

SUPPORTING BUILDING OWNERS AND FACILITY MANAGERS IN THE VALIDATION AND VISUALISATION OF ASSET INFORMATION MODELS (AIM) THROUGH OPEN STANDARDS AND OPEN TECHNOLOGIES

SUBMITTED: July 2016

REVISED: October 2016

PUBLISHED: November 2016 at <http://www.itcon.org/2016/27>

GUEST EDITOR: Dimyadi J. & Solihin W.

João Patacas, PhD Student
Technology Futures Institute, Teesside University
j.patacas@tees.ac.uk

Nashwan Dawood, Professor
Technology Futures Institute, Teesside University
n.n.dawood@tees.ac.uk

David Greenwood, Professor
Northumbria University
david.greenwood@northumbria.ac.uk

Mohamad Kassem, Associate Professor
Northumbria University
Mohamad.Kassem@northumbria.ac.uk

SUMMARY: *Accurate and valid data is essential during the development of building projects and throughout the use phase of buildings. This study proposes a framework to help owners and facility managers in: (a) defining the requirements for asset management tasks in a structured way; (b) validating project and asset data against the established requirements; and (c) visualising asset data, stored in different and distributed sources, in an integrated and interactive way to support specific asset/facility management functions (e.g. maintenance tasks). The framework combines the use of Information Delivery Manual (IDM), Industry Foundation Classes (IFC), Construction Operations Building Information Exchange (COBie), and Content Management Interoperability Services (CMIS) in the development of Asset Information Models (AIM) to fulfil the owner's requirements (Asset Information Requirements) throughout the lifecycle of a building. An AIM is a data model that contains all digital data (graphical, non-graphical, and documentary) required to operate an asset or portfolio of assets. Validation methods are identified for each of the AIM data types and a method for their integration and visualisation is proposed and implemented in a virtual environment.*

The proposed framework was tested in two use cases that involved (1) the validation of the various data sources against the client requirements, defined in the Asset Information Requirement (AIR); and (2) the visualisation of asset data required for a maintenance task in an interactive virtual environment. The two use cases demonstrated the capability of the framework to enable the definition of AIR and the validation of the different AIM's data deliverables. The visualisation of the AIM data - from different and distributed sources - for a maintenance task was successfully performed in an integrated and interactive game environment. Future work will consider other data sources and will evaluate the proposed framework using real industrial data.

KEYWORDS: *BIM, IFC, COBie, CMIS, IDM, Asset Information Requirements, Asset Information Model*

REFERENCE: *João Patacas, Nashwan Dawood, David Greenwood, Mohamad Kassem (2016). Supporting building owners and facility managers in the validation and visualisation of asset information models (AIM) through open standards and open technologies. Journal of Information Technology in Construction (ITcon), Special issue: CIB W78 2015 Special track on Compliance Checking, Vol. 21, pg. 434-455, <http://www.itcon.org/2016/27>*

COPYRIGHT: © 2016 The author(s). This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.



1. INTRODUCTION

The construction industry remains largely focussed on the reduction of capital costs in building projects, despite over half of the total lifecycle costs of buildings occur during their use phase (Becerik-Gerber et al., 2012; Kassem et al., 2014). The adoption of data and information management methodologies from the early project development stages can facilitate the validation of the deliverables across the project lifecycle phases and contribute to reducing the whole lifecycle costs of buildings. In particular, the structured definition and validation of project deliverables against the data and information requirements of owners and facility managers (e.g. Operations & Maintenance manuals, Health & Safety files and other documents) can improve their handover and contribute to support decision making during the operational phase of assets. Research into data and information management methodologies from the early development stages of construction projects is needed to improve the performance of both the information handover activities and the use phase of buildings. Within this context, this research provides methods and tools that enable both the structured definition of data requirements of owners and facility managers and the validation of project and asset data against such requirements.

Building Information Modelling (BIM) provides project stakeholders with the capability of interchanging data and information between different technologies and processes across the whole lifecycle of buildings. BIM implementation at the design and construction stages has resulted in benefits, particularly in the management of design, construction schedules and corresponding costs (Eastman et al., 2011; Love et al., 2014). However, these benefits are relatively small when compared to the overall lifecycle cost of a building or infrastructure asset. With the emergence and growing adoption of BIM, investigations focussed on whole life cycle approaches (e.g. lifecycle costing, lifecycle impact analysis, lifecycle management of information flows, etc.) have been reinvigorated. This has been witnessed not only in research but also in the national BIM initiatives and mandates of countries. For example in the UK, the need to support owner requirements in the definition of Asset Information Models (AIM) - a data model that contains all digital data required to operate an asset or portfolio of assets - has been recognised in PAS 1192-3:2014¹ (BSI, 2014). Therefore, there is a recognition that the key value of 'information' in building models is in enabling project decisions (strategic, technical and operational) and in delivering both a physical asset and a digital asset (AIM) that satisfy the owner's requirements at the handover.

While efforts such as the PAS1192-3:2014 (BSI, 2014) broadly recommend the structured definition and consideration of the owner's requirements in building and infrastructure projects, a methodology to support the definition and validation of the requirements throughout the lifecycle of the building is still lacking. The use of BIM and its underpinning open standards can provide the opportunity for structuring these information requirements and supporting their changes and validation throughout the lifecycle of a building. Using this assumption as a point of departure for this research, we aim to explore how BIM open standards and open technologies can support a methodology for the definition and validation of client requirements throughout the lifecycle of a building.

We propose a framework for the structured definition, validation and visualisation of data from graphical, non-graphical and documentary sources, stored in disparate models and databases. The framework adopts the approach of defining the owner's requirements as part of the Asset Information Requirements (AIR) and performs the validation of these against distinct sources of data (deliverables) throughout the lifecycle of the building. The framework utilises open standards for the definition of asset data requirements including Information Delivery Manual (IDM), Industry Foundation Classes (IFC), Construction Operations Building information exchange (COBie) and Content Management Interoperability Services (CMIS). A method is proposed within the framework for the visualisation of Asset Information Models (AIM) that considers graphical, non-graphical and documentary data sources. The proposed framework is evaluated through the development of use cases focusing on the validation of AIM data sources against AIR, and the visualisation of AIM data for an existing building in a virtual environment through the use of a game engine.

¹ PAS 1192-2:2014 specifies an information management methodology for the operational phase of built assets based on open BIM standards - IFC and COBie

2. RESEARCH AIM AND HYPOTHESIS

The assumption that underpins this research is that the adoption of an information management methodology for the structured definition of Asset Information Requirements (AIR) and their validation for the development of Asset Information Models (AIM) – from several data sources – could improve the efficiencies of data handover at the end of the construction phase and support maintenance and other FM tasks during the use phase of the building. Using this assumption as a starting point and considering the current industry trends that are increasingly requiring information management methodologies to span across the whole lifecycle of facilities, this research aims to: support building owners and facilities managers in the structured definition of requirements (AIR); the validation of data deliverables (AIM) against these requirements; and the visualisation and use of the required data from the AIM – stored in distributed databases - for specific facilities management applications (e.g. maintenance). The overarching implication from achieving this aim is to help building owners and facility managers in obtaining accurate and up-to-date information for the use phase of buildings and in improving the efficiencies of handover phases.

3. RESEARCH METHODS

Different research methods were used in pursuing the research aim. A literature review was conducted to understand the current data models and validation methods that can support the development of AIR and AIM. The findings from the literature review were considered alongside discussions with two designers involved in facilities management projects and one facilities manager. The discussions with these experts were focused on their experiences of applying BIM tools in FM projects, the definition of data requirements for the use phase of buildings, and existing methods and tools for building assets data validation. The findings from both the literature and expert discussions informed the development of the proposed framework for the definition and validation against owner's AIR throughout the lifecycle of a building, using open standards such as IDM, IFC, COBie, and CMIS, and for the development and visualisation of the AIM. The definition of owners' requirements focuses on AIR and considers the input from the design team and facility managers. The IDM methodology is used for the definition of AIR, providing structured requirements that can be used for validation against several different data sources, and supporting the development of the owner's AIM. We identify methods for the validation of AIR against various data sources and propose a visualisation methodology for the AIM using a game engine.

The proposed framework is verified in two use cases of an existing building to demonstrate how the owner and facilities management team can validate data deliverables – submitted as part of the AIM – against the AIR and visualise the AIM's various data sources using open standard and technologies. The use cases are system 'usage scenarios' characteristic of a specific 'actor' – users or external systems communicating with the system being tested (Regnell et al., 1995). In the first use case, the system usage scenario is the 'validation of IFC, COBie and documentary data handed over as elements of the AIM' and the actors are all stakeholders involved in delivering documents and data at the handover stage of a building project. In the second use case the usage scenario is the 'visualisation of AIM including their various data sources' and the stakeholders are the facilities management team (including maintenance personnel) and the owner. The use cases are designed to showcase how handover data from graphical, non-graphical and documentary data sources can be validated against the owner's AIR and its suitability for the development and visualisation of the owner's AIM. The adoption of the IDM methodology as the basis for the use-case-driven approach, as proposed in this research, is part of a global methodology for FM requirement-based testing. Relevant established standards for the definition of FM requirements are selected and used within this methodology. Finally, there is a discussion of the significance of the results and possible future developments.

