DISSERTATION

INFORMATION-AUGMENTED BUILDING INFORMATION MODELS (BIM) TO INFORM FACILITIES MANAGEMENT (FM) GUIDELINES

Submitted by

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ABSTRACT

INFORMATION-AUGMENTED BUILDING INFORMATION MODELS (BIM) TO INFORM FACILITIES MANAGEMENT (FM) GUIDELINES

The asset portfolios of Higher Education Institutions (HEI) typically incorporate a highly diverse collection of buildings with various and often shared campus uses. These facilities are typically at different points in their operational lifecycle, have different characteristics, rehabilitation cost, maintenance costs, and mission criticality. In the resource-constrained context of higher education Facilities Management (FM), building data for all facilities needs to be integrated within a highly-informed decision-making process to promote efficient operation. Further, efficient building FM workflows depend upon accurate, reliable, and timely information for various building-specific systems, components, and elements. Traditional Facilities Information Management (FIM) platforms and processes have been shown to be inefficient and limited for capturing and delivering the extensive and comprehensive data needed for FM decision making. Such inefficiencies include, but are not limited to, information loss, inconsistencies of the available data, and manual data re-entry at construction-to-operation handover and project close out.

Building Information Models (BIMs) are capable of integrating large quantities of data and have been recognized as a compelling tool for facility life-cycle information management. BIMs provide an object-oriented, parametric, 3D environment where meaningful objects with intelligent behavior can contain geometric and non-geometric data. This capability makes BIMs a powerful tool for use beyond building visualization. Furthermore, BIM authoring tools are capable of

automatically integrating data with FM technologies. Although BIMs have the potential to provide a compelling tool to capture, deliver, validate, retrieve, exchange, and analyze facility lifecycle information, implementation of BIMs for FM handover and integration within the context of FIM remains limited. A plethora of academic and industry efforts strive to address various aspects of BIM interoperability for handing over building data for implementation in post-construction building operation workflows. Attempts to incorporate BIMs in FIM have generally focused on one of five domains; what information is to be exchanged, how, when, by whom, and why. This three-manuscript dissertation explores FM handover information exchange scenarios and provides a comprehensive, object-oriented BIM solution that identifies the requirements for model content for FM- specific needs. The results formalize an appropriate process and structured framework to deliver BIM content using FM-specific terminologies and taxonomies. BIMs created for design and construction using this framework provide a suitable 3D resource for post-handover FM and building operation.

The BIM development framework presented herein can facilitate automated model data validation at project close out and the exchange of AEC data with FIM systems. This modeling process can reduce the need for manual data re-entry or interpretation by FM stakeholders during building operation. This study defines requirements for model Exchange Objects (EOs) to meet FM data Exchange Requirements (ERs) in conjunction with the established Industry Foundation Classes (IFC). The ERs, retrieved from closeout deliverables, are mapped to appropriate IFC Model View Definition (MVD) concepts for EOs, which ultimately provide the technical solution for the FM handover exchange scenario. These concepts determine required entities, their relationships, and properties. The author further translated the concepts to the ERs of Level of Development (LOD) definitions to provide the means for an owner to formalize conveyance of

geometric requirements. To formalize a BIMs semantic requirements, not addressed in the LOD schema, this study introduces Level of Semantics (LOS) by mapping ERs to IFC categories and their respective property definitions. The results also include development of an implementation agreement, which customizes the FM handover IFC Model View (MV) according to an organization's specific needs. The IFC MV implementation agreement establishes a common understanding of the FM handover MV content in alliance with the buildingSMART Data Dictionary (bsDD) schema. The modularized and repeatable nature of the resulting framework facilitates its implementation to convey FIM data exchange requirements for future projects.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my committee members for their guidance, patience, and feedback in writing this dissertation.

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DEDICATION

To my parents for their love and support, and my sisters for their faith throughout the challenges of graduate school and life.

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Research Background

The International Organization for Standardization (ISO, 2017) defines Facilities Management (FM) as the "Organizational function which integrates people, place and processes within the built environment with the purpose of improving the quality of life of people and the productivity of the core business"(ISO, 2017). FM encompasses multi-disciplinary and independent disciplines with extensive information requirements (Patacas, Dawood, Vukovic, & Kassem, 2015). The International Facility Management Association (IFMA, 2013) lists Operations and maintenance, sustainability, facility information management, technology management, risk management, and project management among the various FM responsibilities.

Access to reliable and accurate information for various aspects of numerous components in a facility is critical for efficient and successful FM practice. Examples of such information include a building component's location, performance data, manufacturer and vendor data, installation, operation and maintenance requirements, etc. (Becerik-Gerber, Jazizadeh, Li, & Calis, 2011; Matarneh, Danso-Amoako, Al-Bizri, Gaterell, & Matarneh, 2018). Typically, this information, which is critical to successful FM, is created by various stakeholders, during multiple phases of the building lifecycle and is handed over in various formats to FM stakeholders during project close out (Alnaggar & Pitt, 2018). The fragmentation in the creation and storage of facility data brings about interoperability issues (Parsanezhad & Dimyadi, 2014), which exacerbates challenges such as information loss (Teicholz, 2013), duplication and inconsistencies between available data and the time wasted searching for information (Gnanarednam & Jayasena, 2013), that are often associated with traditional Facility Information Management (FIM) practices. Furthermore, previous studies acknowledge the inefficiencies of the construction-to-operation information handover process, which is error-prone due to manual data re-entry, and further emphasize the criticality of accurate AEC information for FM workflows (Bröchner, 2008; Wijekoon, Manewa, & Ross, 2018).

To promote efficient information-sharing, Information Communication Technology (ICT) tools have been developed and employed. These tools range from email document transactions developed during the 1970s, in the form of MS Office, pdf, or jpegs, to more advanced systems such as Computer-Aided Facilities Management (CAFM) (Aziz, Nawawi, & Ariff, 2016; Lavy & Jawadekar, 2014). CAFM tools are capable of capturing and maintaining facility information, including maintenance and operations, budgeting, work orders, inventory management, construction and project management, space management, and energy management (Aziz et al., 2016; Elmualim & Pelumi-Johnson, 2009; Lee et al., 2013). Although this computerization improves capturing and retrieving information, CAFM is not an effective tool for knowledge management and data analysis as it captures and provides information in conventional formats (Gnanarednam & Jayasena, 2013). Recently industry and academia have recognized BIMs as a compelling tool for Facilities Lifecycle Information Management (Akcamete, Akinci, & Garrett, 2010; Terreno, Anumba, Gannon, & Dubler, 2015). BIMs are object-oriented, and inherently parametric, in that they are a combination of building objects with intelligent behavior that can be configured through a set of geometric and non-geometric parameters and rules at the assembly, sub-assembly, and individual model element level. Model elements are defined and controlled by a series of relationships, rules, conditions, and constraints created within a family of components (e.g. a classification of model elements in a categorical family such as doors, windows, walls, etc.).

Nagel et al. (2009, pg. 46) posit that "The logical structure and well-defined meaning of the objects are crucial prerequisites for applications which go beyond pure visualization". A growing interest in exploring implementation of BIMs to improve seamless information exchange during building handover and to integrate BIM within FM workflows is evident in the increasing number of research and case projects on the subject. For instance, the visualization capabilities of BIM and their role in decision making for O&M tasks are receiving increased attention (Patacas et al., 2015). Ibrahim, Abanda, Vidalakis, & Wood (2017) propose a conceptual framework to integrate data from BIM with such technologies as GIS, sensors, and asset databases to improve FM decision making. Potential benefits of integrating BIM within FIM include locating building components (Mohanta & Das, 2017), access to more accurate data and automated data generation (Becerik-Gerber & Kensek, 2009) through a central model (Pärn, Edwards, & Sing, 2017), and improving the efficiencies of FM work orders (Kelly, Serginson, Lockley, Dawood, & Kassem, 2013). Other application areas include daily O&M data management (Peng, Lin, Zhang, & Hu, 2017), scheduling of maintenance work orders (Chen, Chen, Cheng, Wang, & Gan, 2018), failure root cause detection (Motamedi, Hammad, & Asen, 2014), energy control and monitoring (Becerik-Gerber et al., 2011), space management AU, and emergency management (Nicał & Wodyński, 2016; Terreno et al., 2015). In an attempt to mitigate safety hazards to FM staff, Wetzel and Thabet (2018) developed a BIM-based framework to identify, capture, and transform safety-related information from design and construction to O&M.

Nonetheless, in the current practice the implementation of BIMs during the post-construction phases of the facility lifecycle remains limited due to various interoperability issues (Becerik-Gerber et al., 2011; Volk, Stengel, & Schultmann, 2014). According to the National Institute of Standards and Technology (NIST), 2004, pg. ES-3, interoperability "Relates to both the exchange and management of electronic information, where individuals and systems would be able to identify and access information seamlessly, as well as comprehend and integrate information across multiple systems." Other research also emphasizes the importance of addressing interoperability issues beyond mere information exchange among software applications. Grilo and Jardim-Goncalves (2010) identify business processes, culture, values, and contractual issues among interacting firms as important dimensions of interoperability within the AEC industries. The National BIM Standard identifies a consistent information format and exchange process, as well as a common understanding of the exchanged information among stakeholders that is critical for true BIM interoperability to occur (National Institute of Building Sciences, 2015). NIST estimates the annual cost of inadequate interoperability within the United States capital facilities industry at $15.8 billion, of which $4.8 billion is resultant of labor charges in the mitigation costs category. This entails the cost of O&M staff productivity loss, O&M staff rework costs, and O&M information verification costs. This figure is estimated by comparing current AEC and FM practice with a hypothetical model where seamless information exchange and management processes occur throughout the entire project lifecycle. Such processes would prevent financial losses incurred to address technical interoperability issues and respective delays. Furthermore, the report estimates the potential annual savings with respect to automated transfer of information from AEC to FM at $613M (National Institute of Standards and Technology, 2004).

According to Wetzel and Thabet (2018), when addressing the limitations of current technical solutions, there are four prominent strategies for data handover between BIM-authoring tools and FM (Table 1, retrieved from Wetzel & Thabet, 2018, pg. 60).

Table 1. BIM-FM interoperability strategies, retrieved from (Wetzel & Thabet, 2018)

Interoperability Strategy	Descriptions
Hard Entry	Utilizes attribute and value data inputs. Inputs can be stored in a 3D model or non-model format (i.e. Microsoft Excel)
Software Interoperability	Utilizes software compatibility to transfer relevant information from the native/design file to the repository/coordination model
Middleware	A compatibility "bridge" that allows for non-interoperable software applications to transfer information (i.e. EcoDomus)
Proprietary Systems	Utilizing systems such as Open Database Connectivity and Application Programming Interface (API) to develop user defined links for data transfer

Steel et al. (2012) introduced a four level IFC-based interoperability format that governs data exchange. The first two levels, file and syntax, respectively, pertain to the computer applications' capabilities to exchange and analyze shared model information. The third level, visualization, refers to the software's ability to present the visual characteristics of exchanged model components. The fourth level, semantic, describes the software applications ability to understand the parameters of shared model elements. Potential challenges when combining BIMs developed by various stakeholders generally include errors resulting from large file sizes or positioning model elements in incorrect locations when merging BIM files. However, more complicated problems related to different modeling styles and software limitations arise at the semantic level. Problems of this nature remain prevalent when integrating BIMs because participating firms may be required to use applications from the same software vendor or ensure the chosen applications are compatible within the appropriate IFC level (Laakso & Kiviniemi, 2012).

The industry and academia have explored the previously mentioned issues and an increasing number of research and development efforts strive to address these challenges. Several non-proprietary file formats and exchange protocols have been developed addressing one or more of five main domains; what information is to be exchanged, how, when, by whom, and why (Halfawy & Froese, 2005). Corresponding openBIM standards, commonly accepted in North America, are the Industry Foundation Classes (IFCs), Information Delivery Manual (IDM), Model View Definition (MVD), and buildingSMART Data Dictionary (bsDD). The IFCs schema, developed by buildingSMART, pertain to data standards, covering a wide range of domains within the AEC and FM industry. IFCs address data interoperability by specifying an open data schema and neutral file format to promote object-oriented data exchange among heterogeneous BIM platforms used by various participants in the AEC/FM industry (Bedrick, 2019; Kell, 2015; Laakso & Kiviniemi, 2012). The open data schema specifies exchange format definitions in EXPRESS language, including data structure, modeling constructs, and syntactic and semantic requirements. The next section of this dissertation provides a detailed description of the most important components and concepts IFC specification addressed for the purpose of this study.

Although the IFC standard is increasingly being used by software vendors and practitioners, studies reveal difficulty in its implementation. Experts suggest that the IFC schema be refined to promote the robust exchange of semantic information due to the considerable complexity of the data structure and ambiguous content classifications as primary difficulties in implementing IFC for FM purposes (Manu Venugopal, Eastman, & Teizer, 2015; Zibion, Singh, Braun, & Yalcinkaya, 2018). The significant extent and complexity of a full IFC model results in technical difficulties and redundancies such as exporting asset data which is not required for FM. This overgeneralization can be overcome by reducing the scope for specific implementation (Steel, Drogemuller, & Toth, 2012). The IDM and MVD standards provide support for both industry users and software developers by identifying and mapping specific needs, activities, and information required for each exchange scenario within the IFC model, which can facilitate automatic model validation. The MVD concepts provide a technical solution to exchange the information (ERs) (See, Karlshoej, & Davis, 2012; Wix & Karlshoej, 2010). An MVD consists of concepts with predefined specifications and rule sets defining required entities, attributes, properties, and relationships to meet the ERs for a scenario. These concepts comprise the input to software development and the basis for measurement of the exchange success (C. Eastman et al., 2009; M. Venugopal, Eastman, Sacks, & Teizer, 2012). Although these concepts are meant to provide a modularized mechanism for reusability, in practice the "lack of formal definitions on a semantic level" hinders reuse of MVDs, resulting in waste in development and implementation of MVDs on multiple projects (C. Zhang, Beetz, & de Vries, 2013).

The openBIM schema corresponding to this aspect of BIM data interoperability is the bsDD, which provides "meaning" for the exchanged information and is intended to establish a common understanding among various industry experts, end-users of BIMs, and solution providers. The standard establishes a "common technical language", which "works as a semantic mapping tool that connects like-terms based upon their meaning as it pertains to construction" (National BIM Standard, 2017). However, the "common language" among AEC experts to convey the extent of reliance on model elements in a BIM is defined by the Level of Development (LOD) schema developed by the American Institute of Architects (AIA) (Becerik-Gerber, Jazizadeh et al., 2012. National Institute of Building Sciences, 2015). The LOD descriptions identify the specific minimum content requirements and associated authorized uses for each model element at five progressively detailed levels of completeness (e.g. LOD 100 through LOD 500). The Associated General Contractors BIMForum Committee's LOD specifications refer to the LOD classification as a "reference" or a "language", suggesting that by means of this LOD classification, AEC industry practitioners "Can specify and articulate, with a high level of clarity, the content and reliability of BIMs at various milestones in the design and construction process for their specific firms or projects" (BIMForum, 2015). Hence, despite the progress made in this domain, the challenge of bridging the gap between the technical language of these solutions and the non-technical nature of the common language among AEC/FM experts (LOD schema) remains unresolved.

In general, the precision and level of graphic and non-graphic information for model elements increase by their respective LOD level. For a BIM user, the LOD levels indicate the progression to a higher level of model element information, providing more details moving from LOD100 towards LOD500 (BIMForum, 2015). The LOD specification also provides a platform for users to identify required LOD for elements to perform such tasks as design coordination, model-based fabrication and as-built documentation. For instance, at LOD400, the element "Is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information." And, furthermore, that "The LOD schema does not address the non-geometrical requirements, only suggesting that "Non-graphic information may also be attached to the Model Element" (BIMForum, 2019, pg 12). On the other hand, the schema addresses only AEC-specific requirements, and stops at field verification. Differing owner-specific information requirements has led to research proposing LODs that diverge from the original five levels. LODs provide a general classification structure for information requirements and can include less detail than LOD500 given a project's characteristics or the Owner's need for O&M data from the BIM. Research suggests that O&M information requirements can be satisfied with less precision than LOD500 because non-geometrical information is more critical than the high precision level geometrical requirements of LOD500 (Mayo & Issa, 2014). Despite the progress made in this domain, the challenge of bridging the gap between the technical language of these solutions and the non-technical nature of the common language among AEC/FM experts (LOD schema) remains unresolved.

Specific to FM handover exchange scenarios, is the Construction Operation Building information exchange (COBie) schema, which provides the capability to outline a structured method to capture and deliver information required for asset management in the operation phase from an early stage of the facility's lifecycle (East & Carrasquillo, 2013; Patacas et al., 2015). Although COBie aims to facilitate the import of real-time data to an FM system (East, 2007), previous studies criticize the complexity, fragmentation, and labor-intensive process dominating implementation of COBie (Howard & Björk, 2008; Yalcinkaya, Singh, Nenonen, & Junnonen, 2016). Furthermore, while COBie provides the format for the exchanged information, it fails to support the owner in identifying and requesting specific semantic data according to FM information requirements (Love, Matthews, Simpson, Hill, & Olatunji, 2014). Accordingly, FM receives incomplete, unnecessary, or low-quality COBie data at project close out, which impairs its efficient usability during operation (Alnaggar & Pitt, 2018). From a technical standpoint, existing BIM-authoring platforms, with few exceptions, generally do not provide complete support for the COBie schema (Patacas et al., 2015).

Research and development efforts have focused on two significant areas to clarify BIM requirements for FM handover and data exchange; The first comprises the investigation of owner requirements to identify the geometric and semantic model component characteristics to promote FM-specific workflows (Becerik-Gerber et al., 2011; Motamedi et al., 2014) and the associated establishment of ERs for FM handover (Cavka, Staub-French, & Poirier, 2017; Mayo & Issa, 2015;

Patacas et al., 2015). The second primary research focus has addressed the specification and mapping of ERs to provide support for technical solutions that streamline BIM implementation during the FM handover process (Alliance, 2011; Pishdad-Bozorgi, Gao, Eastman, & Self, 2018; William East, Nisbet, & Liebich, 2012). A primary example of the latter is the buildingSMART "FM Basic Handover View", which specifies ERs and MVDs for the "basic" handover of FM information to improve interoperability of commercially available BIM applications, Computer Aided Facility Management (CAFM) and the Computerized Maintenance Management System (CMMS) applications. The scope of this standard is limited to the "basic" requirements for the IFC entities included in Figure 1, not addressing any FM specific needs (Alliance, 2011). Furthermore, and as previously mentioned, existing literature stresses the need for more specific guidelines for successful implementation of IFC MVDs (C. Zhang et al., 2013).

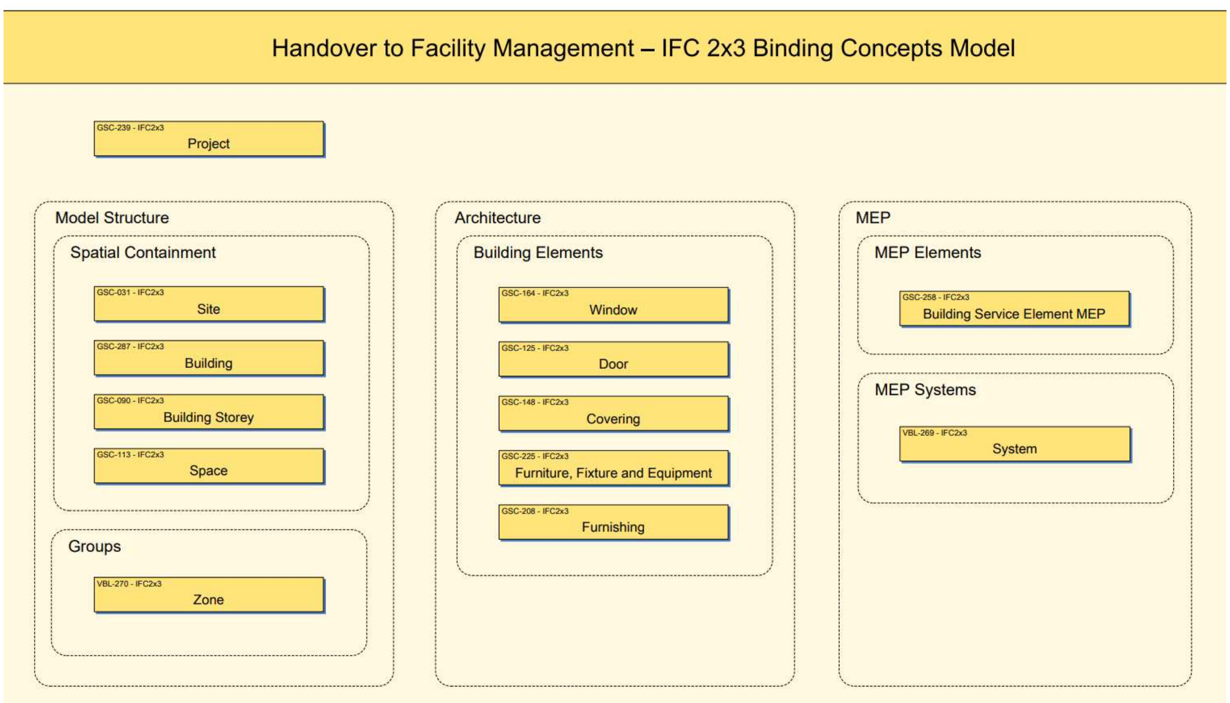


Figure 1. Handover to Facility Management MVD, retrieved from (Alliance, 2011)

Industry Foundation Classes (IFC)

As previously mentioned, the IFC open data schema specifies exchange format definitions, including concepts, data structures, modeling constructs, and syntactic and semantic requirements. This section provides a detailed description of the architecture and most important IFC entities and concepts critical within the scope of this study. The architecture of the IFC schema defines four conceptual layers depicted in Figure 2, incorporating schemas intended to facilitate specific exchange scenarios within the AEC/FM industry. These layers include the Core layer, Domain layer, Interoperability layer, and Resource layer.

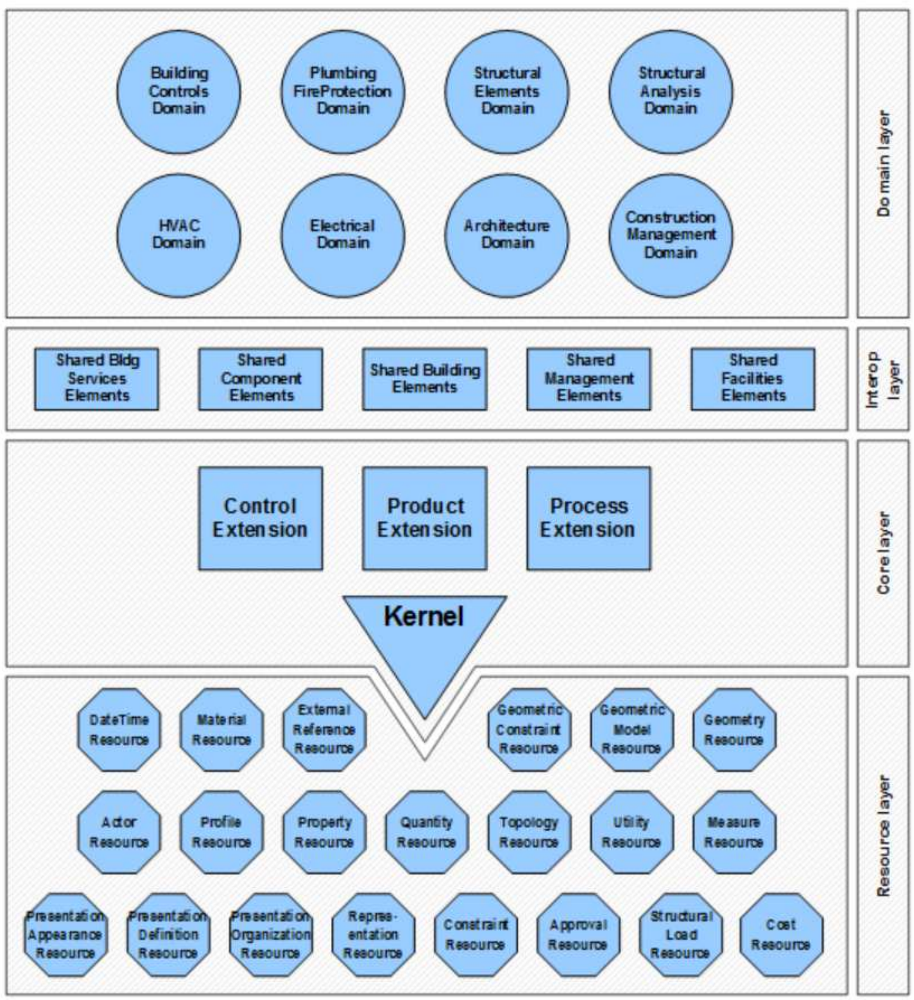


Figure 2. Conceptual Layers of the IFC Data Schema, retrieved from IFC4x2

The "Resource Layer" incorporates individual schemas which consist of supporting data structures to define resources (e.g. Material Resource). Entities and types defined in this layer can be referenced by entities in other layers and cannot exist independently (buildingSMART, 2016).

