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BIM for Facilities Management: a Framework and a Common Data Environment using Open Standards

Abstract

BIM for Facilities Management (BIM for FM) is a relatively new and growing topic of inquiry aiming to fulfil the informational needs of the operational phase of assets within increasingly digitalised project workflows. Research into the management of structured (i.e. graphical and non-graphical) and unstructured data (i.e. documents) has largely focused on design and construction phases. Information management in facilities management and maintenance is still challenged by the lack of a structured framework that can simultaneously fulfil these three capabilities: (1) the delivery of information models (i.e. Asset Information Models) from distributed data sources; (2) the validation of these information models against the requirements; and (3) the use of their information in facilities management (e.g. operation and maintenance). This research aims to develop and test a framework and a prototype Common Data Environment (CDE) to achieve these three capabilities.

The framework and the developed CDE are entirely based on use open standards and integration of existing technologies. A requirements model, underpinning the framework and the CDE was developed during three iterative stages of interviews –in line with the adopted Grounded Theory and Design Science Research methodologies – with industry experts and through a three-stage coding process at each iteration. The framework and the CDE were tested in pilot demonstrations with a use case focused on preventive and reactive maintenance. The testing demonstrated that the implementation of 'BIM for FM' processes is feasible with the proposed framework and CDE using only open standards and existing technologies. Some additional requirements for BIM for FM processes were also identified during the verification sessions with industry and are proposed for future research.

Keywords: Asset Information Model, Asset Information Requirements, Building Information Modelling, Common Data Environment, Facilities Management, Maintenance.

1 Introduction

Accurate and reliable data is essential to operating and maintaining built assets efficiently (Atkin & Brooks, 2009). Data and information that is generated during planning, design and construction is key to accelerate handover and commissioning of built assets (Kassem *et al.*, 2015). However, their handover is usually left until the completion of the construction phase, and typically unfolds in an unstructured way resulting in a labour intensive and error-prone process (Gallaher *et al.*, 2004; Jang and Collinge, 2020). This also adds to the challenges of verification and validation of handed over information (Carbonari *et al.*, 2015).

BIM tools, workflows and their enabling standards provide the opportunity to efficiently manage data exchanges throughout the whole built asset life cycle, including the operational phase. BIM is the current expression of digital innovation in the construction sector (Succar & Kassem, 2015), and can be defined as a digital representation of physical and functional characteristics of a facility, forming a reliable basis for decisions during its life cycle, from earliest conception to demolition (NIBS, 2019).

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To date, as evidenced by the review of existing studies, a solution that addresses the entire BIM for FM workflow from the definition of information requirements, through the development of the data container (i.e. Asset Information Model (AIM) – which represents the data and information deliverables produced to fulfil the specified facilities management requirements), to management of the data container and its use in operation, is lacking. This paper addresses this gap by proposing both a framework and a prototype (called Common Data Environment – CDE) for a holistic BIM for FM workflow addressing information specification, verification, and use.

The paper is organised as follows: Section 2 analyses the state-of-the-art of BIM for FM studies, the relevant standards, and methods used for information verification. Section 3 presents the research methodology in detail. Section 4 explains the framework, the processes that underpinned its development, and its workflows. Section 5 describes the CDE implementation and demonstrates its application in pilot projects. Section 6 presents the results from the validation process of the framework and the CDE. Section 7 summarises the research contributions and limitations of the study, and finally section 8 presents the conclusions of the study.

2 State-of-the-Art review

This section analyses three areas that are related to the core of the proposed research. These include: (1) current BIM for FM academic studies; (2) existing standards that can be used to support the various processes involved in a BIM for FM workflow, and in particular standards for requirements definition and management of data deliverables (i.e. AIM); and (3) compliance checking methods, that can be adopted to ensure the data quality during the development of AIMs.

2.1 BIM for FM: Related studies

BIM can be used by building owners and facilities managers as an information source to support the planning and management of building maintenance activities in both new and existing buildings (Volk *et al.*, 2014). BIM tools and workflows are providing opportunities for integrating the operational phase of built assets with upstream project phases (Patacas *et al.*, 2015). This integration requires adequate workflows, tools and standards to be implemented in order to enable the definition, delivery and management of the information needed for facilities management (Eastman *et al.*, 2011). The potential use of BIM in FM applications was realised from the early stages of the development of the Industry Foundation Classes (IFC) standard. Studies proposing open BIM data models to enable information sharing among computer applications including facilities management applications go back to the early 2000s. Yu *et al.*, (2000) proposed a data model for facilities (i.e. facilities management core model) that included a mapping between IFC and the facilities management domain requirements. In addition to the need for adequate tools, workflows and standards, one of the key challenges facing integration of facilities management into upstream project phases is the need for flexibility to support different use cases depending on project and user roles (Kang & Choi, 2013).

Traditionally, FM data and information are organised and maintained in dispersed information systems such as Computerised Maintenance Management Systems (CMMS), Electronic Document Management Systems (EDMS), Building Automation Systems (BAS), etc. The information and data required for such systems comes from different sources, is created and manipulated several times during the assets life cycle, and is usually not synchronised between systems, resulting in error-prone processes (Becerik-Gerber *et al.*, 2012). Korpela *et al.*, (2015) highlighted the challenges in the integration of several IT systems used for the maintenance of the Center for Properties and Facilities of the University of Helsinki, and how BIM could help address these challenges. The authors proposed that only a subset of BIM data (i.e. a simplified BIM model) is needed for FM and maintenance, and that the definition of such data requirements is essential for the successful integration of various FM and maintenance systems.

Carbonari *et al.*, (2015) proposed a simplified remodelling process for existing facilities considering the facility management strategy. Pishdad-Bozorgi *et al.*, (2018) proposed the development of building information models containing FM data required for FM tasks such as space analysis, retrofitting, and preventive maintenance, and applied their approach in the context of an existing building in the higher education sector. Lin *et al.*, (2016) proposed the development of a BIM execution plan to support building owners during the operational phase of buildings. The application of the proposed BIM execution plan in a case study highlighted how BIM can improve the maintenance management procedure. Motamedi *et al.*, (2014) integrated Computerised Maintenance Management Systems (CMMS) data with BIM visualisation capabilities to enhance the detection of failure root causes in FM. Rasys *et al.*, (2014) proposed an information integration framework for the management of civil and Oil & Gas facilities in which Web3D technology is used for integrating and visualising assets' 3D components and their linked FM data using class libraries. Parn & Edwards, (2017) proposed a bespoke application programming interface (API) for the integration of COBie data with semantic FM data including 3D visualisation capabilities in a design authoring application – Autodesk Revit.

The use of BIM spatial relations for visualisation and analyses of facilities data were also applied in the planning of maintenance activities and repair works in buildings (Akcamete *et al.*, 2010). Lin & Su, (2013) developed an information integration system for BIM and FM and maintenance data to enable maintenance workers to access, review and update BIM models and their related maintenance records. Shi *et al.*, (2016) developed a multi-user virtual environment based on BIM models to enable communication and collaboration to support FM tasks. Similar approaches have been proposed using a game engine for the integration of BIM models with FM data to enable planning of FM and maintenance tasks (Lee *et al.*, 2016; Carreira *et al.*, 2018). More recently, El Ammari & Hammad, (2019) proposed the integration of various sources of facilities information and BIM models through a mixed reality approach to support maintenance workers in carrying out inspection and maintenance operations on site, and provide remote collaboration with FM office staff.

The integration of BIM and Internet of Things has also been highlighted as a fundamental requirement to manage smart buildings (Panteli *et al.*, 2020; Tang *et al.*, 2020). To this end, Tang *et al.*, (2020) developed a Building Automation and Control Networks (BACnet) Model View Definition (MVD) to represent Building Automation Systems (BAS) information in IFC models, enabling its exchange throughout various project development stages using BIM tools.

Semantic web approaches have recently been proposed to achieve the integration of BIM and FM. Kim *et al.*, (2018) proposed an ontology to manage BIM-based FM information by linking the BIM-based building elements to historical work records in a FM system database. Other integration approaches for BIM and FM data have been proposed recently, focusing on the integration of mechanical, electrical and plumbing (MEP) data from as-built BIM models with maintenance data to run routine operation and maintenance (O&M) tasks and respond to MEP-related emergencies (Hu *et al.*, 2018). A similar approach was also used to enable the automatic scheduling of facility maintenance work orders (Chen *et al.*, 2018). The development of AIMs using BIM standards has also been applied to infrastructure asset management. Edmondson *et al.*, (2018) developed a prototype for a Smart Sewer AIM which integrated IFC models with distributed smart sensors, enabling real-time monitoring and reporting of sewer asset performance. Chen *et al.*, (2020) developed a facility management system based on BIM for highway tunnels and highlighted the data integration challenges and their impact on productivity through the development of a pilot study.

Interoperability challenges and unclear requirements definitions have been pointed out as the key issues that are hindering the increased adoption of BIM for FM (Gao & Pishdad-Bozorgi, 2019; Jang & Collinge, 2020). The use of open standards can help address these issues; their critical role stems from the lengthy lifespan of the operational phase which requires long-term storage and management of data for built assets (Patacas *et al.*, 2015). Open standards can be used to structure data requirements for the operational phase so they can be collected and verified during the project development, and to manage the data throughout the built asset life cycle. The PAS 1192-3: 2013 defines an Asset Information Model (AIM) as a model that compiles the structured (i.e. graphical and non-graphical) and unstructured (i.e. documents) data necessary to support asset management, and proposes the use of open standards and data specifications (e.g. IFC, COBie) for the definition of the AIM and for its interface with existing enterprise systems (BSI, 2014b). Open standards also ensure that the compliance checking procedures will be applicable in the long term, which is of interest for building owners and facility managers, when considering the lengthy lifespan of built assets.

This review provides evidence of the increased interest in BIM for FM studies, and the growing role of BIM technologies and open standards in BIM for FM processes. This focus on BIM for FM is also accompanied by significant initiatives at industry-wide level developing the supporting standards (IFC and COBie) and requiring the adoption of the corresponding BIM uses and standards in facilities management. Additionally, there is a lack of studies that systematically investigate whether and how standards can be adopted as sources of data in BIM for FM workflow including specification of information for facilities management, validation of data and information deliverables, use and management of data in facilities management. As this research intends to fills this gap, the next two sub-sections respectively analyse the relevant open standards in relation to their ability of enabling the definition of an AIM's structured and unstructured information; and the role of compliance checking methods in ensuring the quality of data included in the AIM.

2.2 Standards for AIM data sources

Industry Foundation Classes (IFC)

IFC is an open data model, developed by buildingSMART, that describes architectural, building and construction industry data. It was developed to address interoperability when exchanging data and information among disciplines involved in the delivery of built assets. The IFC schema was defined as an EXPRESS schema within ISO 10303 - Standard for the Exchange of Product model data (STEP), and it is now available in EXPRESS, XSD and OWL to allow its representation in STEP Physical File Format (SPFF), eXtensible Markup Language (XML), and the Resource Description Framework (RDF) respectively (Pauwels *et al.*, 2017). IFC is registered with ISO 16739:2018, which specifies the EXPRESS and XML data schema definitions (ISO, 2018). A JSON schema was recently proposed to streamline IFC data exchanges over the web (Afsari *et al.*, 2017). The suitability and ability of IFC to support the structured (i.e. graphical and non-graphical) data requirements of Asset Information Models was tested in Patacas *et al.*, (2015).

Construction Operations Building Information Exchange (COBie)

COBie is used to provide an organised structure for the exchange of information about built assets throughout the life cycle of facilities (NIBS, 2015). The IFC Facilities Handover model view definition specifies COBie as a subset of IFC data. The NBIMS-US V3 standard describes various COBie use cases, related to data access, reusability, and data validation. The standard defines various business processes and highlights how these benefits can be achieved through the use of COBie (NIBS, 2015). COBie was selected as the format for specifying and handing over data for the operational phase of assets in the UK BIM framework. The use of standard product data templates through initiatives such as Life-Cycle information exchange (LCie), Specifiers' Properties information exchange (SPie) and industry initiatives such as Product Data Templates (PDTs) can also streamline the delivery of facility asset data if they are widely accepted and adopted (NIBS, 2015; CIBSE, 2016). The BS 1192-4: 2014 standard was defined to provide guidance on the use of COBie in the UK context, including the transfer of structured information, between project parties, about buildings and infrastructure to fulfil the building owner (or employer) information requirements (BSI, 2014a). The suitability and ability of COBie to support the structured (i.e. graphical and non-graphical) data requirements of Asset Information Models was tested in Patacas *et al.,* (2015).

Content Management Interoperability Services (CMIS)

CMIS is an OASIS standard that supports content and information sharing between different content management systems (OASIS, 2016). Content repositories manage unstructured data sources including documents, images, videos, etc. CMIS was developed with the objective of managing unstructured data sources through the use of metadata, as well as enabling access and exchange of data between different content repositories. This is achieved by standardising repository access, data storage, retrieval, and search operations. CMIS also provides a SQL-based query language to query content through its metadata (Caruana *et al.*, 2010). Interoperability with CMIS allows the reusability of content models across various content management systems, as well as the integration of content management systems with other systems (OASIS, 2016). Using CMIS, developers can create bespoke software applications and web services for specific use cases that will work across various CMIS-compliant repositories (Müller *et al.*, 2013). Due to this flexibility, CMIS was considered a requirement in the development of the CDE for AIM, both for the structuring of data requirements as metadata, and as a standardised communication protocol between the different tools in the CDE.