4. LITERATURE REVIEW

4.1 Supporting Owners and Facility Managers through the definition and management of information requirements

The management of owner requirements in the construction industry has been the subject of numerous studies. Throughout the briefing and design development stages of building projects, a wide range of requirements are developed and evaluated. However, problems in addressing and complying with these requirements are still prevalent in the AEC industry, resulting in both projects and assets that underperform compared to original goals (Kiviniemi, 2005; Parsanezhad et al., 2016). For example, client requirements in the AEC industry are subject to numerous changes throughout the development phase of a project, but often such changes are not documented, or not adequately communicated, making it challenging for the project to comply with the client's initial intent (Kiviniemi, 2005). The formalisation of building owners' requirements is expected to improve this situation and it is increasingly attracting research interest. An emphasis has been placed on developing frameworks and models that enable both the propagation of client requirements to stakeholders across downstream phases of the project lifecycle and the involvement of clients and facility managers as early as possible in the building development lifecycle. For example, Kamara et al. (2000) suggested a framework to convey the information in client requirements to downstream stakeholders in design and construction. Several authors have proposed the use of BIM to support the formalisation of requirements definition in order to improve their management process (Arayici, 2005; Kiviniemi, 2005; Teicholz, 2013; Love et al., 2014). Kiviniemi (2005) developed a requirements model specification which can be linked to project's BIM design models. Love et al. (2014) investigated how asset owners can generate value from investing in BIM and concluded that achieving measurable and tangible value depends on the definition of client requirements in a structured way. It is therefore essential that the information produced throughout the design and construction phase conforms to owner requirements in order to converge into AIM that fulfil the client and facility managers' needs at the operational phase.

Potential benefits that building owners can gain by using BIM for requirements checking include (Eastman et al., 2011): increased building energy performance; reduced financial risks through earlier and more reliable cost estimates; shortening of project schedules by using BIM models for coordination; assuring program compliance through the analysis of the BIM models against owner and local code requirements; and optimised facility management and maintenance through the definition of the relevant information for Asset Information Models (AIM). However, despite these efforts and expected benefits, there is still a lack of clarity in the definition and management of clients' project briefs and a limited engagement of the client in the briefing process (Yu et al., 2010). To fully leverage the benefits of BIM, it is important to consider a formalised approach for requirements definition with from all stakeholders (Parsanezhad et al., 2016). These challenges are becoming more critical with the increasing adoption of digital BIM tools and workflows within the construction industry, and therefore they warrant a special attention.

4.2 Asset Information Model (AIM)

The emerging standards and specifications developed as part of the UK national BIM initiative are in line with the findings from the literature review. According to these specifications and standards, to fulfil the requirements of owners and facility managers for the use phase of buildings, a methodology is required to manage data from different sources and different domains to be adopted from the early stages of a building/infrastructure asset project. PAS 1192-3:2014 outlines an information management methodology for the operational phase of buildings that considers the use of several different data sources and IT systems. It also introduces the concepts of the Asset Information Model (AIM), Asset Information Requirements (AIR), and Organisational Information Requirements (OIR) (BSI, 2014). The AIM consists of graphical, non-graphical and documentary data about assets which can be transferred into asset management systems (BSI, 2014).

The AIM is initially formed of data coming from the Project Information Model (PIM)² which will subsequently

² Project Information Model (PIM) – An information model developed during the design and construction phase of a project (BSI, 2013b)

require updates during the operational lifecycle of the assets (Talamo & Bonanomi, 2015). It can be managed as a single model, including all the information needed to manage building assets, or as a collection of models linked to existing enterprise information systems (BSI, 2014; Talamo & Bonanomi, 2015). Asset Information Requirements (AIR) specify the owner's data requirements for the Asset Information Model. AIR are generated based on the owner's Organisational Information Requirements (OIRs) - which are the data and information requirements required to achieve the owner's and/or FM provider's organisational objectives (BSI, 2014). Five key areas of AIR have been outlined in the PAS 1192-3:2014: legal, commercial, financial, technical and managerial. Some of the main requirement topics in each of these areas are detailed in Table 1.

In recent years several methods to support building information requirements and validation have been proposed. These methods rely on the formalised definition of owners' requirements and can be utilised for the purposes of checking the AIR and developing the AIM. The data requirements for AIM can be conveyed through the structured definition of Information Delivery Manuals (IDMs) and Model View Definitions (MVDs). The IDM methodology AIM to document processes and specify information exchanges between Architecture, Engineering and Construction (AEC) industry stakeholders. The IDM can be used for the definition of use cases in the AEC industry by specifying the interactions between actors; including the data exchanges, their timing or position within the process, their content and requirements (ISO, 2010). A Model View Definition (MVD) defines a subset of the IFC schema that is needed to satisfy one or more Exchange Requirements (buildingSMART, 2016a).

IFC and COBie have been proposed as two schemas for the definition of Asset Information Models (AIM). IFC and COBie can be used as data sources for providing the graphical and non-graphical data for the AIM and for the interface between AIM and existing enterprise systems (BSI, 2014). IFC is an open source data format developed by buildingSMART to address the interoperability challenges within building projects. It is currently registered with ISO as ISO16739 (ISO, 2013). COBie is a subset of the IFC model, based on the Facilities Handover model view definition, which can be used to define the owner's requirements for FM tasks. The development of COBie began in late 2006 under the NIBS Facility Maintenance and Operations Committee and it is currently a part of the United States National Building Information Model Standard (NBIMS-US V2) (East 2014, NIBS 2015). COBie was selected as the format for specifying and handing over data for the use phase of assets in centrally procured UK government projects. In addition, several other relevant standards and industry initiatives were identified during this research. Standards such as Akoma Ntoso (Sartor et al., 2011), LegalDocML (OASIS, 2016b), LegalRuleML (OASIS, 2016c) and Content Management Interoperability Services (CMIS) (OASIS, 2016a) can support the definition of structured data requirements for documents, which will in turn enable validation through the use of rule-based approaches. Industry initiatives such as Product Data Templates (PDTs) can also help in structuring specific documentary requirements such as product data requirements from manufacturers (CIBSE, 2016).

TABLE 1: Asset Information Requirements proposed in PAS 1192-3:2014 (BSI 2014; Talamo & Bonanomi, 2015)

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

Validation of graphical, non-graphical and documentary data components against AIR can be attempted through the adoption of querying and rule-checking approaches. Current domain-specific language approaches to support the validation through the querying of BIM models include the Building Environment Rule and Analysis language

(BERA) (Lee et al., 2015), the BIM Query Language (BIMQL) (Mazairac & Beetz, 2013), the Compliant Design Procedures workflow model (CDP) (Dimyadi et al., 2016), and the BIM Rule Language (BIMRL) (Solihin & Eastman, 2015). MVDXML has also been used as a basis for the definition and execution of rules against IFC and COBie data sets (Zhang et al., 2015a; Patacas et al., 2015). Approaches to support the validation of documentary data include the Regulatory Knowledge Query Language (RKQL) and the Regulatory Knowledge Model (RKM) (Dimyadi et al., 2016). Recently, the use of semantic technology and ontological approaches has also been proposed for the automated checking of BIM data (Beetz et al., 2008; Zhang et al., 2015b; Beach et al., 2015; Pauwels & Terkaj, 2016). Notably, the IFCOWL ontology is currently being developed under buildingSMART's Linked Data Working Group (buildingSMART, 2016b). A summary of current methods to support building data from graphical, non-graphical and documentary sources, and for validation of building data is provided in Table 2.

In spite of the increasing interest in validation of different types of data formats, there is still a dearth of investigations and tools for use in the development of Asset Information Models. Talamo & Bonanomi analysed the COBie schema against the AIR – as proposed in PAS 1192-3:2014 - and concluded that COBie can fulfil most of these data requirements, although some limitations were found regarding data in the commercial category, including the lack of support of data about the condition and performance targets of assets, key performance indicators (KPIs) and criteria for non-conformance of assets (Talamo & Bonanomi, 2015). A previous analysis of IFC and COBie support for asset register information requirements, – as defined in BS 8210 (BSI, 2012), - also revealed the lack of support of some of these requirements for the use phase of buildings (Patacas et al., 2014). An analysis of the support of the IFC schema for information and data requirements for the O&M phase also revealed that the current IFC standard does not include all the required properties and relationships related to the O&M phase (Motamedi et al., 2014). Examples of such properties include: operational statuses (e.g., decommissioned, broken, inactive), downtime information, failure classes, and physical/ operational conditions. While it is possible to include additional information in IFC and COBie files using custom property sets, this could result in models that are heavy, inefficient, and difficult to use. It is therefore necessary to identify and/or define complementary schemas and validation methodologies that are suitable to support the AIM data that is out of the scope of IFC and COBie. It is also necessary to provide a methodology that facilitates the visualisation and use of the AIM data in an integrated fashion for FM areas such as the planning and execution of maintenance tasks.

