue this effort."*
Aaron Johnson, Jacobs Sensor Asset Management consultant	*"The successful adopt of the information requirements methodology the NetworkRail TRU contract in the form of a case study, saw NetworkRail actively engage within the process, with positive feedback received. Furthermore, as a result of the case study, several meetings have taken place with sensor NetworkRail management to discuss the adoption of the methodology for the whole North-West Mainline."*

David Owens, Costain Head of digital design	*"The introduction of Functional Information Requirements and with the framework that supports the direct line-of-sight from objectives to the asset performance themselves is a step change for the industry, I am looking to adopt this framework as a means to support clients on their BIM and Digital Twin journeys"*

Table 9-1 Quotes from industry leaders

9.4. Novelty of this research

This thesis utilised a multidiscipline approach to the development of a concept model and an information requirements framework, including reviewing different academic domains, adoption of technical standards, an industry investigation and several uses of different technologies. The below sections summaries some of the key novel aspects of the thesis.

Concept model: (see **Error! Reference source not found.**) is an outcome of the Background (see Chapter 2) that provided the approach to the development of the information requirements framework. The concept model provided the required alignment between asset management and BIM to support the development of the information requirements framework.

Information Requirements Matrix: was developed as a structured approach to documenting information requirements, both within the JDA workshops and the document review. The matrix itself allows for the development of information requirements within the information requirements categories and at a specific asset classification level, such as an assets functional output or asset system. Feedback noted that the matrix was a practical supporting tool that enabled the capture of information requirements.

Functional Information Requirements (FIR): *FIRs* are a new set of information requirements that address the challenge of an OIR generating an AIR, adopting an assets functional output from the asset classification system. The FIR was a powerful tool that enabled greater collaboration and alignment between different asset management teams (such as cost, sustainability and risk) and the assets they operate and maintain.

BIM model classification: While the classification of the BIM models itself is not the key novel aspect, the development of custom metadata parameters that enabled the multiple classifications of a single BIM object (such as an assets functional output and asset system), along with the linking of the parameters to IFC classes is a key contribution. The developed approach to objects classification within a BIM model enabled an asset management perspective to be built into the model and provide alignment from an assets functional output to the asset systems and sub-systems that support it.

Extraction platform: The use of an extraction platform enabled the transformation of BIM models data directly into the AIM rational database for exploitation within the AIM federated model and future wider information management systems.

Federated Asset Information Model (AIM): Integrated three BIM models and a point-cloud scan of the campus area into a single 3D federated model, along with the AIM and IoT databases. Having the federated model linked with the databases, enabling the case study partner to interrogate the BIM models in new ways that were not possible before.

9.5. Limitations

The concept model and information requirements framework presented within this thesis is not a *"one size it all"* solution to every information requirements development challenge or adoption of BIM within asset management. The methodical, rigours and structured approach to the development of information requirements within the proposed framework is one of its greater strength but is also its most limiting aspect. Compared to traditional approaches (or lack of them) the information requirements framework requires an organisation to dedicate a significant amount of resources and investment in new technology and digital processes. This resource-intensive approach has three consequences that limit its adoption:

(1) As stated within the assumption (see Section 4.2) it is a requirement that an organisation has developed an asset management system and at least have a solid understanding of BIM as a value-adding exercise. While most organisations see both the value of adopting asset management (in line with ISO 55000) they lack the skilled resources available to adopt an asset management system and external consultants are considered prohibitively expensive. While BIM is generally considered value-adding within the design and construction phase, its value and use within the O&M is less understood by the asset management industry and hindering the required resource investment.

(2) While two case studies and two partial case studies have been completed, they are limited in their content, by applying the framework to more studies, perhaps more efficient ways to develop information requirements may be discovered.

(3) While an AIM database is developed in-line with the definitions provided in the BIM standards and literature, it use as a *“middleware”* layer as a means to integrate and link with the wider organisational information management systems is limited. Future integration of an AIM at an enterprise level might indicate more comprehensive approach to an asset data structure.

9.6. Future work

Future research should be focused on the three following aspects (1) requirements engineering tools and techniques, (2) asset data structure, (3) automatic model enrichment, (4) reuse of the developed information requirements and (5) adoption within the emerging concept of a Digital Twins.

(1) While the tools and techniques developed within the domain of requirements engineering are well documented, there use within asset management is limited. Asset management organisations have unique considerations, such as an asset lifecycle and complex asset systems. Tools and techniques should be researched from an asset management domain perspective.

(2) While the case study provided a structured approach to the development of an asset classification system, asset data exchange and structure, it was not without its limitation that requires future research efforts. One of the novel aspects within this thesis is the classification of an assets functional output, but it was not always obvious what was the main functional output of an asset, as an example an air handling unit can support heating, cooling and ventilation. This was achieved in the case study by stakeholders finding a consensus on the *"primary"* functional output, future research should look at a data-driven approach to select the primary functional output, such as Internet of Things (IoT) sensors to remove stakeholders bias. Limitations within the current IFC schema means that only one classification can be allocated to a single BIM object, hence why the researcher developed a set of custom IFC parameters, future research should look at expanding the IFC schema to allow for multiple classification codes on a single BIM object. Finally, the researcher had to select BIM objects manually and classify them within the BIM authoring software, future research should investigate how to automate this process, such as a standard data structure for BIM objects.

(3) As noted, the framework is resource intensive, part of this challenge is reenforced by the manual approach used to classify the BIM models. While it was a conscious choice to use such an approach due to the lack of technology skills within the asset management

industry, future research should consider the use of automatic enrichment techniques to remove this manual process, which would sufficiently reduce the required resources. Such approaches might include prepopulated objects with the required metadata, rules-based applications and automatic 3D object classification.

(4) While the framework within its current form provides a reusable approach to the development of information requirements, it does have to be repeated every time for a new objective or BIM model, which is a tedious process. Given the fact that AIR and FIR are aggregated within a given UNIClass code and categorised within managerial, technical or financial, there is an opportunity to reuse the information requirements between objectives and from asset type to asset type.

One could use the classification of the asset type and the objective to enable the reusing of the AIR for a given objective category. As an example, if I have a financial objective that provides the OIR "Total_operational_cost", that could be cascaded to all asset types that have an operational cost, other than just the asset functional output that are aligned to that OIR, this reuse of FIR should be investigated. Furthermore, it can be seen within the AIR, that asset types within the same classification codes (such as gas heating and electric heating) have similar individual information requirements, this should be explored to see how AIR can be shared between different asset types. Finally, it was noted within the case study that several AIR are similar within an objective category, despite the asset type differing (such as ventilation to electricity), it should be investigated to see if there are a *"common"* set of OIR, FIR and AIR that can be developed for a given objective category.

(5) Digital Twins (within the context of the built environment) is an emerging research domain that has grown out of the BIM and digital construction domains, popularised by several UK government reports. While this thesis focused on the development of an AIM, future research should focus on modifications to the framework that supports the creation of a Digital Twin or an AIM that supports the creation of a Digital Twin.

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Appendix A. Asset Classification Table

This appendix provides a full list of the asset classification developed within the case study. In total 24 functional outputs, 71 asset systems and 134 asset sub-systems have been classified.

Functional output	Asset System	Asset Sub-System
EF_65_80 Air Condition	Ss_65_80_05 Central air conditioning system	Ss_65_80_05_30 Fan coil air unit conditioning system
		Ss_65_80_05_10 Centralized all-air conditioning systems
	Ss_65_80_45 Local air conditioning system	Ss_65_80_45_72 Room air conditioning systems
EF_25_55 Barriers	Ss_25_14_63 Post, rail and board fence systems	Ss_25_14_63_51 Metal post and rail fencing systems
		Ss_25_14_63_97 Wood post and rail fencing systems
		Ss_25_14_63_98 Wrought iron panel fencing systems
	Ss_25_14_67 Post, wire and mesh fence systems	Ss_25_14_67_80 Spring steel and high tensile wire mesh fencing systems
EF_75_10 Communication systems	Ss_75_10_21 Data distribution and telecommunications systems	Ss_75_10_21_21 Data distribution systems
		Ss_75_10_21_48 Local area network (LAN) systems
		Ss_75_10_21_97 Wide area network (WAN) systems

	Ss_75_10_68 Public communications systems	Ss_75_10_68_68 Public address systems
		Ss_75_10_68_42 Information display systems
	Ss_75_10_72 Emergency communication systems	Ss_75_10_72_30 Firefighting intercom systems
EF_75_70 Control and Management	Ss_75_70_54 Metering, monitoring and management systems	Ss_75_70_54_25 Electricity metering systems
		Ss_75_70_54_95 Water metering systems
	Ss_75_70_85 Structural monitoring systems	Ss_75_70_85_18 Crack gauge monitoring systems
		Ss_75_70_85_90 Tilt sensor monitoring systems
EF_25_30 Door and Windows	Doors, shutters and hatch systems	Loading bay doorset systems
		Doorset systems
		Frameless glass door systems
	Ss_25_30_29 Fire and smoke curtain systems	Ss_25_30_29_80 High-security doorset systems
		Ss_25_30_29_30 Fire curtain systems
	Ss_25_30_95 Window Systems	Ss_25_30_95_26 External window systems
		Ss_25_30_95_41 Internal window systems
EF_50_30 Drainage collection	Ss_50_35_45 Land drainage systems	Ss_50_35_45_20 Culvert land drainage systems
		Ss_50_35_45_85 Subsoil drainage pipe drain systems
		Ss_50_35_45_90 Trenchless drain land drainage systems

	Ss_50_35_08 Below-ground gravity drainage systems	Ss_50_35_08_30 Foul wastewater below-ground drainage pipeline systems
		Ss_50_35_08_85 Surface water below-ground drainage pipeline systems
	Ss_50_30_02 Rainwater drainage systems	Ss_50_30_02_28 External gravity rainwater drainage systems
	Ss_50_30_04 Surface and wastewater drainage collection systems	Ss_50_30_04_95 Above-ground external stack wastewater drainage systems
EF_70_30 Electricity distribution and transmission	Ss_70_30_10 Cable management systems	Ss_70_30_10_35 High-voltage cable management systems
		Ss_70_30_10_45 Low-voltage cable management systems
	Ss_70_30_35 High-voltage systems	Ss_70_30_35_30 High-voltage site connection systems
		Ss_70_30_35_35 High-voltage distribution systems
	Ss_70_30_45 Low-voltage systems	Ss_70_30_45_40 Low-voltage site connection systems
		Ss_70_30_45_45 Low-voltage distribution systems
	Ss_70_30_80 Small power systems	Ss_70_30_80_35 Hardwired low-voltage small power systems
EF_55_30 Fire extinguishing supply	Ss_55_30_65 Portable fire extinguisher systems	Ss_55_30_65_65 Portable fire extinguisher systems
		Ss_55_30_65_30 Fire blanket system

	Ss_55_30_96 Water firefighting systems	Ss_55_30_96_25 Dry rise system
		Ss_55_30_96_29 Fire hose reel system
		Ss_55_30_96_30 Fire hydrant system
	Ss_55_30_98 Water fire suppression system	Ss_55_30_98_85 Sprinkler system
EF_30_20 Floors	Ss_30_12_85 Structural deck systems	Ss_30_12_85_16 Composite concrete floor, roof or balcony deck systems
		Ss_30_12_85_70 Reinforced concrete floor, roof or balcony deck systems
		Ss_30_12_85_40 Heavy steel floor, roof or balcony deck systems
	Ss_30_20_30 External deck and boardwalk systems	Ss_30_20_30_25 Decking system
	Ss_30_20_10 Board and rigid sheet floor systems	Ss_30_20_10_15 Battened wood-based rigid sheet floating floor systems
EF_55_20 Gas supply	Ss_55_20_60 Compressed air supply systems	Ss_55_20_60_15 Industrial compressed air supply systems
		Ss_55_20_60_33 Laboratory compressed air supply systems
	Ss_55_20_34 Gas supply system	Ss_55_20_34_46 Liquefied petroleum gas (LPG) supply systems
		Ss_55_20_34_57 Natural gas supply systems
	Ss_55_20_45	Ss_55_20_45_39

	Laboratory gas supply systems	Laboratory hydrogen supply systems
		Ss_55_20_45_56 Laboratory nitrogen supply systems
		Ss_55_20_45_59 Laboratory oxygen supply systems
EF_80_50 Lifts	Ss_80_50_60 Passenger and good lifts	Ss_80_50_60_26 Electric lift systems
		Ss_80_50_60_39 Hydraulic lift systems
		Ss_80_50_60_94 Vertical platform lift systems
EF_70_80 Lighting	Ss_70_80_33 General space lighting	Ss_70_80_33_33 General lighting systems with prefabricated wiring
		Ss_70_80_33_12 Central battery supplied emergency lighting systems
		Ss_70_80_33_35 Hardwired general lighting systems
	Ss_70_80_25 External lighting system	Ss_70_80_25_05 Amenity lighting systems
		Ss_70_80_25_59 Outdoor workplace lighting systems
EF_30_60 Pavement	Ss_30_14_15 Concrete road and pavement system	Ss_30_14_15_16 Concrete paving system
		Ss_30_14_15_14 Concrete grass filled pavement system
	Ss_30_14_90 Unit paving system	Ss_30_14_90_32 Flag and slab bound paving systems
EF_60_60	Ss_60_60_15	Ss_60_60_15_10

Refrigeration	Cold room systems	Catering cold room system
	Ss_60_60_17 Cold storage systems	
EF_30_10 Roofs	Ss_30_10_50 Monolithic roof structure systems	Ss_30_10_50_70 Sprayed concrete roof systems
	Ss_30_10_30 Framed roof structure systems	Ss_30_10_30_03 Aluminium roof framing systems
		Ss_30_10_30_25 Heavy steel roof framing systems
EF_75_50 Safety and protection	Ss_75_50_11 Call and alarm systems	Ss_75_50_11_05 Assistance call systems
		Ss_75_50_11_27 Emergency voice communication systems
	Ss_75_50_28 Fire and smoke detection and alarm systems	Ss_75_50_28_24 Duct smoke detector systems
		Ss_75_50_28_29 Fire detection and alarm systems
	Ss_75_50_45 Electrical protection systems	Ss_75_50_45_45 Lightning protection systems
EF_75_40 Security	Ss_75_40_02 Access control systems	Ss_75_40_02_05 audio intercom systems
		Ss_75_40_02_11 Card access control systems
	Ss_75_40_53 Monitoring systems	Ss_75_40_53_86 Surveillance CCTV systems
	Ss_75_40_75 Security detection alarm systems	Ss_75_40_75_40 Intruder detection and alarm systems
EF_60_40 Space heating and cooling	Ss_60_40_37 Heating systems	Ss_60_40_37_21 Direct gas-fired heating systems
		Ss_60_40_37_26 Electric heating systems

