Development Of BIM-BEM Framework To Support The Design Process

By

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ACKNOWLEDGMENTS

Five years ago, I got on a journey with many wishes and worries in my mind. At that time, I was a newcomer, an international student that wants to build a new life in Canada. There were many things to struggle with, a new marriage, new culture, new language (French) and a new academic program.

I was an architect in my home country and got a Bachelor degree in energy engineering in Sweden. I came to Montreal and decided to combine my knowledge of architectural and engineering to study my Master in building energy efficiency with the supervision of best professors in this field, Danielle Monfet and Daniel Forgues. From the first time they told me about Building Information Modeling (BIM) and the benefits of that in the building industry, specifically for energy simulation, I got into the BIM world with many passions and several questions in my mind. After one year of Master, my supervisors encouraged and supported me to exchange it to Ph. D. program to search and find my answers in this field.
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Développement du cadre BIM-BEM pour soutenir le processus de conception

Aida FARZANEH

RÉSUMÉ

Les travaux de recherche de cette thèse abordent les approches techniques et le processus visant à encourager l'utilisation de la modélisation des informations du bâtiment (BIM) pour la modélisation énergétique des bâtiments (BEM) (appelé BIM-BEM) afin de réaliser des simulations énergétiques pendant le processus de conception. La recherche était motivée par le manque d'interopérabilité et d'intégration du modèle BIM dans les outils BEM et par l'intégration la technologie BIM-BEM au processus de conception. Il était donc nécessaire d'établir comment l'éxécution du BIM-BEM pouvait être complétée avec succès et avec précision pour faciliter le processus de conception.

Par conséquent, les objectifs étaient de combiner les approches techniques et le processus appropriées afin de développer un cadre efficace et holistique pour l'exécution BIM-BEM pendant le processus de conception. Cette thèse s'appuie sur la méthodologie Recherche-Action (AR) pour aborder une perspective réaliste à des problèmes concrets. La méthodologie qui a été suivie inclut un diagnostic, une planification d'action, une prise en charge des actions et une validation au moyen de diverses études de cas.

Les principales lacunes dans ce domaine ont été identifiées à l'aide d'une revue systématique de la littérature sur les aspects techniques et ceux liés aux processus. En conséquence, un modèle général pour le cadre BIM-BEM a été développé, prenant en compte toutes les exigences pour mettre correctement en œuvre BIM-BEM dans le cadre d'un processus efficace pouvant être adopté pour différents types de projets. En ce qui concerne la proposision, un cadre BIM-BEM générique et avancé a été développé illustré à l'aide d'une carte de processus facile à suivre tenant compte des exigences identifiées et pour divers outils testés afin de prendre en charge la modélisation, l'intégration de modèles et le flux de travail / données pendant le processus de conception. Enfin, un protocole d'information novateur a été mis au point afin de simplifier et organiser le cadre BIM-BEM pour permettre un partage précis de l'information à un niveau de développement approprié pour la simulation énergétique à chaque phase de conception.

Cette thèse apporte une contribution originale à la pratique et aux connaissances en fournissant un cadre générique et fiable pour simplifier et systématiser l'utilisation du BIM-BEM lors du processus de conception de bâtiments à hautes performances. Les approches techniques et le processus proposées dans le cadre facilite leur opérationalisation par le protocole d'information avancé pour une exécution réussie du BIM-BIM pendant le processus de conception. En conséquence, l'utilisation du cadre BIM-BEM permet de réduire les erreurs d'interopérabilité, d'économiser du temps de remodelage et de dépannage, d'améliorer la gestion des données et de maximiser la précision des résultats de simulation qui évoquent au total une évolution et une optimisation durables de la conception par les professionnels.

Les professionnels peuvent utiliser le cadre BIM-BEM en suivant et en adaptant les activités de conception proposées, les méthodes d'intégration, le flux de travail / données et le protocole d'information dans leur processus de conception. Pour des types de projets spécifiques, le cadre peut être ajusté et avancé en identifiant des exigences complémentaires pour chaque activité de conception. En outre, il peut être mis à niveau et bonifié en intégrant d'autres approches novatrices d'intégration de modèles et de processus dans les travaux futurs. Dans les travaux ultérieurs, le cadre sera complété par des solutions techniques avancées pour encourager l'industries à déployer de l'expertise en programmation dans leur processus.

Mots-clés: Building Information Modeling (BIM), modélisation énergétique du bâtiment (BEM), processus de conception, protocole d'information, niveau de développement (LOD).

Development of BIM-BEM framework to support the design process

Aida FARZANEH

ABSTRACT

The research work in this thesis investigates the technical and process approaches to encourage the use of Building Information Modeling (BIM) for Building Energy Modeling (BEM) (refer to as BIM-BEM) to perform energy simulations during the design process. The research was motivated by the lack of the interoperability and integration of BIM model into the BEM tools and the adoption of BIM-BEM technology into the design process. Thus, there was a need to establish how BIM-BEM can be executed successfully and accurately to support the design process.

Therefore, the objectives were to combine appropriate technical and process approaches to develop an effective and holistic framework for BIM-BEM execution during the design process. This thesis was rooted based on Action Research (AR) methodology to address realistic perspective with real-practice issues. The methodology had five main steps including diagnosing, action planning, action tacking, and validating using various case studies.

The main gaps in this area were identified using a systematic literature review of technical and process aspects. Accordingly, a general template for BIM-BEM framework was developed considering all the requirements to correctly implement BIM-BEM within an efficient process that can be adopted for different project types. Regarding the proposed template, a generic BIM-BEM framework was developed in an easy to follow process map considering the identified requirements and various tested tools to support the modeling, model integration, and work/data flows during the design process. Finally, an innovative information protocol was developed in order to streamline the BIM-BEM framework to support accurate information sharing in an appropriate Level Of Development (LOD) for energy simulation at each design phase.

This thesis brings an original contribution to the practice and knowledge by providing a generic and reliable framework to streamline and systematize the use of BIM-BEM during the design process for high-performance buildings. The technical and process approaches proposed in the framework are operationalized by the advanced information protocol for a successful BIM-BIM execution during the design process. Accordingly, using the BIM-BEM framework allows reducing the interoperability errors, saving the time of remodeling and troubleshooting, better data management and maximizing the accuracy of simulation results that in total evoke sustainable design evolution and optimization early by professionals.

The professionals can employ the BIM-BEM framework by following and adapting the proposed design activities, integration methods, work/data flow and the information protocol in their design process. For specific project types, the framework can be adjusted and advanced by identifing complementary requirements to each design activity. In addition, it can be upgraded and advanced by including other innovative model integration and process approaches as future work. In future work, the framework will be extended by advanced technical solutions that needs moving current industries toward using programming expertise in their process.

Keywords: Building Information Modeling (BIM), Building Energy Modeling (BEM), design process, information protocol, Level of Development (LOD).

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
API	Application Programming Interface
AR	Action Research
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCA	Building and Construction Authority
BDL	Building Description Language
BEM	Building Energy Modeling
BIM	Building Information Modeling
BPMN	Business Process Modeling Notation
BPS	Building performance simulation
CIC	Computer Integrated Construction (CIC)
CIFE	Centre for Integrated Facility Engineering
COP	Coefficient of Performance
DHW	Domestic Hot Water
ES	Energy Simulation
GBAT	Green Building Assessment Tool
GBS	Green Building Studio
GBXML	Green building XML
GSA	General Services Administration
GUI	Graphical User Interface
HVAC	Heating, Ventilating, and Air-Conditioning

IDM-MP	Information Delivery Manuals Process Mapping
IDP	Integrated Design Process
IFC	Industry Foundation Classes
IR	Information Requirements
LEED	Leadership in Energy and Environmental Design
LOD	Level of Development
LOD (ES)	Level of Development for Energy Simulation
MVD	Model View Defenition
SBT	Space Boundary Tool
SLR	Systematic Literature Review
TPI	Third Party Interface
VDS	Virtual Design Studio
VPL	Visual Programming Language
XML	Extensible Markup Language

INTRODUCTION

The design of high-performance buildings requires evaluation, comparison, and validation of various design scenarios using simulation tools. Several simulation tools are available with different characteristics and abilities to support modeling and estimating building energy. However, using these tools requires creating an accurate Building Energy Model (BEM) as an abstraction of the real building design. Complexity and level of effort to create BEM manually are a hindrance to exploring design solutions (Asl et al., 2015). Traditional BEM is based on the paper-based interpretation that is usually very tedious with a high level of reworks at each phase of the design; especially, when many modifications are applied to the building design (Kumar, 2008). Besides the modeling issues are the challenges from the early phases of the design process of information sharing between architects and engineers in the communication and collaboration process. Thus, inaccurate interpretation of design plans, remodelling, and poor collaboration between professionals lead to several issues during the traditional BEM process such as: modeling errors, omissions, and unexpected costs, delays, and eventual lawsuits between the various parties of the project team (Eastman et al., 2011).

Using building information modeling (BIM) to create BEM opens the door for a more effective design process in which multiple iterations could be made. BIM-BEM approach moves the design process and the involved team from paper-centric processes toward an integrated and interoperable workflow where these tasks are part of a coordinated and collaborative process.

However, currently, significant limitations and challenges exist in terms of data transfer during the design process. Integration of a BIM model into BEM tools is still incomplete because of interoperability issues, and inefficient processes to complete energy simulations. Several technical approaches have been developed to improve the BIM-BEM analysis, such as those proposed by Kim et al. (2016), Choi et al. (2016), and Andriamamonjy, Saelens et Klein (2018). However, these researches disregard its integration to the design process. Besides, few process maps have been suggested to define the BIM-BEM workflow, such as the study proposed by Wu et Issa (2014) and Ilhan et Yaman (2016). However, they are not considered technical solutions. Moreover, in most of the current studies, the work and data flows, the Information Requirements (IR), and the Level Of Development (LOD) are ill-defined or sparse and focus either on BIM model or BEM, not the two simultaneously. Therefore, there is a need for a formalized framework to realize an effective BIM-BEM execution. Thus, the main research question is how to execute BIM-BEM effectively during the design process? Addressing the research question leads to the main objective of this article-based thesis, which is to develop a framework for BIM-BEM execution that provides best-suited technical approaches within an effective process to support building design.

This research thesis is built on Action Research (AR), which supports a practical perspective by collecting data to diagnose problems, searching for solutions, taking action on developing solutions, and verifying the final action results. Three articles are presented as standalone articles, which have been either published or submitted to peer reviewed academic journals, to meet the thesis requirements.

In the first article, a thorough systematic review of the currently available technical and process approaches of BIM-BEM is conducted to define the existing research gaps. Based on these gaps, a BIM-BEM framework template is developed, specifying all requirements to execute BIM-BEM during the design process. It counts as a unique reference in this field to the professionals and researchers to adopt the framework and define the best-fitted technical and process approaches for their BIM-BEM projects.

This framework is employed and advanced in the second article in an easy to follow BIM-BEM process map. It proposes the essential details such as design activities, work and data flows and technical solutions to proceed with the creation of a BIM model for BEM during design exploration to extend the corpus of knowledge necessary to improve the design process. The proposed BIM-BEM framework is finalized in the third article by developing an information protocol for BIM-BEM including accurate and proper IR in classified correct Level Of Development for energy simulation (LOD_{ES}) to support modeling and data sharing during the design process. The proposed information protocol is developed to meet the scope of each design phase and design activities presented in the first and second article. Thus, it provides the modeling and sharing requirements for each BIM-BEM steps presented in the proposed framework.

The research contributes to the body of knowledge by proposing a complete and effective BIM-BEM framework for both technical and process aspects that minimizes data sharing errors and maximizes the accuracy of energy simulation results during the design process. In this regard, it is a dependable basis to develop a specific data exchanger with energy-related coordination view by software developers. In addition, this thesis contributes to the practice with an innovative edge by providing a comprehensive, reliable and executable framework that encourages design industries to use a BIM model for BEM to conduct energy simulations in their design process. It also supports the operationalization of existing frameworks by defining the appropriate LOD and relevant IR for BIM-BEM to conduct energy simulations during the design process.

To follow this thesis, the first chapter provides a foundation literature review, problem statement, research objectives, and research methodology. Accordingly, the three articles are summarized as the outcomes of this thesis that are included in the following chapters. Finally, a generic discussion and conclusion complete the thesis.

CHAPTER 1

LITERATURE REVIEW

The BIM-BEM approach is a combination of technology and process that has three main elements (GSA, 2012): BIM, BEM for energy simulation, and the model integration between them. Therefore, each element is described to clearly understand the theoretical motivation of this thesis.

1.1 Building Information Model (BIM)

BIM is one of the most promising innovations within the building design industry and described using several definitions from different aspects. According to the National Building Information Modeling Committee (2018), BIM is a data-rich digital representation of the physical and functional characteristics of a model as well as a shared information resource that provides a reliable basis for decision making throughout the building life cycle.

BIM allows the users to get the benefits of interoperability with different tools to share the designed model. Interoperability is the ability of communication and data exchange between two separate systems or software programs (Rovas, 2017). This ability of BIM supports avoiding remodelling the same information in other software. Thus, linking a BIM model with non-BIM modeling tools via data exchangers is an important effect of this technology to save time, resources, effort and reduces the risk (Rovas, 2017). Communication and data exchange of a BIM-based project can be done among all internal and external parties using sharing model that leads to improved collaboration and coordination.

From the technical aspect, a building can be constructed digitally in a suitable BIM tool by containing all aspects of building information into a 3D virtual format (Eastman et al., 2011) that can be shared for multiple dimensions. Seven BIM dimensions (Charef, Alaka et Emmitt, 2018) are represented in Figure 1.1 to define physical and non-physical characteristics of buildings during the whole building life cycle (Olsson et Lagerlöf, 2018).

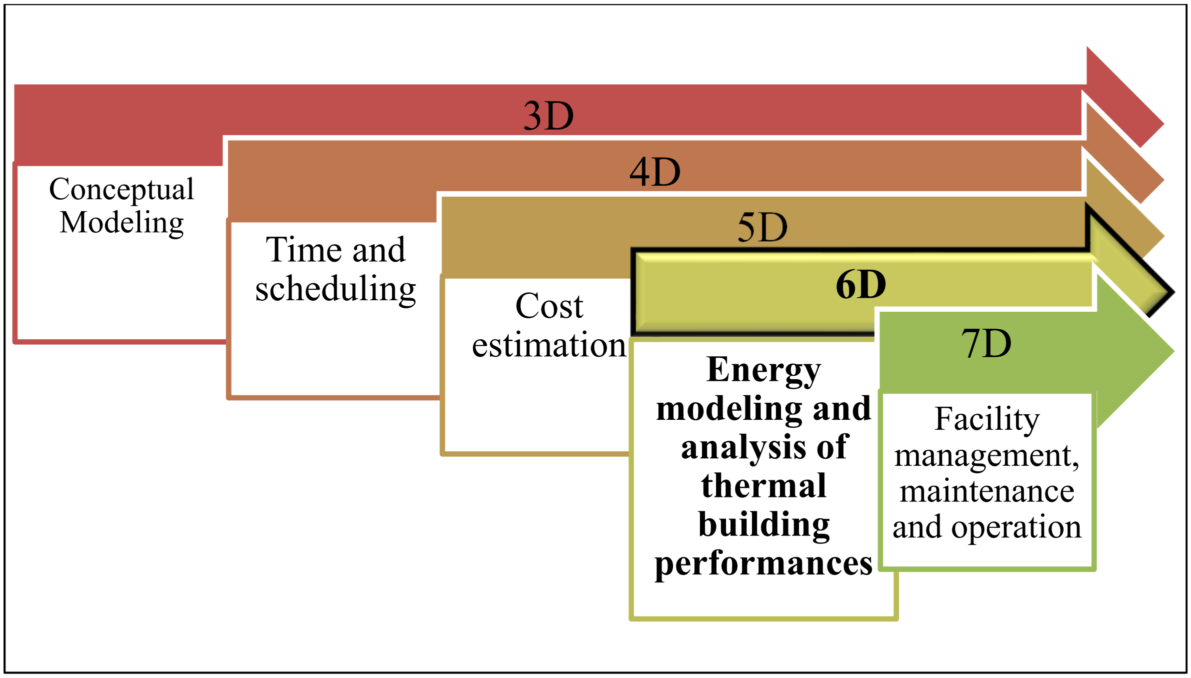

Figure 1.1 Different dimensions of BIM

As illustrated in Figure 1.1, BIM 6D focuses on energy analysis of building towards an optimized building. The BIM-based data sharing capability provides the opportunities for different professionals to exchange energy-relevant information with various energy simulation tools to complete energy performance analysis from the early design to detailed design and operation phases (Kim et Woo, 2011).

1.2 Creation of BEM for energy simulation

Energy simulation tools are being used increasingly in the design of buildings to better understand building performance in particular in terms of energy optimization (Rovas, 2017). Generally, energy simulation tools include a graphical user interface (GUI) and a thermal calculation engine (Figure 1.2). Graphical interfaces enable the users to easily generate input data, run the simulation with the engine and process the output data to illustrate results graphically (Maile, Fischer et Bazjanac, 2007).

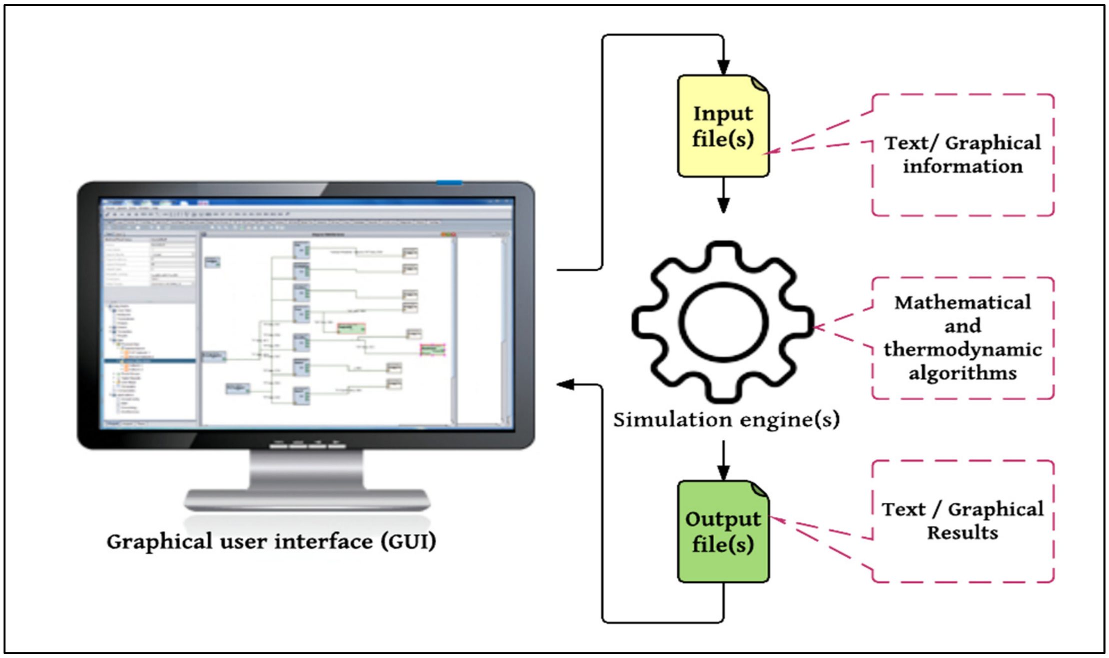

Figure 1.2 General architecture of energy simulation tools

In most cases, simulation engines contain mathematical and thermodynamic algorithms, which use input data as text or graphical information to run a simulation. The typical energy simulation tool requires creating a BEM in their GUI by determining the thermal characteristics of the building and its building systems to calculate thermal loads and energy consumption. The detailed information that needs to be inputted to the BEM includes local weather data, a description of the building geometry and layout, construction type, internal loads, ventilating, and air-conditioning (HVAC) systems, central equipment and operating schedules. The output files contain results from the simulation, warning messages and/or additional information.

During the past years, hundreds of building energy simulation tools have been developed with different features and characteristics. These tools vary from research software to commercial products based on their calculation method, the GUI, the purpose of use, life-cycle applicability, and the ability to exchange data with other software applications. Some of these tools are very popular among users such as, OpenStudio, (2019) and eQUEST (2018). It is essential to know which criteria are important to select the best-suited tool for a specific phase and design process.

In this regard, Attia, Walter et Andersen (2013) identified the most significant criteria that lead to the selection of a suitable energy simulation tool:

- Usability and information management of the interface;
- Integration of intelligent design knowledge-base;
- Accuracy and ability to simulate detailed and complex building components;
- Integration of tools in building design process;
- Exchanging of building model.

Degree of strength and weakness of these parameters vary from one tool to another. Therefore, tools selection is mostly based on project requirements and conditions. Exchanging of building model is one of the main criteria related to this study. It allows for easier workflows and supports the data sharing of building characteristics between collaborating firms and within individual companies (Attia, Walter et Andersen, 2013).

In this regard, BIM can be used to transfer the relevant information to create the BEM in a suitable energy simulation tool to escape from manual input, high level of reworks and iteration process at every stage of energy modeling, which is time-consuming and error-prone. However, it needs to define how a BIM model can be transferred and integrated into a BEM tool.

1.3 BIM-BEM integration methods

The main steps to execute a BIM-BEM project are integrating and translating the BIM model properly into the selected energy simulation tool. In this regard, there are different model integration approaches, which generally allow multidisciplinary storing and sharing of information with one virtual representation of the building. Three model integration approaches have been defined by Negendahl (2015): combined model, central model, and distributed model. Each approach requires certain processes, user interaction and software/interface, which are described in detail in CHAPTER 3 and CHAPTER 4. A summary of these approaches is illustrated in Figure 1.3:

- In the combined approach, the modeling and simulating are performed in the same environment (design and calculation in one tool) by a practitioner that acts as a modeller of both architecture and the engineering information;
- In the central approach, building information modeled in a design tool can be centralized into a data schema and transferred to a simulation tool;
- In the distributed approach, a middleware connects the design and simulation tool in order to modify and enhance the model in real-time for successful interpretation of the information between the tools.

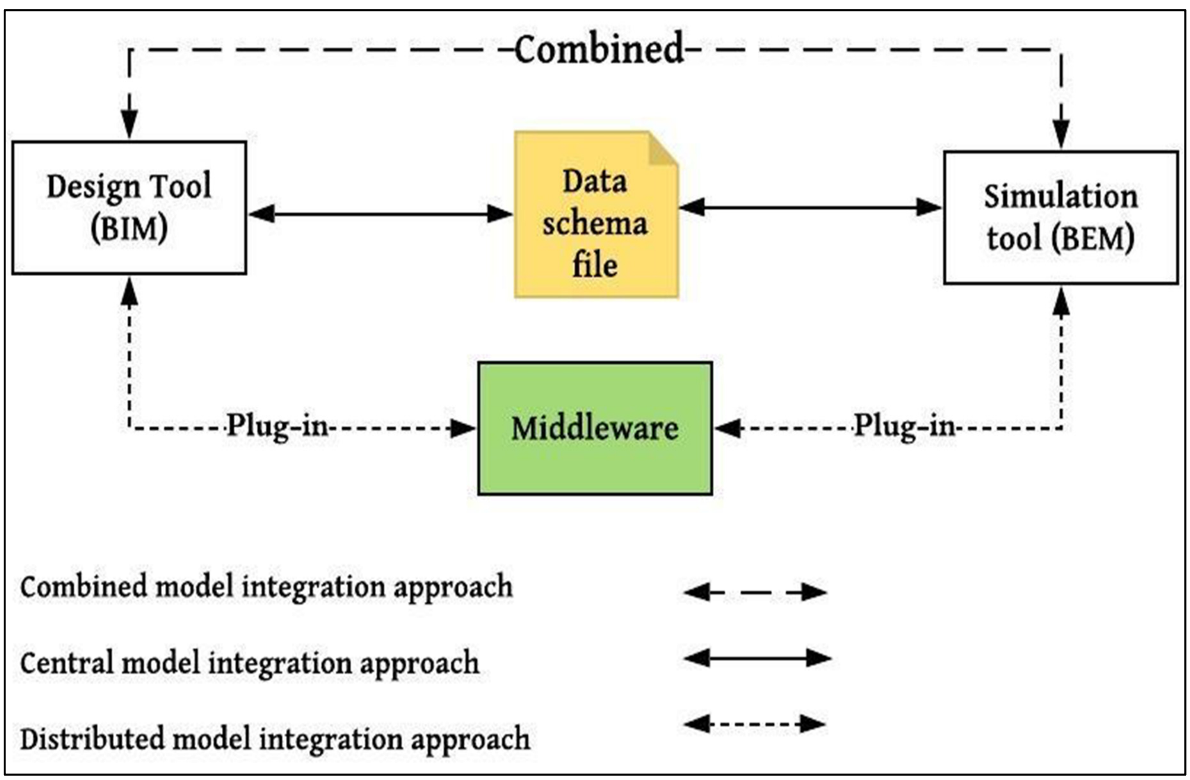

Figure 1.3 Model integration approaches

The central model integration is the most common one for BIM. The data schema plays an important role in correctly implementing the central approach since it provides the data hierarchies and semantics required for interoperability between tools. It can create a common language for transferring the model between BIM and BEM tool. Depending on the data exchanger, specific portions of the platform's native data schema are translated by defining the data into the format needed by the energy analysis tools (Eastman et al., 2011). The common and usable data schemas for BIM-BEM are Industry Foundation Classes (IFC), Extensible Markup Language (XML), green building XML (gbXML) and (ifcXML). Thus, previews of different data schemas are described as follows:

IFC

The IFC schema is developed to define an extensible set of consistent data representations of building information for exchange between Architecture, Engineer and Construction (AEC) software applications (Eastman et al., 2011). This common language is used by all engineering disciplines and allows sharing information between AEC/FM (Facility Management). IFC is object-oriented and describes the behavior and relationships of the component object within a model (Eastman et al., 2011). Sharing an IFC-based BIM model in a multi-user environment allows more than one user work on the same building model and even simultaneously on the same element.

XML

The XML schema is developed to provide alternative schema languages and transport mechanisms, especially suited for Web use (Eastman et al., 2011). These standards may provide a mechanism for interoperability among applications with different internal formats, which leads to a better way to communicate (Construction, 2012).

GBXML

Many users in the HVAC industry are adopting the gbXML file format in efforts to streamline the building design process. It is also developed to transfer the required information for preliminary energy analysis of building envelopes, components, location, thermal zones, and material thickness (Osello et al., 2011). In addition, gbXML is one of the most complete formats, which identifies building adjacencies, interior or exterior elements and shading surfaces (Osello et al., 2011). Therefore, it focuses more on transferring architectural BIM model to energy simulation tools (GSA05, 2012). Green Building Studio (GBS) is one of the most commonly used software that works with gbXML and can import BIM model as a third party interface. The correctness of the BIM model in the GBS is automatically informed by warning the user of issues. Error checking routine of GBS allows iteratively refining the BIM model (Stumpf, Kim et Jenicek, 2011).

IFCXML

The BuildSMART (formerly the International Alliance for Interoperability) created IFCXML file, which provides XML and IFC schema features to promote open and interoperable IT standards. It supports the process and facility management industries (Kim et Anderson, 2011; Kim et al., 2016). However, IFCXML produces very long and complex files even for very simple BIM models.