The "Core Layer" consists of data schemas that provide the basic structure, the fundamental relationships, and the common concepts for all further specialized MVs. This layer defines the base classes which drive from the 'IfcRoot', the most abstract class for all entity definitions that roots in Kernel. This includes definition of objects, object types, relationships between objects, and their properties. Figure 3 depicts the 'IfcRoot' concept and a partial extraction of the subtype trees within the IFC model element classification system.

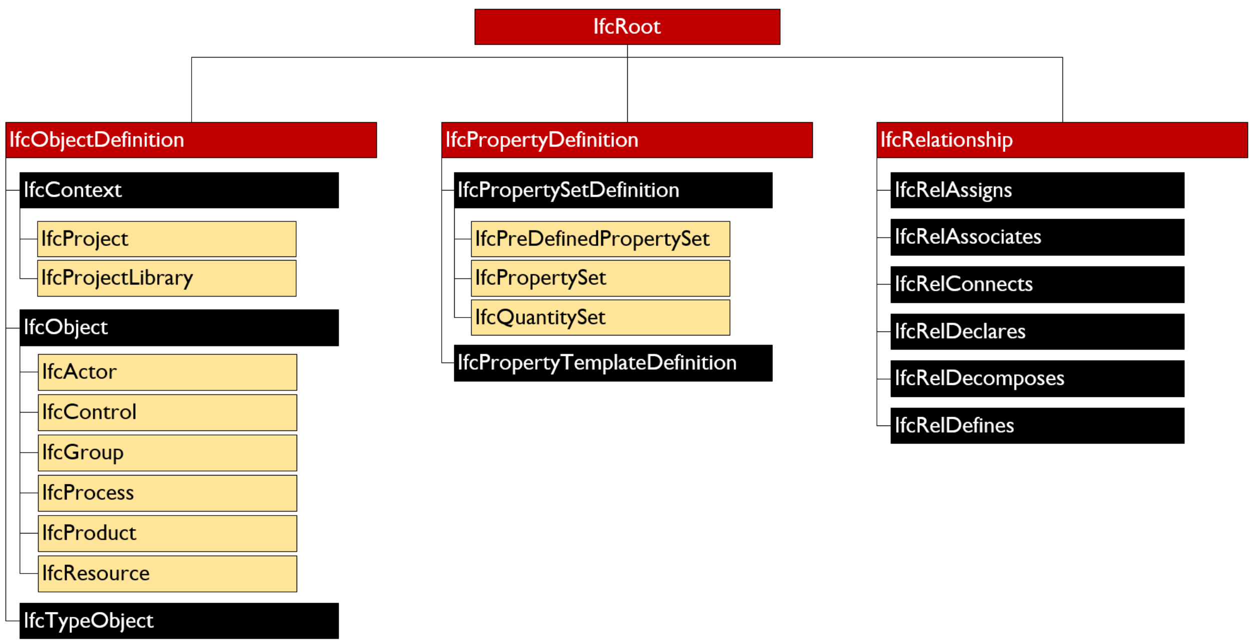


Figure 3. Partial extract of inheritances of IfcRoot, extracted from IFC4x2

buildingSMART (2016) defines IFC objects as "Independent pieces of information that might contain or reference other pieces of information". Six fundamental entity types categorize inheritances of IfcObject; actors, controls, groups, processes, products, and resources. Table 2 provides description for these entity types (introduced in the objects entity subtype tree of Figure 3).

Table 2. IFC object entity subtype tree, retrieved from IFC4x2

Object entity type	Description
Actors	Human agents involved in a project during its full life cycle
Controls	Concepts which control or constrain other objects. Controls can be seen as guide, specification, regulation, constraint or other requirement applied to an object that has to be fulfilled.
Groups	Arbitrary collections of objects (e.g. a zone incorporating multiple spaces)
Processes	Actions taking place in a project with the intent of acquiring, constructing, or maintaining objects. Processes are placed in sequence in time.
Products	Physically existing or tangible objects (manufactured, supplied or created) for incorporation into a project. Products may be defined by shape representations and have a location in the coordinate space.
Resources	Concepts that describe the use of an object mainly within a process

The ‘IfcKernel’ schema, identified above in Figure 2, also defines the syntax and data types for individual properties or property groups (referred to as Property Sets and Quantity Sets), which can be assigned to objects or object types. Property sets are a “container that holds properties within a property tree” and provide definition for objects or object types (buildingSMART, 2016).

‘IfcRelationship’ is defined as “The abstract generalization of all objectified relationships in IFC”. Handling the connection between model components through the objectified relationships “allows to keep relationship specific properties directly at the relationship [level] and opens the possibility to later handle relationship specific behavior” (buildingSMART, 2016). The IFC schema introduces six fundamental relationship types defined in Table 3; assignment, association, connectivity, declaration, decomposition, and definition.

Table 3. IFC relationship entity subtype tree, retrieved from IFC4x2

Relationship type	Description
Assignment	A generalization of "link" relationships among instances of objects and its various subtypes. A link denotes the specific association through which one object (the client) applies the services of other objects (the suppliers), or through which one object may navigate to other objects.
Association	Refers to external sources of information (most notably a classification, library or document) and associates it to objects or property definitions.
Connectivity	Handles the connectivity of objects (of any type)
Declaration	Handles the link between object definitions and property definitions and the declaring context
Decomposition	Defines the general concept of elements being composed or decomposed. The decomposition relationship denotes a whole/part hierarchy with the ability to navigate from the whole (the composition) to the parts and vice versa
Definition	Uses a type definition or property set definition (seen as partial type information) to define the properties of the object instance. It is a specific - occurrence relationship

The “Interoperability layer”, identified above in Figure 2, contains the shared element schemas that provide more specialized objects and relationships shared by multiple domains. The ‘IfcSharedFacilitiesElements’ schema, for instance, defines basic concepts in the FM domain applicable to furniture, asset identification, and the inventory of objects.

The “Domain Layer”, identified above in Figure 2, incorporates data schemas that contain final specializations of entities, which organize definitions according to industry discipline. For instance, the ‘IfcHvacDomain’ schema defines basic object concepts required for interoperability within the heating, ventilating and air conditioning (HVAC) domain. It extends concepts defined in the ‘IfcSharedBldgServiceElements’ schema. This includes segments, fittings and connections that constitute duct and piping distribution systems; equipment used in building services; and Terminal and flow control devices.

Considering the fact that no schema addresses all the requirements for FM handover exchange scenario (the focus of this dissertation), this study carried out an in-depth and schema independent (regardless of object type or exchange scenario) investigation of the specification to develop a comprehensive list of IFC concepts provided in Figure 4.

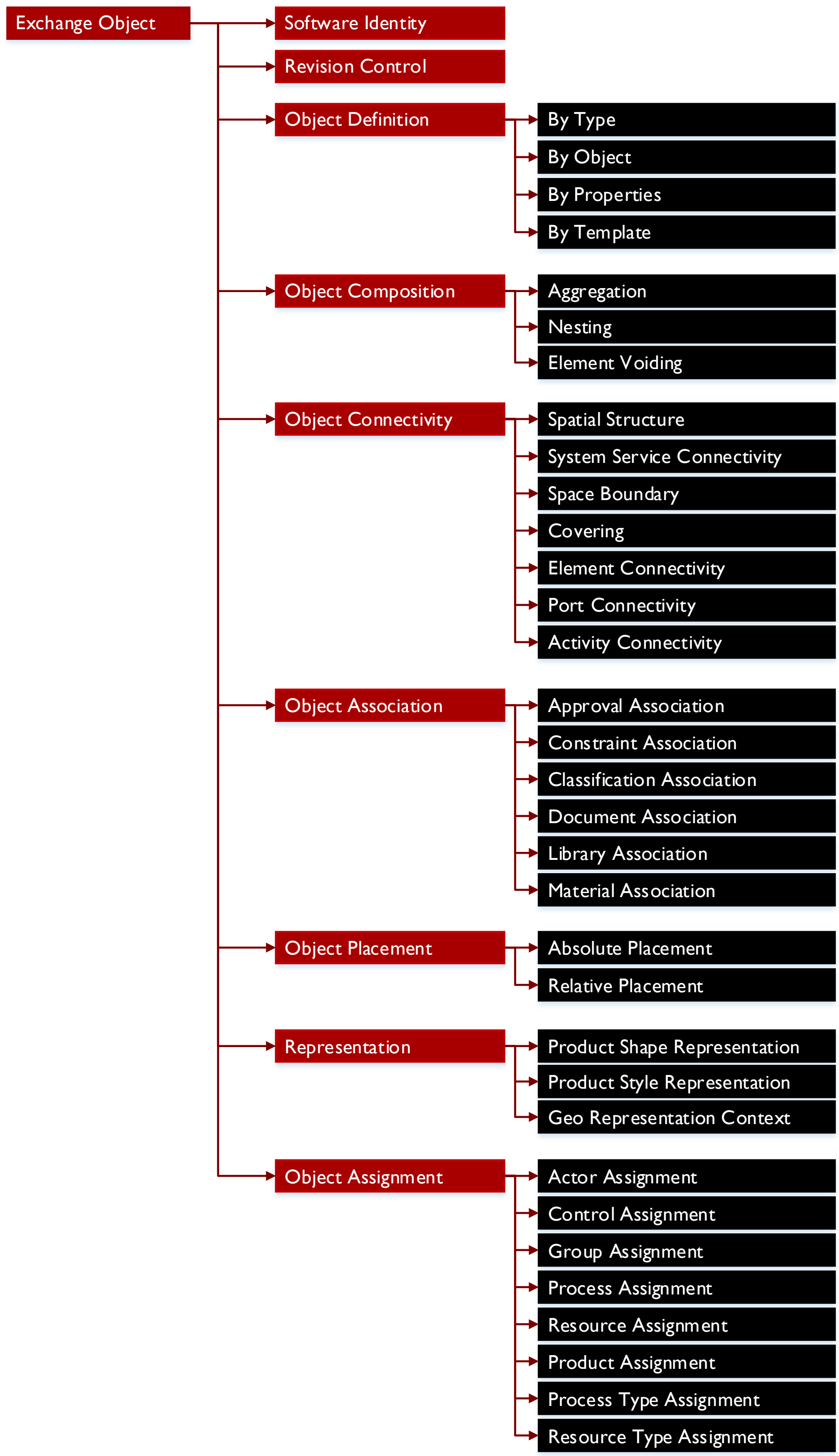


Figure 4. IFC Concepts, extracted from IFC 4x2

The follow provide a brief summary of important concept and definition contributions of this study to the body knowledge for BIM use in FM handover and operation:

Software Identity

With respect to model elements, ‘Identification’ is defined as the capability to “find, retrieve, report, change, or delete specific instances without ambiguity” (buildingSMART, 2016). ‘IfcRoot’ assigns a unique identifier for objects (by means of an attribute ‘GlobalID’) in an IFC model to facilitate their identification for both human and automated processes. It can also provide for additional information via assignment of a “Name” or “Description” attribute.

Revision Control

The concept of model element ‘Revision Control’ aims to reflect the changes any independent object goes through over the course of a project lifecycle. Related information about creation and last modification is directly attached to objects via the entity ‘IfcOwnerHistory’ (buildingSMART, 2016). If applicable, objects may carry information attributes indicating creation and modification dates, owning and modifying user (person or organization), owning application and the software vendor and version, etc. (buildingSMART, 2016).

Object Definition

IFC objects can be defined through assignment of single or a collection of properties, holding various data types. This is done via the definition relationship ‘IfcRelDefinesByProperties’, which assigns items of the ‘IfcPropertySet’ with respect to object occurrences. Another method would be the assignment of properties to instances through their corresponding object type. ‘IfcRelDefinesByProperties’ also relates objects to occurrences of ‘IfcElementQuantity’, each containing multiple quantity occurrences, which define derived measures of an element’s physical property (Figure 5) (buildingSMART, 2016).

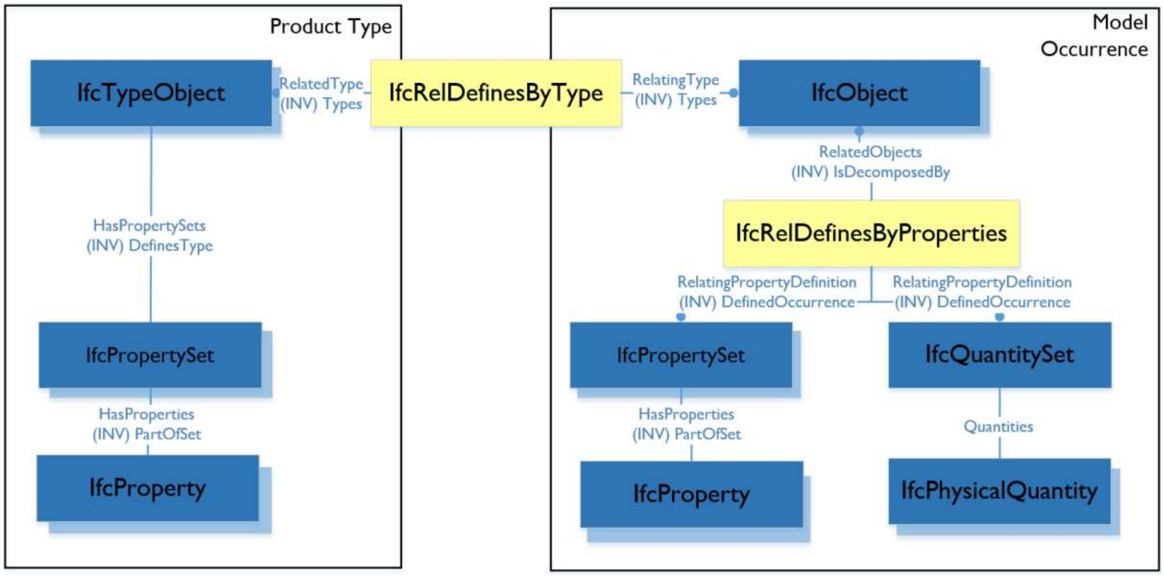


Figure 5. Definition by type and properties, extracted from IFC4x2

<u>Object Composition</u>

Composition in general refers to the relationship to a higher level element (e.g. and instance of 'IfcSpace' is a part of a specific instance of 'IfcBuildingStory'). One subtype of this concepts is Aggregation. As shown in Figure 6, the spatial structure which is a hierarchical tree of spatial elements ultimately assigned to the project (buildingSMART, 2016).

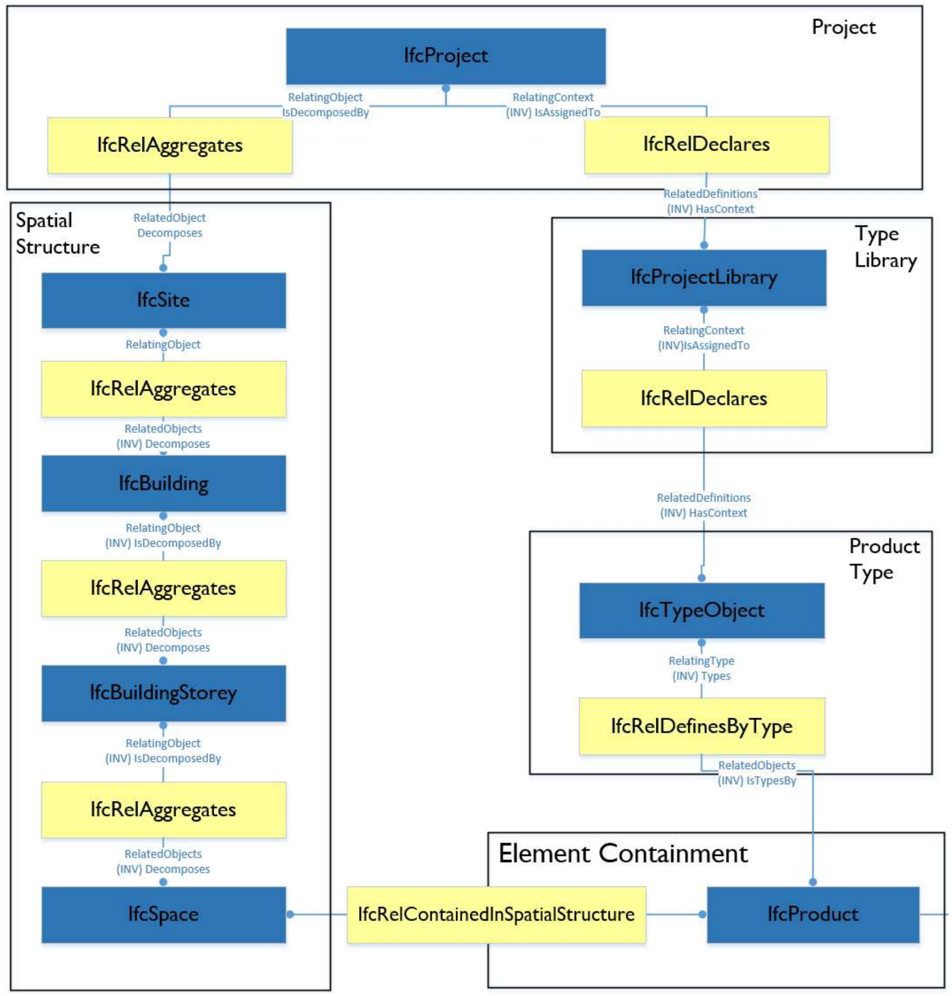


Figure 6. IFC project composition and declaration concepts, extracted from IFC4x2

<u>Connectivity to Other Objects</u>

Another concept depicted in Figure 6 is the spatial containment, which is a subtype of object connectivity concept. Defines the relationship between a physical object (inheritances of IfcProduct e.g. air terminals) and the space containing those.

Objects may participate in various connectivity relationships with other objects. For instance, within distribution systems, the “Port Connectivity” concept connects distribution ports belonging to distribution elements (e.g. duct segments) to one another. This relationship also determines the physical flow direction from the flow source to flow sink element. Another connectivity concepts pertains to the connection between the distribution flow elements (e.g. duct segment) and the control elements (e.g. sensors), which monitor or control the behavior of the flow element (Figure 7) (buildingSMART, 2016).

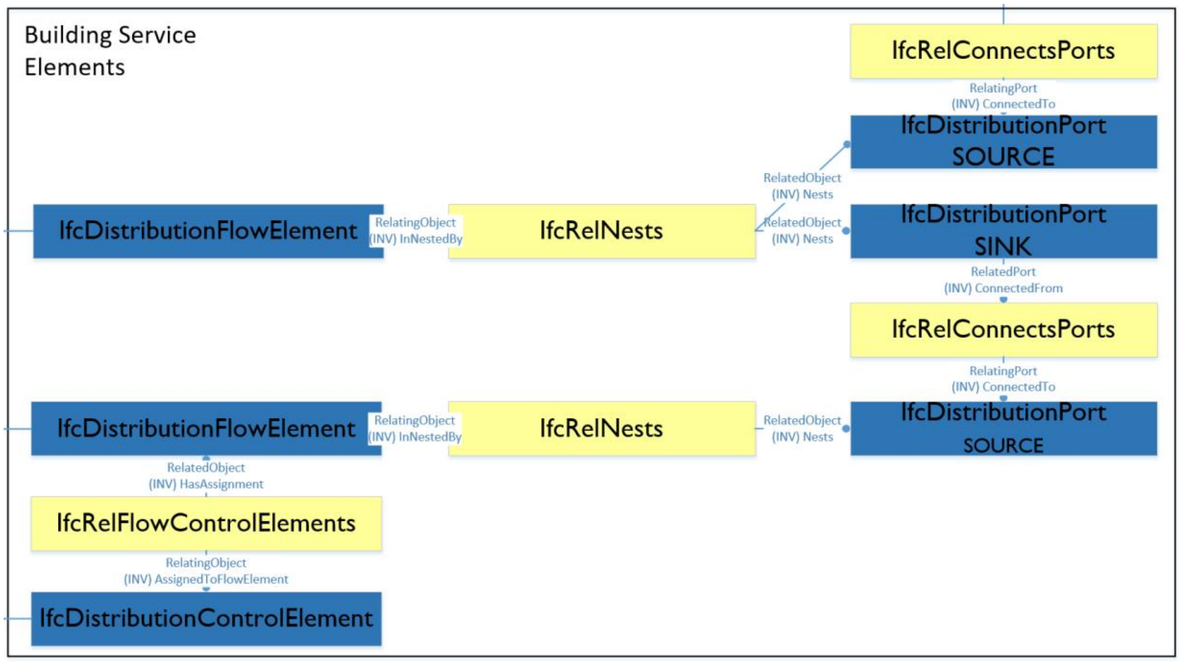


Figure 7. IFC connectivity and nesting concepts for building service elements, extracted from IFC4x2

Declaration within a Context

IfcContext provides the context for all information to define objects, object types, property sets, and properties within a project or a project library. The IfcProject object indicates the unique "root instance", which provides the context for all other information items included within a model. This information includes the project classification structure, project coordinate system, project true north, default units of measurements (e.g. for length, or pressure), etc. (buildingSMART, 2016).

Associations to External/Internal Resource Information

This concept refers to an associate source of information, such as a document or a classification system, to further define an object.

Object Placement

This concept provides information on location of model occurrences in 3D space. This placement established the coordinate system for objects (absolute placement) or location relative to other objects like a grid (local placement).

Assignment of Other Objects

Objects may provide "services" to other objects. There is a general cycle of assignments where actors (people) issue controls (such as work orders or schedules), which may result in groups (such as building systems) comprised of products (such as building elements) operated upon by processes (such as construction tasks) performed by resources (such as labor) which may in turn be fulfilled by actors (people) (buildingSMART, 2016).

