An Approach to Enhance Interoperability of Building Information Modeling (BIM) and Data Exchange in Integrated Building Design and Analysis

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Abstract –

Achieving high energy-efficient building designs requires conducting energy analyses iteratively starting from the conceptual stage to ensure suitable selection of building components to meet energy performance requirements. In recent years, advanced BIM capabilities have allowed designers to assimilate design and energy modeling processes geared towards improving productivity. However, there are shortcomings in many BIM platforms that circumvent effective data exchange between design/analysis models and essential data/information sources, resulting in reduced efficiency in terms of money, time and effort losses.

This paper proposes an approach to enhance data interoperability to allow seamless integration of design and energy analysis processes. The approach reviews data exchange requirements by key stakeholders in the building lifecycle and analyze how a common platform can address their needs. The paper first surveys existing BIM design and analysis software applications and various data sources to identify individual data interface formats. Autodesk Revit and USDOE EnergyPlus are examples of software tools, and ASHRAE climatic/building data are representative of a typical data source. The paper then develops use cases in which different combination of BIMs and data sources may be selected by the design team. For each use case, data exchange formats are analyzed against BIM data exchange standards to evaluate data interoperability. The objective is to identify suitable combinations of design, modeling, and data interface tools to accommodate the need of integrated design team. Finally, based on the results of the use cases, the paper recommends specific BIM tools that can accommodate the required models and data sources.

Keywords –

Data Exchange; Interoperability; Building Information model; Data Interface; Energy Modeling

1 Introduction

The AEC industry is highly diversified and there are a variety of different information systems being used in each organization. Thus, the transfer of information between different systems is and continues to be an apparent need **[1].**

One key issue in AEC industry today is ineffective information and data exchange. Poor information exchange can lead to three major problems: Costly errors in design/ construction, time wasting in making decisions and shorter life-span of design/construction projects due to poor judgement.

It is no doubt that the industry relies heavily on the use of data/information exchange between different professional disciplines for design, analysis, construction, operations and maintainace activities **[7]**. The construction industry is undergoing fundamental change, not unlike the advent of lean manufacturing in auto-making in the 1980s. A revolutionary tool called Building Information Modelling, or BIM, is the reason. BIM is rapidly transforming complex building processes -speeding project completion, lowering costs and improving overall quality at the same time. The possibilities for leveraging BIM are endless. Building Information Modelling (BIM) is currently attracting significant increased attraction of industry stakeholders with a promise of better collaboration with effective flow of data exchange resulting in higher productivity and better-quality products. The goal of this paper is to focus on identifying a suitable approach to enhance data interoperability to allow for seamless integration of design and analysis activities in building construction projects. This will result in suitable combinations of design, modeling, and data interface tools that accommodate the need of integrated design teams.

Acronyms

AEC: Architectural Engineering & Construction
AIA: American Institute of Architects
ASHRAE:American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BCF: BIM Collaboration Format

COBie: Construction Operations Building Information Exchange
FM: Facilities Management
gbXML: Green Building Extensive Mark-Up Language
HVAC&R: Heating Ventilation Air Conditioning and Refrigeration
IFC: Industry Foundation Classes
IFD: International Framework for Dictionaries
IDM: Information Delivery Manuel
MEP: Mechanical Electrical and Plumbing
NBIMS: National BIM Standard-US
PDT: Product Data Template
XML: Extensive Mark Up Language
EUI: Energy Use Intensity

2 Integrated Information Exchange Process

The initiation of steady, continuous, and unambiguous performance information throughout building lifecycle is seen as a catalyst for building optimization. Stakeholders across architectural, engineering, construction (AEC) and facility management (FM) industry can share and exchange information based on the integrated information structure. For a real open process to occur, three factors need to be in place **[2]**:

a. A common data format for the exchange of information – IFC (Industry Foundation Classes),
b. Rules of which data is to be exchanged and who shall exchange them – IDM (Information Delivery Manual) and,
c. A standardized data model which is properly interpreted on each position of the exchange – IFD (International Framework for Dictionaries).

Figure 1 demonstrates the operation of the integrated information exchange structure. The structure works as a guideline for standardized data exchange. In the structure, IDM provides a universal, repeatable, reusable and verifiable collaborative methodology for initiating information exchange; IFC defines the data format of the information to be exchanged and builds the foundation for data exchange between applications. The structured information exchange framework allows preservation of meaning within different design tools.