		Ss_60_40_37_48 Low-temperature hot water heating systems
		Ss_60_40_37_81 Solar heating systems
	Ss_60_40_36 Heat pump system	Ss_60_40_36_05 Air source heat pump systems
		Ss_60_40_36_35 Ground source heat pump systems
	Ss_60_40_84 Space heating and cooling distribution network systems	Ss_60_40_84_22 District heating distribution network systems
	Ss_60_40_92 Underfloor heating and cooling systems	Ss_60_40_92_94 Underfloor low- temperature hot water heating systems
EF_35_10 Stair and ramps	Ss_35_10_25 External stair and ramp systems	Ss_35_10_25_34 Ground bearing external ramp systems
		Ss_35_10_25_35 Ground bearing external stairs systems
	Ss_35_10_85 Structural stair and ramp systems	Ss_35_10_85_65 Precast concrete stair or ramp systems
		Ss_35_10_85_15 Concrete stair or ramp systems
	Ss_35_10_40 Internal stair and ramp systems	Ss_35_10_40_40 Internal ramp systems
		Ss_35_10_40_42 Internal stairs systems
	Ss_35_10_30 Fixed utilitarian access systems	Ss_35_10_30_40 Industrial stair systems
EF_20_05 Substructure	Ss_20_05_15 Concrete foundation systems	Ss_20_05_15_70 Reinforced concrete pad and strip foundation systems
		Ss_20_05_15_71

		Reinforced concrete pilecap and ground beam foundation systems
	Ss_20_05_65 Piling system	Ss_20_05_65_40 In situ concrete augered piling systems
		Ss_20_05_65_42 In situ concrete cased displacement piling system
	Ss_20_20_75 Structural beam systems	Ss_20_20_75_15 Concrete beam systems
		Ss_20_20_75_80 Steel beam systems
	Ss_20_30_75 Structural column systems	Ss_20_30_75_15 Concrete column systems
		Ss_20_30_75_80 Steel column systems
	Ss_20_60_30 Embedded retaining wall systems	Ss_20_60_30_70 Reinforced concrete diaphragm retaining wall systems
EF_20_10 Superstructure	Ss_20_10_60 Prefabricated framed and panelled structures	Ss_20_10_60_34 Glazed structural systems
		Ss_20_10_60_84 Structural insulated panel systems
	Ss_20_10_75 Structural framing systems	Ss_20_10_75_45 Light steel framing systems
		Ss_20_10_75_65 Precast reinforced concrete framing systems
		Ss_20_10_75_70 In situ reinforced concrete framing systems
EF_65_40 Ventilation	Ss_65_40_33 General space ventilation systems	Ss_65_40_33_45 Kitchen extract ventilation systems
		Ss_65_40_33_50

		Mechanical extract ventilation systems
		Ss_65_40_33_51 Mechanical supply ventilation systems
		Ss_65_40_33_56 Natural ventilation systems
		Ss_65_40_33_90 Toilet extract ventilation systems
	Ss_65_40_42 Industrial fume extract systems	Ss_65_40_42_25 Dust extract systems
		Ss_65_40_42_36 Hazardous area extract systems
	Ss_65_40_80 Smoke extract and control systems	Ss_75_70_52_80 Smoke and heat exhaust ventilation systems
EF_25_10 Walls	Ss_25_10_32 Framed wall structure systems	Ss_25_10_32_03 Aluminium wall framing systems
		Ss_25_10_32_58 Plaster wall framing systems
		Ss_25_10_32_90 Timber wall framing systems
	Ss_25_10_35 Framed glazed systems	Ss_25_10_35_97 Window wall glazed screen systems
		Ss_25_10_35_95 Vertical patent glazing systems
	Ss_25_11_16 Concrete wall systems	Ss_25_11_16_65 Precast concrete wall systems
		Ss_25_11_16_70 Reinforced concrete wall structure systems
	Ss_25_13_50 Masonry wall systems	Ss_25_13_50_51 Masonry wall leaf systems

		Ss_25_13_50_49 Masonry exposed feature systems
	Ss_25_10_20 Curtain walling systems	Ss_25_10_20_85 Stick curtain walling systems
EF_55_70 Water supply	Ss_55_70_38 Hot and cold water supply	Ss_55_70_38_40 Incoming water supply systems
		Ss_55_70_38_42 Indirect hot water storage supply systems
		Ss_55_70_38_65 Pumped cold water supply systems
	Ss_55_70_42 Irrigation systems	Ss_55_70_42_85 Sprinkler irrigation systems
	Ss_55_70_95 Water distribution network systems	Ss_55_70_95_66 Private water distribution network systems
	Ss_55_70_97 Water reclamation systems	Ss_55_70_97_35 Grey water reclamation systems
		Ss_55_70_97_70 Rainwater reclamation system

Table A-1 asset classification table

Appendix B. Asset Classification UML Diagrams

Below is the UML concept model developed within step two and part one of the information requirements methodology. The UML diagrams form part of the documentation step (see Section 5.3.3) for the development of an asset classification system, see Section 5.3.

Due to the limitations of Figures within the thesis, an example of 3 figures are provided below, along with 2 examples within the thesis itself, see Figure 5-7 and Figure 8-9. A full list of the UML diagrams can be provided at the request to the author.

In total 24 diagrams where created, with each diagram being a single asset functional output.

Space heating and cooling diagram

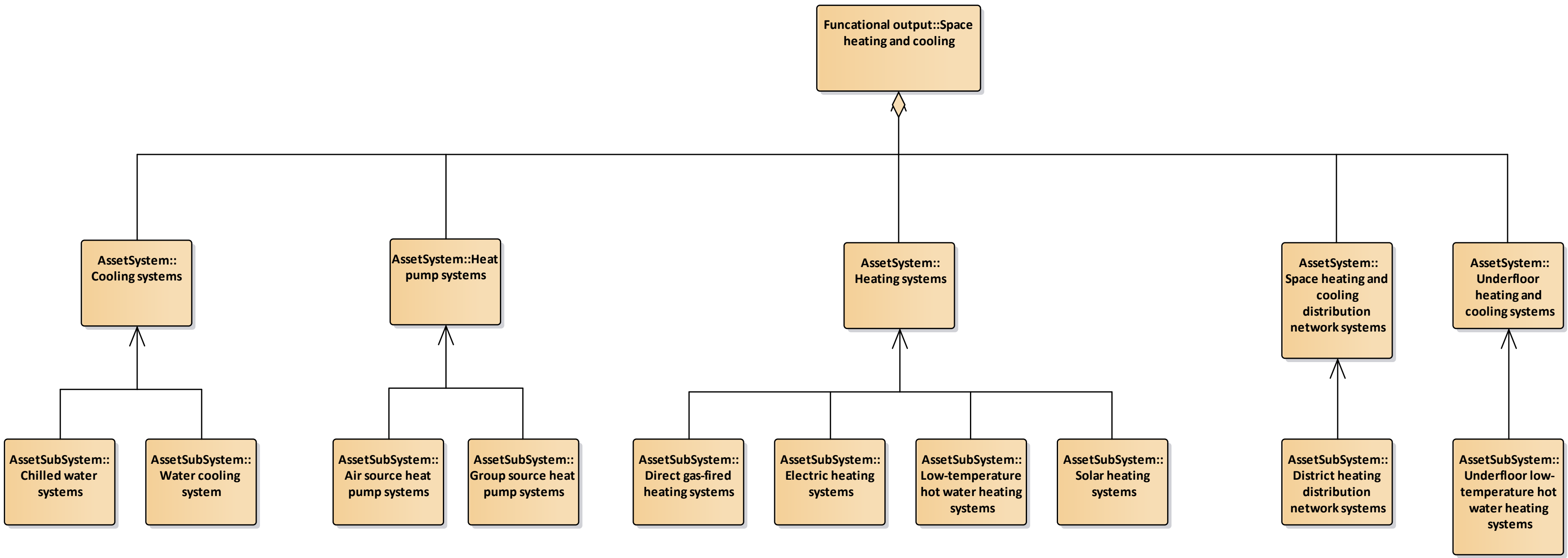

Table B-1 Space heating and cooling

Ventilation diagram

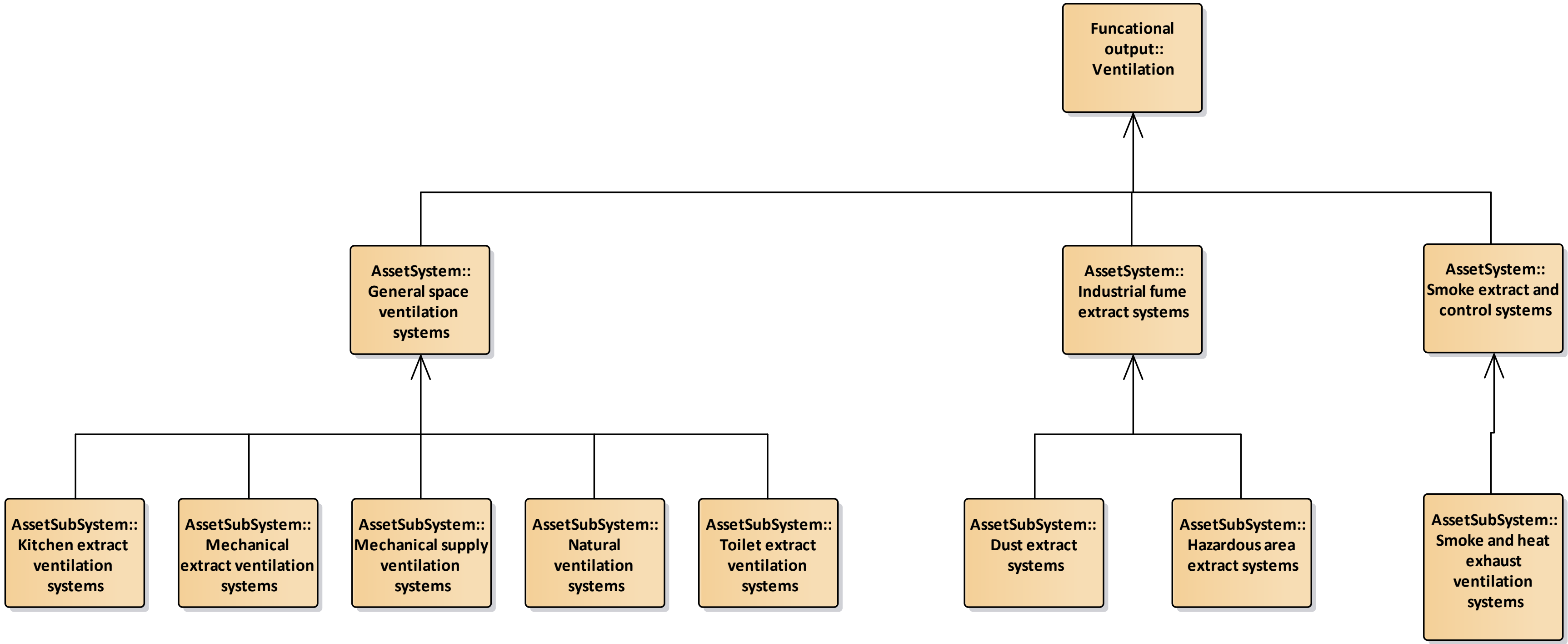

Table B-2 Ventilation

Water supply diagram

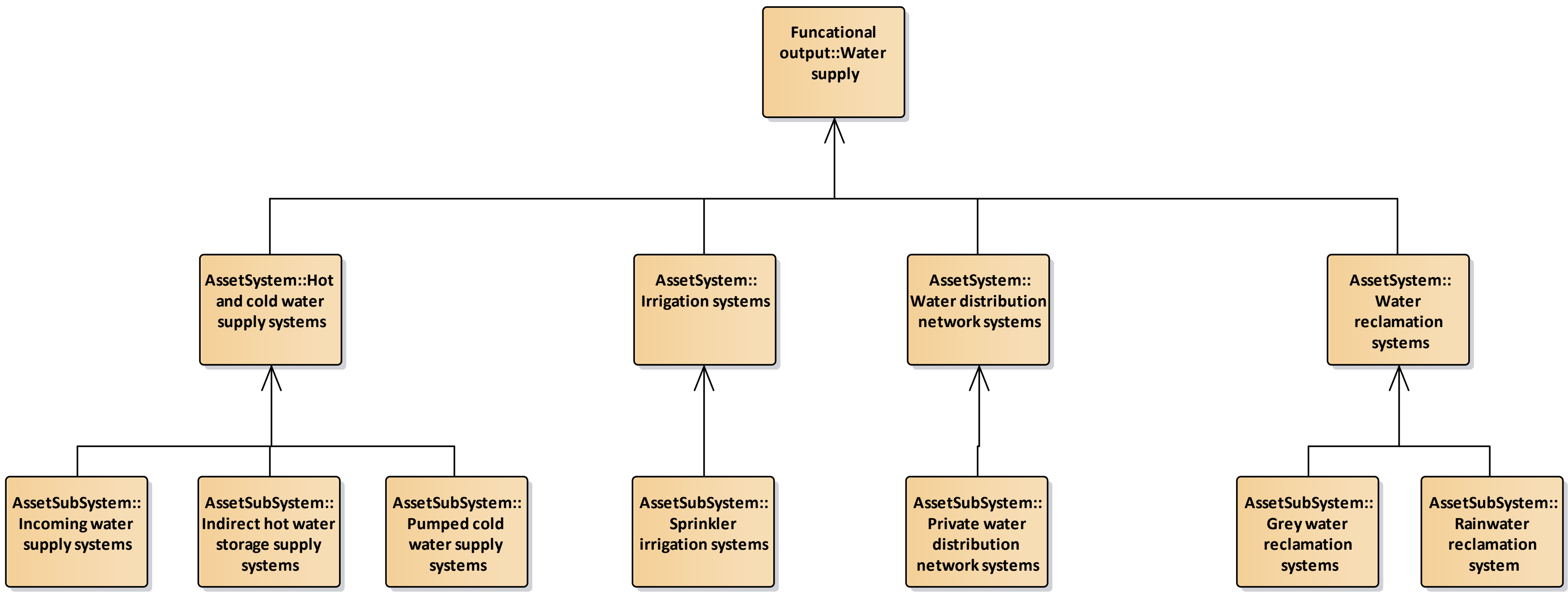

Table B-3 Water supply

Appendix C. Organisational Information Requirements (OIR)

The OIR where developed with step three of the information requirements methodology, see Section 5.4.

