Design and Development of BIM Models to Support Operations and Maintenance

Abstract

Building Information Modelling (BIM) is one of the most significant technological advancements in recent years that has been adopted by the design and construction industry. While BIM adoption is growing, it can be witnessed that adoption is relatively weak within operational and maintenance (O&M) organisations such as Estate and Infrastructure Management, who would ultimately gain the highest value from utilising BIM. While the challenges of BIM adoption are multifaceted, there is a recurring theme of poor data integration between BIM and existing information management systems. There is a clear gap of knowledge on how to structure a BIM model that allows its efficient use in the O&M phase. Furthermore, there is a lack of claritiy on how to exchange information from a BIM model into an Asset Information Model (AIM).

This paper outlines a methodology that enables extraction of BIM-related data directly from a model into a relational database for integration with existing asset management systems. The paper describes the BIM model requirements, development of the extraction platform, database architecture and framework. Furthermore, a case study is presented to demonstrate the methodology. The case study demonstrates that if the BIM model is designed from the start with consideration for the O&M requirements, it can be exploited for development into an AIM. It also shows that a structured approach to object classification within a BIM model supports the efficient exchange of data directly from the BIM model.

Keywords

Building Information Modelling, Asset Management, Asset Information Model, Asset Management Systems, Asset Classification.

1 Introduction

The O&M costs of a project (such as a new school building) are often overlooked by project stakeholders during the design and construction phase, despite evidence suggesting that they contribute to over half of the total lifecycle costs. This can increase to over 80% for significant infrastructure such as roads, rail and bridges [1,2]. There is extensive evidence within the literature to demonstrate that BIM adoption supports the reduction of design and construction cost, increase in productivity and improved risk management processes [3,4]. Despite this, it can be witnessed that the adoption of BIM within the O&M sector is relatively limited [5]. In a recent annual survey of BIM professionals completed by the UK National Building Specification (NBS), 72% of the surveyed professionals agreed with the statement that "*clients do not understand the benefits of BIM*" and 65% highlighted "*no client demand for BIM*" as a barrier to BIM adoption [6]. A recurring theme is the fundamental challenges of demonstrating the value of BIM in the O&M phase [5]. This is partly because asset owners, maintainers and operators fail to address their information requirements, resulting in BIM models that generate little value for the O&M phase. Database Schema, BIM object classification and information exchange requirements – if developed at all – are generally in the form of technical documentation and fail to address the organisational requirements specifically related to the O&M phase.

The challenges of adopting BIM in the O&M phase are multifaceted. This includes cultural challenges in an industry that is historically hesitant in adopting new and emerging technology processes [7], and fiscal challenges in generating a robust business case for BIM adoption [5]. From a technology perspective, the interoperability between BIM-related data (e.g. 3D models) and O&M information management systems such as Enterprise Resource Management (ERM) is limited [8–10]. Furthermore, from an information management point-of-view, the built environment is virtually siloed within individual lifecycle stages and between stakeholders, with data often stored in enterprise software solutions with poor interoperability resulting in manual and often ad-hoc exchange of information. This clearly highlights the need for cross-discipline and whole-life applications [11]. Finally, due to the lack of O&M personnel engagement in the BIM management processes, their requirements are often neglected [12].

Reflecting on the challenges, the following research question has been developed to guide this research effort:

How should a BIM model be designed to support its exploitation within the O&M phase?

This leads to two sub-questions:

1) *How can classification of BIM objects within a BIM model support the development of an AIM?*

2) *How should BIM objects within a BIM model be classified to support the use of BIM within O&M?*

This paper proposes a methodology that allows the design, structure and development of a BIM model for use within an AIM with a specific purpose of supporting O&M. The elements defined within the BIM for O&M specification (PAS 1192-3 [13]) are used to provide the foundation for this research effort. This includes the definition and requirements of an AIM, structured exchange of information and the reuse of BIM related information within the O&M phase. It is proposed that the BIM model is structured for O&M use from the early design stages. This is achieved by creating custom parameters within the BIM model that allows for classification of individual BIM objects according to their functional output. Utilising the classification, an extraction platform is developed that allows the export and grouping of BIM objects based on their functional output. Finally, a series of Universal Mark-Up Language (UML) diagrams based on the classification of the BIM objects are developed that enable the development of a structured query language (SQL) Database that can store the exported information from the BIM model.

This paper begins by providing a background on the current approaches to the BIM data integration challenges within the literature, including industry standards and specifications. Further, the process is described in detail, including BIM model design requirements, an extraction platform and database development. This is followed by a case study that demonstrates the application of the methodology. The results from the case study are presented, along with limitations and recommendations. Finally, the conclusions of the research are summarised with a discussion and future research opportunities highlighted.

2 Background

The operational performance of built assets such as the quality of a school to educate their students and the punctuality of a public transport system is critical to the prosperity of modern societies with their diverse needs and requirements. Further, the advancements of widely available sensors and Internet of Things (IoT) devices, BIM models and the concept of smart connected cities will bring an increase of data to the built environment [14]. On the other hand, the complex nature of the built environment, and the many different stakeholders that define it, brings issues related to the management of unstructured and non-standardised data [15].

BIM as an information management process can help in managing data about built assets by providing a Common Data Environment (CDE) that can support all the phases of the asset lifecycle, i.e., design, construction, operational & maintenance and disposal [16]. BIM has successfully been adopted within the design and construction phases, with evidence demonstrating a reduction in design and construction cost, increase in productivity and improved risk management [3,4].

2.1 BIM standards and specifications

Since this research is heavily influenced by current BIM standards, this section aims to provide the reader with a background in the BIM-related standards and specifications, while highlighting the current challenges and shortcomings within them. Although this review is limited to the British Standards Institute (BSI) series of standards, note that some of these have been adapted as international standards by the International Standards Organisation (ISO) [17,18].

BIM is the process of designing, constructing or operating a building or infrastructure assets using object-oriented design [16]. BIM within the UK is governed by six standards and specifications: one standard and two specifications supporting the individual lifecycle stages of design, construction and O&M [13,16,19], one specification each focused on security-mindedness [20], the use of BIM for health and safety [21] and for the exchange of BIM related data [22]. Table 1 provides a summary of the BIM standards with a brief description and lifecycle phase that is supported by the standard.

Table 1 Summary of BIM 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 freely share design and construction related data. The owner or principal contractor manage the CDE*	*Design / Construction*	*BS 1192* [19]
Specification for information management for the capital/delivery phase of construction projects using building information modelling	Guidance in the management of BIM related data within a CDE. A strong focus on BIM management and required documentation, e.g. BIM Execution Plan	*Design / Construction*	*PAS 1192-2* [16]
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 and Maintenance*	*PAS 1192-3* [13]
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 O&M*	*BS 1192-4* [22]
Specification for security-minded building information modelling, digital built	Guidance on how to support BIM processes with security sensitive information and models	*All*	*PAS 1192-5* [20]

environments and smart asset management			
Specification for collaborative sharing and use of structured hazard and risk information for Health and Safety	Guidance on how BIM can be utilised to aid in health and safety management, both from an information management perspective, e.g. managing the risk register within a digital format and visualisation perspective, e.g. visualising the exclusion zone for a crane operation within a 3D model.	*All*	*PAS 1192-6* [21]

While not directly related to BIM, there are a set of international standards that support the BIM information management processes. ISO 12006-2 provides a hierarchical classification system for objects such as windows, rail track and ventilation systems [23]. ISO 16739 describes a schema for an open-source file format (IFC) that supports the exchange of BIM geometry and attributes between enterprise software solutions [24]. Finally, BS 8536 parts 1 and 2 recommends pre-defined sets of information for delivery after the construction phase to the organisation responsible for O&M [25,26].

While these standards are comprehensive, there is a lack of a framework that supports the development of a BIM model for use within the O&M phase, including extracting, structuring and storing of information from a BIM model into an AIM. Most notably, BS 1192-4 provides a standard structure for the exchange of information called COBie (Construction Operations Building information exchange) but is limited in its use due to the simplicity of the Excel templates that hinders its use within O&M [27]. Furthermore, while the development of IFC standards has advanced at pace in recent years, there are still some limitations with its use for O&M and general organisational functions such as financial management and risk management [28]. This research effort aims to address these limitations by providing a methodology that supports the development of a BIM for use within an AIM.

2.2 Asset Management

Asset Management involves the balancing of costs, opportunities and risks against the desired performance of assets to achieve the organisational objectives. Asset management does not focus on the physical asset itself but the value that it can provide to an organisation [29]. Asset management aims to translate organisational objectives into technical and financial decisions, plans and activities while providing leadership and assurance. An asset within the context of this paper is a physical item, thing or entity that has the opportunity to provide financial or non-financial value, e.g., a railway signal box, a door, a ventilation system. Asset management is an emerging domain both in industry and academic research. The industry is guided by international standards that are supporting the design, development, implementation and management of asset management systems [29–31].