TABLE 2: Summary of standards and methods to support building information requirements and building information validation

Building graphical and non-graphical data	Documents	Methods for validation of BIM data and documents
ISO 16739:2013 Industry Foundation Classes (IFC) (ISO, 2013)	Akoma Ntoso (Sartor et al., 2011)	BERA (Lee et al., 2015)
COBie (East, 2014)	LegalDocML (OASIS, 2016b)	BIMQL (Mazairac & Beetz, 2013)
IFCOWL (Beetz et al. 2008; Pauwels 2016)	LegalRuleML (OASIS 2016c)	BIMRL (BIM Rule Language) (Solihin & Eastman, 2015)
ISO 29481 – IDM (ISO, 2010)	Content Management Interoperability Services (CMIS) (OASIS, 2016a)	RKM (Regulatory Knowledge Model) and RKQL (Regulatory Knowledge Query Language) (Dimyadi et al., 2016)
MVD (buildingSMART 2016a)	Product Data Templates (CIBSE, 2016)	CDP (Compliant Design Procedures) workflow model (Dimyadi et al., 2016) MVDXML (buildingSMART 2016a) Semantic rule checking approaches (Beetz et al., 2008; Zhang et al., 2015b; Beach et al., 2015; Pauwels & Terkaj, 2016)

Current approaches for validation of BIM models and documents are mostly focused on the validation of design requirements and regulations during the design development phases of building projects. The applicability and suitability of such approaches for the definition and validation of FM requirements require further investigation.

5. PROPOSED FRAMEWORK

5.1 Concept

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

We propose a framework to support the structured definition of AIR, and the validation and visualisation of AIM. The definition of AIR and the validation of AIM rely on the use of open standards and open technologies in order to allow their implementation throughout the lifecycle of the building and ensure their prolonged use in future. The proposed framework consists of four key domains to support the development and continuous update of the AIM throughout the lifecycle of the building:

1) Asset Information Requirements definition

We propose the structured definition of AIR using the IDM methodology (ISO, 2010) to allow the validation of graphical, non-graphical and documentary data sources against the AIR throughout the lifecycle of the building. This will ensure that at the handover stage, the client can compile the AIM data and continuously update it throughout the building lifecycle to support maintenance tasks. The inputs from the design team and facility managers are taken into account in the definition of AIR.

2) Identification of Asset Information Model data sources

Data needed for asset management tasks can be found in several different sources, systems and formats. Due to the amount and variety of such data (e.g. building drawings/models, O&M manuals, BMS data, H&S file, FM data, etc.), it becomes unfeasible to adopt and use a single central model or database. Therefore, we identify suitable open data standards and tools to support the development of the AIM using data from disparate models and databases, enabling the use of such data in maintenance planning and execution tasks during the use phase of buildings. Building project data is provided through the use of IFC and COBie. Digital documents including O&M data such as H&S files and O&M manuals can be provided through the use of a CMIS compliant EDMS.

3) Validation of Asset Information Requirements

The framework supports the definition of the processes for the validation of AIR against the various AIM data sources throughout the lifecycle of buildings. The IDM methodology is used for process definition specifying the flow of activities, and the supporting data and information requirements that need to be fulfilled to perform the specified processes. Exchange requirements (ERs) describe specific information requirements which must be achieved to accomplish certain tasks. Using this approach, it is possible to specify and check requirements at building element property level considering data from several disparate systems (e.g. BIM, FM, and EDMS data).

4) Visualisation of Asset Information Models

To accomplish the visualisation of AIM data we propose the use of a game engine for the development of virtual environments where graphical and non-graphical AIM data needed for maintenance can be accessed. It is expected that the use of such a virtual environment can improve the planning of maintenance tasks as a result of its capability of pulling the tasks' required data and information from the disparate data sources.

Each of the previously introduced domains is detailed in sections 5.2 to 5.5.

5.2 Asset Information Requirements (AIR) definition

The definition of AIR is very important to the owner since it specifies requirements for all the disciplines involved

in the development of the project and the management of the building until the end of its lifecycle. In addition, well-defined AIR is essential to control the information-centric tasks of processes across the design, construction, operations and demolition of a building.

We propose the adoption of the IDM methodology for the structured definition of AIR. The purpose of the IDM methodology is to specify the exact information to be exchanged and how this information can be supported in data models (ISO, 2010). In this framework, IDM is used to define specific data requirements for validation of submittals (IFC, COBie, and other documents) ensuring that the data is provided in a suitable format and according to the needs of the asset owner before forming part of the owner's AIM. During the use phase of buildings, IDM can also be used to update the AIR with the AIM data requirements needed for FM and maintenance operations. Process maps are defined using the Business Process Modelling Notation (BPMN), specifying the flow of activities and supporting data and information requirements that need to be fulfilled to perform the activities (ISO, 2010). Exchange requirements are defined by specifying data and information requirements to support the data exchanges that occur in the defined processes. Functional Parts, which are reusable units of information that specify IFC Entities, Property sets and other Functional parts, are grouped together to support Exchange requirements in the form of Exchange requirement models. Process maps and Exchange requirements are independent of the project and data schema to enable their reuse in different contexts and across different data models (i.e. not just IFC/COBie). This way it will be possible to support the data needed for the AIM that is out of scope of IFC/COBie, such as documentary and other FM data.

The design of built assets must fulfil the AIR, including support for the functions that have been defined by the owner, and requirements in building standards and other relevant legislation. For the use phase of buildings, a maintenance policy should be established, where maintenance targets are defined for each of the identified asset functions. Maintenance targets evaluate whether the desired functional performance of an asset is guaranteed (Moubray, 1997). Therefore AIR definition should take into account the input from designers and facility managers from the early stages of project development and throughout the lifecycle of the building. Professionals from these fields can help determine: a) what are the assets and b) what is the intended use of handover data, so that if the required data and information is validated, it can be used by the owner for asset management purposes. The collaborative process for the definition of AIR is proposed in Fig. 1. This process requires input from the Design Team and Facilities Managers, which is coordinated and approved by the Owner. It is a recurring process as changes to the requirements throughout the lifecycle of assets need to be accommodated.

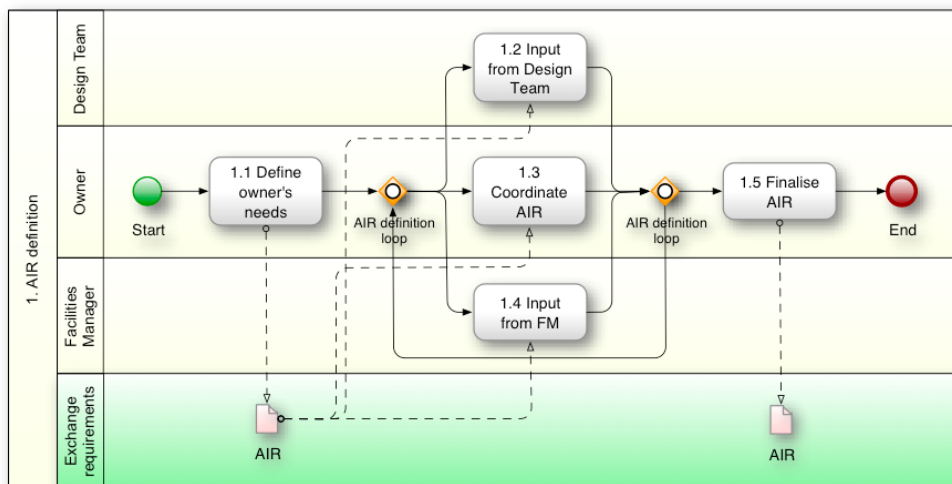


FIG. 1 – Process map to support definition of AIR

5.3 Asset Information Model (AIM) definition

The AIM includes graphical, non-graphical, documentary and other FM data, and AIM to fulfil the AIR defined by the owner with the input from designers and facility managers. The different open standards that could be used for these different data requirements are listed in Table 3.

IFC and COBie can support the graphical and non-graphical asset information requirements for the AIM. Specific IFC entities and Property Sets can be specified via IDM's Functional Parts. While not all data requirements for the AIM are directly supported by the default IFC and COBie entities and property sets, the extensible nature of the IFC schema allows the definition of custom entities and property sets to support additional data requirements. In this research, 'asset criticality' data, defined according to BS 8544:2013 (BSI, 2013a), was added to an IFC model in the form of a custom IFC property set, and was used: 1) to demonstrate the proposed AIR validation methodology, and 2) for classification of critical assets that require the display of data in the virtual environment. BIMserver has been adopted in this framework to support IFC and COBie data. BIMserver supports the storage and management of IFC models in an underlying database structure, and provides several interfaces and capabilities such as data querying and filtering for interaction with the stored models (BIMserver, 2016).

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

To allow the planning of maintenance tasks considering the different data sources from the AIM, the open source Openmaint FM package is used in this framework. Openmaint integrates several application modules using web services - Workflow, EDMS, GIS, BIM – and can be deployed on a server for remote access (Tecnoteca, 2016). Openmaint is supported by the PostgreSQL database, which can support geometric and geographic data through the use of the PostGIS module. The open source Enhydra Shark workflow module is provided with Openmaint and is used for the definition of maintenance workflows, which can be customised by the user. Support for BIM data is provided using the IFC format through the open source BIMserver (BIMserver, 2016). IFC and COBie data is stored in a BIMserver and can be imported into the FM database through BIMSie web service access. Similarly it is possible to upload documents to the Alfresco EDMS through Alfresco's service interface and attach these documents to maintenance tasks in Openmaint. Fig. 2 outlines the integration approach used in this framework to support the AIM data requirements.

