# BIM TEACHING AND LEARNING HANDBOOK: IMPLEMENTATION FOR STUDENTS AND EDUCATORS

## CHAPTER 5H: INTEROPERABILITY AND EMERGING SMART TECHNOLOGIES

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## Abstract

The projects held in the Architecture, Engineering, and Construction (AEC) industry, require collaboration between different parties. Therefore, the stakeholders from different fields come together to fulfil the projects' requirements with high interaction. The AEC industry had digital transformation practices such as Building Information Modeling (BIM) in recent years. However, the adoption of BIM is not straightforward since the usage of BIM requires technical and managerial knowledge. One of this technical knowledge is interoperability, which is challenging and costly for the AEC industry.

Furthermore, lack of human resources was found as one of the BIM implementation hindrance factors in the literature, since skill building and developing training program for white-collars are very costly for companies. Therefore, this chapter aims to inform graduates and readers about interoperability concept, file formats, and developed solutions to overcome interoperability issues. Finally, the knowledge which is obtained from this chapter will facilitate and contributes problem solving capability of graduates and harmonization of new graduates to integrated project delivery approach.

**Keywords:** Building Information Modelling, Interoperability, Industry Foundation Classes, COBie, Facilities Management, GIS, Big Data

## Introduction

In the Architecture, Engineering, and Construction (AEC) industry, the construction projects are developed and conducted under high complexity and ambiguous conditions. Every activity, from which design and construction activities or operation and maintenance activities are performed, needs different expertise. In other words, small construction projects are even beyond capability of single company. In this context, many stakeholders participate in the construction project processes, which are initiation, planning, execution of construction activities, monitoring and controlling, closure, operation and maintenance and demolition. Data produced during the construction project processes cannot be managed with any unique software tool (Ozturk, 2020). Thus, every stakeholder uses different technologies to maximize profitability and efficiency of their activities.

Use of different Information and Communication Technologies (ICT) by different stakeholders induces collaboration issues when managing business and processes. Interoperability, which arises from incompatibility with the reference models adopted by the various software applications, is one of the collaboration issues. Basically, interoperability does not only consider information systems or technology, but also it covers business process, employees and culture, and management of external relationships (Grilo & Jardim-Goncalves, 2010). The ability of enhancement in collaboration is the most important feature of BIM (Oraee et al., 2019).

Building Information Modeling (BIM) is developed as a result of imitation of more stable and advanced sectors solutions such as aeronautics industry to solve fragmentation and heterogeneity issues in the AEC industry. BIM incorporates a technology facet through stakeholders interact with each other intensively to provide exchange of information by using standards such as IFC, COBie, XML, IDM (Grilo & Jardim-Goncalves, 2010; Ozturk, 2020; Steel et al., 2012). During this process, a great deal of information such as architectural, structural, Heating Ventilation and Air-Conditioning (HVAC), mechanical systems, electrical systems is combined in a common BIM model. Therefore, this does not only necessitates information readability from every stakeholder but also necessitates to perform further analysis such as artificial lighting analysis, daylight analysis and energy analysis too (Steel et al., 2012; Taha et al., 2020).

Interoperability allows to share information from the BIM model and helps to manipulate them within different software environment from different perspectives in a structured and common way. Information transfer from one software to another must be without information loss and it must be readable from another software via different protocols and standards such as IFC and COBie (Ozturk, 2020). Goulding et al. (2014) defined interoperability as “incompatibility between inter-products and software applications”. Therefore, fully interoperability between the BIM tools is a challenging task in the AEC industry.

To cope with interoperability issues, some efforts such as development of Industry Foundation Class have been made. However, the National Institute of Standards (NIST) reported that issues originated from interoperability such as information losses cause approximately $16 billion waste of money per year (Gallaher et al., 2004). To solve the issue, smooth interoperability in which clients, architects, engineers, financiers, builders, subcontractors, local authorities and consultants need to collaborate without information loss (Figure 1-b).

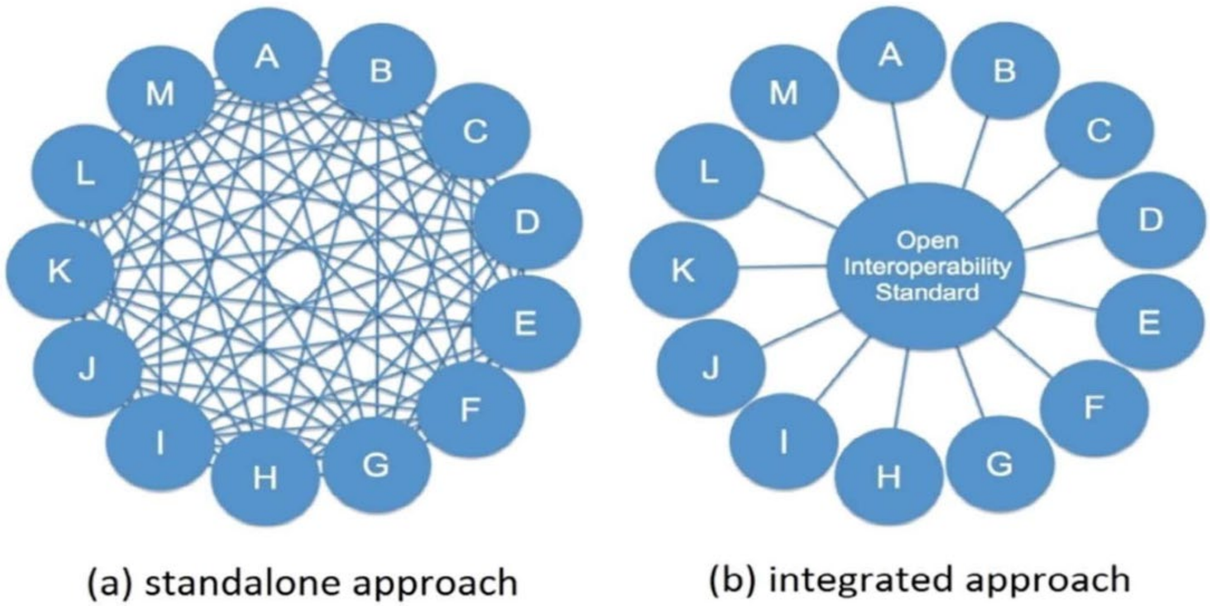


Figure 1. The Ideal Interoperability Environment for AEC Industry (Arayici et al., 2018)

Although interoperability research efforts in BIM are already too much, interoperability remains problematic and to lock on 3D coordination. Furthermore, increase in BIM usage in AEC industry brings more interoperability needs. Therefore, integrated approach, which "uses a translator tool to convert the proprietary format into open data readable by any software" needs to be followed (Arayici et al., 2018; Oraee et al., 2019). Even though there are also some standards such as IFC and IDM, there are some issues in practical implementation of these standards such as performance based design (Arayici et al., 2018). Moreover, interoperability between BIM and asset management software is not intended level (Farghaly et al., 2018). Therefore, introduction of the basic concepts, faced issues and research efforts on interoperability for the graduates and educators will help to conceive the importance of interoperability for the collaborative project management and building life cycle management with BIM. Additionally, the readers find the development of interoperability efforts and common data exchange formats which are used in AEC industry in this chapter. Also this chapter helps better preparation of graduates to transfer and use recently developed (Lidar, Blockchain etc.) concepts, which can be used as a solution of interoperability issues, into the AEC industry by laying a bridge between academia and industry.

## 1. Current state of interoperability at BIM from past to today

Interoperability issues for the integrated project delivery processes were broken out in 1970s in aerospace manufacturing technologies due to the fact that every stakeholder worked on different CAD systems (Liao et al., 2017; Szeleczki, 2019). The same issue is started to observe with increase in AEC by the usage of CAD systems such as Intergraph data transfer between design and bills of material. DXF and IGES were commonly used to solve interoperability problems for CAD systems in 1990s. However, demands for complex models and more expectations from AEC industry alleviated needs for innovation in terms of data interoperability standards and schemas.

STEP is the first effort to solve interoperability issue as an international standard (Sacks, R., Eastman, C., Lee, G., & Teicholz, 2018). STEP is known as ISO 10303, which is used to define product data and geometric data (El Asmi et al., 2015). After that, different schema languages were developed. Some of them is EXPRESS and XML. EXPRESS language was developed according to Part 11 of STEP (ISO 10303). EXPRESS helps to represent product data through schemas and constraints. It is not programming language (Sustainability of Digital Formats: Planning for Library of Congress Collections, 2016). CIS/2 and earlier version of IFC is prepared by using the EXPRESS data language (Kamel & Memari, 2019). Extensible Markup Language (XML), which "is a set of rules for designing text format specification" is used in BIM to define information. With the invention of XML standards, successful schemas were created for the AEC industry such as CityGML, landXML, gbXML, ifcXML and aecXML (El Asmi et al., 2015).

Interoperability should also provide automation during the process. If engineers or architects face with challenges during the process such as manual data entry, it is disappointing activity from their points of views. Interoperability issues are dealt with by organizations and researchers, which will be shown with examples at the next sections.