The need for efficient asset management is critical, as demand for new infrastructure, commercial and domestic buildings worldwide is growing. The UK government alone estimates that over 600 billion pounds of infrastructure and construction investment will be needed within the next ten years [32]. In parallel there is a need to build, maintain and operate the built environment in a more economical and environmentally efficient manner, requiring the development of asset management tools such as Whole-Life Cycle Costing and Environmental Impact Assessments [33,34].

One of the critical challenges of asset management is managing asset information throughout its life, in the current environment where manual and ad-hoc approaches to knowledge management dominate and there is poor definition of asset management requirements [11,35,36]. BIM has been widely cited as a key enabler for the development of information management processes, including knowledge management and requirements development [37]. The methodology proposed in this paper aims to address the information management challenges within Asset Management by utilising BIM information management processes, specifically by supporting the development of an Asset Information Model (AIM) and its integration with asset management systems.

2.3 Asset Information Model

data and information that relates to assets to a level required to support an organization's asset management system

An Asset Information Model (AIM) is defined within the BIM for operational use specification (PAS 1192-3) as a "*data and information that relates to assets to a level required to support an organization's asset management system*" [13]. The AIM acts as a central data repository that supports the organisational requirements, including but not limited to operational and maintenance decisions, capital investment and life cycle costing, planning and budgeting, and contingency/emergency planning. An AIM is formed of two discrete parts: the Electronic Document Management System (EDMS) and a Data Store. The EDMS stores graphical and non-graphical documentation such as 3D models, PDF's, Excel and Word files. The data store is a query-able database storing information such as sensor data for performance monitoring, historical maintenance records and activity costing. Furthermore, a vital element of the AIM is to integrate this data into existing enterprise information systems, with the AIM acting as middleware to enable the exchange between enterprise systems.

Figure 1 illustrates the concept of an AIM as defined in PAS 1192-3 and encompasses both the EDMS and the Data Store as highlighted above. The interface between the AIM and the existing enterprise systems provides two-way connectivity. The enterprise systems can pull data from the AIM as per the operational requirements as and when needed. Furthermore, the enterprise system can also push data into the AIM as and when needed. As an example, if a complete O&M cost analysis needs to be performed for a given period, this would require the systems of cost management, maintenance scheduling, resource management and operational performance monitoring to push and integrate their data within the AIM.

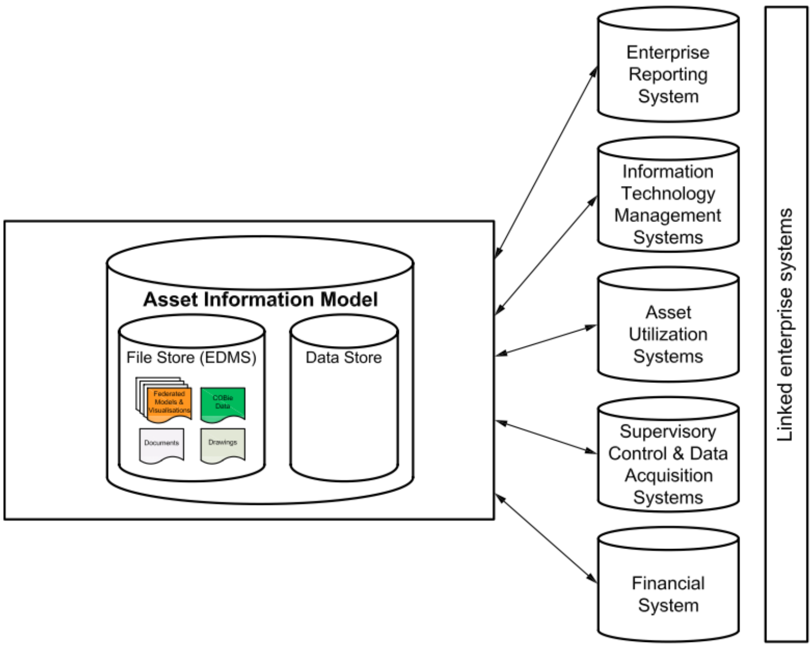

Figure 1 Asset Information Model linking to enterprise solutions [13]

Due to the broad nature of the AIM, there are limited examples within the literature that demonstrate its full development. Patacas et al. [38] demonstrate the visualisation of an AIM by exporting a 3D model from a BIM modelling tool (Revit) into a gaming engine software (Unity) and attaching maintenance data to the 3D objects such as walls, doors or windows. From a live data integration point-of-view, Davis et al. [39] demonstrate a framework based on open-source standards for integrating IoT sensors and a BIM model hosted on a web server, providing a live platform for viewing the 3D BIM model and real-time data analytics. From an information requirements development point-of-view, Navendren et al. [40] provide an examination of how clients and project teams can work together to develop the requirements for an AIM from an operational and maintenance management perspective.

2.4 BIM within Operations and Maintenance

As highlighted earlier, data exchange and interoperability between a BIM model, an AIM model and the broader enterprise systems is a significant challenge. One attempt to address this challenge is utilising the Information Delivery Manuals (IDM) that have been developed by BuildingSMART and adopted as an ISO standard (ISO 29481) [41]. The IDM standard provides a process map-driven methodology that results in a set of information requirements for specific construction related activities by documenting and describing them in a controlled manner. A single IDM is developed for a single activity with the stakeholders mapped as swim lanes within the process map and every point of information exchange between the stakeholders mapped. The IDM methodology aims to serve both industry personnel and software developers using few technical terms. The domain experts can map out their requirements supported by the process maps, while the developers can link these requirements to IDM elements.

Panushev et al. [42] utilised the IDM methodology to develop design requirements for pre-cast concrete. One of the challenges they noted using the IDM for technical development of asset data structure is that its “user-friendly” approach did not support the technical requirements. Kim et al. [43] attempted to address this by demonstrating how an IDM can be converted to a UML concept model and further developed into a database schema. This approach meets the interoperability requirements of an AIM but does not create a direct or indirect link to the BIM model. When considering the exchange of information within a project, BIM Collaboration Format (BCF) has been developed as an open source “simplified” XML schema that enables the communication between BIM software tools, with the added benefits of additional textual comments and screenshots to be associated with an IFC file [44]. It is generally used by BIM auditing software to support the exchange of information around such activities as clash detection and design reviews. Van Berlo et al. [45] developed a service-based workflow for working with BCF on a web-based platform, supporting the sharing of information from a centralised source. While this is an efficient way of sharing and storing information on specific activities, and adopts many of the concepts of an AIM, the simplified XML and lack of an expandable schema means that its use within the broader O&M functions is limited.

From an application point-of-view, there are several attempts to utilise BIM within the O&M phase. Parn et al. [46] developed an Application Program Interface (API) that acts as a plug-in within BIM modelling software and a customer database to integrate O&M data directly within the BIM model. A 3D object (in this case a pyramid) is placed directly within the BIM models within all rooms and other specific locations, with data attached directly to the object via a database link or data attached directly to the BIM object within custom parameters. The end-user can navigate to the objects within the BIM model, click on them and get access to the associated information. While this application does align BIM and O&M information within a visual context, it has several limitations: 1) Information is not associated directly to assets (such as a heating radiator) within the BIM model, so when accessing the data it provides the data for all assets in the room as a whole and on the individual assets themselves; 2) As all of the data is attached to one BIM object, it makes it complex to search and filter the data, specifically in rooms with multiple complex assets (such as a plant room); 3) while data is stored externally it is accessed via the BIM model, this requires personnel to be trained on operating BIM modelling tools.

Motawa et al. [47] investigated how BIM can aid in the development of a knowledge management system for building maintenance. They developed a taxonomy of maintenance processes that aids in the development of Case-Based Reasoning (CBR) for use when developing a knowledge management system. Keywords from the taxonomy are captured directly on BIM objects within the model, which enables a CBR search when making maintenance decisions. While this process captures information directly onto an asset (such as a window), it has shortcomings in classifying them within a hierarchy since it does not address the multiple aspects of assets and how the system can impact O&M requirements.

2.4 Summary

In summary, it can be seen that while both BIM and asset management are emerging research domains, they have developed in isolation from each other. However, BIM has been cited as a core tool to support the information management challenges within asset management, including but not limited to the exchange of information between lifecycles and stakeholders. While there are a few examples in the literature that demonstrate the utilisation of BIM models within the O&M phases, they often use multiple enterprise solutions that fall short of addressing the requirements for O&M use. Furthermore, these solutions are often ad-hoc in nature and lack a standardised approach to the development of a BIM model for use within the O&M phase. As such, it can be seen that there is a clear need for a methodology that supports the exchange of data from BIM models into an AIM, and addressing this need forms the critical contribution of this paper.