2.3 Compliance checking for built assets digital data

The increased availability of semantically rich building information models and the growing capabilities of expressing projects requirements into machine computable formats have led to a surge in research into requirements validation and compliance checking methodologies. Challenges to ensure the quality of information in the development of BIM for FM applications have been recognised in recent studies that are increasingly focussing on quality assurance approaches for the preparation of FM-BIM data sets (Yang & Ergan, 2017; Zadeh *et al.*, 2017; Motamedi *et al.*, 2018).

A variety of compliance checking tools and methodologies exist nowadays focusing on providing compliance checking of project information against different types of requirements. However, research efforts in this area remain fragmented and a holistic approach to address validation and compliance checking problems in the construction industry is still lacking (Hjelseth, 2016; Solihin *et al.*, 2017).

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

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

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

With the proposed framework for the development of AIMs, rule checking approaches can provide the validation of structured (i.e. graphical and non-graphical) and unstructured (i.e. documents) data contents against structured Asset Information Requirements (AIR) throughout the life cycle of built assets.

Solihin & Eastman (2015), Hjelseth (2016) and Solihin *et al.* (2017) have proposed frameworks for the classification of automated compliance checking research efforts. An overview of data validation and compliance checking methods and tools is presented in Table 1.

Table 1. Overview of components of automated rule systems – adapted from Solihin *et al.* (2017)

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

Numerous approaches are being explored to provide compliance checking of digital data sources, however; existing efforts remain isolated, attempting either to provide solutions for automated compliance checking of building data for very specific use cases (e.g. structural regulatory requirements), or to highlight the need for standardisation of the compliance checking process (Dimyadi *et al.*, 2016).

Conventional rule checking systems typically follow a hard-coded implementation approach. In these systems, regulatory knowledge is embedded in the software code, which makes it difficult for domain experts to edit and customise the rules (Dimyadi *et al.*, 2016). Furthermore, since the majority of these systems are proprietary, it is not possible to verify the correctness of the implementation of the rules.

Approaches for automated compliance checking against data models, namely IFC, are also using semantic web standards and technologies. There are several advantages in using semantic data models for compliance checking purposes. Semantic web technologies support both the representation of data models, as well as the representation of the rules, which enables the development of logic-based approaches for compliance checking. The logic-based structure of semantic web languages enables their reuse in different rule checking environments, enabling modularity and flexibility in their implementation (Pauwels *et al.*, 2011). Semantic web technologies can also be used to represent any data model, and they can be used to validate data from several different sources. They can be used to represent the various data sources that are used in Asset Information Models, and perform automated compliance checking of these data sources. However there are still various challenges regarding the management of linked data sources, e.g. ifcOWL is not suited to handle large models efficiently (Krijnen & Beetz, 2020). A set ontologies, focusing on specific building data domains, are currently being developed by the W3C Linked Building Data Community Group to address these challenges (W3C, 2020).

Existing approaches for the validation of building data, which are generally focused on the compliance of information models against design requirements and regulations during the design development phase, are facing different challenges. A particular challenge is the translation of rules and regulations into machine readable format is not fully achievable, and novel methods such as Natural Language Processing (NLP) cannot fully automate this process (Solihin *et al.*, 2017; Zhang & El-Gohary, 2017).

Compliance checking approaches require further investigation to understand their applicability and suitability in the process of definition and validation of FM requirements within a BIM workflow. This research contributes to this area by proposing a methodology for data validation that considers the several data sources involved in the development of AIMs.

3 Research Methodology

To develop and validate the framework and the CDE prototype, this research combines the design science research and the grounded theory methodologies. The combination of the two ensures rigour across the research steps of problem definition, artefact development, demonstration and validation. The design science research methodology guides the overall development of the proposed framework and the CDE for its ability to embrace 'artefact' (i.e. framework and CDE) creation and improve it through its iterations. The grounded theory method helps to achieve an improved identification of the requirements for the proposed framework and CDE, and perform the process of verifying their internal validity.

The research methodology is illustrated in Figure 1. Using the design science research model proposed by Peffers *et al.*, (2007), the entry point for this study is Stage 1: problem identification and motivation.

The research process started with the identification of the research problem related to the integration of the operational phase of built assets with upstream project delivery, as explained in the Introduction section. Then, an understanding of the practices and issues in information and data management was needed and was fulfilled in part by the review of the state-of-the-art (Section 2) and in part through the three interactions with 15 industry experts (Figure 2).

The first interaction with four industry experts aimed to capture the requirements of the framework and the CDE. This was achieved by conducting semi-structured interviews. An interview guide was developed in advance with 12 questions, divided in four themes: benefits and challenges of BIM implementation in facilities management; maintenance and facilities management data requirements; data validation; and IT support for building maintenance. These themes were developed from the extensive literature review and the knowledge of open standards. The coding of the information obtained from the interviews and their use in the development of the proposed framework is described in Section 4.

Following the requirements capture, the framework was developed and instantiated through the implementation of the CDE. The CDE prototype was tested in a technical demonstration using three pilot projects. These pilot projects were used in live demonstrations with industry experts during two validation rounds with 11 experts. The first validation stage with five experts identified some gaps and was used to refine the framework and update the CDE. Once the identified gaps and update had been addressed, the second validation stage with the involvement of six experts was performed for the final verification of the framework and the CDE prototype, focusing on the functionalities of the framework and the usability of the prototype.

The two validation stages were supported with open-ended interviews. This was necessary to guide the discussions according to each participant’s field of expertise, and to obtain specific feedback on each of the framework and CDE functionalities. The validation helped identifying the gaps in the framework and the CDE’s functionalities by reaching ‘theoretical saturation’, i.e., no new or relevant data emerge regarding a category; categories are well developed in terms of their properties and dimensions; and the relationships among categories are well established and validated (Corbin & Strauss, 2014).

The experts involved across requirements gathering and the two validation stages are from assets owning and facility management organisations, design and contracting organisations, engineering professional services organisation, digital construction and information management organisations, commissioning and completion organisations, and specialised software engineering organisations. Their different roles allow the identification of different requirements from each of their respective fields. The profile of participants and their organisations, involved in the requirements capture, and validation stages 1 and 2, are summarised in Table 2 and Table 3, respectively.

The details of the pilot projects and the demonstrations steps and outcomes are described in Section 5.

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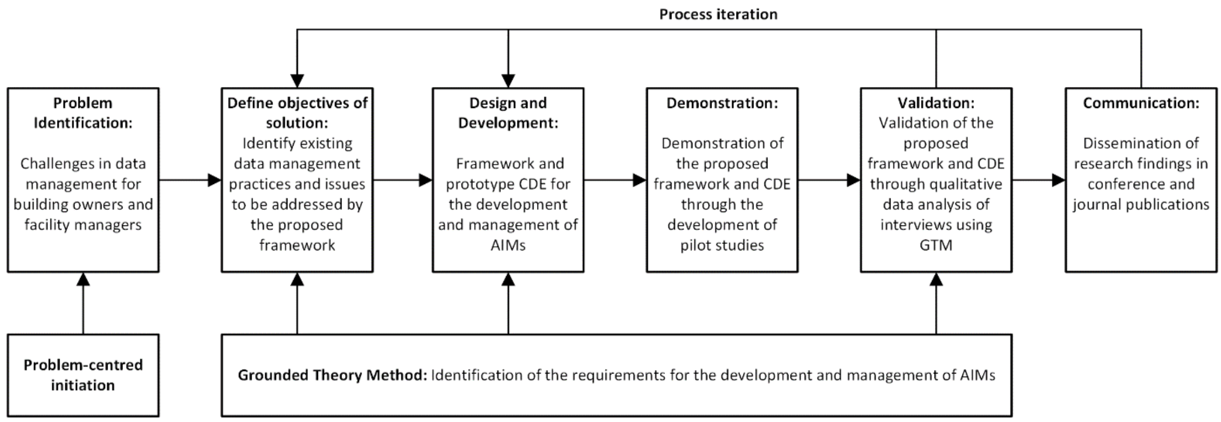


Figure 1. Research methodology

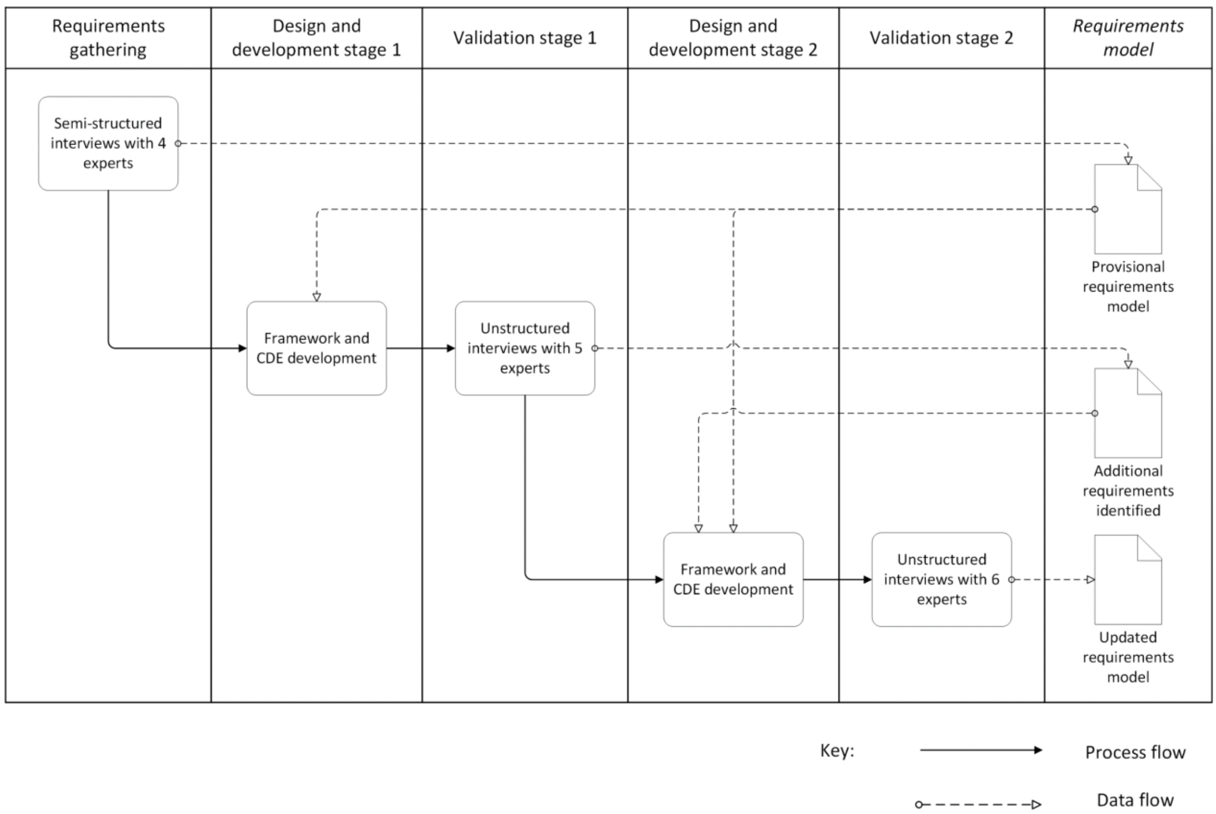


Figure 2. Requirements development strategy

Table 2. Requirements gathering: profile of participants

Expert Code	*Background/Role*	*Organisation*	*Experience (Years)*
A	Director responsible for operation of a large portfolio of assets in London	Major asset owner and manager	12

B	Director in a digital/BIM consultancy company	Leading digital and BIM for FM consultancy	10
C	Designer specialised in buildings renovation	Major design and engineering organisation	12
D	Expert and researcher in Facilities management	Higher Education	20

Table 3. Validation stages 1 and 2: profile of participants

Expert Code	Background/Role	Organisation type/profile	Experience (Years)
Validation Stage 1			
E	Director in a digital/BIM consultancy company	Consultancy specialised in information management	10
F	Software Developer, and Commissioning and Completions Coordinator for oil and gas projects	Leading Engineering Consultancy for information management in the process sector	12
G	Expert/researcher in Linked Data applications for BIM	Software development and Linked Data Consultancy	12
H	Researcher in BIM and Energy Management	Higher Education	10
I	Researcher in Construction management	Higher Education	8
Validation Stage 2			
J	Director and expert in Building Services Engineering	Expert provider of design and consultancy services in the field of Building Services Engineering	20
K	BIM Manager and specialist in building services projects	Information management for Building Services Engineering projects	18
L	Director in a BIM consultancy	Digital and BIM for Facilities management consultancy	10
M	Software Engineer specialised in BIM for FM application	Digital and BIM for Facilities management consultancy	3
N	BIM manager and expert in energy, environment, high rise and healthcare projects	Multidisciplinary leading professional services firms	13
O	Digital Construction Specialist in road, rail, and nuclear projects.	Major construction and civil engineering firm	12

4 A framework for the development and management of AIMs

Various data standards and specifications have been identified in Section 2 for possible use in the development of AIMs due to their ability to support the structured definition of information requirements for facilities management, which can also facilitate the validation of the AIM's deliverables against the requirements. The PAS 1192-3 2014 acknowledges the need to use different data sources and IT systems in BIM for FM, and introduces concepts such as the AIM and AIR to help in establishing requirements for information management in the BIM for FM workflow. However, the definition and development of standards, tools and implementation details needed for the development and management of AIMs are out of scope of the PAS 1192-3 2014.