Nevertheless, the implementation of the current data schemas is still inconsistent and requires manual checking for accuracy. Inconsistency of data schemas happens because of differences among heterogeneous databases. When two objects come from different information sources, some of the values of their corresponding attributes are unlike or distinct causing inconsistency (Anokhin et Motro, 2001). According to Kim et al. (2016), the existing data schema supports partial interoperability in transferring data from BIM-based model to energy analysis tools. Therefore, the simulation results illustrate a large difference between BIM model and imported model due to missing or misplacing information, especially in complex projects. The correct data translation between BIM and BEM tools can be achieved when two domains have the same modeling method such as an object-oriented approach (Jeong et al., 2015). Unfortunately, some of the common BEM databases are not object-oriented and have their own unique input format with highly specialized syntax and semantics.

Besides, many of the BIM models created by architects do not contain the required information for energy modeling (Construction, 2012). Using the wrong toolset with the wrong object types in a BIM application becomes an issue to export the desired data schema. In addition, calculating energy performance with an incomplete BIM model and ambiguous assumptions could result in incomplete and inaccurate output (Kim et Woo, 2011). The big issues occur when geometric errors appear. It is difficult to troubleshoot and determine the source of errors (GSA05, 2012); especially in the iterative process of modifying the architectural model in different design phases (Osello et al., 2011).

Therefore, it is essential to start the BIM model with a standardized and organized approach, particularly when the greatest amount of information must be used in an interoperable way. Thus, the BIM model creation, data input and the communication approach across each design phase can heavily influence the BIM-BEM execution. In this way, 70% of the information required to run the energy simulations can to be defined in the BIM model at each modeling step (Choi et al. 2016). Consequently, the rest of IR can be added manually in the BEM tools.

1.4 Information Requirement (IR) for BIM-BEM execution

A virtual model is constructed by defining the required information based on the project objectives. As described, a BIM model contains most of the IR for BEM that need to be transferred to energy simulation tools (Choi et al., 2016). The energy-relevant categories that can be defined in a standard BIM model for BEM are the architectural and some of the mechanical information detailed in Figure 1.4.

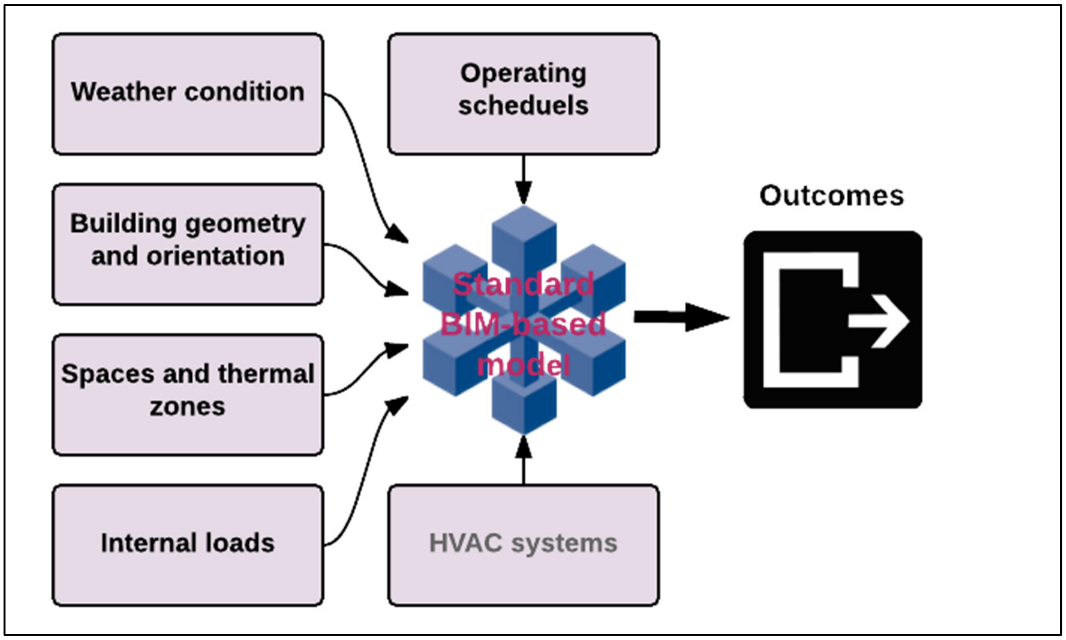

Figure 1.4 General information needed for BEM that can be defined in a BIM model
Taken from Tuomas Laine (2012)

The architectural BIM model contains information such as building geometry, envelope, spaces, and material and construction types. This model can be transferred using data exchangers in two views: (1) Coordination view and (2) Space boundary view, which defines space surfaces and their connection to structures, openings etc.

The mechanical information model such as Heating, Ventilation, and Air Conditioning (HVAC) can be defined in a BIM model. However, transferring this type of information from BIM to BEM tools using the available data exchangers is faced with some interoperability issues and is often impossible (O'Sullivan, 2005).

Defining the relevant IR accurately in the BIM model is very important for BEM since the true data exchange is achieved only through correct data definitions (Latiffi et al., 2015). In the BIM-BEM process, it is essential to understand what are the categories, types, ranges and the units of IR at each modeling step based on the design activity and the scope of the project (Fox et Hietanen, 2007).

In this regard, some guidelines exist that present generic information for all BIM dimensions (3D to 7D) and sectors (AEC), such as the ones developed by Computer Integrated Construction (CIC) group (CIC, 2011) and the series of guidelines developed by Building and Construction Authority (BCA) for coordinators (BCA, 2013b), architects (BCA, 2013a), and engineers (BCA, 2015). These guidelines are very broad and do not focus on the IR for BEM. The detailed information for BEM is outlined in the documents such as the guidelines developed by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Fundamentals, standard 90.1 (2010), and standard 62.1 (2016).

Currently, there is a lack of trust between design professionals to receive a seamless BIM model and continue to work on that model (Pittard et Sell, 2017). The design professionals are still confused by the inconsistent, incomplete, and unclear source of data and the applied information through the BIM-BEM steps. Usually, due to the lack of an information protocol, a BIM model is not created using the accurate IR at each modeling step. In addition, the BIM model is transferred and shared in an inappropriate level during the design process (Wu et Issa, 2014). Thus, the next modeller needs to review the BIM model, adjust the boundaries and redefine the information in an iterative process. Furthermore, as the project advance, change in the level of modeling, which progresses with the different phases of the project, add to the complexity of properly executing BIM-BEM. This change in the level of modeling refers to Level Of Development (LOD).

LOD supports the degree of graphical and non-graphical information at various modeling and sharing steps of a BIM-based project. LOD defines the information and detail that needs to be provided at various points in the design process to track the progress of a model. It allows relying on specific information in the imported model, which enables consistency in communication and execution. Thus, modeling with accurate IR and sharing at the proper LOD is required.

However, the existing LOD contains generic information for all BIM-based purposes, which requires many modifications, simplification, and advancement to be used for BEM purposes.

The development of LOD for energy simulation requires considering the design scope and modelling activities at each phase.

1.5 BIM-BEM during the design process

Design process contains a coordination of the technical and non-technical functions of the design within a project. Building energy simulation is one of the important parts of the design process that allows comparing the performance of design solutions to select the best fitted to the project objectives (Tuomas Laine, 2012). For achieving an optimal solution, the collaboration between architects and engineers from the early phases of the project is essential. Design process traditionally starts with the architect who performs the design of the building geometry based on the qualitative design of the existing buildings and prior experiences. Then, engineers usually carry out simulations during the detailed design phase for validation.

In a traditional design process, the risks of model divergence are high, which leads to all sorts of errors and misunderstandings during the early phases. In addition, many of the decisions and analyses that influence energy uses (such as daylighting analysis) are not considered during the early design phases (GSA05, 2012 and Eastman et al., 2011). Late analysis of building design performance requires several changes and rework in all the drawings (GSA05, 2012), which is not an efficient design process. The cost and time overruns in this approach can eventually lead to disputes, arbitration and litigation, and even total abandonment (Aibinu et Jagboro, 2002).

In contrast, the process for a BIM-based design should be more integrated, for which multiple disciplines and design elements can work in a collaborative environment to create a synergy between the various systems and components (Todd et Hayter, 2003). In this regard, the BIM-BEM process should begin at the project front-end, during which architects and engineers can make design decisions earlier in the project based on correct data instead of assumptions. The information sharing, collaboration and the early decision-making have the most influence on the building performance in terms of reducing the building's resource consumption, the environmental impact and the design conflicts (Azari et Kim, 2015). This also leads to reduce waste time, increase value to owners, and maximize efficiency in the entire project's life cycle.

However, the BIM-BEM process needs to be followed properly through critical thinking and requires a deep understanding of the design process for successful execution (Council, 2014). Figure 1.5 presents the different design phases including the important elements of each phase to proceed with the BIM-BEM execution.

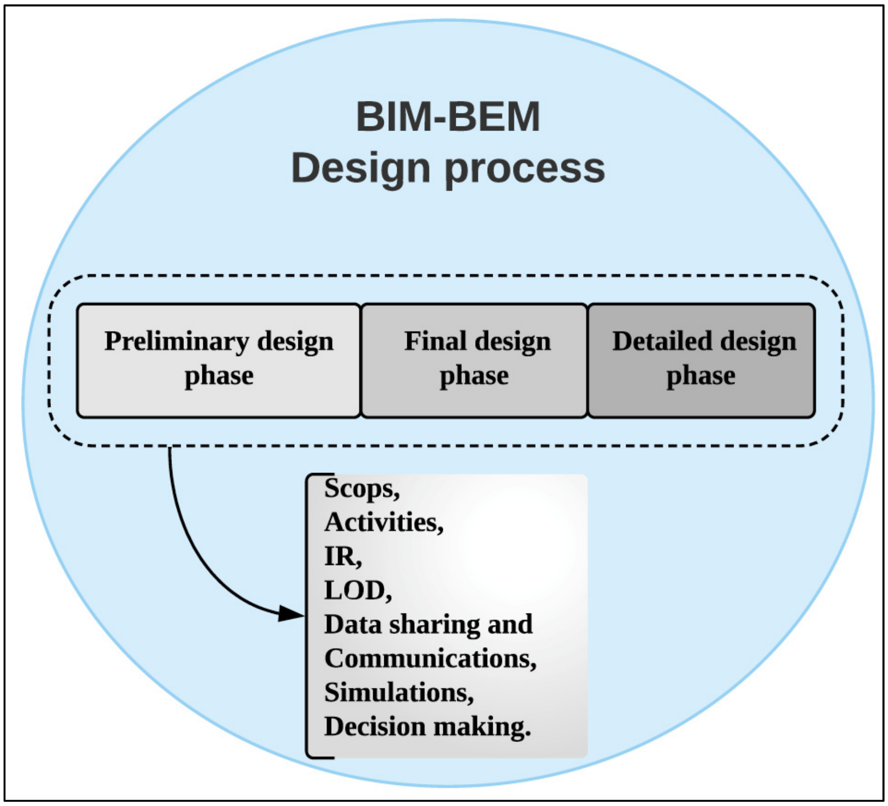

Figure 1.5 Different design phases

There are few process maps developed for BIM-BEM execution by other researchers (Crosbie et al., 2009; Wu et Issa, 2016; Jeong et al., 2015; SALD et al., 2016; and Zanni, Soetanto et Ruikar, 2016) that describes some of the requirements (such as the design phases, the work and data flows at all BIM-BEM steps, the used tools and technologies, the IR and the LOD) to implement BIM-BEM during the design process. These process maps are presented and assessed in Annex I to define whether they covered all the requirements for BIM-BEM execution and to define their specifications and limitations.

Therefore, to properly execute BIM-BEM during the design process, the following aspects need to be clearly established: the design activities, the work and data flows, the LOD and the information requirements (IR) at each design phase.

1.6 Existing limitations for BIM-BEM execution during the design process

Currently, significant limitations and challenges exist to execute BIM-BEM in terms of adopting the data exportation during the design process. Integration and adaptation of a BIM model into BEM tools are still imperfect with the lack of interoperability and inefficient process. The main problems are related to the interoperability and model integration issues, and incoherences between technical and process approaches that lead to difficulties in its implementation by the professionals during the design process (GSA05, 2012).

The BIM models cannot be properly integrated into the current energy simulation tools and are not directly compatible, due to the differences in the attributes and semantics of BIM and energy simulation tools (Jeong et al., 2014). Difficulties in data exchanges and integration of the model between different implementers of exchange functions have differing assumptions, which cause inconsistencies in the reliability of the data.

In addition, there are some limitations to implement the current BIM-BEM approaches, which makes them difficult to use in real projects. These limitations are noted as follows:

- Most of the BIM-based studies do not consider BEM aspects (activities and requirements) in the design process.
- The existing approaches consider the limited technical performance of one step of the whole BIM-BEM procedures for a specific design phase rather than proposing an approach that covers the complete execution during the whole design process.
- There is no effective, generic, and easy-to-use execution process to implement BIM-BEM that specifies required details of proper tools, suitable model integration solutions, and work and data flow within a design process.

- Most of the current approaches require a large number of modifications, simplifications, interpretations, and re-entry of inputs at all BIM-BEM steps. This occurs due to the deficiency of a reliable reference to specify the content of a BIM model for BEM with a high degree of clarity of IRs at various modeling and sharing steps from early design phases.

1.7 Objectives

From a review of the literature on both practical and theoretical perspectives, a holistic, efficient, and reliable BIM-BEM framework that includes an appropriate model integration method, modeling techniques, work/data flow, and IRs at proper LOD to assist the energy conscious decision process is required.

Therefore, the main objective of this thesis is to develop a generic and executable BIM-BEM framework to support the design process that provides best-suited technical approaches within an effective process. In this regard, the research specific objectives are:

1. Identify actual gaps between technical and process aspects by completing a systematic literature review;
2. Define the requirements to use BIM model for BEM during the design process.
3. Develop a complete, generic and standard execution process map;
4. Develop an information protocol including appropriate LOD for energy simulation (LOD_{ES}) and IR.

CHAPTER 2

METHODOLOGY AND STRUCTURE

The originality of the proposed approach is that it is centered on design perspectives to address practical issues and challenges encountered in the industry. Therefore, the research design to reach the objectives of this study built on Action Research (AR), which links theory and practice and aims to solve an immediate practical problem in a real setting (Azhar, Ahmad et Sein, 2009). AR is based on four principal steps: diagnosing, action planning, action taking and validating.

2.1 Diagnosing

Diagnosing is performed by ethnographic methods, analyzing previous approaches and case studies (design firms in this case) containing classifications, grouping, mapping, assessments, and observation records (Stringer, 2013). Therefore, the first step of this research consisted of the identification of the primary research problem(s) or diagnosing that continued until the research project was completed. Diagnosing was started by reviewing the literature to discover the theoretical issues and the actual gaps between the current BIM-BEM approaches; then, it was completed by analyzing and interpreting the identified issues and gaps.

The diagnosing step was the basis of this research, which was identifying the main gaps between the technical and process aspects. In this regard, a Systematic Literature Review (SLR) (Khan et al., 2001; Okoli et Schabram, 2010) approach was employed to complete the diagnosing step. Figure 2.1 illustrates the procedures of applying SLR that started by title screening using proper keywords.

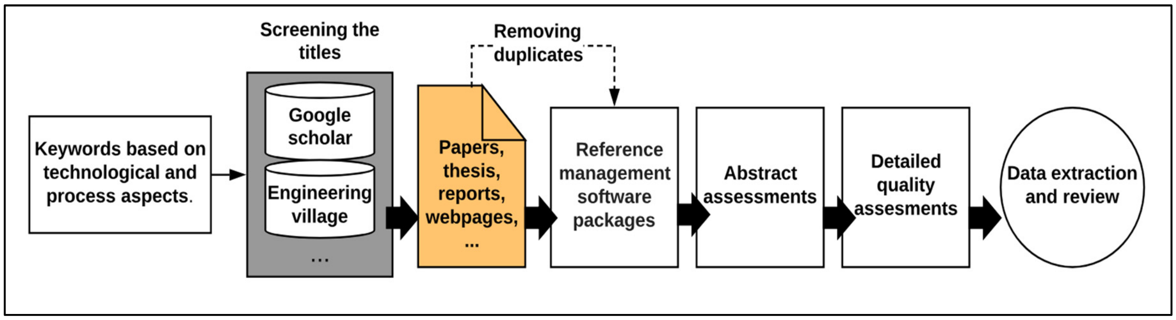

Figure 2.1 SLR procedure

The sources were sifted, assessed, and extracted to be reviewed. Thus, relevant data were collected, analysed, interpreted and classified systematically in the way that the main gaps in BIM-BEM execution during the design process between technical and process aspects were identified (for more detail refer to the first article presented in CHAPTER 3).

2.2 Action planning

Action planning established the targets to propose changes to the currently available approaches. It included three parts: (1) Identify and map the existing BIM-BEM process, (2) Identify the theoretical key parameters at each design phase, and (3) Select the model integration method using a test case.

2.2.1 Identify and map the existing BIM-BEM process

Defining the BIM-BEM process from the current practices and literature was done to troubleshoot and evaluate the potential of improving the process, model and user interaction. Field investigations were completed for five different cases. As illustrated in Table 2.1, two architectural (A1 to A2) and three engineering (E1 to E3) in progress BIM projects were investigated including observations, questioning, analysing, and testing of different modeling tools for real-projects.

Table 2.1 Field investigation project details

Project	A1	A2	E1	E2*	E3
Design phase	Preliminary design	Detailed design	Final design	Detailed design	Detailed design
BIM tool	Revit	Revit	Revit	Revit	Revit
BEM tool	GBS	IES-VE	eQuest	OpenStudio	IES-VE
BIM-BEM steps	BIM pre-processing	All BIM-BEM steps	BEM completing	BEM completing	BIM-BEM interaction and BEM completing
LOD for simulaion	200	400	300	400	400

The results of these investigations were used to define the work and data flows including the available tools, technical approaches and IR. The BIM-BEM process was detailed step by step at each design phase and mapped using the Business Process Modeling Notation (BPMN) approach (White, 2004), presented in Annex II.

In this regard, the preliminary process map presented in Figure-A II-2 was developed to better understand the existing procedures, which includes the principal activities and procedures to create the BIM model, data exchange between BIM and BEM tools, the verification of the integrity of the transferred model to the BEM tool, and the simulation process. The data entry and the source of information to model each element were collected and documented in table formats to extract the IR that were investigated in both BIM and BEM models for all used tools. Also, the LOD to share the BIM model was identified to assess the transferred IR at each design phase. The preliminary process map and the existing LOD used provided the basis of the proposed framework in this thesis.

2.2.2 Define theoretical key parameters at each design phase

Defining the key parameters that include the accurate IRs, recommended modeling technics, and design activities are required for an efficient BIM-BEM framework. In this regard, the energy simulation goals (such as estimating building loads, and energy consumption, (Athienitis et O'Brien, 2015)) were the basis to determine and classify the key parameters during the design process based on a review of the literature and appropriate standards.

2.2.3 Select the model integration method using a test case

In this step, a simple building was selected as a prototype and modeled in a BIM tool (Revit). The IRs, such as building specifications, thermal data, and mechanical system information, were used to model the building at the micro and macro levels. In this way, the verification of the theoretical key parameters and extracting the practical parameters were completed.

The BIM model of the test case is transferred into different BEM tools using available model integration methods to compare and assess them according to the following limitations and needs to select the most appropriate one: the primary BIM-BEM process, the industry preferences, the available tools (which are mostly free packages), and the interoperability, accuracy, and flexibility of the model integration methods.

First, the existing process and preferences of the current industry were considered because of the obstacles and resistance to change their protocols (Kalinichuk, 2015); this study tried to effectively advance the current industry approach by developing an appropriate framework. Then, the best-suited BEM tool options were identified according to criteria defined by Attia, Walter et Andersen (2013) and Attia (2018). The BEM tools were assessed based on their compatibilities and ability to import the BIM model of the test case. The results of compatibility and interoperability assessments defined the proper model integration method for the industry.

After completing the model integration, the accuracy of the imported model and the IRs were verified to identify the missing, miss forming and the common warnings to eliminate them in an iterative process. The imported model was completed in the BEM tool based on the primary BIM-BEM process map to observe the limitations and the essential information required to complete the model transfer. The required actions were classified to be implemented and developed during action taking.

2.3 Action Taking

In this step, the identified implementation issues were addressed and changes were made using complex real projects as test cases in order to detect and solve the complex practical issues, with the aim to develop the most accurate BIM-BEM framework. Accordingly, the implementation process was realized in three steps: BIM pre-processing, BIM-BEM integration, and BEM completion. At each step, the practical IRs and the existing LOD were classified, the work and data flows were optimized and the recommendations for model integration were documented for each design phase. This led to the proposition of an information protocol that includs Level Of Development for energy simulation (LOD_{ES}) to support the appropriate IR for BIM-BEM execution during the design process.

2.3.1 BIM pre-processing

With the notion of garbage in-garbage out, one of the important steps in BIM-BEM procedures is the ability to create a seamless and suitable BIM model to be exported to the selected BEM tool. The procedures of BIM pre-processing development contain create/edit BIM model and prepare the BIM model to transfer into the BEM tool (Figure 2.2). Creation of the BIM model was realized using a complex building as a test case that contains most of the challenges and constraints of interoperability that most users would have to encounter. The first step was to collect the physical and thermal IRs from all the available elements such as architectural and mechanical plans and specifications. Modeling the building components was performed in a BIM tool (Revit) following the principal process map defined in the action-planning step (the current BIM-based framework). Defining the physical parameters, and adding component properties and family sets (e.g. glazing properties and material specifications) completed the architectural BIM model.

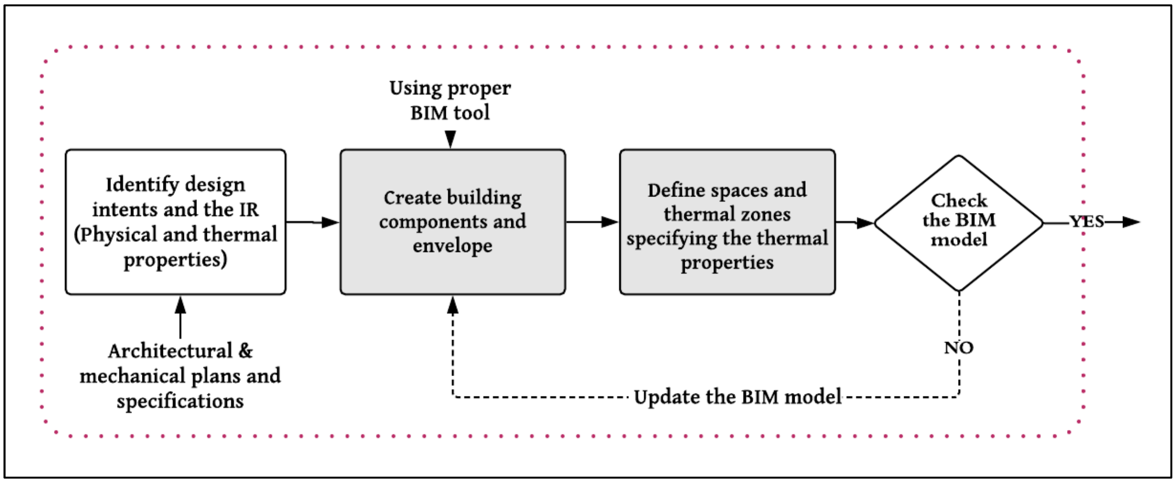

Figure 2.2 BIM pre-processing

To prepare the architectural BIM model for BEM, all the rooms were assigned as spaces in different zones specifying the types and thermal specifications to verify them in the transferring process (Figure 2.2).

At the end of the BIM pre-processing step, the model was verified to be well integrated and accurately attached to eliminate errors and warnings for the exportation of the model. In this way, an iterative process took place in order to edit the BIM model, optimize the process and eliminate the possible errors. Meanwhile, the modeling recommendations, the IRs and the flows were updated to create a more complete framework.

2.3.2 BIM-BEM model integration

In this step, as illustrated in Figure 2.3, the model integration method (the central method), defined in the action-planning step, was implemented in the proposed BIM-BEM framework and embedded in the design process. Accordingly, the data exchanger(s) or the middleware supported by defined BEM tool(s) were identified, customized and tested in order to advance the model integration method.

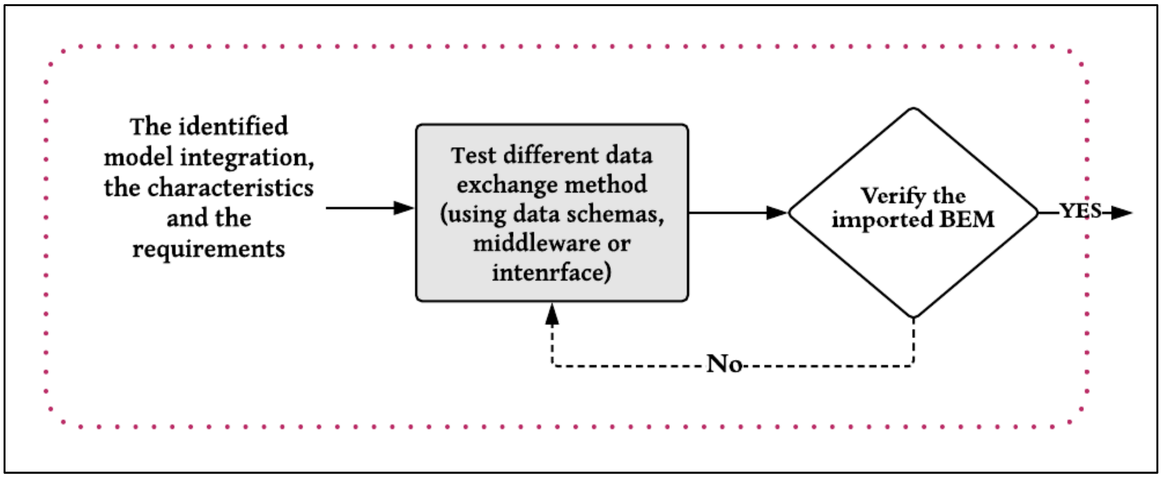

Figure 2.3 Model integration for BIM-BEM

Thus, the prepared BIM model was exported to different types and versions of data exchanger files such as various versions of IFC coordination views, IFCXML, gbXML files, etc. As illustrated in Figure 2.4, various IFC versions, were customized by modifying different options (such as space boundaries) and details (such as property sets) in the file. They were tested with all options and LOD by importing them into the identified BEM tools to check the ability and accuracy of translating the BIM model and the accuracy of the IRs. Thus, the characteristics and features of the data exchangers were compared to select the most appropriate one. To complete this step, a model verification was performed based on the action-planning documentation. In addition, the transferred models were assessed to define the appropriate LOD_{ES} at each BIM-BEM interaction during the design process.

Test	File type	IFC version	Space boundries (1st level/2nd level)	Export only elements visible in view	Use active view when creating geometry	Export Revit property sets	Export IFC common property sets	Export scheduel as property sets	Export base Quantities	Level of detailes (Low/medim/high)	level of details for some element geometry	Description
1	IFC	2x2	Non	_	_	_	Yes	_	_	Low	_	No details appear, just the volumetry
		2x2	2nd level	Yes	_	Yes	yes	yes	_	High	Export part as	Better resolution, just the volumetry
		2x3	Non	_	_	_	Yes	_	_	Low	_	Visualisation of material and the colors of some elements such as column and walls is better than 2x2
		2x3	2nd level	Yes	_	Yes	yes	yes	_	High	Export part as building element	No missing elements, deforming appears in the model. The transparency of curtain walls is high and the color of materials is closer to the basis of the BIM-model.