Appendix C-1 Financial OIR

Reduce total business impact of Estate Facilities' controllable costs by 5%							
OB_ID	**ID**	**Critical Success Factor**	**Category**	**Question**	**Question ID**	**Information_Requirement**	**Data_Type**
AM05	CSF1	prompt response to maintenance requirements	Managerial	What is the current response time to maintenance request?	MQ5	current_maintaince_responce_time	Integer
AM05	CSF1	prompt response to maintenance requirements	Managerial	what is the planned response time to maintenance request?	MQ6	planned_maintaince_responce_time	Integer

AM05	CSF1	prompt response to maintenance requirements	Managerial	what is the different between the planned response time and the current?	MQ7	current_vs_planned_response_time	Integer
AM05	CSF1	prompt response to maintenance requirements	Financial	What is the cost savings to a prompt response to maintenance requests?	FQ2	maintanince_cost_savings	Integer
AM05	CSF1	prompt response to maintenance requirements	Managerial	who is reasonable for planning maintenance?	MQ8	maintanince_owner	String
AM05	CSF2	reduction in operational cost	Financial	What is the current total operational cost?	FQ3	total_operational_cost	Integer
AM05	CSF2	reduction in operational cost	Financial	what is the planned operational costs?	FQ4	planned_operational_cost	Integer

AM05	CSF2	reduction in operational cost	Financial	what is the different between the planned operational cost and the current?	FQ5	current_vs_planned_operational_cost	Integer
AM05	CSF2	reduction in operational cost	Managerial	who is reasonable for the operational cost?	MQ9	operational_financial_owner	String
AM05	CSF3	reduction in maintenance costs	Financial	what is the total maintenance cost?	FQ6	current_maintaince_cost	Integer
AM05	CSF3	reduction in maintenance costs	Financial	what is the planned maintenance costs?	FQ7	planned_maintaince_cost	Integer
AM05	CSF3	reduction in maintenance costs	Financial	what is the different between the planned maintenance cost and the current?	FQ8	current_vs_planned_maintaince_cost	Integer
AM05	CSF3	reduction in maintenance costs	Managerial	who is reasonable for the maintenance cost?	MQ10	maintaince_financial_owner	String

AM05	CSF4	less reactive maintenance and more planned maintenance	Technical	what is the total reactive maintenance requests to date?	TQ2	total_reactive_maintaince	Integer
AM05	CSF4	less reactive maintenance and more planned maintenance	Technical	what is the total planned maintenance to date?	TQ3	total_planned_maintaince	Integer
AM05	CSF4	less reactive maintenance and more planned maintenance	Technical	what is the different between reactive and planned maintenance?	TQ4	reactive_vs_planned_mainta ince	Integer
AM05	CSF4	less reactive maintenance and more planned maintenance	Technical	what is the total completed planned maintenance to date?	TQ5	completed_planned_maintai nce	Integer

AM05	CSF4	less reactive maintenance and more planned maintenance	Technical	what is the acceptable level of reactive maintenance?	TQ6	reactive_maintaince_levels	Integer
AM05	CSF5	have the correct tools and materials	Technical	what is the current inventory level?	TQ7	inventry_level	Integer
AM05	CSF5	have the correct tools and materials	Managerial	does the inventory level meet the currently planned maintenance requirements?	MQ11	inventry_planned_maintainc e	Boolean
AM05	CSF5	have the correct tools and materials	Managerial	what is the current time lost due to low inventory levels?	MQ12	time_lost_inventry	Integer
AM05	CSF5	have the correct tools	Financial	what is the cost to date for maintain the inventory level?	FQ9	inventry_cost	Integer

		and materials					
AM05	CSF5	have the correct tools and materials	Managerial	who is reasonable for the inventory levels?	MQ13	inventry_owner	String
AM05	CSF6	whole-life cost management	Financial	what is the total cost of operating the business?	FQ10	total_business_cost	Integer
AM05	CSF6	whole-life cost management	Financial	what is the planned capital investment?	FQ11	total_capital_investment	Integer
AM05	CSF6	whole-life cost management	Financial	how does my O&M cost compare to my capital investment?	FQ12	O&M_vs_capital_investment	Integer
AM05	CSF6	whole-life cost management	Managerial	who is reasonable for whole-life management?	MQ14	wholelife_owner	Integer

Table C-1 financial related OIR

Appendix C.2 Environmental OIR

Reduce carbon emissions from energy usage by 34% by 2030 against a 2005 baseline							
OB_ID	**ID**	**Critical Success Factor**	**Category**	**Question**	**Question ID**	**Information_requirement**	**Data_Type**
AM19	CSF5	reduction in energy usage	Technical	how much energy is currented used within the estate?	TQ2	energy_useage_level	Integer
AM19	CSF5	reduction in energy usage	Technical	what is the required energy usage to support the energy reduction?	TQ3	required_energy_level	Integer
AM19	CSF5	reduction in energy usage	Technical	what are the most energy	TQ4	highest_energy_function	String

				consumption functional output?			
AM19	CSF5	reduction in energy usage	Technical	what is the least energy consumption function?	TQ20	lowest_energy_function	String
AM19	CSF5	reduction in energy usage	Technical	what is the measurement of energy consumption?	TQ21	measure_enegry_consumption	String
AM19	CSF5	reduction in energy usage	Technical	how is energy consumption measured?	TG22	measurement_enegry_useage	Boolean
AM19	CSF5	reduction in energy usage	Financial	what is the cost saving benefits of reducing my energy?	FQ4	cost_saving_enegry_useage	Integer
AM19	CSF5	reduction in energy usage	Managerial	how is the business owner for reducing energy usage?	MQ11	energy_useage_owner	String

AM19	CSF6	optimisation of assets operational performance	Technical	what is the min performance requirements?	TQ5	min_performance_req	Integer
AM19	CSF6	optimisation of assets operational performance	Technical	what is the max performance requirements?	TQ6	max_performance_req	Integer
AM19	CSF6	optimisation of assets operational performance	Technical	what is the optimise performance?	TQ7	op_performance	Integer
AM19	CSF6	efficient assets operational hours	Managerial	what activity is supported by the functions?	MQ8	activity	String
AM19	CSF6	efficient assets operational hours	Technical	what are the scheduled operational hours of the function?	TQ8	scheduled_op_hours	Integer

AM19	CSF6	efficient assets operational hours	Technical	what are the active operational hours of the function?	TQ9	active_op_hours	Integer
AM19	CSF6	efficient assets operational hours	Technical	are the functions operational requirements time based?	TQ10	operational_time_based	Boolean
AM19	CSF6	efficient assets operational hours	Technical	are the functions operations sensor based?	TQ11	operational_sensor_based	Boolean
AM19	CSF7	increase in renewable operational energy	Technical	how much energy is sourced from no non-renewables?	TQ12	non-renewable_energy	Integer
AM19	CSF7	increase in renewable operational energy	Technical	how much energy is sourced from renewables?	TQ13	renewable_energy	Integer
AM19	CSF7	increase in renewable	Technical	how much energy is produced locally or from the grid?	TQ14	energy_produced_local/grid	Integer

		operational energy					
AM19	CSF7	increase in renewable operational energy	Technical	what is the % difference between renewable and non-renewable?	TQ15	%_different_energy	Integer
AM19	CSF7	increase in renewable operational energy	Managerial	what is the target for % of renewable energy?	MQ9	total_%_renewable	Integer
AM19	CSF8	understanding assets portfolio environmental impact	Managerial	what is the highest populating function?	MQ10	highest_populting_function	String
AM19	CSF8	understanding assets portfolio environmental impact	Technical	what is the current C02 operational output?	TQ16	C02_operational_output	String
AM19	CSF8	understanding assets portfolio	Technical	what is the required C02 output for a 6% reduction?	TQ17	target_C02_operational_output	Integer

		environmental impact					
AM19	CSF8	understanding assets portfolio environmental impact	Financial	what is the financial cost of measuring and decreasing environmental impact by 6%?	FQ3	target_C02_financial_cost	Integer
AM19	CSF8	understanding assets portfolio environmental impact	Technical	what is the measure of water consumption to operate the function, if any?	TQ18	water_consumption	Integer
AM19	CSF8	understanding assets portfolio environmental impact	Technical	what is the amount of hazardous waste going to landfill?	TQ19	hazardous_water_landfill	Integer

Table C-2 Environmental related OIR

Appendix D.3 Operational OIR

Put in place asset risk management approach and methodology for individual risk ratings per asset by 2021							
OB_ID	**ID**	**Critical Success Factor**	**Category**	**Question**	**Question ID**	**Information_requirement**	**Data_Type**
AM12	CSF 1	define critical assets	Managerial	what activities does my functions support?	MQ1	function_activity_support	String
AM12	CSF 1	define critical assets	Managerial	how critical is the activity to Estate Management?	MQ2	activity_criticality	String
AM12	CSF 1	define critical assets	Technical	what asset systems / sub-systems support the function?	TQ1	supporting_systems	String
AM12	CSF 1	define critical assets	Managerial	what is the vulnerability of the identified risk on	MQ3	risk_on_function	String

				the asset function / system			
AM12	CSF 2	identify risks	Financial	what is the financial cost of asset failure?	FQ1	cost_asset_failure	Integer
AM12	CSF 2	identify risks	Managerial	what is the operational risk of asset failure?	MQ4	operational_asset_failure	String
AM12	CSF 2	identify risks	Managerial	what is the reputational risk of asset failure?	MQ5	reputational_asset_failure	String
AM12	CSF 2	identify risks	Managerial	what object-based risks have been identified?	MQ6	object_risks	String
AM12	CSF 2	identify risks	Managerial	what scenario-based risks have been identified?	MQ7	scenario_risks	String
AM12	CSF 2	identify risks	Managerial	what are the common risks associated to each	MQ8	common_risks	String

				asset function / system?			
AM12	CSF 3	analyse the risks	Managerial	what is the classification of the risks?	MQ9	risk_classification	String
AM12	CSF 3	analyse the risks	Technical	what is the severity of impact in the risk occurring?	TQ2	severity_of_risk	Integer
AM12	CSF 3	analyse the risks	Technical	what is the likelihood of the risk occurring?	TQ3	likelihood_of_risk	Integer
AM12	CSF 3	analyse the risks	Technical	what is the allowable amount of risk per asset function?	TQ4	allowable_risk	Integer
AM12	CSF 3	analyse the risks	Managerial	how will the risk be monitor and validated?	MQ10	risk_monitoring	String
AM12	CSF 4	identify ways to reduce the identified risks	Managerial	has a risk management plan been developed?	MQ11	risk_management_plan	Boolean

AM12	CSF 4	identify ways to reduce the identified risks	Managerial	can the identified risk be avoided?	MQ12	aviod_risk	String
AM12	CSF 4	identify ways to reduce the identified risks	Managerial	can asset performance be optimised to support the reduction of risk?	MQ13	optemised_risk_asset_performance	String
AM12	CSF 4	identify ways to reduce the identified risks	Managerial	can the risk be transfer (e.g. outsourced / insurance)?	MQ14	risk_transferd	String
AM12	CSF 4	identify ways to reduce the identified risks	Managerial	if the risk is small and gains are high, is it possible to accept the risk?	MQ15	accepted_risk	String

Table C-3 operational related OIR

Appendix D. Functional Information Requirements (FIR) Matrix

This chapter provides examples of the FIR information requirements matrix.

D.1 FIR related to financial OIR

Information requirements	**Ventilation**		**AM05**
Managerial information	function_owner function_maintainer function_operator	asset_classification Maintenance_history Asset_failure_history	detailed_location access_plan
Technical information	avg_flow_rate max_flow_rate Min_flow_rate	running_time power_supply service_life	Remaining_life running_time
Financial information	total_operational_cost total_maintenance_cost	planned_operational_cost planned_investment	planned_maintenance_cost total_cost Cost_per_timeframe
Asset Systems	**General space ventilation system**	**Industrial fume extract system**	**Smoke extract and control system**

Figure D-1 Ventilation FIR

D.2 FIR related to environmental OIR

Information requirements	Electricity distribution and transmission		AM19
Managerial information	function_owner, building_location, asset_system, function_maintainer, asset_system, building_hours_of_operation		
Technical information	outlets, power_source, size, sections, Total_C02, max_performance, %_of_renewable, renewable_target, unit, capability, min_performance, Total_energy_usage, target_C02		
Financial information	Total_operational_cost, cost_difference, cost_difference, cost_of_renew, Total_non-renewable_cost, Total_renewable_cost		
Asset Systems	Low-voltage systems	High-voltage systems	Small power system

Figure D-2 Electricity distribution and transmission FIR

D.3 FIR related to operational OIR

Information requirements	Water supply		AM12
Managerial information	function_owner, criticality, total_reputational_risk, building_location, asset_system, function_maintainer, active_hours_of_operation, legal_status, maintenance_history		
Technical information	total_operational_risk, total_allowed_risk, supply_volume, supply_type, total_technical_risk, supply_sections, total_risk_rating		
Financial information	total_maintenance_cost, total_cost_of_failures, cost_to_develop_risk_rating, downtime_cost_impact, total_operational_cost		
Asset Systems	Hot and cold water supply system	Irrigation system	Water reclamation

Figure D-3 Water supply FIR

Appendix E. Functional Information Requirements Table

This appendix provides a full table of all the FIR, in total 195 individual information requirements where developed.

Asset functional output	Information requirements	Category	Data type
EF_80_50	function_owner	Managerial	String
Lifts	asset_classification	Managerial	string
	Asset_failure_history	Managerial	String
For objective	function_maintainer	Managerial	String
AM05	site_location	Managerial	String
	Maintenance_history_planned	Managerial	String
	Maintenance_history_reactive	Managerial	String
	lift_type	Managerial	String
	warranties	Managerial	String
	criticality	Managerial	Integer
	Outsourced	Managerial	Boolean
	Contractor	Managerial	String
	power_source	Technical	String
	performance_rating	Technical	Integer
	running_time	Technical	Integer
	total_operational_cost	Financial	Integer
	total_maintenance_cost	Financial	Integer
	replacement_value	Financial	Integer
	planned_operational_cost	Financial	Integer
	planned_investment	Financial	Integer
	whole_life_costing	Financial	Integer
	planned_maintenance_cost	Financial	Integer
	live_running_cost	Financial	Integer
	Running_cost_per_month	Financial	Integer
EF_70_30	function_owner	Managerial	string
	funcation_maintainer	Managerial	String

Electricity distribution and transmission **For objective AM05**	asset_type	Managerial	String
	building_location	Managerial	String
	whole_life_costing	Managerial	Integer
	Inspection_schedule	Managerial	String
	maintenance_history	Managerial	String
	Outsourced	Managerial	Boolean
	Contractor	Managerial	String
	power_source	Technical	String
	running_time	Technical	Integer
	performance_rating	Technical	Integer
	total_operational_cost	Financial	Integer
	total_maintenance_cost	Financial	Integer
	replacement_value	Financial	Integer
	planned_operational_cost	Financial	Integer
	planned_investment	Financial	Integer
	whole_life_costing	Financial	Integer
	planned_maintenance_cost	Financial	Integer
	live_running_cost	Financial	Integer
	Running_cost_per_month	Financial	Integer
EF_55_30 Fire extinguishing supply **For objective AM05**	function_owner	Managerial	String
	function_maintainer	Managerial	String
	unit_amount	Managerial	Integer
	spares_list	Managerial	Integer
	Planned_maintenance	Managerial	String
	Warranties	Managerial	String
	reactive_maintenance	Managerial	String
	inspection_history	Managerial	String
	asset_classification	Managerial	String
	Maintenance_history	Managerial	String
	water_source	Technical	String
	instances	Technical	Integer
	total_M2_cover	Technical	Integer
	asset_system_type	Technical	String
	legal_status	Technical	Boolean

	certification	Technical	String
	powder_source	Technical	String
	total_operational_cost	Financial	Integer
	total_maintenance_cost	Financial	Integer
	planned_operational_cost	Financial	Integer
	planned_maintenance_cost	Financial	Integer
	total_maintenance_cost	Financial	Integer
	planned_investment	Financial	Integer
	inital_cost	Financial	Integer
EF_65_40 Ventilation **For objective AM05**	function_owner	Managerial	string
	function_maintainer	Managerial	String
	function_operator	Managerial	String
	Maintenance_history	Managerial	String
	Asset_failure_history	Managerial	String
	access_plan	Managerial	String
	site_location	Managerial	String
	reactive_maintenance	Managerial	String
	proactive_maintenance	Managerial	String
	operating_hours	Managerial	integer
	avg_flow_rate	Technical	Integer
	Min_flow_rate	Technical	Integer
	max_flow_rate	Technical	Integer
	power_supply	Technical	boolean
	running_time	Technical	Integer
	service_life	Technical	Integer
	running_time	Technical	Integer
	Remaining_life	Technical	Integer
	total_operational_cost	Financial	integer
	total_maintenance_cost	Financial	Integer
	planned_operational_cost total_cost	Financial Financial	Integer
	planned_maintenance_cost	Financial	Integer
	whole_life_cost	Financial	Integer
	Cost_per_operating_hour	Financial	Integer