## 2. Data Exchange Formats

Arayici (2015) stated that there are three main ways to exchange data between software tool. They are namely; direct links, proprietary exchange format and the public product data model exchange formats. Besides, Eastman et al. (Sacks, R., Eastman, C., Lee, G., & Teicholz, 2018) added one more way to exchange data namely; model-server based data exchange.

- **Direct links**: Receiver program re-write information, which is extracted from sender program, through the API (Application Programming Interface).
- **Proprietary exchange format:** This type of data exchange depends on file based data exchange. The underlying reason behind proprietary exchange format is every commercial organization create own product. To support them, the specific file format is produced by organizations. Some of the important example of the proprietary exchange formats is RVT (Revit), DWG (AutoCAD), DGN (Bentley Systems) etc. (Sacks, R., Eastman, C., Lee, G., & Teicholz, 2018).
- **The public product data model exchange formats:** This type of format depends on open and publicly managed language and schemas. Different product data models refer different types of data structure in terms of geometry, relations, process, material, and performance. It means that if there is data definition difference on the same object between two product data models, interoperability issues will be observed during the process (Sacks, R., Eastman, C., Lee, G., & Teicholz, 2018).

- **Model-server based data exchange:** Data exchange between stakeholders is performed on database management system (DBMS). This type of data exchange can be also named as common data environment or BIM server (Sacks, R., Eastman, C., Lee, G., & Teicholz, 2018).

Within this section, product data model exchange standards or schemas and modeling languages will be intensively introduced.

## 2.1. Developments of Data Exchange Standards

The history of standard development for product data exchange started in 1950s. Ad-Hoc solutions (first generation exchange formats) existed between 1950s and 1980s. These solutions are called closed and proprietary solutions. In 1979s, heavy industry CAD users and CAD vendors made an agreement to come together for the development of open exchange mechanism (second generation exchange formats).

The first version of Initial Graphics Exchange Specification (IGES) was established. In the third-generation exchange formats, the developed formats were planned to serve multiple industrial and manufacturing industries. The development of the third generation of standard efforts began in 1980s and lasted mid of 1990s due to the development of EXPRESS language, which was based on the STEP standard, which was called as Standard for the Exchange of Product Model Data (STEP). However, the developed standard was valid for all industries. Accordingly, there was a need for specific standard which support to the AEC industry. Therefore, IFC effort, which is used today, has started (Laakso & Kiviniemi, 2012).

## 2.2. Modeling Languages

The existing data models or data schemas are different each other and they are used to share and exchange of manufacturing data in the model. Also, data models define data objects and their relationships. The development of data models depend on modeling language. Different modeling languages are available such as EXPRESS, XML (eXtensible Markup Language) etc.

The EXPRESS language, which is a data modeling language, was identified in the ISO 10303-Part 11. EXPRESS language contains a set of conditions which are used to establish a domain. According to the constraints, instances are evaluated to determine whether they are in the domain or not. However, EXPRESS contains more set of constraints than XML for validation. “The language elements are formed into a stream of text, typically broken into physical lines. A physical line is any number (including zero) of characters ended by a newline” (Sustainability of Digital Formats: Planning for Library of Congress Collections, 2017).XML is another language which is used to create data schemas. XML is very flexible text format. XML language was developed based on ISO 8879. XML helps to store information and the exchange of a wide variety of data via Web or elsewhere (W3C, 2016). XML was developed by World Wide Web Consortium. However, XML file contains excessive verbose which causes issues in exchange of large data sets (Murphy et al., 2017). Data schemas developed with EXPRESS and XML languages are given in the next section.

## 2.3. Current Standardization Efforts

The most known standards or schema types (IFC, gbXML, COBie, Omniclass, and XML-based schemas) were summarized under this section. However, the schema types or standardization efforts are not limited with IFC, gbXML, COBie, Omniclass, and XML-based schemas. For instance CIS/2 is used as steel integration standard.

**Industrial Foundation Classes (IFC):** Industrial Foundation Classes (IFC) provide an organized data model in terms of geometric and non-geometric information of building elements and their relationships (Zheng, 2014). IFC files don't only enable to attach information to building elements such as walls, columns and beams, but also it enables to attach specific attributes such as material type and vendor information (Kim et al. 2016). IFC is a widely accepted schema type and open standard (ISO 16739-1:2018) by the AEC industry practitioners. IFC was initially developed in 1996 by the International Association for Interoperability (IAI), which is rebranded today as BuildingSMART alliance. BuildingSMART alliance produces data format technology and provides standardization of the processes, workflows and procedures (Ozturk, 2020).

IFC has been continuously developed. Today, the latest version is IFC4.3, which is a potential standard and currently under the review process. As a result of review process, if there is no issue with the applicability of IFC 4.3, the IFC 4.3 will be an official standard (Buildingsmart, 2020). In the IFC schema, there are four layers; resources, core, interoperability and domain. These layers are used to describe information and relationships about building objects in the BIM model. In another words, metadata rather than 3D geometry information or surface information can be embedded by the help of IFC schema (Arayici et al., 2018; Sadeghi et al., 2019a; Steel et al., 2012; Zheng, 2014). Earlier version of IFC was developed by using EXPRESS language. However, later versions of IFC is based on both XML and EXPRESS data speciation language (ISO, 2018).

After progressing data exchange between two BIM applications, there is a need to support workflows and process because every stakeholder needs different data aspects from the BIM model (Sacks, R., Eastman, C., Lee, G., & Teicholz, 2018). Depending on IFC file format, Information Delivery Manual (IDM) and Model View Definition (MVD) are used to identify data exchange requirements. While IDM is used to elaborate information exchange and quality requirements and process map (Ozturk, 2020; Zheng, 2014), MVD is used to show additional constraints at the subsets of IFC schema, such as structural design or energy analysis (Kamel & Memari, 2019; 2016; Sacks, R., Eastman, C., Lee, G., & Teicholz, 2018). The specific focus of MVD is energy simulations (Kamel & Memari, 2019). In the implementation of IFC schema, there are some problems (Arayici et al., 2018; Ozturk, 2020; Steel et al., 2012; Zheng, 2014) such as:

- Lack of information creator in schema,
- Lack of what specific information included in data exchange procedure,
- Lack of what information granularity included in data exchange procedure,
- Missing information in the exchange process,
- Restriction for size of number of model object - Memory consumption issue,

- IfcOpenning,
- Modeling style,
- General data structure,
- Inconsistent naming conventions,
- Myriad of bespoken FM information requirements,
- Inadequate data categorization,
- Poor information synchronization,
- Access accurate data information and knowledge

**Green Building Extensible Mark-up Language (gbXML):** gbXML schema type is very useful to perform data exchange between BIM and Building Performance Simulations (BEPS) (Arayici et al., 2018). gbXML format includes information about building zones, surfaces, fenestrations and environment data. The most prominent feature of gbXML is to give location data, which is not given in other schema types. gbXML is created based on XML language with top-down data structure. Top-down structure is relatively complex schema with large file size. Coding of structure in software is also difficult. However, semantic changes can be easily observed within the schema (Kamel & Memari, 2019).

gbXML data schema is at infancy due to readability of information of complex systems (Arayici et al., 2018). gbXML has an issue in data transfer such as HVAC. It provides database that contains building elements' geometry and its explanations. However, this schema blocks remodel of the building in energy simulation models (Abanda & Byers, 2016). Rectangular geometry is only allowed in the representation of the building geometry in gbXML (Kamel & Memari, 2019).

**Construction Operation Building Information Exchange (COBie):** COBie is a formal scheme to organize data from design and construction to facility management purposes and it provides a standardized level of detail for materials, maintenance information, serial numbers, location, tag, and performance data (Gholami, 2015). COBie is specifically designed to solve facility or asset management interoperability issues and it is related to asset data rather than geometric information.

COBie helps to reduce cost items originated from data loss or data unavailability for the FM stage. COBie is based on Model View Definition (MVD). COBie aims to facilitate transferring of as-built models into Computer Aided Facility Management (CAFM) platforms (Farghaly et al., 2018). COBie presents numerous spreadsheets, in which great deal of information exist. COBie spreadsheets are very convenient to implement sorting, querying and basic formula applications. However, COBie does not include information related to geometric and architectural objects such as wall and door (Gholami, 2015).

Nonetheless, this leads to unintended data burden to interpret data and understand data dependency. Therefore, memory overload is commonly encountered as an issue. Access to specific data between workbooks with COBie is also very challenging. The users have also a problem with the query on spreadsheet data (Yalcinkaya & Singh, 2019). However, COBie implementation is not owner friendly to identify information requirements (Sadeghi et al., 2019b).

Up to date, COBie usage in the construction industry is not fully engaged. The reason for non-usage in the industry was attributed to the conflict between COBie requirements and industry requirements and the rigid structure of COBie for unexpected situations. COBie is not comprehensive to use it in the asset management (Abdirad & Dossick, 2019). COBie implementations are also “complex, fragmented and labor-intensive process” and COBie can present incomplete, unnecessary, low-quality data” (Sadeghi et al., 2019b).