Figure 2.4 Example of testing IFC versions

2.3.3 BEM completion

In this step, the remaining modeling that is mostly detailed HVAC information were performed or adjusted based on the mechanical specifications of the testcase to run the simulation. The procedures of the BEM in the simulation tool were defined to complete the process map and the IRs. The simulation results obtained at each design phase were used to finalize and validate the BIM-BEM framework.

2.4 Validation: verification using test cases

Validation according to AR was not possible. However, the accuracy and applicability of the proposed BIM-BEM framework were verified using test cases. In this way, the BEM was created using traditional approaches (which is an accepted method in the current industry, but not the efficient one) to compare the procedures, the IRs, the LOD_{ES}, and the simulation results with the proposed BIM-BEM approach. The small difference between the simulation results could prove the proposed technical solutions and the accuracy of the model integration method. In addition, the applicability of the BIM-BEM execution, improvement in data sharing, less reworks and faster BEM at each design phase proved the efficiency of the proposed process. Finally, the research outputs generated based on the AR are presented in the three journal articles.

2.5 Structure of the article-based thesis

This section presents the structure of the three articles that constitute the outcome of this thesis (Table 2.2); a multi-layered BIM-BEM framework. Each article has its own demonstration conducted independently; however, the combination of them meets the main research objective to *"develop an effective BIM-BEM framework including appropriate technical and integration methods embedded into the design process"*.

Table 2.2 Structure of articles to answer the research questions

Journal articles	Presents in	Meet the Sub-objectives	Journals	Year of publication
Review of using Building Information Modeling for Building Energy Modeling during the design process	CHAPTER 3	1 and 2	Published in the Journal of Building Engineering (Elsevier)	2019
Framework for using Building Information Modeling to create a Building Energy Model	CHAPTER 4	2 and 3	Published in the Journal of Architectural Engineering (ASCE)	2018
An information protocol for BIM-BEM	CHAPTER 5	3 and 4	Submitted to the Journal of Automation in Construction (Elsevier)	2019

2.5.1 Article 01- Review of using Building Information Modeling for Building Energy Modeling during the design process

Article 01 sets the groundwork of the entire research to meet the first sub-objective of the thesis. It presents a thorough literature review using SLR method identifying and classifying the existing technical and process approaches of BIM-BEM; while detecting the main research gap that highlights the lack of synergy between the existing technological and process approaches (main pillar of BIM-based projects) for BIM-BEM execution. It discusses the need for creating a holistic and practical BIM-BEM framework within the design process. It also proposes an overview of how this could be achieved. In this regard, it contributes to knowledge and practice via a systematic review that details the existing BIM-BEM approaches and available process maps, supplemented with a general framework template for a successful BIM-BEM execution.

2.5.2 Article 02 – Framework for using Building Information Modeling to create a Building Energy Model

Article 02 presents a holistic BIM-BEM framework built on *Action planning, Action taking* and *validating* of AR. The proposed framework is illustrated in an easy to follow process map that combines process and technology for the whole BIM-BEM process including proper model integration method, data/work flows, and categories of IRs during different design phases. The article contributes to the knowledge and practice with a useful and generic process map were the requirements for BIM-BEM execution during the design process are detailed for professionals to create a seamless BIM model for BEM by identifying the requirements to complete energy analysis during the design process.

2.5.3 Article 03 – An information protocol for BIM-BEM

Article 03 addresses the last two sub-objectives of this thesis by proposing an information protocol for BIM-BEM derived from all AR steps. The proposed information protocol contains the appropriate LOD_{ES} considering relevant and accurate IRs at each step and for each design activity during the BIM-BEM process. In this regard, a comprehensive approach is proposed for the entire modeling and sharing process at each design phase to avoid ambiguous definitions and interpretation of the BIM that needs to be transferred to a BEM tool. Thus the article contributes to practice by proposing an information protocol for an efficient execution of BIM-BEM during the design process. This allows the design professionals to understand the process and technological aspects of BIM-BEM and allows to define the relevant IR in the BIM model to be shared in an appropriate LOD_{ES} for BEM and energy simulation. Thus, they can get more accurate simulation results with less time-consuming and cost in the total designing process.

CHAPTER 3

REVIEW OF USING BUILDING INFORMATION MODELING FOR BUILDING ENERGY MODELING DURING THE DESIGN PROCESS

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3.1 Abstract

The use of Building Information Modeling (BIM) for building energy modeling (BEM) is a recent evolution in design practice. The success of BIM-BEM execution relies on considering two important aspects: process and technology. In this paper, a review of the literature using a systematic approach is proposed to highlight that these two aspects are rarely addressed concurrently. This review includes an overview of the BIM-BEM process and recent technological developments, while elaborating on the main research gap. In order to address the identified research gap, the creation of a framework is proposed that would embed the technological approaches within the whole design process by using a proper Level Of Development (LOD) and information requirements via Model View Definition (MVD).

3.2 Introduction

The design of buildings with reduced energy use and high indoor environment quality at an acceptable cost is often accomplished by predicting the energy performance of buildings (Hemsath & Bandhosseini, 2017). A building's energy performance is often predicted by creating a Building Energy Model (BEM) to perform Energy Simulation (ES). Different ES software packages are available, with various capabilities that provide an understanding of the interrelation between design decisions and their impact on energy performance. Using ES to successfully assist the design decision process is achieved by enabling a comprehensive appraisal of design options and complex dilemmas under realistic conditions (Clarke, 2001).

This appraisal requires appropriate communication and data sharing between professionals at each phase of the design process. Building Information Modeling (BIM) related technologies (Chuck Eastman, Teicholz, Sacks, & Liston, 2011) have gained acceptance as valuable tools to improve building design and construction (Summerfield & Lowe, 2012) by enhancing data interoperability and integration. BIM is a "richer repository" than a set of CAD drawings: a BIM model can be constructed digitally and graphically by storing multi-disciplinary information and the characteristics of buildings. BIM enables the use of data available from the architectural model by sharing and exporting the information required to create a BEM, saving model re-creation time and speeding up the project design while allowing for more design iterations (Krygiel & Nies, 2008). The common term for this procedure is BIM-BEM.

Successful BIM projects are characterized by a balance between the process and the technology (Staub-French et al., 2011; Succar, 2009). For BIM-BEM projects, the architectural BIM model is shared in the early design phases to create the BEM and complete the ES in order to reduce the risks of model divergence, errors, and misunderstandings (Klitgaard, Kirkegaard, & Mullins, 2006). BIM-BEM thus must be supported by technological innovations to assist the sharing and visualization of ideas in virtual 3D format. This is possible by creating an intelligent building model, which is referred to as a digital model that defines functional, relational, structural and behavioral relationships between different elements, supporting automatic verification and customization (Singh, Gu, & Wang, 2011).

However, BIM-BEM is still characterized by issues and challenges pertaining to the prevailing design processes and available technological approaches (Smith & Tardif, 2009). This is partially circumvented by (1) the available work and data flows for each design phase that specifies certain details in terms of suitable technological solutions, and (2) specific BIM-BEM technological solutions that consider limited performance criteria of specific design phases rather than proposing an approach that covers the complete design process (Bazjanac, 2008; Hetherington, Laney, Peake, & Oldham, 2011; S. Kim & Woo, 2011). Only a few studies focus on the BIM-BEM design process (e.g. Koppinen and Kiviniemi (2007), Korkmaz et al. (2010), Zanni, Soetanto, and Ruikar (2016), and Ilhan and Yaman (2016)).

Hence, there is a need to identify the gap that exists between currently prevailing processes and available technological approaches. A literature review, using a systematic approach (Kitchenham & Charters, 2007), is carried out to highlight how the available technological approaches fit into the whole design process, how these interactions occur and what are the technical methods used to share and integrate the model.

The identified gaps provide the basis to make the case for the development of a complete BIM-BEM framework and suggest key aspects to be considered. This paper focuses only on implementing unidirectional BIM-to-BEM interactions during the design process. Consequently, operational and optimization processes that require feedback from BEM-to-BIM are out of the scope.

3.3 Survey method

A systematic approach that supports a comprehensive overview of a particular issue is applied to the literature review on BIM-BEM (Abdul Hameed, 2012; Kamal & Irani, 2014) by collecting and combining existing research knowledge using a trustworthy approach. This review includes publications from January 2001- January 2018. The main topics to be reviewed and their associated keywords were first identified, as well as the databases/sources to be searched for scientific papers and industrial reports (Figure 3.1). A total of 192 papers and 15 reports were retrieved from the selected databases for the primary search (Figure 3.1). The documents found (papers and reports) were then exported to EndNote X6 software (Harrison, Summerton, & Peters, 2005) to remove duplicates. The titles were screened and the abstracts were analysed to filter out irrelevant literature.

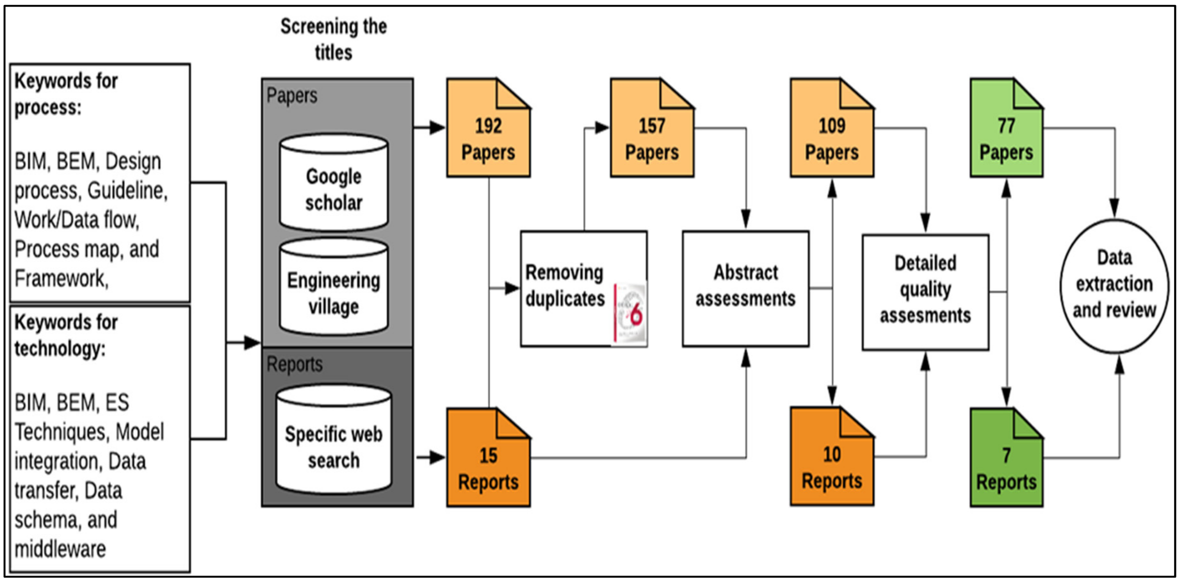


Figure 3.1 Literature review survey method

Finally, a total of 77 papers and 7 reports remained to complete the review; out of these, 27% covered the design process and 59% focused on technological approaches. A mere 14% of the references addressed both aspects. For each aspect, the references are presented and discussed chronologically (Khan, Ter Riet, Glanville, Sowden, & Kleijnen, 2001).

3.4 BIM-BEM literature review

This BIM-BEM literature review focuses on two main aspects: (1) currently prevailing process and (2) available technological approaches.

3.4.1 BIM-BEM process

A building design process for high-performance buildings contains a series of activities and decisions that need to be made by professionals at each design phase. In general, the design process of a new building project includes three phases: preliminary concept design (or program pre-design), final concept design (or schematic design) and design development (ASHRAE, 2006); these are described in Table 3.1, along with their respective component activities.

Table 3.1 Design targets at each design phase
Taken from Anderson (2014) ASHRAE (2006) and Koppinen et Kiviniemi (2007)

Preliminary concept design	Final concept design	Design development
• Evaluate the climate conditions • Study large-scale design alternatives (ex: building mass and form) • Investigate building orientation to maximize natural daylighting • Evaluate the building site and topology	• Study building geometry, spatial configuration, layouts and wall-windows ratio (WWR) to reduce envelope heat gain • Identify and assess the high-performance options based on lifecycle cost • Run the preliminary ESs to estimate the heating and cooling loads • Select the HVAC options	• Refine and finalize the detailed architectural design from inside to outside and top to bottom specifying all characteristics of the envelope, openings, construction types, materials, layers, and thermal properties • Complete advanced analysis of the selected options (architectural and mechanical) • Run the final ES to provide a detailed and accurate building energy prediction

At each phase of the design process, BIM-BEM can be executed to run the ES to achieve the design targets (Clarke, 2001; Klitgaard et al., 2006). Embedding a BIM-BEM procedure in the design process offers the possibility for multiple iterations towards an optimized design in a shared environment.

There are currently several BIM project execution guidelines available that propose BIM workflow/processes, such as those proposed by Eastman et al. (2009), Bloomberg et al. (2012) or Solnosky (2013). In this regard, CIC (2011) proposes a complete BIM guide that presents a detailed process map for BIM execution describing the work flow, the tasks and the information exchanges during the design process. The CIC mainly addresses the BIM aspect, while the BEM aspect is covered more in a holistic project proposed by NewTREND (STAM, 2016), in which a new integrated methodology and tool for ES are developed. A series of reports to implement the method are available, proposing guidelines that detail the process for the selection, design, and optimization of solution for buildings retrofits. However, these guidelines only partly cover the BIM-BEM procedure: the BIM-BEM model integration steps and the technological approach are barely addressed.

Few studies specifically describe the BIM-BEM procedure and management during the design process. Koppinen and Kiviniemi (2007) and Korkmaz et al. (2010) propose a description of the design process for BIM-BEM, including the critical decision points, the information requirements and the information sources for each design phase. Similarly, Tuomas Laine (2012), Wong Wong and Fan (2013), Attia et al. (2013) and Lee (2016) describe the required information for different design phases to achieve a high-performance building.

The reviewed studies on design process for BIM-BEM often disregard details with respect to the identification and implementation of the technological approaches required to complete the ESs. The required work and data flows of BIM-BEM for proper data exchange are scantily detailed. Nevertheless, the gaps identified in the literature are not due to a lack of diligence by the authors, but are rather explained by limited scopes and aims. Thus, they can be refined by integrating BIM-BEM technological approaches within a BIM-BEM design process.

3.4.2 BIM-BEM technological approaches

The proposed technological approaches are driven by different types of model integration methods and technical aspects. Therefore, these methods are discussed first as a foundation to support reviewing the technological papers. How to integrate or link the BIM and BEM tools is the most challenging part of a BIM-BEM process. As defined in the studies conducted by Negendahl (2015) and Toth, Janssen, Stouffs, Chaszar, and Boeykens (2012), there are three methods for model integration: combined, central and distributed methods. These methods are supported by different data schema as briefly defined and described in Table 3.2.

Table 3.2 Technical terms and definitions for BIM-BEM

Technical terms		Definition and description	Authors
Model integration methods	Combined	This method is performed by combining a main model (BIM) and a sub-model (BEM) such that essentially both the design and the ES are completed using one tool. Therefore, a hybrid practitioner (acting both as an engineer and as an architect) completes the modeling and simulating at the run-time level.	(Hensen, 2004; Negendahl, 2015)
	Central	This method consists of centralizing the building information in a shared environment using a specified data schema as the interoperability gateway to transfer semantic information between design and simulation tools.	(Babič, Podbreznik et Rebolj, 2010; Negendahl, 2015; Toth et al., 2012)
	Distributed	This method is performed by transferring data between the design tool (BIM) and simulation tools (BEM) via a middleware. This approach allows the modifying and adapting of a model to be successfully interpreted by other tools.	(Negendahl, 2015; Toth et al., 2012)
Data schema		A data schema describes the organization, structure and the relationship of data sets. It acts as an interoperability gateway between software so that specific portions of the platform's native data model are translated via its gateway. It puts the data (from BIM) into the format required by the receiver tools (BEM).	(Arnold et Teicholz, 1996; Bohm et al., 2008; Cerovsek, 2011; Eastman et al., 2011)
IFC		Industry Foundation Classes define an extensible, intelligent and comprehensive set of consistent data representations of building information to exchange between a set of tools. They are object-oriented and describe the behavior, relationship, and inherence of the component object within a model.	(Bazjanac, 2004; Eastman et al., 2011; IFC; Plume et Mitchell, 2007; Rose et Bazjanac, 2015; Venugopal et al., 2012; Zhao, 2012)
gbXML		Green Building Extensible Markup Language is one of the complete data schemas to transfer the required information for preliminary building energy analysis such as the envelope, thermal zone, and mechanical equipment. gbXML is able to recognize and transfer information regarding building adjacencies, interior and exterior elements and shaded surfaces.	(Ham et Golparvar-Fard, 2015; Osello et al., 2011; Zhao, 2012)

The combined method requires a specific software package supporting both the design and the ES to be produced simultaneously. Combined models are manipulated and simulated only by a hybrid practitioner. This facilitates monitoring the accuracy of the model for all design and ES phases; on the other hand, it creates limitations to be applied by most of the available tools

(2004). Thus, very few studies propose this method for BIM-BEM. Conversely, the central method is the most commonly used approach for BIM projects (Babič et al., 2010). In this method, semantic information can be transferred between BIM and BEM tools through a coupling medium or data schema (Figure 3.2) as the interoperability gateway (BuildingSMART, 2016). A wider range of BIM and BEM tools are available for architects or engineers, which matches with most of their design practices. Therefore, this method is often referred to BIM-BEM.

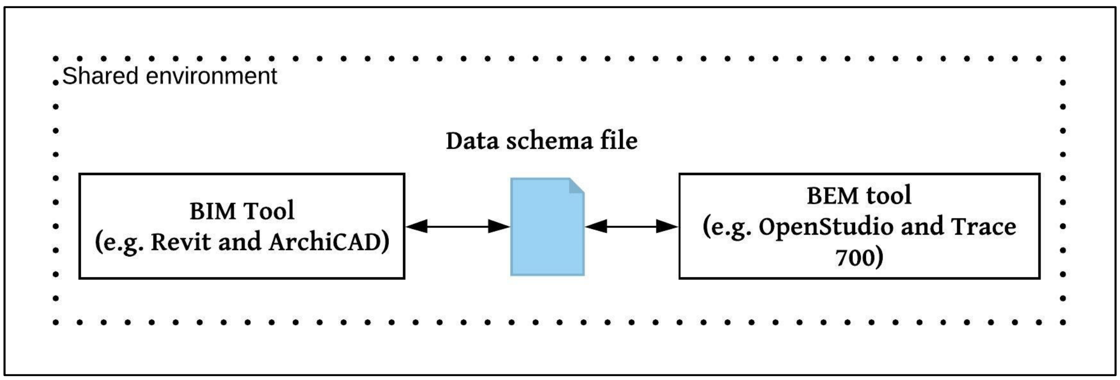


Figure 3.2 Central model integration method

The most well-known and important forms of data schemas used by the central method for BEM are gbXML and IFC. There are three types of software compatibility with these data schemas: Directly compatible, Not compatible, and indirectly compatible (Bazjanac, 2005). Directly compatible is accomplished when there is a mapping interface between the software's internal data model and the data schema model that enables the definitions to be translated directly into the same data semantics of the software. In the absence of the data schema interface or any translator for a BEM tool, the data exchange is impossible, which is referred to as Not compatible.

However, when the BEM tool is unable to translate the data schema format directly or when it cannot accept a particular version of a file, a middle interface with the ability to exchange different model data can be used (Indirectly compatible).

In this case, the solution is to use the distributed model integration method (Negendahl, 2015) that can translate the BIM model to a BEM tool statically or dynamically via one or more middleware. The middleware is key to this method due to its flexibility and features that enable better model interoperability. Unlike the central method, using middleware in the distributed method allows adjusting, tuning, and transforming the BIM model for its successful interpretation by the BEM tool. Thus, the distributed method allows the possibility to enhance or modify part of the model to be prepared for the ES since architectural BIM model does not necessarily reflect the needs of BEM.

Figure 3.3 shows two types of middleware for the distributed method, which are usually a Third Party Interface (TPI), such as SketchUp (Ellis, Torcellini, & Crawley, 2008), or a Visual Programing Language (VPL) tool, such as Dynamo-BIM (2016), Grasshopper (Lagios, Niemasz, & Reinhart, 2010) or Virtual Design Studio (VDS) (Pelken et al., 2013). The coupling of the middleware is also illustrated.

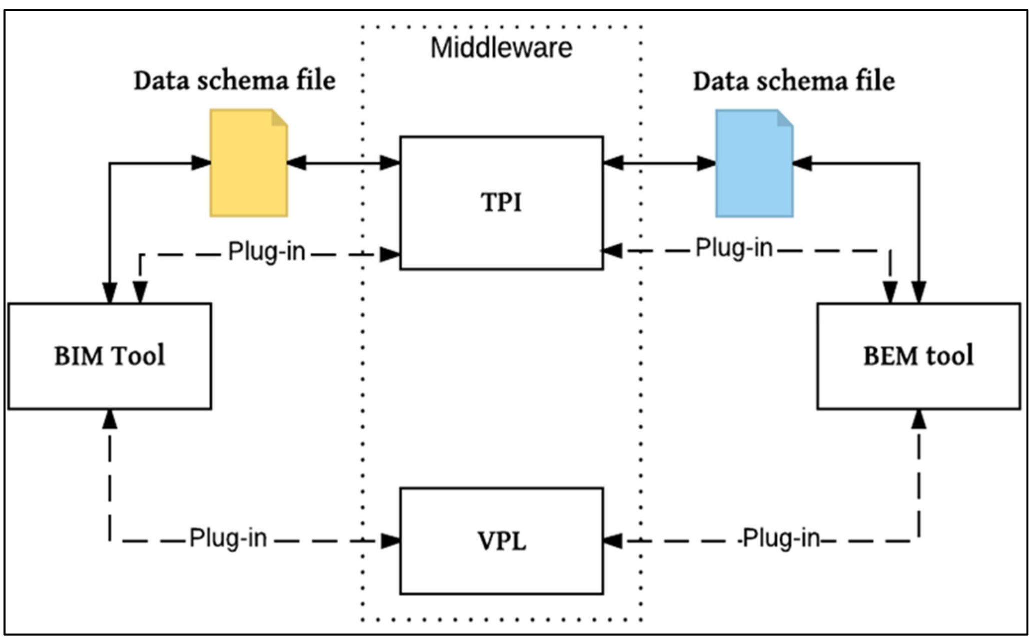


Figure 3.3 Distributed model integration method

The TPI is usually used when the data exchanger is not directly compatible with the BEM tool. It therefore, transfers the model via a data schema. It can also be used to modify or simplify parts of the model. The VPL integrates dynamic modeling, which allows for deep integration by scripting the model in order to filter, modify and extend user definitions. Dynamic modeling is capable of incorporating advanced automation features, providing feedbacks and supporting various simulation tools such as Green Building Studio (GBS) (Mengana & Mousiadis, 2016), IES-VE, and Vasari (Autodesk). In addition, using VPL allows the handling of heavy and complex geometry and non-geometric models by creating and modifying particular algorithms for the model, without having any professional knowledge of programming. These model integration methods provide the technical basis to develop an approach that is more complete for BIM-BEM.

Most of the proposed technological approaches have focused on two main aspects: (1) the development of new middleware or data schemas, and (2) the development of frameworks using proper TPI or modeling techniques. Therefore, the current technological aspects using already available tools for BIM-BEM are discussed.

3.4.2.1 Development of new middleware or data schemas

One of the earliest studies of the central model integration method was suggested by Bazjanac (2001) and focuses on importing building geometry in 3D format via IFC (2X2) into a BEM tool. This format of IFC had interoperability issues in terms of building data transfer, especially for HVAC data. Consequently, a new interface called IFCHVAC was proposed by Bazjanac and Maile (2004) to support the better transfer of HVAC data through an IFC-based file into an Input Data File (IDF) to be used by EnergyPlus, a whole-building ES program (Crawley et al., 2004). This IFCHVAC data schema is limited to BIM model that include HVAC data; thus, its use in the early design phases when there is no HVAC data available is challenging.

Furthermore, numerous issues are encountered when creating an HVAC system. To address these issues, an HVAC Graphical User Interface (Sanguinetti et al.) was devised by O’Sullivan

(2005) as a new TPI between the IFC HVAC-based tool (such as DesignBuilder which is an interface for EnergyPlus) to reduce the interoperability issues and to address the technical problems encountered when creating the HVAC model. However, this approach is limited to this specific ES tool; it focuses on HVAC data and does not address the challenges of transferring building geometries, coordinates, climate location, thermal zones, construction and material property information (Chaisuparasmikul, 2006). The Simulation Domain Model (SimModel) project (O'Donnell, 2012) is another effort. The SimModel, besides supporting translation by IFC and gbXML, proposes a new interoperable XML-based data model that enables geometric and HVAC integration for ES. The SimModel report contains the technical solution and the data flow of the central model integration method via the above-mentioned data schemas for a better implementation of BIM-BEM. However, the required workflow during the design process is not provided.

Certain interoperability limitations and improved functionalities were made possible with the release of IFC (2X3) by IAI (2006). This version was further enhanced by a new file format called IFCXML that provides both IFC and Extensible Markup Language (XML) features to promote open and interoperable IT standards. The IFCXML is used as a data exchanger between a design tool (e.g. ArchiCad) and an IFC-compatible tool (e.g. DeST) by Yi et al. (2007), while Kim and Anderson (2011) propose using IFCXML for BIM-BEM. In the latter case, a new and interoperable IT standard is proposed to support higher interoperability, labeled as a data input (INP) file. The BIM model, reconstructed using IFCXML, and XML file are exported to the INP file to provide the required information to the ES tool, such as eQuest (2011). The creation of the INP file, which produces very long and complex files, requires the building geometry to be remodelled in an interface such as SketchUp (2011) using Ruby code references.

Another substantial extension of the previous IFC version is the IFC4, which provides a richer set of concepts, especially for defining HVAC systems. This data schema enables translating model details between BIM and BEM tools for which a tighter coupling of zones and building objects is achieved. The limitations of this method are that: (1) architects or engineers are required to define thermal zones in the early design stage, and (2) most common BEM tools do not yet support IFC 4.

In general, using the developed data schemas for BIM-BEM purposes is still inconsistent and often requires manual checking for accuracy (Pinheiro et al., 2018). The inconsistency of data schemas occurs because of differences among heterogeneous databases; when two objects come from different information sources and some of the values of their corresponding attributes are not matched (Amor & Faraj, 2002; Anokhin & Motro, 2001).

Hence, Sanguinetti and Abdelmohsen (2012) have proposed a system architecture based on attribute relationships and data semantics to link an Application Programming Interface (API) with IFC. Specific Model View Definition (MVD) is generated by defining a subset of the IFC schema as model data to support interfacing the data required for BIM post-processing. The MVD method allows specifying how and what components will be used for an information exchange based on a specific issue (Pinheiro et al., 2018).
Although the study addressed only a part of the design process, it shows that the semantic mappings of BIM post-processing support design review in a shorter time than manual conversion and selecting of the information needed from the building model.

In this area, Jeong and Kim (2014), Jeong and Kim (2016), and Yan and Clayton (2013) developed a new system interface called Revit2Modelica, linking BIM model and Modelica using an object-oriented physical modeling approach. For this study, the BIM model was created in Autodesk Revit, a popular and powerful BIM tool that supports multi-domain design, visualisation, parametric modeling, interoperability, collaboration, and many other features.