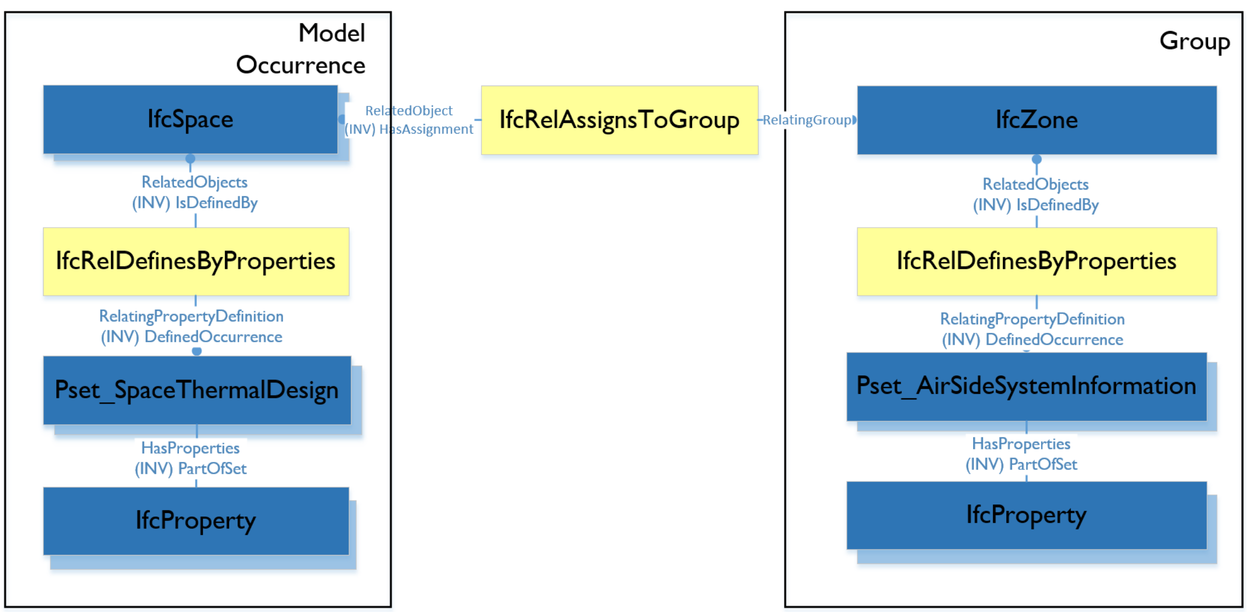


Figure 8. Assignment of groups to objects, extracted from IFC4x2

The Problem Statement

Successful FM workflows require access to timely and reliable information on various aspects of components of the asset portfolio. Fragmentation of the traditional practices in capturing, delivering, and managing FM data brings about such inefficiencies as information loss (Teicholz, 2013), wasted time searching for information (Gnanarednam & Jayasena, 2013), inconsistencies in the available data, and rework (National Institute of Standards and Technology, 2004). Considerable financial losses could occur as the result of insufficient data interoperability from construction to FM, pertaining to such inefficiencies as O&M staff productivity loss, O&M staff rework, and O&M information verification (National Institute of Standards and Technology, 2004). Although BIMs are recognized as compelling tool for facility's lifecycle information management with the potential to overcome these challenges, their implementation in FM handover and post-construction building operation remains rather limited. From a technical standpoint, limitations of commercially available solutions is a driving factor in determination of appropriate interoperability strategy between a BIM-authoring tool and the FM system (Wetzel & Thabet, 2018).

However, more complicated problems related to heterogeneous modeling conventions of various AEC firms arise at the semantic level of interoperability (Laakso & Kiviniemi, 2012). True BIM interoperability occurs with establishment of a consistent information format and exchange process, as well as a common understanding of the exchanged information among stakeholders (National Institute of Building Sciences, 2015). For BIMs to facilitate automated and seamless information flow from construction to FM, Exchange Requirements (ERs) for this scenario (BIM content; what information) need to be clarified at the front end of the building lifecycle according to FM task- and system-specific needs (Kassem, Kelly, Dawood, Serginson, & Lockley, 2015;

Kim et al., 2018; Patacas et al., 2015). Further corresponding formalization of the format (content structure), as well as consistent terminologies and taxonomies (Parsanezhad & Dimyadi, 2013) is also critical. Lack of clear specifications for these aspects hinders automated validation of model data at FM handover, requires rework (in terms of remodeling) and mapping model data and manual re-entry to FM systems.

Research Statement and Outline

Researchers acknowledge that BIMs have the potential to alleviate several of the shortcomings and concerns associated with FM data exchange and handover. In order to explore the potential of BIMs for FM and operation, this dissertation investigated the limitations of traditional FM handover practice and defined a modeling framework to promote an efficient BIM-based data exchange protocol for project handover. This dissertation developed a BIM-intensive framework to support FM decision-making in Higher Education Institutions (HEI) as a developer, building owner and building operator stakeholder. The results have implications for other owner groups, however the study sampling was delimited to Institutions of Higher Education in the state of Colorado. The final phase of this study (manuscript 3, chapter 4) specifically contributes to the body of knowledge through the creation and leveraging of the Level of Semantics (LOS) concept, along with the existing LOD definitions, and within the existing IFC schemas. This document follows the guidelines for a three-manuscript dissertation:

Manuscript 1, Dissertation Chapter 2 - Integrating Building Information Models and Building Operation Information Exchange Systems in a Decision Support Framework for Facilities

Management. The manuscript comprised the results of the initial phase of the research and was published by the Construction Research Congress in April of 2018.

The initial phase (chapter 2) of the study investigated the current FIM practice within the context of FM groups in HEIs. This effort provided an in-depth understanding of four main aspects pertaining to FM, which provide input to the BIM-intensive framework; institutions' asset portfolio, FM workflows and task information needs, currently employed Information Technology (IT) tools, and information management challenges. The target population in this phase was HEIs in the state of Colorado, including public, private, and regional universities and community colleges. The results of this phase revealed that the first challenge in implementation of BIM for FM pertain to the transfer of data during the construction to FM transition of the building lifecycle. The results of chapter one provide evidence that an AEC-purposed BIMs are not suitable for FM purposes.

Chapter 3 - *Extending the Level of Development Schema for Building Handover, Operation and Maintenance.* This manuscript comprised the second phase of the research and was submitted to the Journal of Facilities Management in April of 2018.

The second phase (chapter 3) employed a case study approach to develop a BIM-enabled framework to facilitate FM handover and O&M workflows. The goal of this phase was to identify O&M information requirements and employ BIM to capture, retrieve, and deliver this information in the end-user requested format. Chapter two refers to this model as the Building Handover Information Model (BHIM). The case study is an existing building, a Design-Build project case, in the Rocky Mountain Region of the United States. The BHIM was created specific to this case with the intent of providing more efficient, automatic data retrieval during project closeout, while also increasing the integrity and consistency of the information provided in the final documents.

The geometric and non-geometric requirements for model elements in the BHIM was contextualized given the Level of Development (LOD) and Construction Operation Information Exchange (COBie) schema, respectively. The results revealed that use-based identification of model requirements was critical to avoid delivering incomplete or unnecessary data to FM stakeholders. Furthermore, the lessons learned suggested the need for more systematic clarification in conveying the owner's requirements to overcome interoperability issues pertaining to heterogeneous modeling and naming conventions. This research implication is more critical specifically for large owner organizations to establish a reusable framework.

Chapter 4 - *Information-Augmented Exchange Objects to Inform Facilities Management Handover BIM Guidelines: Introducing the* Level of Semantics (LOS) *Schema.* This manuscript comprised the third phase of the research and is to be submitted to the journal of Automation in Construction in April of 2019).

Following a comprehensive literature review, and in light of the results and research gaps identified during the first and second phase of the research, the final phase of this dissertation (chapter 4) established a repeatable BIM-intensive workflow to identify, clearly specify, and convey the data exchange Requirements (ERs) necessary for BIMs to be utilized for FM-specific purposes. This research effort resulted in the establishment of a protocol that describes a common understanding of expectations and facilitated a seamless validation and transition of handover model data to FM systems. This was accomplished within the existing context of Industry Foundation Classes (IFC), Information Delivery Manual (IDM), Model View Definition (MVD) and buildingSMART Data Dictionary (bsDD). These industry-recognized and existing schemas were employed to formalize content structure, terminologies and taxonomies according to FM system and task needs, and available BIM-FM data interoperability strategies. To bridge the gap between the technical language of bsDD and the non-technical language of the LOD schema, this study provided IFC-based technical solution for LOD ERs. This chapter introduces the Level of Semantics (LOS) schema as the framework for conveying the remaining IFC concepts required for the FM handover scenarios between stakeholders in non-technical language. Application of LOS concept along with clear definitions to formalize semantic requirements for Eos within the FM handover IFC MV eliminates numerous issues associated with traditional construction-to-operation handover practice and promotes data for downstream commissioning, maintenance, and operation workflows on HVAC distribution systems.

The final chapter of this dissertation outlines the connection between the three manuscripts and further provides an overview of the purpose and results of each phase. Chapter 5 also discusses the research contribution, limitations, delimitations and opportunities for further research.

Chapter 2 - Integrating Building Information Models and Building Operation Information Exchange Systems in a Decision Support Framework for Facilities Management[1]

Overview

The Higher Education Institutions' (HEI) asset portfolio include a diverse range of buildings with different characteristics, economic life, rehabilitation and maintenance costs, and mission criticality. All such information is to be integrated in support of a rational and highly informed decision-making process within a resource-constrained environment in the context of Facilities Management (FM). This process needs to build upon accurate, reliable, and timely information about various building systems, components, and component elements of the individual buildings – which comes from a variety of sources. Delivering information in a segregated manner, traditional FM tools fall short in providing requirements effectively. Building Information Models (BIM), capable of capturing and integrating such large information databases, has recently been recognized as a compelling tool for project life-cycle analysis. This study is the first phase of a series of research on a BIM-intensive information management framework to support FM decision-making in HEIs. Four main aspects of building FM are investigated as inputs to the framework; institutions' asset portfolio, FM practice, FM information requirements, and employed Information Technology (IT) tools. Information requirements are classified into four main categories; attributes of the physical facility, operation and maintenance (O&M) data,

[1] Sadeghi, M.; Mehany, M.; Strong, K. (2018); Construction Research Congress, New Orleans, Louisiana

institutional factors, and decision alternatives. This information can be captured, stored, retrieved or exchanged in multiple software packages by integrating BIMs and Building Operation Information Exchange Systems within the FM framework.

Introduction

The larger fraction of a facility's lifecycle expenses, approximately 60% of the total lifecycle cost (Guillen et al., 2016), belongs to post-occupancy (Clayton, Johnson, & Song, 1999; Liu, Stumpf, Kim, & Zbinden, 1994) and a large percentage of activities in this phase is dedicated to maintenance of the facility (Michael P. Gallaher, O'Connor, John L. Dettbarn, & Gilday, 2004). The typically utilized building maintenance practice is reactive and inefficient in nature (Sullivan, Pugh, Melendez, & Hunt, 2010) in that it merely reacts to failures, which brings up the need to move towards more effective approaches (Akcamete et al., 2010; Michael P. Gallaher et al., 2004). One initial measure to support a planned maintenance practice is developing a reliable database by capturing and storing information regarding different aspects of the facility (Akcamete et al., 2010). Nevertheless, access to credible, timely information is a challenge for facilities decision makers as they are often provided with incomplete, inaccurate as-built documents (P. E. D. Love, Zhou, Matthews, & Luo, 2016) and fragmented O&M history data (Motamedi et al., 2014), which are captured in different forms from text to geometrical format (Motamedi et al., 2014). In addition, FM is restricted by such constraints as an annual budget not sufficient enough to address all required projects (NSW, 2004), as well as the scarcity of resources to carry out the job. These limitations highlight the importance of decision prioritization in each budget cycle (Wood, 2009).

BIM has the potential to be a compelling tool for FM, (Akcamete et al., 2010; Terreno et al., 2015), although it still is not being effectively utilized in this phase (Becerik-Gerber et al., 2011; Volk et al., 2014). This paper represents the results of an attempt to study FM information requirements in HEIs which can be integrated into a BIM-intensive framework for the purpose of a more efficient decision-making process**.** Following sections of this paper provide a literature review on the subject of FM, IT, and BIM. Subsequently, research methodology and the results of the study on four aspects of FM in HEIs pertaining information management are presented.

Literature Review

Facilities Management

For the purpose of this study, a facility is defined based on a multi-tiered hierarchy proposed by Xueqing Zhang and Gao (2010) for a set of buildings. These levels include facility buildings with different characteristics, building systems in individual buildings, components of each system, and component elements. According to the International Facility Management Association (IFMA, 2013), FM "Encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process, and technology". The role of FM encompasses multiple disciplines, including but not limited to leadership, maintenance, finance and business, real estate, technology, emergencies, environmental stewardship and sustainability (IFMA, 2013).

Maintenance strategies, as a major component of FM, have gone through major alterations and development over the last few decades, starting from the most basic reactive maintenance – also called corrective, or run-to-failure (Deighton, 2016; Horner, El-Haram, & Munns, 1997). It includes the repair or replacement of elements after they functionally fail in order to retrieve their original operation condition (Horner et al., 1997). The preventive maintenance, ensures maintenance activities take place at regular intervals based on a predetermined schedule (Deighton, 2016) regardless of elements' conditions. The predictive maintenance, also called condition-based (CBM), on the premise that each element follows a failure cycle, monitors changes in facility's operational performance and behavior regarding specific metrics to make it possible to predict the time of failure and take measures before a major failure comes about. More recently developed approaches focus on improving reliability and risk levels in maintenance analysis and activities (Deighton, 2016). A decent example is Reliability Centered Maintenance (RCM) (Niu, Yang, & Pecht, 2010), which employs a structured approach to optimize PM activities, taking into account system's reliability. This approach ranks elements on a qualitative basis and limits analysis to elements of significant importance to the reliability of the system according to such factors as failure modes, frequency, and consequences (Selvik & Aven, 2011). Johnston (2002) recognizes risk reduction and cost saving as two major benefits of employing RCM. The Risk-Based Maintenance (RBM) is a quantitative approach integrating risk assessment and evaluation, risk-based inspection (RBI), and RCM to prioritize maintenance resources and activities for areas of the highest risk (Wang, Cheng, Hu, & Wu, 2012). This method converts maintenance to a high performance and low-cost activity (Selvik & Aven, 2011).

Information Technology in FM

Current FM practices, capturing and storing critical information in a fragmented manner (Ilter & Ergen, 2015), struggle with such issues as information loss (Teicholz, 2013), wasted time on searching for information (Gnanarednam & Jayasena, 2013), and inefficiencies in interoperability (Parsanezhad & Dimyadi, 2014). In search of more efficient information-sharing approaches, Information Communication Technology (ICT) tools have been developed and employed over the years. These tools range from email document transactions developed during the 1970s – in form of MS Office, pdf, or jpegs – (Aziz et al., 2016) to more advanced systems as Computer-Aided Facilities Management (CAFM) (Aziz et al., 2016; Lavy & Jawadekar, 2014), and such platforms as BIM, Construction Operation Building Information Exchange (COBie) (Ilter & Ergen, 2015), and GIS (X Zhang, Arayici, Wu, Abbott, & Aouad, 2009).

CAFM is a tool capable of capturing and maintaining facility information, including maintenance and operations, budgeting, work orders, inventory management, construction and project management, space management, and energy management (Aziz et al., 2016; Elmualim & Pelumi-Johnson, 2009; Lee et al., 2013). Although this computerization improves capturing and retrieving information, CAFM is not a potent tool for knowledge management and data analysis as it captures and provides information in conventional formats (Gnanarednam & Jayasena, 2013).

In recent years, BIM has been recognized as a compelling analytical tool for FM by both researchers and practitioners (Becerik-Gerber et al., 2011; Golabchi, Akula, & Kamat, 2013), although there are very few owners who employ it in the FM practice (Becerik-Gerber et al., 2011). BIM benefits include access to more accurate data and automated data generation (Becerik-Gerber & Kensek, 2009) through a central model (Pärn et al., 2017), cost savings, locating building components (Mohanta & Das, 2017), visualization, and enhanced emergency and space management (Terreno et al., 2015). Furthermore, BIM has the capability to work in integration with CAFM systems (Akcamete et al., 2010) to not only improve information handover from design and construction to FM (Gnanarednam & Jayasena, 2013), but improve efficiency after occupancy (Becerik-Gerber et al., 2011). Open-standard information exchange systems are required to facilitate BIM integration with CAFM systems. COBie, a data exchange format capable of capturing project lifecycle information and sharing it through Industry Foundation Class (IFC) standard, is an example of such system (E. W. (2007). East, 2007). Becerik-Gerber et al. (2011) proposed a six-layered structure of non-geometric data requirements for FM that BIM is capable of capturing – that is, ID and Name, Service Zone, Group and Type, manufacturer/Vendor Data, Specification and attributes, and Operation and Maintenance Data.

Methodology

Research methodology in this study consists of two main steps which build upon one another. Initially, the authors carried out a comprehensive literature review based on searching for keywords in journal articles, proceedings, and reports on the subject of FM, Information Technology (IT) in FM, BIM, O&M, and FM information requirements. Next, an interview protocol was developed upon the results from the literature review and pilot interviews. This protocol was aimed to investigate four main aspects of FM; the asset portfolio, FM practice, information requirements, and information management challenges. A preliminary set of interview guide, prepared based on literature review as well as research and interview goals, were used to carry out pilot interviews with two BIM FM experts in HEIs to increase reliability and validity of gathered data in interviews with participants. Modifying the primary interview protocol according to the results and process of pilot interviews, the authors developed the final guide for interviewing research participants. This was achieved by obtaining experts' opinion through structured phone or in-person interviews with open-ended questions.

The target population in this study is HEIs in the state of Colorado, including public, private, and regional universities and community colleges. Research sample consists of a deliberately selected group of ten institutions with different missions and asset portfolios from all four mentioned groups to represent the target population. Respondents were an intentionally designated panel of ten experts selected among top management levels of FM departments in those institutions. The intention is to increase the credibility and validity of the results. Prior to interviews, the interview guide (entailing a brief introduction to the study, research goals, and explanation of terminologies, along with interview questions) were sent to respondents via email. This facilitated establishment of a common understanding of terms used in the interviews hence enhanced the validity of the gathered data. Interview questions were to attain data on interview's background, characteristics of the institution's asset portfolio, established FM practice (organizational chart, responsibilities, decision-making process, and established maintenance strategies), information requirements, as well as in-practice IT tools and challenges.

Finally, an objective third party with experience in BIM FM, oversaw the overall interview development process, from the primary interview questions and the pilot studies to identification of the patterns in the collected data.

Results

Asset portfolio

Asset portfolios of HEIs incorporate various buildings of different characteristics, accommodated in one main campus or multiple, satellite campuses. This includes academic and administrative buildings, libraries, healthcare facilities, recreation centers, student centers, and housing. The number of buildings operated and managed by HEIs investigated in this study, either owned or rented by the institution, ranges from 10 to more than 360. Institutions with a greater number of buildings further categorize their facilities for the purpose of more efficient management. One common classification scheme is the funding mechanism, which categorizes buildings into auxiliary and general-fund ones. Auxiliary buildings – recreation centers, etc. – are generally revenue producing and therefore have a separate operating budget than general-fund buildings, a library, etc. The budget source for these buildings might be the annual budget, or outside sources such as state funds (in case they are eligible), or donations.

FM practice

All the institutions have an FM department – with diverse organizational charts, divisions, and the number of employees – responsible for managing and operating the university's facilities. Those of smaller size might outsource portions of their liabilities – facility auditing and condition assessment, for instance – due to constraints in resources. In larger institutions, however, the department consists of various specialized sectors, which work either as a subdivision of FM or as an independent division working in conjunction with FM. Regardless of the organizational chart, FM oversees capital projects; planning, design, and construction; O&M; custodial services; outdoor services; utility services and energy management; recycling; inventory; inspections and facility audits; space planning and management; transportation and parking; budgeting and accounting; safety; and trades management.

The results of this study reveal frequent decisions that respondents make at building level of the facility hierarchy, which includes capital renewal, renovate, repurpose, upgrade, defer, abandon, demolish, address emergencies, and carry out custodial services. Maintenance strategies are employed at the system, component, and element levels of the facility hierarchy. Figure 9 illustrates the frequency (number and respective percentage) of responses participants provided when they were asked which of the five maintenance strategies of corrective, scheduled, condition-based, reliability centered, and risk-based they employ at system and component/element levels of facility hierarchy. Although corrective remains the most common strategy, altogether facility managers employ a combination of these three methods at different levels of the facility hierarchy. For instance, they might run such elements as lighting fixtures that have no impact on health and safety to failure, while they change filters according to a predetermined schedule based on maintenance instructions, employ condition-based maintenance for mechanical systems, and take risk of failure into account for laboratory exhaust systems. Furthermore, health and life safety issues are the highest priority for all respondents. That is to mention, two strategies of reliability-centered and risk-based are eliminated from the results as these recent advances in maintenance strategies are underutilized in studied institutions.

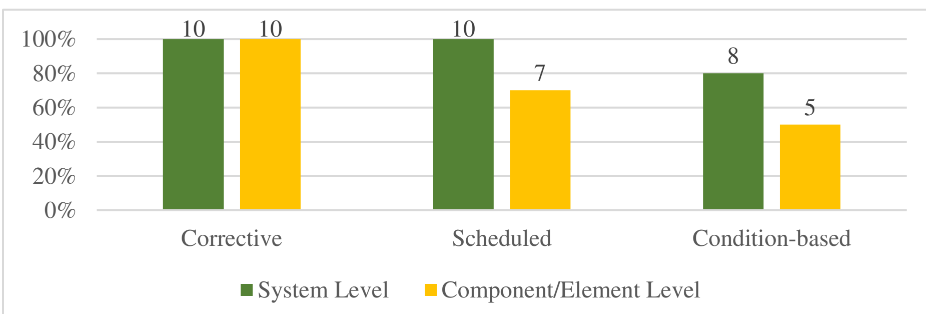


Figure 9. Frequency of responses on in-practice maintenance strategies

FM Information Requirements

This study classifies required information for FM into four main categories described in Table 4. The technologies respondents employ to capture each category are represented in the last column. All respondents agree on the importance of the information represented below, although the details in each category might vary. In the case of specifications, for instance, respondents – depending on the maintenance strategy – might or might not consider deterioration rate in their analysis and decision-making process. HEIs employ different CAFM systems, including Work Order System (WOS), CMMS (Computerized Maintenance Management System, and Integrated Workplace Management System (IWMS).

Table 4. FM information requirements and implemented technology

Information Requirements	Description	Implemented Technology
Attributes of the Components of the Physical Facility	* ID/Name * Location * Specifications * Manufacturer Data	* CAFM system, * Spreadsheets * O&M manuals * As-built documents * Energy/Water Management System * GIS
O&M Data	* Maintenance Strategy * Work order history * Maintenance status * Condition Assessment/Audits	* CAFM system * Building Automation System (BAS) * Spreadsheets * Digitalized/hard copy reports
Institutional Factors (Internal/External)	* External Factors; Laws and regulations, state funds, donors * Internal Factors; mission criticality, annual budget, business or historical criticality	* Spreadsheet * Digitalized/hard copy reports * Not captured
Decision Alternatives	* Total Cost of Ownership (TCO) * Time * Expected lifespan * Owner's other priorities	* Spreadsheet * Digitalized/hard copy reports * Not captured

As far as BIMs are concerned, the studied HEIs receive three dimension (3D) models from construction firms as part of project hand-over documents mostly for new construction – not all HEIs have such requirement. However, the majority of FM departments do not employ those models in their practice and merely archive the BIMs.

Integration of the above-mentioned information requirements into a BIM-intensive FM framework is a continuous portion of this research. Follow-up interviews with three industry experts were carried out to validate the potential interlink between BIM and the identified information. As for Attributes of the Components of the Physical Facility, BIMs can capture both geometrical and non-geometrical information at element, component and system level. At the campus level, however, BIMs need to be integrated with such infraworks systems as Geographic Information System (GIS). In the case of O&M information, institutional factors, and decision alternatives depending on institution's specific goals, BIMs can integrate with COBie-type systems to capture and provide information for decision-makers.

Information-Management Challenges

Figure 10 depicts percentage (and number) of responses on major information-management challenges FM is facing in the current circumstances.