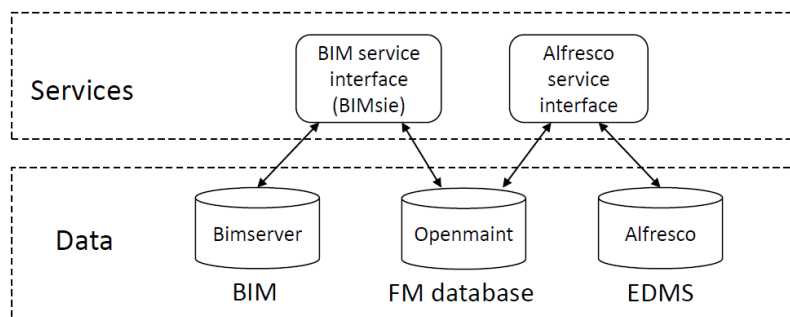


FIG. 2 – AIM data integration approach

5.4 AIR Validation

Central to the proposed framework is the AIR validation process. In the proposed framework, the IDM methodology is adopted in the definition of AIR, and several query approaches are adopted to support AIR validation against graphical, non-graphical and documentary data sources through the execution of rules. Open tools and data standards were chosen for AIR validation in order to support the process throughout the lifecycle of the building. To support validation of AIR, Business Rules from the IDM methodology have been adopted for the definition of rules. This way it is possible to define specific rules to support specific AIR defined in Exchange Requirements and Exchange Requirement Models. Exchange Requirements, which are schema-independent, can be used to support AIR in FM, EDMS, and other systems, and are used as the basis for the definition of Exchange Requirement Models.

The definition of Exchange Requirement Models provides a structured approach that is particularly suited for the validation of IFC and COBie models. The BIMserver Java API has been identified for the execution of rules against IFC and COBie models. Through the definition of internal service plugins it is possible 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.

The validation of documentary data against AIR can also be supported by queries, provided that data requirements have been specified in a structured format. Exchange requirements can be used to specify documentary data requirements, which can be supported by CMIS content models as metadata. Validation of documentary data can be accomplished through the execution of CMIS queries which can be performed against a CMIS-compliant repository, or through one of the CMIS APIs. Table 3 includes the data models and validation methods for the AIM within the proposed framework.

5.5 AIM visualisation

To demonstrate the visualisation of AIM data, we propose the use of a game engine. We propose the use of the Unity game engine to perform the visualisation of AIM data in an integrated virtual environment, however the approach could be used with other tools. Since Unity only supports the direct import of geometric data (in the form of FBX files), a method was developed to allow for the import of non-geometric, documentary and FM data to support the requirements of the AIM. The method requires importing geometric data into the Unity game engine, and attaching non-geometric and documentary data to the corresponding game objects as metadata using the elements' IFC Global Unique ID (GUID). For this reason, IFC GUID has been added as a property to the CMIS content model metadata (Table 3). FM data is accessed from an FM database at runtime.

The method used for the visualisation of integrated AIM data consisted of the following steps, which are summarised in Fig. 3:

1. Export geometry of BIM model as an FBX file from the design application (e.g. Autodesk Revit).
2. Export BIM model as an IFC file from the design application.
3. Import FBX file in 3DS Max software.
4. Assignment of materials and textures in 3DS Max to the geometric model for accurate rendering of the model in the game engine, according to design or as-built specifications.
5. Export geometric model as an FBX file from 3DS Max. The model should be exported as separate geometric objects (as opposed to a single mesh) to allow for the mapping of non-geometric and documents data.
6. Set up a new scene in the Unity game engine and import the FBX file. At this stage it is possible to assign mesh colliders to the model's game objects. Depending on the size of the model, individual colliders might have to be simplified to improve performance.
7. Checking and fixing import errors. (Errors that were experienced by the authors included errors in material assignments and in the geometry of the model).
8. Convert the IFC model to COBie using the open source BIMserver environment.
9. Export data from CMIS compliant EDMS (e.g. Alfresco).
10. Retrieve building maintenance data from FM database.
11. Attach COBie, CMIS, and building maintenance data to game objects as metadata through the definition of scripts in Unity.

Access to CMIS-compliant content repositories is provided through a .Net API – DotCMIS, which has the minimum requirement of .Net framework version 3.5 (Apache, 2016). Since the Unity game engine runs on .Net framework version 2.0, it was not possible to directly access CMIS repository data from the game engine. For this reason, a separate .Net application was developed to access the CMIS-compliant repository (Alfresco) and export the metadata from the AIM content model in the form of comma-separated value (.csv) files. The Openmaint environment (Tecnoteca, 2016) is used to support the AIM maintenance data requirements. The Npgsql framework (Npgsql, 2016) is used to access Openmaint's underlying PostgreSQL database and retrieve the relevant maintenance data to be displayed in the virtual environment. Table 3 provides a summary of the various open standards, validation methods and tools used in the validation and visualisation of the Asset Information Model (AIM).

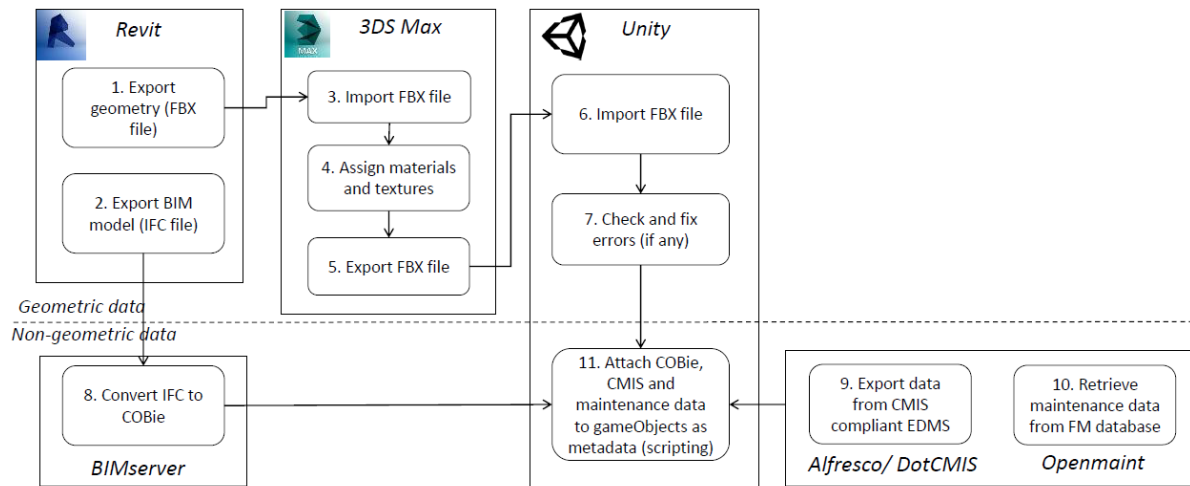


FIG. 3 - Workflow for visualisation of the AIM in the Unity game engine

TABLE 3: Summary of open standards, validation methods and tools used in the validation and visualisation of the Asset Information Model (AIM)

Asset Information Model (AIM) data sources	Supporting standards	Validation method	Supporting tools
Graphical Model	IFC	BIMserver Java API	Unity (game engine)
Non-graphical data	IFC and COBie	BIMserver Java API	BIMserver
	PostgreSQL database (maintenance data)	SQL queries	Openmaint
Documents	CMIS	CMIS queries / CMIS APIs	Alfresco

6. USE CASES

The proposed framework is illustrated and verified through the development of use cases focused on the delivery of building product data required for operations and maintenance at the handover stage using IFC, COBie and digital documents, and visualisation of data needed for maintenance tasks during the use phase of the building.

The key objectives of the use cases are: 1) to show how the proposed framework enables the definition and validation of owner's maintenance requirements against different sources of data – IFC, COBie and other documents delivered at the handover stage, and 2) to demonstrate the visualisation of the AIM including various data sources in order to support the planning of maintenance tasks. The maintenance requirements and the document metadata requirements are defined based on the BS8544:2013 (BSI 2013a) and on the Product Data Templates (CIBSE, 2016), respectively.

The development of the use cases showcases the four parts of the framework. Section 6.1 starts with the definition of Asset Information Requirements using the IDM methodology. Section 6.2 describes the support of Asset Information Model data for documents and FM data. In section 6.3 validation for AIR is carried out using documentary and IFC data sources. In section 6.4, the method for the visualisation of the AIM is demonstrated, focusing on the display of maintenance tasks data. The development of both use cases is based on IFC, COBie, Revit BIM models, and handover documents of an existing building - 'Project 1. Duplex Apartment' (East, 2016).

6.1 AIR Definition

The development of the use cases follows the IDM methodology, including the definition of a Process Map (Fig. 4), AIR Exchange Requirements (Table 4) and AIR Exchange Requirement Model including the supporting

Functional Parts (Table 5). The process map describes the sequence of tasks and how they are supported by the exchange requirements. Exchange requirements are used to support the data exchanges in the process. Since ERs are schema independent, they can be used to describe the graphical, non-graphical and documentary data requirements for AIM. In this research, the asset criticality methodology proposed in BS 8544:2013 is adopted for the classification of critical assets that require the display of data (BSI, 2013). The AIR exchange requirement model defines specific data requirements that must be included in M&E components, which are defined as a custom IFC property set in the corresponding Functional Part. These are Asset Criticality Ranking (ACR), which can be critical, or non-critical; Percentage of Asset Remaining Life (PARL), which is given by equation (1) (BSI, 2013); and Asset Renewal (Table 5). These data requirements are used to demonstrate the AIR validation process. In section 6.3, a business rule is defined to check if the information requirements specified by the owner in the AIR have been fulfilled in the submitted data drops (Table 8).