With the Revit2Modelica interface, a set of required modifications and work/data flows is proposed to create an updated and complete BIM model. The modifications are applied in Revit first, through prototyping an Application Programming Interface (API) in order to build the BEM for Modelica, a modeling language that has an environment to perform ES. Using

API allows direct access to BIM data and parametric modeling that cannot be accomplished through IFC or gbXML. Also, the object-based modeling proposed by the Revit2Modelica approach addresses the interoperability issues and facilitates an automatic translation of the BIM model to BEM tool with high efficiency and accuracy. However, a high level of programming skills is required to proceed with the BIM pre-processing and Revit2Modelica, which is its main limitation. More importantly, it does not provide insight as to how to effectively use this technological approach during the design process.

More recently, a novel technical approach for BIM-BEM was proposed by Jabi (2015), where the dynamic distributed model integration method is employed to link BIM and BEM tools. A software development kit for OpenStudio called DSOS (Jabi, 2014) works as a middleware to link 3Ds-MAX (2015) and EnergyPlus. The simulation results can be retrieved from the EnergyPlus database using a standard SQL database query so that it can be automatically displayed in the 3Ds-MAX. This real-time approach allows the leveraging of the object-oriented capabilities between the BIM and BEM tools to address the interoperability issues. However, it only focuses on the early design phase, rather than tackling the whole design process.

These latest approaches require a high proficiency in scripting different programming languages, which can be an obstacle for its use by design professionals. Therefore, some researchers try to use the existing technological approaches in the form of a guideline or framework in order to address the BIM-BEM issues.

3.4.2.2 Development of a framework including a TPI

One of the interesting studies that develop a framework for BIM-BEM was completed by the Centre for Integrated Facility Engineering (CIFE) (Maile, Fischer, & Bazjanac, 2007). This study identified the characteristics of different BEM tools and their compatible data exchangers. Based on those results, some useful TPIs are proposed in order to check the created architectural model before exporting to the BEM tools to prevent incorrect or poor quality inputs that results in faulty outputs. For example, a model checker (Solibri) for the IFC format is used in an iterative process by exporting and importing building geometry and correcting the detected errors in the design tool.

Likewise, in this approach and in the other approaches conducted by Bazjanac & Kiviniemi, (2007) and Bazjanac (2008), a geometry simplification tool is employed to automatically simplify the original building geometry in IFC format to meet geometry input data requirements for EnergyPlus. Since an IFC file usually contains lots of information and detailed data that are not essential for ES, a simplification process is required to make the file lighter and more usable.

Another proposition is to use a text editor tool such as GBS (Autodesk, 2007) to reduce the number of errors within gbXML files (Maile et al., 2007). GBS also has the ability to correct inconsistencies and to reinforce the standardization of gbXML, as in Azhar, Brown, and Farooqui (2009) proposed BIM-BEM framework. In general, an accurate, integrated and simplified BIM model helps reduce the errors transferred into the BEM tool. However, these techniques are focused on a singular object and are not sufficient to address all the limitations within the whole design process.

A comprehensive approach proposing a series of modeling techniques on the original BIM model before being exported to the BEM tool (BIM pre-processing step) in order to minimize the interoperability issues was conducted by Miller (2010). The study contains technical guidance for the building shell, geometry and boundaries to create a seamless BIM process. The BIM pre-processing guideline is detailed in another study conducted by Kim and Woo (2011) that identifies different procedures that could affect the simulation results compared to the traditional ES approach. Completing the BIM pre-processing steps and model integration steps via the central method are also applied by Osello et al. (2011) to assess the available data exchanger in various formats from the BIM to the BEM tools. In this study, the characteristics of the data schemas were reviewed in order to define what type of data passes well and what type does not pass or passes with errors. Some software packages (such as IES-VE and Ecotect) and data exchangers (IFC and gbXML) are analyzed in an iterative process to optimize the process in the most interoperable manner and minimize the risk of permanent data loss. This study includes one of the most valuable approaches, providing additional knowledge to this domain.

More specifically, O'Donnell (2014) develops a semi-automated workflow for BIM-BEM, suggesting several key techniques, such as a geometry simplification tool that is superseded by a Space Boundary Tool (SBT-1) to simplify building geometry for BEM. A space boundary describes the boundaries for spaces and the relationships between spaces and the building elements which usually are broken down into a 1st and 2nd level of space boundary (Hitchcock & Wong, 2011). SBT is able to modify and add space boundaries to the IFC in order to recognize different types of heat transfer surfaces in a BEM tool.

The proposed recommendations and key techniques on BIM-BEM technological approaches do not yet guarantee the translation of a complete and seamless BIM model into BEM tools. Furthermore, two main gaps are noted: (1) the proposed BEM tools and data exchanger are not always those for tools typically used by design firms, and (2) the execution, work/data flow and the rightful place of the technological approaches in the entire design process are not considered, or are only considered for one design phase.

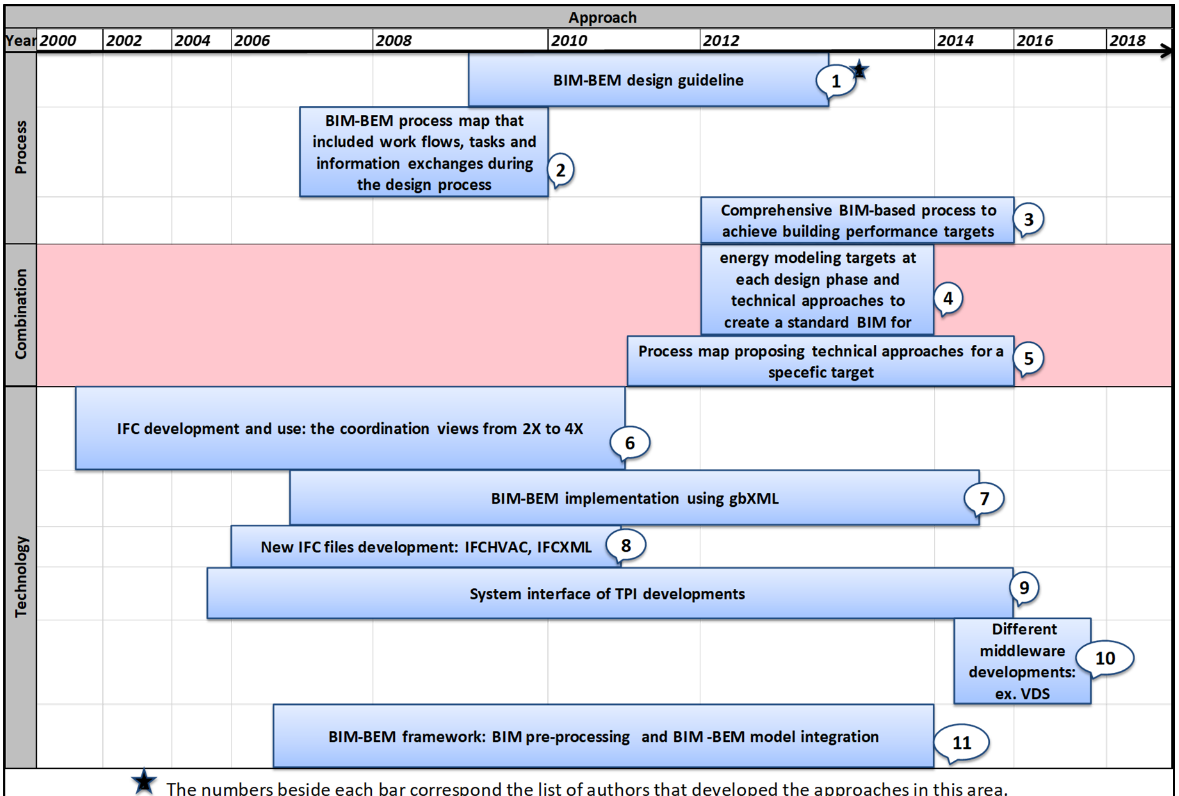
3.5 BIM-BEM framework requirements

The review of the existing studies highlighted the fact that the design process and the technological approaches are generally explored separately, as demonstrated in Figure 3.4.

As illustrated, about 59% of the current BIM-BEM studies (refer to section 3.3) focus on technological approaches. In addition, the few studies that focus on the process approaches, such as the currently available guidelines and process maps, only address the managerial side of the story and the technical solutions for each design target are missing. Three reasons are noted to explain the identified gaps:

1. The seamless implementation of BIM-BEM is still challenging and lacks a high level of interoperability, which is influenced by the market design process;
2. There is a lack of knowledge, experience, expertise and understanding, for both technical and process aspects by professionals and researchers that limits the prospect of addressing this gap; and
3. To our knowledge, no previous studies have clearly recognized the gap identified in this paper to support further investigation.

In addition, linking the technological and process approaches is challenging, troublesome and one of the main limitation for the successful execution of BIM-BEM by professionals. In light of the defined issues, there is a need to propose an approach for BIM-BEM that embeds the technical aspects within the design process in order to assist current design practices to depart from impromptu processes. Developing such a reliable and comprehensive framework is essential for the BIM-BEM professionals within the construction industry to effectively deliver accurate information over the design process.



	Authors
1	Bloomberg, Burney et Resnick (2012); CIC (2011); Eastman et al. (2009); Solnosky (2013); STAM (2016).
2	Koppinen et Kiviniemi (2007); Korkmaz et al. (2010).
3	Attia, Walter et Andersen (2013); Lee (2016); Tuomas Laine (2012); Wong et Fan (2013).
4	AIA (2012); D. Rovas (2017); GSA (2012); SALD (2016); Scherer (2017).
5	Arayici et al. (2018); Ilhan et Yaman (2016); Stumpf, Kim et Jenicek (2011); Wu et Issa (2014); Zanni, Soetanto et Ruikar
6	Bazjanac (2001; 2004; 2008); Bazjanac et Kiviniemi (2007); Bazjanac et Maile (2004); Hetherington et al. (2011); Maile, Fischer et Bazjanac (2007); O'Sullivan et Keane (2005); Plume et Mitchell (2007).
7	Azhar, Brown et Farooqui (2009); Ham et Golparvar-Fard (2015); Maile, Fischer et Bazjanac (2007); Osello et al. (2011).
8	Bazjanac et Maile (2004); Kim et Anderson (2011); Yi et al. (2007).
9	Jeong et al. (2014; 2016); O'Sullivan et Keane (2005); Sanguinetti et al. (2012); Yan et al. (2013).
10	Jabi (2014; 2015).
11	Bazjanac (2008); Bazjanac et Kiviniemi (2007); Hitchcock et Wong (2011); Maile, Fischer et Bazjanac (2007); Miller (2010); O'Donnell (2014); Osello et al. (2011).

Figure 3.4 BIM-BEM development from 2001 to 2018

In this regard, the details presented in the existing studies, such as the approaches to create proper BIM model for BEM, the procedures required for BIM-BEM model integration and the main design management activities to finalize a BEM for ES can support the development of a complete and general BIM-BEM approach for all of the design phases.

A few studies have attempted to address both aspects, as shown in the middle row of Figure 4, such as the guidelines proposed by AIA (2012) and GSA (2012). AIA (2012) defines the energy modelling goals at each design phase, suggesting technical approaches for the early use of BEM in the design process. Likewise, GSA (2012) recommends to prepare the BIM model towards an appropriate model to minimize errors in geometry and to simplify the model. It describes BIM-BEM during the design process and offers the potential to support the use of new BIM-BEM technologies. Although these guidelines present valuable information for BIM-BEM from both aspects, there are still details missing about the technological execution flow in different design phases.

Some major research projects, such as OptEEmal, eeEmbedded, and Design4Energy, have been realized in this area and consequently some of their related reports are published with a boarder scope showing awareness of concepts that address a consistent BIM-BEM approach. In the OptEEmal project (Rovas, 2017), an Optimised Energy Efficient Design platform was developed to support the energy efficient retrofits design of buildings. The guideline to use BIM model for BEM using OptEEmal platform includes an optimization process map embedding technical solutions, but does not tackle the overall design process.

The eeEmbedded project (Scherer, 2017) is an extension of the work completed by Laine (2012) that suggests an information management framework using their own ES platform to support the design process. The holistic design methodology proposed by eeEmbedded defines concept, procedural (including setups, design development, analysis, refinement and decision-making), and software solutions (such as modeling steps) to address BIM-BEM execution. While it provides BIM-BEM technologies based on the central model integration method (using IFC as the data exchanger) considered within the design process, it can only be used for their own platform.

Design4Energy (SALD, 2016) has also developed an innovative methodology using an information platform to define relevant information for energy matching and performance optimization. In this regard, a holistic interoperable data exchange protocol is suggested for use in the platform for the complete design, operation and maintenance phases. The study conducted by Arayici, Fernando, Munoz, & Bassanino (2018) employed the Design4Energy method to apply BIM-BEM practice in a collaborative process. The technical aspects are detailed in this process, which enhanced interoperability between BIM and BEM tools. However, the required technical solutions are only partly covered and are exclusive to the Design4Energy workspace. Still, the developed work and data flow could be extended for their use in more general aspects.

The combination of BIM-BEM technology and design process maps are mostly addressed in the studies conducted by Stumpf, Kim, and Jenicek (2011), Wu and Issa (2014) and Zanni et al. (2016), which propose improved process maps for BIM-BEM. The process maps include the planning procedures, BEM in macro (building envelope) and micro (design detail) levels and validation of the models. Some of the studies focus only on certain targets; for example, Wu and Issa (2014) focus on LEED certification, while Zanni et al. (2016) propose a more holistic approach for sustainable design. The process maps detail the activities and responsibilities within the design process, while also defining when BEM should be created and transferred. The technology used in these studies is based on the central model integration method using different TPIs. The technical aspects are more detailed in the process proposed by Ilhan and Yaman (2016), where an IFC-based framework using a green building assessment tool (GBAT) to properly define sustainable material choices for green buildings is developed.

In general, the few studies addressing these issues confirm that this combination is hardly ever tackled and requires additional investigations. Moreover, even when a process map is suggested, it does not embed the technological approaches within the design phases. The other point to be considered is that previous efforts have mostly focused on some part of the complete BIM-BEM steps (1) BIM pre-processing which consists of creating a proper BIM model before transfer; (2) BIM to BEM transferring, including the details of interaction and verification steps; and (3) BIM-post processing, to fix the imported BEM.

To our knowledge, there is no available framework that simultaneously describes the whole BIM-BEM steps and related technical aspects to be followed during the design process. However, the main activities, roles and technologies presented in the existing process maps can be the basis with which to develop a comprehensive and more general approach.

Thus, an operational framework embedded in a process map is needed to detail all the recommended steps for the creation of a complete BIM-BEM approach for each of the design phases. As an example, Figure 3.5 illustrates the different aspects to be included in the creation of such a framework that could be adapted to different types of design process, for specific design phases, for different BIM/BEM tools and data exchange formats. It details the different elements to be included, such as the activities, the Information Requirement (IR) for each activity, the LOD, the flows as well as the exchange and data sharing files.

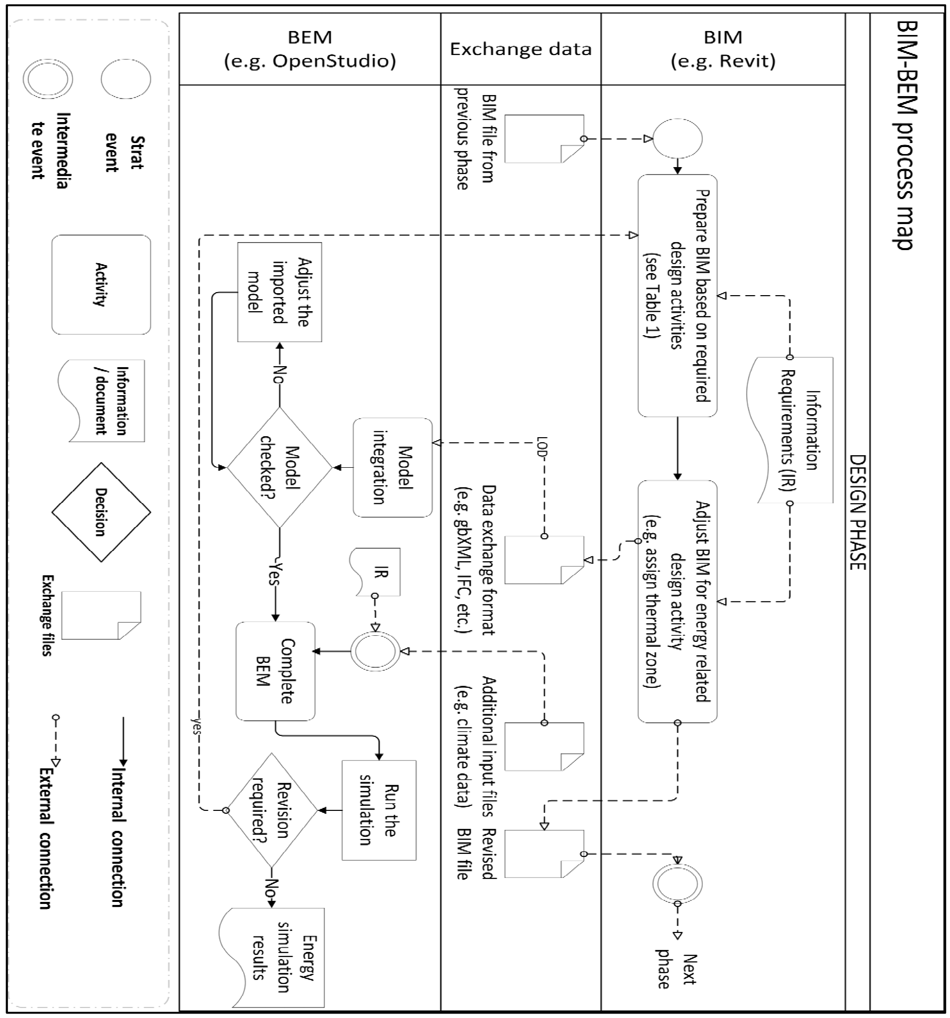


Figure 3.5 An overview of the proposed framework in a process map

For each design phases, the BIM pre-processing step, the design activities and the proper IR to create a complete and integrated BIM model for BEM are defined. The list of IR can be provided in a table format where the parameters, scales and the range of values are specified. The process map would also be completed by providing details as to how to create each building element and how to attach them seamlessly.

In the BIM-BEM interaction step, the activity required for exchanging files, such as extracting gbXML data from the BIM model, the steps to integrate the exchanged file into the BEM tool, and the procedures to fix the imported BIM model would be detailed. It also provides decision points, including model verification techniques, especially to ensure proper BIM-BEM interactions. The work and data flows are adjusted for each design phase to complete the BEM for ES, including the steps to prepare the simulation results documents. The definition of IR for each design phase to complete the ES will provide the basis to define the required Level Of Development (LOD) to support BIM-BEM execution for each design phase. The LOD allows the receivers to rely on imported information by specifying the content of the BIM model with a high degree of clarity at various modelling and sharing steps (NATSPEC, 2013).

Therefore, such a complete process map allows the design team to create a BIM model that is well integrated by defining the proper space boundaries, thermal zones and defining accurate IR for BEM. Thus, it is easily transferrable with the appropriate LOD, while limiting both the amount of simplifications required and the model integration errors. In addition, the LOD and the information requirement specified for the BIM-BEM process have the potential to be used for creating adapted MVD to easily extract the BEM from the existing architectural model to proceed with the ES. This step would fill the gaps noted in this literature review on the BIM-BEM process and technological approaches.

3.6 Synthesis and conclusion

This paper contributes to professional knowledge by demonstrating that efficient use of BIM-BEM requires addressing the main pillar (process and technology) of a BIM-based project. This can be realized by proposing the proper techniques for all of the design phases and embedding the technical approaches within the design process. Based on the results derived from the systematic literature review conducted for this paper, this combination is rarely found among the current BIM-BEM studies. Even in the few suggested studies that somehow attempted to use this combination, the interaction between these aspects is not fully detailed. The identified gap within the existing academic and professional knowledge for executing proper BIM-BEM calls for further research in this area.

Therefore, a comprehensive and general framework is needed that defines technical approaches (i.e. model integration method), the modeling and design activities (i.e.

specification of the spaces and thermal zones) and the flows in the whole design process (i.e. design activities and data sharing steps) to properly execute complete BIM-BEM steps. This framework should clearly define the ES targets, the design procedures, the work and data flows, the relevant modeling and integration techniques, the information requirements, the LOD, and the BIM-BEM interactions at each design phase. The process of how to link the design phases and verify each design target can be determined in the BIM-BEM framework.

While there are some research projects that propose a BIM-BEM framework, these frameworks are software-specific and compatible only with particular ES package, developed by the same research team. The literature in each of these areas nonetheless provides valuable insights into devising a holistic and general framework considering both aspects. Thus, as future work, the following tasks will be investigated to develop a complete and effective BIM-BEM framework:

- Define suitable techniques and the key modeling and model integration methods for each design target during the design process; and
- Create a process map for the whole design process including complete work/data flows for complete BIM-BEM steps, the appropriate LODs, and the appropriate technologies and information requirements that correctly fit together.

Creating a systematic BIM-BEM framework as suggested in this paper may reduce the level of effort required for traditional BEM in an iterative process, and encourage better use of ES for designing high-performance buildings. The compilation and assessment of the main BIM-BEM approach over the years and the quantity of studies in each area is already a help to fill in the existing gaps.

CHAPTER 4

FRAMEWORK FOR USING BUILDING INFORMATION MODELING TO CREATE A BUILDING ENERGY MODEL

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4.1 Abstract

The use of Building Information Modelling (BIM) to create a Building Energy Model (BEM) compared to traditional simulation practices offers significant time-saving potentials by minimizing efficiency issues, legal disputes, added costs, and delays. BIM-BEM strategy avoids remodelling the building to create the BEM by exchanging architectural information to complete the energy analysis. However, most existing frameworks do not simultaneously describe the BIM-BEM process and related technical aspects to be followed during the design process. Therefore, this paper proposes a comprehensive BIM-BEM framework initially created based on theoretical and field investigations and then enhanced by a trial investigation using a testing case. The proposed framework is illustrated in an easy to follow process map that includes work/data flow and specifies data exchangers and information requirements. The framework is verified using a complex case study to demonstrate its applicability for different BEM tools. The proposed framework intends to provide the industry with a useful and generic process for BIM-BEM that enables professionals to create proper BIM and BEM to complete energy analysis during the design process.

4.2 Introduction: Building Information Modeling-Base Energy Model during the Design Process, a Review of Literature

In recent years, the use of Building Information Modelling (BIM) has gained acceptance as a valuable tool to improve building design and the construction processes (Jokela, Laine et al. 2012, Summerfield and Lowe 2012). The whole design process is usually divided into three main phases: preliminary concept design (or program pre-design), final concept design (or schematic design) and design development (ASHRAE 2010, General Services Administration (GSA) 2012, Jokela, Laine, et al. 2012). For every step of this process, BIM has changed the way professionals interact by allowing sharing of relevant design information leading to an enhanced collaboration process (Krygiel and Nies 2008, Schlueter and Thesseling 2009), including potential improvements in terms of interoperability and data integration for different users (Eastman, Teicholz et al. 2011).

BIM allows the visualization of ideas in a virtual 3D format as well as being an object-oriented, intelligent and parametric model constructed digitally that stores multi-disciplinary information describing different aspects of the building (Barlish and Sullivan 2012). In this context, BIM offers the possibility to create dynamic building models that could be used to extract the required information to be transferred directly to the Building Energy Model (BEM) tools (GSA 2012). The comparison and validation of different energy optimization scenarios leading toward the design of an energy efficient building during the decision-making process are thus enhanced by facilitating more design iterations (Jung, Lee et al. 2013). Albeit, the design of high-performance buildings using BIM and interaction of BIM-BEM are complex and non-linear; the iterative nature of the process requires comprehensive guidance or instruction to deliver accurate information effectively over the design (Yang, Zou et al. 2013, Zanni, Soetanto, et al. 2016).

However, most proposed BIM-BEM approaches focus either on specific performance aspects for a particular tool or a specific design phase rather than tackling the complete design process (Bazjanac 2008, Hetherington, Laney et al. 2011, Kim and Anderson 2011). Therefore, there is still a necessity to propose to the building industry reliable approaches for BIM-BIM to assist the energy conscious decision process during the different design phases (Kim and Anderson 2011, Wu and Issa 2014, Negendahl 2015, Ilhan and Yaman 2016).

The objective of this research is to propose an effective BIM-BEM framework that embeds the BIM-BEM technical aspects within the design process in order to assist current design practices to depart from the impromptu process. The framework intends to address the existing gaps within the current studies by recommending easy to follow work/data flows of the whole BIM-BEM activities, and proper key modelling and information sharing at different phases of the design to support building loads and systems analysis. It aims to improve currently available and emerging building design practices with a framework outlined in a process map.

However, it does not address in details the design exploration process or design evolution. The proposed framework can be used either for new or existing buildings. In this paper, a review of the existing BIM-BEM framework is first presented, followed by a description of the research approach carried out to create the proposed BIM-BEM framework. Accordingly, the proposed framework also addresses existing issues and is validated using a complex case study. The implementation of a complete BIM-BEM process is divided into three main steps: (1) BIM pre-processing which consist of creating a BIM before transfer, (2) BIM to BEM data transfer, including detailed steps, and (3) BIM-post processing, which is completing the BEM for simulation.

Previous efforts to apply BIM-BEM in the design process mostly focused on one of these steps or on specific technical aspects that addressed interoperability issues. For example, Maile et al. (2007), Bazjanac (2008) and Azhar, Brown, et al. (2009) proposed the use of Geometry Simplification Tool (GST) to assist the BIM-BEM process in order to automatically simplify the original building geometry in an Industry Foundation Classes (IFC) format. Also, Maile, Fischer et al. (2007), GSA (2012), and O'Donnell (2014) suggested the use of Model Checker to correct the detected errors caused by the lack of interoperability between BIM and BEM tools.

In parallel, a series of technical recommendations, tips, and tricks for modeling an accurate architectural BIM is suggested, such as correctly attaching the building elements to allow the creation of a more seamless model before being exported to BEM tools (Hitchcock and Wong 2011, Kim and Woo 2011, GSA 2012). Simplifiers, model checkers, and revisions are advantageous and useful in the BIM-BEM process to create a more integrated BIM in which unnecessary details are eliminated. They can support quick and more interoperable model transfer; however, they cover mainly the BIM pre-processing step, rather than providing a complete work/data flows of the BIM-BEM process.

For the early design phase, Stumpf, Kim et al. (2009) proposed an approach to assess the potential of using BIM to create BEM. Thus, a brief process map is developed for a specific BEM tool that includes: (1) identifying the project requirements, (2) performing the energy modelling that is divided into two sub-processes: macro (building envelope) and micro (design detail) levels, and (3) refining and validating the early design energy analysis. Also, Crosbie, Dawood et al. (2010) developed an Intelligent Use of Buildings' Energy Information (IntUBE) to integrate simulation and real-time data-capturing sensors to enhance the measurement and evaluation of building energy performance with BIM-based energy profiling tools. The IntUBT focuses more on real-time simulation, rather than focusing on design aspects. These studies provided interesting information to support the development of more detailed BIM-BEM process maps.

Other studies focused on BIM post-processing such as Nasyrov, Stratbücker et al. (2014) who evaluated the ability of a specific BEM tool to use information extracted from BIM to complete the energy analysis; or Reeves, Olbina et al. (2015) who proposed an evaluation approach to select a BEM tool to complete the energy analysis. Both approaches included the procedures to create the BEM, the building design optimization, and the building control optimization. However, the information for the complete BIM-BEM process and the flow between the design phases were not addressed.