A precise data exchange format in the BIM framework will not only lead to enhanced sustainable design and information exchange but will also bring about an increased project life-span, reduced life-cycle cost as well as fast-track design and construction turn-around time. This, when done properly, will create a win-win situation for all project stakeholders.

The subsequent sections will shed more light on how to identify suitable BIM authoring tools and data exchange formats that enable an open process and how they advance interoperability as well as generating reliable data.

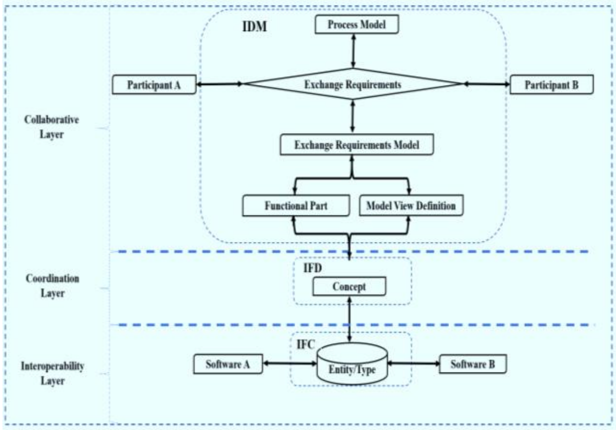

Figure 1. BIM process integrated information exchange structure

Table 1. Existing BIM authoring software application tools

BIM tool	Functionality	Phase(s)
Autodesk Revit	Building energy and carbon analysis & exchange capabilities	Conceptual & detailed design phase
Autodesk FormIt	Building energy analysis	Conceptual & detailed design phase
Revit/ArchiCAD	Certification support	Conceptual & detailed design phase
Revit/Vasari	Solar studies	Conceptual &detailed design phase
Vector works	Documentation/collaboration	Conceptual design phase
AECOsim Building Designer	Documentation/collaboration	Conceptual design phase
eTakeoff Bridge	Estimating	Conceptual &detailed design phase
Archibus	Operation/work process	Detailed analysis
Assemble Insight	Support decision making	Web based solution
Tekla BIMsight	Collaboration	Check conflict at design phase
SketchUP	Exchange capabilities	Conceptual phase

3 Survey of BIM Authoring and Analysis Software Tools

There are many BIM design and analysis software application tools available in the market today and each caters to different users.

In many cases, the functionalities of different BIM software over-lapped one another requiring the users to carefully evaluate the software capabilities to ensure that the application will meet their needs. Table 1 constitutes a survey of dominant software applications available for BIM and integrated practice [3]. A brief description of functionalities and the phases of implementation/analysis are provided for information and evaluation purposes. The list is not meant to be exhaustive.

4. Data Format and Exchange Standards

Design and analysis activities in the BIM environment can leverage the wealth of data available electronically from various sources. Today, many manufacturers of building products provide BIM objects that can be imported directly into BIM applications and vice versa. Professional organizations such as ASHRAE (American Society of Refrigeration and Air-Conditioning Engineers) and AIA (American Institute of Architects) develop standards and design guidelines for the AEC industry and those can be used to support the building design and analysis process, although in most cases, much effort is required to integrate them into the BIM environment. Additionally, building codes and research data are available from government agencies such as state building commissions and USDOE (United States Department of Energy) that can be used to enhance the robustness of the design. Table 2, reviews "open standards" and BIM, non-proprietary file format and exchange protocol technologies that have been developed by public, private, and public/private entities [4]. Table 2 also provides a brief summary of different standard data exchange formats and the level of relevancy of each type of format relative to effective data transfer. The level of relevancy indicates the likelihood of the data exchange format would be used by one or more BIM software applications. As an example, BIM authoring software such as Revit and ArchiCAD have functionalities to convert BIM models into COBie, XML schemas, IFC, OmniClass, gbXML etc. There are countless number of supplies of BIM file formats out there [5, 8, 9] few of them are listed in (Table 2) for purposes of this study.

5. Data exchange use case methodology

Use cases are a useful tool in the process of evaluating interoperability of data exchange in the BIM environment. In order to capture the use case, it was necessary to first establish a set of properties by which they can be defined [6]. The data domain categories were also identified which was based on the major information contents of the Data Exchange Use Case. These include:

- The project;
- The site and the building;
- The building stores
- Spaces and their type information (space type, space intended use etc.);
- Building elements and their information (construction type) or building element material information;
- 3D – shape of the building elements (geometry) and;
- Location information of building elements.