2.5 Novelty compared to current approaches

When reflecting on the existing approaches discussed so far, some key comparisons with our proposed approach can be highlighted. Firstly, in comparison with the attempts to create an AIM from the use of BuildingSMART standards including the creation of XML schema directly from the use of the IDM process [41–44], the proposed methodology creates a schema directly from the organisational asset classification system. This enables a direct link between a classified BIM model and other enterprise systems which also utilise the classification system. As opposed to this, the XML schema developed using existing approaches are developed specifically from an IDM and therefore has no direct link with the BIM model and limited integration within the wider enterprise systems. The attempt to use the simplified XML BCF schema as a centralised database allows for the integration of enterprise systems. However, this has limited capability within the O&M phase due to its simplified nature and lack of a detailed schema [45].

Secondly, from an application perspective there are several examples of the use of an API and custom BIM modelling tools and plug-ins that aim to enable the use of BIM within O&M, with the common aspect being the linking of O&M-related data directly to a BIM object [46]. In such approaches, the O&M data is directly accessible via a BIM modelling interface, which means that O&M personnel will need to be educated on using BIM-specific software. For example, consider the heating function discussed earlier. The BIM objects developed using such an approach are custom objects that are placed in the centre of the room and link all of the data associated to that specific room. This means that the data is not associated with the specific BIM object that represented the assets (such as a heating radiator). While this approach creates the link between O&M data and the BIM model, it is limited by not creating a direct link between the individual BIM objects and the associated O&M data. The approach within this paper proposes a classification that is inserted directly on the BIM objects allowing for a direct export from the BIM model into the AIM. This means that O&M personnel do not have to interact with the BIM modelling software to gain the benefits of the BIM model.

Finally, there is an attempt to create a taxonomy of O&M keywords and attach them directly to BIM objects for the development of CBR within knowledge management [47]. This methodology takes the approach of attaching data directly to the BIM object (such as a window) but is limited in addressing the hierarchy of assets and how asset systems can impact on O&M requirements. In comparison, the methodology presented in this paper addresses the O&M requirements of an asset by classifying its functional output and associated asset systems through an appropriate hierarchy.

3 Methodology

This section proposes a methodology that allows for the extraction of objects within a BIM model into a relational database to support the development of an AIM. Figure 2 illustrates a four-step methodology that enables the design of a BIM model to support the development of an AIM. The individual steps are summarised below.

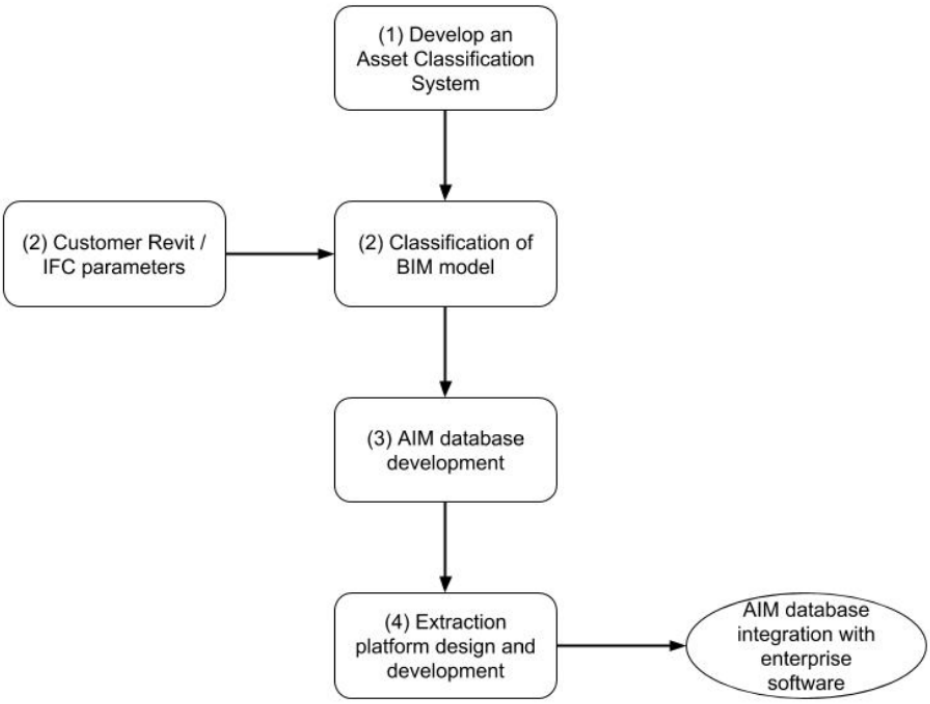

Figure 2 BIM data extraction methodology

- Step 1 – An asset classification system is developed that supports a structured approach to the classification of BIM objects within the BIM model. Any classification system should have a structured hierarchy. As an example, the classification of the functional output of heating will be supported by the asset systems of radiators, underfloor heating or electric heaters.
- Step 2 – The newly developed classification system is designed into the BIM model. Every BIM object within the BIM is classified as per its functional output and asset system. Most common BIM modelling tools do not allow for multiple classification codes on individual BIM objects. Therefore, a set of custom parameters are developed within the BIM modelling software. Furthermore, these custom parameters are aligned to new IFC property sets, so they can be included within an IFC export file.
- Step 3 – The asset classification is used to support the development of a relational database. The database will act as the data store of an AIM. UML diagrams are created per asset functional output and aid in developing the database – mainly in defining the Primary Keys (PK) and the Foreign Keys (FK).
- Step 4 – An interface is developed that allows for the export of data from an IFC model and extraction of the attached classification data and any associated data such as fire rating, design details (materials, width, height, length) and cost parameters into the newly developed database.

3.1 Developing an Asset Classification System

The first task is for an organisation to develop an asset classification system for its physical assets. When considering the classification of assets, it is essential to consider the understanding of the asset within the whole organisation and by the end-user, as often the leadership team and the end-user of an asset are not from a technical background. To support the understanding of an asset's performance throughout a group of diverse stakeholders, it is proposed to utilise a parent-child relationship classification methodology. One of the key advantages of developing such a classification is the ability to start at the functional output level of an asset, which is easily understood throughout the whole organisation and is ultimately how the end-user understands the assets. As an example, the customer engagement team within a university asset management department will not have expert knowledge on the asset systems or products that support the function of heating, but they will understand the performance requirements (e.g. temperature) that the student and teachers require.

Furthermore, from a data management perspective having the classification of functional output allows efficient data search, filtering and export based on the function of the asset. As an example, if the estate management team wanted to analyse the operational performance of heating for a whole university campus, it would be possible to extract data from multiple systems (such as finance, resource management and scheduling) based on the functional output.

An asset system is defined as a group of assets (or products) that are of the same nature and work within a system to support the functional output. The asset systems should be classified according to the functional output that they support. Each functional output should be considered in turn. Using the heating example, the functional output of heating might be supported by a ground source heat pump system, an electric heating system or a natural gas heating system. Only those asset systems that support the particular functional output in focus should be classified at each turn. A sub-system might be required to be classified depending on the specific requirements. Finally, the individual asset products should be classified if deemed business critical. Classification of individual products is sometimes deemed too detailed and does not support asset management decisions. As an example, there is rarely a need to classify individual door handles on doors or window panels within a window frame. Alternatively, there might be a requirement to classify a thermostat of a gas heating system if there is a regulatory requirement to service them every year. In this case, there is a definite requirement to capture that information directly on individual thermostats.

As noted in section 2.1, ISO 12006-2 provides the foundations for the development of a hierarchical classification system. There are several classification systems in development – UNIClass [48] developed by NBS [49] in the UK and OmniClass [50] developed by International Construction Information Society (ICIS) in USA being the most comprehensive. Figure 3 illustrates the classification hierarchy that has been adopted within UNIClass, conforming to ISO 12006-2 and at each level of the hierarchy provides examples that are typically found in buildings. Table EF within UNIClass provides a total of 76 functions [51], Table Ss has a total of 2086 system classifications [52] and Table Pr has a total of 6870 product classifications [53].