EF_70_80 **Lighting** **For objective AM19**	function_owner	Managerial	string
	function_maintainer	Managerial	String
	light_type	Managerial	String
	asset_system	Managerial	String
	building_location	Managerial	String
	supporting_activity	Managerial	String
	hours_of_operation	Managerial	Integer
	power_source	Technical	string
	Total_energy_consumpution	Technical	Integer
	Total_C02	Technical	Integer
	target_C02	Technical	Integer
	voltage	Technical	Integer
	%_of_renewable	Technical	Integer
	service_life	Technical	Integer
	remaining_life	Technical	Integer
	%_energy_saving	Technical	Integer
	Total_operational_cost	Financial	Integer
	Total_non-renewable_cost	Financial	Integer
	Total_renewable_cost	Financial	Integer
	cost_difference	Financial	Integer
	cost_of_LED_lighting	Financial	integer
EF_60_40 **Space heating and cooling**	function_owner	Managerial	string
	schedule_hours_of_operation	Managerial	String
	function_maintainer	Managerial	String
	asset_system	Managerial	String
	building_location	Managerial	String
	active_hours_of_operation	Managerial	integer
	%_of_renewable	Technical	Integer
	Total_C02	Technical	Integer
	power_source	Technical	string
	Total_energy_consumpution	Technical	Integer
	temperature_unit	Technical	string
	max_temperature	Technical	Integer
	min_temperature	Technical	Integer

	required_temperature	Technical	Integer
	cost_difference	Financial	Integer
	cost_of_renew	Financial	Integer
	Total_operational_cost	Financial	Integer
	cost_difference	Financial	Integer
	Total_renewable_cost	Financial	Integer
	Total_renewable_cost	Financial	Integer
EF_55_70	function_owner	Managerial	string
Water supply	function_maintainer	Managerial	String
	criticality	Managerial	String
For objective	active_hours_of_operation	Managerial	String
AM12	total_reputational_risk	Managerial	integer
	asset_system	Managerial	String
	maintenance_history	Managerial	String
	building_location	Managerial	String
	legal_status	Managerial	Boolean
	total_operational_risk	Technical	integer
	total_risk_rating	Technical	integer
	total_allowed_risk	Technical	integer
	total_technical_risk	Technical	integer
	supply_volume	Technical	integer
	supply_sections	Technical	integer
	supply_type	Technical	String
	water_testing_results	Technical	String
	total_cost_of_failures	Financial	integer
	downtime_cost_impact	Financial	integer
	cost_to_develop_risk_rating	Financial	integer
	total_maintenance_cost	Financial	integer
	total_operational_cost	Financial	integer
EF_20_10	function_owner	Managerial	string
Superstructure	function_maintainer	Managerial	String
	Criticality	Managerial	String
For objective	reputational_risk	Managerial	String
AM12	building_location	Managerial	String

	maintenance_history	Managerial	String
	asset_system	Managerial	String
	total_inspections	Managerial	integer
	total_structural_risk_rating	Technical	Integer
	total_risk_rating	Technical	Integer
	total_allowed_risk	Technical	Integer
	condition_rating	Technical	Integer
	sensor_reading	Technical	String
	total_scenario_risk_rating	Technical	Integer
	total_cost_of_repairs	Financial	Integer
	cost_to_develop_risk_rating	Financial	Integer
	total_maintenance_cost	Financial	Integer
	total_inspection_cost	Financial	integer
EF_50_30 Drainage collection For objective AM12	function_owner	Managerial	String
	reputational_risk	Managerial	String
	function_maintainer	Managerial	String
	maintenance_history	Managerial	String
	building_location	Managerial	String
	supporting_activity	Managerial	String
	asset_system	Managerial	String
	risk_owner	Managerial	String
	legal_status	Managerial	Boolean
	flow_monitoring	Technical	integer
	total_risk_rating	Technical	integer
	total_allowed_risk	Technical	integer
	remaining_life	Technical	integer
	service_life	Technical	integer
	scenario_risks	Technical	string
	condition_rating	Technical	integer
	cost_to_develop_risk_rating	Financial	integer
	total_cost_of_failures	Financial	integer
	total_cost_of_repairs	Financial	integer
	total_inspection_cost	Financial	integer

Table E-1 Functional Information Requirements table

Appendix F. Asset Information Requirements matrix

AIR where developed with step four of the information requirements methodology, see Section 6.2

The AIR related the FIR within Appendix C are included below.

F.1 AIR related to financial FIR

Information requirements	General space ventilation system		AM05
Managerial information	asset_system_owner, asset_system_maintainer	total_M2_ covered, asset_type	Maintenance_history, Asset_failure_history
Technical information	total_outputs, total_sections	total_power_ consumption, instances	total_length, total_capability
Financial information	operational _cost_week, maintenance_cost	initial_cost	total_running_cost _year
Asset Systems	Mechanical extract ventilation system	Mechanical supply ventilation system	Natural ventilation system

Figure F-1 Space ventilation system AIR, asset system of Ventilation

Information requirements	Mechanical supply ventilation system		AM05
Managerial information	detailed_location assetSub_spare_list assetSub_system_owner hours_of_operation assetSub_system_maintainer make model asset_type		
Technical information	flow_rate_per_M2 service_life Remaining_life power_consumption maintenance_guide access_plan SFG20 BMS_sensor		
Financial information	cost_per_M2 asset_maintenance_cost running_cost_year asset_operational_cost running_cost_week initial_cost		
Asset Systems			

Figure F-2 Supply ventilation system AIR, asset sub system of space ventilation

F.2 AIR related to environmental FIR

Information requirements	High-Voltage systems		AM19
Managerial information	schedule_hours_of_operation detailed_location asset_system_maintainer sched_planned_maintenance asset_system_type asset_system_owner total_reactive_maintenance		
Technical information	measuring_unit highest_energy_consumption_function most_active_time energy_useage most_active_day BMS_sensor		
Financial information	asset_system_non_renewable_cost cost_of_C02_per_asset_system asset_system_renewable_cost		
Asset Systems	High-Voltage Distribution system	High-Voltage site connection system	

Figure F-3 High-Voltage system AIR, asset system of Electricity distribution and transmission

Information requirements	High-Voltage Distribution system		AM19
Managerial information	active_hours_of_operation asset_sub_system_maintainer asset_sub_system_owner	supporting_activity	maintenance_schedule
Technical information	outputs branches sections BMS_rating max_voltage min_voltage C02_reduction_level	CO2_per_output capability	running_total_C02
Financial information	non_renewable_power_cost renewable_power_cost CO2_cost_Saving	cost_per_CO2_output	cost_of_CO2_saving
Asset Systems			

Figure F-4 High-Voltage Distribution system AIR, asset sub system of High-Voltage

F.3 AIR related to operational FIR

Information requirements	Hot and cold water supply system		AM12
Managerial information	detailed_location asset_system_owner asset_system_maintainer maintenance_outsourced	instances_of_asset_sub_system total_reactive_maintenance	contractor water_test_report
Technical information	total_water_volume water_pressure potable water_pressure	asset_system_risk_rating asset_system_technical_risk	asset_system_operational_risk
Financial information	asset_system_operational_cost total_risk_occurring_cost	total_asset_failure_cost	total_water_test_cost
Asset Systems	Incoming water supply system	Indirect hot water storage supply system	

Figure F-5 Hot and cold water supply system AIR, asset system of water supply

Information requirements	Incoming water supply system		AM12
Managerial information	detailed_instances_location, asset_sub_system_owner, asset_sub_system_maintainer, supporting_activity, reactive_maintenance, reputational_risks, risk_management_plan		
Technical information	branches, risk_rating, risk_criticality, operational_risks, risk_severity, risk_classification, BMS_sensor, SFG20, scheme_drawings, risk_likelihood, technical_risks		
Financial information	asset_failure_cost, asset_failure_running_cost, operational_cost, cost_of_risk_occurring, running_total_of_risk_cost		
Asset Systems			

Figure F-6 Incoming water supply system AIR, asset sub system of hot and cold-water supply

Appendix G. Asset Information Requirements table

This appendix provides a full table of all the AIR, in total 347 individual information requirements where developed.

G.1 asset system, asset information requirements

Asset System	Information Requirement	Category	Data type
Ss_80_50_60 Electric lift systems **For objective AM05**	Usage	Managerial	string
	model	Managerial	String
	ID	Managerial	String
	make	Managerial	String
	Maintenance_responce_time	Managerial	integer
	detailed_location	Managerial	String
	spares_list	Managerial	Integer
	total_maintenance_schedule	Managerial	Integer
	total_maintenance_reactive	Managerial	Integer
	maintenance_schedule	Managerial	String
	maintenance_responce_time	Managerial	Integer
	capability	Technical	Integer
	hours_of_operaton	Technical	Integer
	power_consumption	Technical	Integer
	power_unit	Technical	String
	access_plan	Technical	String
	SFG20_code	Technical	String
	maintenance_records	Technical	String
	service_life	Technical	Integer
	remaining_life	Technical	Integer
	operational_cost	Financial	Integer
	maintenance_cost	Financial	Integer
	running_cost_year	Financial	Integer
	initial_cost	Financial	Integer

	running_cost_week	Financial	Integer
Ss_70_30_35 High-voltage systems	asset_system_owner	Managerial	string
	asset_system_maintainer	Managerial	String
	building_location	Managerial	String
	Instances_of_systems	Managerial	integer
For objective AM05	asset_system_planned_maintenance	Managerial	String
	asset_system_reactive_maintenance	Managerial	String
	supporting_system	Managerial	String
	criticality	Managerial	Integer
	total_ouputs	Technical	Integer
	max_voltage	Technical	Integer
	min_voltage	Technical	Integer
	total_sections	Technical	Integer
	total_capability	Technical	Integer
	total_length	Technical	Integer
	operational_cost_week	Financial	Integer
	maintenance_cost	Financial	Integer
	initial_cost	Financial	Integer
	total_running_cost_year	Financial	Integer
	operational_cost	Financial	Integer
	Whole-life-costing	Financial	Integer
Ss_55_30_96 Water firefighting systems	asset_system_owner	Managerial	String
	asset_system_maintainer	Managerial	String
	maintenance_schedule	Managerial	String
	Planned_maintenance	Managerial	String
	total_spares_list	Managerial	Integer
For objective AM05	location_zones	Managerial	String
	maintenance_responce_time	Managerial	Integer
	asset_type	Managerial	String
	Maintenance_history	Managerial	String
	maintenance_records	Technical	String
	capability	Technical	Integer
	outputs	Technical	Integer
	sections	Technical	Integer

	length	Technical	Integer
	branches	Technical	Integer
	maintenance_cost	Financial	Integer
	operational_cost	Financial	Integer
	running_cost	Financial	Integer
	initial_cost	Financial	Integer
	whole_life_costing	Financial	Integer
Ss_65_40_33 General space ventilation systems For objective AM19	asset_system_owner	Managerial	String
	asset_system_maintainer	Managerial	String
	total_M2_covered	Managerial	Integer
	asset_type	Managerial	String
	Maintenance_history	Managerial	String
	location_zone_level	Managerial	String
	Asset_failure_history	Managerial	String
	total_outputs	Technical	Integer
	total_sections	Technical	Integer
	total_power_consumption	Technical	Integer
	instances	Technical	Integer
	total_length	Technical	Integer
	total_capability	Technical	Integer
	operational_cost_week	Financial	Integer
	maintenance_cost	Financial	Integer
	cost_per_section	Financial	Integer
	initial_cost	Financial	Integer
	total_running_cost_year	Financial	Integer
Ss_70_80_33 General space lighting For objective AM19	schedule_hours_of_operation	Managerial	Integer
	sub_system_type	Managerial	String
	location_level_zone	Managerial	String
	active_hours_of_operation	Managerial	Integer
	asset_system_maintainer	Managerial	String
	asset_system_owner	Managerial	String
	total_lighting_per_M2	Managerial	String
	scheduled_planned_maintenance	Managerial	String
	total_reactive_maintenance	Managerial	Integer

	total_power_consumption	Managerial	Integer
	total_asset_systems	Managerial	Integer
	target_asset_system_C02	Technical	Integer
	asset_system_C02	Technical	Integer
	total_asset_systems_instances	Technical	Integer
	total_power_consumption	Technical	Integer
	asset_system_non_renewable_cost	Financial	Integer
	asset_system_renewable_cost	Financial	Integer
	cost_of_C02_per_asset_system	Financial	Integer
	difference_of_costs	Financial	Integer
Ss_60_40_37	Location_zone_level	managerial	String
	asset_system_owner	Managerial	String
Heating systems	Asset_type	Managerial	String
	total_planned_maintenance	Managerial	Integer
	total_reactive_maintenance	Managerial	Integer
For objective AM19	scheduled_planned_maintenance	Managerial	String
	totating_heating_M2	Managerial	String
	performance_rating	Technical	Integer
	max_temperature	Technical	Integer
	min_temperature	Technical	Integer
	total_energy_consumption	Technical	Integer
	target_C02	Technical	Integer
	asset_system_C02	Technical	Integer
	active_operational_cost	Financial	Integer
	active_maintenance_cost	Financial	Integer
	unit_cost	Financial	Integer
	planned_investment	Financial	Integer
	planned_maintenance_cost	Financial	Integer
	planned_operational_cost	Financial	Integer
Ss_55_70_38	location_zone_level	managerial	String
Hot and cold	asset_system_owner	managerial	String
water supply	asset_system_maintainer	managerial	String
	maintenance_outsourced	managerial	Boolean
	instances_of_asset_sub_system	managerial	Integer