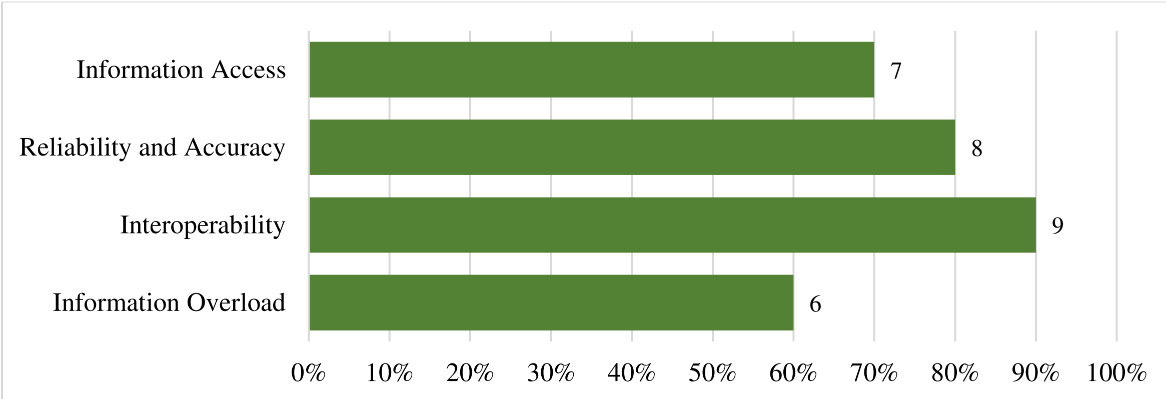


Figure 10. FM Information management challenges

The current FM practice is relatively low-tech, especially in smaller institutions where information might even be partially stored in piles of paper in "plan rooms". This makes retrieving information a demanding task, prone to mistakes – a challenge within the resource-constraint environment. Furthermore, reliability and accuracy of available information remain an issue. In the case of as-built conditions, for instance, available information might not represent construction changes or those made during O&M. On the other hand, different types of information captured by different stakeholders in various software and formats that often cannot read one another bring about interoperability issues. This diversity of information sources during facility's lifespan might result in information overload and discrepancies in the provided information. Considering all such challenges, research participants recognize the need to move towards more efficient and systematic information management practices to provide the "right information at the right time".

Conclusion

Information management in FM of HEIs mainly employs a low-tech process in which decision makers struggle with keeping track of and having access to reliable, timely information in an integrated manner. Required information is provided by various stakeholders, in different formats implementing different software packages, or merely in hardcopy reports.

This research builds upon previous studies focusing on building FM information requirements and its integration with BIM. Its contribution to the body of knowledge is the identification of specific FM information requirements in HEIs as unique owner/operator/developer organizations, which are to be taken into account in the decision-making process. An interview protocol was developed based on literature review and pilot studies to acquire expert's opinion on FM information management within the target population. The results demonstrate that the current practice falls short in providing credible, timely information. Bearing in mind the aforementioned challenges, practitioners recognize the need to move towards a more data-driven process. This requires employing more efficient and systematic approaches to capture, store, and utilize knowledge. This goal can be achieved by integrating BIMs within the FM information management practice for various purposes from visualization and space management, to generating work orders and scheduling preventive maintenance. Although practitioners have come to the understanding that employing BIM has the potential to be beneficial, its implementation is far from its infant stages.

Currently, the majority of institutions under study archive 3D models developed by participating firms for new projects, which are intended to address specific design and construction purposes. The important issue to take in mind is that each of those models is developed by different firms, which typically does not reach FM requirements. Adjusting these models requires skilled experts to develop, update, and implement BIMs.

Future study based on the results of this research could be for institutional owners to work on integrating BIMs and COBie-type systems which make data interchangeable among various technologies that HEIs employ. The results of this study were limited to a set of buildings within the asset portfolio of HEIs in the state of Colorado and are not to be overgeneralized for other institution types or other HEIs in different geographical districts.

Chapter 3 – Developing Building Information Models (BIM) for Building Handover, Operation and Maintenance

Purpose – This paper represents the results of a case study to establish a BIM-enabled workflow to capture and retrieve facility information to deliver integrated handover documents.

Approach – The Building Handover Information Model (BHIM) framework proposed herein is contextualized given the Construction Operation Information Exchange (COBie) and the Level of Development schema. The process employs AutoDesk Revit as the primary BIM-authoring tool and Dynamo as an add-in for extending Revit's parametric functionality, BHIM validation, information retrieval, and documentation in generating O&M deliverables in the end-user requested format.

Findings – Given the criticality of semantics for model elements in the BHIM and for appropriate interoperations in BIM collaboration, each discipline should establish model development and exchange protocols that define the elements, geometrical and non-geometrical information requirements, and acceptable software applications early in the design phase. In this case study, five information categories (location, specifications, warranty, maintenance instructions, and CSI MasterFormat division) were identified as critical for model elements in the BHIM for handover purposes.

Originality/Value – Design- and construction-purposed BIM is a standard platform in collaborative AEC practice and those models are available for many recently constructed facilities.

However, interoperability issues drastically restrict implementation of these models in building information handover and Operation and Maintenance (O&M). This study provides essential input regarding BIM exchange protocols and collaborative BIM libraries for handover purposes in collaborative BIM development.

Paper type: Case study

Overview

Architecture, Engineering, Construction (AEC) and Facilities Management (FM) represent an information-intensive but often fragmented industry (Froese, 2003; Laakso and Kiviniemi, 2012). However, efficient information sharing and integration among disciplines and software applications is critical throughout the building's lifecycle to facilitate seamless building Operation and Maintenance (O&M) (Gökçe et al., 2012). Researchers and practitioners recognize Building Information Models (BIM) as a compelling tool for collaborative building information management because they can provide a consolidated source of both geometrical and semantic data (Eastman et al., 2011; Preidel et al., 2017a). However, while the AEC industries are increasingly integrating BIM within the context of integrated project delivery approaches (Cavka et al., 2015; Preidel et al., 2017a), the later phases of the project's lifecycle rarely implement these models in a meaningful way for handover and O&M practices. An AEC-purposed BIM is typically developed by various stakeholders using different modeling applications, and adapting these design models to accurately provide pertinent and specific O&M information is challenging (Laakso & Kiviniemi, 2012; Steel et al., 2012; Cavka et al., 2015; Edirisinghe et al., 2017). Various interoperability issues, including software limitations and different methods for developing a BIM, contribute to the difficulty of using the AEC-purposed model for O&M (Laakso & Kiviniemi, 2012).

Organizations at the leading edge of Virtual Design and Construction (VDC) have developed standards in order to promote consensus on various aspects of interoperability for BIM development and implementation (buildingSMART, 2015). Since established standards for BIM development have not become mainstream until recently, industry stakeholders have developed in-house modeling standards over time which vary between firms (Bedrick, 2017). Thus, limited consensus exists regarding the ways of developing a BIM in terms of the content and implemented information technology (Steel et al., 2012; Yoders, 2013).

This paper represents the results of a case study approach to establish a BIM-based building handover workflow to identify information requirements, and to capture, validate, retrieve, and document this information as final O&M deliverables with proper content and in the client's desired format. Lessons learned in this process contribute to development of a BHIM framework that contextualizes two established openBIM standards in determining information needed for model elements in a BHIM according to the client's O&M requirements. Built upon BIM development efforts during design and construction, the results of this research contribute to identifying interoperability issues that need to be addressed in BIM exchange protocols for building handover.

Literature Review

BIM in Building Handover

Project closeout is defined as the transition to the operation phase of a building lifecycle following substantial completion of the construction phase. This includes handing over critical facility information provided by various participating firms, who have often implement heterogeneous software tools during previous phases for use in activities associated with building O&M (Fallon & Palmer, 2006; National Institute of Building Sciences, April 2012; Gökçe et al., 2012; BC Housing, 2012; Alvarez-Romero, 2014). Handover information comprises construction and installation data, performance tests, operator training, and maintenance requirements, all of which are essential to successful project commissioning. Consequently, generated prior to closeout, handover information requirements are greatly dependent upon the AEC firms to create suitable, navigable and comprehensive documents to facilitate building O&M after project closeout (National Institute of Building Sciences, 2012).

In current practice, building information is typically handed over in large quantities of paper documents including O&M manual binders, 2D as-built drawings, and record drawings (Wu & Issa, 2012). For contractors, the process of handing over building information includes mapping and gathering data for installed equipment, compiling the approved submittals and commissioning documents in binders, and indexing the document sets within the binders for navigation purposes (William East et al., 2012). The inefficiency dominating this practice is twofold; 1) the process is tedious, manual, labor-intensive, and error-prone (Wu & Issa, 2012; Brooks & Lucas, 2014; Thabet et al., 2016); and 2) the outcome documents are ineffective for utilization during the O&M phase of the building's lifecycle (East & Nisbet, 2010; East et al., 2012; Cavka et al., 2015). The ineffectiveness of handover documents is mainly due to submitted information being erroneous, incomplete, irrelevant, and of inconsistent formats (Clayton et al., 1999; East, 2007; East & Nisbet, 2010; Wang et al., 2015; Thabet et al., 2016). Due to the extensive amount of information in these hardcopy manuals, locating and retrieving critical O&M data is a time consuming process. Moreover, the final documents are often fraught with inaccuracies and misinformation given the fact that product submittals might not correctly represent the true as-built conditions of a building after completion (Clayton et al., 1999; East & Nisbet, 2010; Wu & Issa, 2012; Brooks & Lucas, 2014; Thabet et al., 2016).

While clients and building operators struggle with efficient utilization of the O&M documents provided at project closeout (East & Nisbet, 2010; Mayo & Issa, 2014), previous studies recognize BIM as a potential tool in providing design and construction information for use during building operation. Capabilities of a BIM pertain to a seamless transition of information from designers and contractors to owners (Brooks & Lucas, 2014), more efficient data collection and retrieval (NRC, 2012); access to real-time building information during operation through a central model (Forns-Samso, 2011; Pärn, Edwards, & Sing, 2017). However, despite these potential advantages, BIM implementation during the operation and maintenance stages of a building's lifecycle has lagged (Cavka et al., 2015; Steel et al., 2012). In industry practice, various participating firms develop a BIM using different, and often discipline-specific, computer applications. This necessitates the exchange of files developed using various platforms to create a comprehensive multi-disciplinary building model (Wix & Karlshoej, 2010). Considering the fragmented nature of building data and the resulting software interoperability issues when exchanging a BIM between AEC and FM stakeholders, establishment of consistent BIM development and exchange protocols is critical (William East et al., 2012).

Interoperability

According to the National Institute of Standards and Technology (NIST), 2004, pg. ES-3, interoperability "Relates to both the exchange and management of electronic information, where individuals and systems would be able to identify and access information seamlessly, as well as comprehend and integrate information across multiple systems." NIST posits that $15.8 billion are lost each year in the United States capital facilities industry due to inadequate software interoperability. This figure is estimated by comparing current AEC and FM practice with a hypothetical model where seamless information exchange and management processes occur throughout the entire project lifecycle. Such processes would prevent financial losses incurred to address technical interoperability issues and respective delays. Other research emphasizes the importance of addressing interoperability issues beyond information exchange and software applications. Grilo and Jardim-Goncalves (2010) identify business processes, culture, values, and contractual issues among interacting firms as important dimensions of interoperability within the AEC industries. The National BIM Standard identifies that a consistent information format, exchange process and a common understanding of the exchanged information are critical for true BIM interoperability to occur (National Institute of Building Sciences, 2015).

Industry Foundation Classes (IFC)

Several non-proprietary file formats and exchange protocols have been developed as open standards for BIM by industry and academic researchers (Halfawy & Froese, 2005), among which the American Institute of Architects (AIA) identifies the Industry Foundation Class (IFC) (AIA, 2017). IFC is a widely-accepted, open-standard, object-oriented file format administered by buildingSMART; an alliance of industry practitioners, researchers, and software vendors (Froese, 2003). IFC specifies a data schema and file format structure to promote compatibility among different software applications in the AEC and FM industry, which is necessary for lifecycle information modeling and exchange protocol (Laakso & Kiviniemi, 2012). buildingSMART's Handover Exchange Requirements (ER's) are applied to Facilities Management standards to address a specific portion of the IFC schema that pertains to information exchange in the FM handover domain. According to buildingSMART (2009), ER's provide the essential standard attributes that govern model object creation and formatting for model handover to FM stakeholders.

Steel et al. (2012) introduced a four level IFC-based interoperability format that governs data exchange. The first two levels, file and syntax, respectively, pertain to the computer applications' capabilities to exchange and analyze shared model information. The third level, visualization, refers to the software's ability to present the visual characteristics of exchanged model components. The fourth level, semantic, describes the software applications ability to understand the parameters of shared model elements. Potential challenges when combining BIMs developed by various stakeholders generally include errors resulting from large file sizes or positioning model elements in incorrect locations when merging BIM files. However, more complicated problems related to different modeling styles and software limitations arise at the semantic level. Problems of this nature remain prevalent when integrating BIMs because participating firms may be required to use applications from the same software vendor or ensure the chosen applications are compatible within the appropriate IFC level (Laakso & Kiviniemi, 2012).

Construction Operation Building Information Exchange (COBie)

The Construction Operation Building information exchange (COBie) schema provides a structured protocol that is intended to capture and deliver required BIM information for asset management during the operation phase of a facility's lifecycle (East & Carrasquillo 2013; Patacas, Dawood et al. 2015). According to Zibion et al. (2018), spreadsheets are the most commonly utilized format to deliver COBie data for building rooms, technical equipment, and so on. While COBie was designed to facilitate the import of as-built data to FM systems (East 2007), studies criticize the complexity, fragmentation, and labor-intensive processes required to implement the schema (Howard & Björk 2008: Yalcinkaya et al. 2016). COBie can provide the format for the exchanged information, however, it often fails to support the owner in identifying and requesting specific semantic data according to FM information requirements (Love et al. 2014; Zibion et al. 2018). FM professionals can receive incomplete, unnecessary, or low-quality data at project close out, which further impairs the efficient usability of COBie during building operation (Alnaggar & Pitt 2018). Hence, implementation of the COBie guidelines requires customization reflecting region-, project-, and client-specific requirements (East & Carrasquillo 2013). According to Patacas et al. (2015), nearly all existing BIM-authoring platforms do not provide complete technical support for COBie schema implementation.

Level of Development (LOD)

The Associated General Contractors BIMForum Committee's specifications defines LOD as "A reference that enables practitioners in the AEC Industry to specify and articulate with a high level of clarity the content and reliability of BIMs at various stages in the design and construction process" (BIMForum, 2015, pg. 10). For instance, LOD200, indicates that "The Model Element is graphically represented within the model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element" (AIA, 2013, pg. 2). The LOD specifications clearly state that "There is no such thing as a LOD### model…project models at any stage of delivery will invariably contain elements and assemblies at various levels of development." (BIMForum, 2015, pg.10). In general, the precision and level of graphic and non-graphic information for model elements increase by their respective LOD level, providing more details moving from LOD100 towards LOD500 (BIMForum, 2015).

The LOD classifications suggest that the specification is rather “A language by which users can define these requirements for their own firms or projects” (BIMForum, 2015, pg. 11). Different owner-specific information requirements have led to research proposing LODs that diverge from the original five levels. LODs provide a general classification structure for information requirements and can include less detail than LOD500 given a project’s characteristics or the Owner’s need for O&M data from the BIM. Research suggests that O&M information requirements can be satisfied with less precision than LOD500 because non-geometrical information is more critical than the high precision level geometrical requirements of LOD500 (Mayo & Issa, 2014).

Object-Oriented Modeling

BIMs provide a 3D representation of buildings that are enriched with semantic data on all building elements; this allows for automated information retrieval, filtering, and analyzing of the model for use across a building’s lifecycle (Nagel et al., 2009; Preidel et al., 2017b). Nagel et al. (2009, pg. 46) posit that “The logical structure and well-defined meaning of the objects are crucial prerequisites for applications which go beyond pure visualization”. BIMs are object-oriented and inherently parametric in that they are a combination of building objects with intelligent behavior that can be configured through a set of geometric and non-geometric parameters and rules at the assembly, sub-assembly, and individual model element level. Model elements are defined and controlled by a series of relationships, rules, conditions, and constraints created within a family of components (e.g. a classification of model elements in a categorical family such as doors, windows, walls, etc.). The values for these parameters can vary for different model elements according to their unique settings (Eastman et al., 2011; Yenerim & Yan, 2011). The value of this approach is realized in several ways; 1) it provides the capability of automatically setting and changing geometrical and non-geometrical element properties; 2) it allows automated updates in the model after low-level changes; and 3) it allows extraction of model data information for use during analysis in different phases of the project lifecycle (Eastman et al., 2011).

Revit and Dynamo

Collaborative interactions between BIMs can take place through various AEC and FM domain-specific software packages (Rundell, 2008; Kensek, 2014). Recent developments in object-oriented Computer Aided Design (CAD) applications that support BIM allow the development and exchange of semantically-rich models across disciplines through their parametric functionality based on the Application Programming Interface (API) (Singh et al., 2010). Autodesk Revit is well established as an IFC-based, object-oriented, parametric modeling tool for collaborative BIM development given its API compatibility (Pazlar & Turk, 2008; Eastman et al., 2011). The Revit API allows third-party developers to create custom tools that can integrate with Revit through different programming languages.

Dynamo is an open-source, visual programming platform developed by Autodesk that can work as a visual scripting interface with the Revit API to extend its parametric capabilities for various lifecycle information management purposes. Dynamo enables users to create, customize, retrieve, and document data from a Revit file by scripting in a visual workspace (Autodesk Dynamo Studio, 2017). Applications of such functions include, but are not limited to, scripting behavior, generating both geometric and non-geometric information (e.g. enrichment of the semantic information levels for model elements in a BIM), information retrieval, and validating existing models (Preidel et al., 2017b). The visual programing interface is a significant advantage of Dynamo as it allows users with little computer programming knowledge to carry out various project lifecycle analysis on BIMs (Danhaive & Mueller, 2015). Within Dynamo's workspace, data flows through "wires" to support input and output ports to "nodes", establishing the logical flow of data in the visual program. Nodes process and execute the input data by performing an operation to create the output and represent the sequence of executed actions. Various functions are provided in the Dynamo library, grouped in different categories, available for use in composing an intended information process. Users also can extend Dynamo for their specific needs by creating custom nodes using existing core nodes and publish those for future applications (Autodesk Dynamo Studio, 2017, Preidel et al., 2017b).

In light of the literature and progression of BIM use in building operation, this case study explores a BIM-based framework to capture, retrieve, document, and transmit facility handover information between a design-build contractor and a client during closeout. The framework described herein customizes the ER's standard (BuildingSmart, 2009), IFC schema (BuildingSmart, 2016), and LOD specification (Bedrick, 2017) for developing a BHIM given the project- and client-specific closeout information requirements. These requirements are determined according to O&M needs both in terms of the content and format of final O&M deliverables. The process employs Autodesk Revit to develop the BHIM, which builds upon previous efforts in developing a design-purposed BIM. Dynamo is used as an add-in to Revit for BHIM validation, model data creation, retrieval and documentation to generate the final deliverables presented in this study.

Case Study Description

The construction project in this case study comprises a 9567 square foot addition to a two-story educational building located in the Rocky Mountain Region of the United States. The additional space comprised classrooms, offices, and recreational areas. The project, handed over to the owner in 2016, was delivered using the Design-Build (DB) project delivery methodology. The client's information requirements for project handover, as indicated in the contract, included a binder comprised of hard copies of two-dimensional (2D) drawings and approved product submittals. All client-requested FM and operation documents were compiled according to an established checklist organized following the Construction Specification Institute's (CSI) 16-division MasterFormat classification.

In this project, navigating large numbers of sometimes non-comprehensive and contradictory documents proved to be difficult and time-consuming for the client's O&M purposes. Specifically, difficulty was expressed regarding the O&M stakeholders ability to quickly and easily locate building elements, navigate through the hardcopy O&M submittal binders to retrieve relevant information, and finally validate such information. This resulted in the Integrated Design-Build (IDB) firm receiving frequent Request for Information (RFIs) from the client about different building elements after closeout and throughout the project's warranty period. RFIs included, but were not limited to, queries regarding the exact locations of building systems, components, and elements, as well as product-specific information regarding specifications, maintenance instructions, and warranties. These inefficiencies pertaining to the traditional building information handover practice in this project required the expenditure of additional resources on the part of the operation team and IDB firm.

Steps in BHIM development

In light of the above-mentioned issues, this paper represents the results of implementing a BHIM to generate a comprehensive document including all handover information requirements in the client-requested format. The BHIM is created for this case with the intent of providing more efficient, automatic data retrieval during project closeout, while also increasing the integrity and consistency of the information provided in the final documents. The steps carried out to identify the requirements for the case-specific BHIM and develop the model accordingly as the central database to deliver the integrated handover documents to the client in their requested format are represented in Figure *11*.

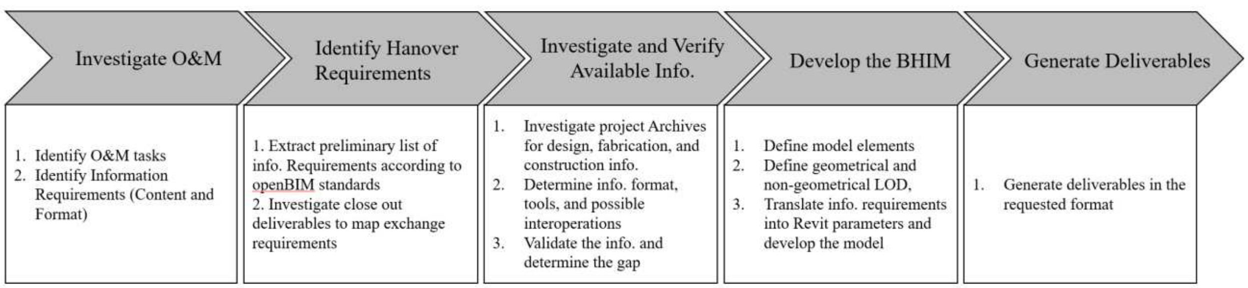


Figure 11. BHIM Development Steps

This section describes the implementation of the steps shown in Figure 11 within the current project case.

1. Investigate O&M

To identify critical handover stakeholders, the authors referred to established roles and responsibilities of project participants according to the contract, project specifications, and the stakeholder's organizational charts. The IDB firm was the single source of responsibility for delivering the project to the client. Stakeholders, for the purpose of this study included 1) the client, responsible for determining the content and format of the final handover submittals according to their specific O&M practice, 2) the design, fabrication, and construction participating firms providing the discipline-specific input to the closeout process and 3) the Client Services (CS) department, of the IDB firm, responsible for gathering, compiling, and delivering the requested handover information. In addition the CS department is responsible for supporting the client's O&M experts during the warranty period. The authors recognize the CS and the client's O&M experts as the potential end user of the BHIM for handover and operation purposes.

2. Identify Handover Requirements

The authors identified and obtained the critical information for model elements within the central BHIM from three main sources: 1) established openBIM standards (the LOD, and the COBie specification); 2) project- and product-specific documents, including the specifications, the drawings, and the contract; and 3) interviews of the identified handover stakeholders (CS experts). The latter aimed to determine the use-case for BHIM according to owner specific needs, and further customize the COBie requirements to ensure delivering all (and only) the semantics with use during operation (a use-case based approach in BIM development). Within the same context, the LOD definitions were used to convey the geometric requirements for model elements.

The content and format of handover submittals is determined according to the client's information requirements and the available technologies to be utilized during the O&M process. Given the established O&M practices of the client and their lack of knowledge and technology to use the BHIM, the ultimate handover documents comprised a single interactive Portable Document Format (PDF) file for each room in the project. The model however, could be employed by the CS to more efficiently update, retrieve, and manage information to support the operation team during the warranty period.