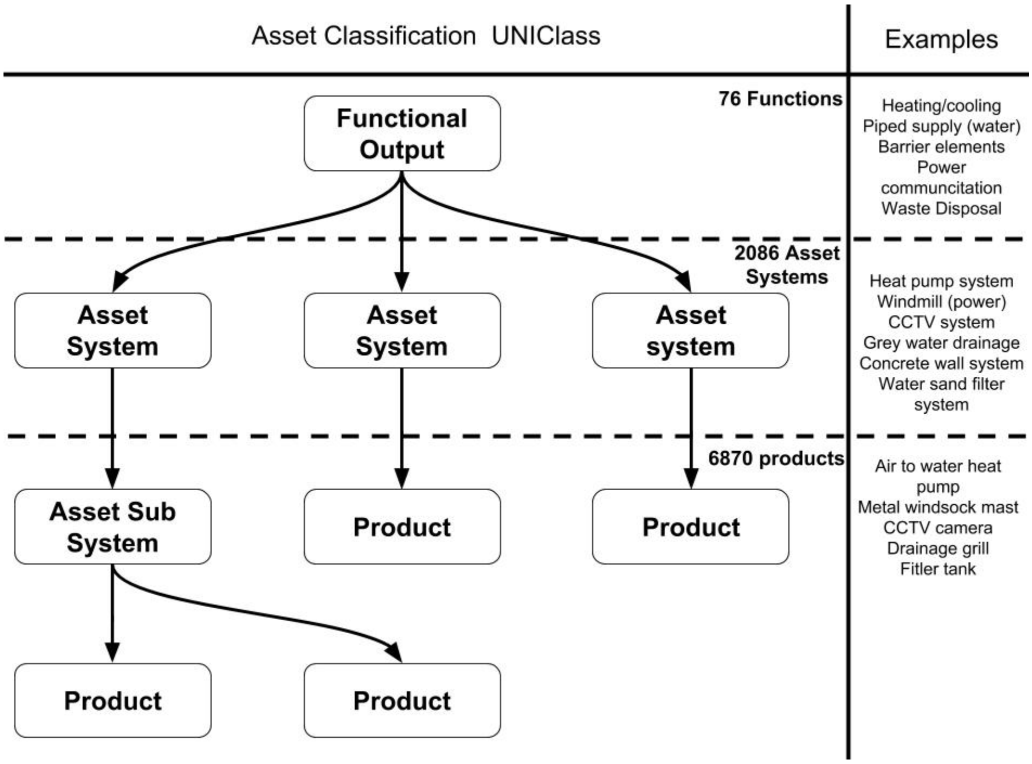

Figure 3 Asset classification hierarchy

The critical outcome of this step is a documented classification system that comprehensively defines and captures the relationship between physical assets.

3.2 Classification of the BIM model

The second step is to implement the newly established asset classification system within a BIM model. Individual BIM objects are classified as per their functional output, asset system and product (if required). As an example, a BIM object model of a radiator would have the classification of the functional output of (heating), asset system (central heating system) and the product (radiator). This classification must be completed directly within the BIM modelling software. Object filtering and the development of specific views within the modelling tools can aid in the selection of objects and the classification of multiple objects at the same time.

By default, BIM modelling software (to date) does not provide the attributes required to classify objects by the functional asset output and asset systems [37]. This is due to the fact that more than one attribute is required for classification. Furthermore, the IFC schema lacks a property set that is specific to asset classification [54]. Property sets are used to assign individual data entries or properties to IFC objects. Major BIM modelling software such as Autodesk Revit [55], Bentley

MicroStation [56] and Graphisoft ArchiCAD [57], provide the functionality to create user-defined requirement based on the object category, type or family. Revit allows for the creation of custom parameters, while MicroStation and ArchiCAD support the creation of user-defined attributes. To support the open source exchange of a BIM model, it is necessary to map the customer parameters/attributes to IFC property sets so that they appear within an IFC export. Due to the current lack of a suitable IFC property, it is necessary to create a new one (`Pset_classification`). Most major BIM modelling tools allow for the development of custom IFC property sets that can be embedded within an IFC export. Figure 4 demonstrates the development of a new IFC property set, called `Pset_Classification`, and its mapping. The left column is the name of the custom parameters developed within the BIM model, the middle column defines the data type and the last column is the name of the parameter within the property set.

```
#
# User Defined PropertySet Definition File
#
 Format:
       PropertySet:    Pset_Classification     I       IfcElementType
       FunClassification       Text    FunClassification
       GroupClassificayion     Text    GroupClassification
       SystemClassification    Text    SystemClassification
       SubSystemClassification Text    SubSystemClassification
```

Figure 4 Revit custom IFC property set, mapping from custom parameters to IFC elements

The outcome of this step is a comprehensive BIM model where all objects are classified as per their functional output and asset systems. Custom parameters or attributes need to be created to support the various classification requirements. Furthermore, the custom parameters/attributes must be mapped to a new IFC property set.

3.3 AIM database development

The third step is to develop a database that supports the requirements of an AIM as defined within section 2.2, most importantly acting as a central repository and having the ability to integrate with existing enterprise systems. Furthermore, the AIM needs to support the design and development of asset management, including asset operational performance management, financial management and risk management. As such, it is critical that the database represents the structure of the organisational assets, including the relationships between the different asset systems and functional outputs.

It is proposed to utilise the already developed asset classification within Step 1 to support the development of a relational database such as SQL or Microsoft Access. The links between the hierarchical asset classification (see Figure 3) are utilised to create primary and foreign key links between the database tables. Exploiting this approach supports the capture of information at the required level, such as capturing the set temperature of the functional output of heating for a given building or the electricity consumption for a given electric heating system.

The outcome of this step is a developed database that is designed around the asset classification definition and hierarchical relationships. The database should allow for the flexibility of integration with enterprise software through an API or similar.

3.4 Extraction platform design and development

The fourth and last step requires an application to be developed that extracts BIM objects directly from an exported IFC model and groups them by their classification for importing into the AIM database. The platform must be capable of extracting, filtering, merging and exporting individual BIM objects, including all their attributes, not just limited to the newly created classification attributes. The design of the platform should be based on the asset classification developed within step one, extracting objects firstly by their functional output, then moving to asset systems and sub-systems when required.

There are several applications and source codes that can aid in platform development. IfcOpenShell is a Python module that supports the manipulation of an IFC file within a Python build application [58]. FME Desktop is a data integration and manipulation application that supports the direct import of an IFC file for editing within a visual interface [59]. Finally, the whole IFC schema is a STEP physical file structure that is defined in ISO 10303 and the schema is provided in full under an open source licence, allowing for self-development around the schema.

4 Case Study

This section demonstrates the implementation of the above methodology to develop a systematic BIM and AIM for the Institute for Manufacturing building at the University of Cambridge. This was carried out as part of a larger research effort to develop a digital twin of the building and the surrounding campus funded by the Centre for Digital Built Britain [60] and the Centre for Smart Infrastructure and Construction [61].

The university asset management team provides all the university O&M requirements while controlling the financial cost, allocating resources within the schedule and managing the commissioning of new assets or buildings into operational use. Furthermore, the team also manages the Information Technology (IT) infrastructure and architecture that support the requirements of financial management, resource allocation and O&M management, which are mostly within enterprise solutions. Historically the asset management team has struggled to report efficiently and respond to an asset's performance (financial or non-financial) and are therefore forced to respond reactively to poor asset performance. This is partly due to a lack of good information management processes within the department. Recently, the asset management team embarked on a digital transformation strategy with a strong focus on adopting BIM. While BIM adoption has been successful within the design and construction of new assets and buildings, the commissioning of them into operational use has been less successful. The asset management team notes that the BIM model is "simply not fit for purpose" and does not meet their requirements, with often bulk COBie excel sheets handed over with little structure in place. This is a pressing issue, with several new buildings coming into use within the next year that have been developed within BIM models. To address these issues the asset management team adopted the methodology presented within this paper.

4.1 Case Study approach

The case study implemented the BIM extraction methodology as shown in Figure 3. Asset classification development involved four semi-formal workshops with 4 to 6 personnel from the asset management team. UNIClass was used as a support tool to help identify the assets that are within the asset portfolio. Furthermore, an extensive review of asset management documentation, including an asset register, was utilised to gain an understanding of the kinds of assets that are maintained and operated. Both the BIM model and database development were developed in line with best practice after an extensive literature review. Furthermore, fortnightly to monthly meetings were organised to ensure that the BIM objects were classified correctly in line with Estate Management's requirements. Finally, the extraction platform was focused on usability, so that staff who are not software experts could use the platform, and to allow for possible extension as the asset classification grows within the organisation.

The overall outcomes and results from the case study were reviewed in three aspects. Firstly, interviews were conducted to gain feedback from key personnel from the asset management team, including managerial and technical personnel. Secondly, the efficiency of the process itself was reviewed, analysing the effort required for the classification process and the amount of BIM objects transferred from the BIM model to the AIM. Thirdly, the utility of using the AIM to aid in the asset management team in creating better-informed decisions around their assets was analysed.

Finally, the approach presented in this paper was compared to existing methodologies within this field, with key challenges and lessons learnt highlighted.

4.2 Asset system classification development

The first step of the research was to develop a physical asset classification system, as none was currently being used by both the BIM management team and asset management team. While the asset management team strived to utilise a uniformed approach to asset naming, the manual and vast amount of data input inherently create inconsistencies within the datasets, making it impossible to find and extract the data within a structured process.

Several workshops were held with crucial O&M personnel from the asset management team, to gain insight into the physical assets that they maintain including Mechanical Electrical Plumbing (MEP), architectural and structural. Flow diagrams were hand drawn to illustrate the asset hierarchicy and relationships to other asset systems. An export of the existing asset register was analysed and classified to UNIClass standard [48], providing further evidence of the completeness of the developed classification system.