For objective AM19	total_reactive_ maintenance	managerial	Integer
	contractor	managerial	String
	water_test_report	managerial	String
	total_water_volume	technical	Integer
	water_pressure	Technical	Integer
	potable	Technical	Boolean
	water_volume	Technical	Integer
	asset_system_risk_rating	Technical	Integer
	asset_system_technical_risk	Technical	Integer
	asset_system_operational_risk	Technical	Integer
	asset_system_operational_cost	financial	Integer
	total_risk_occurring_cost	Financial	Integer
	total_asset_failure_cost	Financial	Integer
	total_water_test_cost	Financial	Integer
Ss_20_20_75 Structural beam systems For objective AM12	asset_system_maintainer	managerial	String
	asset_system_owner	managerial	String
	location_zone	managerial	String
	asset_sub_system_types	managerial	String
	total_reactive_ maintenance	managerial	Integer
	instances_of_asset_sub_systems	managerial	Integer
	total_beams	technical	Integer
	asset_system_structural_risk_rating	technical	Integer
	asset_system_scenario_risk_rating	technical	Integer
	precast_poured	technical	Boolean
	total_structurial_load	technical	Integer
	asset_system_repair_cost	financial	Integer
	asset_system_insepction_cost	financial	Integer
	asset_system_maintenance_cost	financial	Integer
Ss_50_35_08 Below-ground gravity drainage systems	asset_system_maintainer	Managerial	String
	asset_system_owner	Managerial	String
	asset_sub_system_type	Managerial	String
	location_area_zone	Managerial	String
	maintenance_outsourced	Managerial	Boolean
	contractor	Managerial	string

For objective AM12	total_reactive_maintenance	Managerial	Integer
	instances_of_asset_systems	Managerial	Integer
	overflow_risk_rating	technical	Integer
	contamination_risk_rating	technical	Integer
	blackage_risk_rating	technical	Integer
	asset_system_repair_cost	financial	Integer
	asset_system_insepction_cost	financial	Integer
	asset_system_ maintenance_cost	financial	Integer

Table G-1 Asset system - Asset Information Requirements Table

G.2 asset sub system, asset information requirements

Asset Sub-System	Information Requirements	Category	Data type
Ss_55_30_96_29 Fire hose reel system **For objective AM05**	asset_sub_system_owner	managerial	string
	asset_sub_system_maintainer	Managerial	String
	maintenance_schedule	Managerial	String
	Asset_failure_histroy	Managerial	String
	asset_system_spares_list	Managerial	String
	next_inspection_date	Managerial	Date
	Planned_maintenance	Managerial	Date
	detailed_location	Managerial	String
	last_maintained	Managerial	Date
	maintenance_responce_time	Managerial	Integer
	Maintenance_history	Managerial	String
	access_plan	technical	String
	SFG20_code	Technical	String
	compliance	Technical	boolean
	instances	Technical	Integer
	useage_amount	Technical	Integer
	tools_list	Technical	Integer
	Spares_list	Technical	String
	remaining_life	Technical	Integer
	service_life	Technical	Integer

	maintenance_cost	Financial	Integer
	insepction_cost	Financial	Integer
	initial_cost	Financial	Integer
	legal_costs	Financial	Integer
Ss_65_40_33_51 Mechanical supply ventilation systems For objective AM05	asset_sub_system_owner	Managerial	String
	asset_sub_system_maintainer	Managerial	String
	model	Managerial	String
	Make	Managerial	String
	ID	Managerial	String
	detailed_location	Managerial	String
	location_room	Managerial	String
	asset_type	Managerial	String
	asset_sub_spare_list	Managerial	string
	active_hours_of_operation	Managerial	Integer
	flow_rate_per_M2	Technical	Integer
	access_plan	Technical	String
	service_life	Technical	Integer
	Remaining_life	Technical	Integer
	maintenance_guide	Technical	String
	SFG20_guide	Technical	string
	BMS_sensor	Technical	boolean
	power_consumption	Technical	Integer
	cost_per_M2	Financial	Integer
	asset_operational_cost	Financial	Integer
	asset_maintenance_cost	Financial	Integer
	initial_cost	Financial	Integer
	running_cost_year	Financial	Integer
	running_cost_week	Financial	Integer
Ss_70_30_35_35 High-voltage distribution systems	active_hours_of_operation	Managerial	Integer
	asset_sub_system_maintainer	Managerial	String
	asset_sub_system_owner	Managerial	String
	supporting_activity	Managerial	String
	maintenance_schedule	Managerial	string
	outputs	Technical	Integer

For objective AM05	branches	Technical	Integer
	sections	Technical	Integer
	BMS_rating	Technical	Integer
	max_voltage	Technical	Integer
	min_voltage	Technical	Integer
	capability	Technical	Integer
	C02_reduction_level	Technical	Integer
	CO2_per_output	Technical	Integer
	running_total_C02	Technical	Integer
	non_renewable_power_cost	Financial	Integer
	renewable_power_cost	Financial	Integer
	CO2_cost_Saving	Financial	Integer
	cost_per_CO2_output	Financial	Integer
	cost_of_CO2_saving	Financial	Integer
Ss_70_80_33_33 Lighting systems with prefabricated wiring **For objective AM19**	asset_sub_system_maintainer	Managerial	String
	supporting_activity	Managerial	String
	detailed_location	Managerial	String
	asset_sub_system_owner	Managerial	String
	maintenance_schedule	Managerial	String
	schedule_hours_of_operation	Managerial	Integer
	min_watts	Technical	Integer
	max_watts	Technical	Integer
	outputs	Technical	Integer
	sectons	Technical	Integer
	voltage	Technical	Integer
	BMS_sensor	Technical	Boolean
	power_consumption	Technical	Integer
	C02_per_output	Technical	Integer
	C02_reduction_level	Technical	Integer
	running_total_C02	Technical	Integer
	%_of_non_renewable	Technical	Integer
	%_of_renewable	Technical	Integer
	CO2_cost_Saving	Financial	Integer
	cost_per_CO2_output	Financial	Integer

	cost_of_C02_per_asset_sub_system	Financial	Integer
	cost_of_CO2_saving	Financial	Integer
Ss_60_40_37_26 Electric heating systems	asset_sub_system_maintainer	Managerial	String
	asset_sub_system_owner	Managerial	String
	active_hours_of_operation	Managerial	Integer
	detailed_location	Managerial	String
For objective AM19	supporting_activity	Managerial	String
	criticality	Managerial	Integer
	maintenance_histroy	Managerial	String
	planned_maintenance	Managerial	String
	location_room	Managerial	String
	next_maintenance_schedule	Managerial	Date
	reactive_maintenance	Managerial	String
	voltage	Technical	Integer
	outputs	Technical	Integer
	sections	Technical	Integer
	C02_per_outlet	Technical	Integer
	sensor_rating	Technical	Boolean
	C02_reduction_level	Technical	Integer
	service_life	Technical	Integer
	running_time	Technical	Integer
	running_total_C02	Technical	Integer
	Remaining_life	Technical	Integer
	%_of_renewable	Technical	Integer
	%_of_none_renewable	Technical	Integer
	CO2_cost_Saving	Financial	Integer
	cost_per_CO2_output	Financial	Integer
	cost_of_CO2_saving	Financial	Integer
Ss_55_70_38_40 Incoming water supply systems	asset_sub_system_owner	Managerial	String
	asset_sub_system_maintainer	Managerial	String
	detailed_instances_location	Managerial	String
	supporting_activity	Managerial	String
For objective AM12	reactive_ maintenance	Managerial	String
	reputational_risks	Managerial	Integer

	risk_management_plan	Managerial	String
	branches	Technical	Integer
	SFG20_guide	Technical	string
	risk_classification	Technical	String
	risk_rating	Technical	Integer
	scheme_drawings	Technical	String
	risk_criticality	Technical	Integer
	BMS_sensor	Technical	Boolean
	operational_risks	Technical	Integer
	risk_likelihood	Technical	Integer
	risk_severity	Technical	Integer
	technical_risks	Technical	Integer
	asset_failure_cost	financial	Integer
	asset_failure_running_cost	Financial	Integer
	operational_cost	Financial	Integer
	cost_of_risk_occurring	Financial	Integer
	running_total_of_risk_cost	Financial	Integer
Ss_20_20_75_15 Concrete beam systems **For objective AM12**	asset_sub_system_maintainer	Managerial	String
	asset_sub_system_owner	Managerial	String
	inspection_plan	Managerial	String
	inspection_reports	Managerial	String
	appearance_rating	Managerial	Integer
	maintenance_reports	Managerial	String
	detailed_instances_location	Managerial	String
	condition_report	Technical	String
	condition_sensor	Technical	Boolean
	system_beams	Technical	Integer
	service_life	Technical	Integer
	SFG20_guide	Technical	String
	remaining_life	Technical	Integer
	pre_cast	Technical	Boolean
	max_load	Technical	Integer
	scenario_risk	Technical	Integer
	structural_risk	Technical	Integer

	structural_drawings	Technical	String
	risk_rating	Technical	Integer
	repair_costs	financial	Integer
	asset_repair_running_cost	Financial	Integer
	cost_of_risk_occurring	Financial	Integer
	running_total_of_risk_cost	Financial	Integer
	cost_of_inspections	Financial	Integer
Ss_50_35_08_30 Foul wastewater below-ground drainage pipeline systems **For objective AM12**	asset_sub_system_maintainer	Managerial	String
	asset_sub_system_owner	Managerial	String
	last_inspected	Managerial	Date
	schedule_inspection	Managerial	date
	schedule_maintenance	Managerial	date
	reactive_maintenance_histroy	Managerial	String
	risk_management_plan	Managerial	String
	SFG20_guide	Technical	String
	technical_risks	Technical	Integer
	total_bends	Technical	Integer
	flow_sensor_reading	Technical	Integer
	scheme_drawings	Technical	String
	risk_classification	Technical	String
	blackage_risk	Technical	Integer
	risk_likelihood	Technical	Integer
	operational_risks	Technical	Integer
	pipe_type	Technical	String
	outlets	Technical	Integer
	risk_impact	Technical	Integer
	branches	Technical	Integer
	asset_failure_cost	Financial	Integer
	inspection_cost	Financial	Integer
	asset_failure_running_cost	Financial	Integer
	cost_of_risk_occurring	Financial	Integer
	running_total_of_risk_cost	Financial	Integer

Table G-2 Asset Sub-System - Asset Information Requirements

Appendix H. Database Schema UML Diagrams

Below are the UML diagrams that where derived from the asset classification UML diagrams to aid in the building of the Asset Information Model (AIM) database, see Section 7.3.

For a point of clarity, the individual attributes within the database tables have been removed, leaving the Primary Keys (KY) and Foreign Keys (FK) relationships visible between the tables.

Due to the limitations of Figures within the thesis, an example of 3 figures are provided below, along with 2 examples within the thesis itself, see Figure 7-7 and Figure J-1. A full list of the UML diagrams can be provided at the request to the author.