Each room-specific PDF document (Figure 14, described further below) provides end-user-required information in three formats as follows:

1) A room-specific schedule including information about the room (name, number, level, and area) and a 16-division MasterFormat-organized list of all model elements within that room and their specifications
2) PDF files of warranty and maintenance instructions for building elements, hyperlinked to the room schedule created in Step 1 above.
3) Eight 2D drawings in JPEG format, extracted from the BHIM, showing the architectural, interior, HVAC, electrical, and fire protection model elements within the room (It should be noted that, in this project case, the structural, civil, and landscape disciplines were excluded from the handover documents per the client's request.)

3. Investigate and Verify Available Information

The authors investigated project archives to search for relevant available information on the design, fabrication, construction, operation, maintenance and warranties of building elements provided by the IDB firm, consulting firms, and subcontractors/suppliers prior to project handover. Available information for the current study project included the following:

- Architectural and interior designs modeled in Autodesk Revit (.rvt), developed to LOD300
- Mechanical and HVAC systems modeled in Autodesk Revit (.rvt), developed to LOD250
- Building structure designed in 2D Autodesk AutoCAD and Tekla 3D
- Electrical systems designed in 2D Autodesk AutoCAD

- Fabrication model of fire protection and fire alarm systems modeled in AutoSprink software
- As-built updates to the project as PDF bookmarks on the construction documents in Bluebeam
- Non-editable, PDF, soft copies of O&M documents for building elements provided by subcontractors and suppliers

Several approaches were implemented to validate the integrity and consistency of the available building element information. Given the fragmentation inherent to multiple stakeholders developing AEC-purposed models in various software applications, the authors also visited the project, corresponded electronically, and held meetings with the stakeholder groups identified in step 1 to confirm modeled elements with actual building components for accuracy. This step was completed in addition to mining the project archives for available information.

4. Develop the Building Handover Information Model (BHIM)

The authors developed the central BHIM in a cumulative effort built upon the existing Revit-generated BIM for design. The base model used in the case study includes the architecture and interior disciplines as well as the linked mechanical model. The other option would be to develop the model from scratch. However, given the quality of the AEC-purposed BIM in this project it was deemed suitable as a basis for BHIM creation. The BHIM development process consists the following steps:

The authors identified all model elements to be included in the BHIM according to the stakeholders' information requirements established in step two of the framework. In this project, participating firms provided building information in various software packages. While Revit could support most of the existing file formats provided in this project, interoperability between some file types and Revit does not satisfy the requirements to develop and populate a comprehensive BHIM. For instance, when the AutoCAD drawing for electrical systems is linked to Revit, it merely provides a read-only, 2D representation of the elements, as opposed to providing the basic requirements for object-oriented modeling in Revit. Considering the criticality of the semantic information within the BHIM for the purpose of this case study, remodeling building elements from the 2D drawings as families or stand-alone instances was a necessary but lengthy and time-consuming process.

Next, the researchers defined the geometrical and non-geometrical information required for all model elements within the BHIM. In the case of doors, for instance, the geometrical requirements in this project case were limited to LOD300 with the exact location and dimensions in the final handover deliverables. The required semantics include the element specifications (with varying parameters depending on model element), warranty information, maintenance instructions, and CSI MasterFormat division.

The third step was to create appropriate Revit Parameters to capture and develop each model element to handover information needs, retrieve and document information to generate the final deliverables per the client-specified format. The parameters in this project are as follows:

Model Element Location. The best practice for linking components to a precise location in this case study was to tie each model element to its surrounding room using the “Room Calculation Point” in Revit families. Figure 12 depicts the information flows in Dynamo to set the value of this parameter for model elements of the furniture category, using the existing node “SetParameterValueByName”.

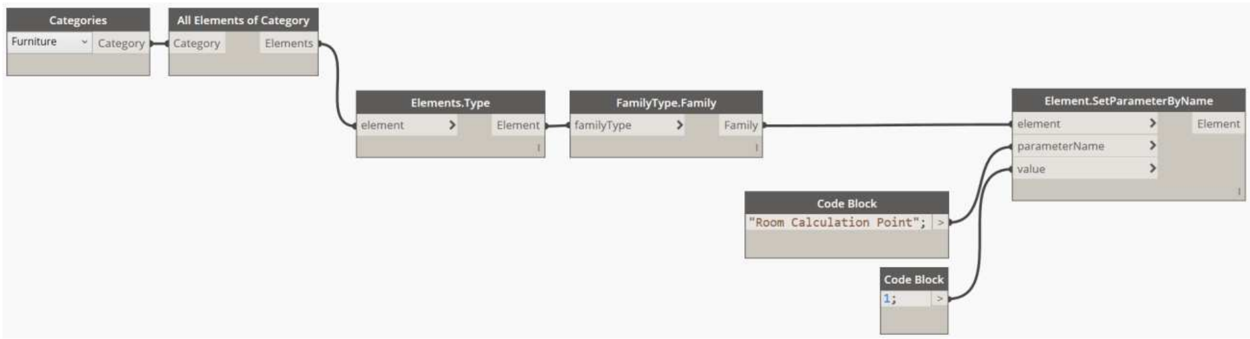


Figure 12. Dynamo information flow to set value for parameter "Room Calculation Point"

The researchers developed visual programs in Dynamo to retrieve this information and document it in the final deliverable from the BHIM. The "Elements from Room" node in Dynamo, this flow extracts a comprehensive list of all local model elements in each room of the central BHIM. In the case of elements placed in linked Revit files, such as the mechanical model in the current case study, a different information flow is developed in Dynamo to extract a list of elements using the "Elements from Linked File in Room" node. This information flow is represented in Figure 13, where the "Code Block" links the mechanical model with the determined index number in the Revit database among all linked documents into the final node.

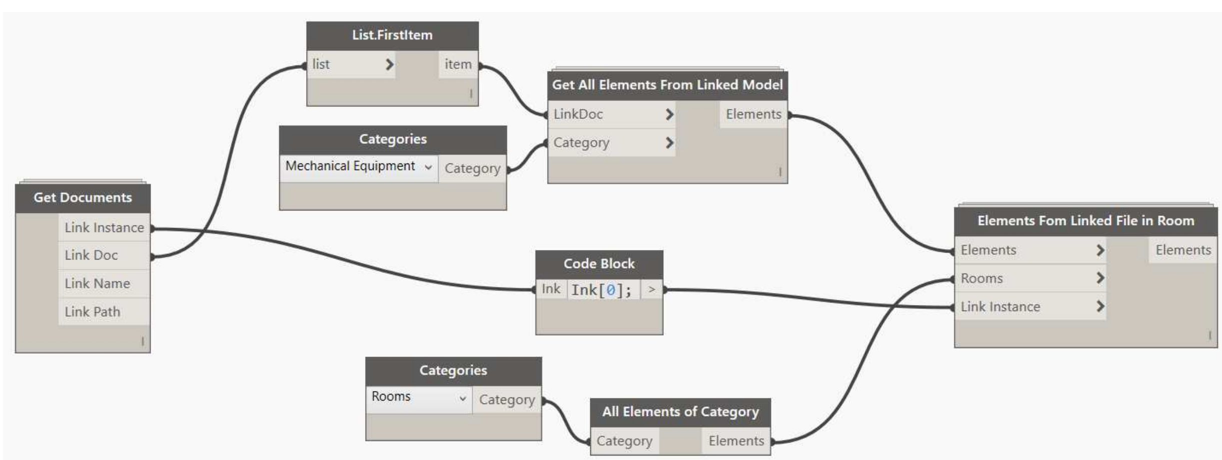


Figure 13. Dynamo information flow to retrieve linked model elements in each room

Model Element Specifications. Schedules for model element specifications can be created in Revit or extracted from Dynamo if each element is properly populated with appropriate parameters during initial model development. In this case study, many model element parameters were populated in the BHIM after building handover to facilitate building O&M. It should be noted that early BHIM development and exchange protocols (e.g. through the BIM XPlan) could be established to require this information be provided by project stakeholders during initial model development efforts. This would minimize the time spent in this case study to complete the labor intensive and retroactive approach to create parameters for model elements and populate those with appropriate values in the BHIM.

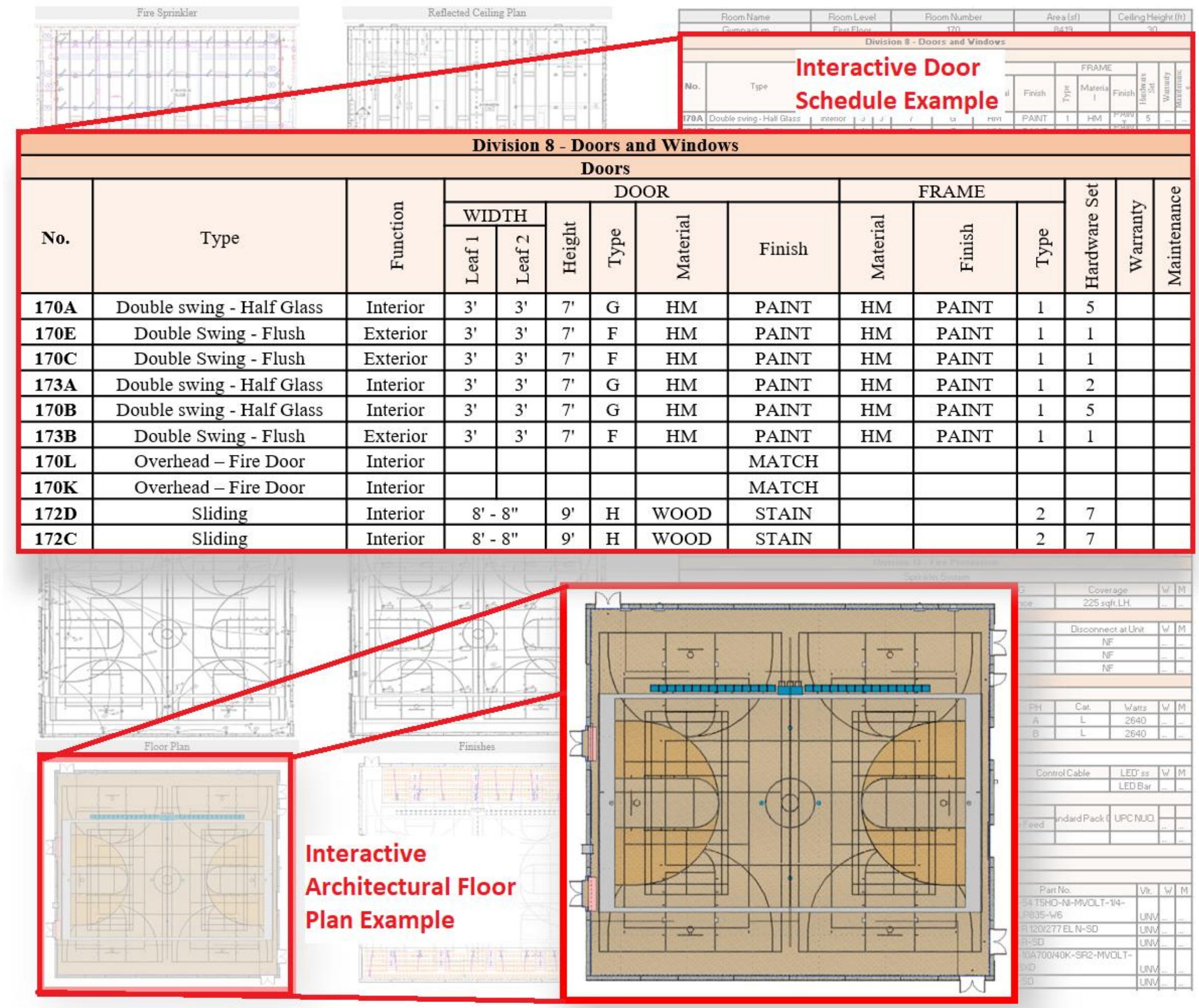
Model Element Warranty and maintenance instructions: Provided the client required the BHIM as the final deliverable, it would be possible to embed a website address (URL) in the Revit parameters with a direct link to the PDF files for building elements' warranty and maintenance instructions. However, in this project, this information is included as hyperlinks in the final PDF deliverables using Bluebeam software.

Model Element Classification (CSI MasterFormat Division): A Dynamo workflow is created to populate the "MasterFormat Division" parameter with appropriate value in the BHIM (e.g. Division 15 Mechanical, Division 16 Electrical, etc.). This flow, for instance, creates the value "15" for elements in the mechanical model using the node "Element.SetParameterbyName" in Dynamo. Following that, while generating the final handover deliverables (see table of doors example in Figure 14), this information can be used to identify, filter, and categorize all elements inside a room (local or linked) according to their MasterFormat division.

5. Generate Deliverables in the Requested Format

As previously discussed, the established format for final deliverables comprised one interactive PDF file for each building room. In order to promote seamless use of the interactive PDF deliverable for O&M purposes, the client also required that the information for all building element inside each room be organized by CSI MasterFormat division. Per the client's request, each room-specific interactive PDF file includes scaled 2D representation of the room, the associated table of specifications (model element parameters), and hyperlinked warranty and maintenance instructions for all model elements in that room. Once the above BHIM framework steps 1 through 4 were completed, this final step comprised retrieving all required information from the BHIM and exporting it to Microsoft Excel as tables using Dynamo to compile the integrated PDF files. Figure 14 provides the specifications for all the doors as an example of a specification table included in the final deliverables for one of the rooms (the gymnasium). Two columns "Warranty" and "Maintenance" were manually populated with the appropriate URLs in the final deliverables. These cells include a hyperlink that directs users to a PDF file of the approved submittals provided by the responsible manufacturers or subcontractors.

Each room-specific PDF file contains eight 2D plan views including the architectural floor plan, finishes plan, reflected ceiling plan, plumbing plan, HVAC plan, electrical plan, lighting plan, and fire sprinkler plan. This was done to ensure all the trade-specific associated model elements, and their locations, were clearly visible and uncluttered for O&M use in the field. The authors applied filters using the "visibility graphics" in Revit to color code elements to further enhance visualization of the components by trade in the final O&M deliverables.



Division 8 - Doors and Windows															
Doors															
No.	Type	Function	DOOR						FRAME			Hardware Set	Warranty	Maintenance
			WIDTH		Height	Type	Material	Finish	Material	Finish	Type			
			Leaf 1	Leaf 2										
170A	Double swing - Half Glass	Interior	3'	3'	7'	G	HM	PAINT	HM	PAINT	1	5		
170E	Double Swing - Flush	Exterior	3'	3'	7'	F	HM	PAINT	HM	PAINT	1	1		
170C	Double Swing - Flush	Exterior	3'	3'	7'	F	HM	PAINT	HM	PAINT	1	1		
173A	Double swing - Half Glass	Interior	3'	3'	7'	G	HM	PAINT	HM	PAINT	1	2		
170B	Double swing - Half Glass	Interior	3'	3'	7'	G	HM	PAINT	HM	PAINT	1	5		
173B	Double Swing - Flush	Exterior	3'	3'	7'	F	HM	PAINT	HM	PAINT	1	1		
170L	Overhead – Fire Door	Interior						MATCH						
170K	Overhead – Fire Door	Interior						MATCH						
172D	Sliding	Interior	8' - 8"		9'	H	WOOD	STAIN			2	7		
172C	Sliding	Interior	8' - 8"		9'	H	WOOD	STAIN			2	7		

Figure 14. Final handover deliverable example (Gymnasium) w/ blown up of Architectural Floor Plan and Door Schedule

Discussion and Conclusion

This case study reports on one method of providing a client with a comprehensive and integrated source of facility information that builds upon BIM-based workflows. The framework proposed in this paper describes the steps taken to identify the requirements, develop and implement a central handover- and operation-specific model (referred to as the Building Handover Information Model; BHIM). The objective is to establish a more integrated, efficient, and owner-need driven data retrieval, analysis, management, and handover of building information during closeout for O&M functions. In a use-cased base approach, the framework contextualizes two established openBIM schemas according to project characteristics; the Construction Operation Information Exchange (COBie) and the Level of Development specifications. The former was employed to identify general semantic requirements for handover purposes and the latter to convey the geometric requirements. The lessons learned in development of the BHIM confirm the literature in demonstrating the need for customization of the COBie requirements according to owner's specific needs to avoid delivering redundant or incomplete data (Alnaggar & Pitt 2018). In consideration of the intrinsic fragmentation in initial AEC-purposed BIM development efforts, the results further reveal the need for more specific clarification of requirements for the BHIM since the non-technical language of these two schemas (COBie and LOD) leave room for heterogeneous modeling and naming conventions. Such practice would have helped minimize inefficiencies in the current case study pertaining to re-modeling, information loss or inaccuracy, and potential data misinterpretation. The interoperability issues identified and addressed in the construction to FM exchange scenario in this case study include the definition and classification of the objects that should be placed in the model, clarification of both geometric and non-geometric information requirements for each model element, required parameters for objects, data types, naming conventions for objects and parameters, and BIM software applications in view of their interoperability capabilities. To facilitate seamless BHIM development, the authors suggest that project stakeholders should develop and maintain agreed upon standards that govern these aspects of model development and exchange throughout the project lifecycle.

The input data to the BHIM was initially created during design, fabrication, and construction by various discipline-specific firms in different formats using multiple software tools.

This fragmentation introduces interoperability issues in the development of the central BHIM for handover purposes that builds on design- and construction-purposed BIMs, as opposed to developing the model from scratch. Challenges in BHIM development, as well as inefficiencies in terms of re-modeling, would likely be reduced if participating firms only worked with compatible software packages that can exchange data on the appropriate level of interoperability given project-, client-, and organization-specific requirements. Further, considering the intrinsic fragmentation in initial AEC-purposed BIM development efforts, the results highlight the importance of upfront establishment of a collaborative and collective BIM development and exchange protocol. The results revealed that use-based identification of model requirements was critical to avoid delivering incomplete or unnecessary data to FM stakeholders.

This study contributes to the body of knowledge by providing AEC and FM stakeholders with a practical framework towards establishing an integrated process for the development of a BIM that maintains its usefulness and value during construction to FM handover and O&M phases. Once BIM libraries and modeling protocols are adapted to create a BHIM based on a given end-user's required FM deliverables, the labor intensive portion of the BHIM development framework (e.g. Steps 1-3) is greatly reduced. Repetition and streamlining of the BHIM development process will make this framework very attractive to repeat customers, particularly those who build, own, and operate their facilities throughout the building lifecycle.

Limitations and Future Research

The framework discussed in this paper presents one proposed method of development and implementation of a BIM for FM handover purposes for an existing building, a Design-Build project case, in the Rocky Mountain Region of the United States. Therefore, the framework developed should be interpreted as such. It should be noted that various factors might impact the level of collaboration between participating firms and the interoperability issues to address in the collaborative BIM development and exchange process. Important factors to consider include the project's characteristics, BIM applications implemented by participating firms, the end-user capabilities to work with a BIM, owner FM system needs, the client's FM handover and downstream O&M task information requirements, and the chosen project delivery method. Therefore, the proposed framework may require customization given project, owner and end-user needs. Future BHIM framework development should focus on additional studies where models are implemented and tested on various project types and for implementation for different O&M tasks. Since O&M is a lengthy and on-going phase in a building's lifecycle, an effective BHIM would need to be adjusted over time in accordance with building changes to remain useful. Several promising next steps include the identification of methods for seamlessly updating the BHIM during the maintenance phase, integrating the model with other technology tools, and the challenges and benefits of this practice in terms of the client's intended end-use for the BHIM. Further research should also investigate implementation of the lessons learned in collaborative BIM development for future projects within the context of the BIM Execution plans (BIM XPlan), BIM library development, and model exchange protocols.

Chapter 4 - Information-Augmented Exchange Objects to Inform Facilities Management Handover BIM Guidelines: Introducing the Level of Semantics (LOS) Schema

Overview

Although BIMs have the potential to provide a compelling tool for facilities lifecycle information management, the challenges of systematic and robust identification, formalization, and conveyance of owner's exchange requirements for FM handover (Exchange Requirements) remain unresolved. This study develops an object-oriented framework to use-case based identification of ERs for FM handover BIMs corresponding to owner's requirements at project close out. The framework further specifies the model content and content structure through an integrated IDM-MVD approach in conjunction with the Industry Foundation Classes (IFC) schema. To address interoperability issues pertaining to modeling and naming conventions, the framework also formalizes the terminologies and taxonomies in conjunction with the buildingSMART Data Dictionary (bsDD) schema. The results reveal the need for customized implementation of the IFC-MV – in term of further specification of object types, naming conventions, definitions, property and data types, and units of measurements – according to organization's FM specific needs and guidelines for model development through an "implementation agreement". To provide the means for systematic conveyance of the requirements among AEC/FM experts, this study bridges the gap between the technical language of bsDD and the non-technical language of Level of Development (LOD) schema (the common language among industry experts to convey geometric requirements). This approach also provides a technical solution for systematic specification of LOD definitions to address heterogeneous modeling and naming conventions. In addition, to systematically specify and convey the identified semantic requirements in close out deliverables, this study introduces the Level of Semantics (LOS) definitions. The LOS definitions map the owner's semantic requirements for FM workflows at project close out (e.g. warranty information) to appropriate IFC concepts, and respective properties specified within the implementation agreement.

Introduction

Building Information Models (BIM) have the potential to be a compelling tool for efficient Facilities Information Management (FIM) across the building lifecycle (Nagel et al., 2009; Preidel et al., 2017b., Cavka, Staub-French, & Poirier, 2017). BIMs are inherently object-oriented, parametric, and data rich, when utilized to their potential, can provide the end-user with building objects with intelligent behavior as well as geometric and non-geometric data within the 3D environment (Eastman et al., 2011). The logical structure and meaningful definition of objects in an object-oriented, parametric, environment are critical when implementing BIMs for use beyond pure visualization (Nagel et al. 2009). Furthermore, BIM authoring tools are capable of automatically integrating data with Facilities Management (FM) technologies including Building Automation Systems (BAS) (Lewis, 2013a), Geographic Information System (GIS) (Kang & Hong, 2015), sensors (Ibrahim et al., 2017), Augmented Reality (AR), and the Internet of Things (IOT). BIMs that effectively integrate these tools can be utilized to facilitate comprehensive data management on the large scale required for the efficient operation of complex buildings.

The existing literature indicates the existence of inefficiencies during the construction-to-operation information handover process. Researchers posit that these inefficiencies are the root cause of information management issues during the post-construction building operation phase. Further, FM experts emphasize the importance of properly including model object information within AEC BIMs to facilitate efficient FM workflows. The inefficiencies of the construction-to-operation transition are mainly due to the fragmented process of gathering and submitting data in unlinked documents consisting of large quantities of hard copy manuals, 2D Drawings, and documents. Thus, the FM team may be provided outdated, erroneous, incomplete, and irrelevant data in inconsistent formats. In the current O&M information delivery method, data retrieval is time consuming and a lack of sufficient coordination results from late facility manager involvement (Bröchner, 2008; Anderson, Marsters, Dossick, & Neff, 2012; Clayton, Johnson, & Song, 1999; East, 2007; East & Nisbet, 2010; Thabet, Lucas, & Johnston, 2016; Wang, Bulbul, & Mccoy, 2015; William East, Nisbet, & Liebich, 2012; Wu & Issa, 2012; Wang et al., 2015; Wijekoon, Manewa, & Ross, 2018). Hence, current construction-to-operation handover practice culminates in ineffective data utilization during O&M. This existing method of data handover requires extensive interpretation and manual re-creation of information by the end-user which hinders efficiency and negatively affects productivity in building operation workflows (East & Nisbet, 2010; Lucas, Bulbul, & Thabet, 2013 (Sadeghi, Elliott, Strong, & Porro; under review).