The objects (lists) above are applicable according to general product modelling principles, the common information required that all objects should be uniquely identified (through unique ID). The main principle of the information content is that, at least the 3D-geometry data is transferred as a basic input for design analysis.

In the data exchange implementation, the data exchange representation and format for the exchange of the information is content specified. There may be alternative ways of implementing the data exchange for some information content (e.g. the internal format specific software application, default standards, or official standard).

In a specific building projects, the data exchange implementation method must be agreed upon (mostly from the early days of the project) by the stakeholders separately.

Data implementation process using the IFC specification as an example [12, 14] is described here. The description is intended to be used, firstly, by software vendors for their implementation exchange interfaces and, secondly, by the individual stakeholders to select data exchange solutions as their requirements description when the data exchange is to be implemented using IFC.

Data exchange implementation and format description procedure has been briefly explained in the ensuing sections. The use case defines only the representation and format of the implementation i.e. in which form the information should be used during data exchange transaction. The definition by which means the transfer process is done is outside the scope of the use case interpretation.

Table 2. Data format/exchange standards

Standard	Format	Efficiency Level High	Efficiency Level Low
IFC	Provides a framework for organizations to produce interoperable software to exchange information on building objects and processes to creates a language that can be shared among the building disciplined	✓	
XML	Set of rules for designing text formats to structure information. XML supports data transaction between different software applications, leading to a better way to communicate information.	✓	
gbXML	gbXML is the most widely supported data format for the exchange of building information between BIM/CAD and energy performance applications.	✓	
CIBSE -Product Data Template (PDTs)	PDTs are the source of consistent data to be used in the management of the constructed asset, allowing facilities managers to find the information they require for operation and maintenance of the facility in a structured and standardized format, improving the efficiency and productivity of the FM process, and supporting automation in the management of asset information.	✓	
COBie	Supports the sharing of data among facility management tools, such as BIM authoring tools, CMMS, and computer-aided facility management (CAFM) software. The standard eliminates the need to re-collect data, and it reduces the number of inconsistencies between similar data sets used for different purposes within a facility management organization	✓	
BIMXML	an XML schema developed to represent a simplified subset of BIM data for web services.	✓	
MVD	Model View Definition, the specification for subsets of all available BIM data to serve a stated purpose or process	✓	
IDM	Information Delivery Manual, the business case specification for exchange BIM data, including end user Exchange Requirements (ERs)	✓	
RVT	This is Autodesk's proprietary format for Revit files. These can vary significantly in size depending on the level of development. They can only be opened in Revit.	✓	
BCF	BIM Collaboration Format, an XML schema that encodes messages to enable workflow communication between different BIM (Building Information Modeling) software tools.	✓	
IFD	Describes what kind of information is exchanged by providing a mechanism that allows the creation of unique IFD IDs, to connect information from existing databases to IFC data models.		✓
PDF	Portable Document Format originally developed by Adobe for the electronic exchange of any printable document.		✓
OGC	Open Geospatial Consortium, international industry consortium for developing standards for geospatial data-enabled technologies.		✓
NWD	This is Autodesk's proprietary format for Navisworks files. NWD files are also read-only, although you may be able to save them under a new name and edit from there if the file was saved with that option enabled. These can only be open in Navisworks Freedom or Navisworks Manage.		✓
DWF/DWF	Design Web Format, originally developed by Autodesk, as a PDF alternative for CAD data/documentation.		✓
OmniClass (UniFormat Std II)	Framework for Classification of Information. A guidance document, and establishes common concepts used in building information exchange	✓	
NIBS-National BIM Guide for Owners	Serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions making during the life cycle of a facility from inception onward.	✓	

5.1. Data Exchange Implementation using IFC

The data exchange implementation using IFC is based on current release IFC4 addendum 2, publish in July 2016, as a buildingSMART final standard [12]. The Data Exchange Use Case architectural design to HVAC&R (MEP) design is closely related to the predefined IFC coordination view. The main difference is that the construction type is not supported in the coordination view.