The use cases focus on asset maintenance for building mechanical and electrical (M&E) systems. The process starts with the definition of AIR, which has previously been detailed in Fig. 1 (section 5.2). AIR can be stored in digital format in the owner's EDMS system. During the construction stage, the contractor/design-build team will contact manufacturers to obtain specific information for building products. Building product data should be provided according to PDTs and can be supported through the definition of a CMIS content model, which is detailed in section 6.2. The Design-Build Team/Contractor uses the building product data provided by manufacturers to input data into the handover deliverables according to the AIR. Finally, IFC/COBie deliverables and building product documents are handed over to the owner who accepts or rejects them based on their conformance to the AIR. In section 6.3 the validation method for IFC/COBie data drops and building product documents against AIR (Decision Point 1. Requirements Validated) is detailed.

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

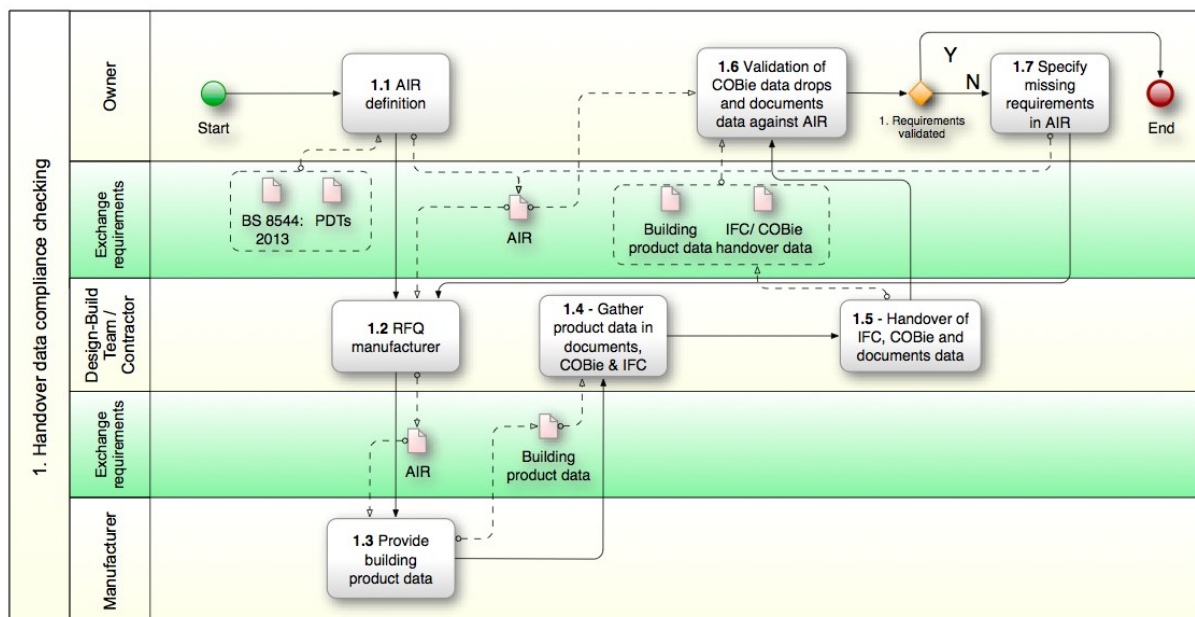


FIG. 4: Process map to support handover of IFC, COBie and documents data according to AIR

TABLE 4: Definition of AIR Exchange Requirements

Type of Information	Required information	Supplying actor	Data type
Non-graphical BIM data	Asset Criticality Ranking (ACR)	Owner	String
	Percentage Asset Remaining Life (PARL)	Owner	Real
	Asset Renewal	Owner	Boolean
Documentary data	Manufacturer ID	Manufacturer	String
	Manufacturer Website	Manufacturer	URL
	Product Model Number	Manufacturer	String
	CE Approval	Manufacturer	String
	O&M Manual	Manufacturer	String

TABLE 5: Definition of AIR Exchange Requirement Model

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

6.2 AIM Data requirements

To address the AIM documentary data requirements, a content model is defined in a CMIS compliant content repository, Alfresco Community Enterprise Content Management. Alfresco provides an implementation of the CMIS bindings, including the mapping of the Alfresco content metamodel to the CMIS domain model. This allows content models defined in Alfresco to be exposed and manipulated via CMIS. Alfresco content models are defined as XML documents, which must comply with the content metamodel XSD schema provided by the Alfresco content repository (Alfresco Software, 2016).

The content model metadata was defined based on generic requirements identified in Product Data Templates (PDTs) (CIBSE, 2016) and deployed into the Alfresco EDMS using the bootstrap approach. The IFC Type property was included in the content model to support validation of documentary data requirements against IFC/COBie data. The Alfresco content model schema is represented in Fig. 5. The definition of custom properties to support the AIR is described in Table 6.

The Openmaint FM environment is used for the planning of maintenance tasks. Openmaint provides a default database schema for building facilities management, which can be extended through its ‘administration’ interface. In this case study, the existing ‘GenericHvacDevice’ Openmaint class is used for the import of IFC Boiler elements. A mapping is defined and inserted into the underlying PostgreSQL database to allow the import of IFC Boiler elements from BIMserver into the Openmaint environment. In Table 7 an excerpt of the XML mapping is shown.

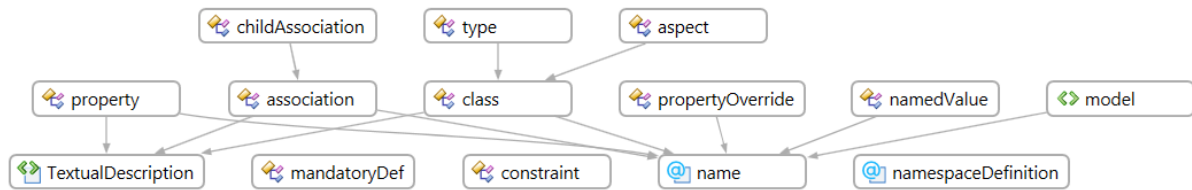


FIG. 5: Alfresco content model XML schema definition (XSD) (Alfresco Software 2016)

TABLE 6: Alfresco content model properties for the Asset Information Model

Property	CMIS property name	Property Type
IFC Type	bim:IFCType	Text
Manufacturer name	bim:Manufacturer	Text
Manufacturer website	bim:ManufacturerWebsite	Text
Product Model Number	bim:ProductModelNumber	Text
CE Approval	bim:CEApproval	Text
O&M Manual	bim:OMManual	Text

TABLE 7: Excerpt of XML import mapping configuration in 'ImportMapping' column of 'public._BimProject' table

Import mapping configuration excerpt	
1.	<bim-conf xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="import-conf.xsd">
2.	<entity name="IfcEnergyConversionDevice" label="GenericHvacDevice">
3.	<attributes>
4.	<attribute type="simple" name="Name" label="Code" />
5.	<attribute type="simple" name="Name" label="Description" />
6.	...
7.	</attributes>
8.	...
9.	</entity>
10.	</bim-conf>

6.3 AIR validation

6.3.1 Graphical and non-graphical data (IFC and COBie)

Validation of COBie/IFC data drops against the owner's AIR is specified in Decision Point 1 ('Requirements validated') of the 'Handover data validation' process map (Fig. 4), and is accomplished through the definition and execution of business rules against IFC/COBie data drops. Decision support at this point is provided by a Business Rule (Table 8), which has been defined through the implementation of a BIMserver internal service plugin using BIMserver's Java API. The purpose of the business rule is to check if submitted IFC/COBie files include the required asset criticality data requirements according to BS 8544:2013 (BSI, 2013a). The internal service plugin is defined using the Eclipse Mars.1 IDE and added to the list of plugins in a local installation of BIMserver (version 1.4.0 Final). The plugin can be executed on a new revision of an IFC model. On execution, the plugin looks for instances of the custom property set defined based on the AIR Exchange Requirement Model (Table 5), checks if the properties are according to the defined rule, and returns the execution results as extended data in text format.

TABLE 8: Business rule definition to support Decision Point 1. Asset Renewal; Textual description, Pseudo code definition, and excerpt of rule definition using BIMserver Java API

Business rule – Asset Renewal		
Documentation	Pseudo code	Rule definition using BIMserver Java API
Determination of PARL is mandatory for critical assets. If PARL is less or equal than 20%, asset must be renewed.	<ol style="list-style-type: none"> 1. Rule AssetRenewal { 2. If ACR == "critical" 3. Evaluate PARL 4. If PARL <= 20 5. AR = true } 	<ol style="list-style-type: none"> 1. if (PARL <= 20 && ACR.equals("critical") && AR == true) 2. status ="PASS" 3. else status ="FAIL";

Fig. 6 shows the results of the execution of the defined rule against an IFC file for the ‘Project 1. Duplex Apartment’ (East, 2016) and the class diagram for the developed plugin.