According to the National Institute of Standards and Technology (NIST, 2004), $15.8 billion is spent annually to address inadequate software interoperability issues within the United States capital facilities industry. Of this total, $4.8 billion is resultant FM staff productivity loss, rework costs, and O&M information verification to mitigate these issues during the post construction phase. Furthermore, the report estimates a potential savings of $613M specifically associated with automated transfer of information from AEC to FM. Therefore, establishment of consistent protocols that address various aspects of BIM interoperability in a systematic manner is necessary (East et al., 2012; Steel et al., 2012; Yoders, 2013). Previous efforts to increase AEC to FM model data transfer have focused on five domains; 1) what information needs to be exchanged; 2) how this information will be transferred; 3) when this data should be populated in a model; 4) Who is responsible for capturing and delivering the model data and; 5) why the data is required for the exchange scenario (Ashworth, Tucker, & Druhmann, 2018; Maltese et al., 2017).

Given the literature, expense of capital management inefficiencies and need for a more seamless data extraction and information gathering process during building operation, the objective of this paper is to develop a model object-oriented specification for BIM execution across the building lifecycle. The specification discussion herein provides a modeling standard that conveys FM requirements for exchange models provided during the construction-to-operation information handover process. Specifically, this paper addresses a framework for standardizing the content, format, terminology and taxonomies of the exchange models in conjunction with the Information Foundation Class (IFC) schema and buildingSMART Data Dictionary (bsDD).

A review of literature indicates an interest in exploring the implementation of BIMs, to promote seamless information exchange during building handover and integrate BIM within FM. For instance, Patacas, Dawood, Vukovic, & Kassem (2015), investigated the visualization capabilities of BIMs and their role in decision making for O&M activities. Studies have also explored the implementation of BIMs for daily O&M data management (Peng et al., 2017), scheduling of maintenance work orders (Chen et al., 2018), and failure root cause detection (Motamedi et al., 2014). Other application areas include energy control and monitoring (Becerik-Gerber et al., 2011), commissioning processes (Jiao et al., 2013), space management, emergency planning (Nicał & Wodyński, 2016; Terreno et al., 2015), and mitigation of safety hazards to FM staff (Wetzel & Thabet, 2018). Additional studies investigated the potential benefits of integrating BIM within the context of FIM include locating building components (Mohanta & Das, 2017), access to more accurate data and automated data generation through a central model (Pärn et al., 2017), and improving the efficiencies of FM work orders (Kelly et al., 2013). Nonetheless, ongoing research and development efforts strive to address the aforementioned challenges in integration of BIM in FM handover. It is critical to understand that for BIM to make automated and seamless information flow from construction to FM possible, Exchange Requirements need to be clarified at the front end of lifecycle according to FM task-, and system-specific needs (Kassem et al., 2015; Kim et al., 2018; Patacas et al., 2015; Sadeghi, Elliott, & Porro, 2018). This entails BIM content (what information) and format (content type and structure), as well as consistent terminologies and taxonomies (Parsanezhad & Dimyadi, 2013).

This study develops an object-oriented, and use-case based framework to identify the ERs for FM handover exchange models and furtehr formalize the content, format, and terminology and taxonolmies for this exchange scenario. This research study further provides the means for AEC/FM experts to systematically convey the geometric requirements for Exchnage objects (EOs) in terms of LOD definitions. Within the same context, this research introduces the concept of Level of Semantics (LOS) to systematic specification of semantic requirements, following owner's specific FM needs. This framework provides the technical solution for ERs of the FM handover MV through the object definitions concepts within the IFC schema. Clearl definition of LOS in conjunction with the IFC and bsDD schema aims to ensure the greatest accepntance among various AEC/FM and developers.

Literature Review

BIM implementation for FIM

BIMs, inherently object-oriented and parametric, are data rich and provide building objects with intelligent behavior, geometric and non-geometric data in a 3D environment (C. M. Eastman, Eastman, Teicholz, & Sacks, 2011). The logical structure and meaningful definition of objects in the object-oriented and parametric environment are critical to take implementation of BIMs beyond pure visualization (Nagel, Stadler, & Kolbe, 2009). Furthermore, BIM authoring tools are capable of automatically integrating data with other technologies within the context of FM, including Building Automation Systems (BAS) (Lewis, 2013a), Geographic Information System (GIS) (Kang & Hong, 2015), sensors (Ibrahim et al., 2017), Augmented Reality (AR) (Chung, Kwon, Moon, & Ko, 2018), and Internet of Things (IOT) (GhaffarianHoseini et al., 2019) to facilitate "Big Data" management.

A growing interest in exploring implementation of BIMs to improve seamless information exchange during building handover and to integrate BIM within FM tasks is evident in the increasing number of research and case projects on the subject. For instance, the visualization capabilities of BIM and their role in decision making for O&M activities are receiving an increased attention (Patacas et al., 2015). Studies also implement BIM for daily O&M data management (Peng et al., 2017), scheduling of maintenance work orders (Chen et al., 2018), and failure root cause detection (Motamedi et al., 2014). Other application areas include energy control and monitoring (Becerik-Gerber et al., 2011), commissioning processes (Jiao et al., 2013), space management, emergency planning (Nicał & Wodyński, 2016; Terreno et al., 2015), and mitigation of safety hazards to FM staff (Wetzel & Thabet, 2018). Potential benefits of integrating BIM within the context of FIM include locating building components (Mohanta & Das, 2017), access to more accurate data and automated data generation (Becerik-Gerber & Kensek, 2009) through a central model (Pärn et al., 2017), and improving the efficiencies of FM work orders (Kelly et al., 2013).

Ongoing research and development efforts strive to address the aforementioned challenges in integration of BIM in FM handover. It is critical to understand that for BIM to make automated and seamless information flow from construction to FM possible, Exchange Requirements need to be clarified at the front end of lifecycle according to FM task-, and system-specific needs (Kassem et al., 2015; Kim et al., 2018; Patacas et al., 2015; Sadeghi et al., 2018). This entails BIM content (what information) and format (content type and structure), as well as consistent terminologies and taxonomies (Parsanezhad & Dimyadi, 2013). The buildingSMART alliance and several leading solution providers (software developers) have taken the initiative to establish a "Universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows", referred to as "openBIM". openBIM standards corresponding to these aspects include Industry Foundation Classes (IFC), Information Delivery Manual (IDM), Model View Definition (MVD), and buildingSMART Data Dictionary (bsDD) (buildingSMART, 2015). Specific to FM handover exchange scenario, is the Construction Operation Building information exchange (COBie) schema.

openBIM Standards

The Industry Foundation Classes (IFCs) standard, developed by buildingSMART, pertain to data standards, covering a wide range of domains within the AEC and FM industry. IFCs address data interoperability by specifying an open data schema and neutral file format to promote object-oriented data exchange among heterogeneous BIM platforms used by various participants in the

AECFM industry (Bedrick, 2019; Kell, 2015; Laakso & Kiviniemi, 2012). It specifies exchange format definitions in EXPRESS language, including data structure, modeling constructs, and syntactic and semantic requirements. Although the standard is increasingly being used by software vendors and practitioners, studies reveal objections towards implementation of IFC – including considerable complexity of the data structure, ambiguous content, and difficulties in working with IFC (Zibion et al., 2018) – and advocate that reforms are required to make more robust exchange of semantics possible (Manu Venugopal et al., 2015). The significant extent and complexity of a full IFC model results in technical difficulties, and redundancies (e.g. exporting asset data which is not required), unless this overgeneralization is overcome by means of reducing the scope for specific implementations (Steel et al., 2012).

The IDM and MVD standards provide support for both industry users and software developers by specifying and mapping specific needs, activities, and information required at each exchange scenario for the IFC model, also making automatic model validation possible. This requires an understanding of configuration and flow of tasks for the specific exchange scenario in the AECFM industry. Accordingly, a set of required information (Exchange Requirements) to fulfill the exchange purpose needs to be identified. The description of the ERs are developed in non-technical terms, which provide a connection between the process and model data. An Exchange Requirement Model (ERM) provides a graphical representation of the required Exchange Concepts (EC) for an exchange scenario. The technical solution to exchange these concepts are the MVD concepts (See et al., 2012; Wix & Karlshoej, 2010). An MVD consists of concepts with predefined specifications and rule sets defining required entities, attributes, properties, and relationships to meet the ERs for the scenario. These concepts are the input to software development and the basis for measurement of the exchange success (C. Eastman et al., 2009; M. Venugopal et al., 2012). Although the exchange concepts are meant to provide a modularized mechanism for reusability, in practice the "lack of formal definitions on a semantic level" hinders reuse of MVDs, resulting in waste in development and implementation of MVDs (C. Zhang et al., 2013). On the other hand, currently the transition from IDM to MVD is heavily manual (hence, prone to error) since the details of ERs for exchange process are not specified (Manu Venugopal et al., 2015).

The buildignSMART Data Dictionary (bsDD) is an openBIM standard provides "meaning" for the exchanged information, striving to establish a common understanding among various industry experts, end users of BIMs, and solution providers. The standard establishes a "common technical language", which "works as a semantic mapping tool that connects like-terms based upon their meaning as it pertains to construction" (National BIM Standard, 2017).

The Construction Operation Building information exchange (COBie) schema provides the capability to outline a structured method to capture and deliver information required for asset management in the operation phase from an early stage of the facility's lifecycle (East & Carrasquillo, 2013; Patacas et al., 2015). Although COBie aims to facilitate the import of real-time data to FM system (E William East, 2007), previous studies criticize the complexity, fragmentation, and labor-intensive process dominating implementation of COBie (Howard & Björk, 2008; Yalcinkaya et al., 2016). Furthermore, while COBie provides the format for the exchanged information, it fails to support the owner in identifying and requesting specific semantic data according to FM information requirements (P. E. Love et al., 2014). Accordingly, FM receives incomplete, unnecessary, or low-quality COBie data at project close out, which impairs its efficient usability during operation (Alnaggar & Pitt, 2018). From a technical standpoint, existing BIM-authoring platforms, with few exceptions, generally do not provide complete support for COBie schema (Patacas et al., 2015).

FM Handover

The industry and academia is quite aware of the previously mentioned issues in integration of BIM for FM handover and downstream O&M workflows and an increasing number of research and development efforts strive to address the subject. Pertaining to clarification of BIM requirements in the case of FM handover exchange scenarios, these efforts mainly focus on two aspects; 1) helping owners to identify general (geometric or semantic) requirements for FM workflows (Becerik-Gerber et al., 2011; Motamedi et al., 2014), and ERs for FM handover scenario (Cavka et al., 2017; Mayo & Issa, 2015; Patacas et al., 2015); 2) to specify ERs and map those to provide support for technical solutions to streamline BIM implementation for FM handover (Alliance, 2011; Pishdad-Bozorgi et al., 2018; William East et al., 2012). One example of the latter is the buildingSMART "FM Basic Handover View", which specifies ERs and MVD for the "basic" handover of FM information to improve interoperability of commercially available BIM applications and Computer Aided Facility Management (CAFM) and Computerized Maintenance Management System (CMMS) applications. The scope of this standard is limited to "basic" requirements, not addressing any FM specific needs (Alliance, 2011).

Level of Development (LOD)

The LOD schema, developed by the American Institute of Architects (AIA), is meant to provide a systematic way of conveying the extent of reliance on model elements in a BIM, to enable automated data transmission and workflow communication between IFC BIMs (Becerik-

Gerber, Jazizadeh et al., 2012. National Institute of Building Sciences, 2015). The LOD descriptions identify the specific minimum content requirements and associated Authorized Uses for each Model Element at five progressively detailed levels of completeness. The Associated General Contractors BIMForum Committee's LOD specifications refer to the LOD classification as a "reference" or a "language". It suggests that by means of this classification the AEC industry practitioners "Can specify and articulate, with a high level of clarity, the content and reliability of BIMs at various stages (milestones) of design and construction process for their specific firms or projects" (BIMForum, 2015). In general, the precision and level of graphic and non-graphic information for model elements increase by their respective LOD level. This is to indicate progression to a higher level of model element information, providing more details moving from LOD100 towards LOD500 (BIMForum, 2015). The specification also provides a platform for users to identify required LOD for elements to perform such tasks as design coordination, model-based fabrication and as-built documentation. For instance, at LOD400, the element "Is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information." (BIMForum 2019, pg 12). According to Abualdenien and Borrmann (2018) further attempts are required to clearly define the requirements for LOD definitions. As for non-graphical information, however, the specification only states that "Non-graphic information may also be attached to the Model Element" (BIMForum, 2019, pg 12). On the other hand, the schema addresses only AEC-specific model requirements, and stops at field verification. Due to differing owner-specific information requirements, to communicate BIM data requirements for O&M purposes, previous research propose LODs that diverge from the original five levels. Given a project's characteristics or the owner's need, less precision than LOD500 – a field verified representation - might be sufficient since non-graphic information is more critical for FM (Mayo & Issa, 2014).

This research aims to address interoperability issues of FM handover exchange scenario identified in previous literature, which hinder seamless transition of data from construction to FM; identification of owner's required data at project close out to support FM workflows; systematic and robust conveyance of geometric and semantic requirements; and clear specification and formalization of requirements for content, format, and terminologies and taxonomies to facilitate automated data validation and transition from BIM-authoring tools to FM system.

Research Method

In light of the in-depth literature review and the results of the previous phases of this longitudinal research, this phase develops a framework for identification, formalization, and systematic conveyance of BIM requirements (geometric and non-geometric) for FM handover exchange scenario for a large university in the Midwest United States as a demonstrative case study. At the earliest stages of this research study, the authors carried out semi-structured interviews with the key stakeholders from the owner's FM department to have a clear understanding of the FM handover process, as well as owner's FM practice, information requirements, and FM systems. The asset portfolio of the organization under study consists of over 200 buildings of various types, including academic and administrative buildings, libraries, healthcare facilities, recreation centers, student centers, and housing. Regardless of buildings' location (main or satellite campuses) the FM department oversees the development, operation and maintenance of the buildings. The FM department responsibilities include planning, design, and new construction; Operation and Maintenance (O&M); custodial services; outdoor services; utility services and energy management; recycling; inventory; inspections and facility audits; space planning and management; transportation and parking; budgeting and accounting; safety; and trades management. The organization is in transition from an outdated FM system to an IFC-compatible Integrated Workplace Management System (IWMS), which is capable of providing a consolidated repository of information required for asset management, capital planning, operation and maintenance, space management, and energy management. Although the organization receives an AEC-intent BIM on new construction projects the challenges of BIM data interoperability remains as follows;

- The AEC-intent models are not developed to address FM needs, hence these models fall short in providing the required data for FM handover (e.g. warranty information)
- Various AEC firms on different projects employing heterogeneous modeling and naming conventions brings about challenges for FM team (end users of the model) to understand and map model data
- Data validation of the AEC-intent BIM and the transition from AEC to FM remains a manual, tedious, and error-prone process

To address these issues, the authors employed an integrated IDM-MVD methodology as shown in Figure 15, which utilizes an object-oriented and use-based approach to identify and formalize ERs for FM handover MV following FM needs in this organization.

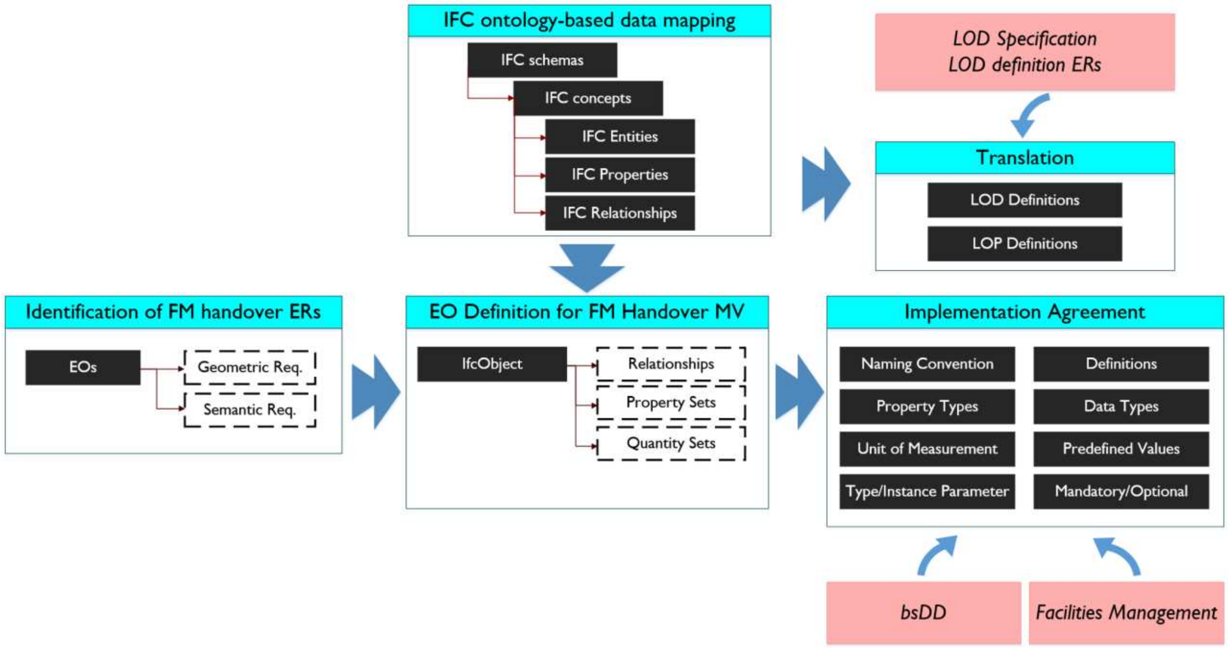


Figure 15. Research Methodology Map

This study focuses on identification, systematic specification and conveyance of required information to be exchanged (from construction to FM) at the close out phase to support commissioning, maintenance, and operation workflows on HVAC distribution systems. The steps of the methodology map are described hereunder:

1. *Identification of FM handover ERs*

First within the context of IDM methodology, the authors carried out content analysis on project close out deliverables to identify ERs for FM handover MV following the identified FM workflows (and information requirements) for the scope of this study. This includes identification of Exchange Objects (EOs) (the objects to be placed in the FM handover MV), and the required geometric and non-geometric (semantics) information relating to the FM workflows within the scope of this study.

2. *IFC Specification: An ontology-based data mapping*

An in-depth and schema-independent content analysis of the IFC specification (Release 4x2) determined a comprehensive list of definition concepts and their subtypes for EOs. The authors also mapped the EOs to the respective inheritances of IfcObject and the ERs to appropriate IFC concepts, which provide the technical solution for ERs. These concepts determine the required entities, their relationships, and properties in the FM handover IFC MV.

3. *Exchange Object (EO) definition*

This step includes development of a complete, schema-independent list of applicable IFC concepts for the identified IFC objects in step two (these objects represent the identified objects in step one required to be placed in the FM handover MV). The authors mapped the identified ERs for each object type to appropriate IFC concept, hence the respective properties, relationships, and information attributes.

4. *Implementation Agreement*

Following the IDM-MVD approach (step one to three), the research team developed an implementation agreement which provides detailed guidelines to formalize the terminologies and taxonomies according to FM specific needs and interoperability solution of this organization. This agreement specifies definitions, naming conventions, and property and data types in conjunction with the bsDD schema. Further, measurement units, parameter types (instance/type parameters) and whether the requirements are optional or mandatory are specified following the owner's FM needs. These items are critical in supporting the establishment of a common understanding of the FM's requirements and facilitating automated data validation and transition from BIM-authoring tool to FM system.

5. *Translate to AEC/FM common language*

The last step of this research provides a compelling framework for owners to systematically convey the geometric and non-geometric requirements for FM handover MV. This study refers to the LOD schema as the 'common language" among the AEC/FM experts to convey the geometric requirements. The authors mapped the required IFC concepts (identified in the previous step) to appropriate ERs of LOD definitions to provide a systematic solution for AEC/FM experts to convey the requirements for the FM handover MV in a non-technical language. Following the same methodology, this study introduces the Level of Semantics (LOS) concepts to formalize the specification of semantic requirements (ERs identified from close out deliverables) through their counterpart IFC concept, not addressed in LOD definitions. This approach bridges the gap between the technical language of bsDD and IFC and the non-technical language of the ERs (from the close out deliverables). The LOS concepts equivalent the semantic requirements for the FM handover MV (e.g. warranty information, or manufacturer data) in the non-technical language common in the AEC/FM industry. This study maps the LOS concepts to appropriate IFC concepts (which provide technical solution for ERs), and respectively identifies the required properties and property sets for EOs within the FM handover MV. Further formalization of taxonomies and terminologies for LOS definitions in conjunction with the bsDD schema provides systematic specification of the requirements, addressing modeling and naming conventions.

6. *FM handover BIM development*

Finally, the authors validated the results of this study on a pilot project and proposed a framework for the owner organization to identify the FM handover requirements corresponding to FM workflows and systematically convey these requirements by means of LOD and LOS definitions in the early phases of the project lifecycle. The framework also includes the development of FM handover-intent BIM in compliance with the specific guidelines of the implementation agreement to meet the identified requirements, and exchange the model data with FM system.

Analysis and Results

This sections references the research methodology mapping to discuss the analysis and results pertaining to each step described in the previous section.

Identification of FM Handover Requirements

In the current practice, the FM department in the owner organization requests Design-Build teams to hand over the close out documents containing data created during design, fabrication, and construction. The authors carried out content analysis on these close out deliverables to identify the required EOs, and geometrical and semantic information requirements at the close out phase. These requirements are in non-technical terms (common language among AEC/FM experts) and eventually define the content of the FM handover exchange model (what information needs to be exchanged). Table 5 lists the close out deliverables typically requested by the owner organization and a general information identified for each.

Table 5. Description of owner-requested Close out deliverables

Close out deliverable	Description
Record Documents	Includes a 3D model developed for design coordination purposes, as-built and record drawings and project specifications following the MasterFormat classification. These documents contain such information as as-built conditions, project true north, spaces and building zones, design codes, etc.
Project Information	A document containing information such as project name, location, building name, building type, building number, substantial completion date
Project Contact Information	This document contains information about project participants involved throughout project lifecycle; organization name, (representative) person name, roles, physical address, phone number, fax, email address
Owner Project Requirements (OPR)	Including owner's project goals (e.g. pertaining to sustainability, or system performance).
Site Documents	Pertains to geotechnical reports and topographic surveys (out of scopes of this research).
Warranties	Includes information on warranty coverage, product model number (tag number or serial number), warrantor name, warrantor contact information, warranty start date, length of warranty, warranty finish date, exceptions
Installation, Operation and Maintenance manuals	These documents include information on product description, product use case, product mark number, manufacturer information, shipping information, safety information, product life span, maintenance type, required work order, work order frequency, risk of failure, replacement parts, design performance requirements, test procedures, installation instructions, access requirements, required tools/equipment, and shutdown/startup procedures
Performance Test Reports	Documents including information on processes which aim to assure system performance according to design criteria.

As an example, Figure 16 provides a graphic representation of the information pieces (ERs) provided in the leakage test report for duct elements of the HVAC distribution system.