5.2. Minimum Content of IFC Product Model

The IFC product model and specification sets some specific minimum requirements for what the information content of file-based product model IFC data exchange should be. Regarding the Use Case, the required minimum IFC product model is specified in Table 3. Separately, for the exchange of the 3D (Revit) model in figure 2 and building product model exchange sub-cases.

Table 3. The minimum IFC product model content in the two sub-case of Use Case

3D Reference model exchange	
Class	Properties
Project	-Identification and owner history -3D coordinate system -Project context and common measurement units
Site, Building & Stores	-Identification and owner's history
Building elements	-Identification and owner history -3D-shape and location
Building product model exchange	
Class	Properties
Project	-Identification and owner history -3D coordinate system -Project context and common measurement units
Site, Building and Stores	-Identification and owner
Space	Space type 3D-shape and location

5.3. IFC Data Exchange Format

IFC data exchange has two alternative formats for the exchange of some information content [14]. These formats are:

- IFC format or IFC part 21 Format, which is based on the ISO 10303 -21 standard,
- The ifcXML format, which is based on an XML Schema definition of the IFC product data model. Currently the specification is based on the IFC4 Addendum 2.

IFC implementations in commercial software application use the IFC part 21 format for IFC-based data exchange.

6. Case Study

Using Autodesk Revit, a BIM-based Architectural model is designed as a test case for this study, see Figure 2. In this example, it is assumed that the owner and architect have decided to use Autodesk Revit for the architectural design. Considering the involvement and the need of various project stakeholders, the objective is to evaluate interoperability of the data exchange in this process. EnergyPlus and Revit energy analyze are considered for energy simulation engine & tool respectively, ARCHICAD is used for structural analysis, and gbXML format was chosen as the data exchange protocol between the architectural model and analysis program.

The owner specified BIM model described below presented an opportunity to identify key interfaces between Autodesk Revit and other BIM authoring software application tools identified in Table 1, for their compatibilities in data exchange protocols.

Three of the BIM authoring tools below were selected in no order of preference for this experiment/demonstration. The authors only had in mind those BIM authoring tools which are not common and not most frequently used.

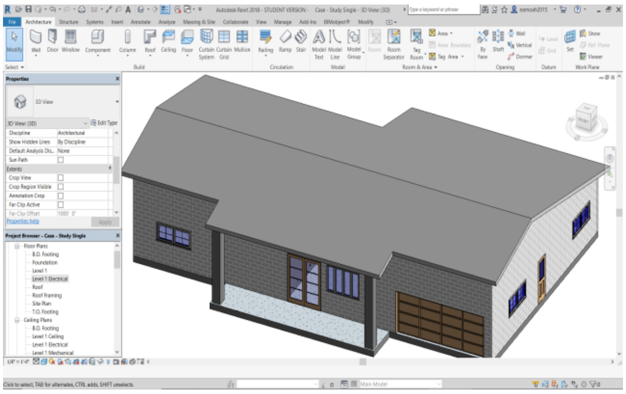

Figure 2. Sample owner specified BIM based 3D architectural model using autodesk revit

6.1. Revit/ArchiCAD Data Exchange Interface

This section discusses the GRAHISOFT ArchiCAD connection for Autodesk Revit. The Add-In improves the IFC based and bi-direction data exchange between GRAHISOFT ArchiCAD and Autodesk Revit [11,15]. The GRAHISOFT ArchiCAD connection Add-In for Auto Revit has three capabilities:

- **Improved IFC Import"** - imports IFC models to Revit using extra features that improve the interpretation of architectural models;

- **"Link IFC"**- merges IFC models into the current Revit project as a non-editable reference;
- **"Export to ARCHICAD"** - exports Revit model elements in IFC files that are specially enhanced for use in GRAPHISOFT ARCHICAD.

To obtain the best data exchange results, it is important to ensure latest version (18.2.0 or later) of Autodesk's IFC 2018 import-export for Revit is used.

6.2. Revit/Vasari Data Exchange Interface

Project Vasari is a design tool with analysis capabilities available via cloud [13]. The problem is that, Revit/Vasari doesn't know how to pass separate conceptual masses with different building/space types to the analysis engine. There is no provision for separate buildings within the data exchange format from Revit (it is in the gbXML schema). To get around this problem, there are two options that must be considered [10, 11 13,]:

- Model the building as different masses, and run the energy analysis on each space type;
- For the initial analysis, lump the masses together and choose a building type and schedule that is the most appropriate when taken as a whole.