In this section, a framework for the development and management of AIMs is introduced. The framework's requirements and processes are explained in detail. The framework provides processes for establishing structured requirements for facilities management, developing the AIM throughout asset life cycle (project development phases and operational phase), and validating various AIM sources against the requirements. The framework was implemented into a web-based BIM for FM CDE.

The data from the three rounds of semi-structured and unstructured interviews with experts from industry and academia was transcribed and analysed using the Grounded Theory (GT) approach, proposed by Corbin & Strauss, (2014). Coding was used as the core process to both assimilate the data and achieve the required conceptualisation of data by identifying the links between data and theory. Codes are not predefined, instead they emerge from the analysis of the qualitative data and provide an abstract view of the data (Charmaz, 2006; Holton, 2007). To develop the provisional requirements model for the development of the framework and CDE, illustrated in Figure 3, the coding process adopted to analyse the interview transcripts involved three stages.

- Open coding: consists of two coding stages - initial coding, and focused coding. Initial coding is a line-by-line or incident-by-incident analysis of the interviews' transcripts. Focused coding examines the initial codes and merges similar codes into categories (Charmaz, 2006). Table 4 shows an extract of initial coding for one focused codes, - 'Standards'. This process is undertaken for each of the focused codes in Table 5.

Table 4. Initial codes for the 'Standards' focused code – a small extract

Initial code	***Supporting quote***	***Expert code***
Using standards for PPM and H&S	"Some of the critical standards for maintenance management are: SFG20, H&S compliance standards (asbestos register, legionella, etc…)"	B
Issues from the use of different local standards	"Each country will have their own system. I've been working with the Swiss BIM library where we've been looking at how they could manage FM criteria for the assets and they've looked at COBie/ IFC, the norms for Austria, the DIN specs from Germany and they're so different that it's not feasible to define all the criteria for a BIM object."	D
FM engagement from start of projects	"If you're writing a contract with a BIM methodology in mind, you should make sure to refer to BS 8536, which helps to ensure that the FMs are thoroughly engaged at the beginning of a project."	D

Table 5. Relation between focused codes and supporting quotes

Focused codes	**Expert codes**				**Frequency**
	A	**B**	**C**	**D**	
Challenges in BIM for FM	x	x	x		5

Classification		x		x	2
Data integrity		x		x	3
Data management		x		x	8
Expected benefits of BIM for FM		x	x	x	8
FM & maintenance requirements	x	x	x	x	15
Handover			x	x	4
Interoperability	x	x		x	3
IT tools requirements	x	x	x	x	22
Owner requirements management	x	x	x	x	17
Standards	x	x		x	6
Uses of BIM data in FM	x	x	x	x	18
Validation		x		x	3
Visualisation		x	x	x	6

- Axial coding: identify the relationships between the categories identified at the previous stage, and describe them by specifying their properties and dimensions. Axial Coding provides the initial steps in defining the major categories in the study (Charmaz, 2006; Corbin & Strauss, 2014). Table 6 shows an extract for one category, the ‘Owner’s requirements’. This process is undertaken for each of the categories identified.

Table 6. A small extract showing axial coding for ‘Owner’s requirements’

category	***description***
Classification	Use of a classification system is essential to manage the wide variety of data needed for the AIM (D).
	Existing CAFM/IMMS tools already use a classification system, the owner should specify this as a requirement in the EIR (B).
Handover	BIM is not being used to its full potential at the handover phase, currently its application is mostly focused on the design and construction phases (C,D).
	The use of BIM object libraries compliant with local building regulations could improve the handover of data to CAFM/IWMS systems, and improve the maintenance planning process (C,D).
	There are data management challenges in handover of non-BIM data because the handover process varies from project to project, according to what’s defined in the project specification requirements (D).
FM & maintenance requirements	There are currently several challenges regarding the availability of data needed for maintenance purposes. Current CAFM/IWMS tools already support the data requirements for FM and maintenance (B). FM data can be used as an input for new build and refurbishment/renewal projects.
	As a result of inexistent or inadequate data, most maintenance contracts end up focusing on reactive maintenance approaches. While information needed for FM and maintenance tasks is typically available, it is usually provided in unstructured format (D). It is up to the owners and facility managers to define the format and content of the data that they require using a methodology such as the EIR. This way it will be possible to manage the data using e.g. CAFM/IWMS tools, since these tools already support this data (B,D).

- Selective coding: consists in identifying the core category that emerges from the collected data, and systematically relating it to the other categories (O’Connor, 2012).

Following this coding approach, the key concepts or categories, their domains and relationships were identified and assimilated in the provisional requirements model (Figure 3). The requirements model outlines the relationship between the core category (i.e. Asset Information Model) and the other four identified main categories: owner requirements definition; owner requirements validation; CDE; and benefits and challenges of BIM implementation in FM.

Supporting the owner in the definition of requirements, and the management and validation of information deliverables against these requirements was identified as one of the core requirements. It is important to ensure that the AIM produced can be effectively used in the operational phase of built assets. The structured definition of requirements for the operational phase of facilities, with input from designers, contractors and facility managers or building owners, was also recognised for its importance in maximising the performance of built assets for the owner and occupants. The use of open standards such as IFC and COBie for the organisation of information for facilities management tasks, was also considered given the multitude of technological systems used across the long lifespan of built assets. These key capabilities for the proposed framework are summarised as follows:

- Structured identification and organisation of facilities management requirements in the form of AIR;
- Use of suitable open data standards and specifications for the AIM;
- Validation of deliverables produced for the AIM against the AIR throughout the built asset life cycle;
- Development of the AIM by either integrating or linking its ‘distributed’ information deliverables; and
- Utilisation of the AIM at the operational phase (e.g. AIM visualisation, use of AIM in maintenance planning, service life planning, etc.) of built assets.

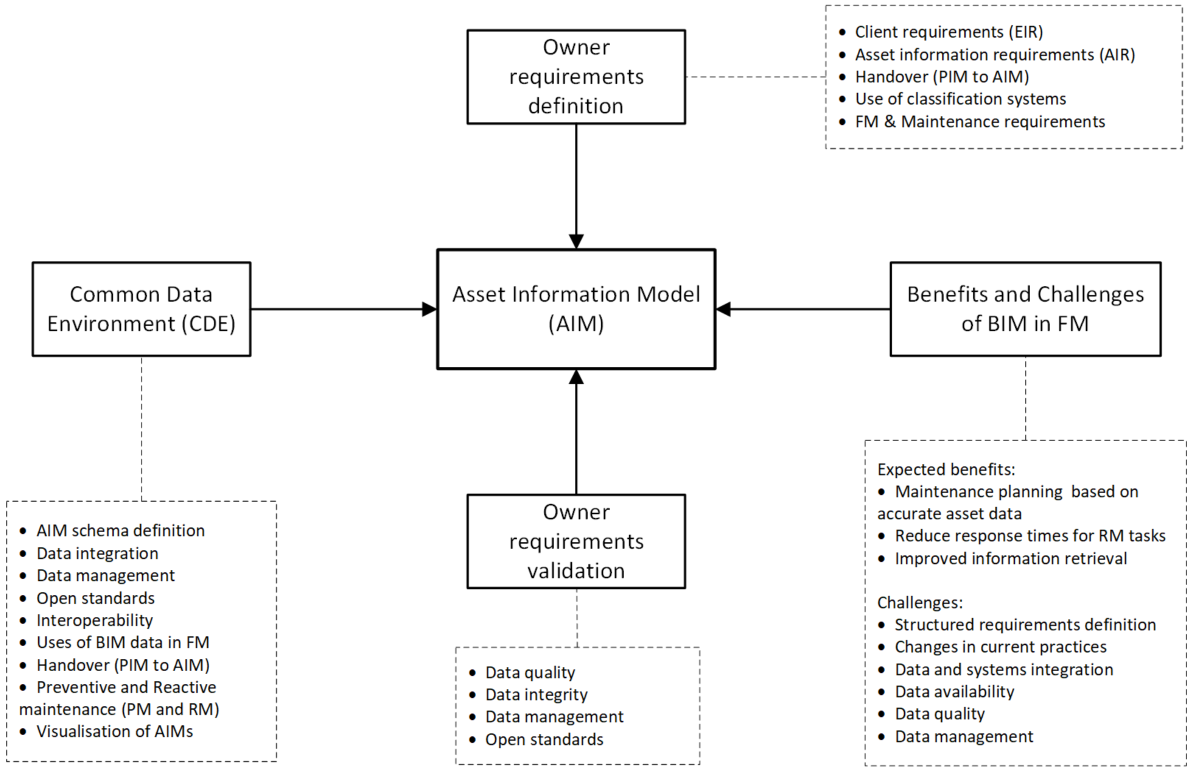


Figure 3. Provisional requirements model for the development of the framework and CDE

4.1 Framework processes

A framework is proposed to fulfil the requirements and functionalities explained in the previous section. Processes are developed for definition of AIR, and the production and validation of the AIM. The definition of AIR and the validation of AIM data sources rely on the use of open standards, in order to allow their implementation throughout the life cycle of the built assets, and ensure their continued use in future. The proposed framework consists of four key functions (Figure 4).

Patacas, J., Dawood, N. and Kassem, M. (2020) 'BIM for facilities management: A framework and a common data environment using open standards', Automation in Construction, Vol 120, https://doi.org/10.1016/j.autcon.2020.103366

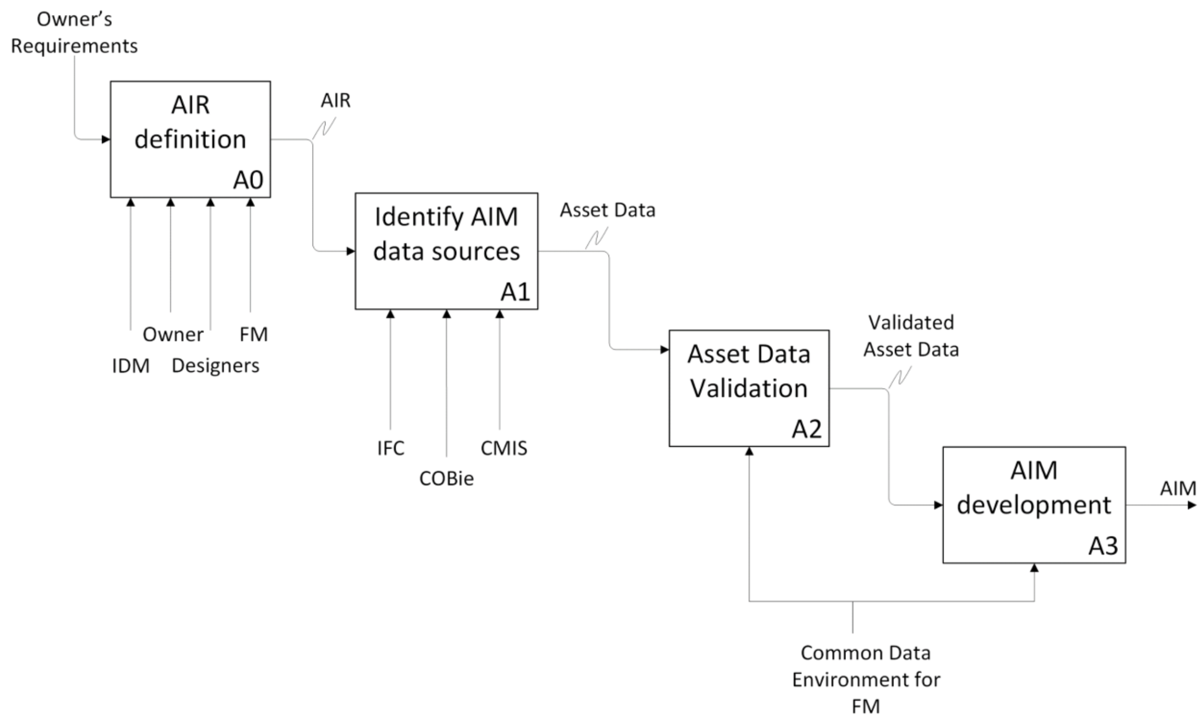


Figure 4. IDEF0 diagram of the proposed framework

Asset Information Requirements (AIR) definition

The AIR specifies the information requirements for all the disciplines involved in the development of the project, and the management of assets. An accurate specification of AIR is essential to ensure that the owner's needs are fulfilled throughout the design, construction, operation and demolition of built assets.

AIR definition is coordinated by the owner, or their information manager at the project outset, and it requires the input from designers and facilities managers. Project actors from these disciplines help determine the information requirements that are needed to manage the facility during the operational stage. If there are changes in the owner's requirements, these should be communicated to the other actors using the Common Data Environment.

In this framework, the IDM methodology (ISO, 2016) is used to structure the definition of AIR. It addresses the structured (i.e. graphical and non-graphical) and unstructured (i.e. documents) data sources included in the AIM, and ensures that the information deliverables produced as part of the AIM can be checked against the AIR. IDM is selected because it is independent from the project and data schema, and hence can be reused in different contexts and across different data models, other than IFC and COBie. The data needed for the AIM that is out of scope of IFC/COBie, such as documents sources and other FM data sources, can also be supported. The client can compile the AIM data at the handover stage and continually update it throughout the built asset life cycle to support various FM and maintenance tasks. Figure 5 summarises the collaborative definition of the AIR.