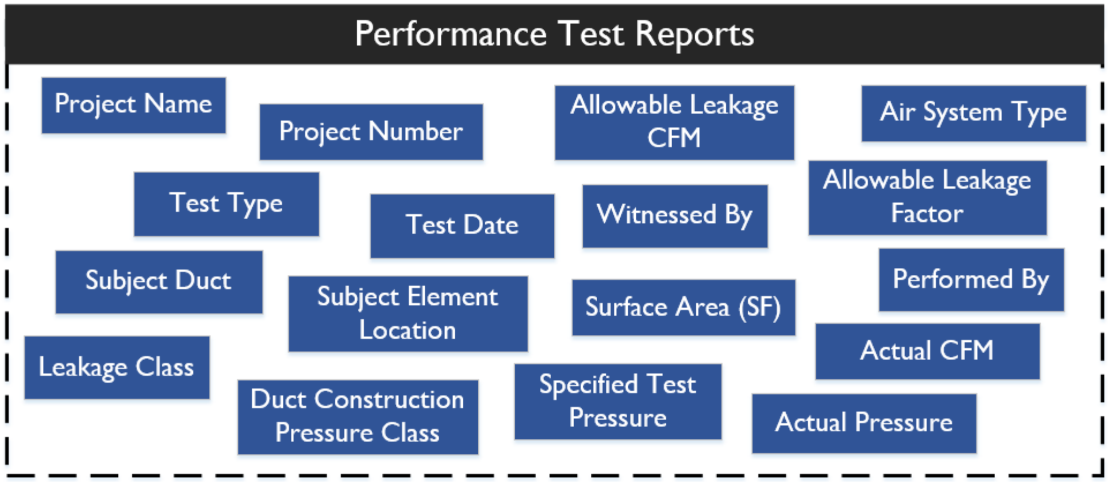


Figure 16. FM Information Requirements at Project Close out

IFC Specification: An ontology-based data mapping

With reference to the IfcKernel schema within the IFC Specification (Release 4x2), the authors mapped the required EOs, identified in the previous step, to the respective IFC entity. This consist of the inheritances of the IfcDistributionFlowElement and IfcDistributionControlElement, which are representative of elements of HVAC distribution systems.

The comprehensive, schema-independent content analysis of the IFC specification, revealed a list of definition concepts and their subtypes (the third level of the breakdown in Figure 4) for inheritances of IfcObject, regardless of the object type or any exchange scenario. For instance, the "Object Placement" concept applies to the inheritances of the IfcProduct, while the "Activity Connectivity" concept applies to those of the IfcProcess. These concepts include Software Identity, Revision Control, Object Definition, Object Composition, Declaration within a Context, Connectivity to Other Objects, Assignment of Other Objects, Association to External/Internal Resource Information, Object Placement, and Representation. These concepts, if applicable, determine the required entities, their relationships and properties within the FM handover IFC MV and provide the means for EOs to contain the ERs.

Figure 17 depicts partial list of applicable concepts to instances of IfcDuctSegment, which determine required properties and related objects for the FM handover BIM. For instance, the concept of “Spatial Containment” requires instances of IfcDuctsegment to be assigned to the appropriate instance of IfcSpace containing the element.

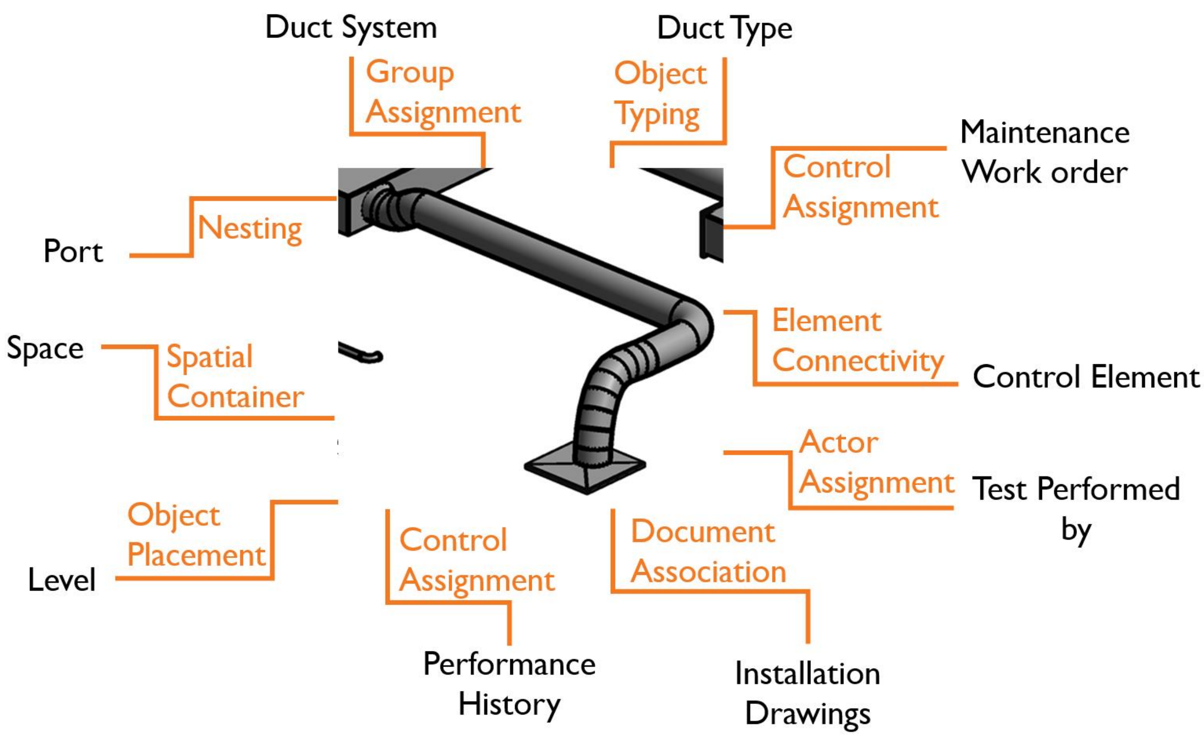


Figure 17. IFC concepts for instances of IfcDuctSegment

Accordingly, instances of IfcSpatialStructureElement, IfcPort, IfcSystem, IfcZone, and IfcProject (along with the previously mentioned classes) were identified as required EOs for the FM handover MV in this project were identified as depicted in Figure 18.

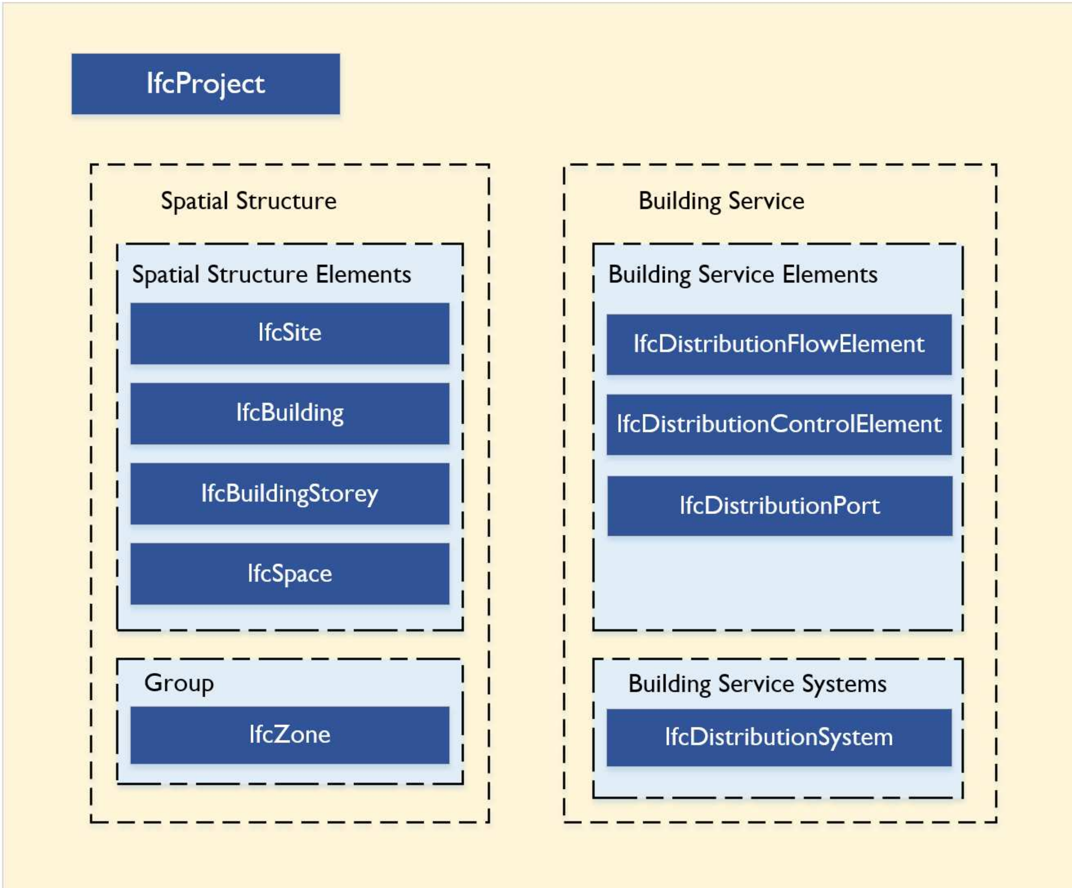


Figure 18. Conceptual Diagram of Model Elements

Exchange Object Definition

To provide a technical solution for EOs to entail identified requirements for this exchange scenario, the ERs need to be mapped to appropriate IFC definition concepts. The ontology mapping resulted is development of a comprehensive, schema-independent definition for the required EOs and their relating objects for the purpose of this scenario. Consequently, these definitions reveal the relationships between EOs and required properties within the FM handover MV. For example, Figure 19**Error! Reference source not found.** depicts the required entities determined by “Definition by Type” and “Definition by Properties” concepts for IfcDuctSegment. The “Object Typing” concept, defines model occurrences (instances) by relating those to their type object by means of the relationship IfcRelDefinesByType. This means, the properties which are a part of Pset_DuctSegmentTypeCommon define instances of IfcDuctSegment through the type object IfcDuctSegmentType. The occurrences are also defined by direct assignment of appropriate quantity sets and property sets through the relationship IfcRelDefinesByProperties.

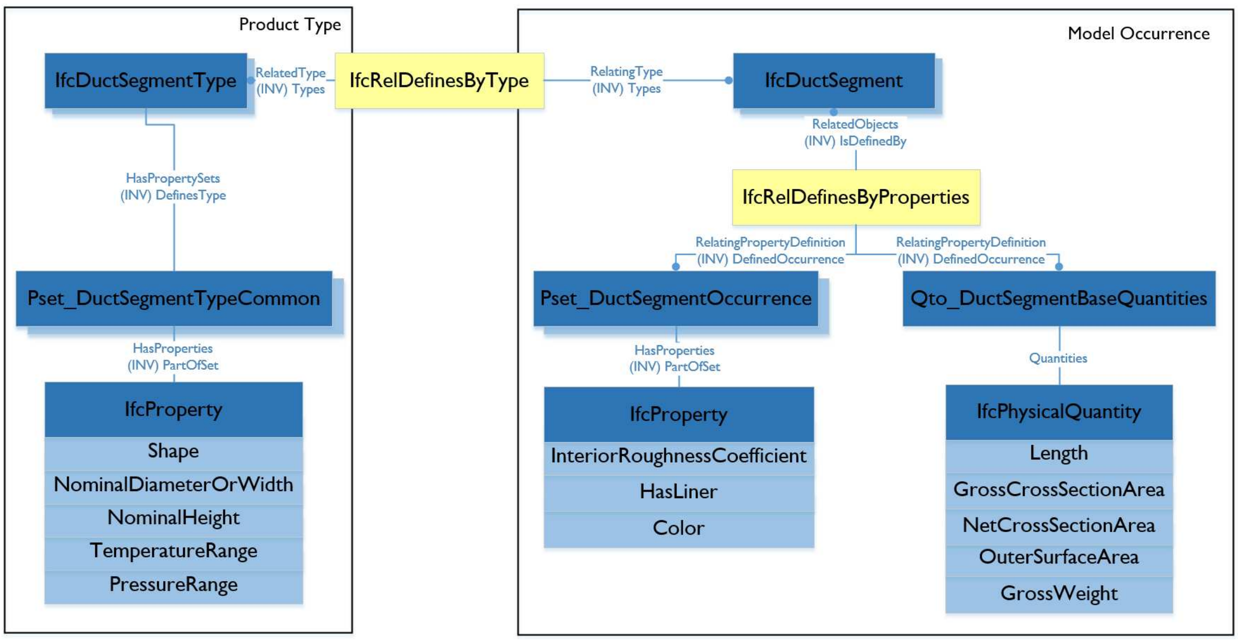


Figure 19. Partial definition of IfcDuctSegment by type and properties

Implementation Agreement

The implementation agreement provides a detailed guideline for implementation workflows to provide a robust and systematic solution, which facilitates automated data validation and BIM-FM data interoperability. More importantly, it creates a unanimous formality for specification of the terminology and taxonomies of the ERs for the FM handover MV in conjunction with the buildingSMART's Data Dictionary (bsDD) schema and in accordance to owner's FM needs and BIM data interoperability solutions. This includes detailed clarification on naming conventions for parameters, definitions, property type, data type, agreed-upon predefined values for enumerated data types, and units of measurement as shown in table Table 6. For instance, with reference to the implementation agreement, all project participants will have a common understanding that if performance history is required for model duct occurrences, the EO shall have the information attribute named “FluidFlowLeakage”, which provides information on the “Volumetric leakage flow rate” (definition) in Cubic Foot of Air per Minute (CFM) – measurement unit. According to the agreement this property is of type “IfcPropertyReferenceValue”, which contains data of type “IfcVolumetricFlowRateMeasure”. Consequently, participants will have a common understanding of the requirements with no need for interpretations. This level of clarity through such commonly accepted specifications as bsDD provides various AEC firms with the opportunity to utilize any object-oriented, parametric, and IFC compliant BIM-authoring platform of choice to develop the model and later map model data following the guidelines and export to IFC format (to hand over the model to FM at project close out).

Table 6. IFC Implementation Agreement for Pset_DuctSegmentPHistory

Definition Concept							
Attribute Group							
	Property Name	Property Type	Data Type	Definition	Unit	T/I	O/M
Control Assignment - Performance History							
Pset_DuctSegmentPHistory							
	FluidFlowLeakage	IfcPropertyReferenceValue	IfcVolumetricFlowRateMeasure	Volumetric leakage flow rate.	CFM	I	M
	LossCoefficient	IfcPropertyReferenceValue	IfcReal	Dimensionless loss coefficient used for calculating fluid resistance representing the ratio of total pressure loss to velocity pressure at a referenced cross-section.		I	M
	LeakageCurve	Quantity		Leakage per unit length curve versus working pressure. If a scalar is expressed then it represents LeakageClass which is flowrate per unit area at a specified pressure rating (e.g., ASHRAE Fundamentals 2001 34.16.).	LeakageClass (Inches)	T	M
	AtmosphericPressure	IfcPropertyReferenceValue	IfcPressureMeasure	Ambient atmospheric pressure.	in-wg	T	M

Another critical aspect that needs to be formalized in the implementation agreement is the owner organization’s specific FM system and BIM use case, which drives selection of the data interoperability solution. This study aims to facilitate hard data entry, software interoperability, and proprietary systems. These requirements dictate that the required inheritances of the IfcGroup, and IfcProduct (as well as IfcProject) shall be modeled as an EO, while those of the IfcActor, IfcControl, IfcProcess, IfcResource are optional. Hence, to develop a realistic solution (with no imposed changes to the project delivery), the implementation agreement required AEC firms to provide information attributes for the EOs, providing information on their relating objects. Table 6 represents the required properties for instances of the IfcDuctSegment, driven by the relationship IfcRelAssignsControl which assigns IfcPerformanceHistory to the duct (as opposed to requiring the instances of IfcControl to be provided as an EO (refer to Figure 21).

Within the same context, in the case of object assignment concept, the agreement determines whether the assigned objects are required as an entity or it would be sufficient to provide the required information through properties. For instance, the FM department in this owner organization intends to develop the maintenance schedule following project close out. Consequently, the ERs for maintenance work orders are captured in the model by assignment of the Pset_ProjectOrderWorkOrder to the IfcFilterType directly, as opposed to including the entities of the IfcProjectOrderWorkOrder. Regardless of the data type, the implementation agreement also needs to specify the appropriate IFC entity each property needs to be assigned to. One example is the clarification in assignment of “MaintenanceType” to inheritances of IfcObject or IfcTypeObject – Type or Instance parameter (Table 7).

Table 7. IFC Implementation Agreement for MaintenanceType

Definition Concept							
Attribute Group							
	Property Name	Property Type	Data Type	Definition	Unit	T/I	O/M
Control Assignment - Maintenance Work Order							
Pset_ProjectOrderMaintenanceWorkOrder							
	MaintenanceType	IfcPropertyEnumeratedValue	PEnum_MaintenanceType CONDITIONBASED CORRECTIVE PLANNEDCORRECTIVE SCHEDULED other NOTKNOWN unset	Identifies the predefined types of maintenance that can be done from which the type that generates the maintenance work order may be set where: ConditionBased: generated as a result of the condition of an asset or artefact being less than a determined value. Corrective: generated as a result of an immediate and urgent need for maintenance action. PlannedCorrective: generated as a result of immediate corrective action being needed but with sufficient time available for the work order to be included in maintenance planning. Scheduled: generated as a result of a fixed, periodic maintenance requirement.		T	M

Translate to AEC/FM common language

The LOD schema is recognized as a common "language" among industry experts to convey requirements for "Model Elements" in a use-case approach for AEC purposes. Industry experts refer to LOD definitions to convey geometric requirements for EOs in BIM guidelines. For instance, according to buildingSMART's LOD specification (2019, pg 154) at LOD400 the "components of the HVAC air distribution system" are:

- "Modeled as actual size, shape, spacing, and location/connections of duct, dampers, fittings, and insulation for risers, mains, and branches"
- "Actual size, shape, spacing, and clearances required for all hangers, supports, vibration and seismic control that are utilized in the layout of all risers, mains, and branches";
- "Actual floor and wall penetration elements modeled";
- "Actual access/code clearance requirements modeled";
- "Supplementary components added to the model required for fabrication and field installation".

Although these definitions determine the ERs for EOs, to provide a formalized technical solution for these requirements in the FM handover IFC MV, the ERs need to be mapped to their counterpart IFC concepts. For instance, the authors mapped "location" as an ER, retrieved from the LOD definition for instances of IfcDistributionFlowElements, to the "object placement" concept and its subtypes (local and absolute location). Consequently, required properties of EOs to meet the expectations of LOD definitions are automatically determined, providing a formalized and technical solution for the non-technical language of LOD schema. Figure 20 includes all the ERs specified for "components of the HVAC air distribution" at LOD400 (retrieved from the LOD400 definition), and the IFC concepts the ERs are mapped to for instances of IfcDistributionFlowElement. The implementation agreement (explained in previous step) provides more clarification in guidelines for development of the model. For instance, location of duct segment relative to floor levels or grid lines.

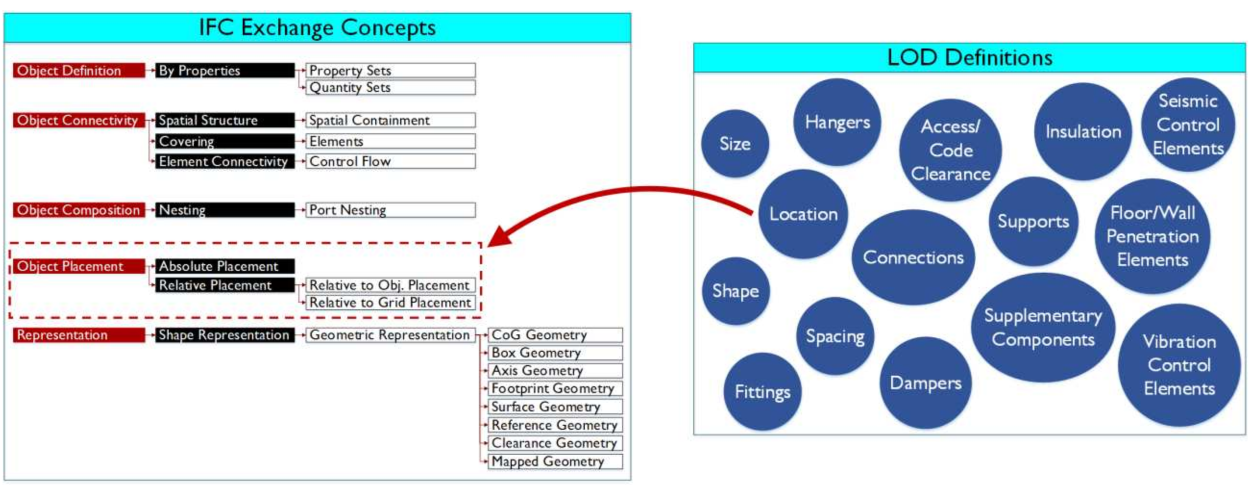


Figure 20. LOD to IFC concept mapping for instances of IfcDistributionFlowElement

The language of these ERs retrieved from LOD definitions resembles that of the close out deliverables. The owner's semantic requirements (including warranty information, or manufacturer data) are not addressed by the LOD definitions. Considering the criticality of the semantics for the purpose of FM handover, this study introduces the concept of Level of Semantics (LOS), to formalize identification, specification, and conveyance of semantic requirements for EOs (not addressed within the LOD schema). The LOS definitions, relate ERs retrieved from close out deliverables (e.g. semantic requirements for performance tests) to the appropriate IFC concepts (and the respective properties, entities, and relationships) applicable to EOs for the purpose of the FM handover exchange scenario. For instance, Figure 21 provides a partial representation of the IFC concepts and following entities, relationships and properties mapped to formalize ERs identified from “Performance Test Reports” depicted in Figure 16 for instances of IfcDuctSegment. The information attribute “AssessmentDate” formalizes the FM handover ER “Test Date” identified in the first step (retrieved from the close out deliverables). The implementation agreement provides further clarifications on definitions, property and data type. The LOS definitions are independent of any IFC schema; Pset_Condition is retrieved from the IfcSHaredFacilitiesManagement schema, while “Assignment to Control” is a concept within the “Control Extension” schema.

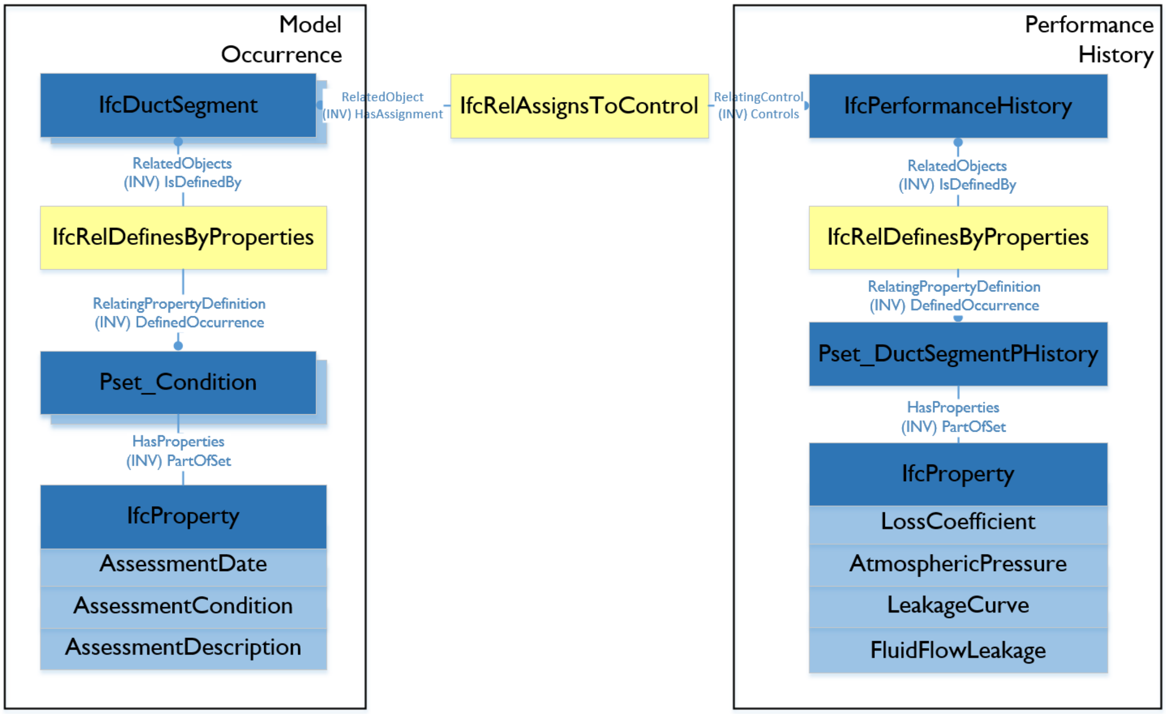


Figure 21. IFC concepts and properties mapped to LOS definitions

The results clearly indicate that the LOD and LOS definitions are independent of one another. This means the required LOD for an EO does not necessarily reflect on the LOS required (or provided in the model) for the same object. In the case of the IfcDuctSegment, for instance, while the EO with LOD500 can contain properties required for performance history (through the specified information attributes), LOD200 would also be sufficient (if this is the only requirement for the EO) for the model occurrence to capture this LOS.