It is possible to make some preliminary conclusions massing and orientation from this rough analysis – and only drill down into analysis of the different space types if the analysis is not justified.

6.3. Revit/Tekla Structures Data Exchange Interface

The general collaboration/exchange with Tekla Structures to Autodesk Revit is best done on a neutral platform built for such purpose [11,16] for example, Autodesk Navisworks or Tekla BIMsight which is dedicated collaboration software with clash-checking and reporting.

Data exchange between Tekla structures and Autodesk Revit can be done using Autodesk approved IFC files through the following process:

- Export from Tekla Structures to Revit using an IFC file (Tekla > Export > IFC) from Tekla Structures,
- Import into Revit. From Revit 2015 version and later, it is possible to Insert > IFC file directly.

Where there are project co-ordinates, use Site Definition in Revit to locate the inserted Tekla Structures model correctly or use a manual model insertion point (Right click IFC model after inserting > reposition to project base point)

BIM can now be employed to co-ordinate the Structural file with the Architectural / MEP project in Revit.

7. Energy Modeling/Simulation

Kamel, E., & Memari, A. M. (2019). "Review of BIM's application in energy simulation: Tools, issues, and solutions", reviewed the challenges, issues, and shortcomings in BIM-to-BEM interoperability process (BBIP) and proposed a detailed classification for these issues and available solutions. This paper also explains how a corrective middleware, which is developed by the authors using Python, can be utilized to modify a gbXML file prior to adoption in energy simulation to resolve the issues related to building envelope in BBIP. The authors initially reviewed different types of BIM schemas such as IFC and gbXML and energy simulation tools capable of reading these files such as Green Building Studio (GBS), DesignBuilder, Integrated Environmental Solutions-Virtual Environment (IES), and OpenStudio [17]. The authors showed that not all the required data for energy simulation such as HVAC system data, schedules, and loads are exported properly to the gbXML file using Revit, and that data need to be added manually.

Autodesk Insight 360 allows architects/ designers to explore the energy impacts of different choices as they design **[11]**. Insight 360 uses EnergyPlus to calculate heating and cooling loads. It provides option of using EnergyPlus to evaluate annual energy impacts **[11]**. Insight 360 offers EnergyPlus simulations to all users through Revit and FormIt.

In figure 3, the authors developed/presented energy optimization and data transfer process framework to allow for seamless integration of design and energy modeling. The study also focused on investigating BIM authoring tools capable of providing a versatile platform for transferring all require data/file with little or no difficulty. During the first stage of the process, material specifications, construction preplanning and key decisions regarding data transfer approaches are considered. Also, the energy modeler/designer and other stakeholders come together to propose assumptions underlying the choice of building envelopes and system types at this stage. The assumptions made are used as a decision process for both design and energy simulation analysis. The authors considered EnergyPlus, gbXML and Insight 360 as the simulation engine and Revit as design tool. EnergyPlus was used to assess the initial heating and cooling loads regarding the impact of the annual energy consumption for envelopes and HVAC systems. These design and energy analysis results are to assist the stakeholders to make an inform decision. gbXML file provided us with a whole building simulation analysis result through Green Building Studio (GBS). Detailed results can be assessed, for example, Annual Energy Consumption in kWh, Energy Use Intensity (EUI) in kBtu/ft²/year, Annual Peak Energy Demand in kW, Annual Lifecycle Energy in kW etc. as indicated in the "Detailed Simulation Analysis portion of

Figure 3. The results are carefully studied, a thoughtful decision is made whether to approve the results or not. If the results are approved, the project moves to construction sage. If rejected, the updates become necessary, new assumptions and materials selection are considered. The framework for Figure 3 allows you to go back to the input stage to kick start your new materials/assumptions.

The main issue and limitation identified in the framework relates to how the key assumptions lies in the hands of the stakeholders, especially the owner who might not have enough technical know-how. If these assumptions are found to be unreasonable at the later of stage the simulation/design process, the entire energy analysis result becomes irrelevant. Fortunately, the process developed by the authors in Figure 3 makes it possible to correct any wrong assumptions made at any stage of the process. In fact, you can always go back to alter the building envelope (walls, windows or roof materials) at any time from the Specs & construction/data transfer decision stage.