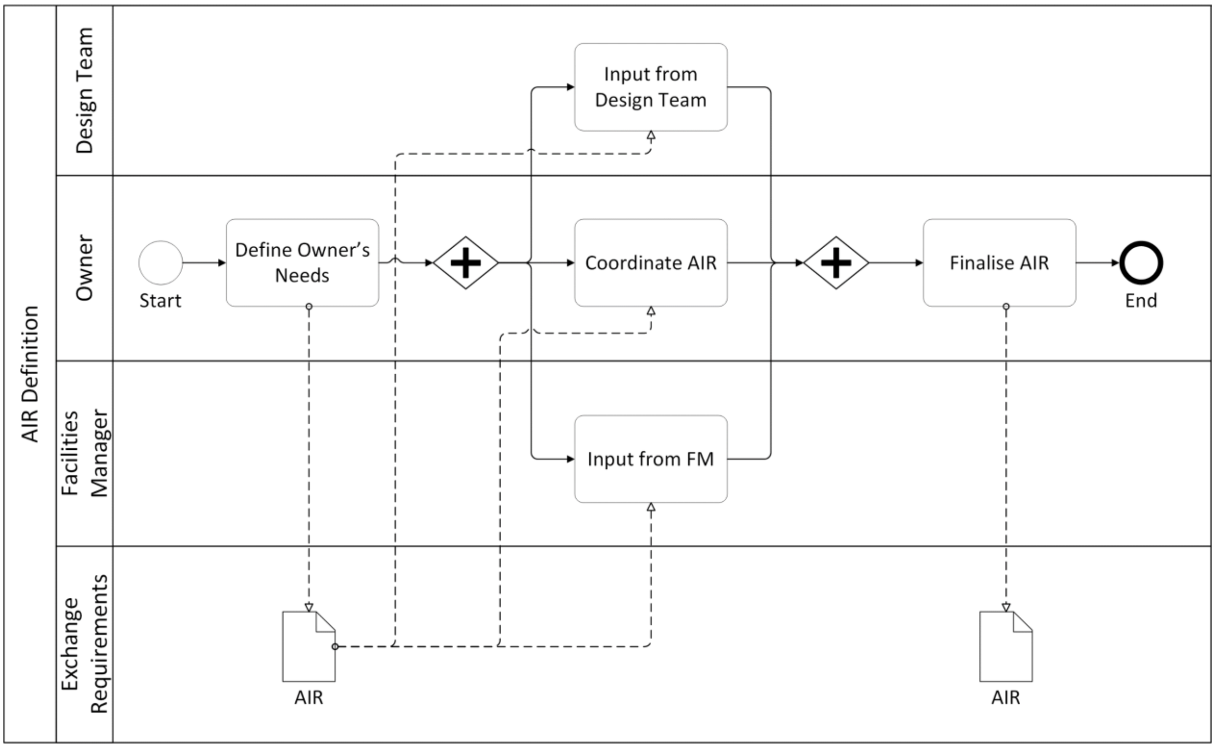


Figure 5. Process map to support the collaborative definition of AIR

AIM data sources

Data needed for facility management and maintenance tasks can be found in several different sources, systems and formats. Due to the amount and variety of such data (e.g. drawings and information models, operation and maintenance (O&M) manuals, building management systems data, health and safety (H&S) files, facilities management data, etc.), the adoption and use of a single central model or database is not a practical solution. In Section 2.2, the different open standards that support the development of the AIM using data from distributed data sources have been identified and discussed. These standards will not only enable the development of the AIM but will also support its use during the operational phase.

Structured project data (i.e. graphical and non-graphical data) can be provided through the use of IFC and COBie. The requirements for digital documents including O&M data such as H&S files and O&M manuals can be provided using a CMIS compliant EDMS. Facilities management data is managed in a CDE consisting of several connected repositories enabled by web-service standards. Additional data sources can also be integrated if they are available via standard web-service interfaces. The process for the identification of AIM data sources is summarised in Figure 6.

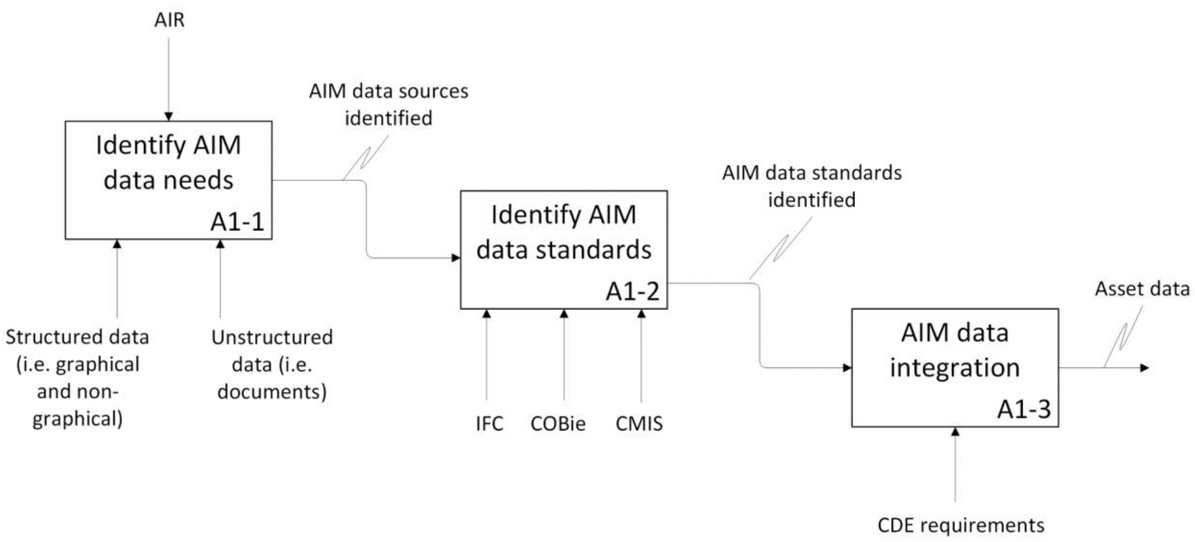


Figure 6. IDEF0 diagram to support the identification of AIM data sources

AIR validation

The validation of owner's requirements is central to the proposed framework. This process follows the general rule checking sequence previously outlined in Section 2.3. In the proposed framework, the AIR is translated into rule executable format, and semantic web query approaches are adopted for the execution of rules against structured (i.e. graphical and non-graphical) and unstructured (i.e. documents) data sources of the AIM.

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

The definition of Exchange Requirement Models provides a structured approach that is particularly suited for the validation of IFC and COBie deliverables. BIMserver, which is used to manage structured (graphical and non-graphical) data in the CDE, can be used for the definition of internal service plugins to execute rules against IFC and COBie models and attach the execution results as extended data in a new revision of the model. This enables changes to be tracked throughout the submission process of IFC/COBie deliverables. This approach can also be used to check data from external sources, such as CMIS-compliant repositories, since these can be accessed using their respective web APIs.

The proposed validation process should be performed at key stages during the project development, at the handover stage, and during the operational phase. For example, it can be performed every time an information deliverable is produced for the AIM and to validate the key information exchanges defined in the AIR. Once the various sources of AIM have been validated, the AIM can be developed in the CDE for Facilities Management. This process is summarised in Figure 7.

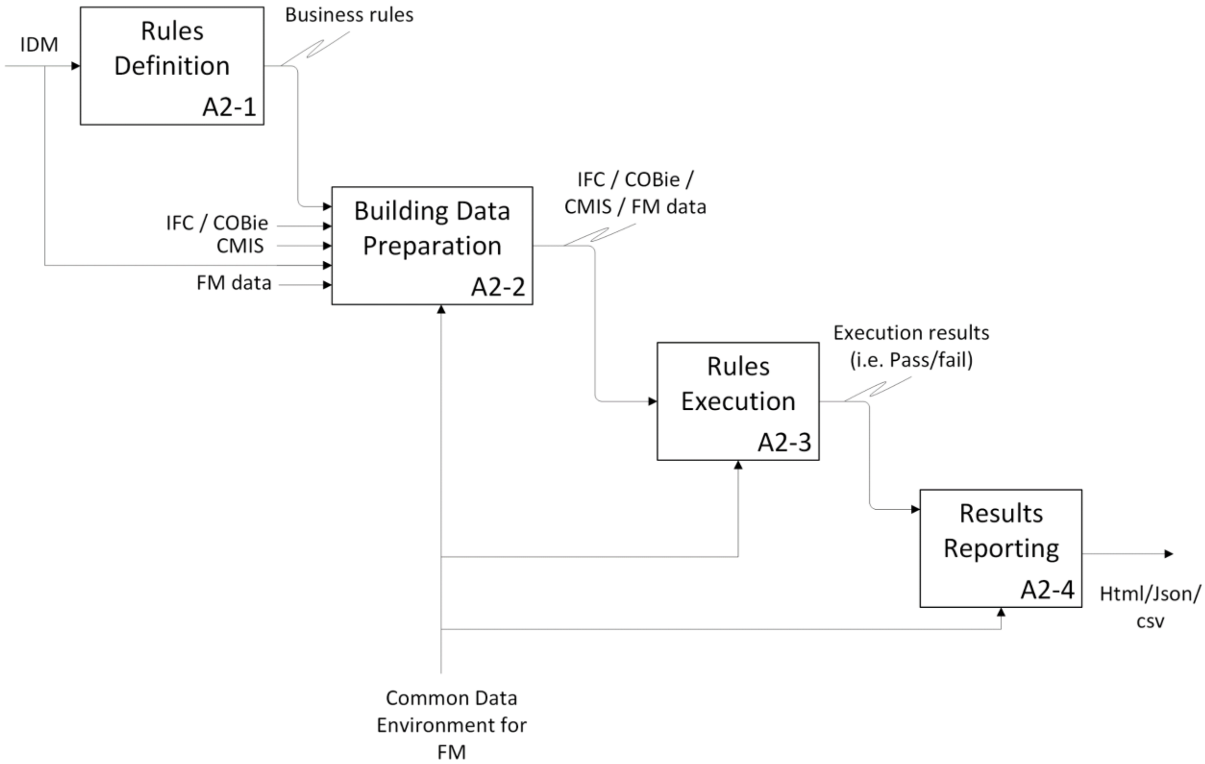


Figure 7. IDEF0 diagram for AIM validation

5 Common Data Environment: development and demonstration

The proposed framework was instantiated through the development of a Common Data Environment (CDE) that can be used for the development, validation and visualisation of AIMs. In this research, the use case considered at the operational phase is the generation of reactive and preventive maintenance (RM and PM) tasks. Hence, the demonstration will show how the CDE enables the definition of maintenance requirements, their validation, and usage for the automated generation of reactive and preventive maintenance tasks. An existing information model, called the 'Clinic' model, was used for the purpose of testing as it provides a comprehensive data set, including structured (i.e. IFC, COBie, and Autodesk Revit models) as well as unstructured data (i.e. handover documentation data including operation and maintenance manuals) (East, 2019).

5.1 CDE implementation

The CDE (Figure 9) provides the following capabilities:

- AIR validation: where structured (i.e. graphical and non-graphical) and unstructured (i.e. documents) data sources are validated against the AIR;
- Linking structured and unstructured data sources of the AIM: to provide access and management of the information models, data and documents in the FM environment;
- Definition of preventive and reactive maintenance tasks: using the information within the AIM to automate the definition of PM and RM tasks in the FM environment; and

- Visualisation of the AIM.

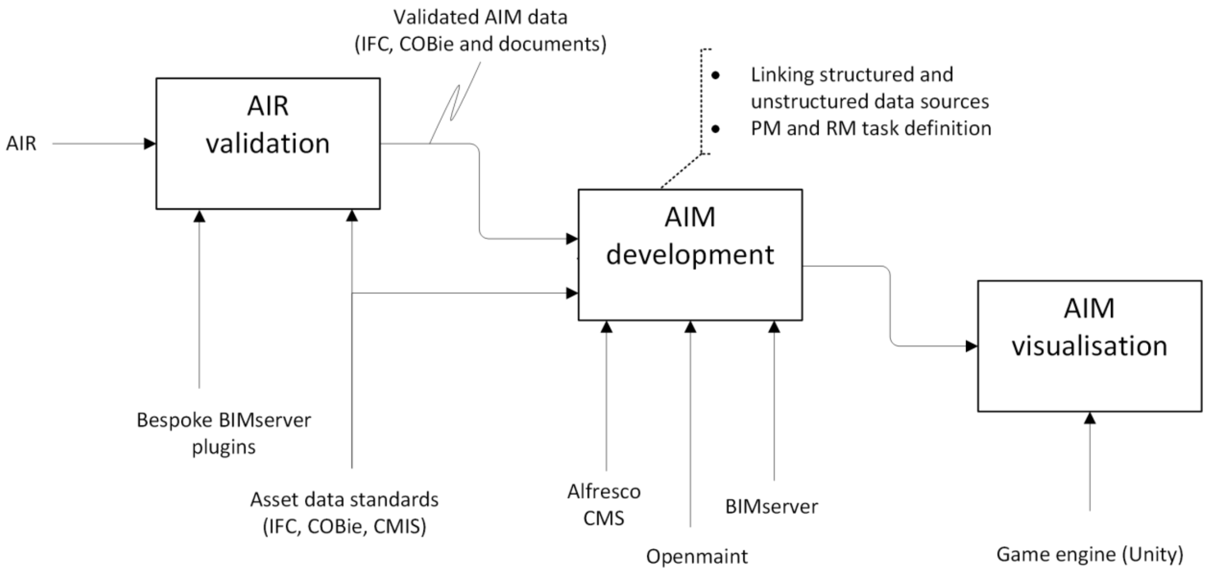


Figure 8 – CDE workflow

A FM platform, called Openmaint, which is based on an object-relational database model (PostgreSQL), was selected to host the FM and maintenance data of the AIM. Openmaint enables importing and linking data from several sources into the facility management environment through its web service interface. This is a key requirement for the AIM since requirements for maintenance and other facilities management functions will vary depending on the facility. The default PostgreSQL database schema was adopted and extended with additional tables and attributes to allow importing and linking IFC and COBie data.