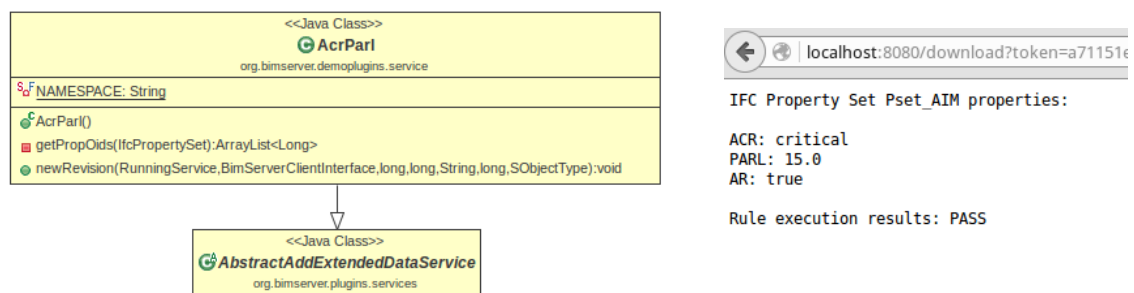


FIG. 6: Output from the execution of the internal service plugin to support the defined business rule

6.3.2 Documentary data (CMIS)

To support the validation process for documentary data, a CMIS content model was defined based on generic PDT requirements (Table 6). CMIS supports SQL-based queries, which can be used to check if the content model has been defined according to the owner’s AIR. After the definition of the content model in Alfresco, one of the handover documents from the ‘Project 1. Duplex Apartment’ (East, 2016) project was uploaded into the repository, the content model was assigned to it and its properties were defined. Finally, it is possible to query the repository to check for compliance of the uploaded handover documents (Fig. 7).

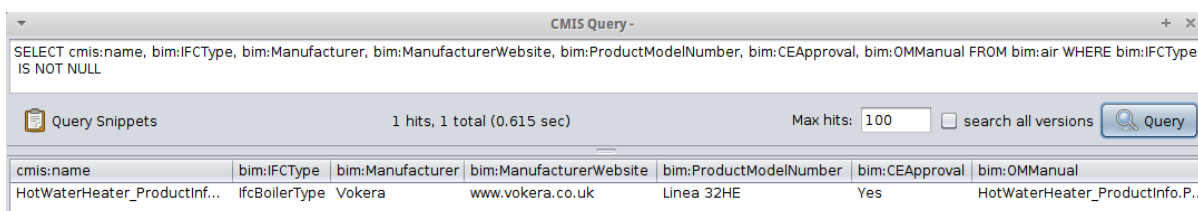


FIG. 7: Performing a CMIS Query in CMIS Workbench application to check for compliance of uploaded handover documents

To check if the handover documents specified in the COBie documents sheet have been submitted to the repository, an internal service plugin was developed using the BIMserver Java and OpenCMIS APIs (Apache, 2016). The application connects to Alfresco through the AtomPub 1.1 service interface and retrieves the documents name through the cmis:name property. The BIMserver Java API was used to query the COBie file and return the document names from the IfcDocumentReference entities that match document names in the Alfresco repository. The plugin returns the list of documents defined in COBie and whether they were found in the repository or not. A class diagram of the application and the results of its execution are provided in Fig. 8.

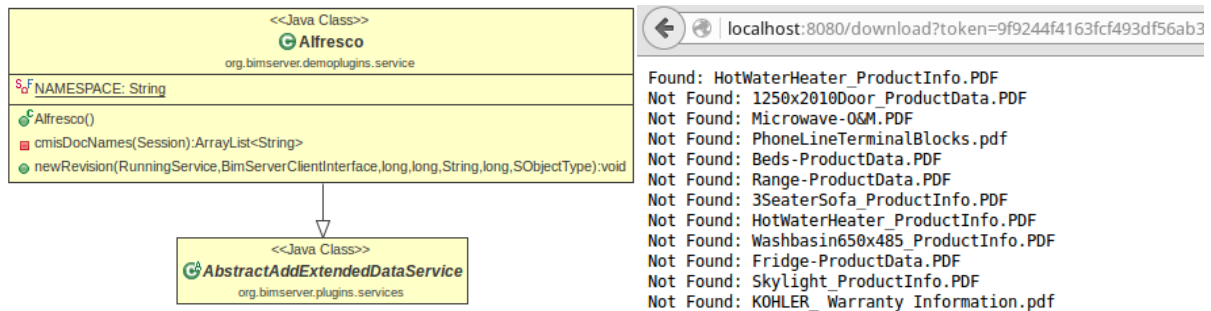


FIG. 8: Class diagram for the BIMserver internal service plugin to support validation of documents (left); Execution output from the plugin (right)

6.4 AIM visualisation

The visualisation of the AIM within a virtual environment was performed according to the process described in Section 5.5. The as-built Revit BIM model from the 'Project 1. Duplex Apartment' (East, 2016), along with its COBie handover file and documentary data was used to demonstrate the proposed method. Following the steps described in section 5.5, an empty scene was set up in Unity, where the geometric model (FBX file) with texture and material definitions was imported. The First Person Controller package is imported into the project and added to the scene to enable navigation through the model.

Non-geometric data from COBie can be imported into the game engine and attached to the model's objects within the game environment. The spreadsheet COBie model was imported into the BIMserver where it was converted to the COBieLite XML-based COBie format (Bogen & East, 2016; BIMserver, 2016). Finally, it was imported into the Unity project as a project asset. COBie data can be included in the model as metadata of game objects. Following the method proposed by Boeykens (2016), two scripts were defined in the Unity project and are initialised when the game starts: 1) a script that adds metadata to game objects, and 2) a script that parses the COBieLite file using LINQ queries.

To display on-screen information about the building, scripts can be defined to react to users' interactions with the game objects. This functionality can be achieved through the definition of colliders and their association with the game objects (Fig. 11). This allows the information to appear on-screen when the user walks through a Space defined in COBie, or when the user clicks on a game object that contains COBie data. For this purpose, it is important to identify the key assets (critical assets) which require the display of their data and information. In this research, the asset criticality methodology proposed in BS 8544:2013 is adopted for the classification of critical assets that require the display of data (BSI, 2013).

Asset data from a CMIS-compliant repository (e.g. Alfresco) can be attached to game objects in a similar way. An application connects to the repository and exports the data as a csv file, which is then imported into the project Assets folder in Unity. A script that parses the csv file is defined and initialised at the start of the game. The metadata script defined previously adds the documents metadata to the corresponding game objects. By clicking on the game objects the user can access the asset's COBie and CMIS metadata, and the attached documents through a link to the repository. Fig. 9 shows COBie space data can be displayed when the user walks through a space with a defined collider and the asset data that is available when the user clicks on an object with attached data. Fig. 10 shows the collider definitions for the display of data. To support the display of FM data from Openmaint in the Unity game engine, a connection to Openmaint's underlying PostgreSQL database was setup using the Npgsql framework (Npgsql, 2016). Once the data is imported into Openmaint, it is possible to initiate maintenance requests. A reactive maintenance task is scheduled for one of the Boilers in the 'management' interface, and the corresponding documents are attached to it. When the game is initialised, information about existing work orders is displayed on the screen. Fig. 11 shows the definition of the work order in Openmaint and the display of the corresponding data when the game is initialised.

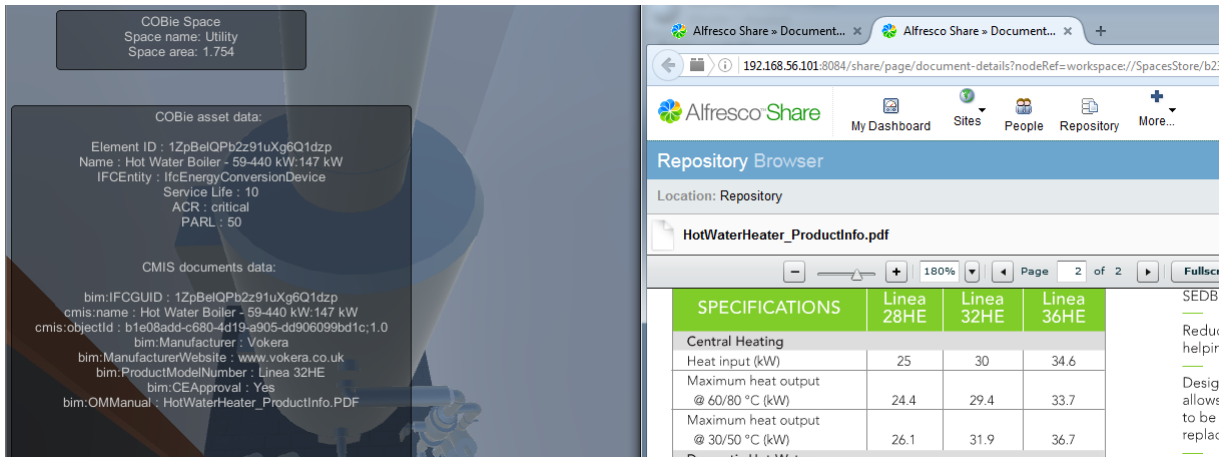


FIG. 9: Displaying COBie space data and COBie documentary asset data in Unity

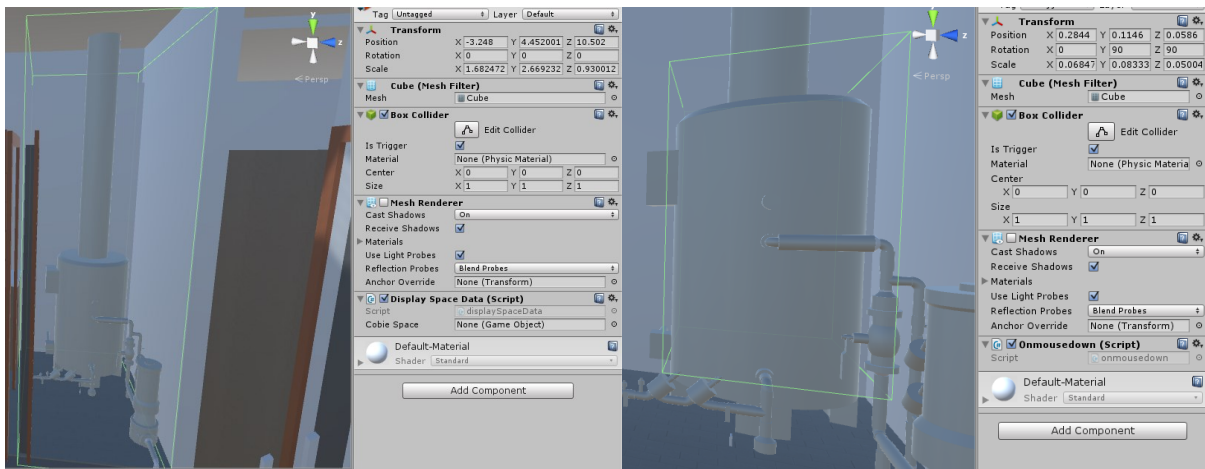


FIG. 10: Definition of colliders in Unity to allow the display of COBie space data (left) and COBie and documentary asset data (right)