Once the full breadth of the asset portfolio was classified, there was a need to capture the definitions and relationships within a structured approach. UML diagrams were used to demonstrate the asset classification structure. UML was chosen for the modelling language due it is usability, flexibility and visualisation aspects. Furthermore, UML can be used to aid future database development. Figure 5 provides an example of the asset classification hierarchy for the functional output of heating within a UML concepts model that was developed using Enterprise Architecture (EA) [62]. The diagram runs top down, with high-level function at the top and asset systems and sub-systems at the bottom. In this example, the functional output is heating, that supports heating of space (in comparison to the heating of a railway track), and is delivered by multiple systems and sub-systems such as solar heating, direct gas-fired central heating and electric heating. The arrows highlight the relationship between the functional output, asset system and sub-systems. In total, 42 functional outputs and associated asset systems have been defined and relationships modelled, with each functional output having an individual UML concept diagram.

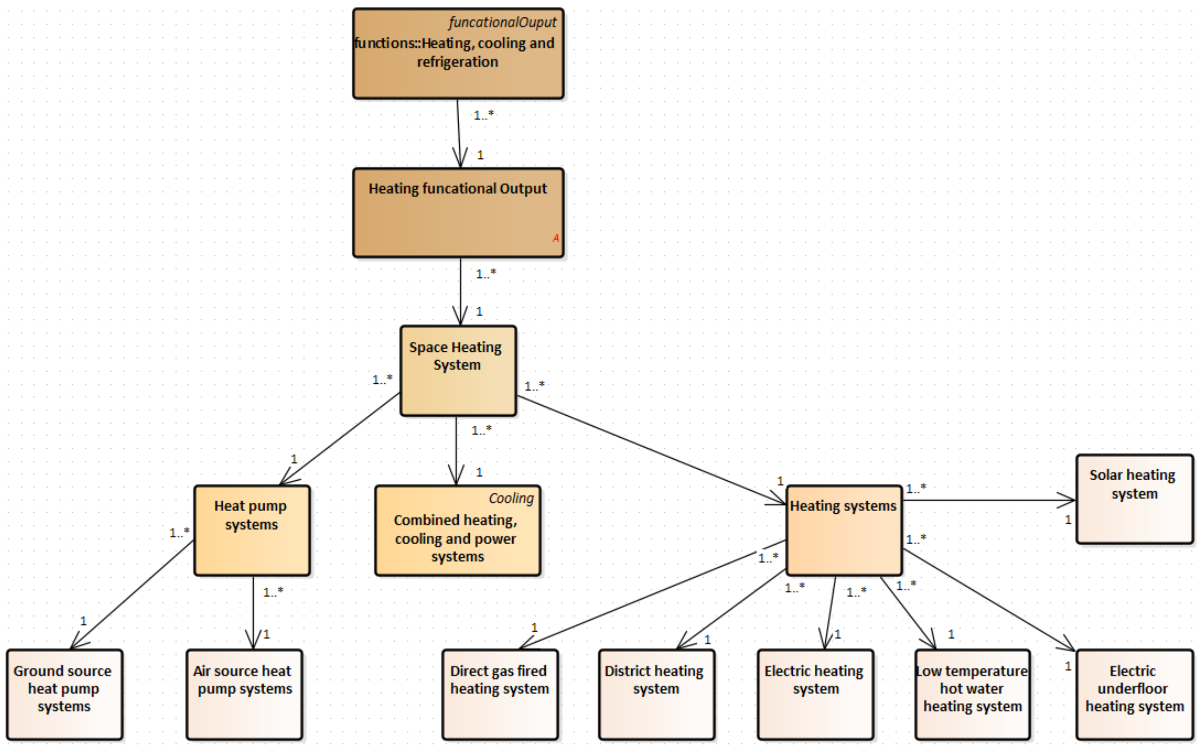

Figure 5 UML concept diagram of an asset classification hierarchy

4.3 BIM model development and classification

As part of the Digital Twin research project, a comprehensive BIM model including the architectural, structural and MEP objects was developed. Figure 6 illustrates the BIM model, the left-hand side provides an overview of the full model, while the right-hand illustrates a snapshot of the MEP elements including ventilation (extract and supply), lighting, plumbing and water supply for a section of the building.

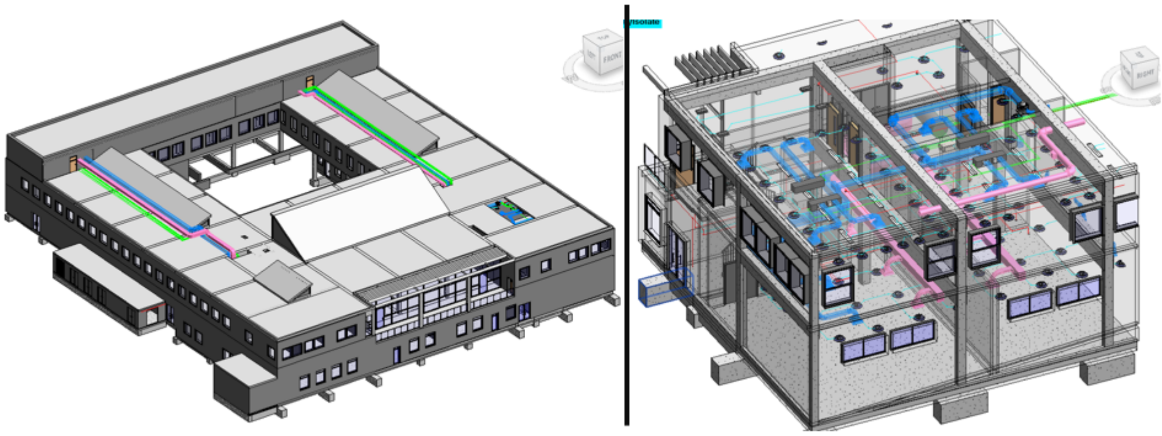

Figure 6 BIM model with architectural, structural and MEP objects

The Digital Twin BIM model was created in Revit and therefore the required custom parameters were created to support the classification hierarchy (see Figure 5) including functional output, functional group, asset system, asset subsystem and product. The customer parameters were created using the parameters manager tool within Revit, the new parameters were associated with all object family and categories, meaning every object within the BIM model could be classified. Figure 7 illustrates the five custom parameters within the properties panel when selecting a BIM object of a supply air ventilation duct. The asset functional output, system and sub-system have all been populated for the required BIM object. Views and filters were utilised within the BIM modelling software to select multiple BIM objects of the same functional output and asset system to optimise the BIM model classification process.

The final task was to map the newly created customer parameters to a new IFC property set. Revit has a built-in text-based function that allows for the mapping of customer parameters to new IFC elements. This feature was used to ensure that the customer parameters were imbedded within an exported IFC model, see Figure 4. The result is a newly created property set called `PSet_Classification` that can be utilised by any enterprise software that supports integration with IFC models.