A key requirement for the CDE prototype was to enable the development of the AIM and the use of its information in facilities management using distributed information containers for structured (i.e. graphical and nongraphical data) and unstructured (i.e. documents) data. Considering this, the CDE technology architecture and configuration are provided in Figure 9 and Table 7, respectively. A Linux virtual machine was used for the implementation of the server side systems of the CDE. The operating system used was Ubuntu 16.04 64bit with 8GB RAM. Openmaint, Alfresco and BIMserver were deployed in separate Apache Tomcat[1] instances. All applications can be accessed through a web interface. The Openmaint FM application, accessible via a web browser, is the main access point for the various stakeholders during the operational phase of the built asset, and functionalities of other applications are accessed through their web-service interfaces. A virtual environment is defined in Unity game engine to provide real time access to AIM data via web services and Socket.IO.

[1] Apache Tomcat is an open-source implementation of the Java Servlet, JavaServer Pages, Java Expression Language and WebSocket technologies. Tomcat provides a "pure Java" HTTP web server environment in which Java code can run.

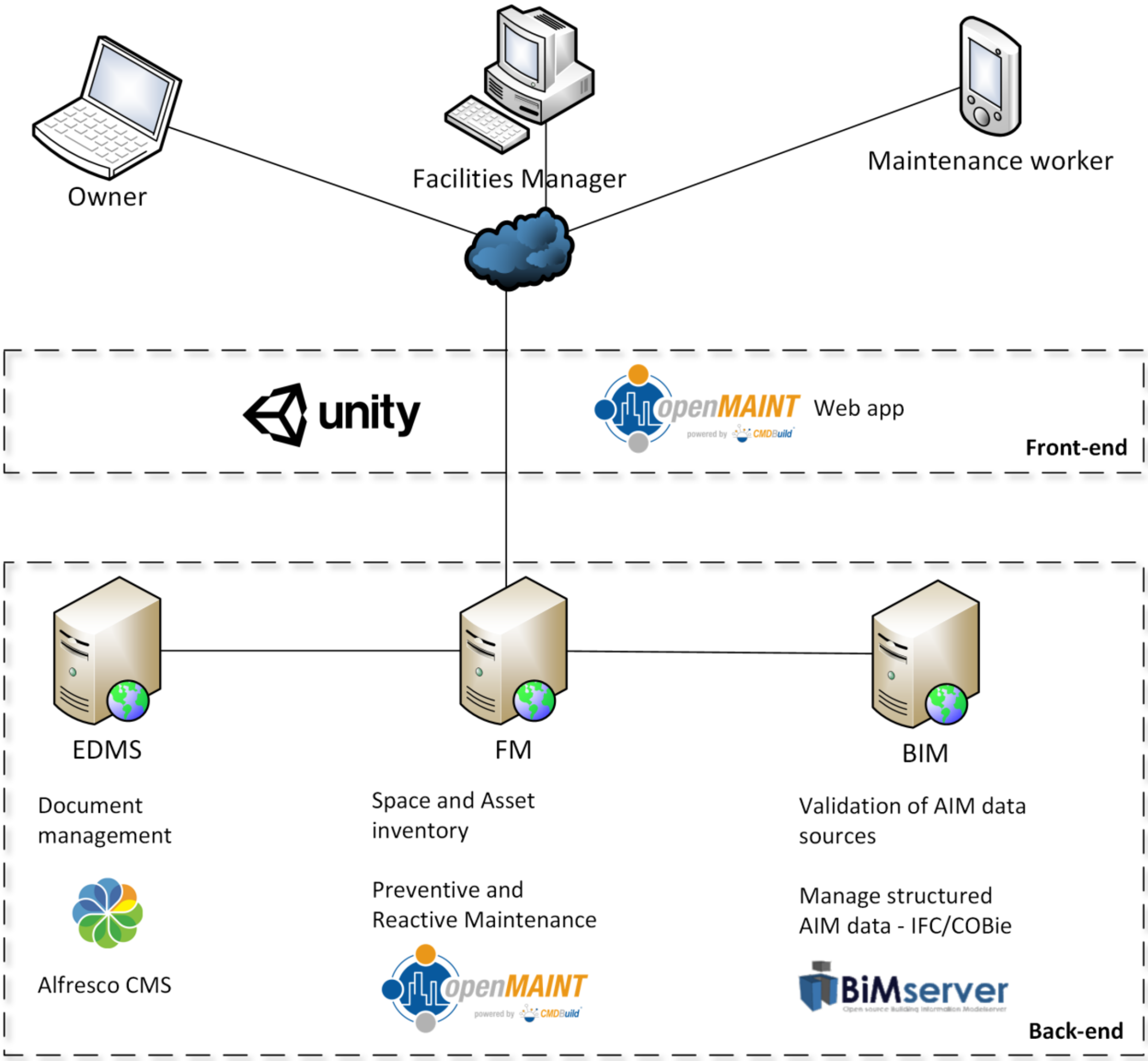


Figure 9. CDE technology architecture overview

Table 7. CDE configuration details

	Openmaint	***Alfresco***	***BIMserver***	***Node.js***	***Unity***
Software version	1.1 (CMDbuild 2.5.0)	5.2.0 Community	1.5.81	10.11.0	2017.4.40f1
JDK	1.8	1.8	1.8	n/a	n/a
Apache Tomcat version	8.5	7.0	7.0	n/a	n/a

Patacas, J., Dawood, N. and Kassem, M. (2020) 'BIM for facilities management: A framework and a common data environment using open standards', Automation in Construction, Vol 120, https://doi.org/10.1016/j.autcon.2020.103366

5.2 Definition and validation of maintenance requirements

AIR definition

A representative use case, focused on preventive and reactive maintenance tasks, was selected for testing the framework and the CDE prototype. The definition and validation of maintenance requirements is a prerequisite for the development of an AIM, which accurately represents the building and can be used as a basis for maintenance planning and other FM tasks. This process is covered in the definition of AIR, involving the owner, designers and FMs (Figure 5). AIR documents are stored in digital format in the owner's EDMS system as part of the CDE. During the construction stage, the design-build team/contractor will obtain information about specific building products from manufacturers. Building product data should be provided according to Product Data Templates (PDTs) to allow referencing in IFC/COBie data drops. The design-build team/contractor uses the Product Data Sheets (PDS) provided by manufacturers to input data into the IFC/COBie deliverables according to the AIR. Finally, IFC/COBie deliverables are handed over to the owner who accepts or rejects them based on the results of the compliance checking process. A process map, describing the sequence of tasks and information exchanges that occur during the compliance checking process is provided in Figure 10. Various maintenance data requirements were identified, which should be validated during the handover stage, in order to enable the development of the AIM (Table 8).

IFC and COBie allow the specification of the various operation and maintenance documents that are needed for the operation of the building. These documents are a key prerequisite for successful operation of the building, and are needed for the definition and execution of PM and RM tasks.

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

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

The definition of maintenance requirements follows the IDM methodology, including the definition of AIR Exchange Requirements (ER) and Exchange Requirement Models (ERM). The definition of the ER and the ERM for preventive maintenance are described in Table 9.

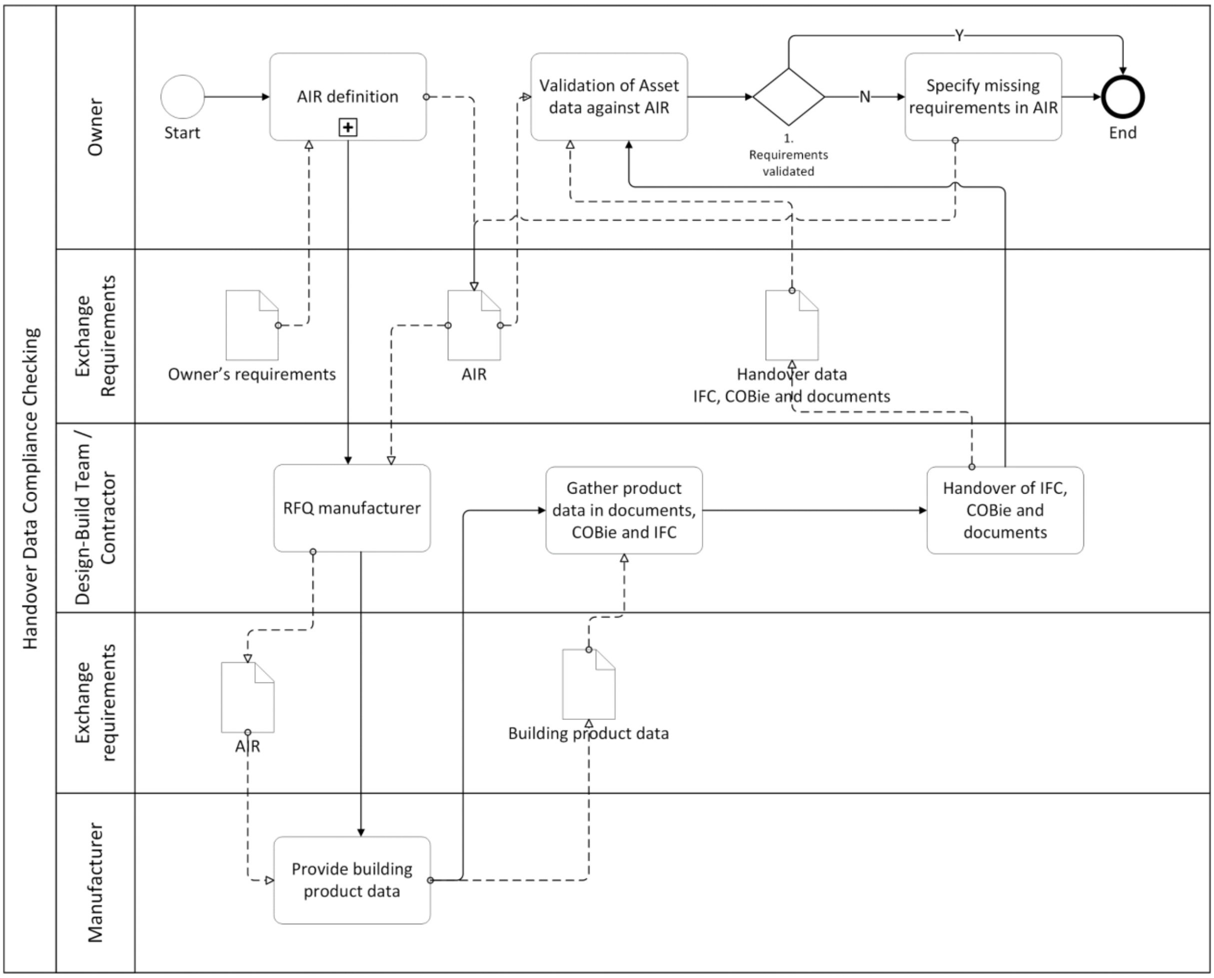


Figure 10. Process map for compliance checking of AIM data sources at the handover stage

Table 8. Overview of data requirements for the maintenance use case

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

$$PARL\ (\%) = \frac{Remaining\ Service\ Life}{Design\ Service\ Life} \times 100 \quad (1)$$

Table 9. AIR Exchange Requirement Model: Preventive maintenance data

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

AIR validation

Following the definition of ER and ERM, business rules are defined to check if the maintenance requirements specified by the owner are satisfied by the submitted data drops or information deliverables. Business Rules are defined through the implementation of BIMserver internal service plugins using BIMserver's Java API, allowing complex logic to support a wider variety of Owner and FM requirements. BIMserver plugins can also connect to external web services and applications, through web service interfaces. Checking if the required data for preventive maintenance are specified in the COBie job sheet can be achieved through the execution of a bespoke BIMserver plugin which checks if the properties are according to the defined rule, and returns the execution results as extended data in text format. The plugin is executed when a new revision of a COBie dataset is uploaded to the BIMserver.

An overview of the process and tools used for the validation of asset data using BIMserver plugins is provided in Figure 11. This process has been detailed further in a related publication (Patacas *et al.*, 2016).