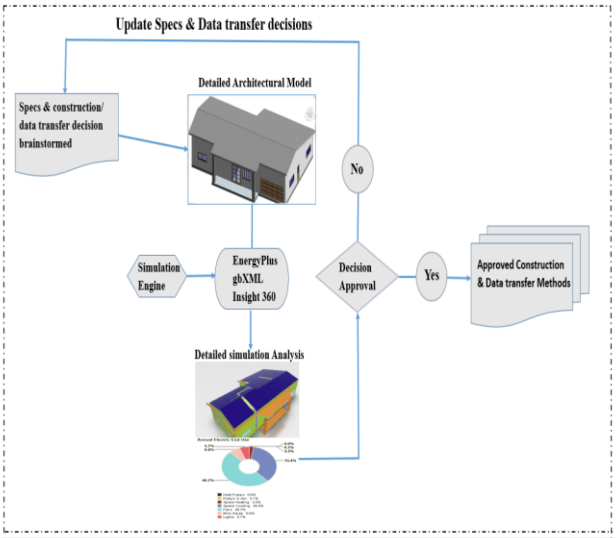

Figure 3. Data transfer decision & energy simulation process

8. Results and Discussion

Data interoperability allowing smooth integration of design and energy analysis has been investigated. The study has identified a suitable process of data exchange requirements to enable stakeholders to address their information exchange needs via a common platform.

The authors developed an integrated information exchange method, in section 2, to identify an unambiguous information sharing process throughout the building lifecycle for the industry stakeholders. The paper defined the data and information flow from IDM (Information Delivery Manual), IFD (International Framework for Dictionaries) and IFC (Industry Foundation Classes). The illustration in Figure 1 summarizes the information exchange process.

In section 3 and 4, the authors investigated several existing BIM authoring software application tools and data exchange formats, respectively. Table 1 lists the state-of the-art existing BIM software tools, their functionalities and performance phases was developed to aid decision making. Table 2 identifies data exchange formats/standards that provide guidelines to leverage data sharing electronically to minimize errors in exchange/communicating information among the team members in an ongoing project. Table 2 also ranks the efficiency level "High or Low" when selecting data exchange file/format. "High" indicates transfer with very minimal or no error while "Low" indicates substantial difficulty regarding data transfer and interpretation. The paper outlined methods for developing Use Cases with an inclusion of data exchange implementation process with IFC (Industry Foundation Classes) as an example. The properties and components that needs to be included in the IFC identified.

Finally, a case study was introduced as an example, demonstrating what constitutes an element of a building model. Autodesk Revit was used to design a BIM-based architectural model. This was used as a test case to demonstrate the data exchange interfaces with other identified BIM authoring software application tools in Table 1 (ArchiCAD, Vasari and Tekla Structures) to assist the stakeholders in making decision in relation to selecting an appropriate design and analysis BIM application tool.

Apart from Building Information Modeling (BIM) currently being adopted by the construction industry to facilitate and promote collaboration between the industry players within projects, there are ongoing deliberations and research on further digitalization and automation of the construction industry. A future research direction is to incorporate an Artificial Intelligence (AI) technology in the BIM process. This area requires more research to bring the power of artificial intelligence to assist the construction industry in tackling some challenges such as reducing design errors, enhancing greater collaboration and better software tools.

9. Recommendations

BIM-based data exchange and analysis processes are constantly evolving with emerging software products and technologies. Based on lessons learned in this study, following recommendations are proposed:

- The industry stakeholders should revolutionize the construction and engineering activities to embrace the artificial intelligence technology solution to avoid the fast-emerging trend of technological disruption to consume the industry.

- Early collaboration among stakeholders should be made mandatory or guided by strict standards irrespective of the project size to minimize cost and save time.
- Emerging/existing software technologies should be streamlined and be made to follow a cutoff standards and regulation.
- Autodesk Revit was found to be a versatile BIM tool capable of accommodating a wide variety of design and analysis models and data sources.

10. Conclusion

This paper reviewed approaches to enhance collaboration among key stakeholders in building design and construction projects. It analyzed how a common platform could help solve the present needs of data interoperability.

Use cases were found to be a useful tool for evaluating the stakeholders' data exchange requirements, leading to the identification of appropriate software tools and data format for a specific project. Suitable combination of design, modeling, and data interface tools will help improve the project cost and schedule overruns.

The next phase of this research would be centered on using BIM to investigate into generating a comprehensive & interactive database of building data to facilitate smart designs through information to create virtual model from high-powered project data.

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