COBie also presents a document in which information types are identified. To use COBie in the project, the owner side needs to choose necessary information types for FM use. However, the lack of knowledge of owner side in terms of determining necessary information types leads to data loss or unnecessary data collection for FM stage (Abdirad & Dossick, 2019). There are many stakeholders in a project. For the delivery of the necessary information to the owner side, role and responsibilities of the project, stakeholder needs to be identified before the project start (Alnaggar & Pitt, 2019b).

**Omniclass:** Omniclass has been developed by considering internationally accepted standards (International Organization for Standardization-ISO and the International Construction Information Society-ICIS) in the early-1990s. Especially, ISO 12006-2, which is used as a standard for classification framework, and ISO 12006-3, which is used for tagging and managing of objects and their attributes play an important role for the development of Omniclass (CSI, 2020).

Omniclass is used for organizing and retrieving information which is used in the construction industry by segregating objects’ information into discrete and coordinated tables. Additionally, filtering and sorting can be performed with Omniclass. Also, Omniclass can be used to communicate with other schemas such as COBie. Omniclass can be used throughout facility’s life cycle (Ceton, 2019).

**XML-Based Schemas:** XML-based schemas are alternative for IFC models. It helps to data exchange by simplifying data in AEC applications. The simplification is made by converting building data (sites, buildings, floors, spaces, and equipment and their attributes) in spatial building model (extruded shapes and spaces) (BIMXML, 2020). For instance, CityGML, was developed by the Open Geospatial Consortium (OGC), was created by using XML-based schemas. City GML is an open data model to store and exchange 3D city models. The CityGML schema types aims to create common definitions for entities, attributes, and relations of 3D city model (OGC, 2020). Furthermore, in the AEC industry, different XML schemas are available. OpenGIS, gbXML, ifcXML, aecXML, agcXML, BIM collaboration format, CityGML are examples of XML schema types (Sacks, R., Eastman, C., Lee, G., & Teicholz, 2018).

# 3. Interoperability Problems and Advanced Solutions in BIM Applications

This section aims to explain interoperability issues and advanced methods to solve these interoperability issues from the existing studies specific to building energy performance simulations, facility management and geographical information systems.

## 3.1. BIM Servers

A BIM-server is a collaboration platform that maintains a repository of the building data and allows native applications to import and export files from the database for viewing, checking, updating and modifying the data”. Also, BIM server create multidisciplinary platform for project teams (Singh et al., 2010). BIM servers are used to manage building life cycle data on a server or database specific to a single project (Graphisoft, 2017). The advantageous of the BIM-server are.

- Partial models/views,
- Ad hoc queries,
- Merge function,
- Concurrent usage,
- Team members' rights/security, speed/performance/integrity,
- Version control,
- Transaction processing,
- Audit (user's roles, decisions, and issue tracking),
- Data protection (mirroring/back-up) and
- Storage (Singh et al., 2010).

Different BIM servers which were published by research institutions and software vendors are available. Some of them are summarized below.

- IFC Model Server: IFC Model Server was established by SECOM. The developed service helps to manage and share BIM models on the internet. To use the IFC model server, first of all the user needs to upload the BIM model into server. After that, the users can access the model on the internet by using APIs which is provided the IFC Model sever. The stored BIM model can be also used with AR/VR, simulations etc. (Secom, 2020).
- Bimserver.org: Bimserver.org is an IFC STEP Express based open-source BIM server which has a multi-layer design with a generative, model-driven architecture. Bimserver.org was developed by TNO Netherlands and TU of Eindhoven. By using Bimserver.org, the users can make import, export, modify, tracking, filtering and query on an IFC model (Beetz, 2010; Zhang et al., 2014).
- Express Data Manager (EDM) Model Server (ifc): It is an IFC and ifcXML-based source server. T was developed by Jotne EPM Technology. EDM model server allows to read and write IFC model (Zhang et al., 2014). EDMmodelServer(ifc) is also able to check-out and check-in partial data (IT, 2020).

- Bentley I-Model: Bentley-I Model is used to exchange lifecycle information of assets. Bentley I-Model is an open source. It enables to retain knowledge about their source. By using Bentley, I-Model, the users can query and filter on a model. Additionally, component information, business property, geometry and relationship can be observed on Bentley I-Model (Bentley, 2020).

### 3.2. BIM cloud

Data which is available in BIM models are still stored and transferred in the form of either files such as rvt. or neutral format such IFC. Nowadays, cloud computing technologies have developed rapidly. According to technological breakthroughs in cloud computing, BIM modeling has recently started to move cloud servers. The transformation from single file or neutral format to BIM cloud helps to performance issues, high costs and interoperability between stakeholders (Zhang et al., 2014). Cloud BIM has a positive effect on data availability and accessibility, scalable storage, effective use of data, and environmental effects (due to reduce in energy consumption) (Alreshidi et al., 2017).

BIM cloud helps to multinational or large companies to manage multiple and complex project on a cloud technology by dividing projects on BIM cloud server. Also, the number of users on BIM cloud is more than BIM servers (Graphisoft, 2017). Therefore, cloud technology is used to provide multi-user network and central repository. Three types of cloud technology model can be used in the AEC industry. They are namely; “Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS)”.

The fundamental difference between these cloud technology model is that renting of software on the cloud platform (SaaS), needs for interaction with existing software (PaaS) and using only servers (IaaS) (Zheng, 2014). In other words, While IaaS allows usage of servers, storage, network security, and data center, PaaS adds more services (operating system and database management, business analytics) to IaaS service. In SaaS, applications which is used by stakeholders are added to PaaS services (Microsoft Azure, 2020). Open BIM idea is developed to solve the below issues, which are reported by (Ding & Xu, 2014);

- Numerous stakeholders participate project life cycle,
- The amount of information,
- Large investment needs for BIM,
- Life cycle perspective, and
- Security issues.

Different BIM cloud solutions which were published by research software vendors are available. Some of them are summarized below;

- **BIMcloud:** BIMcloud was developed by Graphisoft. The company aimed to enable “real-time, secure teamwork between architects, regardless of the size of the design project, the location of the offices, or the speed of the Internet connection” (Graphisoft, 2020).

- **BIMPLUS:** is a cloud-based building life cycle management platform. The solution enables different teams on a model such as architects, engineers, BIM coordinator, Building contractor, MEP engineer, facility manager etc. By using BIMPLUS, model management, document management, filtering, collaboration, clash detection can be performed (BIMPLUS, 2020).
- **Autodesk BIM 360**: BIM 360 is a unified platform on which project stakeholders can make arrangements on model or make a decision by using available data from BIM servers. By using Autodesk BIM 360, the users can benefit from services related RFIs & Submittals management, document management, communication between stakeholders, safety management, quality management, constructability, design collaboration and data & analytics in a real-timely manner.

However, there are some worries about usage of cloud BIM. They are security and privacy, internet connection dependency, lack of legal considerations (related to country laws where datacenters are found), anonymous control (data management transparency), physical location of data storage concerns, and initial set-up cost (Alreshidi et al., 2017).

### 3.3. Energy Analysis Simulations

Construction industry is responsible for 23% of energy consumption and 40% of $CO_2$ emissions globally. Therefore, keeping energy consumption under control is important for the AEC industry (Choi et al., 2016). To enable control and optimize energy consumption in the building environment, Building Energy Performance Simulations (BEPS) are intensively used especially at the design stage. While BEPS software helps to reduce energy consumption, it also helps to increase occupancy comfort at the same time (Garwood et al., 2018). However, manual creation of building energy model, data replication, data leaks, and redundant data issues can be faced in the conventional building energy analysis.

BIM can provide 70% of the needs for BEPS when performing the building energy analysis via BEPS (Choi et al., 2016). In other words, today's 3D-CAD/BIMs provide the users with an opportunity to explore different energy saving alternatives in the early design while avoiding the time-consuming process of re-entering all the building geometry, enclosure and HVAC information necessary for a complete energy analysis (Stumpf et al., 2009). Besides, BIM facilitates understanding of users in terms of building environment and components.

Data transfer from BIM to BEPS can be realized with data schema types such as COBie, IFC or gbXML to enable interoperability among them. Geometric and property data are transferred with the usage of these schema types. However, gbXML is the most common schema type when transferring building data to energy analysis simulations (Gerrish et al., 2017). The data requirements and the place interoperability schema types were simply summarized in Figure 2 by adopted from (Choi et al., 2016).