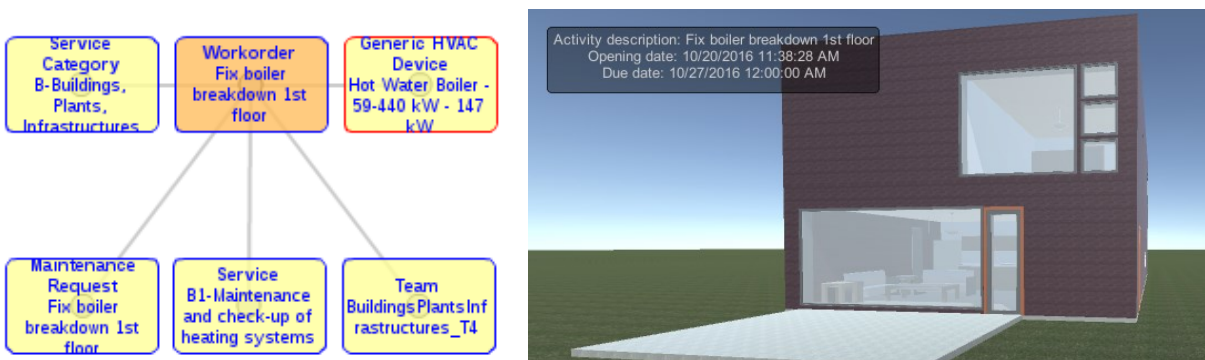


FIG. 11: Definition of a maintenance work order in Openmaint (left) and displaying maintenance work order data in Unity

7. DISCUSSION

The goal of the developed use cases was to demonstrate the framework's capabilities in the: a) definition of generic reusable IDMs; b) validation of IFC/COBie files and documents against owner's AIR to deliver a reliable AIM for the use phase of the building and c) visualisation of AIM data from different graphical, non-graphical and

documents data sources. The use cases illustrated how the IDM methodology can be used to define owner's AIR requirements considering graphical, non-graphical and documentary data sources. To perform the validation of submittals, business rules were defined using the IDM methodology, and executed against IFC/COBie files and documents. Business rules were adopted to provide flexibility for the proposed framework to satisfy different contexts and scenarios. For example, in the validation use case, a business rule was used for the definition of information and data requirements for asset maintenance according to the asset criticality method proposed in BS 8544:2013 (ISO, 2013).

The validation of graphical and non-graphical data requirements was executed within the BIMserver environment where an internal service plugin was developed to execute the defined business rules. In an earlier study we tested the feasibility of using MVXML rules for the validation of graphical and non-graphical data requirements of AIR (Patacas et al., 2015) and identified limitations regarding its capability in supporting some of the logic in the business rules. In this study, the adoption of BIMserver's Java API helped overcome these issues and enabled the execution of the defined rules. For the validation of documentary data requirements, the CMIS standard was adopted for the definition of a content model based on generic properties from PDTs. PDTs are part of a recent industry initiative and have just started to be adopted by the UK construction industry. Through the development of this use case it is demonstrated that their standardised format can help the automated validation of information and data requirements of document sources against the owner's AIR.

As part of the proposed framework, a method was proposed for the visualisation of an integrated AIM that combines the graphical, non-graphical and documentary data coming from disparate open data sources. While we adopted a specific workflow using Revit, 3DS Max and the Unity game engine for this purpose, the methodology can be adapted for use with other tools. The proposed approach, tested in a case study, revealed a number of challenges: 1) issues in the import of geometric models, particularly models with complex geometry (e.g. stAIR) and 2) Incompatibility in the use of external APIs due to the version of the .Net framework used in the Unity engine (version 2.0). Geometric errors can be rectified through the editing of the model in the design applications but this process would require a demanding inspection of the models, particularly in the case of large models. BIM models typically contain complex geometry that is not suited for use in game engines. This challenge did not cause significant performance issues within the proposed case study. However, mesh optimisation methods will have to be performed to enable running the game in less powerful machines, particularly on mobile platforms. Such methods include, but are not limited to, the mesh optimisation capabilities of 3DS Max (on export) and Unity (on import). Regarding the integration of documentary data, it was not possible to establish a direct connection between the Unity environment and the Alfresco repository. We overcame this limitation by exporting the asset documentary metadata from Alfresco through the implementation of a separate application, and importing this data into Unity. The established direct link is beneficial for both performance purposes and data integrity. The non-graphical and documentary data, which is parsed and added to the model during the initialisation of the game – due to performance issues –, will be reliable if the data in the corresponding repositories (Alfresco, BIMserver and Openmaint) is kept up to date and in compliance with the owner's requirements.

The adoption of the proposed approach is expected to provide building owners and facility managers with effective ways for the planning of maintenance tasks. Maintenance personnel can use the virtual model to locate assets and their associated data and documents before reaching the intervention space. This can also contribute to decrease the downtime of the building while work is being performed on assets. The asset criticality methodology proposed in BS 8544:2013 was successfully adopted to select which game objects require non-graphical and documentary data to be displayed (BSI, 2013). The interactive visualisation provided for the user, including the possibility of accessing the required data for critical assets during the walkthrough, enable an enhanced and tailored approach compared to those of design applications. Finally, it is possible to deploy the game on several platforms including mobile devices thus, providing the owner and FM team with access to the model and data on site.

The owner's requirements frequently change during the building lifecycle. The proposed framework support these changes by using a recurring collaborative process for the definition of AIR which can accommodate changes in data requirements, and can be supported by various data sources throughout the lifecycle of the building. This way it will be possible to support the phased delivery of IFC/COBie, documents and other submittals throughout the development of the building project, using concepts of data exchanges such as the COBie data drops and the US COBie guide (East, 2012; Cabinet Office, 2012). The proposed AIR definition method also supports the definition

of requirements for FM/maintenance tasks and their validation based on the data sources identified for the AIM. The proposed use of PDTs to support documentary data requirements according to the owner's AIR can also help the structured definition of AIM and improve the transition between the construction and use phases.

8. CONCLUSIONS

The proposed framework enables (a) the definition of owner's requirements in the form of AIR; (b) the validation of AIM data deliverables against the AIR; and (c) the integrated and interactive visualisation of the AIM including graphical, non-graphical and documentary data sources while they are stored in disparate sources, using open standards and open technologies. This will ensure that the owner can obtain and use AIM that are adequate for the use phase of buildings (e.g. maintenance tasks). The definition of AIR requires input from the design team and facility managers. The approved AIR by the client guides the validation of data drops and deliverables before they become part of the final AIM. The framework combines the use of existing methodologies and open standards - IDM, IFC, COBie and CMIS. This approach enables the reuse of the defined processes and their business rules, and the automation of requirements validation against IFC/COBie and documentary deliverables.

The validation of AIM data was successfully demonstrated in a use case involving graphical, non-graphical and documentary data sources as defined in the AIR for the handover stage. The capability of the proposed framework to perform numerous specific use cases – such as the one developed in this paper – is an encouraging indication of its adaptability for different project contexts and use cases. These results represent an important starting point for the wide implementation of the framework since they show how the concepts of logic abstraction and process reusability can be achieved. The automation of the AIM validation can be enabled by the definition of a service inventory based on the defined IDMs, which separate the process logic from the business rules logic. These concepts are key to enhance the process of defining and validating information and data requirements of owners and facilities managers for the operational phase uses (e.g., building maintenance purposes).

The testing of the visualisation of the AIM in a use case focussed on reactive maintenance was also successfully performed in a game environment. The game environment provided visualisation of the geometric objects and display of data (non-graphical and documentary) required for the critical assets/objects that require maintenance. The user (client and facility manager) can interactively navigate the model and access the required information and data about each critical asset/object. A workflow using specific proprietary tools was adopted for this purpose, however the methodology can be adapted for use with other tools during the use phase of the building. Since this process is independent of the definition of AIR and validation of AIM, the integrity of AIM data sources will be preserved.

Future developments include (1) evaluation of the proposed approach with owners and facility managers using real industrial data; (2) consideration of additional external data sources that can make part of asset data requirements (e.g. data related to energy management and other FM application areas), and (3) optimisation of the virtual environment for deployment on mobile platforms.