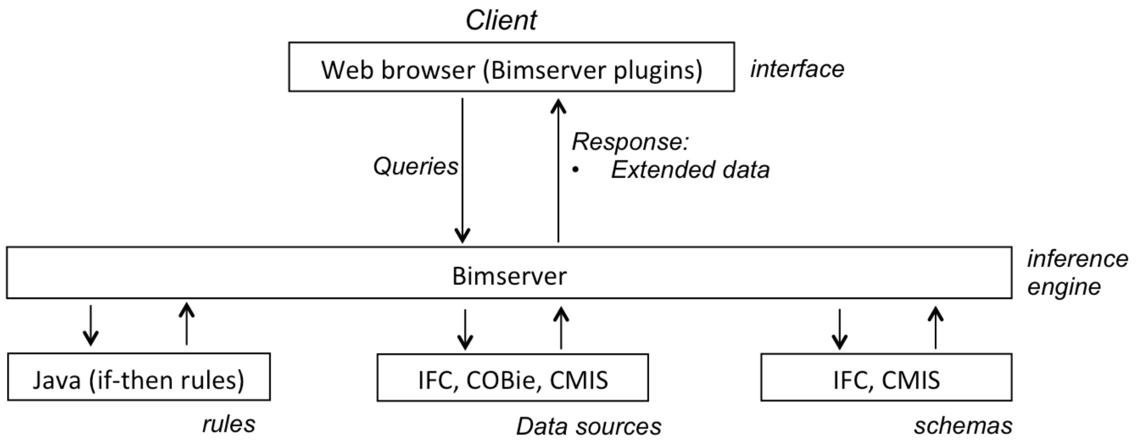


Figure 11. Asset data validation process and tools using BIMserver plugins

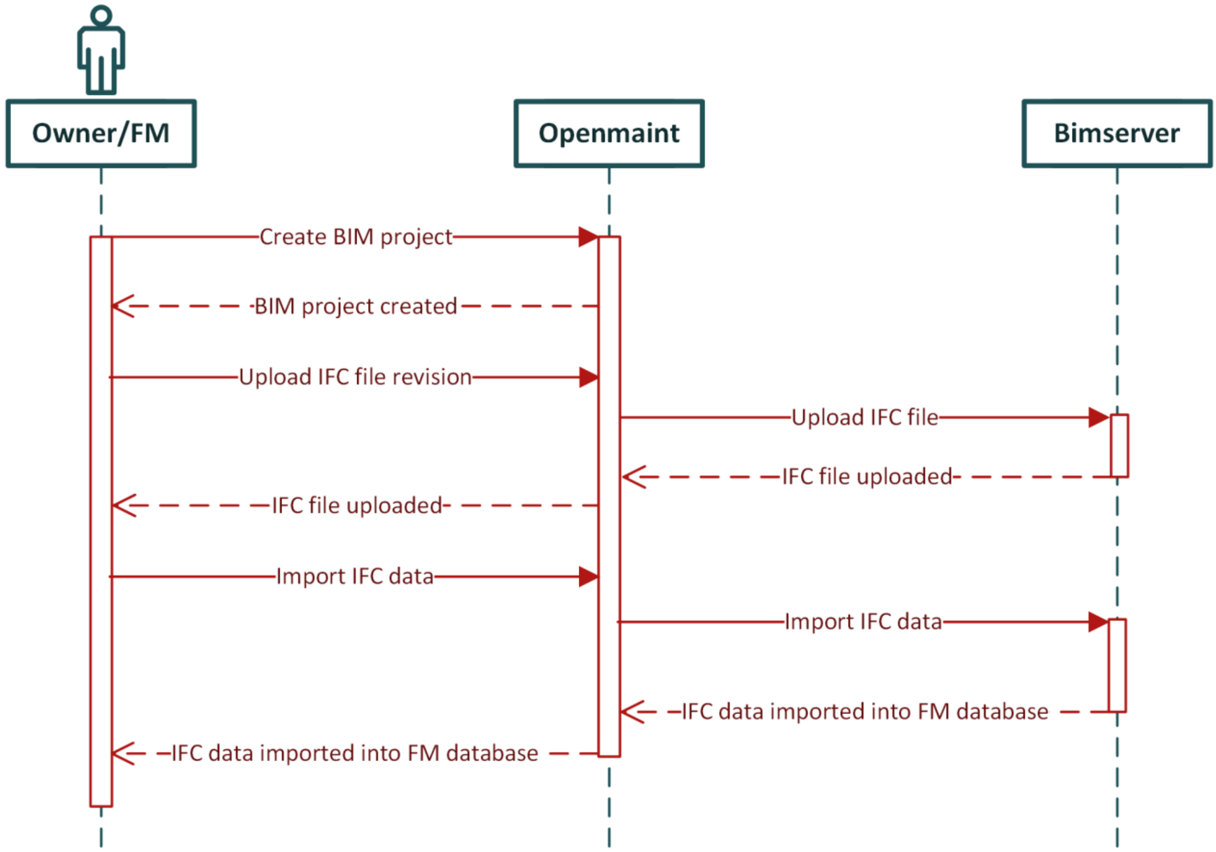
5.3 AIM development

Linking information models, data and documents into facility management

Once the various data sources have been validated against the maintenance requirements, they can be uploaded into their respective repositories. This is achieved by defining a new BIM project in Openmaint's administration interface and uploading the IFC files to a BIMserver instance through Openmaint's interface. To link IFC models to the facility management database and import the required data from the information model according to the previously defined maintenance requirements, an XML script is defined according to Openmaint documentation (Tecnoteca, 2015). Additional SQL scripts are defined to retrieve and map the 'IfcRelContains' spatial containment relationships to the facility management database.

This process enables owner/facility managers to import selected or specified data into the facility management environment according to their requirements and access it through the IFC model viewer from the facility management web interface. It also assures the quality and compliance of the data with the AIR. Figure 12 illustrates the interaction between the owner/facility manager, the Openmaint and the BIMserver applications that enables this process.

Once the information models have been linked to Openmaint and maintenance data has been imported into the facility management database according to the Owner/ FM requirements, a maintenance manual can be defined by uploading the various operation and maintenance documents – as defined in COBie – to the CMIS-compliant EDMS, which can be linked to building assets. The documents can be uploaded to a CMIS-compliant repository via the CMIS REST web service interface and can be accessed through Openmaint. To automate this task, a Java client application was developed to upload all the documents referenced in an IFC model through the 'IfcDocumentReference' entity. Figure 13 provides an overview of this process. This process can also be used throughout the operational phase of the built assets, e.g. every time there is a new COBie data drop with associated documents.



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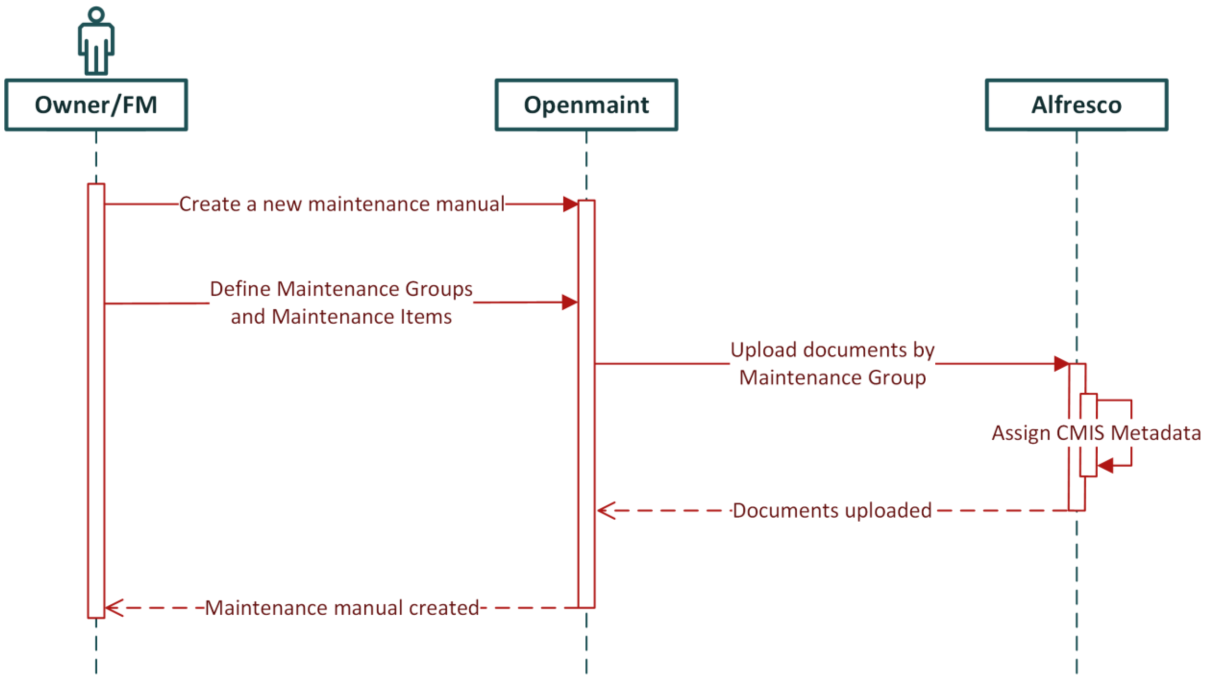
599 **Figure 12. UML sequence diagram for the integration of BIM and FM data**



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601 **Figure 13. UML sequence diagram for the definition of the 'building maintenance manual'**

Definition of preventive and reactive maintenance tasks

Once the preventive maintenance activities have been imported, a preventive maintenance calendar can be generated for a selected period through the execution of the ‘Maintenance Calendar generation’ workflow in Openmaint. A list of work orders is automatically generated for a given maintenance calendar through the execution of the ‘Workorder generation’ workflow and their associated data is stored in PDF format in a CMIS-compliant EDMS. The list of work orders and their requirements can also be emailed to the ‘Team’ responsible for the preventive maintenance activity. Figure 14 shows the UML sequence diagram of this process.

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

The ‘Asset Renewal’ AIR can be used as a basis for the automated generation of reactive maintenance tasks. To demonstrate this capability of the framework and the CDE, a Java client application was developed, which checks the ‘Asset Renewal’ AIR requirements for MEP assets, and generates a Renewal work order for assets where the ‘Asset Renewal’ parameter is critical. Figure 15 illustrates the UML sequence diagram of this process. Figure 16 shows an example of how a Reactive Maintenance work order can be defined.

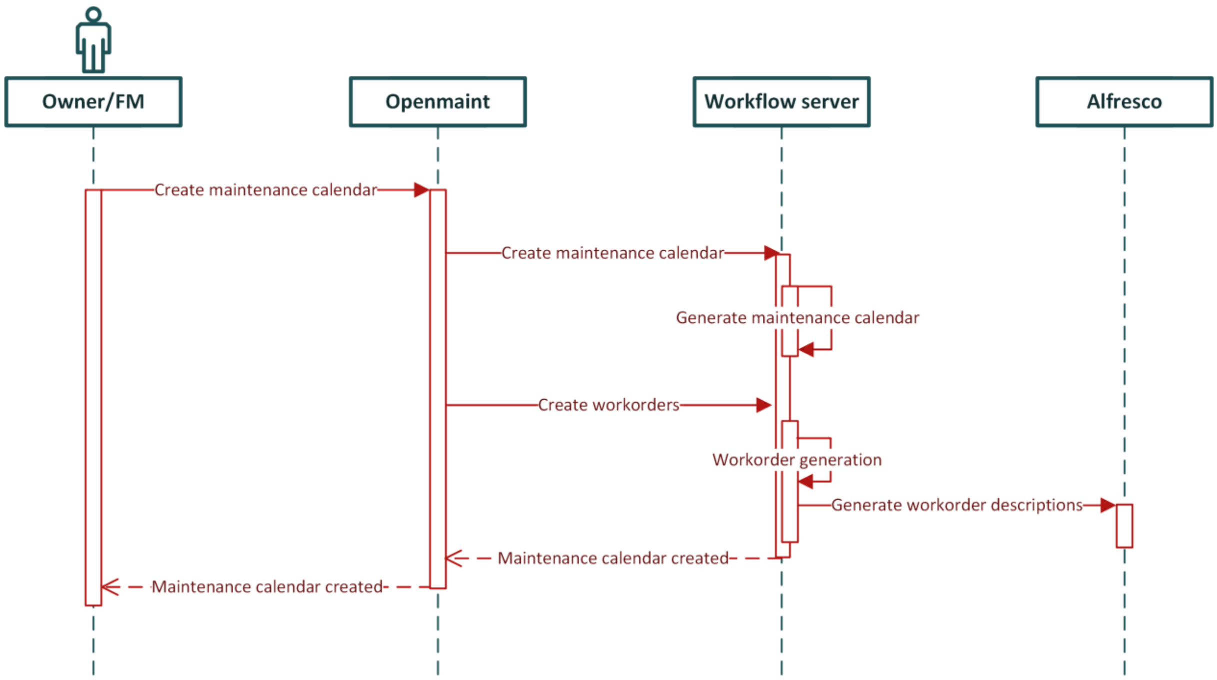

Figure 14. UML sequence diagram for the automated definition of preventive maintenance tasks

Patacas, J., Dawood, N. and Kassem, M. (2020) 'BIM for facilities management: A framework and a common data environment using open standards', Automation in Construction, Vol 120, https://doi.org/10.1016/j.autcon.2020.103366