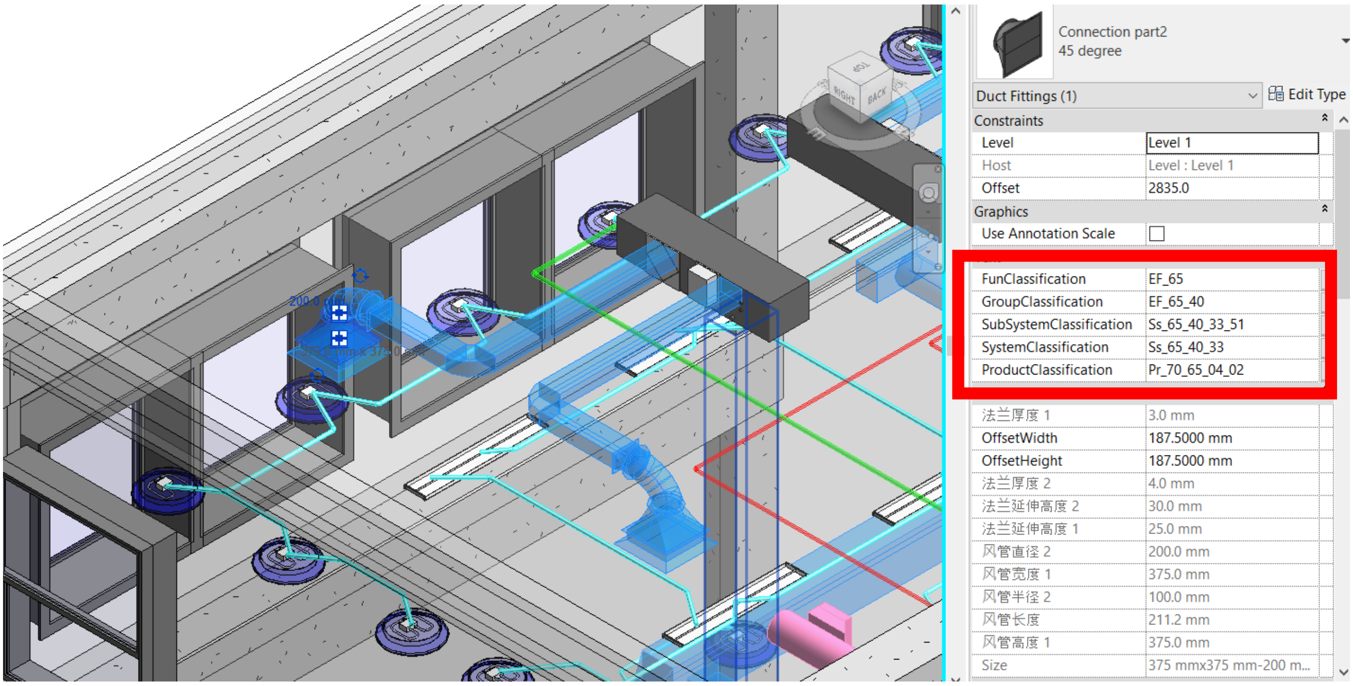

Figure 7 Asset hierarchy classification within the BIM model

4.4 Database Development

The third step is to develop a database that supports the requirements of the AIM and the broader asset management requirements of the organisation. The database development process utilises the 42 conceptual UML diagrams developed in Step 1. An example of such a UML diagram is shown in Figure 5. The conceptual diagrams were further developed into data modelling diagrams. This includes modelling the individual tables, relationships, indexing and columns, including their constraints such as data types, range and character limits. A single table within the database was created for each functional output, asset system, subsystem and product that are in the BIM model. Each table includes the following columns: asset classification, object name and a Global ID generated by the BIM modelling software. The arrows within the UML models were used to develop the primary and foreign keys within a SQL schema, with the classification codes themselves acting as the keys to ensure consistency within the Database. As an example, it would not be possible to put the asset system of solar heating under the function of cooling. Enterprise Architecture (EA) was used as the UML modelling tool and the Database Builder add-on was utilised to automatically develop a SQL database based on the data modelling diagrams. Furthermore, while out of the scope of this paper, it was noted that there is an opportunity at this stage to develop the organisational information requirements in the database model. A process for developing organisational information requirements can be found in [63].

4.5 Extraction Platform

The final step is to develop the extraction platform that enables the export of BIM objects data directly from an IFC model. FME Desktop was the application of choice due to its flexibility and repeatable workflows [59]. Furthermore, it is capable of reading in native IFC files. Figure 8 provides a visual illustration of the extraction platform within the FME Desktop workplace environment. Sections 1, 2 and 3 highlighted within the figure are explained in more detail below, the sequence goes in logical order from left to right.

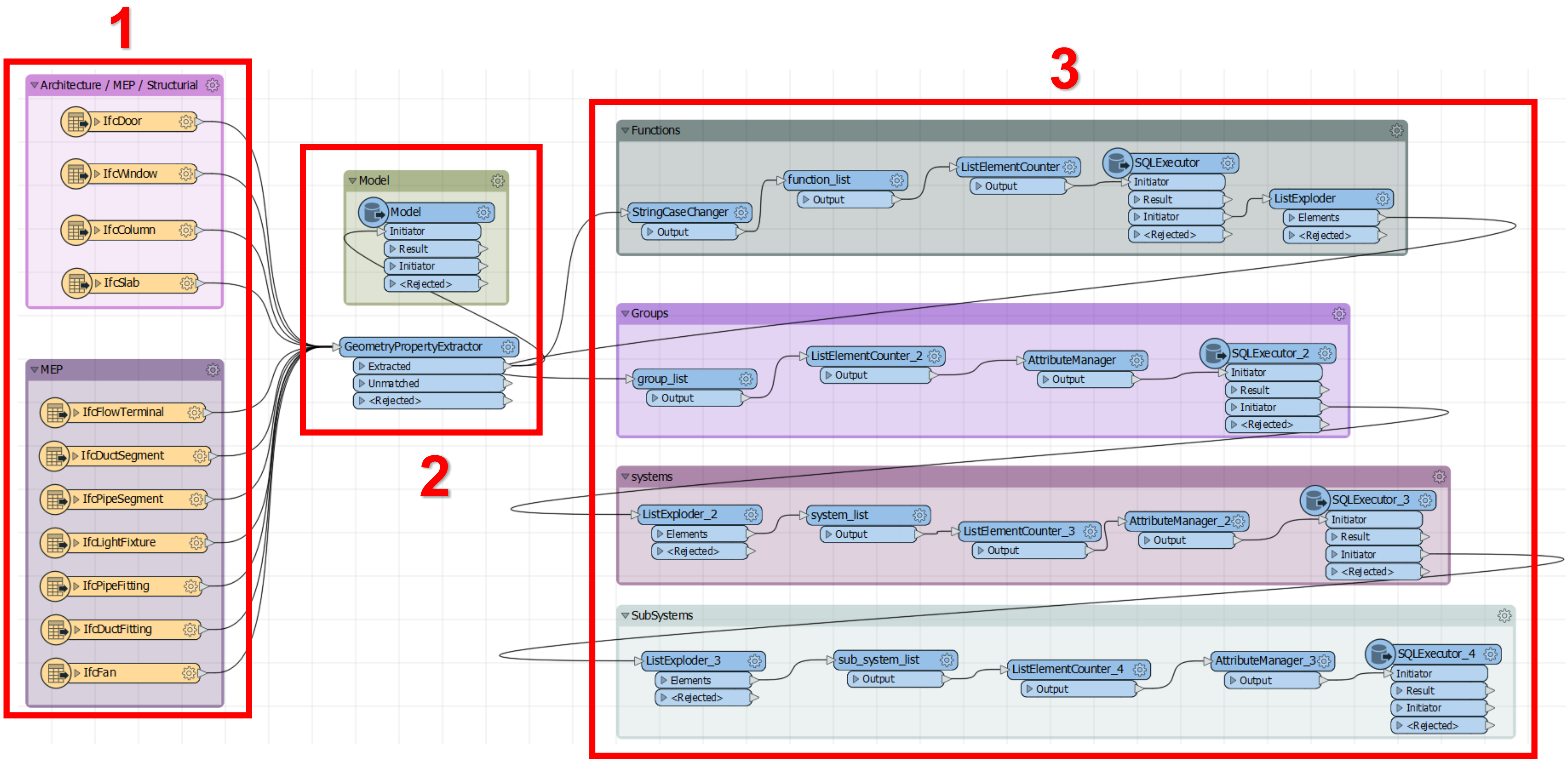

Figure 8 Overview of the BIM model extraction platform in FME Desktop

- Section 1 – This is where the IFC model is imported within FME Desktop, which is noted by the yellow rectangles and grouped in MEP and architectural/structural elements. Even though there is only one IFC model of the Digital Twin, when importing the IFC model into FME Desktop, the individual BIM objects such as doors, windows and walls are imported as individual groups as they are defined within the IFC schemas such as `IFCDoors`, `IFCWindows` and `IFCWalls`. This is because IFC models are complex and have many data points in them that are not required for this step, and separating the IFC elements and just reading the specific requirements allows for a more optimised platform.
- Section 2 – This is where the classified parameters for each BIM object are exposed. This involves performing a Geometry Property Extractor (GPE), which includes exposing the newly developed IFC classification property set (see Figure 4) into FME Desktop. The GPE works by extracting any given attribute from geometry (or BIM objects) within the model. In this case, the GPE is used to extract the associated classification within a BIM object. These parameters are used downstream in the process to support grouping and formatting for inserting into a SQL database. Furthermore, a full export of the raw BIM model data is exported into a single table called 'model' within the database. This allows for future analytics of the data without the constraints of the SQL database as a whole.
- Section 3 – This is where the data is validated, grouped, stored and directly inserted into the AIM database. Firstly, the data is validated to ensure it conforms to the database schema requirements, this includes removing symbols, changing characters from upper case to lower case and ensuring that the character length is within the limits. Secondly, the data is grouped into lists (array) based on their classification. As an example, all of the BIM objects that are classified as the functional output of heating would be grouped, while all of the BIM objects for a solar heating system would also be grouped. Figure 9 shows an example of the grouping of BIM objects with the classification of ventilations, UNIClass code EF_65 within FME Desktop. The top half shows the 3D BIM objects within the group, with blue indicating a supply of air and red indicating the extraction of air. The bottom half (Table View) shows the individual BIM objects that are within the group, with each line being an individual BIM object with a unique GlobalID and IFC Unique ID, in total there are 553 BIM objects within the EF_65 list.