Air condition diagram

Table H-1 Air condition

Floors diagram

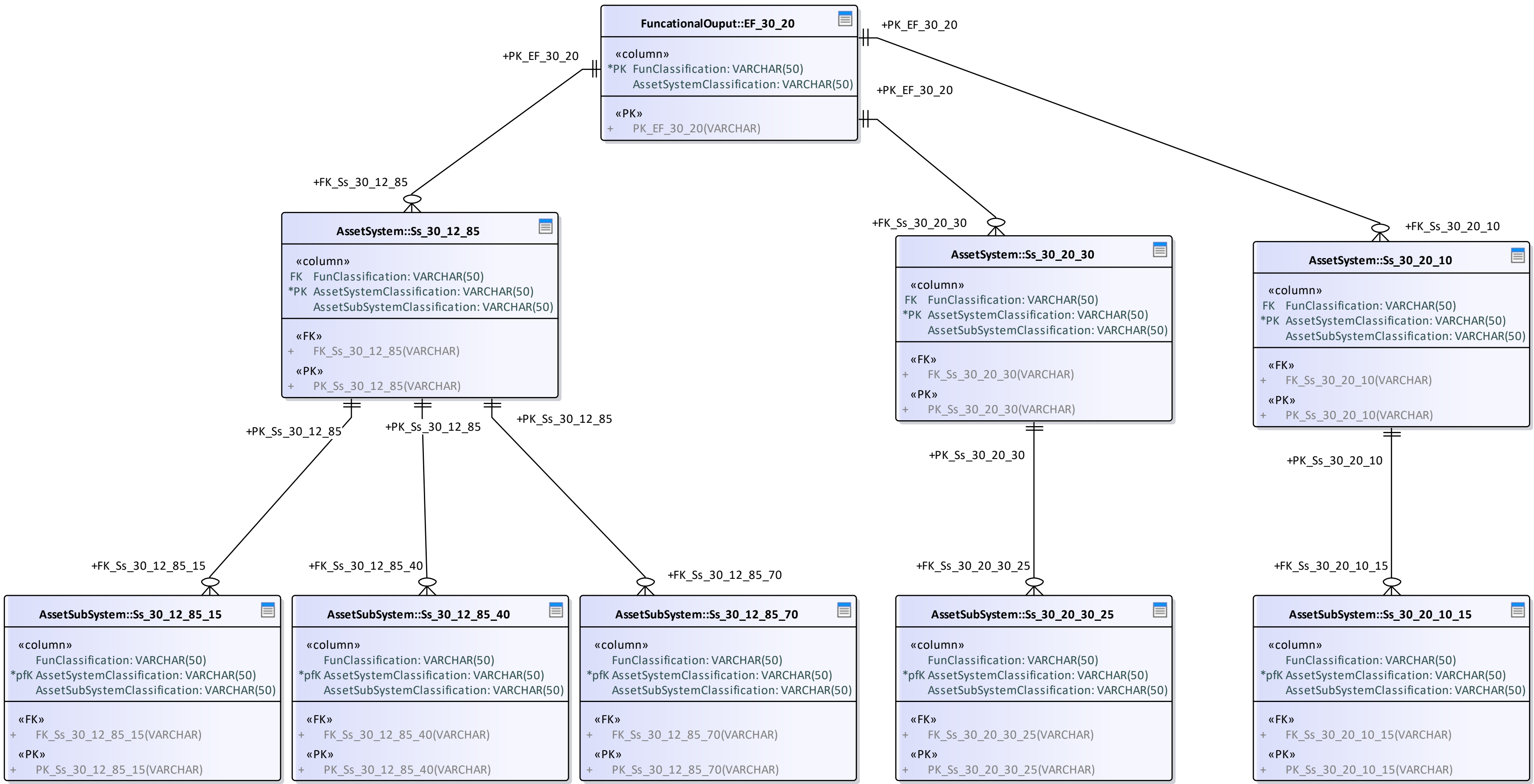

Table H-2 Floors

Lighting diagram

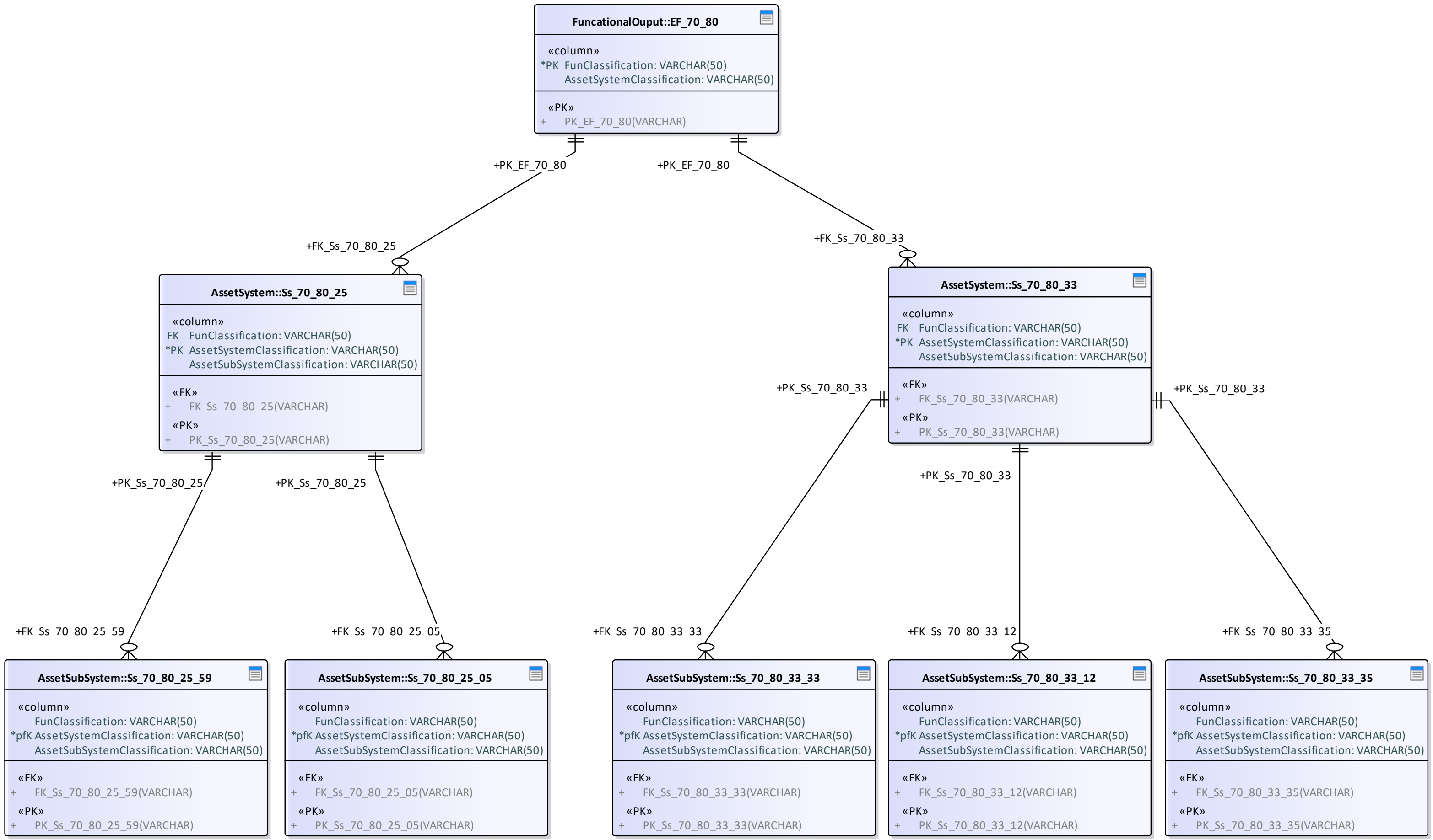

Table H-3 Lighting

Appendix I. Third-party case study results

This chapter provides the results from a case study that was conducted by a third-party industry partner within a NetworkRail project, using the information requirements methodology discussed within this thesis.

ID	Organisational Objective	Target Completion Year	Corporate Initiative Category
O.1	increase net tonnes of material moved by freight	2024	Growing
O.2	improve asset reliability	2024	Reliable
O.3	reduce number of service affecting failures by 6.6%	2024	Reliable
O.4	improving business to business connectivity	2024	Growing
O.5	improving access to workers for businesses	2024	Growing
O.6	improve access to educational establishments and major leisure venues	2024	Growing
O.7	train per km growth by Control Period (%)	2024	Growing
O.8	increase freight traffic in Scotland by 7.5%	2024	Growing
O.9	use whole life cost techniques to seek benefit/cost optimisation	2024	Efficient
O.10	prioritise capital investments programmes based upon an assets contribution to service	2024	Efficient
O.11	reduce risk of train accident by 10%	2024	Safe
O.12	reduce risk to the public at level crossings by 13%	2024	Safe
O.13	improve lost time injury frequency rate (LTIFR) by 54%	2024	Safe

O.14	increase mental health resilience by 25%	2024	Safe
O.15	increase biodiversity on and around railway	2024	Growing
O.16	no more freight delay caused to passenger than 1.8 minutes per 100km	2024	Reliable
O.17	reduce energy consumption by 18%	2024	Growing
O.18	reduce number of delayed trains by 28%	2024	Reliable
O.19	improve information communication to passengers during disruption	2024	Reliable
O.20	save £3.5bn through developing and applying efficiencies	2024	Efficient
O.21	increase female workforce by 100%	2024	Growing
O.22	Financial Performance Measure Gross Renewals per Annum	2020	Reliable
O.23	achieve freight delivery metric at 94%	2024	Reliable
O.24	Financial Performance Measure Gross Enhancements per Annum	2020	Reliable
O.25	Financial Performance Measure Gross Profit and Loss per Annum	2020	Efficient
O.26	minimise compensation to train operators per annum	2020	Efficient
O.27	close out 85% of workforce close calls within 90 days	2024	Efficient
O.28	composite reliability index at 19%	2024	Reliable
O.29	raise 205,000 close calls	2024	Safe

O.30	achieve 90% of investment project milestones	2024	Reliable
O.31	undertake specified renewal volume on seven key volumes per annum	2020	Reliable
O.32	deliver land for 12,000 homes by 2020	2024	Growing
O.33	reduce carbon emissions by 25%	2024	Growing
O.34	deliver 90% of schemes within scheduled control period	2024	Efficient
O.35	reduce frequency of Temporary Speed Restrictions (TSRs) per annum	2020	Reliable
O.36	improve overall asset management capability to 72%	2024	Efficient
O.37	reduce volume of Railway Work complaints	2024	Efficient
O.38	divert 95% of waste from landfill	2024	Growing
O.39	improve reduction in, and management of, environmental incidents	2024	Efficient
O.40	reduce frequency of Signals Passed at Danger per annum	2020	Safe
O.41	for workforce ethnicity diversity to be refletive of UK population	2024	Growing
O.42	improve customer satisfaction	2024	Efficient
O.43	complaints per 100,000 customer journeys at 28	2024	Efficient
O.44	80% of Your Voice Actions completed	2024	Efficient
O.45	achieve required level of composite sustainability index	2024	Growing

O.46	train accident risk reduction	2024	Safe
O.47	reduce frequency of derailments per annum	2020	Safe
O.48	improve occupation related mental health absence by 25%	2024	Safe
O.49	deliver CP6 within agreed funding	2024	Efficient
O.50	attract third party investment	2024	Growing
O.51	prevent discharge of effluent on track	2024	Efficient
O.52	support wider economic growth facilitate by railway improvements	2024	Growing
O.53	no more than 10 injuries to freight staff over a 1-year period	2024	Safe
O.54	optimise the use of operational land for new homes, generate capital and improve facilities	2024	Efficient
O.55	introduction of robotics into processes	2024	Efficient
O.56	increase value customers place on NR services	2024	Growing
O.57	to build trust and confidence in NRs ability to deliver for passenger and freight users	2024	Growing
O.58	increase key audience understanding of what NR do and values followed	2024	Growing
O.59	provide right level, quality and volume of resource	2024	Efficient
O.60	strengthen behavioural and technical competencies across NR	2024	Efficient

Table I-1 Network Rail Organisational Objectives

Organisational Objective	Critical Success Factor
improve customer satisfaction	value for money
improve customer satisfaction	customer needs understood
improve customer satisfaction	consistent service
improve customer satisfaction	on time service
improve customer satisfaction	transparent way of working
improve customer satisfaction	passenger comfort
improve customer satisfaction	reduce complaints received

Table I-2 Critical Success Factors

Organisational Objective	Critical Success Factor	Plain Language Questions	Organisational Information Requirements
improve customer satisfaction	on time service	where are trains late?	<location of train when delayed>
improve customer satisfaction	on time service	what are the causes of lateness?	<description of delay cause>
improve customer satisfaction	on time service	how many passengers were disrupted?	<measure of passengers disrupted>
improve customer satisfaction	on time service	how many trains are on time?	<measure of trains on time>
improve customer satisfaction	on time service	how many trains are late?	<measure of trains late>
improve customer satisfaction	on time service	where is the cause of lateness located?	<location of cause of delay>

improve customer satisfaction	customer needs understood	typical connections and have they been met?	<connections made at each train station>
improve customer satisfaction	passenger comfort	how many passengers can access WiFi?	<typical WiFi connectivity on route>
improve customer satisfaction	passenger comfort	how many passengers seated vs standing?	<measure of passengers seated on their journey>; <measure of passengers standing on their journey>
improve customer satisfaction	passenger comfort	what percentage of journeys offer catering?	<services with catering>
improve customer satisfaction	passenger comfort	what is average luggage availability per journey?	<measure of luggage transported>; <luggage capacity by service>
improve customer satisfaction	passenger comfort	what percentage of journeys have access to all?	<journeys without access to all>
improve customer satisfaction	value for money	what are Network Rail's outgoing costs?	<details of outgoing costs>
improve customer satisfaction	value for money	what is the average ticket price by journey?	<ticket pricing>
improve customer satisfaction	value for money	what is the cost per train km travelled?	<distance of stock transported>;<operation cost by service>
improve customer satisfaction	value for money	what costs are avoidable?	<measure of avoidable expenses>

improve customer satisfaction	value for money	total cost of investment?	<measure of total investments>
improve customer satisfaction	value for money	what investments have been made?	<description of investment>
improve customer satisfaction	value for money	where have investments been made?	<investment location>
improve customer satisfaction	value for money	primary driver behind recent investments?	<reason(s) for investment>
improve customer satisfaction	customer needs understood	what are typical passenger flows?	<passenger destination>;<passenger arrival>;<passenger connection>
improve customer satisfaction	reduce complaints received	who has complained?	<source of complaint>
improve customer satisfaction	reduce complaints received	what are the reasons of complaint?	<complaint reason>
improve customer satisfaction	reduce complaints received	total number of complaints?	<measure of complaints>
improve customer satisfaction	transparent way of working	how was incident communicated to public?	<method of communication to public>
improve customer satisfaction	reduce complaints received	what positive feedback has been received?	<feedback type, positive or negative>

Table I-3 Organisational Information Requirements

Critical Success Factor	Functional Output	Functional Information Requirement
on time service	control movement(s) of traffic	<train path planned>
on time service	control movement(s) of traffic	<train path actual>
on time service	control movement(s) of traffic	<trains affected>
on time service	control movement(s) of traffic	<train acceleration>
on time service	control movement(s) of traffic	<train stopping distance>
on time service	control movement(s) of traffic	<train operator>
on time service	control movement(s) of traffic	<rules of route (TSRs & ESRs)>
on time service	control movement(s) of traffic	<train driver training>
on time service	control movement(s) of traffic	<bi-directional running>
on time service	control movement(s) of traffic	<trains per hour>
on time service	control movement(s) of traffic	<trains delayed>
on time service	control movement(s) of traffic	<detailed train location>
on time service	control movement(s) of traffic	<detailed incident location>
on time service	control movement(s) of traffic	<detailed train running time>
on time service	control movement(s) of traffic	<detailed incident time>

Table I-4 Functional Information Requirements

Functional Output	Asset System	Asset Information Requirement
control movement(s) of traffic	Interlocking	<location>
control movement(s) of traffic	Interlocking	<age>
control movement(s) of traffic	Interlocking	<type of interlocking>

Table I-5 Asset Information Requirements

Appendix J. AIM database Development

This section discusses the development of an AIM database, that is derived from the UML concept model diagrams developed in Section 8.5.2.

Given the fact that the UML diagrams are developed for an asset classification system that is hierarchical, a relational database was chosen as it maintains the relationships, compared to an object database such as NoSQL. MySQL [171] was chosen as the database server, it meets the requirements of the AIM and has several user-friendly interfaces that support the engagement of non-technical stakeholders, such as MYSQL Workbench.

The AIM development consists of two steps: (1) converting UML concept model diagrams into UML database model diagrams and (2) building the AIM database from the UML database model diagrams.

As a note of clarification, this section focuses on developing an AIM database that is derived from the BIM model and not the AIM itself, the AIM is discussed in Section 8.10.

Converting concept model diagrams to database model diagrams

This section discusses the development of UML database model diagrams from the asset classification UML concept model diagrams. Enterprise Architecture (EA) was chosen as the tool to create the UML database model diagrams, utilising the same software that was used to develop the UML concept model diagrams.

Similar to developing the concept model diagrams, a single database model diagram is created for each asset functional output, that contains the relationships to the asset systems and sub-systems. The classes developed as part of the UML concept model diagrams are reused within the database diagrams, this is done by dragging and dropping the classes into the database diagrams, at which point they are converted into SQL tables. While the concept model diagrams use the human-readable name of the assets functional output such as *"pre-cast concrete wall",* the database diagrams uses the asset classification code itself, such as *“Ss_70_43_50”* this is done automatically within the database view properties, via the classes alias.

Secondly, a link between the database tables is created in the form of a Primary Key (PK) and Foreign Key (FK), the links within the concept model diagrams were merely for visual effect and therefore the relationships have to be created for the database diagrams. This is done by drawing an arrow from table to table, a PK is created from the start table and an FK from the end table.

Figure J-1 is an overview of a UML database diagram, the light blue boxes are the tables, with the top section being the table name, the middle section is the attributes within the table and the bottom section is the PK and FK. The lines between the tables represent the relationships between the different tables, as it goes from the top of the diagram, the assets functional output to the bottom of the diagram, asset systems and sub-systems.

Figure J-1 UML database diagram

The final aspects of the UML database diagrams is the need to capture the information requirements developed in Section 8.5.2, 8.6.1 and 8.6.2, this is achieved by right-clicking on the tables within the diagrams and clicking on *" Edit Columns",* which will open the settings window in Figure J-2.