An almost complete process map that tries to cover the entire BIM-BEM steps has been developed by Jeong, Kim et al. (2014), Jeong, Kim et al. (2016). A system interface, called Revit2Modelica, is created between BIM and Modelica-based BEM using an object-oriented physical modelling approach. A set of required modifications and data flow to create an updated BIM is proposed in this study. The modifications are completed in Revit through an Application Program Interface (API) in order to build a model that could be translated to Modelica (developed by the Lawrence Berkeley National Laboratory) to complete the energy simulation. The limitation of this process map is the uniqueness of the mapping that is specific to the tool used, Modelica. Overall, these studies emphasis has been mostly on the technical procedures, rather than considering the BIM-BEM work/data flow during the design process.

AIA (2012) suggested a process for the early use of performance modelling in the design process and described how it can support the comparison of design alternatives. The information presented is well detailed, but the use of BIM to assist the design process is not sufficiently addressed, i.e. BIM is mentioned but no detailed information is provided as to how it can assist the creation of BEM. In this regard, there are few studies that propose process maps providing insights into various aspects of BIM-BEM. Though, most of them focused mainly on green building projects, especially on meeting Leadership in Energy and Environmental Design (LEED) requirements.

For example, Azhar, Carlton, et al. (2011) developed a conceptual framework to assist the LEED rating process and validated its use with a case study. The framework covered the BIM-BEM transferring steps for a specific BEM tool without detailing the requirements for BIM pre-processing. To assist the potential of using different BEM tools throughout the design process, a system architecture is proposed by Sanguinetti, Abdelmohsen et al. (2012) that consisted of using Model View Definition (MVD) to support the data transfer process from one tool to another. The study supported the semantic mappings of BIM post-processing to do design review in a shorter time than manual conversion. Another green building BIM approach that used MVD is proposed by Ilhan and Yaman (2016) focusing more on embodied energy and sustainable material choices rather than specifically addressing approaches for creating

BEM. The use of BIM for sustainable design is also addressed in the study proposed by Motawa and Carter (2013) which focuses instead on populating an ontology and a data flow that identified the information required for energy management through the post-occupancy phase. A more generic process map is proposed by Attia, Walter et al. (2013) to assist the design of net-zero energy buildings. The main activities, roles, and tools are considered in the process map for different design phases without covering the BIM-BEM implementation process and related issues.

Several of the developed process maps covered the essentials for one phase of the design process. However, the entire BIM-BEM process is sparsely addressed. The attempts to combine a more complete BIM-BEM process in different design phases are addressed in Wu and Issa (2014), Zanni, Soetanto et al. (2016).

Wu and Issa (2014) proposed a design framework that articulates an integrated green BIM process map specifying the sequences and types of energy analysis required within the design process. The process map is mainly focused on LEED targets and oriented towards a process model derived from CIC (2011) BIM Execution Plan rather than specifying the work/data flow explicit to the creation of a general BEM. On the other hand, Zanni, Soetanto et al. (2016) focused on organizational aspects of BIM to propose a framework that used sustainability criteria, including BEM criteria, to identify decision points. A list of decomposition levels detailing the required information is also proposed. However, the detailed interaction of BIM and BEM and the integration process would be desirable to complete the framework.

The review of available BIM-BEM approaches revealed that most of the proposed solutions tackled specific technical aspects rather than looking at how to integrate the proposed approaches to the whole design process followed by the professionals. Furthermore, most of the existing process maps focused on some part of BIM-BEM implementation during the design process. Indeed, there is only limited information to support an effective and comprehensive work/data flow embedded in the complete BIM-BEM process that covers all the building design phases.

Therefore, in this study, a generic framework detailing the work/data flows for different activities and the Information Requirements (IR) is proposed to support the use of BIM for the creation of BEM to enhance the use of energy simulation analysis within the design process. The proposed framework focuses on the following aspects to support the use of BIM for BEM: (1) the work/data flows required and (2) the occurrence of interactions between the BIM and BEM.

4.3 Research Approach

Proposing a generic BIM-BEM framework, which combines both work/data flows and IRs, requires both theoretical and practical investigations. Thus, the research approach consisted of three types of investigations that are illustrated in Figure 4.1. The two first investigations are used respectively to initially create the framework and refining it using knowledge gained from current professional practices. This framework is then tested and completed following the trial investigation using a complex testing case and a BEM tool that support BIM file. The proposed framework is then validated using a different BEM tool to demonstrate that the framework is applicable for different BEM tools.

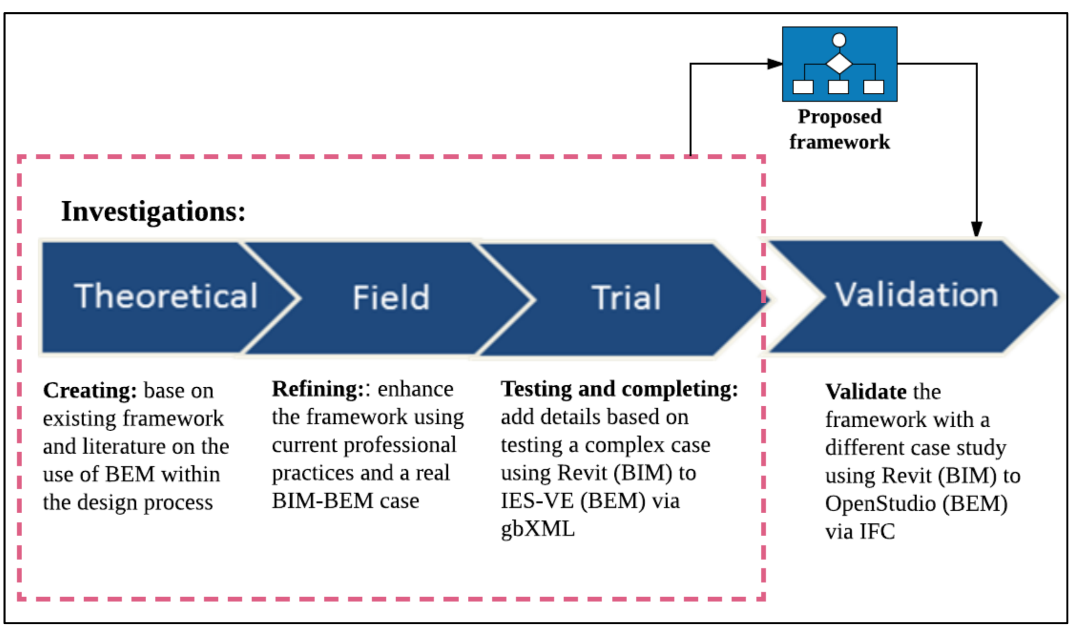

Figure 4.1 Research design

4.3.1 Theoretical investigation: creating the basic framework

The creation of the basic framework is based on documenting the main BIM process activities during the design phases using a survey of relevant academic references and available documented practices. The proposed basic framework is primarily built on the basis of BEM process suggested by AIA (2012) and the essentials of BIM-based approach recommended by CIC (2011), where the focus of the proposed framework is to develop a more energy efficient design by the creation of a BEM using BIM. Thus, the main activities and flows that are presented separately in the mentioned studies are combined and refined to create the basis of the proposed BIM-BEM framework. Also, the IRs to create a standard energy model are derived from ASHRAE-90.1 (2010) and are adjusted for different design phases, as more information becomes available. This allows a comprehensive identification of the relevant input required for most building simulation tools to support the proposed BIM-BEM framework.

The documented information is presented in a process map to easily visualize the flows. The process map is articulated around the notation proposed by CIC (2011), the Business Process Modelling Notation (BPMN) approach (White 2004). It is enhanced using valuable information and approaches proposed in the literature such as Messner, Anumba et al. (2010), Wu and Issa (2014), and is corroborated with the information available in GSA (2012), Jokela, Laine et al. (2012), Ilhan and Yaman (2016), Zanni, Soetanto et al. (2016).

However, since it has been recognized that there is a gap between theory and practices for implementing BIM-based projects (e.g. Forgues and Iordanova (2010)), an investigation of current industry practices allows documenting more practical issues found on real-world projects to enhance the proposed basic framework for both technical and process aspects.

4.3.2 Field investigation: enhancing the basic framework

The field investigation consisted of extracting knowledge from current professional practices. Thus, a real BIM-BEM case, proposed by a consulting firm, is documented to enhance the basic framework and create a more detailed process map. The firm is selected based on its high skill and experience in the implementation of BIM-BEM project: it offers technical support and expertise for the design of high-performance buildings by providing solutions that take into account a whole range of performance characteristics.

This practical experience allowed the documentation of the approach undertaken to proceed with BIM-BEM and of the optimization process during the design of a real-world case. The principal activities proposed by the consulting firm and the IRs used during the modeling process are compared and refined with the documented information from the literature presented in theoretical investigation. Then, the practices proposed by the consulting firm are evaluated and analyzed. They provided additional information to be added to the process map for each of the design phase from BIM pre-processing to BIM post-processing. This included details about the interaction between BIM-BEM tools and determining IRs. Nevertheless, to create a reliable BIM-BEM framework, a trial investigation is essential, especially to address specific technical aspects.

4.3.3 Trial investigation: completing the framework

BIM-BEM application is challenging. In order to complete the framework, the proposed process map is tested using a case study to investigate, identify and solve possible real-world issues. The testing case study is selected based on its complexity in terms of building geometry, and envelope characteristics. Thus, different interoperability and practical issues could be detected. The initially proposed process map is completed and refined with the findings from this investigation. This led to a generic BIM-BEM framework illustrated in a final process map based on the BPMN approach. The BPMN approach provides a standard graphical notation, an understandable communication language that links business design process and implementation.

An existing building having a floor area of 2180 m2 spreads over two storeies is used as the testing case study. This building is an innovation hub that includes offices, conference rooms, and innovation labs, showcase rooms (a place where all sorts of innovative products can be found) and brainstorming areas. The second floor is a dome devoted to creativity, a space for collective creation for students and companies. The 2D architectural plans and mechanical plans and designs as well as the required specifications were available.

The process map, which shows the different steps required to build the architectural BIM in a particular BIM platform, as well as specifying the data exchange format, the required steps and inputs especially for BEM at each design phases, is tested on the case study. In this case, Revit 2016 (Krygiel and Vandezande 2014) is used as the BIM platform, the Integrated Environmental Solutions-Virtual Environment (IES-VE 2016) as the BEM tool (Crawley, Hand et al. 2008) and the green building Extensible Markup Language (gbXML) as the data exchanger format to transfer the BIM data.

The architectural BIM is built in Revit using AutoCAD overlays of the current building and following the approach proposed in the preliminary process map. In order to prepare the model for load calculation, first, the global site location and weather data are determined in the BIM platform to explore the correct orientation, form, building mass and floor levels. Then, all spaces, thermal zones, construction types, and thermal properties are assigned in Revit before being transferred to the BEM tool. The gbXML file is extracted from the created BIM to be transferred into IES-VE. In Figure 4.2, the 3D BIM and the imported model into IES are illustrated. There appeared to be some missing elements in the imported model such as the thickness of interior/exterior walls and the roof. The thermal zones and spaces are imported properly, while construction type’s information is missing.

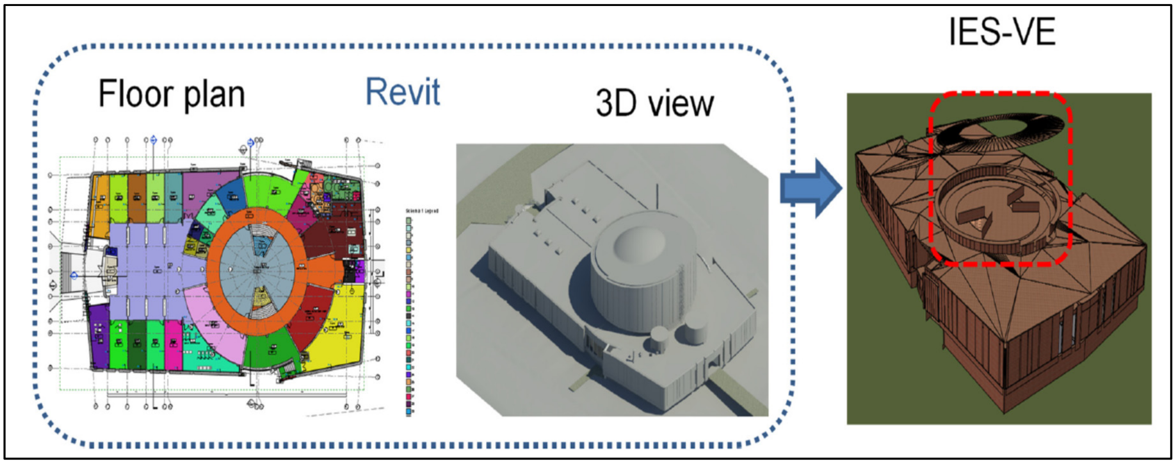

Figure 4.2 Comparison of the created BIM of the testing case and the transferred model in Integrated Environmental Solutions-Virtual Environment

During the BIM creation and BEM transfer, BIM pre-processing issues are identified that should be solved to ensure proper transfer of the required information. Various issues noticed in the imported model are categorized into three main cases: the missing elements, the miss-placed elements and the non-transferred information. As shown in the Figure 4.2, there are missing walls in the dome, the roof is miss-placed and thermal conductivity of glasses and construction layers are missing. These issues occur because of the differences between a model that is built for architectural purposes and one for energy simulation, more specifically in terms of the localization and the composition of the building envelope and elements in the model. For example, the location of the envelope components, such as the walls, must be made to ease and support thermal zoning of the building rather than only being a representation of the reality of the building site.

Therefore, the essential steps to create complete and seamless BIM (BIM pre-processing) are identified and documented during this trial investigation. Also, to properly integrate the BIM to the BEM tool, a serie of verifications and modifications was documented that is required to better synchronizing the transferred data with the existing thermal template embedded in IES-VE (interaction of BIM and BEM tools that was missing in the previous process maps in the literature). To complete the construction types, the missing information is extracted from Revit to an Excel file and added to the IES-VS construction library. The other steps to complete the

BEM that are not well supported by the data exchanger are added manually such as the Heating, Ventilation, and Air Conditioning (HVAC) system model, which its modeling is currently limited to the BEM tool (BIM post-processing).

In general, the proposed framework is improved by considering both the modeling process and technical requirements. It does not focus on design exploration issues, but rather ensures that the proposed framework would lead to an errorless BEM containing the required level of information. This led to an enhanced and generic process map where complementary work/data flows are added based on the issues encountered during the trial investigation. Moreover, the identified IRs during the trial investigation are used to extend the list of relevant IRs (from the theoretical and field investigations) and are presented in tables containing the required elements, the property members, the property sets and a general description. The IRs are attached to the final process map to easily find the required input data at each design phase. The proposed framework including the final process map and the detailed explanation is described in the following section.

4.4 Proposed framework

The proposed framework is presented as a process map in Figure 4.3. It is divided into three sections: the top row shows the tasks to be completed in the BIM platform, the lower row describes the work and data flows that need to be completed in the BEM tool, while the middle row is used to show data exchange actions including details pertaining to IRs, data exchange files (data schemas), and data transfer needs between the design phases. The following presents short explanations for each of the activities defined in the process. The BIM-based energy modelling starts with the preliminary concept design phase with the purpose of defining the site location and building orientation.

Set the site location, orientation and base point: The building location is set using an Internet mapping service to select specific weather data. The building site is defined with the information about its longitude, latitude, and bounding box. The Google image file can be used to quickly draw the site property line and find the correct orientation. It is important to calculate the angle of rotation and to clearly identify the rotation angle of the true geographic north of the project as this can influence the energy simulation results.

Define form and floor levels: The building is shaped and created using different floor levels (number of stories and story height in the spatial container) in 3D view considering the effects of daylighting. Thus, the preliminary massing and form evaluation can be completed using sun path tool available within the BIM platform. For details pertaining to BIM-based early design exploration aspects, the recommendations made by Krygiel and Nies (2008) can be consulted. The preliminary concept design model is used as the starting point for the schematic design phase (final concept design) where a coarse baseline energy model is created to estimate the preliminary building energy loads used to recommend HVAC options. In this order, iterative assessments are completed to design the building geometry, envelope, and openings (such as window-to-wall ratio), as documented by Hensen and Lamberts (2012), who describe various building optimization options.

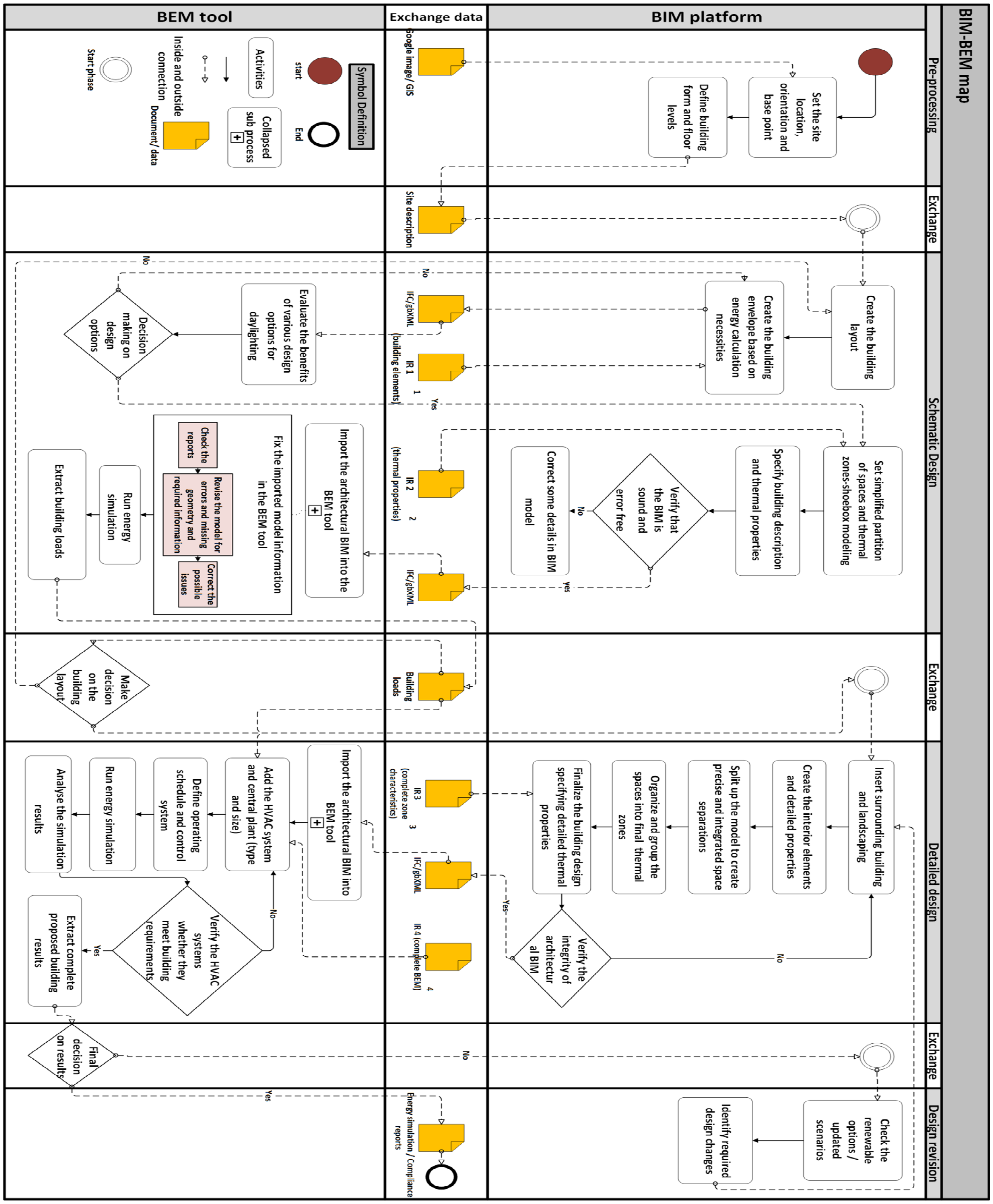

Figure 4.3 Proposed BIM-BEM framework (Note: GIS = geographic information system)

Create the building layout: The required basic geometry and building layout (floor area) need to be modelled seamlessly to be transferred to the BEM tool. The design challenges in this part are simplifying the building layout and minimizing square footage considering the project design and energy targets.

Create the building envelope based on energy calculation necessities: Modelling the envelope is the most challenging step in this process, particularly for curtain walls that need to be completely enclosed. It is recommended to build the exterior walls first so that their centerline aligns with the outline of the floor level. This goes also for the thickness of the walls; it is preferable that the walls being modelled all have the same thickness regardless of their type. Modelling floors, roof, and openings can be completed in parallel to this step. The last elements to be modelled are interior walls, doors, columns, and stairs. Different families and types of elements are available in the BIM platform to build a precise model that specifies the parameters required for energy simulation. Specific IRs need to be defined in order to create the BEM and complete the energy simulation such as those presented in Table 4.1.

Table 4.1 Minimum IR1

Elements	Property Members	Property set	Description
Building common	Net planned area	Pset_BuildingCommon.NetPlannedArea	Total planned net area for the building Used for programming the building.
	Number of storeys	Pset_BuildingCommon.NumberOfStoreys	The number of storeys within a building.
Wall common	Element	Pset_WallCommon	Properties common to the definition of all occurrences of wall.
	Thermal transmittance (U-value)	Pset_WallCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
Window common	Element	Pset_WindowCommon	Properties common to the definition of all occurrences of window.
	Thermal transmittance (U-value)	Pset_WindowCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
	Glazing area fraction	Pset_WindowCommon.GlazingAreaFraction	Fraction of the glazing area relative to the total area of the filling element.
Roof common	Element	Pset_RoofCommon	Properties common to the definition of all occurrences of Roof.
	Thermal transmittance (U-value)	Pset_RoofCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
Curtain wall common	Element	Pset_CurtainWallCommon	Properties common to the definition of all occurrences of curtain wall.
	Thermal transmittance (U-value)	Pset_CurtainWallCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
Door common	Element	Pset_DoorCommon	Properties common to the definition of all occurrences of door.
	Thermal transmittance (U-value)	Pset_DoorCommon.ThermalTransmittance	Thermal transmittance coefficient (U-Value) of a material.
	Glazing area fraction	Pset_DoorCommon.GlazingAreaFraction	Fraction of the glazing area relative to the total area of the filling element.

Evaluate the benefits of various design options for daylighting: The effect of each design option on building daylight is evaluated using simulation results obtained by transferring the BIM into the BEM tools (such as Ecotect or Radiance for daylighting analysis) via proper data-exchanger (IFC or gbXML). The detailed information for this type of analysis can be found in Azhar, Brown et al. (2009) and Kota et al. (2014) studies that focus on the design optimization process using BIM.

Decision-making on design options: The optimal options are identified and evaluated in terms of lifecycle costs to support the final decision.

Set simplified partition of spaces and thermal zones/shoebox zoning*:* The preliminary thermal zones are then allocated in the model. A zone is a single space or a group of spaces that have the same functional and thermal characteristics (GSA 2012). The space boundaries and the zoning need to be checked in 3D view and section plans to make sure that everything matches, especially the space and plenum heights.

Specify building description and thermal properties: In order to complete the BIM-based energy model, the second set of information requirements (IR2) are specified that are based on space templates describing the occupancy density and activities, including outdoor air requirements, space comfort design conditions (temperature and humidity set points, lighting density, etc.) for each zone. An example of such information requirements is presented in Table 4.2.

Verify that the architectural BIM is sound and error free: Once the required attributes are defined, the model needs to be checked in detail for errors and integrity issues ensuring proper information transfer to the selected BEM tool. To complete this task, various Model checkers have been proposed and used to ensure the completeness of the model such as Green Building Studio (Azhar, Brown et al. 2009), which is used to reduce the number of errors in gbXML file or Solibri (Maile, Fischer et al. 2007), which is used to verify IFC file.

Import the architectural BIM into the BEM tool: The ability to import different data-exchangers varying between the currently available BEM tools, due to the differences in their attributes and semantics (Jeong, Kim et al. 2014). Thus, the corrected architectural BIM is exported using an appropriate data exchanger file read by the selected BEM tool.

Table 4.2 Minimum IR2

Elements	Property Members	Property set	Description
Space occupancy requirements	Area per occupant	Pset_SpaceOccupancyRequirements.AreaPerOccupant	Design occupancy loading for this type of usage assigned to this space.
	Occupancy type	Pset_SpaceOccupancyRequirements.OccupancyType	Occupancy type for this object. It is defined according to the presiding national building code.
Space thermal design	Cooling relative humidity (positive ratio)	Pset_SpaceThermalDesign.CoolingRelativeHumidity	Inside relative humidity for cooling design.
	Heating relative humidity (positive ratio)	Pset_SpaceThermalDesign.HeatingRelativeHumidity	Inside relative humidity for heating design.
	Heating dry bulb temperature	Pset_SpaceThermalDesign.HeatingDryBulb	Inside dry bulb temperature for heating design.
	Cooling dry bulb temperature	Pset_SpaceThermalDesign.CoolingDryBulb	Inside dry bulb temperature for cooling design.
Thermal load design criteria	Lighting load intensity	Pset_ThermalLoadDesignCriteria.LightingLoadIntensity	Average lighting load intensity in the space per unit area.
	Receptacle load intensity	Pset_ThermalLoadDesignCriteria.ReceptacleLoadIntensity	Average power use intensity of appliances and other non-HVAC equipment in the space per unit area.
	Outside air per person-flow rate	Pset_ThermalLoadDesignCriteria.OutsideAirPerPerson	Design quantity of outside air to be provided per person in the space.

Fix the imported model information in the BEM tool: The information transferred from the BIM to the BEM tool is still error-prone and inconsistent, which requires manual checking for accuracy. Inconsistencies happen because of differences among heterogeneous databases when two objects coming from different information sources and some of the values of their corresponding attributes are disparate (Anokhin and Motro 2001). Therefore, the imported model in the BEM tool needs to be checked for missing, miss-forming building elements and issues.

Run energy simulation and extract the results: When the geometrical information is entered correctly, the default values of the HVAC systems, central plant and operating schedules embedded in the BEM tool are used to run the simulation. The cooling and heating loads can then be extracted from the output reports to specify equipment and systems. Then, the performance of different systems or equipment can be evaluated using the BEM tool. The studies conducted by Geyer (2009) and Welle, Haymaker et al. (2011) can be consulted for additional information on this specific design activity.

Make decision on the building layout: The decision is made on the preliminary architectural design based on the simulation results and initial design goals. Once the building architectural main features are confirmed by the team members, the detailed design phase begins. The detailed design phase is aimed to complete the design process and to provide annual energy use charts to determine the most efficient and cost effective solutions for HVAC equipment and systems. Therefore, required information to complete this analysis needs to be added to the BIM.

Create the interior elements and detailed envelope properties: Rooms and interior elements, such as partitions, interior walls, ceilings, as well as the required opening details, such as shading devices are added to the BIM to refine the energy simulation results.
Split up the model to create precise and integrated space separations: The detailed model needs to be split up using space separation to create precise spaces; since rooms cannot be recognized as spaces by the BEM tools.

Organize and group the spaces into thermal zones: The thermal zones are re-assigned on the detailed model. The grouped spaces in the thermal zones need to be similar in all thermal aspects such as orientation, occupancy, lighting, and equipment loads. Also, the conditioned and unconditioned spaces need to be specified.

Finalize the building design specifying detailed thermal properties: the thermal properties are specified accurately as far as the BIM platform allows. In this order, the examples of information required to complete the characteristics of each zone for analyzing thermal comfort are presented in Table 4.3. The information describes the internal loads such as the occupancy density and lightings as well as the design temperature and airflow rates for heating, cooling, and ventilation.