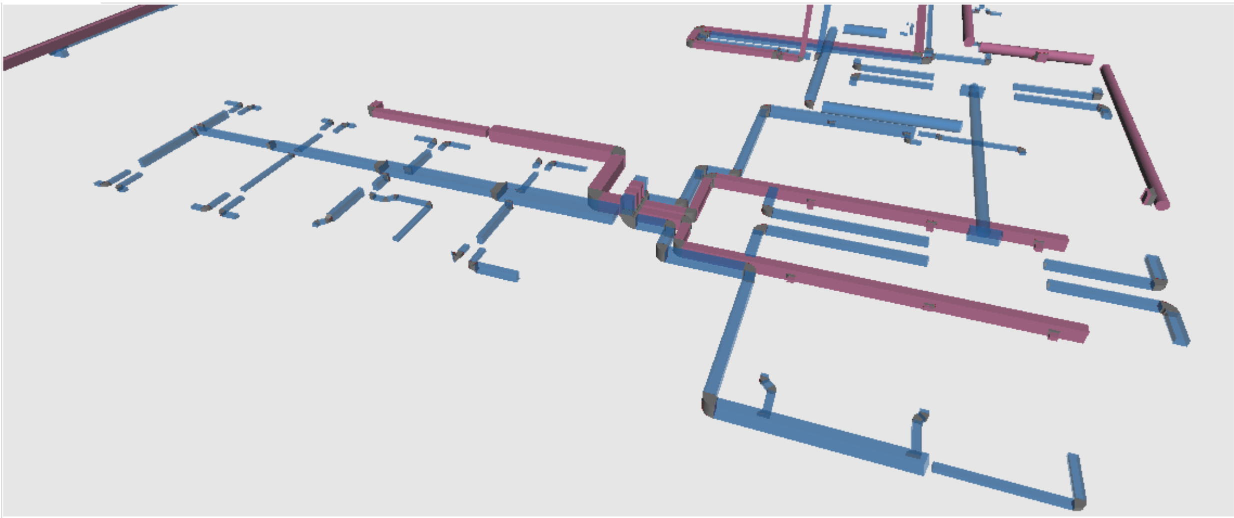

Table View

AttributeManager_4_Output - AttributeManager_4_Output

	GlobalId	ifc_unique_id	FunClassification	GroupClassificatio	SubSystemClassification	SystemClassification
130	1A$A23BKf1lvnoF5KGCMtq	1A$A23BKf1lvnoF5KGCMtq_682217	EF_65	EF_65_40	Ss_65_40_33_51	Ss_65_40_33
131	1A$A23BKf1lvnoF5KGCMt$	1A$A23BKf1lvnoF5KGCMt$_682452	EF_65	EF_65_40	Ss_65_40_33_51	Ss_65_40_33
132	1A$A23BKf1lvnoF5KGCMrU	1A$A23BKf1lvnoF5KGCMrU_682586	EF_65	EF_65_40	Ss_65_40_33_51	Ss_65_40_33
133	1A$A23BKf1lvnoF5KGCMrc	1A$A23BKf1lvnoF5KGCMrc_682821	EF_65	EF_65_40	Ss_65_40_33_51	Ss_65_40_33
134	1A$A23BKf1lvnoF5KGCMwD	1A$A23BKf1lvnoF5KGCMwD_682953	EF_65	EF_65_40	Ss_65_40_33_51	Ss_65_40_33
135	1A$A23BKf1lvnoF5KGCMwQ	1A$A23BKf1lvnoF5KGCMwQ_683188	EF_65	EF_65_40	Ss_65_40_33_51	Ss_65_40_33
136	1A$A23BKf1lvnoF5KGCMup	1A$A23BKf1lvnoF5KGCMup_683320	EF_65	EF_65_40	Ss_65_40_33_51	Ss_65_40_33

Figure 9 Grouping of BIM objects for the functional output of ventilation

Thirdly, the individual BIM object (instances) within the list are counted, and this provides a total of BIM objects within a given function output or asset system. As an example, the functional output of heating has four asset systems with a total of 324 BIM objects within it, as can be seen within Table 2.

Finally, a SQL Executor is used to create SQL `INSERT` statements based on the lists and associated classification. Furthermore, the SQL Executor also executes the `INSERT` statement on the AIM database. This process is repeated four times (highlighted by the four different colour rectangles within section 3) for the functional output, asset system, asset sub-system and product. After each step the list is "exploded" to allow a new list to be created based on the next level of classification. As an example, the list for the functional output of heating is "exploded" to allow for the creation of a list for heating systems such as gas and electric heating systems.

On average, the time for the platform to import the IFC model, expose the geometry properties including the classification and `INSERT` the data into the appropriate tables was 3 minutes and 40 seconds. The platform was run 5 times by the authors on the same personal computer with the same IFC model and the data being inserted into a localhost MYSQL Community Edition version. The data that was inserted into the database was deleted after each run to ensure that the conditions were the same for the individual runs. Analysing the logfiles from the individual five runs we can average the times to complete section 1,2 and 3 which are noted below.

- *Section 1 – importing IFC model – average run time: 1 minute 45 sections*
- *Section 2 – exposing geometry properties – average run time: 50 seconds*
- *Section 3 – inserting data into the AIM – average run time: 1 minute and 5 seconds*

4.6 Results

Step 1 resulted in the classification of 46 functional outputs and associated asset systems and sub-systems. Workshops were held with key personnel from the asset management team in order to gain an understanding of the critical functional outputs and the complexity of the asset systems. The team chose to use UNIClass as the classification system due to its hierarchical nature, extensive database and well-documented website that allows for easy collaboration between teams. Finally, the results of the workshops and documentation review resulted in the development of a set of 46 UML diagrams for visualisation and future database development. An example of such a UML diagram is provided in figure 5.

Step 2 saw the newly developed classification system embedded into the BIM objects within the BIM model. The initial classification process took 3 working days to complete. Furthermore, as the classification system was being developed, the research team had regular meetings with the asset management team, and the classification in the BIM model was updated and edited several times throughout the process. A summary of the classification in the BIM model is summarised in Table 2, highlighting the total number of BIM objects within each functional output, asset system and subsystem with associated UNIClass codes.

Table 2 Summary of BIM objects classification within the BIM model

Function	Instances	Group	Instances	Asset System	Instances	Asset Subsystem	Instances
Structural elements EF_20	243	Substructure EF_20_05	76	Concrete foundation SS_20_05_15	76	Reinforced concrete pad and strip foundation SS_20_05_15_70	76
		Columns EF_20_30	167	Structural columns SS_20_30_75	167	Structural concrete columns SS_20_05_75_15	167
Wall and barrier elements EF_25	263	Doors and windows EF_25_30	263	Doors, shutters and hatches SS_25_30_20	92	Frame and door leaf set SS_25_30_20_30	86
						Hing doorset SS_25_30_20_39	5
						Sliding doorset SS_25_30_20_77	1
				Fire and smoke doors	15	Fire doorset SS_25_30_29_38	15

				SS_25_30_29			
				Windows SS_25_30_95	155	Framed external windows SS_25_30_95_26	155
Roofs, floor and paving elements **EF_30**	63	roofs EF_30_10	41	Monolithic roof structure SS_30_10_50	41	Sprayed roof concrete SS_30_10_50_70	41
		floors EF_30_20	22	Raised floor SS_30_20_70	22	Wooden raised floor system SS_30_20_70_70	22
Heating, cooling and refrigeration functions **EF_60**	717	Space heating and cooling EF_60_40	717	Cooling systems SS_60_40_17	717	Variable refrigerant flow system SS_60_40_17_94	717
Ventilation and air conditioning functions **EF_65**	553	ventilation EF_65_40	553	Space ventilation SS_65_40_33	553	Mechanical extract ventilation SS_65_40_33_50	121
						Mechanical supply ventilation SS_65_40_33_51	432
Electrical power and lighting functions **EF_70**	3951	Lighting EF_70_80	3951	Space lighting SS_70_80_33	3951	Hard-wired general lighting SS_70_80_33_35	3951
Communications, security, safety and protection functions **EF_75**	1452	Safety and protection EF_75_50	1425	Detection and alarm system SS_75_50_28	1452	Fire detection and alarm system SS_75_50_28_29	1524

Step 3 takes the UML diagrams developed in step 2 and further develops them into the AIM database schema with the relationships between the functional output, asset system and subsystems were used as the primary key and foreign key, resulting in a total of 149 tables created. Figure 9 is an Enhanced Entity-Relationship (EER) diagram that demonstrates the relationships between tables for the functional output of barrier (ef_25), category of doors and windows (ef_25_30), asset system of doors (ss_25_30_20) and assets of fire doors (ss_25_30_20_35) and internal doors (ss_25_30_20_30).