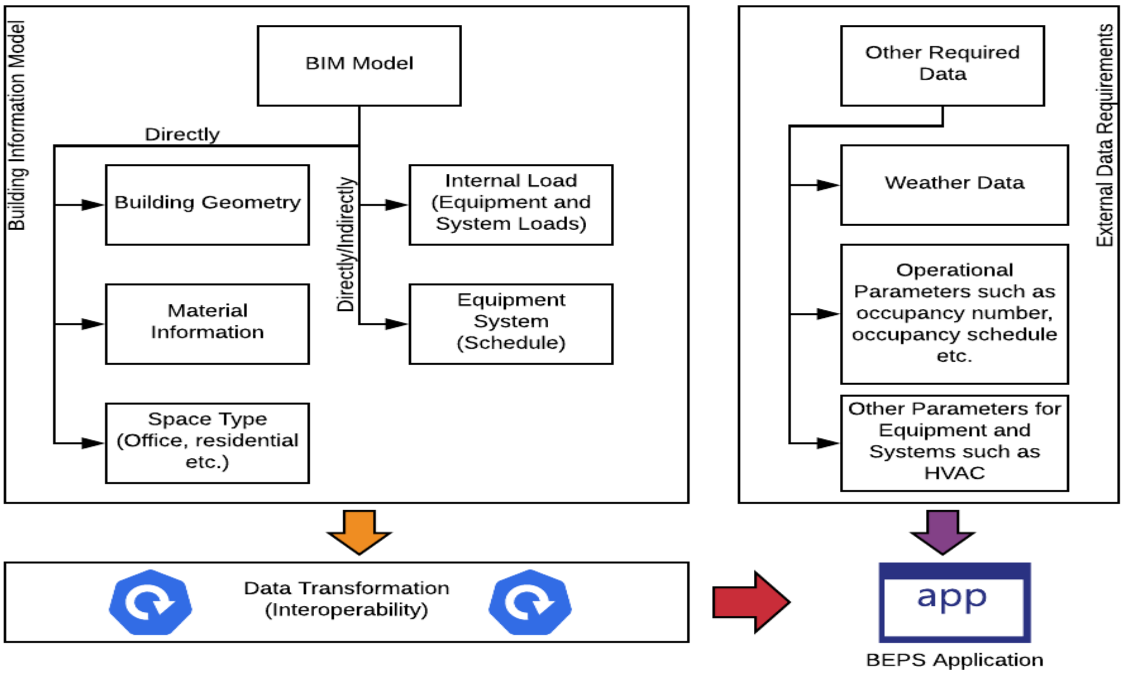


Figure 2. Interoperability in the Integration of BIM and BEPS (adopted from (Choi et al., 2016))

The AEC industry has a wide range BEPS software such as BLAST, BSim, DOE-2, DeST, Ecotect, eQuest, EnergyPlus etc. (Crawley et al., 2008; K. Kim et al., 2013). These BEPS tools have pros and cons. Therefore, the user needs to be careful to choose BEPS software. In other words, every data transfer process could be different for different BEPS software. For example, Choi et al. (Choi et al., 2016) stated that Geometry Simplification Tool (GST) which is used data transformation from BIM to Input Data Format (IDF, used in EnergyPlus) has errors when exporting IFC file from BIM software except from ArchiCAD.

When integration of BIM data into BEPS is performed, some barriers are also observed in the practical implementations. Choi et al. (2016) summarized some of them; (i) some building elements in BIM has no correspondence in BEPS data structure such as column and beam. This brings oversimplification issue for BIM elements to make them, (ii) unavailability of data in BIM models, which requires for BEPS analysis such as heat transfer coefficient and (iii) data exchange issues-interoperability.

Low interoperability also induces low implementation of building energy analysis due to the fact that it necessitates rework and correction of transferred data after data exchange is performed. High deviations between predicted energy consumption and the actual energy consumption can be observed since energy simulations highly depend on assumptions such as occupancy schedule (Ham & Golparvar-Fard, 2015). To overcome these issues, external databases (H. Kim et al., 2016) and data extraction with Dynamo (Gerrish et al., 2017) can be used. Dynamo helps to extract geometric and material information from BIM and the extracted information is converted into

JavaScript Object Notation (JSON) lightweight data-interchange format (Gerrish et al., 2017). Briefly, Dynamo is an open-source visual programming application that interacts with Revit to extend its parametric capabilities to the Revit projects (Rahmani Asl et al., 2015).

### 3.4. Facility Management

Facility management (FM) corresponds to the longest duration in the building lifecycle(Koch et al., 2014). Also, the studies acknowledged that OPEX (operational expenditures-85% of building lifecycle cost) is more costly than CAPEX (capital expeditures-15%) (Edirisinghe et al., 2017; Koch et al., 2014). Additionally, financial losses due interoperability was found $15.8 billion in the USA, annually. Furthermore, 67% of financial loses is related to interoperability issues at the FM stage (Terreno et al., 2019).

FM consists of integration of people, place, process and technology (Gao & Pishdad-Bozorgi, 2019). Under the FM process, cleaning services, support services, property services, energy, catering services and security services are performed (Potkany et al., 2015). Therefore, FM requires data driven decisions which are performed by facility managers who collect, analyze, store, exchange and manage facility data (Alnaggar & Pitt, 2019a). To provide efficient facility management, FM systems such as Building Automation Systems (BAS), Building Management System (BMS), Building Energy Management Systems (BEMS), Computerized Maintenance Management Systems (CMMS), Building Information Models (BIM) or simulation tools are used (Kučera et al., 2013; Kučera & Pitner, 2018; Lee et al., 2018). These management systems can be integrated with BIM because BIM does not only provides geometric data, but also it provides databases to show and store processed data such as alarms to the users (Shalabi & Turkan, 2016).

The practitioners believed that integration of BIM and FM systems helps to create a single management source for FM decisions since BIM can host as-built information, records of maintenance, details of warranty and service, assessment and monitoring, space making and energy monitoring, emergency procedures, retrofit planning, reduced implementation costs, the provision of feedback to eliminate design-related performance issues and visualization data. Terreno et al. (2019) asserted five different methods that can be followed for data transfer between BIM and FM software (Table 1).

Table 1. Methods and Approaches to link BIM with FM software

| Approach | Methods/Approaches for Linking Information | |
|---|---|---|
| Manual; Spreadsheets | Extract, Transform and Load (ETL); Data Warehouse (DW) | Hyperlinking |
| COBie Spreadsheets | BIM-based neutral file format; Design Pattern and Application Program Interface (API); ETL; DW | Hyperlinking, exchanging, and synchronizing data |
| IFC format | BIM-based neutral file format | Exchanging and synchronizing data |
| Application Program Interface (API) coupling | Design and API coupling | Portal solution |
| Proprietary Middleware | BIM-based neutral file format; Web Service; ETL and DW; IDM and MVD | Portal solution using middleware such as EcoDomus, FM: Interact and Onuma Systems |

However, Dixit et al. (2019) stated that interoperability issues between BIM-FM technologies hinder BIM usage in FM. During the data exchange between BIM and FM systems, COBie and IFC are intensively used in the industry (Alnaggar & Pitt, 2019b). However, COBie has not reached sufficient maturity. In other words, the organizations need guidance how COBie will be implemented in data transfer between BIM and FM software. When users follow COBie as a data exchange format, unnecessary data such as architectural and structural information can be seen in spreadsheets (Terreno et al., 2019). Data burden in COBie spreadsheets induces filtering issues for the building operation and maintenance requirements. Alnaggar and Pitt (Alnaggar & Pitt, 2019a) found that COBie may not be the future of the industry due to rigid data structure, ambiguity and data exchange process.

There is also a lack of clarity about roles and responsibilities, lack of mapping process between COBie and CAFM systems, and lack of precise COBie requirements. In addition to COBie, IFC presents partially interoperability solution for data exchange between BIM and FM software, since it causes data complication and data losses (Pärn et al., 2017; Terreno et al., 2019). Implementing changes on the schema with MVD is not smooth process due to the lack of user friendly interface. Therefore, data transfer between BIM and FM systems are not error-free process due to the interoperability problems (Dixit et al., 2019; Heaton et al., 2019; Sadeghi et al., 2019a; Shalabi & Turkan, 2016). The interoperability issues are not only seen in BIM implementations. It is also seen between CMMS and other FM systems (Shalabi & Turkan, 2016). Manual and ad-hoc solutions are produced and followed for the interoperability issues by the AEC industry stakeholders (Heaton et al., 2019).

However, facility manager needs to give a quick response to changes and issues in facility environment. In the literature, interoperability solutions for effective FM were developed. To solve interoperability issues Model View Definition (MVD) to find necessary information from models (William East et al., 2012), Naviswork DataTools (Lucas & Thabet, 2018), IfcOpenShell which is a Python module to manipulate IFC file (Heaton et al., 2019), application programing interface (API) plug-in in which as-built BIM model is updated and maintained (Pärn & Edwards, 2017), Cloud-BIM (Ding & Xu, 2014) etc. can be used.

### 3.5. Geographical Information Systems (GIS)

Combination of BIM and Geographical Information Systems (GIS) is commonly used due to the fact that GIS can support resource arrangements, selection of appropriate crane location and safety analysis. GIS helps to manage georefenced data, used in 3D analysis, spatial analysis, queries such as distance calculation and optimal location, for which BIM has lack of capability (D'Amico et al., 2019; Sani & Rahman, 2018). While GIS is used to manage building geographical data, BIM focuses more on building elements and life cycle data of the projects (Sani & Rahman, 2018).