Table 4.3 Minimum IR3

Elements	Property Members	Property set	Description
Space detail properties	Heating design airflow rate	Pset_SpaceThermalDesign.HeatingDesignAirflow	The air flowrate required during the peak heating conditions, but could also be determined by minimum ventilation requirement or minimum air change.
	Cooling design airflow rate	Pset_SpaceThermalDesign.CoolingDesignAirflow	The air flowrate required during the peak cooling conditions.
	Total sensible heat gain	Pset_SpaceThermalDesign.TotalSensibleHeatGain	The total sensible heat or energy gained by the space during the peak cooling conditions.
	Exhaust air flowrate	Pset_SpaceThermalDesign.ExhaustAirFlowrate	Design exhaust air flow rate for the space.
	Total heat gain	Pset_SpaceThermalDesign.TotalHeatGain	The total amount of heat or energy gained by the space at the time of the space's peak cooling conditions.
	Ventilation airflow rate	Pset_SpaceThermalDesign.VentilationAirFlowrate	Ventilation outside air requirement for the space.
	People	Pset_SpaceThermalLoad.People	Heat gains and losses from people.
	Equipment sensible	Pset_SpaceThermalLoad.EquipmentSensible	Heat gains and losses from equipment.
	Infiltration sensible	Pset_SpaceThermalLoad.InfiltrationSensible	Heat gains and losses from infiltration.
	Lighting	Pset_SpaceThermalLoad.Lighting	Lighting loads.
	total radiant load	Pset_SpaceThermalLoad.TotalRadiantLoad	Total electromagnetic energy added or removed by emission or absorption.
	total sensible load	Pset_SpaceThermalLoad.TotalSensibleLoad	Total energy added or removed from air that affects its temperature.
	total latent load	Pset_SpaceThermalLoad.TotalLatentLoad	Total latent/sensible energy added or removed from air that affects its humidity or concentration of water vapor.
	ventilation indoor air	Pset_SpaceThermalLoad.VentilationIndoorAir	Ventilation loads from indoor air.

Verify the integrity of the architectural BIM: The BIM needs to be revised in terms of model integrity and possible modelling and geometry errors such as clash or gap between building elements. The process of model checking is performed again to ensure the correctness of the simulation results.

Import the architectural BIM into the BEM tool: The intended data schema file (IFC or gbXML) is extracted from the BIM to be imported to the BEM tool. The imported model is checked for missing, miss-forming building elements and additional required information, which need to be addressed.

Add the HVAC systems and central plant: The type, size, and information about the selected HVAC systems and central plant are specified only in the BEM tool. Accordingly, example of information requirements (IR4), which details the characteristics of those systems such as properties of air terminal box, boiler, chiller, coil, fan, pump and so forth, is presented in Table 4.4.

Define operating schedules and control system: The operating schedules and control system are defined to complete the BEM.

Run energy simulation: The complete building energy model is simulated to estimate the annual energy consumption and operation of HVAC systems.

Verify the HVAC systems: The simulation results are interpreted to understand whether the selected HVAC systems can meet the building loads and project targets. If not, other solutions can be recommended by the engineers.

Extract complete proposed building results and final decision: The complete building design and the simulation output are documented with an energy simulation report.
In some cases, there are requests for design optimization and updates. Therefore, other options, such as renewable design scenarios are identified to update the detailed design model in BIM platform and check the results of their effects.

Table 4.4 Minimum IR4

Elements	Property Members	Property set	Description
Air terminal box	Air pressure range	Pset_AirTerminalBoxTypeCommon.AirPressureRange	Allowable air static pressure range at the entrance of the air terminal box.
	Arrangement type	Pset_AirTerminalBoxTypeCommon.ArrangementType	Terminal box arrangement. SingleDuct or DualDuct, etc.
	Operation temperature	Pset_AirTerminalBoxTypeCommon.OperationTemperatureRange	Allowable operational range of the ambient air temperature.
	Reheat type	Pset_AirTerminalBoxTypeCommon.ReheatType	Terminal box reheat type.
	Airflow rate	Pset_AirTerminalBoxTypeCommon.AirflowRateRange	Range of airflow that can be delivered.
Boiler	Type	Pset_SpaceHeaterTypeCommon	Space heater type common attributes.
	Heat output	Pset_SpaceHeaterTypeCommon.OutputCapacity	Total nominal heat output as listed by the manufacturer.
	Nominal efficiency	Pset_SpaceHeaterTypeCommon.ThermalEfficiency	Overall Thermal Efficiency is defined as gross energy output of the heat transfer device divided by the energy input.
	Power	Pset_SpaceHeaterTypeCommon.Power	Boiler power
Chiller	Type	Pset_ChillerTypeCommon	Chiller type common attributes.
	Full load ratio	Pset_ChillerTypeCommon.FullLoadRatioCurve	Ratio of actual power to full load power as a quadratic function of part load, at certain condensing and evaporating temperature.
	Capacity curve	Pset_ChillerTypeCommon.CapacityCurve	Chiller cooling capacity is a function of condensing temperature and evaporating temperature, data is in table form.
	Coefficient of performance	Pset_ChillerTypeCommon.CoefficientOfPerformanceCurve	COP is function of condensing temperature and evaporating temperature, data is in table form.
Coil	Type	Pset_CoilTypeHydronic	Hydronic coil type attributes.
	Capacity	Pset_CoilTypeHydronic.WaterPressureDropCurve	Water pressure drop curve, pressure drop – flow rate curve.
	Sensible heat ratio	Pset_CoilTypeHydronic.SensibleHeatRatio	Air-side sensible heat ratio or fraction of sensible heat transfer to the total heat transfer.
Fan	Type	Pset_FanTypeCommon	Fan type common attributes.
	Pressure range	Pset_FanTypeCommon.NominalStaticPressure	Pressure rise = f (flow rate).
	Capacity	Pset_FanTypeCommon.CapacityControlType	InletVane. VariableSpeedDrive. BladePitchAngle.
	Efficiency	Pset_FanTypeCommon.EfficiencyCurve	Fan efficiency =f (flow rate).
	Nominal rotation speed	Pset_FanTypeCommon.NominalRotationSpeed	Nominal fan wheel speed.

Elements	Property Members	Property set	Description
Pump	Type	Pset_PumpTypeCommon	Common attributes of a pump type.
	Pressure	Pset_PumpTypeCommon.Pressure	Pressure rise
	Efficiency	Pset_PumpTypeCommon.Efficiency	Pump Efficiency
	Nominal rotation speed	Pset_PumpTypeCommon.NominalRotationSpeed	Pump rotational speed under nominal conditions.
Space heater	Type	Pset_SpaceHeaterTypeCommon	Space heater type common attributes.
	Capacity	Pset_SpaceHeaterTypeCommon. OutputCapacity	Total nominal heat output as listed by the manufacturer.
	Efficiency	Pset_SpaceHeaterTypeCommon. ThermalEfficiency	Overall Thermal Efficiency is defined as gross energy output of the heat transfer device divided by the energy input.
Air to air heat recovery	Type	Pset_AirToAirHeatRecoveryTypeCommon	Air to Air Heat Recovery type common attributes.
	Primary airflow rate	Pset_AirToAirHeatRecoveryTypeCommon.PrimaryAirflowRateRange	Possible range of primary airflow that can be delivered.
	Secondary airflow	Pset_AirToAirHeatRecoveryTypeCommon.SecondaryAirflowRateRange	Possible range of secondary airflow that can be delivered.
	Operational temperature	Pset_AirToAirHeatRecoveryTypeCommon.OperationalTemperatureRange	Allowable operation ambient air temperature range.
Cooling tower	Type	Pset_CoolingTowerTypeCommon	Cooling tower type common attributes.
	Control strategy	Pset_CoolingTowerTypeCommon.ControlStrategy	FixedExitingWaterTemp. WetBulbTempReset.
	Capacity control	Pset_CoolingTowerTypeCommon.CapacityControl	FanCycling. TwoSpeedFan. VariableSpeedFan.

4.5 Comparision of the proposed framework using different BEM tool

The proposed framework is further evaluated using a case study in order to assess if it is applicable for different BEM tools and data exchanger format. This validation is done for the complete BIM- BEM process.

The validation case is a new building that has a floor area of 12 077 m^2 spreads over six storeys with an additional two stories of underground parking. This building includes classrooms, a pharmacy, a bank, offices, study area, and a coffee shop. To realize the case study, Revit is selected as the BIM tool, while OpenStudio (Guglielmetti, Macumber, et al. 2011) is selected as the BEM tool to verify the proposed framework since it is a free, open source, and cross-platform for the EnergyPlus/Radiance calculation engine for national labs, code/standard officials, and third parties. Also, OpenStudio is a SketchUp plugin that allows visualizing the transferred model and easily extend the base capabilities of EnergyPlus for various purposes. Different data exchanger file formats to transfer the architectural BIM can be read by SketchUp or directly by OpenStudio via gbXML and IFC. In this case, IFC is selected as the data exchanger file for this test because of its potential to be used during building operation.

Thus, at the early design phase, the building used for the case study is modeled in Revit, following the proposed work/data flows presented in the process map. In this regard, Figure 4.4 shows the procedures for evaluating building location, orientation, form, mass and floor levels. In addition, the preliminary daylighting assessments are completed using the sun path features of Revit.

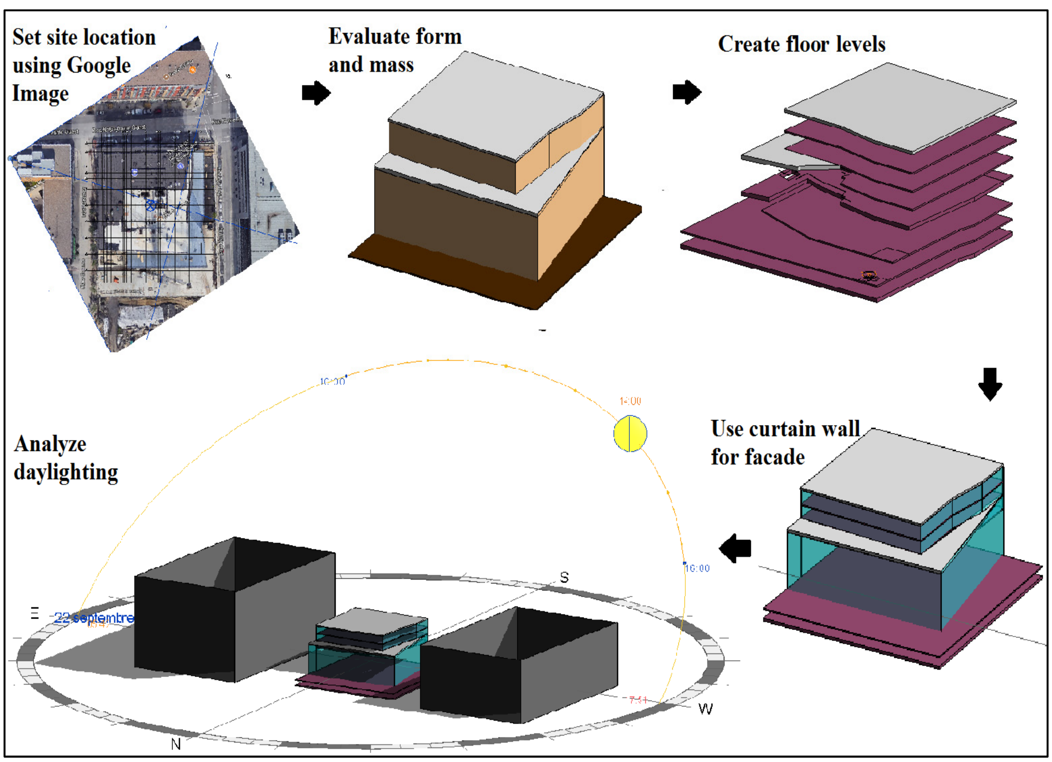

Figure 4.4 Design evolution at the early design phase for the case study

Then, the thermal zones are created based on the shoebox approach and later on detailed as illustrated in Figure 4.5.

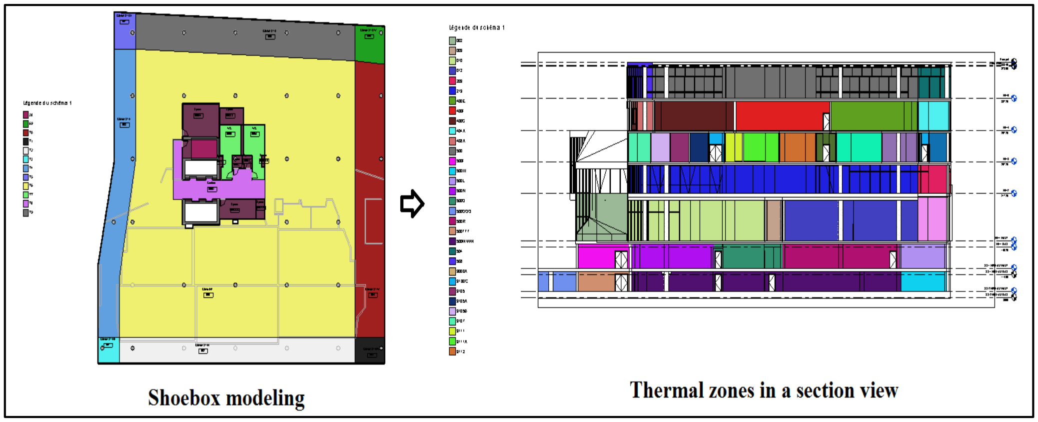

Figure 4.5 Preliminary zoning to detailed zoning of the case study

For each of the BIM-BEM interaction step, the created architectural BIM of the case study is revised following the proposed BIM pre-processing procedures in Revit such as verifying the integrity of the BIM, simplifications and checking the IRs (1, 2, and 3). Once the BIM is verified, the IFC file is extracted and imported to OpenStudio via a BIMserver (Yu, Jiang, et al. 2013). The BIMserver supports the storage, maintenance, and query of IFC-based building information model. It can identify the IFC elements and passes the inputs using the Java query code. The Open Studio Model (OSM) generator in BIMserver enables data exchange between BIMserver and OpenStudio. Thus, the exportation and integration of BIM to OpenStudio are performed using this approach.

The transferred 3D model is visualized in SketchUp to check and fix the imported information based on the procedures in the proposed framework. Some missing and miss-placed elements may be found due to interoperability issues between IFC and OSM converter. For example, the sloped walls are misplaced and the curtain walls could not be recognized. Hence, the required adjustments are applied to the curtain walls in the BIM platform by editing its family from glass to solid material for proper import to SketchUp and then reverting to curtain walls in the BEM tool. This can be a very quick and simple way to solve this error. Also, the sloped walls are fixed in SketchUp by selecting and moving the element to the right place. Figure 4.6 shows the final BIM-BEM model transfer for the case study. The building elements, the spaces, the thermal zones and the IRs (1, 2, and 3) are imported from BIM into OpenStudio as input data. Some of the construction types presented in IR2 were retrieved from the OpenStudio library rather than directly transferred from BIM, due to lack of interoperability to transfer all the required data. The HVAC systems (IR4) are completed in OpenStudio following the proposed BIM post-processing steps.

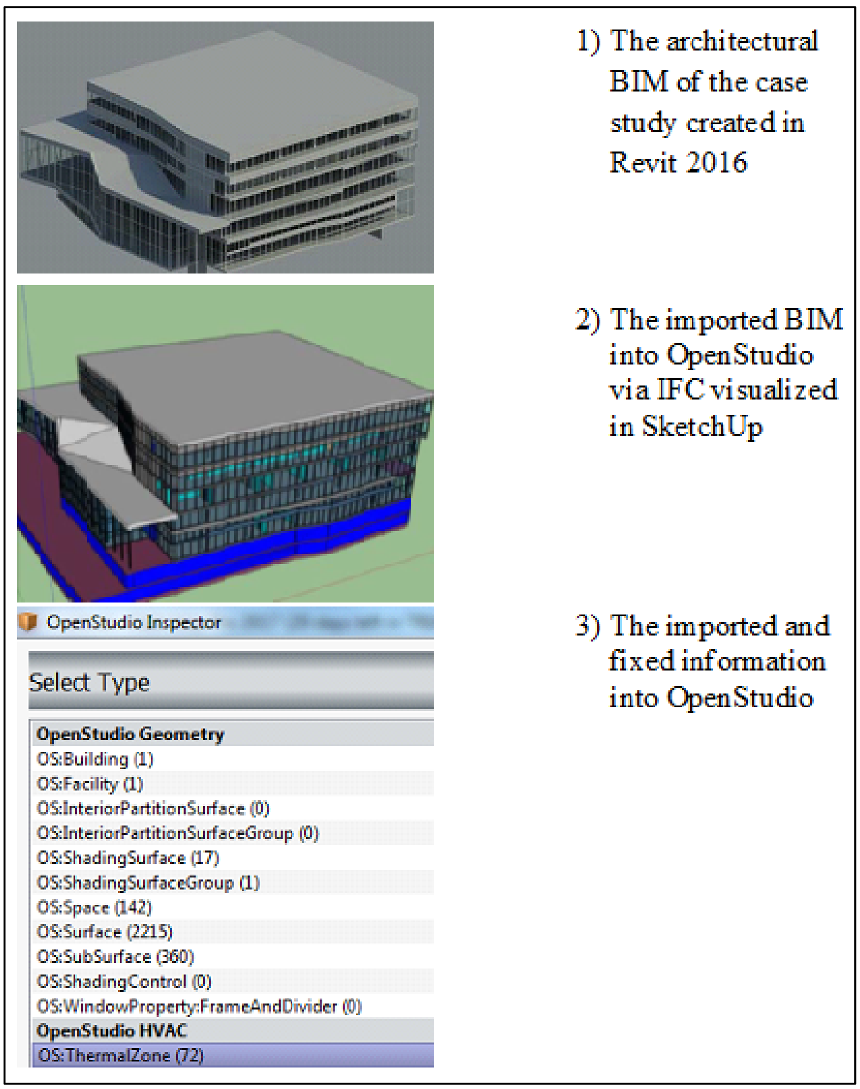

Figure 4.6 Comparison of the created BIMof the case study and the transferred model in OpenStudio

In the end, the simulation is performed using the EnergyPlus engine to complete the process. The outcomes show that the proposed framework is also functioning for OpenStudio and IFC. The proposed framework is easily applied to another BEM tool using a different data schema, thus validating its applicability for most of the popular BEM tools and data exchanger formats.

4.6 Discussion

The concept of BIM-BEM is not new. Its advantage over the currently used simulation approaches has been highlighted by GSA (2012). However, approaches to integrate BIM-BEM into a process have been sparse, incomplete and mostly software-based. The available BIM-BEM process maps in the literature, such as those in Stumpf, Kim et al. (2009), CIC (2011), Attia, Walter et al. (2013), Motawa and Carter (2013), Wu and Issa (2014), Ilhan and Yaman (2016), Zanni, Soetanto et al. (2016) detailed the main design management activities. However, the combination of process and technological aspects for the whole BIM-BEM process is sparsely addressed. The details as to how to create a proper BIM for BEM and BIM-BEM interaction procedures are not described for each of the design phases. For example, how to transfer the BIM to the BEM tool, the model verification steps, and the approach undertaken to fix the imported BEM are hardly addressed in the currently available process maps.

The proposed framework addresses the gaps identified in the literature by introducing a design guideline for BIM pre-processing, BIM-BEM interaction procedures and BIM post-processing in a comprehensive process map. The novelty of the proposed framework is that it does not only focus on the technical aspects but also look at embedding the modelling steps into the design process. It includes an easy to follow work/data flows, key modelling steps and IRs derived from theoretical and field investigations. Also, the trial investigation supported the amelioration and completion of the technical and practical aspects for the whole BIM-BEM framework. Moreover, the validation of the framework demonstrated that the proposed framework is applicable to different BEM tools and data exchanger formats, showing its effectiveness and comprehensibility as well as its generality and usability for BIM-BEM interactions; an important aspect that was missing in currently available process maps.

Thus, the design activities, the integration process and the modeling techniques presented in the proposed framework provide the basis for design firms to develop innovative design of BIM projects. However, there are some limitations in this framework that could be considered for future work, for example:

- Modelling HVAC systems in the BIM platform are not presently detailed since there still exist a lack of interoperability between the currently available MEP and BEM tools;
- The operation phases are not included because of the complexity of the calibration process and the challenges of high modelling effort from captured building data into semantic BIM objects.

4.7 Conclusion

The aim of this paper was to propose an effective, generic and streamline BIM-BEM approach that is embedded into the design process used by professionals. It tackles aspects that are currently only partially addressed in the literature and covers the complete design process by proposing a framework presented in the form of a process map (Figure 3). It covers three main aspects in details: the steps to be completed in the BIM platform (BIM pre-processing), the BIM-BEM integration (for both technical and work/data flow aspects), and the steps to be completed in the BEM tool for each of the design phases. Moreover, the addition of IRs to the process map allows a better understanding of which inputs are essential at each modelling step. This generic, easy to follow framework may encourage architects and engineers to use BIM collaboratively for building energy simulations. The proposed framework also extends the corpus of knowledge necessary to improve the design process by identifying the essential information required to proceed with BEM.

This study led to two important findings that were considered in the proposed framework: (1) the approach undertaken to create the model in BIM authoring tools influences its capabilities to be transferred to BEM tools, and (2) there are differences between a model that is built for architectural purposes and one for energy simulation. An adequate and appropriate level of development is required for BEM. Strategies to overcome this issue were proposed and as future work, the following are suggested:

1. Advance the IRs by defining the Level of Developments (LOD) during the BIM-BEM process, the standards for building specifications such as ASHRAE, and the complete IFC sets that could then be used to define MVD. This would allow to easily extracting the required information from the existing architectural model to proceed with energy simulations.
2. The aspects considered in this article are important to enhance the BIM-BEM process; however one of the most valuable ideas is to extend the life of the BIM to be used also during the building operation phase. Thus, the framework could be extended to cover the whole building life cycle and be validated using a case study from early design until the operation phase.

Also, there are still technical aspects to be overcome to reach a seamlessly BIM-BEM transfer process as highlighted in this article. For example, the transfer of the BIM (Revit) to BEM (OpenStudio) via BIMserver requires additional modifications of the imported model that are not completed automatically. Thus, improving the interoperability between IFC and OSM would enhance the proposed approach.

CHAPTER 5

AN INFORMATION PROTOCOL FOR BIM-BEM

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5.1 Abstract

The creation of a Building Energy Model (BEM) during the design process requires specific graphical and non-graphical information that can be transferred from a Building Information Model (BIM). The correct execution of BIM-BEM is possible using inputs that change with the level of modelling, which this level progresses with the different phases of the project. However, existing studies barely focus on the adequate information required to create an accurate BIM for the creation of a BEM. The existing Level of Development (LOD) that defines the content of BIM at each design phase suffers detailed information for energy simulation. Therefore, in this paper, an information protocol for BIM-BEM was proposed based on the concept of Level of Development for energy simulation (LOD_{ES}), which specifies a list of information requirements (IR) for the accurate execution of BIM-BEM during the design process. This protocol provides the foundation for operationalizing existing frameworks and creating a specific Model View Definition (MVD) for BIM-BEM execution.

Keywords: Building energy model, BIM, Information Requirements, LOD_{ES}, Energy simulation

5.2 Introduction

The use of Building Information Model (BIM) to develop Building Energy Models (BEM) is becoming a primary approach for evaluating energy performance and estimating energy consumption during the design process. A BIM can present the complete building information in an intelligent format (Bazjanac, 2004), referred to as a digital model, which defines functional and behavioural relationships between different elements, termed BIM elements; these include geometrical, spatial, lighting, geographical, construction, space and occupant information, quantity, and property elements (Singh, Gu and Wang, 2011). BIM is capable of holding more than 70% of the information required to develop a BEM to perform energy simulations (Choi et al. 2016). Energy simulations are often defined using modelling sequences and general modelling requirements, as described by Clarke (2007); Maile, Fischer and Bazjanac (2007); Osello et al. (2011), and in ASHRAE Standard 209 (2018). In general, the following information is required to run energy simulations during the design process: climate and location, geometry and building envelope, thermal properties of building elements, spaces and thermal zones, internal loads, heating, ventilation and air-conditioning (HVAC) systems, and operation schedules.

Thus, most of the needed information defined in BIM can be transferred to create the BEM in order to avoid remodelling and manual inputs. This BIM-BEM process comprises three main steps: BIM pre-processing, BIM-BEM interaction and completing the BEM to run energy simulations (Farzaneh et al., 2018). In the BIM-BEM interaction steps, the model can be transferred using different data exchangers, such as the Industry Foundation Class (IFC) or green building Extensible Markup Language (gbXML). These data exchangers, especially the IFC file, contain a wide range of data that are not required or adequate to support the preparation of BEMs (Pinheiro et al., 2018).

The content of a BIM model can be defined and classified by using the Level of Development (termed LOD in this paper) at different phases of the design process. However, the LOD need to be developed to include the required BEM information in the BIM model. The BIM model often contains additional and unnecessary information, leading to difficulties in creating the

BEM, since a much simpler model is required to run the energy simulations, especially during the early phases of design (O'Donnell et al., 2013; Rose and Bazjanac, 2015). Several simplifications, modifications, interpretations, translations, and data re-entry are thus required for all of the BIM-BEM steps. The iterative process of modifying the model to transfer a heavy data exchanger file is usually very time-consuming and error-prone (Bazjanac and Kiviniemi, 2007; Pinheiro et al., 2018). Therefore, to successfully complete and reduce the constraints of BIM-BEM execution, a reliable reference is needed that specifies a clear set of Information Requirements (IR) at the different LODs for the BEM creation during the design process.

In this study, a BIM-BEM information protocol specifying the LOD for the creation of a BEM to complete energy simulations, including IR for all BIM-BEM steps during the design process, is proposed. This protocol aims to enhance the existing LOD to enable the production of a BEM containing the information required to run the energy simulations for different design activities and scopes.

The design activities, work and dataflow originate from existing BIM-BEM frameworks, such as the one proposed by Stumpf, Kim, and Jenicek (2011), Zanni, Soetanto, and Ruikar (2017), and Farzaneh, Carrier, Forgues, and Monfet (2018), and are realized by the development of the BIM-BEM information protocol. This protocol defines which information, at what level and when is required to be transferred at each BIM-BEM step during the design process. This protocol defines the BIM content, information required to support the BIM-BEM interactions during the design process. It supports the operationalization of existing frameworks by defining the adequate LOD and specifying the IR to be made available in a BIM to create a BEM, in order to conduct the recommended energy simulations during the design process. It enriches input data generation for different modelling activities (Latiffi et al., 2015), provides a better understanding of the characteristics of the model elements (Reinhardt et al., 2017), and minimizes the number of modifications to be made at each of the BIM-BEM interactions during the design process.

5.3 Review of existing LOD and IR for BIM-BEM

Various terminologies and classifications have been proposed to define the different levels of BIM during the design process, such as the *Level of Detail*, *Level of Definition* and *Level of Development*. All these terms use LOD as an acronym in the literature. However, in this study, the use of LOD refers only to the *Level of Development*. The *Level of Detail*, *Level of Definition* and *Level of Development* all contain different level classifications, information coverage and ranges, and influence on BIM-BEM execution, which are assessed for their use in a BIM-BEM information protocol.