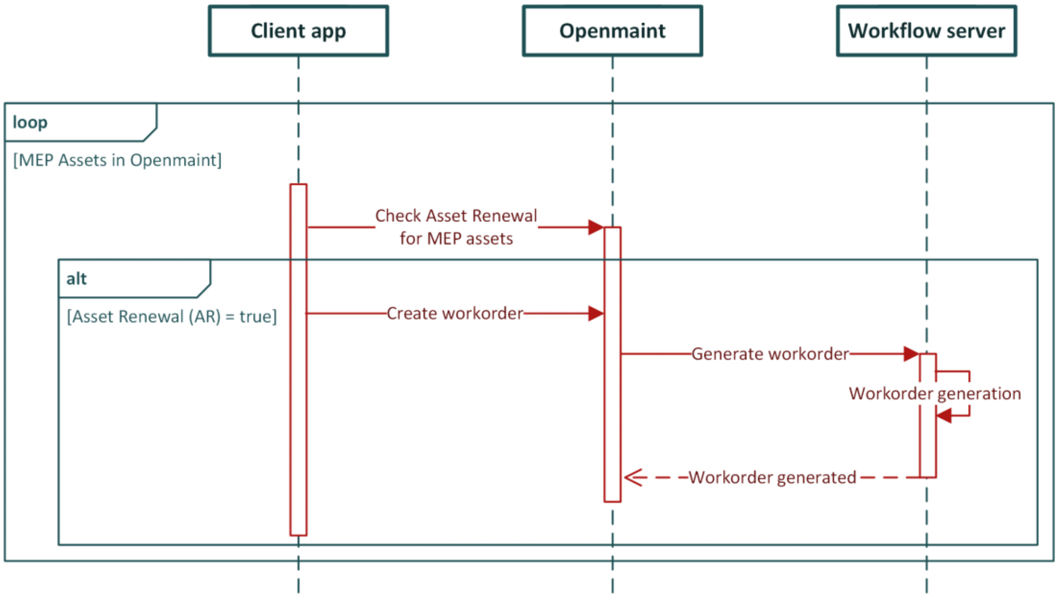

Figure 15. UML sequence diagram for the automated definition of reactive maintenance tasks

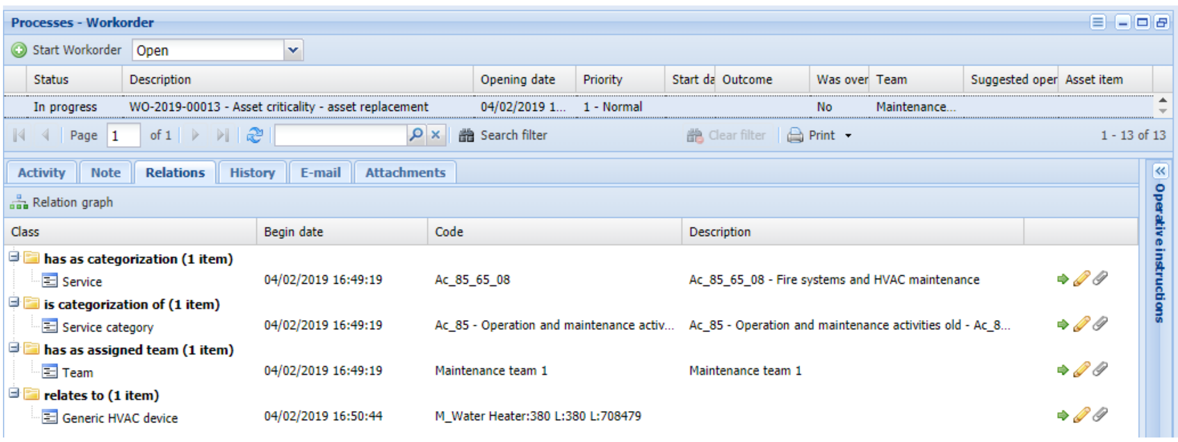

Figure 16. Work order details for a reactive maintenance task

5.4 AIM visualisation

Openmaint includes an IFC viewer to visualise the AIM and associated data, however this had several limitations: the viewer failed to render a large number of IFC entities (only 8868 entities for the MEP model were successfully rendered, when comparing to a total of 16542 entities using the bimvie.ws BIMserver plugin). Additionally, typical IFC viewers are not suitable to quickly locate assets and evaluate their accessibility onsite, which becomes apparent when considering the complexity of the 'Clinic' model. Game environments are proposed for the visualisation of the various AIM data sources. They can provide smooth navigation capabilities and can help in understanding accessibility requirements for maintenance tasks. The workflow used in this method to provide the visualisation of the integrated AIM consists of a series of steps, summarised in Figure 17 and described in Table 10. The Unity game engine was selected for the visualisation of the AIM; however, the underpinning approach is generic and could be used with alternative game environments or visualisation libraries. To enable the adequate visualisation of the AIM using a unified interface, the linking of geometric, non-geometric, documents and other facilities management data from the different sources of the CDE was required. The approach requires importing geometric data into the Unity game engine and attaching non-geometric and documents data to the corresponding game objects as metadata.

When the game is initialised, information about existing maintenance work orders is retrieved from the CDE and displayed on screen (Figure 18). The interface enables users to dynamically interact with the objects and access the various sources of associated structured (IFC and COBie data) and unstructured data (i.e. documents), and display the corresponding FM information based on the space they are located in. Figure 19 shows COBie space data displayed when the user walks through a space, and the asset data that is retrieved from the CDE when the user clicks on a critical asset.

In order to provide a suitable user experience, the game was optimised via occlusion culling (i.e. only rendering what is visible by the camera, instead of the entire model) and light mapping (i.e. generating static lightmaps for the scene). The game was tested on a laptop machine powered by a Intel Core i7-7700HQ CPU @ 2.80GHz CPU, 16 GB RAM, and a Nvidia GeForce GTX 1050 graphics card, achieving a steady framerate of 60-80 FPS, using 20-30% CPU power.

The combined use of web services and WebSocket technologies within the game engine ensures that the virtual environment is always synchronised with the data in the CDE. This approach can also be extended to include data from other data sources.

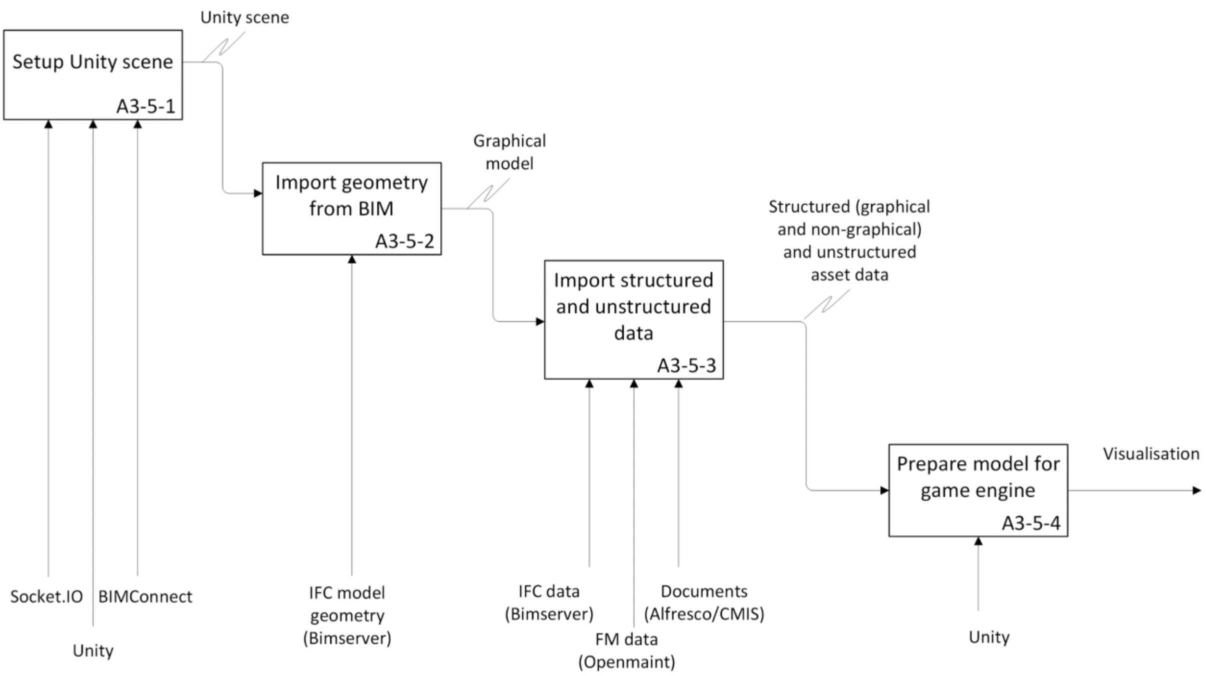

Figure 17. IDEF0 diagram for AIM visualisation

Table 10. Activity description for AIM visualisation process

Task code	***Description***
A3-5-1	Set up a new scene in the Unity game engine including the Socket.IO and BIMconnect Unity packages.
A3-5-2	Import the geometry from the BIM model in Collada format through BIMserver's service interface. Fix geometry errors within the Unity editor or using an external design tool.

A3-5-3	Configure access to structured and unstructured data of the AIM. Structured BIM data is retrieved through BIMserver web service interface; FM and Documentary data is retrieved using the Socket.IO library.
A3-5-4	Assign mesh colliders to the model’s game objects to enable navigation and interaction with the model. Depending on the size of the model, individual colliders might have to be simplified to improve performance. Attach structured BIM data and documents to game objects as metadata through the definition of scripts in Unity. Optimise performance via occlusion culling and light mapping.

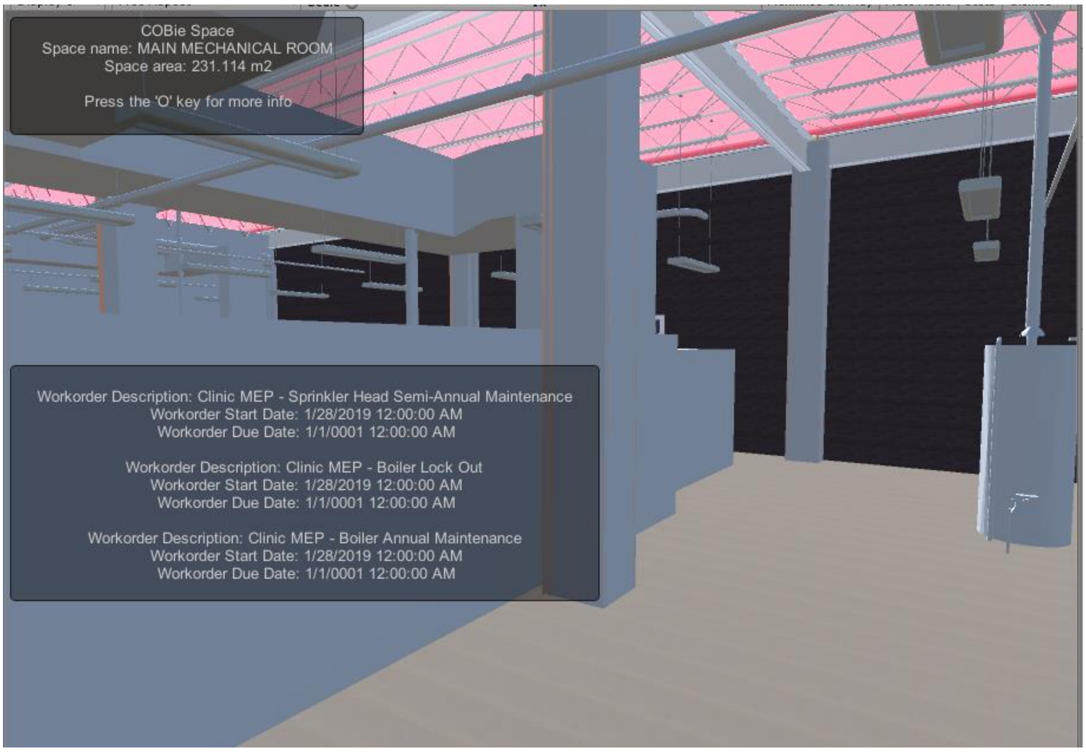

Figure 18. Displaying maintenance work order data in Unity

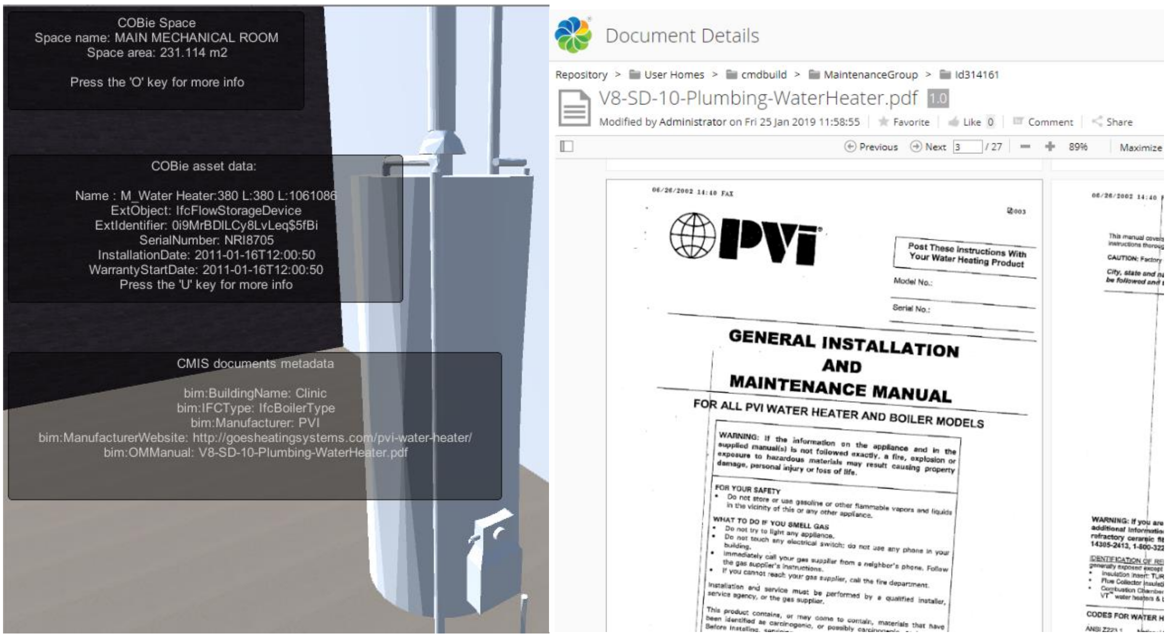

Figure 19. Displaying COBie space data and asset documents in Unity

6 Validation

The validation was performed with 11 experts from industry and academia. It involved live demonstrations of the CDE followed up by discussions of the framework and the CDE's usability and functionalities. In particular, the focus was on validating the framework components and the CDE capabilities in the development, management and visualisation of AIMs, in the context of preventive and reactive maintenance tasks.