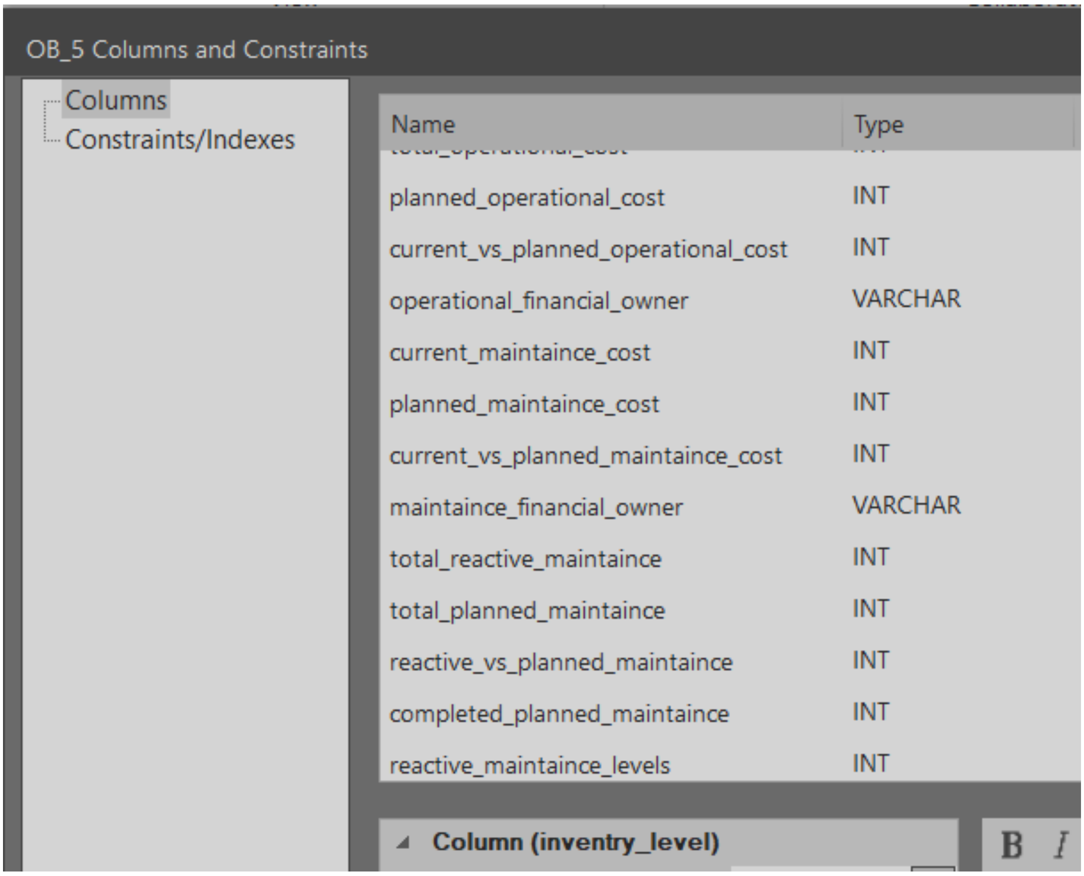

Figure J-2 Columns adding / editing settings

The Name column represents the information requirements, while the type column represents the datatypes. As the information requirements were documented within the machine-readable format of CSV, the information requirements were imported and automatically populating the columns. This step is repeated for each table in the database diagrams.

Building the AIM database

This section discusses the building of the AIM database, while the UML database diagrams are a representation of the database, the diagrams themselves do not build the database. EA has a set of database modelling tools that were used to build the AIM database.

In this case study, we have chosen SQL as the database structure with MySQL as an open-source distribution for installing and running the server. Along with installing MySQL server, MySQL Workbench was also installed as a means of a Graphic User Interface (GUI) for manipulating the server.

A default Latin character set schema should be created within the MySQL server, where the AIM database will be developed.

Developing the database diagrams themselves does not directly build the database, they act as the visual representation of the database in which SQL queries can be developed from, to build the AIM database. In the bottom of the project viewer in EA, the database connection button is selected, this opens up the database work screen, in which the database hostname, username and password are populated to connect EA to the AIM database.

Once the connection to the database has been made, the database toolbox is loaded, see Figure J-3. One of the tools available is the DDL executer that automatically creates SQL statements based on the database diagrams. The left-hand side of Figure J-3 shows the queries that have been created, while the right-hand side shows the SQL script.

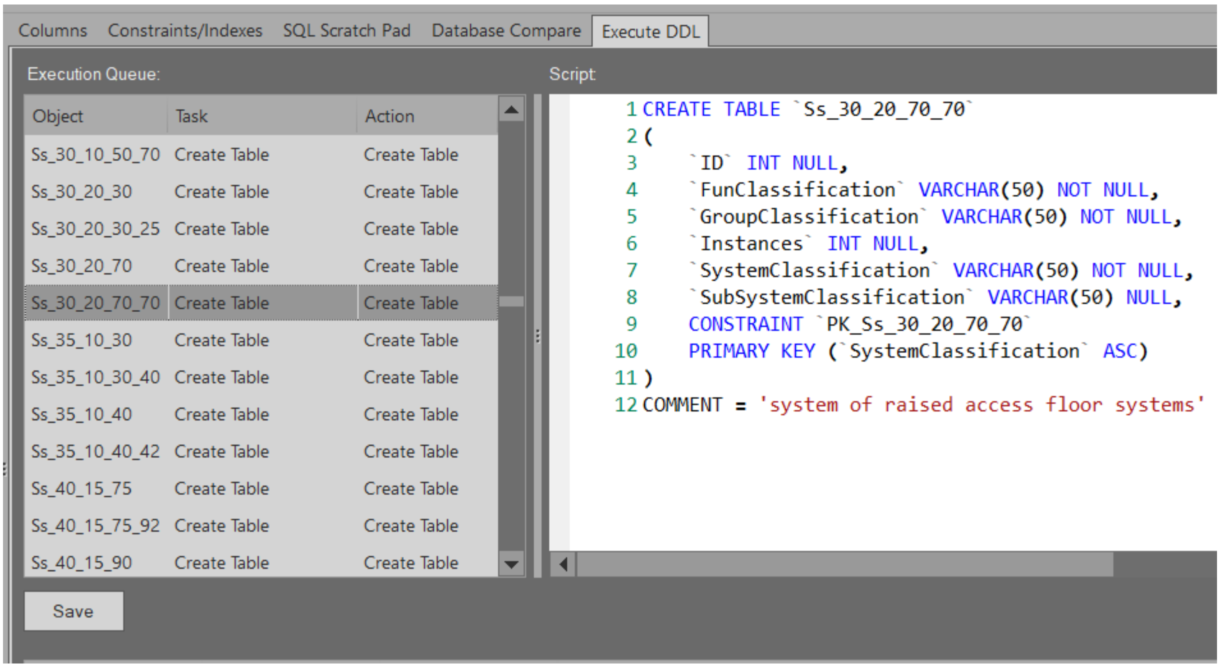

Figure J-3 SQL queries generation

Once the statements are created, they are executed onto the AIM database, creating all of the tables and constraints (PK and FK) within the UML modelling diagrams directly within the AIM database.

The outcome of this section is an SQL database that is derived from the asset classification system, along with the information requirement developed as attributes within the SQL tables. The database is used to store the BIM object data within the following section.

J.1 Platform Extraction Development

This section discusses the development and implementation of a platform extraction, which is the final step (ten) within the information requirements framework, see Figure 4-1.

The development of the platform extraction consisted of two steps: (1) development approach and (2) development of the platform itself.

Justification for chosen platform development

An Extract Transform Load (ETL) approach was chosen as a means to develop the extraction platform over a hard coding approach, such as Python, C# or C++. The research noted several advantages of developing within an ETL approach in Section 7.4.2.

FME Desktop, developed by Safe Software, was chosen as the ETL development. The industry investigation within Section 2.5 highlighted the fact that the use of FME Desktop is growing within the asset management industry. Furthermore, FME Desktop can read and write IFC files by default.

ETL Platform development

This section discusses the platform development in detail, which is divided into three steps: (1) importing and reading the IFC model into FME Desktop, (2) exposing properties of the BIM objects within the IFC model and (3) the properties are validated, grouped, sorted and inserted directly into the AIM database. Figure J-4 is an illustration of the workflow in FME Desktop, the three sections discussed above are shown within the workflow, with the IFC model being imported on the left-hand side, exposing the properties in the middle and exporting the data on the right-hand side.

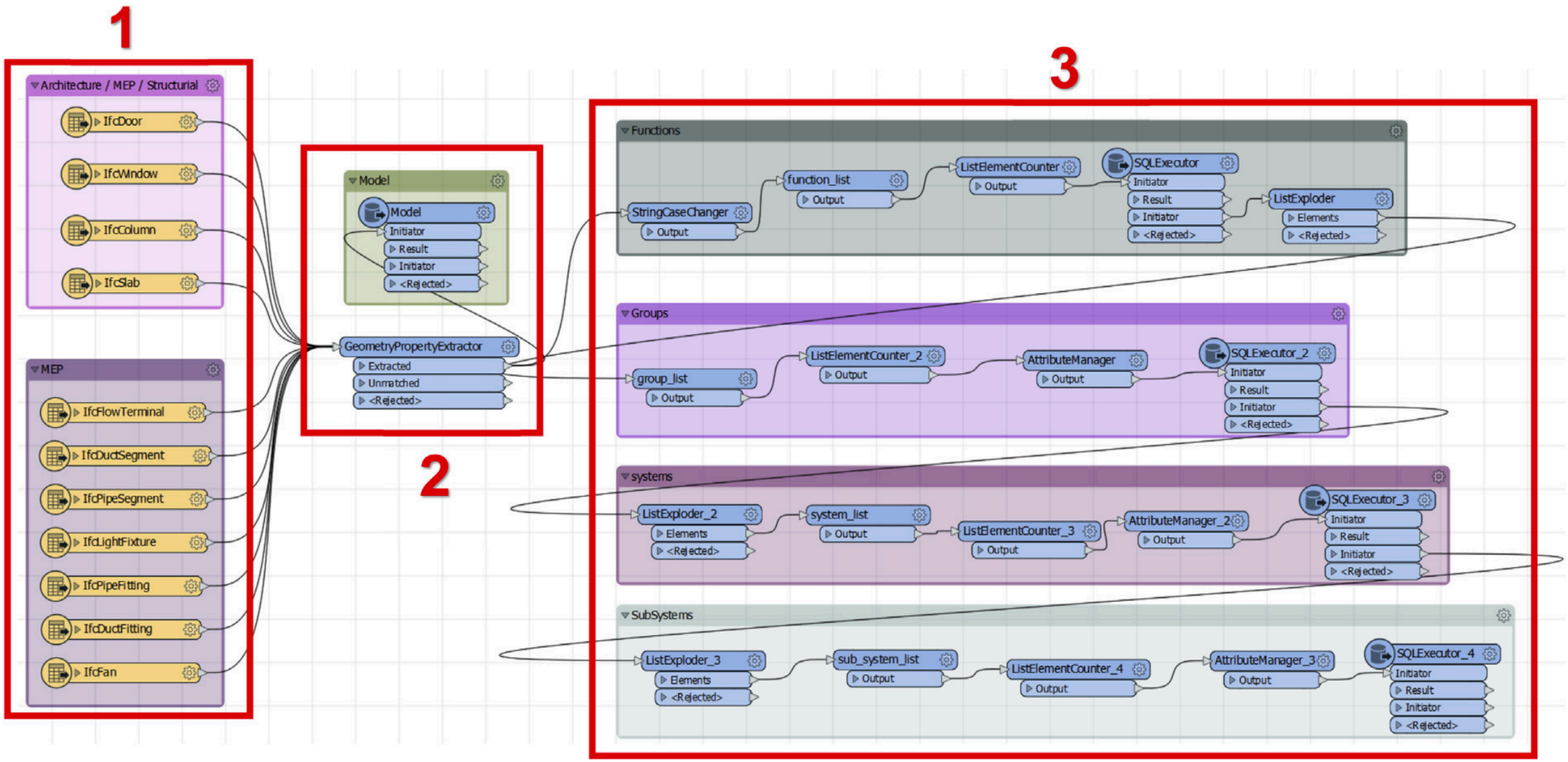

Figure J-4 Extraction platform within FME Desktop

Section 1 - loading and reading the IFC files.

The first task is to load the IFC model into the workflow, which requires adding a reader. Figure J-5 shows the settings for the reader, the format is selected to IFC. While the dataset points to the IFC model, no settings need to be changed in the parameters.

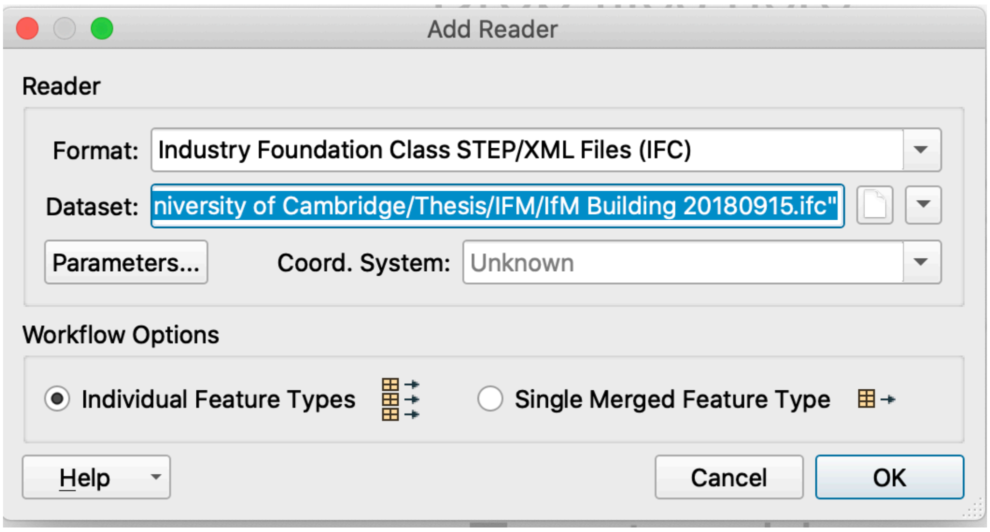

Figure J-5 Reading an IFC model into FME Desktop

When looking at the workflow options, there are two options, individual feature types or single merged feature type. The single merged feature option loads the model as a single object, while the Individual feature types read in individual objects, such as doors, windows and MEP. The latter option was chosen, as it has several advantages. Firstly, it enables the researcher only to select the objects that are required within the workflow, avoiding such objects as landscaping, spaces and dimensions, therefore optimising the importing step. Secondly, having individual feature types enables parallel processing, meaning that multiple objects can be read in at the same time, reducing the time for importing.

Section 2 - exposing properties

Once the IFC files have been read and imported into the workflow, it is then required to expose the properties that are within the files, common IFC properties are exposed by default. Figure J-6 shows the IFC common properties that have been exposed within the workflow, the custom asset classification parameters are not within this list, so they have to be exposed within the workflow.