5.3.1 Level of Detail and Level of Definition

The Level of Detail defines the steps of the logical progression of BIM elements at five levels, as developed in Australia, from low to high precision (Bedrick, 2013; Bedrick and Davis, 2012). It corresponds to the description of the details for each object, geometrically as well as semantically (Figure 5.1). The Level of Detail specifies elements in the BIM at each design phase that must correspond to the needs of different design purposes. However, as illustrated in the definition of each Level of Detail in Figure 1, they support graphical inputs to the BIM model containing only details with regards to parts of the BIM element, i.e., concept, development, documentation, fabrication, installation, and operation details (Innovation, 2009).

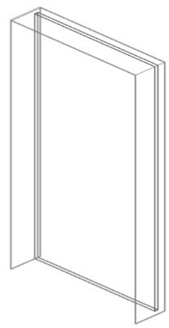
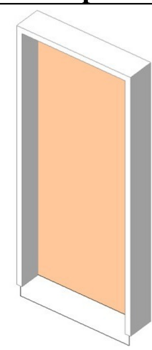
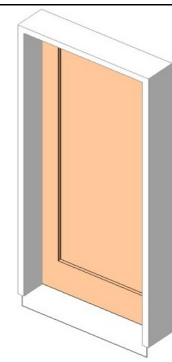
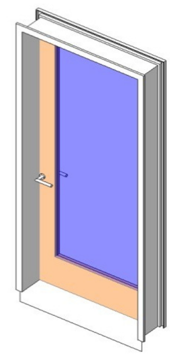
	100 Concept	**200 Development**	**300 Documentation**	**400 Fabrication**	**500 Installation**
Level of Detail					
Definition	Primitive design model contains generic representation	Approximate design model contains basic information	Final design model contains detailed information	Construction model contains fabrication and assembly information	Post construction or as-built model contains installation information

Figure 5.1 Example of different Levels of Detail for a window as a BIM element

The Level of Detail concept for BIM-BEM is applied by Löwner et al. (2013) and Ferriès and Bonhomme (2014) to carry out heat loss calculations, daylighting analysis, and energy consumption estimation. In the presented cases, the graphical model at each Level of Detail is modified to create the BEM needed to proceed with the energy simulation; however, the non-graphical IR required to complete the BEM are entered manually based on plans and specifications (such as thermal properties). The energy performance analysis is performed using the Level of Detail (400). Thus, many simplifications are needed in creating the BEM to purge detailed graphical structural and manufacturing-related information (Löwner, et al. 2013 and Ferriès, et al. 2014). Moreover, non-graphical information, which describes various characteristics of the building elements, performance requirements, and associated documentation, is not considered in this Level of Detail.

The definition of the existing Level of Detail is generally very descriptive in terms of graphical information, especially in the later design phases, while the non-graphical information is often missing or incomplete. The combination of graphical and non-graphical IR is the main prerequisite for BIM-BEM execution, which is clarified in the Level of Definition and in the Level of Development. For the Level of Definition, which follows the UK system, few details are available since the latest version was developed in 2013. It is, however, a more complete concept, and is often compared to its US equivalent, the Level of Development, with new versions being published on a yearly basis, including added detailed graphical representation and explanations at each level. In addition, the word “development” refers to the level of certainty of an object rather than the definition of elements at a graphical level.

5.3.2 Level of Development

The idea of Level of Development (LOD) at the early stages based on the development of a 3D working method (BIPS, 2007). In this method, graphical information is specified by adding a number of object attributes during the process. In this regard, the American Institute of Architects (AIA, 2008) developed LOD as a foundation for collaboration using a standard and consistent protocol. Table 5.1 presents a brief definition of each level of the existing LOD.

Table 5.1 Definition of each level specified for LOD during the design process
Taken from the National Building Specification , AIA (2008)

LOD	Definition
100	At this level, estimated graphical information (such as overall area or overall volume) is provided for building elements in the model.
200	At this level, approximate graphical and non-graphical information (such as approximate size, shape, location, and orientation) is provided as a generic system for building elements in the model.
300	At this level, accurate graphical and non-graphical information (such as detailed material and quantities) is provided with respect to the project origin as a specific system for building elements in the model.
400	At this level, very detailed graphical and non-graphical information (such as detailed fabrication, assembly, and installation) is provided with respect to the project origin as a specific system for building elements in the model.

As retrieved from the definition of each LOD, at each level the minimum dimensional, spatial, quantitative and qualitative data included in a model element during the design process are specified (AIA 2008). The LOD covers both graphical and non-graphical elements of models (Reinhardt, 2017). The existing LOD (Table 5.1) is constructed using IR corresponding to each described level, since LOD is pointless without specifying relevant IR (Volk, Stengel and Schultmann, 2014). Therefore, the IR defined for the existing LOD are assessed for their capacity to support BIM-BEM:

- At level 100: The climate and weather data, site and topology information are not specified in the existing LOD, and need to be input into the BEM for early design energy simulations.
- From levels 200 to 400: The thermal properties of the building elements need to be specified in the BEM for any energy simulation; these are missing in the existing LOD.
- Prior to level 300: Information related to the spaces and thermal zones must be specified.
- At level 400: Additional information related to the fabrication, assembly, and installations is provided in the existing LOD, but is not required to create the BEM. However, at a lower level, information on HVAC systems must be provided to estimate the final energy consumption.

From the preceding general description, the LOD thus has the potential to be applied for BIM-BEM execution. However, defining accurate and proper IR is necessary for understanding what kind of information is available in a BIM model, and which information at which LOD may be required for BEM (Fox and Hietanen, 2007). The range, scale and details of the IR at each LOD are different based on the design scopes of each phase, especially when creating BEM for energy performance analysis.

5.3.3 IR linked with LOD

Some relevant guidelines are available and propose different forms of IR that focus only on BIM or BEM aspects. For example, the BIM execution plan developed by the Computer Integrated Construction (CIC) group (2011) suggests a checklist containing general BIM information in all dimensions, such as 4D, 5D, etc. Similarly, there are a series of guidelines developed by the Building and Construction Authority (BCA), which stipulates BIM execution requirements for coordinators (2013b), architects BCA (2013a), and engineers BCA (2015).

In these guidelines, some BIM-BEM examples are prepared for specific projects and presented in the three documents. The information provided in these documents mostly represents large building components such as building mass, which is not enough for creating a BEM: required information regarding openings, construction, and thermal properties is not covered. In addition, the scale and the range of information are not specified for different design phases.

Detailed energy-related elements are outlined in the documents developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), such as ASHRAE 90.1 (2016a) and ASHRAE 62.1 (2016b), and the Title 24 - California (CA) energy commissioning standard (2016). These guidelines cover the standards for architectural (e.g., envelope), internal gains (e.g., occupancy), and mechanical (e.g., HVAC systems) information in order to improve building energy efficiency, HVAC systems design, indoor air quality, thermal comfort, and sustainable development for different design phases. The documents provide information to support the development of a database for IR, best practices and recommendations for BEM. Since they provide greater and wider information in this area, they can represent a valid starting point for proposing IR for BIM-BEM execution. However, BIM and LOD aspects are rarely considered in these guidelines.

An example of IR for BIM-based energy analysis is proposed by the US General Services Administration (2009), and covers a macro level of IR at the conceptual design phase only, to develop a BEM using BIM. Azhar et al. (2011) and Choi et al. (2016) address the BIM-based sustainability analysis during the entire design process. However, they focus on the general IR categories to meet the credits for Leadership in Energy and Environmental Design (LEED) certification. The required details and characteristics for BEM are not defined in the presented categories. In addition, when and where they should be specified during the design process to create a proper BIM for developing a BEM are not examined.

More detailed exchange requirements are identified by the Holistic Energy Efficiency Simulation and Management of Public Use Facilities (HESMOS) committee (Liebich et al., 2011), AIA (2008), NATSPEC (2010) and BIMForum (Jan Reinhardt, 2017). These authors used LOD to develop an object element matrix including properties and attributes of the model for specific information exchanges, milestones in a design work plan, and deliverables for specific functions. Models provided for BIM authoring tools at each LOD contain architectural, electrical, structural, mechanical, and facility management information.

Thus, there is a lot of irrelevant information in the BIM model to be removed for the creation of the BEM, as well as some required information that is missing and needs to be added. This leads to many simplifications and modifications being required for the execution of BIM-BEM. One promising approach, developed through the International Energy Agency Energy in Buildings and Communities (IEA EBC) Annex 60, proposes using Model View Definition (MVD) to create IFC files for BIM-BEM (Pinheiro, Wimmer et al., 2018). It focuses on facilitating the transfer of appropriate IR using IFC from BIM to create a BEM, using a specific tool. It does not adjust the IR with the BIM LOD. It however details IR for later design stages, which were used as a basis for the proposed BIM-BEM information protocol.

In general, the review of the existing LOD and IR reveals that in most cases, they present general information that is not enough for creating a BEM, or detailed enough, which leads to several errors in BIM-BEM interactions. The review does not specifically focus on BIM-BEM execution covering accurate IR at proper LOD for the whole design process. As stated by Gao et al. (2011), LOD development requires considering the model scope, the data structure in BIM (layers, hierarchy), the level of model design and a number of levels in BIM for analyzing certain aspects. However, in the current BIM-BEM process, it is not clear what IR should be available in a model for a particular LOD.

The proposed BIM-BEM information protocol extends the existing Level of Development (LOD) to complete earlier frameworks for BIM-BEM execution. Therefore, it proposes an efficient LOD for energy simulation named LOD_{ES}, aligned with proper IR for BIM-BEM execution. The proposed IR covers the value, quantity, scale and the degree of detail based on building modelling and design activities from a vague conceptual idea to a precise description (BIPS, 2007).

5.4 Development of the BIM-BEM information protocol

The approach undertaken for the development of the BIM-BEM information protocol included two main steps:

1) Specifying a list of IR for each BIM-BEM activity: This was accomplished by completing the following two tasks:

    a. Identifying the BIM-BEM activities during the design process: The design process begins by defining the project requirements and activities based on the design scope (McArthur and Sun, 2015). In this regard, the BIM-BEM frameworks proposed by Stumpf, Kim and Jenicek (2011), Zanni, Soetanto and Ruikar (2017), and Farzaneh et al. (2018) were used as a foundation to review the main design activities.
    b. Identifying IR based on BIM-BEM activities: The implementation of the BIM-BEM activities into the design process requires navigating through the data inputs and information exchange (Bernstein, Russo, et al. 2010). Therefore, the appropriate IR were identified based on design activities at each step of the BIM-BEM process. As such, the range and scale of the specified IR were assessed and then detailed according to each of the design phases (preliminary concept, final concept, and detail design). Several studies and guidelines, which individually address BIM (Innovation 2009, Messner, Anumba et al., 2010, BCA 2013, BCA 2015, Reinhardt, 2017) and BEM (ASHRAE 2016 (a, b), and Title 24 CA 2016), were employed to derive, combine, filter and optimize the information toward accurate IR for each BIM-BEM activity and scope of the design process.

2) Developing the LOD_{ES} aligned with the identified IR: The IR identified for BIM-BEM in step (1) were categorized based on the scope of the design phases to include the information missing in the existing LOD and generate the proposed LOD_{ES}. Some of the existing levels of the LOD were enhanced by the LOD_{ES} that specified additional IR (graphical and non-graphical information) to create the BEM and run the energy simulations. Moreover, there were some IR categories (e.g., thermal zone properties) for

implementing particular BEM activities (e.g., assigning thermal zones) that could not be built into the existing LOD classification. These IR were grouped to create new LOD_{ES} to support the BIM-BEM interaction steps for energy simulation during the design process. The design activities specified in each LOD_{ES} with the specified IR for each design phase formed the BIM-BEM information protocol.

The information protocol was then verified using a test case. The BIM-BEM execution was completed for the test case using the identified LOD_{ES} and activities at each design phase: (1) the architectural BIM was created and revised in Revit (2017), (2) the BIM was transferred to a BEM tool (OpenStudio, version 2.7), and (3) the BEM was completed for energy simulation. At each step, the identified IR were verified and enhanced, if required, using lessons learned from applying the information protocol.

5.4.1 BIM-BEM information protocol

The information protocol detailed the LOD_{ES}, which specified a list of information requirements (IR) for accurate execution of BIM-BEM during the design process. The existing LOD served as the basis for developing the proposed LOD_{ES}, which were detailed for three main design phases (preliminary concept, final concept, and detail design), and included BIM-BEM data input, and sharing of specific data elements, referred to as IR. The proposed LOD_{ES} were categorized into five numbered groups (LOD_{ES} 100, 200, 250, 300 and 350), depending on the characteristics, definition and scope of the design phases, as listed in Table 5.2. The LOD_{ES} 250 and 350 were proposed to specify the missing IR to create the BEM and complete the energy simulations. For the preliminary concept, no new LOD_{ES} were proposed since only one additional BIM-BEM activity was identified to complete the required energy simulation. Therefore, this activity and related IR were added to LOD 100 to create a LOD_{ES} 100 instead of adding a LOD_{ES} 150.In the proposed LOD_{ES}, the preliminary concept consisted in evaluating the initial building options using an approximate geometric model, the architectural BIM. In this phase, it was important to ensure early in the process that the geometry of the building in the BIM corresponded to the project requirements before creating the BEM.

In the final concept, different façade options and indoor conditions for different types of spaces and zones were evaluated to estimate their impacts on loads and evaluate the energy performance according to the BIM-BEM procedures. In this phase, different HVAC system options were also assessed using the architectural BIM to estimate the energy consumption.

During the detailed design, the architectural BIM was updated with detailed exterior and interior building envelopes, spaces, and the corresponding detailed thermal specifications. Accordingly, the final HVAC systems were modelled based on the updated loads. In this phase, a complete analysis was carried out based on the architectural and mechanical models to estimate the total energy consumption.

In Table 5.2, the graphical model refers to the model constructed using the information presented visually in 2D or 3D formats in the BIM or BEM tools. It provides a visual reference, location, and context, establishing the relationships between the elements in a virtual building model. The physical size/dimension information is required to establish a graphical model.
The non-graphic model refers to the model constructed by the information that presents itself, usually in text format, for the elements or the properties of the elements, as digital attributes in BIM or BEM tools; these include component specification, thermal properties, etc.

Table 5.2 Definitions of different LOD$_{ES}$

LOD$_{ES}$	Definitions	Design phase
100	Graphical model covering approximate building elements at macro level: area, mass, and form.	**Preliminary concept design**: The target is early and wide-space design, evaluating climate conditions, building orientation, and large-scale impacts of design alternatives in order to provide early feedback on building design and daylighting.
	Non-graphical model covering general project specifications, **climate and location characteristics.**	
200	Graphical model covering approximate building elements at meso level (indicates a population size that falls between the micro- and macro-levels): geometry, spatial, size, layout, and orientation.	**Final concept design:** The target is a space-by-space design to define high-performance options, evaluate building geometry, spatial configuration, layouts, window-to-wall ratio and solar radiation. The preliminary simulation is completed to estimate building loads and energy consumption.
250	**Graphical and non-graphical model covering spaces, thermal zones, and preliminary HVAC systems.**	
300	Graphical model at micro level covering accurate building elements and detailed information of geometry, spatial, openings, layout, location, quantity, and orientation.	**Detailed design:** The target is a detailed space-by-space design from inside to outside and top to bottom in order to provide accurate energy predictions and carry out final technical system decisions and energy cost estimation.
350	**Graphical and non-graphical information covering accurate and detailed thermal properties of building elements, construction, and material types, internal loads, detailed HVAC systems.**	

Accordingly, the proposed IR aligned with each LOD$_{ES}$, which have been identified and optimized, are detailed in Annex III. These IR were classified by numbers and listed by types, elements, and specifications for each LOD$_{ES}$. The LOD$_{ES}$, the relevant IR, and the scopes are presented in the BIM-BEM information protocol (Figure 5.2) for each design phase. The details as to how this was developed were presented at the beginning of section 3, where the approach undertaken to develop the BIM-BEM information protocol was described.

The information protocol illustrated in Figure 5.2 shows the evolution of the BIM, the sharing points for BIM-BEM execution and the complementary levels to the existing LOD. The two complementary LOD$_{ES}$ (250 and 350) specified IR to complete the energy simulations, which were missing in the existing LOD. The proposed LOD_{ES} were compared with the existing LOD to clearly highlight the differences and the advancements:

- LOD_{ES} 100 was completed by defining the IR assessing site conditions such as typology and climate. From the early phase of the project, this level is required to understand how temperature, humidity, wind, and solar radiation of the location can influence the whole building design.
- LOD_{ES} 100, 200 and 300 were developed for the energy-related IR to follow the BIM-BEM activities in order to circumvent simplification, data exchange errors, and remodelling.
- LOD_{ES} 250 was proposed to execute the necessary modelling activities of BIM pre-processing (such as thermal zoning) to complete BEM by adding the proper IR to complete load calculation. This allowed selecting the HVAC systems and sizing the equipment based on preliminary heating and cooling loads. The HVAC equipment and systems included the primary systems (such as chillers, boilers, and cooling towers, equipment, etc.) and the secondary systems (such as air handling, air distribution and heating, cooling, and humidity-conditioning equipment, etc.) to maintain thermal comfort and acceptable indoor air quality.
- LOD_{ES} 350 was proposed to meet the last required BIM-BEM interaction during the design process. It contained the accurate and appropriate IR for completing the building design and finalizing the selection of HVAC systems for the final energy simulation in the design process. In this regard, the LOD_{ES} 350 provided a complete set of IR to create the BEM in the last design phase. This allows understanding the required BIM content in a model sharing process to create a BEM and run energy simulations.

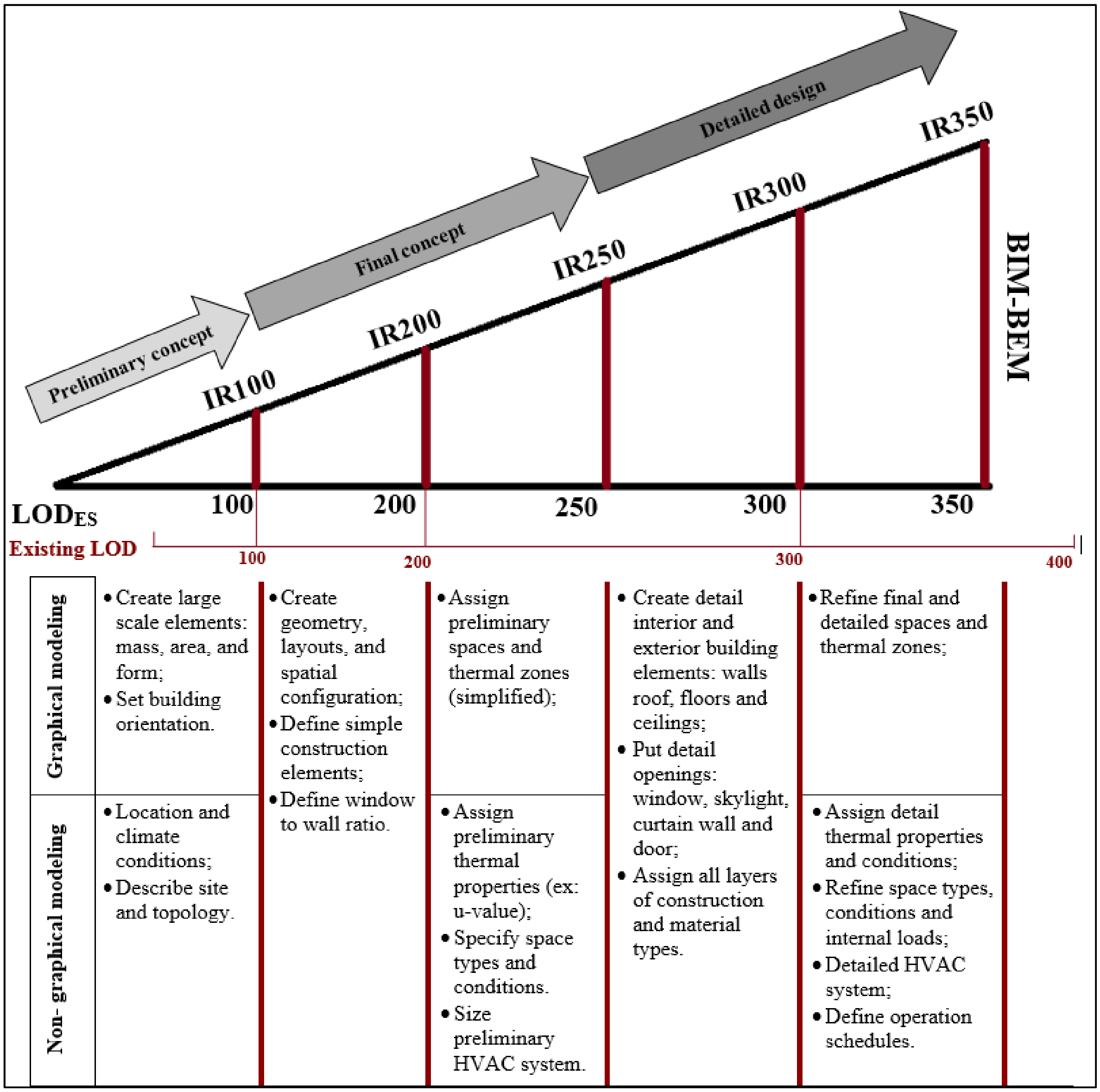


Figure 5.2 BIM-BEM information protocol

5.4.2 Verifying the information protocol using a test case

The LODES and the identified IR were assessed by modelling and simulating a test case to verify the BIM-BEM information protocol.

5.4.2.1 Modelling of the test case

An office building located in Montreal, Canada, with a floor area of 3062 m^2 spread over three storeys was used as the test case. Each floor included offices, conference rooms, a photocopy room, a coffee room, and a large open area (Figure 5.3). The additional information concerning the test case is presented in Annex IV

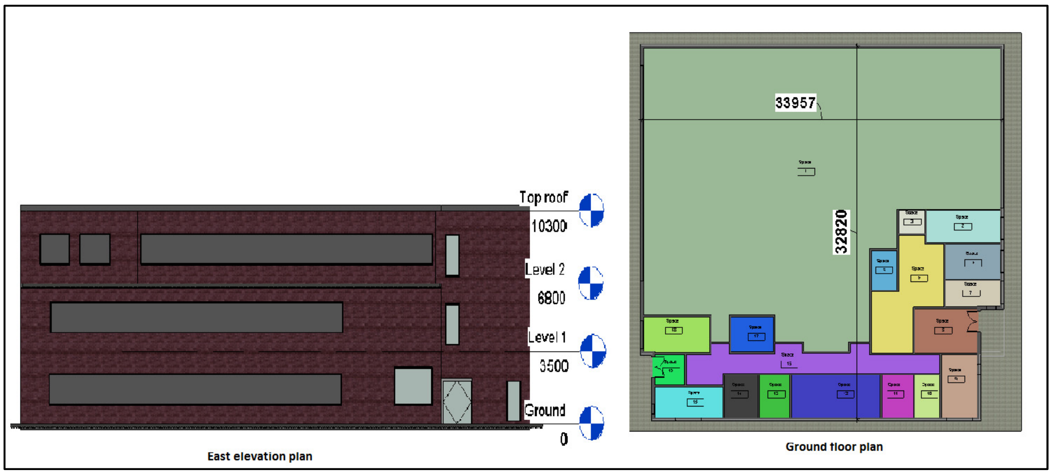


Figure 5.3 Floor and elevation plan of the test case

The data structure for inputting the IR in Revit was based on object inheritance, which typically starts with a base object (such as a parent) and then derives other objects (such as child) from it. In Revit, the object called Family, works as a family inheritance, i.e., each generation inherits all of the properties of its parent, and then adds properties of its own. As an example, this relationship would be such that a door (child) would have its own properties, and in addition, inherit the properties of the wall (father) to which it is linked, which itself would be linked to the envelope (grandfather). For modelling the test case, the schematic model used for defining the proposed IR for each object is displayed in Figure 5.4.

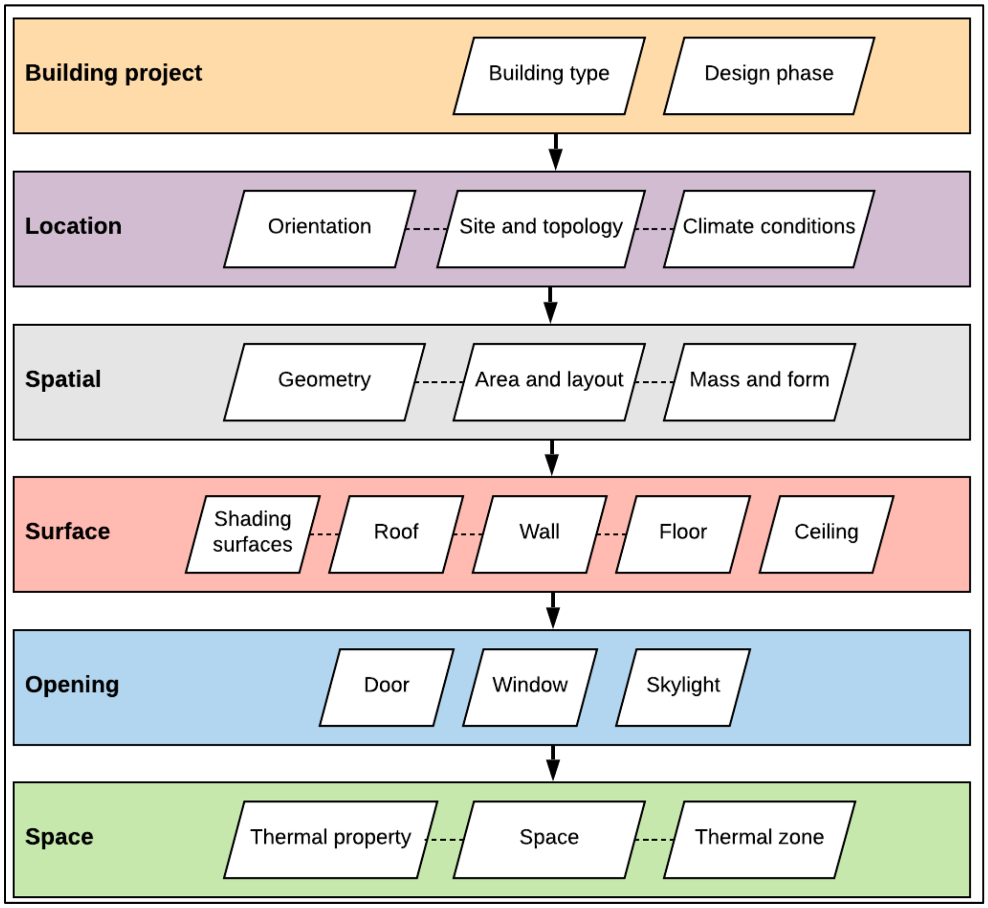


Figure 5.4 Schematic model of object inheritance in architectural BIM tool

According to Demchak, Dzambazova and Krygiel (2009), there are three possible ways to define the IR for each element or object in Revit, which the user can select based on project types, complexity of the model, and the available data library:

- **Built-in:** The information is directly defined in the object properties without special editing. The general and basic parameters that represent a different kind of building component can be found in the central library that is already created for common building types and designs.
- **Types:** The information is defined in a class of objects for particular models. It allows editing or creating new objects that do not exist in the built-in library.

- **Instance:** The information is defined in a single placement of the specific object for a specific design. The instances can be edited using dynamic or parametric modelling which is performed by combining a set of relations and rules that control the parameters by which element instances can be generated. Dynamic modelling has the potential to manipulate the model elements via parametric relationships among objects and properties that would be otherwise impossible with conventional inputs (Rahmani Asl, Zarrinmehr, Bergin, and Yan, 2015).