FM Handover BIM Development

This final step pertains to validation of the results using a case study approach within the asset portfolio of the owner organization. The pilot project (case study) is a 48,000 SF addition to an existing educational building on main campus, which features the college's very first student success center, new teaching and study spaces, meeting rooms, and informal spaces for a variety of gatherings, and will house business offices, and center for collaborative conservation. The project was delivered in a Design Build approach and received a LEED silver certificate. The authors simulated the workflow for use-based identification of ERs for FM handover MVs, systematic specification and conveyance of geometric and non-geometric requirements for EOs in terms of LOD and LOS definitions, and development and handover of the model in compliance to the implementation agreement – following the proposed framework in Figure 22.

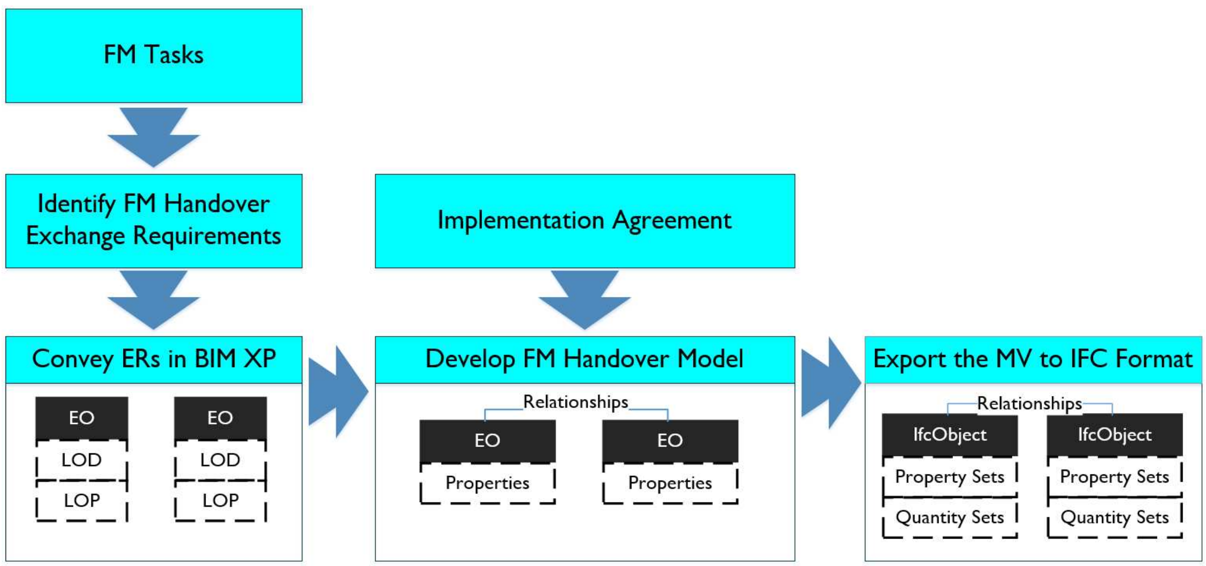


Figure 22. Deployment of the developed solution

Using the integrated IDM-MVD framework on this pilot project, the following results were achieved:

- Owners can convey the geometric and semantic data requirements for EOs in earlier phases of project lifecycle in terms of LOD and LOS definitions respectively.
- The implementation agreement provides clear guidelines for model development workflows, which includes detailed clarification on naming conventions for parameters, definitions, property and data types, agreed-upon predefined values for enumerated data types, and units of measurement.

- The AEC experts can develop the FM handover model in any native BIM application of their choice (shall be object-oriented, parametric, and IFC compatible platform like Autodesk Revit) in compliance with the implementation agreement and LOD and LOS definitions, and export the MV to IFC format to deliver to FM team at project close out.

The results suggest that this object-oriented and modularized framework provides a reusable solution for development of partial MVs for any of the specific FM tasks determined in the first step.

Conclusion and Future Research

Considerable financial losses could occur as a result of insufficient data interoperability from construction to FM. These losses can be in the form of O&M staff productivity loss, O&M staff rework, and O&M information verification (National Institute of Standards and Technology, 2004). Although BIMs are recognized as a compelling tool for facility's lifecycle information management with the potential to overcome these challenges, their implementation in FM handover and post-construction phases remains rather limited. True BIM interoperability occurs with establishment of consistent information format and exchange process, as well as a common understanding of the exchanged information among stakeholders (National Institute of Building Sciences, 2015). For BIMs to facilitate automated and seamless information flow from construction to FM, Exchange Requirements (ERs) for this scenario (BIM content; what information) need to be clarified at the front end of lifecycle according to FM task-, and system-specific needs. Further corresponding formalization of the format (content structure), as well as consistent terminologies and taxonomies is also critical. Lack of clear specification of these aspects hinders automated validation of model data at FM handover, requires rework (in terms of remodeling) and mapping model data and manual re-entry to FM system, an error-prone process due to possibility of misinterpretations.

This study explores FM handover exchange scenarios and provides a comprehensive, object-oriented solution that identifies the requirements for the model content (what information) following FM specific needs (why), and further formalizes the format (content structure), terminologies and taxonomies (following FM system needs) of a model developed by AEC teams (who) and handed over to FM at project close out (when). The aim is to provide a reusable framework to facilitate automated model data validation and exchange to FM systems. This is accomplished through defining model Exchange Objects (EO) to meet FM data Exchange Requirements (ER) in conjunction with the Industry Foundation Classes (IFC) schema. The ERs, retrieved from close out deliverables, are mapped to appropriate IFC concepts, which ultimately provide the technical solution for the FM handover exchange scenario. These concepts determine required entities, their relationships, and properties. The results also include development of an implementation agreement, which customizes the FM handover IFC Model View (MV) according to an organization's specific needs and further establishes a common understanding of the content in alliance with the buildingSMART Data Dictionary (bsDD) schema. The framework described herein addresses naming conventions, property and data types, predefined values for enumerated data types, optional or mandatory, and instance or type parameters. The modularized nature of the resulting framework can be used to convey exchange requirement for partial MVs in future projects.

The provided framework establishes a common understanding of FM handover requirements and corresponding model content, and further facilitates automated model data validation and transfer to FM by formalization of the content format, terminologies and taxonomies. This study is one of the pioneer efforts to provide a technical solution for LOD definitions by bridging the gap between the technical language of bsDD and the non-technical language of LOD, the common schema among AEC experts to convey geometric requirements for objects in a use-case based approach for design and construction purposes. The author mapped the ERs of Level of Development (LOD) definitions to appropriate IFC concept and the respective properties. Hence, the LOD definitions are mapped to the specific properties clarified in the guidelines of the implementation agreement.

The originality of the results of this chapter specifically pertain to systematic identification and specification of semantic requirements for FM handover BIM by introducing the LOS concept. To formalize the semantic requirements, not addressed in the LOD schema, this study introduces Level of Semantics (LOS), defined by mapping ERs to the remaining of IFC definition concepts and their respective property definitions. This translation provides the means for an owner to formalize conveyance of geometric and semantic requirements accompanied with detailed guidelines which establish a common understanding among experts and prevents heterogeneous modeling and naming conventions. Practical implications of the results of this study pertains to the input to FM handover BIM guidelines. The owner organization can employ the documented definitions and the developed implementation agreement early on in future projects to request AEC teams develop a model accordingly. Further, the owner can provide the model developers with the Revit shared parameter files authors developed for the pilot project to avoid rework. Implementation of this workflow can eliminate the need for manual data re-entry or interpretation by FM stakeholders during building operation.

The results have implication for other owner groups, however the study sampling was delimited to Institutions of Higher Education in the state of Colorado. Future research can focus on extending the developed workflow in this study for other building systems or FM purposes, for instance formalization of ERs for emergency management and evacuation planning purposes. Furthermore, a lean approach towards development of a process map for efficient, and seamless development of the BIM from early phases of the lifecycle and delivery of the BIM at close out seems vital. Finally, implementation of the developed FM handover MV during O&M phase for the initially identified FM workflows and reflecting on the lessons learned would be of great value.

Chapter 5 - Discussion and Conclusion

Overview

Access to reliable and accurate information on various aspects of numerous components in the facility is critical to the success of Facilities Management (FM) practices. Considerable financial losses could occur as the result of insufficient data interoperability from construction to FM, pertaining to such inefficiencies as O&M productivity loss, rework, and information verification (National Institute of Standards and Technology, 2004). Although BIMs are recognized as a compelling tool for facility's lifecycle information management with the potential to overcome these challenges, their implementation in FM handover and post-construction phases remains limited. This dissertation investigated FM in Higher Education Institutions (HEI) as a developer, building owner and building operator stakeholder, and developed BIM-intensive frameworks to identify owner requirements and further specify and convey corresponding ERs for FM handover exchange model in a systematic manner.

The initial phase of this dissertation (chapter 2), provided a comprehensive literature review and identified FM information requirements and potential application areas for BIM within Facilities Information Management (FIM) and the context of Higher Education Institutions (HEIs). An interview protocol was developed, based on the literature review and pilot studies, to acquire expert opinions on FM within the HEI target population. Specifically, the sample included public and private universities and community colleges in the state of Colorado. The selected group comprised a sampling of ten Colorado HEIs with different missions and asset portfolios from the four mentioned groups to represent the target population. Respondents were an intentionally designated panel of ten experts selected among top management levels of FM departments in those institutions. Semi-structured interviews were conducted to attain data on the characteristics of the institution's asset portfolio, established FM practice (organizational chart, responsibilities, decision-making processes, and established maintenance strategies), information requirements, as well as in-practice Information Technology (IT) tools and information management challenges. The results confirmed previous research on the inefficiencies inherent to current FIM practice in providing FM decision makers with credible, timely information in an integrated manner (Clayton et al., 1999; East, 2007; East & Nisbet, 2010; Wang et al., 2015; Thabet et al., 2016). The majority of institution studied received, but in general, merely archived the AEC-purposed 3D models developed by participating design firms for new projects constructed on campus.

In light of the results of the first phase (Chapter 2), Chapter 3 investigated the limitations of traditional FM handover practice and developed a framework to promote an efficient BIM-based data exchange protocol for project handover. In a case study approach, this chapter reported on one method of providing a client with a comprehensive and integrated source of facility information by building upon BIM-based workflows. The proposed framework described the required steps needed to implement use-based identification of owner's maintenance-specific information requirements.

The study developed and presented an implementation framework detailing the creation of a central handover model, e.g. a Building Handover Information Model (BHIM). This BHIM framework contextualized two established OpenBIM standards according to project characteristics; the Construction Operation Information Exchange (COBie) and the Level of Development (LOD) schema. The results revealed that use-based identification of model requirements was critical to avoid delivering incomplete or unnecessary data to FM stakeholders.

Furthermore, considering the intrinsic fragmentation in initial AEC-purposed BIM development efforts, the lessons learned suggested the need for more systematic clarification in conveying the owner's requirements to overcome interoperability issues pertaining to heterogeneous modeling and naming conventions. The relating issues identified and addressed in this case study included the definition and classification of the objects that should be placed in the model, clarification of both geometric and non-geometric information requirements for each model element, and BIM software applications in view of their interoperation capabilities.

This research phase also recognized the need to establish a common modeling language among participants and to clarify the expectations from each discipline-specific BIM and the central BHIM. To facilitate seamless BHIM development, the results suggest that project stakeholders develop and maintain agreed upon standards that govern these aspects of model development, and model sharing, throughout the project lifecycle. Such standards to provide guidelines for model development and model sharing may be more critical for larger owner organizations, such as HEIs, that operate and maintain multiple buildings throughout the lifecycle since an owner-specific BHIM development framework has the potential to be reusable on numerous projects.

In light of the challenges and lessons learned from the pilot project reported in chapter 3, and the identified FM information requirements in chapter 2, Chapter 4 strived to develop a robust and systematic framework for owners to identify and systematically convey, in an object-oriented manner, the requirements (both geometric and semantic) for FM handover BIMs according to their specific task and system needs. The inputs to this framework are the FM workflows and corresponding information requirements, FM system and BIM data interoperability solution used in FM handover, IFC concepts (and corresponding object properties), buildingSMART Data

Dictionary (bsDD), owner's information requirements at close out (close out deliverables), LOD definitions, and requirements for automated data validation.

This manuscript focused on BIM data pertaining to HVAC distribution systems to support downstream commissioning, maintenance, and operation workflows in a large university in the Midwest United States. This chapter suggested that for BIMs to facilitate automated and seamless information flow from construction to FM (validation and exchange), Exchange Requirements (ERs) for this scenario (BIM content; what information) need to be clarified at the front end of the building lifecycle according to FM task- and system-specific needs. Further corresponding formalization of the format (content structure), as well as consistent terminologies and taxonomies are also critical for this purpose. This is accomplished in an Information Delivery Manual (IDM)-Model View Definition (MVD) approach in conjunction with the IFC and bsDD schema. Chapter 4 further translated the technical language of bsDD to the common language among the AEC/FM experts (LOD) and furtehr introduced the LOS concept to provide a solution for systematicly conveying semantic requiremnts for EOs. The results reveal the need for customization of the IFC-MV according to an organization's FM specific needs through an "implementation agreement", which further specifies object types, naming conventions, definitions, property and data types, and units of measurements.

Research Contribution

The cumulative contribution of this dissertation to the body of knowledge is the development of a robust protocol to identify owner-specific FM information requirements and formalize FM-specific ERs through BIM-based information handover at closeout of the construction phase of the building life-cycle. This work was carried out in conjunction with openBIM standards (for greater acceptance among experts and developers) to support seamless model data validation at project close out and the transition to FM systems and processes.

Chapter 2, provided input on FM general information requirements, current implemented IT tools, the information management challenges and potential areas for BIM implementation within the context of FIM. This manuscript provided an in-depth understanding of the four main aspects pertaining to FM, which provide input to the BIM-intensive framework; institutions' asset portfolio, FM workflows and task information needs, currently employed Information Technology (IT) tools, and information management challenges.

Chapter 3 provided AEC and FM stakeholders with a practical framework and a significant step towards establishment of a BIM-intensive workflow for FM handover purposes. This manuscript revealed the challenges of conveying geometric and non-geometric requirements for FM handover BIM in conjunction with the LOD and COBie schemas. This research also illuminated the need for more systematic and robust clarifications of the ERs to address inefficiencies inherent to BIM data interoperability. Specifically, issues pertaining to misinterpretations, heterogeneous modeling and naming conventions were addressed. This research phase also provided input to BIM libraries and modeling protocols according to FM handover ERs. The practical implications of this framework pertains to customized (in terms of both content and format) final deliverables to provide an integrated repository of all required information to support FM workflows. Repetition and streamlining of the BHIM development process will make this framework attractive to repeat customers, particularly those who build, own, and operate their facilities throughout the building lifecycle.

Chapter 4 expanded the LOD schema for specific utilization during FM handover and downstream FIM workflows. The LOD 100-500 level numeric schema is the common systematic definition among AEC experts to convey geometric requirements for objects in a use-case based approach for design and construction purposes. The manuscript was contextualized within the five commonly accepted openBIM standard/schemas (IFC, IDM, MDV, and buildignSMART Data Dictionary (bsDD)), to receive the greatest acceptance among industry experts and developers. This study further contributes to the body of knowledge, by bridging the gap between the technical language of bsDD and the non-technical language of LOD. The originality of the results of this chapter specifically pertain to systematic identification and specification of semantic requirements for FM handover BIM by introducing the Level of Semantics (LOS) concept. The framework established in this manuscript provides a common understanding of FM handover requirements and corresponding model content, and further facilitates automated model data validation and transfer to FM by formalization of the content format, terminologies and taxonomies. This study stands as one of the pioneering efforts to provide a technical solution for LOD definitions in conjunction with the concepts of the commonly accepted IFC schema.

Limitations and Future Research

The identified FM information requirements (both at handover and in O&M) in Chapter 2 are limited to a set of buildings within the asset portfolio of HEIs in the state of Colorado and are not to be overgeneralized for other institution types or other HEIs in different geographical districts. Moreover, the framework developed in the second phase (chapter 3) presents one proposed method of development and implementation of a BHIM for an existing building, a

Design-Build project case, in the same geographic area of the United States. Therefore, the framework developed should be interpreted as such.

It should be noted that various factors might impact the level of collaboration between participating firms and the interoperability issues to be addressed in the collaborative BIM development and exchange process. Therefore, the proposed framework may require customization for future projects given owner's specific FM needs.

The BIM-intensive framework developed in Chapter 4 supports FM decision-making processes within the scope of commissioning, maintenance, and operation workflows for HVAC distribution systems. The results have implications for other owner groups, however the study sampling was delimited to Institutions of Higher Education in the state of Colorado. Accordingly, the implementation agreement provided as part of the final solution in this chapter customizes the implementation for the organization's specific FM system needs and implemented interoperability data strategy.

Given consideration of the stated limitations and delimitations, the results of manuscript 3 can be generalizable for handover of FM information on HVAC distribution systems in a variety of building types. Future research could focus on extending the results of this study for other FM workflows, for instance formalization of ERs (traditionally provided in close out deliverables) for emergency management and evacuation planning purposes. In addition, a lean approach towards development of a process map for efficient, and seamless development of the BIM at early phases of the lifecycle and delivery of the BIM at close out seems vital. Studying the feasibility of development of a technical solution to provide a complete object-oriented MVD and the impacts of such an approach on project delivery and funding mechanisms could be of great value to both industry experts (AEC/FM industry) and developers. Several promising next steps include the identification of methods for seamlessly updating the BHIM during the maintenance phase, integrating the model with other technology tools, and the challenges and benefits of this practice in terms of the client's intended end-use for the BHIM.

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Glossary

Attribute is a unit of information within an entity, defined by a particular type or reference to a particular entity (buildingSMART, 2016).

BuildingSMART Data Dictionary (bsDD) is a reference library intended to support improved interoperability in the "building and construction industry" through mapping of terms (buildingSMART, 2015).

Classification is the act of distribution (or categorization) of things into classes or categories of the same type. For the purpose of this study, classification refers to either of three well-established systems within the United States construction industry; MasterFormat, UniFormat, or OmniClass.

Entity is a class of information defined by common attributes and constraints as defined in [ISO 10303-11] (buildingSMART, 2016).

Enumeration is the construct that "allows an attribute value to be one of multiple predefined values identified by name" (buildingSMART, 2016)

Exchange Objects, the "building blocks" of EMs, are encapsulated definitions of the information objects that are to be exchanged, defined in language that is in common use by domain experts (C. Eastman, Jeong, Sacks, & Kaner, 2009).

Exchange Requirements (ERs) are a set of information conveyed in non-technical terms, required to be exchanged to support a particular business requirement at a particular stage of a project lifecycle (See, Karlshoej et al. 2012).

Facilities Management (FM), according to the International Facility Management Association (IFMA), is "A profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology" (IFMA, 2013).

FM Information Handover refers to the transition of AEC data to FM during project close out.

Industry Foundation Classes (IFC) Specification, an openBIM standard developed and maintained by buildingSMART International, includes terms, concepts and data specification items that originate from use within disciplines, trades, and professions of the construction and facility management industry sector and is exchanged and shared among project participants. The IFC 4x2 release is accepted as ISO 16739 standard (buildingSMART, 2016).

Information Delivery Manual (ISO 29481) is the method used and propagated by buildingSMART to define Exchange Requirements for one or more scenario. It "captures (and progressively integrate) business process whilst at the same time providing detailed specifications of the information that a user fulfilling a particular role would need to provide at a particular point within a project" (buildingSMART, 2015).

Interoperability relates to "both the exchange and management of electronic information, where individuals and systems would be able to identify and access information seamlessly, as well as comprehend and integrate information across multiple systems" (National Institute of Standards and Technology, 2004).

Model View Definition (or IFC View Definition) define a subset of the IFC schema, required to support specific data exchange requirements (**ERs)** of one or multiple exchange scenarios within the AEC/FM industry. It represents the software requirement specification for the implementation of an IFC interface to satisfy the ERs (buildingSMART, 2016).

Model View is any subset of the IFC schema, "representing the data structure required to fulfil the data requirements within one or several exchange scenarios" (buildingSMART, 2016).

Object refers to "anything perceivable or conceivable that has a distinct existence, albeit not material" (buildingSMART, 2016).

Object Type represents common characteristics shared by multiple object-occurrences (buildingSMART, 2016).

Object Definition Concepts are "rules on using a subset of the schema structure identified as a concept template to enable a certain functionality within the context of a concept root contained in a model view" (buildingSMART, 2016).

openBIM is a "Universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows". It is an initiative of buildingSMART and several leading software vendors using the open buildingSMART Data Model (buildingSMART, 2015).

Owner Project Requirements (OPR) provides a framework through which the owners specify criteria for system function, performance and maintainability. It forms the basis from which all design, construction, acceptance and operational decisions are made (Cavka, Staub-French et al. 2017).

Product is defined as a physical or conceptual object that occurs in space. Inheritances of IfcProduct are categorized into eight types of IfcAnnotation, IfcElement, IfcGrid, IfcPort, IfcProxy, IfcSpatialElement, IfcStructuralActivity, and IfcStructuralItem (buildingSMART, 2016).

Property is a unit of information that is dynamically defined as a particular entity instance (buildingSMART, 2016).

Property Sets are sets of properties (usually defined by a name, value, unit triple), which can be assigned to objects, types, or performance (buildingSMART, 2016).

Quantity Sets contain multiple quantity occurrences with data types of count, length, area, volume, weight, time, or a combination of quantities. Each quantity is defined by its name, value, and optionally a description and a formula. Quantity sets are expressed by instances of IfcElementQuantity, where the *Name* attribute determines the common designator of the quantity set (buildingSMART, 2016).

Relationship is a unit of information describing an interaction between entities. Objectified relationships (instances of IfcRelationship) are the preferred way to handle relationships among objects. This allows to keep relationship specific properties directly at the relationship and opens the possibility to later handle relationship specific behavior. The IFC specification introduces six types of relationships; assignment of other objects, association to other objects, connectivity, declaration, decomposition, and definition (buildingSMART, 2016).

Schema provides “the definition of the structure to organize data for storage, exchange and sharing, using a formal language” (buildingSMART, 2016).

List of Abbreviations

2D	Two Dimensional
3D	Three Dimensional
API	Application Programming Interface
AEC	Architecture, Engineering, Construction
AEC/FM	Architecture, Engineering, Construction, and Facilities Management
BAS	Building Automation System
BIM	Building Information Model
bsDD	buildingSMART Data Dictionary
CAFM	Computer Aided Facility Management
CMMS	Computerized Maintenance Management System
COBie	Construction Operation Building Information Exchange
EO	Exchange Object
FIM	Facilities Information Management
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IT	Information Technology
MV	Model View
MVD	Model View Definition
O&M	Operation and Maintenance
OPR	Owner's Project Requirements
TCO	Total Cost of Ownership
WO	Work Order