GIS systems has also great flexibility to interoperate CMMS, CAFM, Integrated Workplace Management System (IWMS) and EDMS. Together, the integrated GIS-BIM platform offers the total scalability in which from geospatial data at the building environment to building system information can be elaborated. Therefore, desired business needs such as energy management, facility management, space management etc. can be provided with the integration of BIM and GIS (W. Wu et al., 2014).

Amirebrahimi (2015) defined three level for data integration process namely; data, application and process levels. In the first level, data level, the requirements of the application are met by the manipulation of the data models and structure. In the second level, application level, adoption of new applications is performed via a successful and efficient data interoperability. In the last level, process level, a workflow is provided between BIM and GIS.

Integration of BIM into GIS or vice versa requires a comprehensive data exchange. However, while BIM is generally used with IFC schema, GIS is used with City Geography Markup Language (CityGML) or shapefile (D'Amico et al., 2019). In the literature, the researchers developed lots of solution to solve integration issue between GIS-BIM. To solve, unidirectional approaches (GIS to BIM or BIM to GIS), new tools, or CityGML and IFC were commonly observed studies in the literature. However, information loss due to schema types can be also seen in the integration of BIM and GIS.

BIM (local placement system) and GIS (geographic coordinate system) use different coordinate systems. Two systems have different view in definition of Level of Detail. CityGML has less classes compared to IFC classes. For instance, stair is not defined in CityGML (Sani & Rahman, 2018). There is a limitation in representing of utility components in IFC and CityGML. Some information such as inspection history is also not included in both schema (M. Wang et al., 2019). Interoperability issues can be solved with the implementation of cloud systems (W. Wu et al., 2014) and Extract, Transform and Load (ETL) method (Kang & Hong, 2015) .

### 3.6. Light Detection and Ranging (LIDAR)

The construction industry is less innovative when comparing other industries. However, the state has started to change with increase in the application of remote sensing technologies such as Lidar technologies, photogrammetry etc. These technologies facilitate as-built model creation. Therefore, some issues such as outdated data, manual data entry etc. can be eliminated. Lidar is one of technology which takes digital snapshot from building environment. By the help of Lidar, point cloud (3D geometric information) is gathered by measuring distance between sensor and measured surfaces (Puri & Turkan, 2020; J. Wang et al., 2015). Lidar can perform the same work with laser scanning technologies. Furthermore, they can be used as synonym in some resources. However, there is a little difference between them. According to (J. Wang et al., 2015), laser scanning has limited capability to perform scanning activity in wide variety construction conditions. Lidar technology can also support real-time data collection from site.

Laser scanning is an important technology to “gather in-situ geometric date” from building. This technology has wide range of application areas such as damage assessment, construction monitoring, retrofitting, energy analysis, creating of blueprinting for existing building (Cabaleiro et al., 2014; Sanhudo et al., 2020). Lidar scanning provides point clouds, which are datasets representing surface of objects with Cartesian coordinate system (X, Y and Z) points. By the help of datasets, topography, building elements, and equipment/systems can be modeled. Usage of Lidar technology helps to produce millions of data points with a high precision (Garwood et al., 2018). The superiority of this technology is to have automation, shorter duration and accuracy. Transfer of the gather data from laser scanning technology into BIM is an important method to solve interoperability issues. Thus, scan to BIM commercial services are developed with the combination of machine learning technologies (Sanhudo et al., 2020).

Integration of BIM and Lidar technologies is used in variety areas. For instance, construction monitoring is one of the challenging process for construction projects. The progress tracking in construction projects necessitates comparison of planned and actual project status. In this process, Lidar technology can be used to detect actual progress status of on-going construction project. The comparison of the output from laser scanning with 4D design helps to evaluation of project performance rapidly (Puri & Turkan, 2020). Additionally, real-time quality controlling is very important to detect defects earlier.

Current approaches are time consuming and it is less effective than automated process due to openness to human errors (J. Wang et al., 2015). Therefore, the integration of BIM and Lidar technology enables real-time construction quality control (J. Wang et al., 2015). Furthermore, building performance analysis for existing buildings has attracted more attention with increase in energy consumption rate of building industry within the global energy consumption. Creation of building model manually is labor-intensive. Therefore, laser scanning and Lidar technologies can be used as a solution. Lidar technologies help to create as-is BIM. The developed model can be also saved as gbXML format. So that, interoperability issues can be eliminated (C. Wang & Cho, 2015).

### 3.7. Big Data Analytics

Even though BIM involves data related to building life cycle, these data are rarely used to increase productivity in following process. Therefore, application of Business Intelligence and Analytics (BI&A) such as Big Data Analytics has gained importance in AEC industry. BI&A is an umbrella term which encompasses techniques, technologies, systems, practices, methodologies and applications to retrieve necessary business information from raw data sources (Ahmed et al., 2018). The need arises for data analysis techniques with diffusing of BIM, databases, Internet of Things (IoT) into AEC industry. Additionally, data sources such as IoT devices necessitates analysis of huge data stack as dynamically. Therefore, Big Data Analytics have promising features for data analysis. Farghaly et al. (2017) stated that Big Data Analytics have a positive impact on interoperability issues.

Big Data applications has grown tremendously while the data collection is beyond the ability of commonly used software tools to capture, manage, and process within a tolerable elapsed time" (X. Wu et al., 2013). Also Big Data is defined with V's concepts (Assunção et al., 2015). These concepts are;

- Variety: It refers multi data types.
- Velocity: It refers data production and processing speed.
- Volume: It refers data size.
- Veracity: It refers data reliability of processed data.
- Value: It refers worth of derived from data analysis.

According to Kambatla et al.'s study (2014), there are four types data structure. These are;

- Structured data: such as financial, electronic medical records, government statistics
- Semi-structured data: such as text, tweets, emails
- Unstructured data: such as audio and video
- Real-time data: such as network traces, generic monitoring logs.

Big Data Analytics are used in data monitoring, collection, analysis, and prediction. As a result of analysis, the users can create reports, graphs, and charts to retrieve information easily (Al-Ali et al., 2017).

Nowadays, the size of BIM models is increasing depending on project size. When increasing the size of project, stand-alone BIM software remains incapable to manage building information, multiple project information, unfriendly information-sharing environment, and data analysis on model information. On the contrary, cloud BIM comes into prominence with huge data storage, powerful computing capabilities and allowing multiple working environment for stakeholder.

Cloud service providers give also a service for big data application on cloud BIM. With the implementation of Cloud-BIM, queries about the facility and operational data (such as energy management, emergency management etc.) in the facility can be more effectively performed (Arslan et al., 2017; Chen et al., 2016; Kang & Choi, 2018; Stavropoulos et al., 2015). However, Farghaly et al. (2017) stated that "a suitable schema that allows fast and efficient queries, and deals with graphical information and geographical reference location is required", when data transfer between stand-alone BIM and Big Data Analytics is performed.

IFC has a lack of capability in dynamic data while the implementation of Big Data Analytics is not limited to the FM stage. Big Data Analytics can be also used at the construction stage. For instance, lots of image and videos are taken from the construction site. For example, 325,000 images by photographer or 95,400 images by webcams can be collected from construction sites for a typical project. However, it is not possible to use them effectively without using analysis tool. These data sources can be effectively used in comparison of as-planned and as-build. Therefore, big visual data needs to be analyzed with Big Data Analytics (Han & Golparvar-Fard, 2017).

### 3.8. Blockchain

BIM model is created by entering information from different expertise area. However, this brings new issues in the AEC industry, because of ownership of the model. For instance, different design groups share companies' knowledge on a BIM model. However, there is a legal gap to protect companies' right. Therefore, some disputes can be observed depending on ownership of the model. Also, need for review records in BIM model is another issue (Hargaden et al., 2019).

Depending on technological developments and the above issues, Blockchain technology has been recently implemented in construction industry. Blockchain technology can be thought as a distributed database which is used for data replication, sharing and synchronizing. Also, Blockchain technology helps to govern data from different geographical locations. "Equality, direct dealing, openness, consensus and mutual trust" play an important role under the Blockchain logic (Perera et al., 2020). More technically, Blockchain consist of blocks in which every hash contains cryptographic hash and every hash contains operation sets (Alharby & Moorsel, 2017). This architecture helps to store transactions of stakeholders reliably and synchronously. If any stakeholder wants to make a transaction on project network, other stakeholders who are affected from this transaction need to approve transaction (Ahmadisheykhsarmast & Sonmez, 2018). Furthermore, the records cannot be changed to record historical records (Ahmadisheykhsarmast & Sonmez, 2018).

BIM provides important opportunities for digital management of the building's product and process information. Blockchain technology allows more data storage than BIM. With the integration of BIM and Blockchain technology, the data exchange and communication between the stakeholders depending on time and relationship between 3D model and paper-based can be solved (Hargaden et al., 2019).