REFERENCES

- Alfresco Software (2016) *Alfresco Documentation*. Available at: <http://docs.alfresco.com/> [Accessed 24 October 2016].
- Apache (2016) *OpenCMIS Client API Developer's Guide*. Available at: <https://chemistry.apache.org/java/developing/guide.html> [Accessed 24 October 2016].
- Arayici, Y., Aouad, G. and Ahmed, V. (2005) 'Requirements engineering for innovative integrated ICT systems for the construction industry', *Construction Innovation*, 5(3), pp. 179-200.
- Beach, T.H. et al., (2015). A Rule-based Semantic Approach for Automated Regulatory Compliance in the Construction Sector. *Expert Systems with Applications*, 43, pp.1–30.
- Becerik-Gerber, B., Jazizadeh, F., Li, N. and Calis, G. (2012), "Application Areas and Data Requirements for BIM-Enabled Facilities Management", *Journal of Construction Engineering and Management*, vol. 138, no. 3, pp. 431-442.

- Beetz, J., van Leeuwen, J. & de Vries, B., (2008). IfcOWL: A case of transforming EXPRESS schemas into ontologies. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 23(01), p.89.
- BIMserver (2016) *BIMserver: Open source building information modelserver*. Available at: <http://BIMserver.org/> [Accessed 24 October 2016].
- Bogen, C. & East, W.E. (2016) *COBieLite: A lightweight XML format for COBie data*. Available at: https://www.nibs.org/?page=bsa_cobielite [Accessed 24 October 2016].
- Boeykens, S. (2016) *Getting BIM data into Unity*. Available at: <http://cad-3d.blogspot.co.uk/2016/03/getting-bim-data-into-unity-part-5.html> [Accessed 24 October 2016].
- BSI (2012), *BS 8210:2012: Guide to facilities maintenance management*, BSI Standards Limited.
- BSI (2013a), *BS 8544:2013: Guide for life cycle costing of maintenance during the in use phases of buildings*, BSI Standards Limited.
- BSI (2013b), *PAS 1192-2:2013: Specification for information management for the capital/delivery phase of construction projects using building information modelling*, BSI Standards Limited.
- BSI (2014), *PAS 1192-3:2014: Specification for information management for the operational phase of assets using building information modelling*, BSI Standards Limited.
- buildingSMART (2016a), *MVD Overview summary*. Available at: <http://www.buildingsmart-tech.org/specifications/mvd-overview> [Accessed 24 October 2016].
- buildingSMART (2016b), *Linked Data Working Group*. Available at: <http://buildingsmart.org/standards/standards-organization/groups/linked-data-working-group/> [Accessed 24 October 2016].
- Cabinet Office (2012) *COBie Data Drops*. Available at: <http://www.bimtaskgroup.org/wp-content/uploads/2012/03/COBie-data-drops-29.03.12.pdf> [Accessed 24 October 2016].
- CIBSE (2016) *Product Data Templates*. Available at: <http://www.cibse.org/knowledge/bim-building-information-modelling/product-data-templates> [Accessed 24 October 2016].
- CIC (2012), *Building Information Modeling Planning Guide for Facility Owners*.
- Dimyadi, J., Clifton, C., Spearpoint, M., and Amor, R. (2016). Computerizing Regulatory Knowledge for Building Engineering Design. *Journal of Computing in Civil Engineering*, C4016001, pp.1–13.
- East, W. E. (2012). *The COBie Guide*. USACE/OBO. Available: https://www.nibs.org/?page=bsa_cobieguide [Accessed 24 October 2016].
- East, W.E. (2014), *Construction-Operations Building Information Exchange (COBie)*. Available: <http://www.wbdg.org/resources/cobie.php>. [Accessed 24 October 2016].
- East, W.E. (2016), *Common Building Information Model Files and Tools*. Available: http://www.nibs.org/?page=bsa_commonbimfiles. [Accessed 24 October 2016].
- Eastman, C., Teicholz, P., Sacks, R. and Kaner, I. (2011). *BIM handbook : A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons, Inc.
- ISO (2010), *ISO 29481-1: Building information modelling – Information delivery manual – Part 1: Methodology and format*, International Organization for Standardization, Geneva, Switzerland.
- ISO (2013), *ISO 16739: Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*, International Organization for Standardization, Geneva, Switzerland.
- Kamara, J.M., Anumba, C.J., and Evbuomwan, N.F.O. (2000). Process model for client requirements processing in construction, *Business Process Mgmt Journal*, 6(3), pp. 251-279.

- Kassem, M.; Kelly, G.; Dawood, N.; Serginson, M.; Lockley, S. BIM in facilities management applications: A case study of a large university complex. *Built Environment Project and Asset Management*, 2015, 5, 261–277.
- Kassem, M., Dawood, N. and Mitchell, D. (2011). A structured methodology for enterprise modeling: a case study for modeling the operation of a British organization, *ITcon* Vol. 16, pg. 381-410.
- Kelly, G., Serginson, M., Lockley, S., Dawood, N. & Kassem, M. (2013). BIM for Facility Management: A review and case study investigating the value and challenges, *Proceedings of the 13th International Conference on Construction Applications of Virtual Reality*, Teesside University, 30-31 October, pp. 191.
- Lee, J., Eastman, C. and Lee, Y.C. (2015) 'Implementation of a BIM Domain-specific Language for the Building Environment Rule and Analysis', *Journal of Intelligent & Robotic Systems*, 79(3), pp. 507-522.
- Love, P.E.D., Matthews, J., Simpson, I., Hill, A. and Olatunji, O.A. (2014). A benefits realization management building information modeling framework for asset owners, *Automation in Construction*, 37(0), pp. 1-10.
- Mazairac, W. & Beetz, J., (2013). BIMQL – An open query language for building information models. *Advanced Engineering Informatics*, 27(4), pp.444–456.
- Motamedi, A., Hammad, A. and Asen, Y. (2014), "Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management", *Automation in Construction*, vol. 43, pp. 73-83.
- Moubray, J. (1997). *Reliability-centred Maintenance*. Great Britain.
- NIBS (2015) National BIM Standard - *United States - Construction Operation Building information exchange (COBie) – Version 2.4*. National Institute of Building Sciences buildingSMART alliance.
- Npgsql (2016) *Npgsql .NET Data Provider for PostgreSQL*. Available at: <http://www.npgsql.org/> [Accessed 24 October 2016].
- OASIS (2016a) *OASIS Content Management Interoperability Services (CMIS) TC*. Available at: https://www.oasis-open.org/committees/tc_home.php?wg_abbrev=cmis [Accessed 24 October 2016].
- OASIS (2016b) *OASIS LegalDocumentML (LegalDocML) TC*. OASIS. Available at: https://www.oasis-open.org/committees/tc_home.php?wg_abbrev=legaldocml [Accessed 24 October 2016].
- OASIS (2016c) *OASIS LegalRuleML TC*. Available at: https://www.oasis-open.org/committees/tc_home.php?wg_abbrev=legalruleml [Accessed 24 October 2016].
- Parsanezhad, P., Tarandi, V. and Lund, R. (2016) 'Formalized requirements management in the briefing and design phase, A pivotal review of literature', *ITcon*, 21, pp. 272-291.
- Patacas, J., Dawood, N. and Kassem, M. (2014). Evaluation of IFC and COBie as data sources for asset register creation and service life planning, *14th International Conference on Construction Applications of Virtual Reality and conference on Islamic Architecture*. Sharjah, UAE, 16-18 November 2014.
- Patacas, J., Dawood, N. and Kassem, M. (2015). A framework to support owner's asset information requirement throughout building lifecycle, *15th International Conference on Construction Applications of Virtual Reality*. Banff, Alberta, Canada, 5-7 October 2015.
- Pauwels, P. and Terkaj, W. (2016) 'EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology', *Automation in Construction*, 63, pp. 100-133.
- Regnell, B., Kimbler, K. and Wesslen, A. (1995) 'Improving the use case driven approach to requirements engineering', *1995, Proceedings of the Second IEEE International Symposium on Requirements Engineering*, pp. 40-47.
- Sartor, G., Palmirani, M., Francesconi, E. and Biasiotti, M.A. (2011) *Legislative XML for the Semantic Web*. Netherlands: Springer.
- Shetty, N., Hayes, A., Pocock, D. and Watts, J. (2014) *Leveraging the Relationship between BIM and Asset Management*. UK: ICE.

- Solihin, W. & Eastman, C., (2015). Classification of rules for automated BIM rule checking development. *Automation in Construction*, 53, pp.69–82.
- Talamo, C. and Bonanomi, M. (2015) 'Methodological Experimentation: Proposal of a Datasheet Template for FM Activities in the BIM Environment', in 'Methodological Experimentation: Proposal of a Datasheet Template for FM Activities in the BIM Environment' *Knowledge Management and Information Tools for Building Maintenance and Facility Management*. Switzerland: Springer International Publishing, pp. 179-196.
- Teicholz, P. (2013) *BIM for facility managers*. Hoboken, N.J.: Wiley.
- Yu, Ann T.W., Chan, Edwin H.W., Chan, Daniel W.M., Lam, Patrick T.I. and Tang, Peony W.L. (2010). Management of client requirements for design and build projects in the construction industry of Hong Kong, *Facilities*, 28(13), pp. 657-672.
- Zhang C., Beetz J., Weisen M. (2015a) Interoperable validation for IFC building models using open standards, *ITcon* Vol. 20, Special Issue ECPPM 2014 - 10th European Conference on Product and Process Modelling , pg. 24-39
- Zhang, S., Boukamp, F. & Teizer, J., (2015b). Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, 52, pp.29–41.