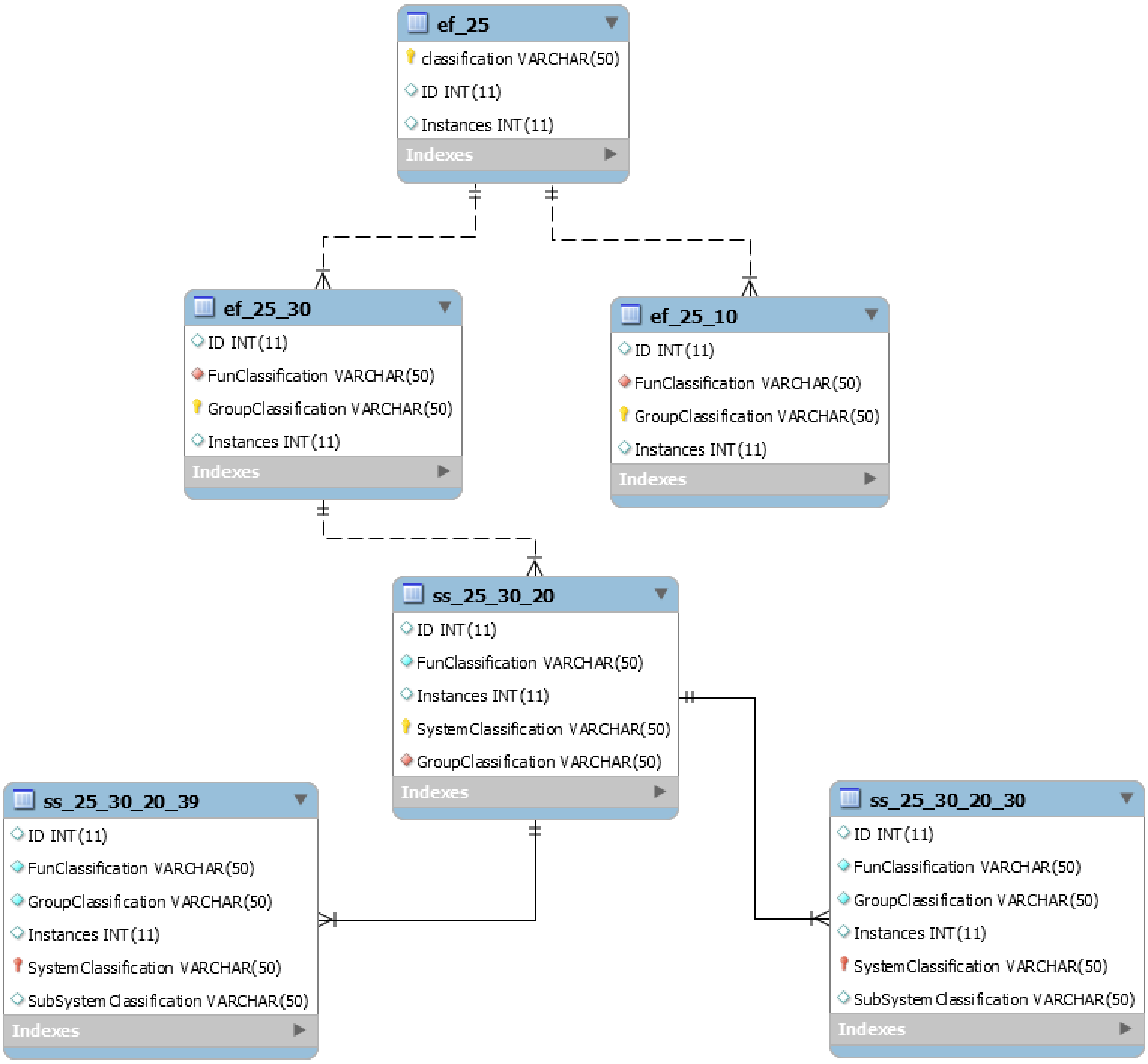

Figure 8 Example EER diagram from the AIM

Step 4 demonstrated how the extraction platform was able to read in the native IFC model export from the BIM modelling software. The platform used the newly created classification within the IFC model to group BIM objects and insert the associated data into the AIM. Furthermore, all of the BIM objects were inserted in a single table called Model, including objects that have not been classified. Quite a few BIM objects in the model were not classified due to the fact that several objects did not represent the functional output of any asset, only objects that have a functional output are classified and therefore exported into the AIM. One example is ‘zones’ and ‘rooms’ which act as 3D objects of an enclosed space (such as an office) or an associated zone (such as an open-planned kitchen). These objects are exported in the IFC model as `IFCSpace` but are not classified and therefore not within the AIM. Other objects that are exported and not included in the AIM are annotation (text, polyline, hatch, polygon), site survey points and landscaping.

When examining the Model table within the AIM, which contains both classified and non-classified objects a total of 8,482 BIM objects have been exported from the IFC model. In Table 2 we can see the total number of BIM objects classified is 7,242. When comparing these two numbers, there is a total of 1,240 BIM objects in the BIM model that have not been exported into the AIM. These objects did not perform a functional output and therefore were not required in the AIM, as described above. Furthermore, when comparing the 7,242 objects in the AIM against the original classified BIM model, it was witnessed that all of the objects were successfully imported.

4.7 Challenges and limitations

This section provides an overview of the challenges faced in implementing the above-mentioned framework in the case study and the limitations of the approach.

- **Stakeholder engagement**. Ensuring that the correct managerial and technical level personnel were present at the workshops for the asset classification development was a challenge. A greater emphasis should be put on stakeholder engagement and selection [64].
- **Classification**. Current approaches only allow for a single classification of a functional output, which was a challenge when considering assets with multiple functional outputs, such as a reverse cycle air supply system that supports the functional output of heating, cooling and ventilation. This was addressed in the case study by determining its "primary" functional output by developing a consensus amongst stakeholders. A more evidence-driven approach could be developed for this step.
- **Resource-intensive retrofitting**. In this case study, the BIM model was already developed before the asset classification was developed, resulting in the BIM model being classified retrospectively. Despite the effort in creating views, filters and selection lists, it was often a manual task to select individual objects and classify them, which was time-consuming. All effort should be taken to ensure a classification system is developed and documented before modelling starts. Furthermore, a standard library of BIM objects would allow for objects to be pre-classified in their settings, thereby eliminating the need for manual classification.
- **Integration with legacy systems**. While the AIM development followed the same logic as the asset classification and was developed to support the integration of multiple asset management systems, it did not directly communicate with them. This is partly due to the fact that the asset

management team had never used a standard classification system and struggled with an array of legacy enterprise systems with inadequate integration tools. It was noted that the same classification used in the BIM model should be used within all of the asset management systems, including financial management, risk management and resource allocation, thereby creating a link from BIM to AIM and the existing asset management system.

- **IFC Schema limitations**. Due to the limitations in the current IFC schema, the extraction platform is limited in exporting IFC properties that are mapped to custom parameters within the given BIM models. To use the platform, a custom property set is required. To date, the IFC schema is unable to support multiple classification codes on an individual BIM object. Future research should aim to aid the ability for hierarchical asset classification within the default schema.

It was also noted that further work and documentation would be needed for the methodology to be used by industrial practitioners on a large scale without the support of the authors.

5 Conclusions

This paper proposes a methodology that allows for the development of an AIM. Specifically, it supports the exchange of data directly from an IFC into a relational database based on BIM object classification. This addresses one of the critical challenges of exchanging BIM-related information from the design and construction phases into the O&M phase.

The literature review (section 2) reviewed the many standards and specifications within BIM, asset management both as a research domain and industry practice, and the design and development of an AIM. It was noted that while there is a specific specification on how to harness BIM within the O&M phase (PAS 1192-3), there is a lack of methodologies, tools and frameworks to support its implementation. Furthermore, it can be witnessed that one of the key challenges of asset management is the management of information throughout its life.

The methodology section introduced a four-step process comprising the development of a hierarchical asset classification system, classification of a BIM model, development of an AIM and design and development of a BIM object extraction platform.

A case study was presented that implemented the above methodology within an existing industry collaborative research effort. The case study demonstrated the fact that the development of an asset classification system is key to the development of an AIM. Custom parameters were created within the BIM model to support the capture of hierarchical classification directly on the BIM objects. Furthermore, the parameters were mapped to a new IFC property set to ensure they are within an IFC export. A SQL database was developed utilising the conceptual UML diagrams from the hierarchical classification to develop SQL modelling diagrams. Finally, a BIM object extraction platform was developed that supported the extraction of BIM objects directly from an IFC file into the newly developed SQL database.

Future research should focus on how this methodology can support greater integration of BIM within asset management. Firstly, an AIM must be properly defined since its current broad definition is limiting research focus and also industrial applications. Secondly, research into the development of new IFC element classes and property sets that support hierarchical asset classification needs to be completed. Finally, the challenges and possible approaches to linking enterprise asset management software to an AIM need to be explored.

Acknowledgements

This research was supported by the Engineering and Physical Sciences Research Council and Costain Plc through an Industrial CASE Award (voucher number 16000184). The authors also thank the support of the EPSRC Innovation and Knowledge Centre for Smart Infrastructure and Construction (EP/N021614/1) as well as the Centre for Digital Built Britain.

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