Depending on use of Blockchain technology in AEC industry, smart contract has been started to implement in building life cycle stages. Smart contracts help to monitor and control contract protocols with the help of Blockchain codes (Ahmadisheykhsarmast & Sonmez, 2018; Alharby & Moorsel, 2017). In other words, contract clauses are managed via codes. If the contract clauses are fulfilled by any stakeholder, predefined actions are performed via codes. For instance, if subcontractor performs his work package on construction site, crypto currency is transferred to subcontractor. Every contract is stored in a file which has a 20-byte storage capacity. Also, if transactions cause a change in other contract, the change can be reflected on the affected document automatically (Alharby & Moorsel, 2017).

## 4. Conclusion

BIM or CAD systems are an ICT solution to eliminate inefficiency related to conventional work process from AEC industry (Wong et al., 2013). BIM helps to handle building design holistically. Therefore, BIM helps to improve collaboration and communication issues among stakeholders. It is believed that project quality, time and cost control and errors can be more strictly performed with the implementation of BIM in construction projects (Ratajczak et al., 2015).

Effective stakeholder management and smooth information sharing between stakeholders are the key project success factor (Jergeas et al., 1986). Therefore, application of BIM or CAD systems in construction projects is inevitable. The nature of construction projects requires participation of numerous stakeholders to construction projects. Also, it is not limited with design and construction stage but also, it involves demolition stage.

In the building life cycle, stakeholders use different ICT technologies to perform their activities. However, output of one stakeholder can be input of another stakeholder or outputs can be used in another software. This requires a common language which can be readable and writable by stakeholders. Therefore, this chapter aims to explain interoperability which provides data exchange between stakeholders. Additionally, standardization efforts, faced challenges in interoperability and a few examples from literature were summarized in the chapter. This chapter will help to improve in skills of graduates in terms of technical side of BIM. Thus, the knowledge from this chapter will harmonize graduates for new project delivery approaches (integrated project delivery). Besides this, adaption or transfer of recent developments and solutions which has been developed in universities into industry can be facilitated.

The time history of interoperability effort showed that interoperability cannot be perfectly solved by AEC industry practitioners. The underlying issue can be attributed to demand and complexity of projects, since these constraints requires new solutions specific to AEC industry. Therefore, new software solutions have been produced and will produce with different requirements. Also, software vendors present wide range products. To actually penetrate the use of the same vendors' products, the vendors hampers the users with interoperability issues.

Nonetheless, the literature review specific to BEPS, facility management, GIS, Lidar technology, Big Data Analytics and Blockchain technology don't only show the development of interoperability solutions, but also it shows that interoperability or data loss is not unsolvable issue. New technologies such as BIM servers offers promising features to solve interoperability issues. The introduction of these concepts to AEC graduates will facilitate to find new career opportunities in the AEC industry. Also, the adoption of new technologies with the transfer of skilled graduates into industry will help to eliminate and be a remedy low productivity, poor functionality, rework and wastes that are observed in construction projects.

## Questions

1. What is interoperability and its importance for AEC industry?
2. What is the main difference between EXPRESS and XML languages?
3. Please explain why the AEC industry practitioners needed the development of IDM and MVD.
4. Please explain data formats which are used in energy analysis. Why is BIM used with building energy performance simulation programs? And what should be considered when using BIM and BEPS together?
5. What is the main difference between BIM servers and BIM cloud? Please explain under which conditions BIM server needs to be chosen.
6. Please discuss the benefits of the collocation of BIM and Lidar technologies.
7. Please explain relationship between data formats and Big Data Analytics. What is the benefits of analysis of existing data that is stored in BIM?

## References


Abanda, F. H., & Byers, L. (2016). An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling). *Energy*, *97*, 517–527. https://doi.org/10.1016/j.energy.2015.12.135

Abdirad, H., & Dossick, C. S. (2019). Normative and descriptive models for COBie implementation: discrepancies and limitations. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-10-2018-0443

Ahmadisheykhsarmast, S., & Sonmez, R. (2018). Smart Contracts in Construction Industry. *5th International Project and Construction Management Conference (IPCMC2018)*, *December*, 767–774.

Ahmed, V., Aziz, Z., Tezel, A., & Riaz, Z. (2018). Challenges and drivers for data mining in the AEC sector. *Engineering, Construction and Architectural Management*, *25*(11), 1436–1453. https://doi.org/10.1108/ECAM-01-2018-0035

Al-Ali, A. R., Zualkernan, I. A., Rashid, M., Gupta, R., & Alikarar, M. (2017). A smart home energy management system using IoT and big data analytics approach. *IEEE Transactions on Consumer Electronics*, *63*(4), 426–434. https://doi.org/10.1109/TCE.2017.015014

Alharby, M., & Moorsel, A. van. (2017). *Blockchain Based Smart Contracts : A Systematic Mapping Study*. 125–140. https://doi.org/10.5121/csit.2017.71011

Alnaggar, A., & Pitt, M. (2019a). *Lifecycle Exchange for Asset Data ( LEAD ) dataflow between building stakeholders using BIM open standards*. *17*(5), 385–411. https://doi.org/10.1108/JFM-06-2019-0030

Alnaggar, A., & Pitt, M. (2019b). Towards a conceptual framework to manage BIM/COBie asset data using a standard project management methodology. *Journal of Facilities Management*, *17*(2), 175–187. https://doi.org/10.1108/JFM-03-2018-0015

Alreshidi, E., Mourshed, M., & Rezgui, Y. (2017). Factors for effective BIM governance. *Journal of Building Engineering*, *10*, 89–101.

Amirebrahimi, S., Rajabifard, A., Mendis, P., & Ngo, T. (2015). A data model for integrating GIS and BIM for assessment and 3D visualisation of flood damage to building. *CEUR Workshop Proceedings*, *1323*(January), 78–89.

Arayici, Y., Fernando, T., Munoz, V., & Bassanino, M. (2018). Interoperability specification development for integrated BIM use in performance based design. *Automation in Construction*, *85*(January 2016), 167–181. https://doi.org/10.1016/j.autcon.2017.10.018

Arslan, M., Riaz, Z., & Munawar, S. (2017). Building Information Modeling (BIM) Enabled Facilities management using hadoop architecture. *PICMET 2017 - Portland International Conference on Management of Engineering and Technology: Technology Management for the Interconnected World, Proceedings*, *2017-January*, 1–6. https://doi.org/10.23919/PICMET.2017.8125462

Assunção, M. D., Calheiros, R. N., Bianchi, S., Netto, M. A. S., & Buyya, R. (2015). Big Data computing and clouds: Trends and future directions. *Journal of Parallel and Distributed Computing*, *79–80*, 3–15. https://doi.org/10.1016/j.jpdc.2014.08.003

Beetz, J. (2010). *BIMSERVER . ORG – AN OPEN SOURCE IFC MODEL SERVER*. *January*.

Bentley. (2020). *What are iModels ? Exchange Information for AEC Projects*. https://www.bentley.com/en/i-models/what-is-i-model/about-i-models

BIMPLUS. (2020). *Features*. https://www.bimplus.net/en/features/

BIMXML. (2020). *Building Information Model Extended Markup Language (BIMXML)*. http://bimxml.org/

Buildingsmart. (2020). *IFC Schema Specifications - buildingSMART Technical*. https://technical.buildingsmart.org/standards/ifc/ifc-schema-specifications/

Cabaleiro, M., Riveiro, B., Arias, P., Caamaño, J. C., & Vilán, J. A. (2014). Automatic 3D modelling of metal frame connections from LiDAR data for structural engineering purposes. *ISPRS*

*Journal of Photogrammetry and Remote Sensing*, *96*, 47–56. https://doi.org/10.1016/j.isprsjprs.2014.07.006

Ceton, G. (2019). *OmniClass ® A Strategy for Classifying the Built Environment Introduction and User's Guide*.

Chen, H., Chang, K., & Lin, T. (2016). Automation in Construction A cloud-based system framework for performing online viewing , storage , and analysis on big data of massive BIMs. *Automation in Construction*, *71*, 34–48. https://doi.org/10.1016/j.autcon.2016.03.002

Choi, J., Shin, J., Kim, M., & Kim, I. (2016). Development of openBIM-based energy analysis software to improve the interoperability of energy performance assessment. *Automation in Construction*, *72*, 52–64. https://doi.org/10.1016/j.autcon.2016.07.004

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, *43*(4), 661–673. https://doi.org/10.1016/j.buildenv.2006.10.027

CSI. (2020). *OmniClass-Background*. https://www.csiresources.org/standards/omniclass/standards-omniclass-background

D'Amico, F., Calvi, A., Schiattarella, E., Prete, M., & Veraldi, V. (2019). BIM And GIS Data Integration: A Novel Approach Of Technical/Environmental Decision-Making Process In Transport Infrastructure Design. *AIIT 2nd International Congress on Transport Infrastructure and Systems in a Changing World (TIS ROMA 2019)*, 803–810.