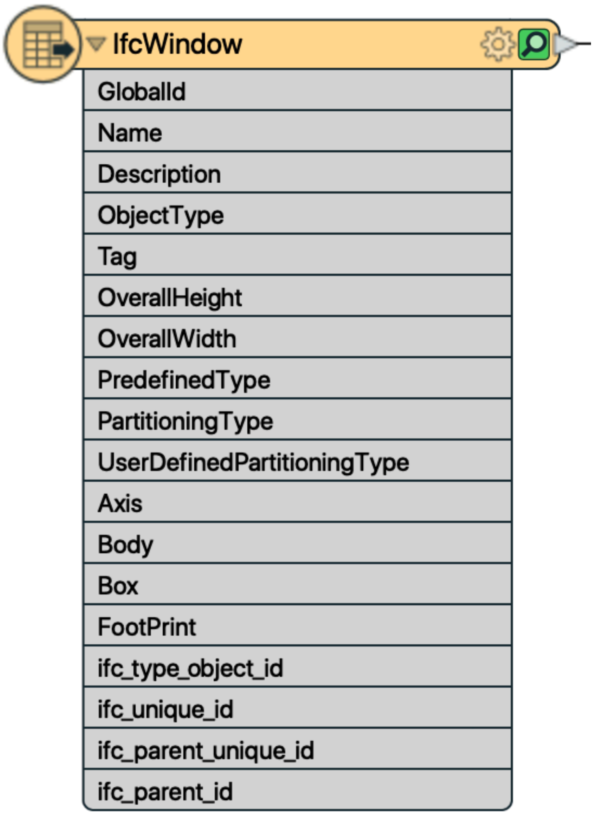

Figure J-6 Parameters exposed in FME Desktop

To expose the asset classification parameters, the researcher used the Geometry Property Extractor (GPE) transformer. The transformer works by exposing parameters that are attached to geometry based on the parameters name. Figure J-7 shows the settings within the transformer, the parameters directly related to the custom parameters that are developed within the BIM model and included within the IFC export. Reviewing section 2 in Figure J-4, it can be seen that the IFC readers that are imported into the workflow in section one are linked to the GPE, ensuring that all of the objects within the BIM model have their asset classification parameters exposed.

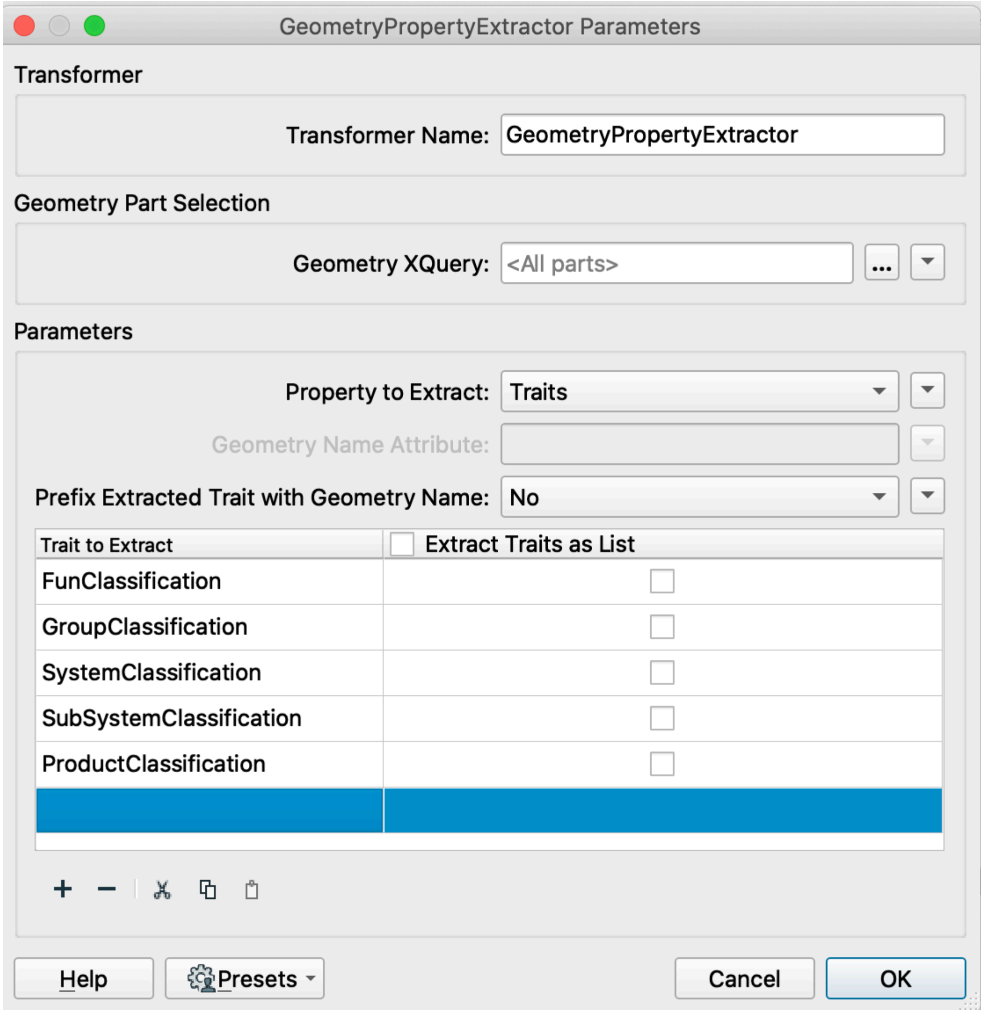

Figure J-7 Exposing asset classification parameters

Reviewing a small sample of the GPE output in Figure J-8, it can be seen that 155 window objects have been exposed within the workflow, along with the common IFC properties of ID, type, width and height, the asset classification has also been exposed.

	ifc_unique_id	ObjectType	OverallHeight	OverallWidth	FunClassification	GroupClassification	SystemClassification	SubSystemClassification	F
29	3NrNCDS3PB0ONLwRqm6T_65...	Windows_Sgl_Case...	3450	1900	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
30	3NrNCDS3PB0ONLwRqplF_655...	Windows_Sgl_Case...	3450	1900	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
31	3NrNCDS3PB0ONLwRqpVv_65...	Windows_Sgl_Case...	3450	1900	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
32	3NrNCDS3PB0ONLwRqpVw_65...	Windows_Sgl_Case...	3450	1900	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
33	00Kcidbxv42viJxftiQHN8_170075	Shutters:Shutters	2200	1683	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
34	1IGjHI5ZL33RLzSua565ug_278597	Top-hung window:...	1800	1200	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
35	1IGjHI5ZL33RLzSua565yK_278763	Top-hung window:...	1800	1200	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
36	1IGjHI5ZL33RLzSua565zo_278856	Top-hung window:...	1800	1200	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
37	1IGjHI5ZL33RLzSua565Yw_278949	Top-hung window:...	1800	1200	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
38	1IGjHI5ZL33RLzSua565Yo_279042	Top-hung window:...	1800	1200	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	
39	1IGjHI5ZL33RLzSua565Yg_279135	Top-hung window:...	1800	1200	EF_25	EF_25_30	Ss_25_30_95	Ss_25_30_95_26	

in any column — 155 row(s)

Figure J-8 Example of a set of the exposed IFC model within FME Desktop

Along with exposing the asset classification parameters, section 2 of the workflow in Figure J-4 also has a SQL Executor (SQL-E) transformer, the SQL-E transformer executes a predefined SQL statement within a database, in this case, the AIM database. The purpose of this transformer is to insert the all of the data as a *"raw"* dump into a single table, the table can then act as a testbed for analytics on the data without impacting the broader AIM database. Furthermore, it also acts as a point of validation for the output of the platform by providing a controlled comparison.

The asset classification parameters are used within the following section to group, sort and insert data into the AIM database.

Section 3 - data validation, grouping, counting and inserting into the AIM database

Section three has four sub-sections for each of the asset classification levels (assets functional output, asset system, asset sub-system and products), with five transformers each (see Figure J-4). Furthermore, a single transformer of String Case Changer is used to ensure that only lowercase characters are within all of the values, to meet the syntax requirements of the AIM database.

Figure J-9 shows the five transforms used within the sub-sections including list builder, list element counter, attribute manager, SQL executor and list exploder, which are discussed in detail below.

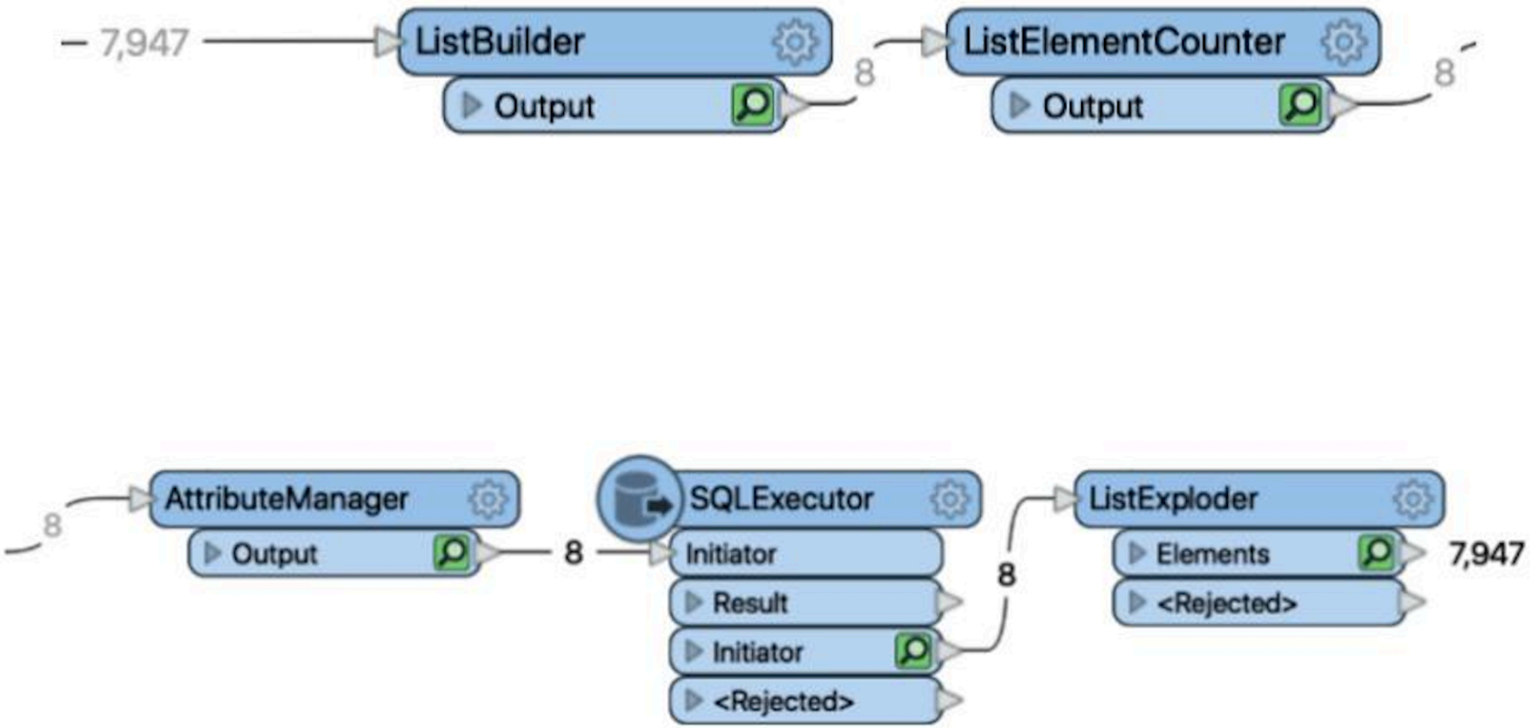

Figure J-9 transformers used within the sub-section

The list builder creates a list (group) based on a common parameter, in this case, the asset classification. In Figure J-9 on the left-hand side, it can be seen that 7,947 objects are going into the list builder transformer that creates eight lists based on the FunClassification parameter, which can also be seen on output of the list builder in Figure J-9.

The list element counter transformer simply counts all of the objects within a given list. Figure J-10 continues the example by showing the eight lists of the FunClassification alongside the number of objects within those lists.

	FunClassification	ObjectCount
1	EF_20	427
2	EF_70	3951
3	EF_25	576
4	EF_75	1599
5	EF_60	768
6	EF_65	553
7	EF_35	10
8	EF_30	63

Figure J-10 the count of objects within the FunClassification list

Attribute manager transformer is used to rename and remove parameters within the workflow that are not required within the AIM database. While the parameters could remain within the workflow and not be inserted into the AIM database, removing them at this point is for workflow optimisation.

The purpose of the SQL executor transformer is to execute SQL statements within a database, parameters within the workflow can be used as variables within a SQL statement. Reviewing Figure J-9 we can see that eight lists are outputted from the attribute manager and are inputted into the SQL executor, having the values shown in Figure J-10, these values are used to create eight SQL statements automatically.

As a point of reference, below is a typical SQL statement for inserting data in a table, followed by the FME SQL statement.

INSERT INTO `AIM`.`FunClassification` (`Classification`, `ObjectCount`) VALUES ('EF_45', '4556');

INSERT INTO is an SQL statement for inserting data, AIM is the name of the database, FunClassification is the name of the table, Classification and ObjectCount are the names of two columns within the table that will receive the data. VALUES states what should be inserted into the columns, in this case, EF_45 within Classification and the 4556 within ObjectCount.

The statement within the workflow is similar, as it points to the same database tables and columns, but the VALUES statement relates to the parameters of FunClassification and ObjectCount that are exposed within the workflow, see Figure J-10. Creating the SQL statement using the parameters, means that a statement is created automatically in the four sub-sections for each asset classification code in the IFC model.

INSERT INTO `AIM`.`FunClassification` (`Classification`, `ObjectCount`) VALUES ('@Value(FunClassification)', '@Value(ObjectCount)')

The final transformer is the list exploder, the purpose of the transformer is to *"explode"* the lists back into the original number of objects. Reviewing the workflow in Figure J-9, we can see that 7,947 objects go into the list builder on the left-hand side creating eight lists, with the list exploder on the right-hand side exploding the lists back to the original 7,947 objects.

The five transformers are repeated for each of the asset classification codes. The list is built based on the asset classification, objects within the list counted, formatted for syntax compliance, inserted into the AIM database and finally, the list is exploded back to the original amount.

J.2 Summary

Part two (Section 8.5) and three (Section 8.6) of the information requirements framework provides a structured approach to the development of information requirements, including a new set of information requirements (FIR) to address the challenge of an OIR generating an AIR, this section focused on the development of an AIM database. Addressing the challenges of adopting BIM models within the

O&M phase by providing a structured approach to the design and development of BIM models for use within an asset management organisation.

Step eight (see Section 8.7.1) saw the classification of BIM model A via the development of four new custom parameters to store the asset classification system developed within step two (see Section 8.5.2). To classify the objects within BIM model A they had to be manually selected, several tool and techniques were used to optimise this process, but ultimately it was a manual and ad-hoc process that took several days to complete.

Step nine (see Section Appendix J) saw the development of the AIM database. The asset classification UML concept model diagrams were converted to UML database diagrams, with the classes converted into SQL tables and primary/foreign keys added. Furthermore, the information requirements were attached to the SQL tables as attributes. Finally, database tools in EA were used to convert the diagrams into SQL queries which then created the tables and constraints within the AIM database, based on the design within the diagrams.

Step ten (see Section 0) is the final step that enables the export of BIM model A into the AIM database, via the extraction platform. The platform was developed in FME Desktop as it has a visual representation within a workflow style, which supports the useability requirement of non-technical stakeholder. The platform uses the asset classification code that was attached to the BIM model in step eight to extract and group the objects, inserting them into the correct tables in the AIM database.

The outcome of this section is an AIM database that is derived from the asset classification system, with the SQL tables containing the information requirements developed within the FIR and AIR. Furthermore, the AIM database is populated with 7,974 objects from BIM model A, via the extraction platform developed in step ten.