The decision to perform two stages of validation and interviews is consistent with the research design, as it ensured the co-evolution of the requirements model and the developed CDE through an iterative process. One development iteration was also undertaken considering feedback from the first round of interviews, to improve the CDE functionalities, which are demonstrated in the final form of the pilot.

The profile of the experts involved in the two rounds of validation is described in Table 3. Open-ended interviews were adopted during these validation rounds due to their flexibility in enabling the discussion to be adapted to each participant's field of expertise, and to obtain feedback on each of the framework components and CDE functionalities.

The data analysis adopted for the validation followed the same approach adopted for the requirements capture described in Section 4. The feedback from discussions is collated in detail in Tables 11, 12 and 13 for the CDE and AIM requirements, the owner requirements definition, and the owner requirements validation, respectively. It is clear from Tables 11, 12 and 13 that the feedback about the framework and its components was satisfactory as the industry experts thought that most the requirements were either fully (denoted with 'Yes') or partially achieved. However, both new requirements and areas for improvement emerged from the discussions and were addressed in the subsequent development iteration.

The aspects to improve according to the experts are related to the usability of the prototype CDE and the need for streamlining the processes of requirements definition and validation, and data management of the AIM. Following the same coding approach used to develop the initial requirements model, a number of features were proposed to address these improvement aspects. These included improved integration between the AIM's data and the visualisation of the 3D model, the development of a mobile interface to enable access to the CDE on site, and support of additional data sources.

Figure 20 provides the updated requirements model. The added requirements representing new CDE functionalities are represented in italic.

Table 11. Validation of framework requirements: CDE & AIM

CDE & AIM requirements	***Achieved***	***Details***
AIM schema definition	Yes	It is possible to fully customise the AIM schema using the administration tools in Openmaint.
AIM data integration	Yes	Integration of structured and unstructured data sources for the AIM using IFC, COBie and CMIS standards.
Building portfolio management	Yes	The facilities management environment (e.g. Openmaint) allows the management of multiple buildings within the same interface.
COBie-based AIM management	Yes	It is possible to develop an AIM with the proposed CDE using solely structured and unstructured based on the COBie standard.
Preventive maintenance (PM) and reactive maintenance (RM) tasks definition	Yes	The prototype CDE enables importing PM task information from COBie, and automatic definition of RM tasks based on key parameters (e.g. Asset Criticality Rating).
AIM visualisation: Interaction with 3D model to retrieve AIM data from various sources	Yes	Through the use of the virtual environment (e.g. Unity game engine), it is possible to navigate and interact with the 3D model of the AIM and retrieve its associated maintenance and other FM data.
AIM visualisation: retrieve associated maintenance data directly from the FM environment	No	Improvements to the IFC viewer in Openmaint could be used to provide this functionality.
Standards-based Interoperability	Yes	Standards-based interoperability using IFC, COBie and CMIS.
AIM data maintenance	Partially	Currently, the processes for importing and managing the AIM data are not completely automated. These processes can be automated in the future, using the CDE's web service inventory to ensure that all the AIM data sources are relevant and up to date.
Use of classification systems	Yes	The CDE requires the use of classification systems for the definition of maintenance tasks. Owners will need to use the same classification system across the building portfolio to enable cross estate queries based on classification.
Handover (PIM to AIM)	Yes	Demonstrated through the development of the pilot studies.
Change of ownership (AIM to AIM)	No	Further developments are needed to support this process within the prototype CDE. The use of open standards and the proposed structured definition and

		validation of requirements will play a fundamental role in the process.
FM and maintenance workflow customisation	Partially	It is possible to define custom workflows using the facility management environment (e.g. Openmaint). However, the owner will need technical support to achieve this.
CDE access customisation	Yes	Access rights to the AIM data can be configured for different users through the facility management environment (e.g. Openmaint) administration tool.
Supporting additional AIM data sources	No	The integration of the AIM along with other external data sources can be achieved using web services.
Mobile interface	No	Since the proposed CDE is composed of web-based systems, a dedicated mobile interface can be developed to achieve this requirement.

Table 12. Validation of framework requirements: owner requirements definition

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

Table 13. Validation of framework requirements: owner requirements validation

Owner requirements validation	***Achieved***	***Details***
Translation of owner requirements into Business rules	Yes	The requirements defined using IDM are coded as business rules in bespoke BIMserver plugins, which are then used to validate the various data sources of AIMs.
Compliance checking of the AIM data sources against owner requirements	Yes	An instance of BIMserver is used to store the IFC and COBie data. Bespoke BIMserver plugins are used to verify the AIM data sources against the owner's requirements, ensuring the validity of the AIM during its development and management processes.
Enabling building owners to validate their requirements	Partially	Further developments are needed to simplify, or abstract the query development and execution process for non-technical users.

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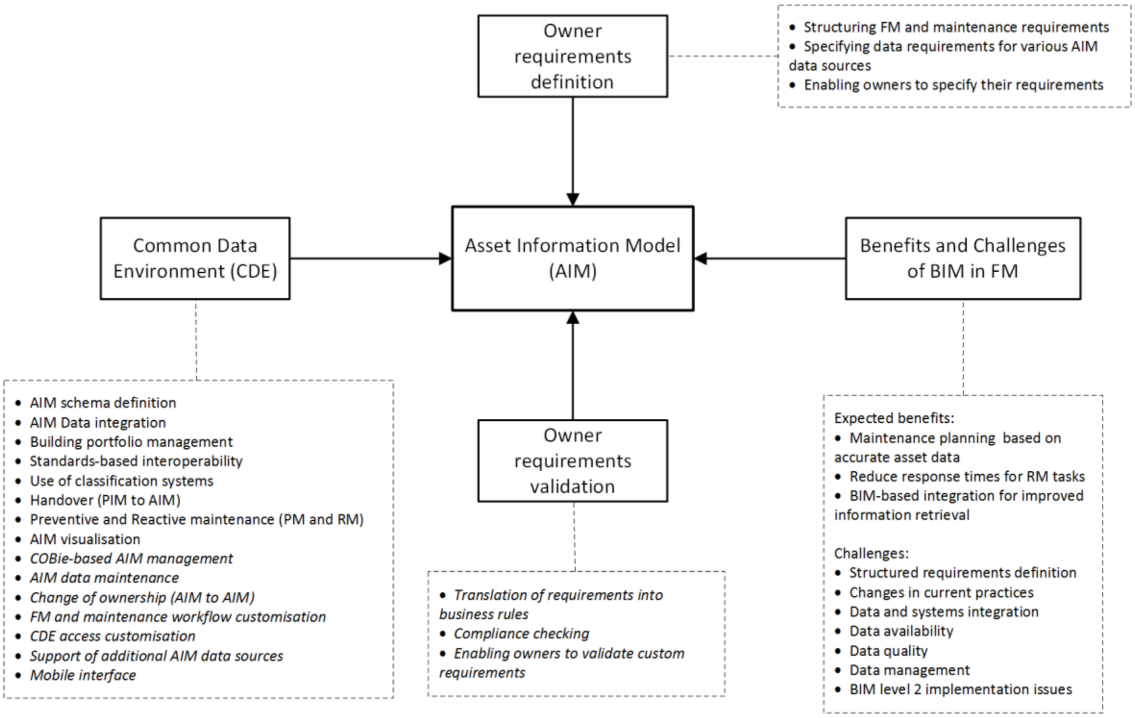

Figure 20. Updated requirements model for the proposed framework and CDE (additional requirements in italic)

7 Research contribution and limitations

This research generates theoretical and technical contributions to the BIM for FM field as well as a methodological contribution. Both the theoretical and technical contributions concur to improve the understanding of the information management lifecycle from the perspective of facilities management, including definition, production and validation of AIMs and their use in operation and maintenance. The requirements and the detailed processes for defining, validating and using AIM in operation and maintenance are lacking in both the BIM for FM academic literature and industry standards. The methodological contribution stems from the adoption of a methodological approach combining the design science research methodology with the grounded theory method. The use of the grounded theory method across the requirements gathering and validation stages complemented the iterative approach offered by the design science research methodology, which provided the necessary theoretical guidance through the various steps of problem definition, artefact development, demonstration and validation. Indeed, the complementary use of these two methods together is still limited in existing studies, despite its critical role in information systems research – i.e. enabling the development of substantive theory entailing relationships between the IT artefact, human behaviour (i.e., people), and the organisation (i.e., tasks) (Gregory, 2011).

From a theoretical perspective, this research contributed to the existing knowledge by: a) identifying a set of key requirements for the development and management of AIMs that can be used as a basis for FM and maintenance functions, and b) through the design of a framework for the development and management of AIMs to fulfil the identified requirements. Also, the research contributes to the CDE process defined in PAS 1192 and ISO 19650, by identifying the requirements that need to be considered for their implementation using web-stored integrated electronic information with fully automated connectivity, i.e. 'BIM level 3', which according to BSI (2014b) is the information management context that will underpin future collaboration and information management processes in the construction sector.

The prototype CDE for the development and management of AIMs, which provides the instantiation of the proposed framework, constitutes the technical contribution of this research. The CDE prototype, by combining the use of open standards, standard data transfer and communication protocols, and existing tools, successfully enabled the development of AIMs which can be used as a basis for the definition and execution of preventive and reactive maintenance tasks. The framework and the proposed CDE also represent an advancement compared to current collaboration and information management approaches that are adopted in practice and in industry standards (such as those enabled by 'BIM Level 2' and sustained by standards such as the ISO19650 series or the UK PAS 1192 series). A file-based approach presents challenges to the effective development and use of the AIM such as verification and validation of its data (Benghi, 2019) and its use in facilities management (Farghaly *et al.*, 2018). The framework and CDE presented in this paper addressed these challenges by enabling the development and management of the AIM from structured (i.e. IFC and COBie models) and unstructured (i.e. documents) data sources. Finally, the implementation of a service-oriented architecture in the development of the CDE ensures flexibility and scalability, which can be used to incorporate the additional requirements that were identified during the validation activities of the research.

This research is affected by some methodological and technical limitations. Methodologically, the framework and the CDE were evaluated with industrial data but not in real life projects. Future research should address this limitation by conducting the evaluation of the proposed framework and CDE in real world projects in order to evaluate the impact of the 'organisation' aspect (e.g. data gathering limitations, usability testing, etc.). The technical limitation is that this research posed the key requisite of having structured information in certain formats in order to implement the compliance checking procedures against data models. Translation of requirements into a structured format that can be used for rule checking is a challenging process that currently requires the input of experts. Future research should focus on how to perform this process independently.

8 Conclusions

This research identified a number of gaps within the BIM for FM domain which included: the lack of a framework that addresses the entire BIM for FM workflow; limited applications of compliance checking methods in the BIM for FM domain; limited use of open standards for the data sources required for the operational phase; and the lack of a CDE that can validate and assemble the required structured (i.e. graphical and non-graphical) and unstructured (i.e. documents) data for maintenance and operations, and enable its use in facilities management activities.

Using open standards and existing technologies, a framework and a prototype CDE were developed to address key processes of information management involved in BIM for FM. These included: the structured definition of information requirements for facilities management (e.g. maintenance); the validation of information deliverables against the established requirements; and management and visualisation of built asset data at the operational phase. The requirements model, which is at the core of the framework and the prototype CDE, was developed according to the combined grounded theory and the design science research methodologies – with industry experts and through a three-stage coding process performed at each iteration. The framework's processes and the prototype CDE were successfully demonstrated in pilot projects and showed that AIMs can be developed and managed

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using disparate data sources that can be integrated and synchronised via standard communication protocols such as web service interfaces. This proposed data integration approach can also accommodate additional data sources for AIMs if required by the owner/FM. The pilot projects were used in live demonstrations with experts in two stages of validation. The analysis of the primary data gathered in the validation sessions, built upon the initially identified requirements, resulting in a comprehensive list of requirements for the development and management of AIMs. The results of the validation sessions also indicated that the key processes of the proposed framework have been achieved. The framework and the prototype CDE successfully enabled the development of the AIM by capturing and managing the required data from various distributed sources, and supported its use in operation and maintenance (i.e. automatic launch of preventive maintenance work orders and provision of the required information to support the maintenance tasks). Additional requirements for the development and management of AIMs were identified during the validation sessions. These included the need to address the 'change of ownership' (AIM to AIM), and 'major works' (AIM to Project Information Model) processes outlined in PAS 1192-3 (BSI, 2014b); and to integrate additional external data sources, such as data related to energy management and other facilities management application areas. As an improvement to the proposed CDE, future developments should also address the integration of BIM data and external asset data sources using Semantic Web standards and Linked Data in the development and validation of the AIM.

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