Ding, L., & Xu, X. (2014). Application of cloud storage on BIM life-cycle management. *International Journal of Advanced Robotic Systems*, *11*(1). https://doi.org/10.5772/58443

Dixit, M. K., Venkatraj, V., & Ostadalimakhmalbaf, M. (2019). *Integration of facility management and building information modeling ( BIM ) A review of key issues and challenges*. *37*(7), 455–483. https://doi.org/10.1108/F-03-2018-0043

Edirisinghe, R., London, K. A., Kalutara, P., & Aranda-Mena, G. (2017). Building information modelling for facility management: Are we there yet? *Engineering, Construction and Architectural Management*, *24*(6), 1119–1154. https://doi.org/10.1108/ECAM-06-2016-0139

El Asmi, E., Robert, S., Haas, B., & Zreik, K. (2015). A standardized approach to BIM and energy simulation connection. *International Journal of Design Sciences and Technology*, *21*(1), 59–82.

Farghaly, K., Abanda, H., Vidalakis, C., & Wood, G. (2017). *BIM Big Data System Architecture for Asset Management: A Conceptual Framework*. *July*, 289–296. https://doi.org/10.24928/jc3-2017/0163

Farghaly, K., Wood, G., Fonbeyin, ;, Abanda, H., & Christos Vidalakis, ; (2018). Taxonomy for BIM and Asset Management Semantic Interoperability PhD on the treatment of ecology in the planning system View project PhD Research-BIM and AM interoperability View project Taxonomy for BIM and Asset Management Semantic Interoperability. *Article in Journal of Management in Engineering*. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000610

Gallaher, M. P., O'connor, A. C., Dettbarn, J. L., & Gilday, L. T. (2004). *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*. https://doi.org/10.6028/NIST.GCR.04-867

Gao, X., & Pishdad-Bozorgi, P. (2019). BIM-enabled facilities operation and maintenance: A review. In *Advanced Engineering Informatics* (Vol. 39, pp. 227–247). https://doi.org/10.1016/j.aei.2019.01.005

Garwood, T. L., Hughes, B. R., O'Connor, D., Calautit, J. K., Oates, M. R., & Hodgson, T. (2018). A framework for producing gbXML building geometry from Point Clouds for accurate and efficient Building Energy Modelling. *Applied Energy*, *224*, 527–537. https://doi.org/10.1016/j.apenergy.2018.04.046

Gerrish, T., Ruikar, K., Cook, M., Johnson, M., & Phillip, M. (2017). Using BIM capabilities to improve existing building energy modelling practices. *Engineering, Construction and Architectural Management*, *24*(2), 190–208. https://doi.org/10.1108/ECAM-11-2015-0181

Gholami, E. (2015). Implementing Building Information Modelling ( BIM ) in Energy- Efficient Domestic Retrofit : Quality Checking of BIM Model Implementing Building Information Modelling ( BIM ) in Energy-. *W78*, *October*, 11. https://www.researchgate.net/publication/284189992

Goulding, J. S., Rahimian, F. P., & Wang, X. (2014). Virtual reality-based cloud BIM platform for integrated AEC projects. *Journal of Information Technology in Construction*, *19*(August 2013), 308–325.

Graphisoft. (2017). *BIMcloud and BIM Server User Guide GRAPHISOFT® BIMcloud and BIM Server User Guide*. www.graphisoft.com

Graphisoft. (2020). *Overview*. https://www.graphisoft.com/bimcloud/overview/

Grilo, A., & Jardim-Goncalves, R. (2010). Value proposition on interoperability of BIM and collaborative working environments. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2009.11.003

Ham, Y., & Golparvar-Fard, M. (2015). Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. *Automation in Construction*, *49*, 214–224. https://doi.org/10.1016/j.autcon.2014.07.009

Han, K. K., & Golparvar-Fard, M. (2017). Potential of big visual data and building information modeling for construction performance analytics: An exploratory study. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2016.11.004

Hargaden, V., Papakostas, N., Newell, A., Khavia, A., & Scanlon, A. (2019). The Role of Blockchain Technologies in Construction Engineering Project Management. *Proceedings - 2019 IEEE*

*International Conference on Engineering, Technology and Innovation, ICE/ITMC 2019*. https://doi.org/10.1109/ICE.2019.8792582

Heaton, J., Parlikad, A. K., & Schooling, J. (2019). Design and development of BIM models to support operations and maintenance. *Computers in Industry*, *111*, 172–186. https://doi.org/10.1016/j.compind.2019.08.001

ISO. (2018). *ISO - ISO 16739-1:2018 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries — Part 1: Data schema*. https://www.iso.org/standard/70303.html

IT, J. (2020). *EDMmodelServer$^{TM}$ (ifc)*. https://jotneit.no/edmmodelserver-ifc

Jergeas, G., Williamson, E., Skulmoski, G., & Thomas, J. (1986). Stakeholder Management on Construction Projects. *Preventing School Failure*, *51*(3), 49–51.

Kambatla, K., Kollias, G., Kumar, V., & Grama, A. (2014). Trends in big data analytics. *Journal of Parallel and Distributed Computing*, *74*(7), 2561–2573. https://doi.org/10.1016/j.jpdc.2014.01.003

Kamel, E., & Memari, A. M. (2019). Review of BIM's application in energy simulation: Tools, issues, and solutions. In *Automation in Construction* (Vol. 97, pp. 164–180). https://doi.org/10.1016/j.autcon.2018.11.008

Kang, T. W., & Choi, H. S. (2018). BIM-based Data Mining Method considering Data Integration and Function Extension. *KSCE Journal of Civil Engineering*, *22*(5), 1523–1534. https://doi.org/10.1007/s12205-017-0561-6

Kang, T. W., & Hong, C. H. (2015). Automation in Construction A study on software architecture for effective BIM / GIS-based facility management data integration. *Automation in Construction*, *54*, 25–38. https://doi.org/10.1016/j.autcon.2015.03.019

Kim, H., Shen, Z., Kim, I., Kim, K., Stumpf, A., & Yu, J. (2016). BIM IFC information mapping to building energy analysis (BEA) model with manually extended material information. *Automation in Construction*, *68*, 183–193. https://doi.org/10.1016/j.autcon.2016.04.002

Kim, K., Kim, G., Yoo, D., & Yu, J. (2013). Semantic material name matching system for building energy analysis. *Automation in Construction*, *30*, 242–255. https://doi.org/10.1016/j.autcon.2012.11.011

Koch, C., Neges, M., König, M., & Abramovici, M. (2014). Natural markers for augmented reality-based indoor navigation and facility maintenance. *Automation in Construction*. https://doi.org/10.1016/j.autcon.2014.08.009

Kučera, A., Glos, P., & Pitner, T. (2013). Fault detection in building management system networks. *IFAC Proceedings Volumes (IFAC-PapersOnline)*. https://doi.org/10.3182/20130925-3-CZ-3023.00027

Kučera, A., & Pitner, T. (2018). Semantic BMS: Allowing usage of building automation data in facility benchmarking. *Advanced Engineering Informatics*.

https://doi.org/10.1016/j.aei.2018.01.002

Laakso, M., & Kiviniemi, A. (2012). The IFC standard - A review of history, development, and standardization. *Electronic Journal of Information Technology in Construction*, *17*(May), 134–161.

Lee, P. C., Wang, Y., Lo, T. P., & Long, D. (2018). An integrated system framework of building information modelling and geographical information system for utility tunnel maintenance management. *Tunnelling and Underground Space Technology*. https://doi.org/10.1016/j.tust.2018.05.010

Liao, Y., Ramos, L. F. P., Saturno, M., Deschamps, F., de Freitas Rocha Loures, E., & Szejka, A. L. (2017). The Role of Interoperability in The Fourth Industrial Revolution Era. *IFAC-PapersOnLine*, *50*(1), 12434–12439. https://doi.org/10.1016/j.ifacol.2017.08.1248

Lucas, J., & Thabet, W. (2018). Using a Case-Study Approach to Explore Methods for Transferring BIM-Based Asset Data to Facility Management Systems. *Proceeding of Construction Research Congress 2018*, *1*, 148–157. https://doi.org/10.1213/01.ANE.0000149897.87025.A8

Microsoft Azure. (2020). *IaaS nedir? Hizmet Olarak Altyapı*. https://azure.microsoft.com/tr-tr/overview/what-is-iaas/

Msc, K. M., & Lawton, W. (2016). Identifying Use Cases and Data Requirements for BIM Based Energy Management Processes. *CIBSE Technical Symposium*, *May*. https://www.researchgate.net/profile/Hendro_Wicaksono2/publication/303524258_Identifying_Use_Cases_and_Data_Requirements_for_BIM_Based_Energy_Management_Processes/links/5746d14908ae9f741b4445ca/Identifying-Use-Cases-and-Data-Requirements-for-BIM-Based-Ene

Murphy, S. N., Chueh, H. C., & Herrick, C. D. (2017). Information Technology. In *Clinical and Translational Science: Principles of Human Research: Second Edition* (pp. 227–242). Elsevier Inc. https://doi.org/10.1016/B978-0-12-802101-9.00013-2

OGC. (2020). *CityGML*. https://www.ogc.org/standards/citygml

Oraee, M., Hosseini, M. R., Edwards, D. J., Li, H., Papadonikolaki, E., & Cao, D. (2019). Collaboration barriers in BIM-based construction networks: A conceptual model. *International Journal of Project Management*, *37*(6), 839–854. https://doi.org/10.1016/j.ijproman.2019.05.004

Ozturk, G. B. (2020). Interoperability in building information modeling for AECO/FM industry. *Automation in Construction*, *113*. https://doi.org/10.1016/j.autcon.2020.103122

Pärn, E. A., & Edwards, D. J. (2017). Conceptualising the FinDD API plug-in: A study of BIM-FM integration. *Automation in Construction*, *80*, 11–21. https://doi.org/10.1016/j.autcon.2017.03.015

Pärn, E. A., Edwards, D. J., & Sing, M. C. P. (2017). The building information modelling trajectory in facilities management: A review. *Automation in Construction*, *75*, 45–55. https://doi.org/10.1016/j.autcon.2016.12.003

Perera, S., Nanayakkara, S., Rodrigo, M. N. N., Senaratne, S., & Weinand, R. (2020). Blockchain technology: Is it hype or real in the construction industry? *Journal of Industrial Information Integration*, *17*(August 2019), 100125. https://doi.org/10.1016/j.jii.2020.100125

Potkany, M., Vetrakova, M., & Babiakova, M. (2015). Facility Management and Its Importance in the Analysis of Building Life Cycle. *Procedia Economics and Finance*, *26*, 202–208. https://doi.org/10.1016/s2212-5671(15)00814-x

Puri, N., & Turkan, Y. (2020). Bridge construction progress monitoring using lidar and 4D design models. *Automation in Construction*, *109*. https://doi.org/10.1016/j.autcon.2019.102961

Rahmani Asl, M., Zarrinmehr, S., Bergin, M., & Yan, W. (2015). BPOpt: A framework for BIM-based performance optimization. *Energy and Buildings*, *108*, 401–412. https://doi.org/10.1016/j.enbuild.2015.09.011

Ratajczak, J., Malacarne, G., Krause, D., & Matt, D. T. (2015). The BIM Approach And Stakeholders Integration In The AEC Sector – Benefits And Obstacles In South Tyrolean Context. *Proceedings of the Fourth International Workshop on Design in Civil and Environmental Engineering, 30-31 October 2015, NTU, Taiwan*, *November 2016*, 1–9.

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM handbook: a guide to building information modeling for owners, designers, engineers, contractors, and facility managers*. John Wiley & Sons.

Sadeghi, M., Elliott, J. W., Porro, N., & Strong, K. (2019a). *Developing building information models ( BIM ) for building handover , operation and maintenance*. *17*(3), 301–316. https://doi.org/10.1108/JFM-04-2018-0029

Sadeghi, M., Elliott, J. W., Porro, N., & Strong, K. (2019b). Developing building information models (BIM) for building handover, operation and maintenance. *Journal of Facilities Management*, JFM-04-2018-0029. https://doi.org/10.1108/JFM-04-2018-0029

Sanhudo, L., Ramos, N. M. M., Martins, J. P., Almeida, R. M. S. F., Barreira, E., Simões, M. L., & Cardoso, V. (2020). A framework for in-situ geometric data acquisition using laser scanning for BIM modelling. *Journal of Building Engineering*, *28*. https://doi.org/10.1016/j.jobe.2019.101073

Sani, M. J., & Rahman, A. A. (2018). GIS and BIM integration at data level: A review. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(4/W9), 299–306. https://doi.org/10.5194/isprs-archives-XLII-4-W9-299-2018

Secom. (2020). *IFC Model Server - SECOM Intelligent Systems Laboratory*. https://www.secom.co.jp/isl/en/research/ifc-model-server/

Shalabi, F., & Turkan, Y. (2016). IFC BIM-Based Facility Management Approach to Optimize Data Collection for Corrective Maintenance. *Journal of Performance of Constructed Facilities*, *31*(1), 04016081. https://doi.org/10.1061/(asce)cf.1943-5509.0000941

Singh, V., Gu, N., & Wang, X. (2010). *A theoretical framework of a BIM-based multi-disciplinary collaboration platform*. https://doi.org/10.1016/j.autcon.2010.09.011

Stavropoulos, G., Krinidis, S., Ioannidis, D., Moustakas, K., & Tzovaras, D. (2015). A building performance evaluation & visualization system. *Proceedings - 2014 IEEE International Conference on Big Data, IEEE Big Data 2014*, 1077–1085. https://doi.org/10.1109/BigData.2014.7004342

Steel, J., Drogemuller, R., Toth, B., by Tony Clark, C., Bettin Steel, J. J., Drogemuller, R., & Toth, B. (2012). Model interoperability in building information modelling. *Softw Syst Model*, *11*, 99–109. https://doi.org/10.1007/s10270-010-0178-4

Stumpf, A., Kim, H., & Jenicek, E. (2009). Early Design Energy Analysis Using BIMs (Building Information Models). *Construction Research Congress 2009*, 426–436. https://doi.org/10.1061/41020(339)44

Sustainability of Digital Formats: Planning for Library of Congress Collections. (2016). *EXPRESS data modeling language, ISO 10303-11*. http://www.loc.gov/preservation/digital/formats/fdd/fdd000449.shtml

Sustainability of Digital Formats: Planning for Library of Congress Collections. (2017). *EXPRESS data modeling language, ISO 10303-11*. http://www.loc.gov/preservation/digital/formats/fdd/fdd000449.shtml

Szeleczki, S. (2019). Interpreting the Interoperability of the Nato's Communication and Information Systems. *Scientific Bulletin*, *24*(1), 95–107. https://doi.org/10.2478/bsaft-2019-0011

Taha, F. F., Hatem, W. A., & Jasim, N. A. (2020). Effectivity of BIM technology in using green energy strategies for construction projects. *Asian Journal of Civil Engineering*, *21*(6), 995–1003. https://doi.org/10.1007/s42107-020-00256-w

Terreno, S., Asadi, S., & Anumba, C. (2019). An exploration of synergies between lean concepts and BIM in FM: A review and directions for future research. *Buildings*, *9*(6). https://doi.org/10.3390/BUILDINGS9060147

W3C. (2016). *Extensible Markup Language (XML)*. https://www.w3.org/XML/

Wang, C., & Cho, Y. K. (2015). Performance Evaluation of Automatically Generated BIM from Laser Scanner Data for Sustainability Analyses. *Procedia Engineering*, *118*, 918–925. https://doi.org/10.1016/j.proeng.2015.08.531

Wang, J., Weizhuo, ·, Wenchi, S. ·, Xiangyu, S. ·, Changzhi, W. ·, Chong, W. · H.-Y., Liu, Y., Sun, C., Wang, J., Shou, · W, Wu, · C, Chong, H.-Y., Shou, W., Wu, C., Sun, W., Wang, X., Liu, Y., Sun, · C, & Sun, C. (2015). Integrating BIM and LiDAR for Real-Time Construction Quality Control. *J Intell Robot Syst*, *79*, 417–432. https://doi.org/10.1007/s10846-014-0116-8

Wang, M., Deng, Y., Won, J., & Cheng, J. C. P. (2019). An integrated underground utility management and decision support based on BIM and GIS. *Automation in Construction*, *107*. https://doi.org/10.1016/j.autcon.2019.102931

William East, E., Nisbet, N., & Liebich, T. (2012). Facility Management Handover Model View. *Journal of Computing in Civil Engineering*, *27*(1), 61–67. https://doi.org/10.1061/(asce)cp.1943-5487.0000196

Wong, A. K. D., WONG, F. K. . W., & NADEEM, A. (2013). Comparative Roles of Major Stakeholders for the Implementation of BIM in Various Countries. *Journal of Chemical Information and Modeling*, *53*(9), 1689–1699. https://doi.org/10.1017/CBO9781107415324.004

Wu, W., Yang, X., & Fan, Q. (2014). *GIS-BIM Based Virtual Facility Energy Assessment (VFEA)—Framework Development and Use Case of California State University, Fresno*. *758*, 339–346. https://doi.org/10.1061/9780784413616.043

Wu, X., Zhu, X., Wu, G.-Q., & Ding, W. (2013). Data Mining with Big Data. *IEEE Transactions on Knowledge and Data Engineering*, *1*, 97–107.

Yalcinkaya, M., & Singh, V. (2019). VisualCOBie for facilities management: A BIM integrated, visual search and information management platform for COBie extension. *Facilities*, *37*(7–8), 502–524. https://doi.org/10.1108/F-01-2018-0011

Zhang, J. P., Liu, Q., Yu, F. Q., Hu, Z. Z., & Zhao, W. Z. (2014). A Framework of Cloud-computing-based BIM Service for Building Lifecycle. *Computing In Civil And Building Engineering*, 1514–1521.

Zheng, D. (2014). Cloud and Open BIM-Based Building Information Interoperability Re-search. *Journal of Service Science and Management*, *7*, 47–56. https://doi.org/10.4236/jssm.2014.72005