In general, the Built-in and the Type inputs are user-friendly and suitable for defining the proposed IR in most BIM projects, including the test case of this study. Thus, these two approaches were employed to define the graphic-related and some of the non-graphical IR using the advanced energy setting of Revit.

During the implementation of the test case, the BIM was completed for BEM, up to the levels that were suitable for each BIM-BEM interaction during the design exploration according to the design scopes. Thereafter, the model at the specified LOD_{ES} was transferred to OpenStudio via gbXML and verified for data transfer accuracy and possible warnings. The assessment of the imported model showed that transferring an appropriate BIM constructed using proper IR led to a more accurate BEM, with no simplifications required and with fewer transfer errors. However, the version of OpenStudio (2.7) used in the study did not have the capacity to import all the defined construction sets and the detailed HVAC systems from the BIM tool. Therefore, the model was completed directly in the BEM tool using the remaining IR for the specific LOD_{ES}. The IR at each LOD_{ES} were verified in order to detect the missing information and refine the proposed one.

An overview of the model evolution in the proposed protocol is shown in Figure 5.5, while Figure 5.6 illustrates the verification step at the last BIM-BEM interaction during the design process, i.e., at the LOD_{ES} 350 that contained detailed IR needed for BEM. It shows the model in the BIM tool, the imported BIM to BEM, the imported building storeys, the imported thermal zones and the imported IR that were assigned in the BIM tool.

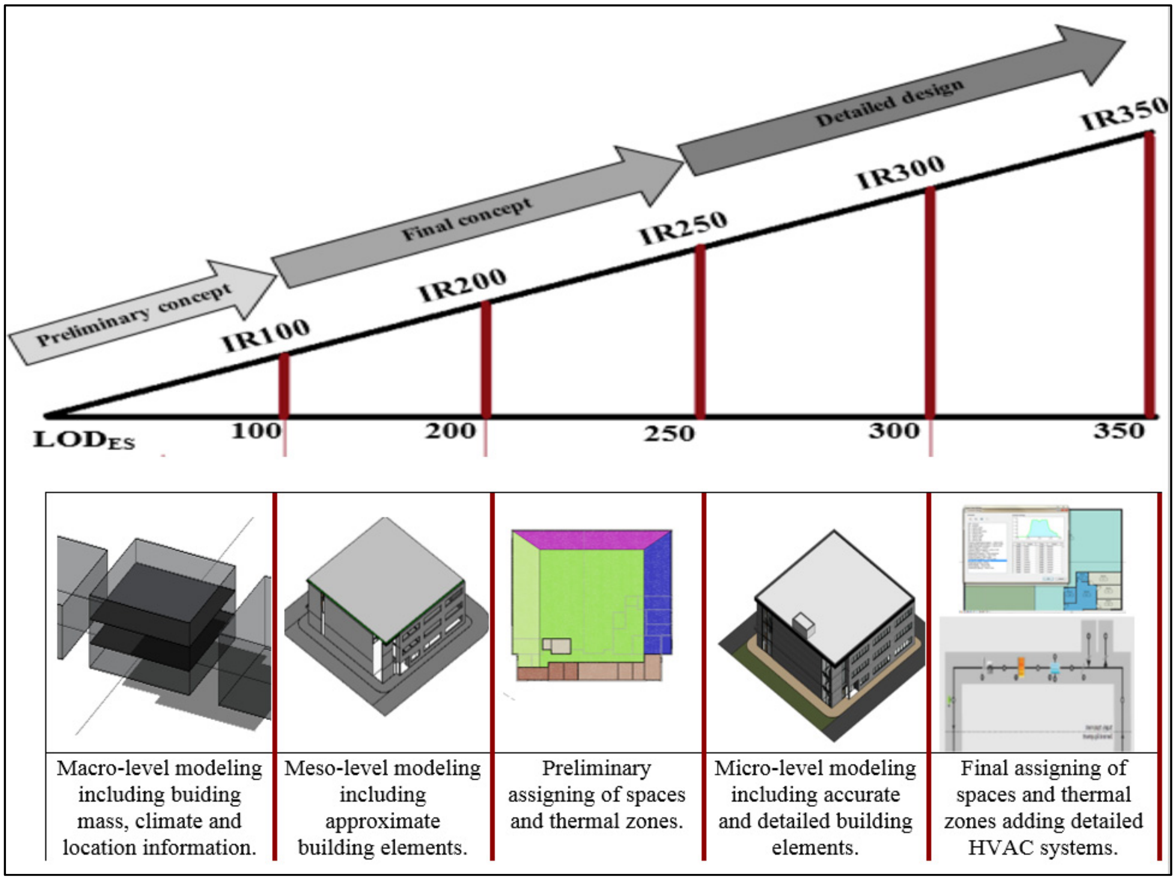


Figure 5.5 Overview of the test case model evolution

The OpenStudio inspector (Figure 5.6) showed that the construction sets were not transferred, and thus, they were completed in the BEM tool. However, this issue is supposed to be resolved in the upcoming versions of OpenStudio.

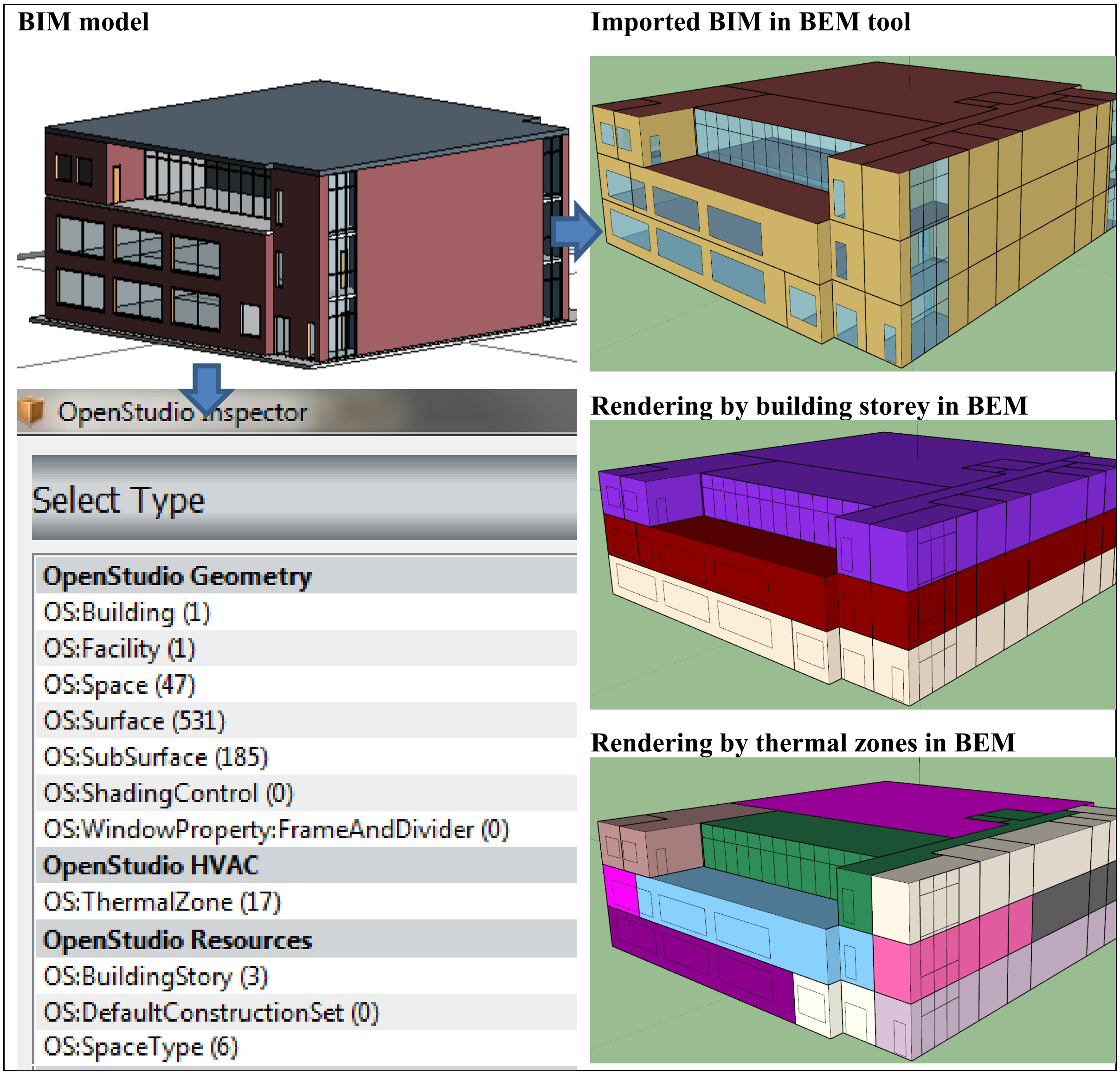


Figure 5.6 Verification of the IR at last LOD_{ES} for the test case

5.4.2.2 Results comparison of the test case

The information protocol developed for the BIM-BEM execution was verified by comparing the simulation results using a manual BEM approach (or non-BIM approach).The manual BEM was completed by creating and completing the data entry manually by an independent modeller. The manual creation of BEM has been used for several years, and is known to be a reliable approach, but not as an effective one during the design process within design firms.

Figure 5.7 illustrates the two procedures, the BIM-BEM and the manual BEM procedures. The creation of the manual BEM began by extracting the IR from the architectural and mechanical 2D plans and specification documents to be remodelled in the BEM tool (OpenStudio 2.7) by an independent modeller. The graphical information (such as envelop, geometry) was completed by space-by-space manual entry. Regarding the proposed LOD_{ES} (e.g. 350), the thermal zones were assigned graphically to complete the non-graphical information (such as construction and thermal properties). Consequently, the HVAC systems and the related IR were defined in the BEM tool to finalize the energy simulation.

However, in the BIM-BEM procedures, the architectural BIM created using the defined IR was used to transfer and create the BEM directly in the selected tool at each proposed LOD_{ES}. Thus, all the graphical IR (including spaces and thermal zones) and some of the non-graphical IR (such as thermal properties) defined in the BIM model were imported into OpenStudio. Therefore, only some non-graphical IR elements were added manually in the last LOD_{ES}; these included details of the HVAC systems to run the simulation to estimate the energy consumption.

When comparing the two procedures (Figure 5.7), it was shown that the manual BEM included an extra step that was very time-consuming and error-prone, especially when remodelling was required at each design phase. Although the manual BEM process is often considered as inefficient, the simulation results are still considered trustworthy and used in practice.

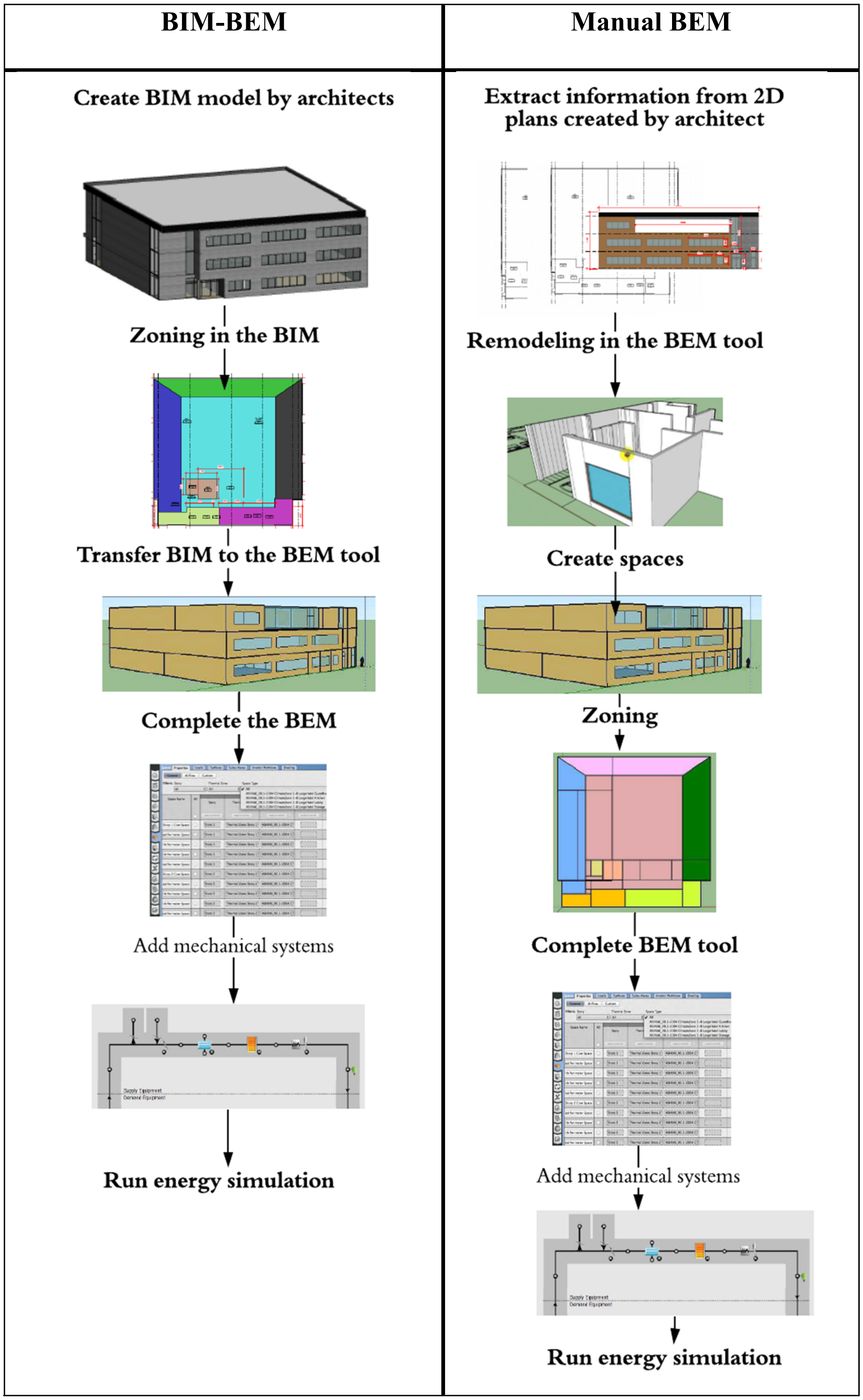


Figure 5.7 BIM-BEM vs. manual BEM procedures

To complete the analysis, the heating and cooling peak loads estimated using both procedures were plotted, as illustrated in Figure 5.8 to compare the accuracy of IR defined at each LOD_{ES}.

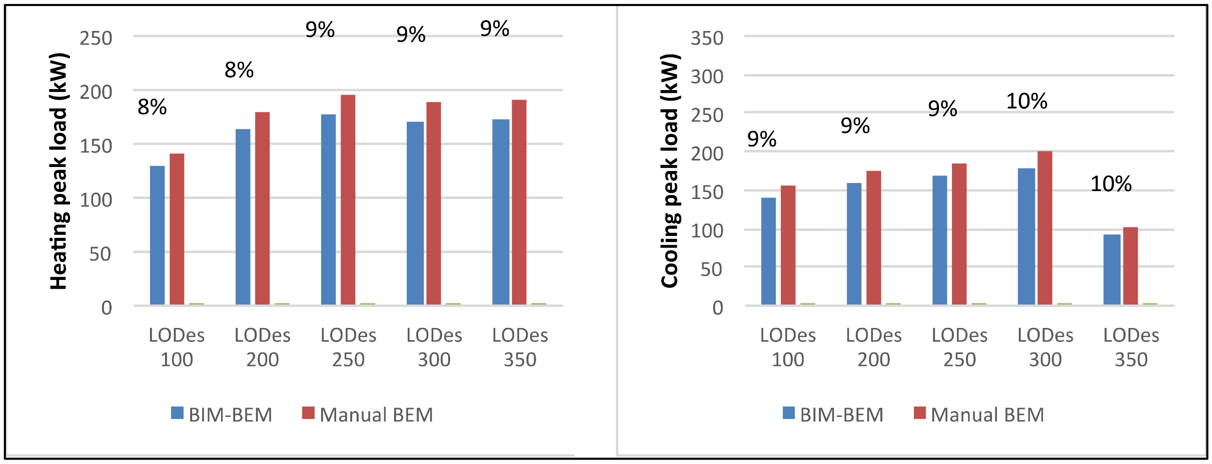


Figure 5.8 Peak load comparison at each LOD_{ES}: (a) heating and (b) cooling

The results showed a relative difference of approximately 8 to 10% at each LOD_{ES}. These discrepancies at each LOD_{ES} were explained by slight differences in the IR defined in the BIM model as compared to the IR that were set manually in the BEM tool (see Annex IV for additional details). These included a 5.5% difference in terms of total floor area, which was explained by differences in the way thermal zones were assigned in Revit versus in the BEM tool, as well as a slight differences in how the opening areas were modelled manually, as compared to the information exported from BIM to BEM. Furthermore, the differences were more significant at LOD_{ES} 250, 300 and 350 when more detailed IR for the building envelope and geometry were defined in the BIM. The difference in these cases was also attributed to interoperability issues with exchanging the model between BIM and BEM, rather than only geometrical variations. As illustrated in Figure 5.9, the cooling load also dropped at LOD_{ES} 350. This was explained by the modelling of the HVAC system, which influenced the loads more significantly. In general, these discrepancies are caused by differences in modelling techniques, such as the interpretation of the architectural plans by the independent BEM modeller, and interoperability issues.

To complete the comparison, the energy consumption estimated using both procedures were compared at LOD$_{ES}$ 350, where the detailed HVAC systems and relevant IR were defined. Figure 5.9 shows the yearly distribution of energy consumption (in GWh) for both approaches, displaying the relative differences between them. The slight discrepancies seen were attributed to the initial difference in calculated building loads (see Figure 5.8) and the HVAC systems that were defined to meet those loads. Among them, the lighting results from the BIM-BEM procedures showed more consumption as compared to manual BEM. This was due to interoperability issues with the BIM-BEM, which cannot support the lightning data exchange that needed to be verified manually.

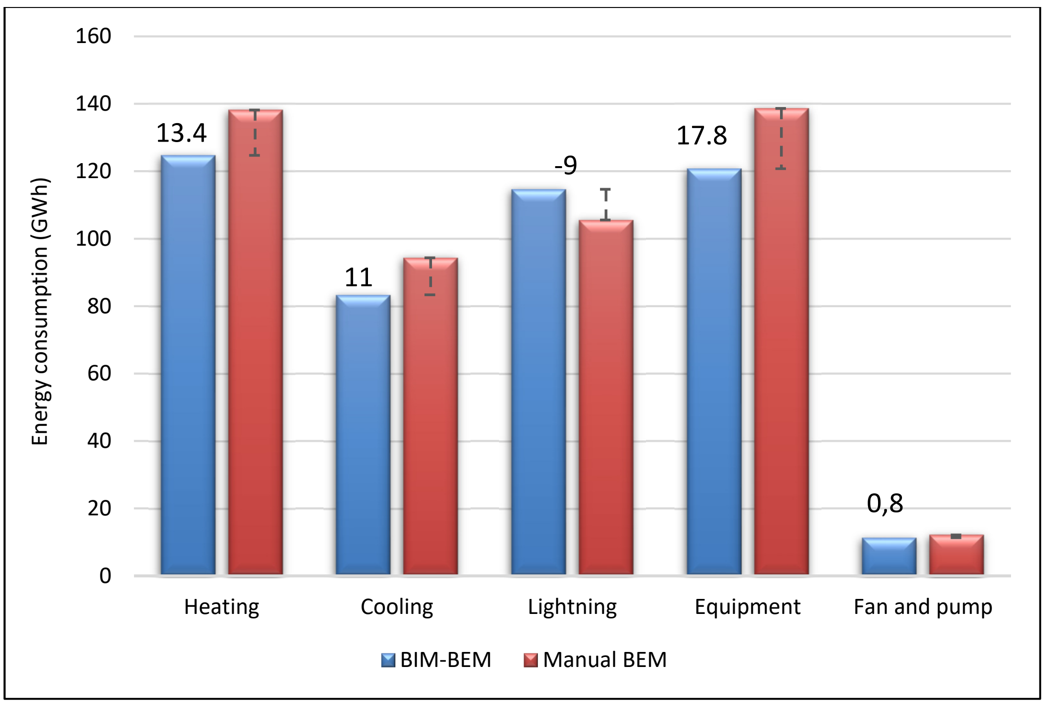


Figure 5.9 Energy consumption comparison at LODes 350

The total energy consumption results at LOD$_{ES}$ 350 were also compared using the Coefficient of Variation of the Root Mean Squared Error (CV-RMSE) and the Normalized Mean Bias Error (NMBE), using hourly data which should be below 20% and 10%, respectively (ASHRAE guideline 14, 2002). The CV-RMSE quantifies the degree of dispersion of a set of

BIM-BEM results around the mean of the manual BEM results, whereas the NMBE measures how close the calculated energy consumption by the BIM-BEM simulation approach corresponds to the manual BEM approach. Accordingly, the calculated CV-RMSE and the NMBE were respectively 12.3% and 4.7%, showing an acceptable difference between the results obtained from the manual BEM with those obtained with the BIM-BEM approach.

One advantage of the proposed procedure of this study was that the architectural BIM was used directly, without the need for any assumed values and wrong interpretations. Thus, the imported geometry in the BEM was more precise, as compared to the manual BEM procedure. Besides, the overall simulation process and the procedures for the proposed BIM-BEM information protocol showed that the total time required to complete the simulation was less when the BIM was created correctly for BEM and transferred using the recommended IR at each LOD_{ES}. Thus, the impact of the BIM-BEM information protocol on the efficient use of BIM for BEM during the design process was demonstrated.

5.5 Discussion

A review of the information defined in the existing LOD (e.g., BIMForum (Reinhardt, 2017)) or NATSPEC (2010) highlighted their inconsistency and incompleteness for BIM-BEM execution. The classification of the existing LOD shows that it does not fully address the BIM-BEM requirements, due to a lack of appropriate IR and inefficient sharing levels during the design process. The identified shortcomings of the existing LOD are two-fold: (1) there are missing non-graphical IR, more specifically, thermal specifications in LOD 100, 200 and 300; and (2) the very detailed and overabundant graphical information linked to LOD 300 and 400 leads to the need for many simplifications on BIM before a transfer to BEM. This includes checking for unreliable information, remodelling and fixing errors, which leads to time waste and increased labour costs.

In order for the BIM-BEM procedure to be completed seamlessly, LOD_{ES} are proposed. These LOD_{ES} adjust the existing IR of the architectural BIM at the 100, 200 and 300 levels by specifying the required detailed envelope information completed by non-graphical IR. To handle the additional BIM-BEM scopes and activities, the LOD$_{ES}$ 250 and 350 are added, including the IR for the creation of the BEM. The IR at specific LOD$_{ES}$ can be defined either using graphical or non-graphical elements. This is the case for site location, in LOD$_{ES}$ 100, which contains the IR for longitude, latitude and true north orientation degree, which can be defined with numbers in the site properties sections (non-graphical modelling) or by sketching the site orientation (graphical modelling) in the BIM tool. The proposed IR, including subject types, specifications and measures, at each LOD$_{ES}$, addresses the appropriate level of information required as inputs to complete the BIM-BEM procedure without defining supplementary or less information needed. The design scopes and the BIM-BEM activities developed in Table 5.2 and Figure 5.2 form the proposed BIM-BEM information protocol.

70% of the IR can be specified for BEM in a BIM model (Choi et al., 2016); however, most BEM tools, such as the one tested in this study (OpenStudio, version 2.7), are not able to import all the defined IR, such as construction sets and the detailed HVAC systems, from the BIM tool. This can be due to a lack of interoperability of the data exchanger (i.e., gbXML) or non-compatibility of the BEM tool for the imported file. One suggested approach to address this issue consists in creating MVD, which is based on the creation of an IFC subset, to accurately transfer related IR for energy simulation (Pinheiro, et al., 2018). MVD requires a complete list of IR: important guidelines such as AIA (2008), NATSPEC (2010), ASHRAE 90.1 (2016b) and Title 24 (2016) document IR, but do not explain how these IR change with the modelling level or should be handled from phase to phase. The proposed information protocol, including the LOD$_{ES}$, addresses this gap by providing a list of IR that could be used to develop MVD and support the operationalization of the existing BIM-BEM framework and execution plans.

Thus, the proposed BIM-BEM information protocol identifies both the IR for modelling activities and the appropriate LOD$_{ES}$ for BIM-BEM interaction steps during the design process. In addition, it can support an efficient BIM-BEM framework and facilitate information exchange between different stakeholders when energy analysis is complete.

5.6 Conclusion

The proper execution of BIM-BEM does not boil down to the amount of information exchange taking place, but rather, is about the quality of the information provided in the model. This research was mainly concerned with the characteristics and accuracy of BIM for BEM for different levels of information required during the design process. Therefore, the main contribution of this study is providing a BIM-BEM information protocol including adequate LOD_{ES} aligned with appropriate IR fitted to design activities to meet design scopes. It included the information required, as well as when such information should be exchanged for each BIM-BEM step. In addition, this study promoted the concept of an MVD approach to create an energy-related IFC coordination view for BIM-BEM. The proposed information protocol provided an independent study to be employed in all model integration methods and existing BIM-BEM frameworks.

As demonstrated in the verification process, the information protocol proposed in this study provided a higher architectural BIM precision resulting in fewer errors in the BIM-BEM interaction without a lot of time being spent on troubleshooting and remodelling. Thus, it provides the support needed to operationalize existing frameworks and should also support the development and implementation of efficient data and work flows by design professionals. This will be achieved by embedding the proposed information protocol within their process to avoid ambiguous definitions and interpretations of the BIM being used to create a BEM.

It should be noted that the LOD_{ES} and the IR may vary for particular BIM projects that include different design scopes. In this case, they can be used as a basis to support further explorations for particular BIM-BEM projects planned for future work. In future work, this study will be extended to cover the operation phase and the whole life cycle of a BIM project. Thus, the proposed LOD_{ES} can act as a standard for all BIM projects in which where IR are specified for BEM.

CHAPTER 6

DISCUSSION

BIM-BEM technologies offer the opportunity to complete multiple iterations to compare design options and generate the best solution to improve the building ecological footprint. However, as observed in this research, design professionals are still struggling to reorganize their processes to maximize the benefits of these technologies. In this thesis, a BIM-BEM framework is proposed to streamline and systematize the information sharing during the design process for high-performance buildings.

The previous studies in this area, such as OpEEmal (Rovas, 2017), eeEmbedded (Scherer, 2017), and Design4Energy (SALD, 2016) presented solutions to tackle the problems of BIM-BEM execution. However, most of them focused on a particular project or tried to address only part of the BIM-BEM transfer aspects. They mostly tackled technical issues, regardless of their implementation within the design process. A successful BIM-based project requires a synergy between these two important aspects: technology and process.

A few of these studies, such as the framework proposed by Wu et Issa (2014), Ilhan et Yaman (2016), and Zanni, Soetanto et Ruikar (2017), provided more generic solutions that considered both aspects. They described the workflows and disciplines to be involved within the design process and specified when BEM should be created and transferred. However, some of them focused only on one design phase or on singular BIM-BEM step. Usually, the type and the implementation process of model integration methods were not defined in their execution process map.

Among these studies, using LOD during the design process for BIM-BEM execution was only recommended by Wu et Issa (2014), a consideration that was not addressed in later studies. Modeling and sharing an accurate BIM model for BEM requires using appropriate LOD. In the existing LOD such as the one developed by BIMforum (2017), the detailed and appropriate

IRs for BEM and energy simulation were not considered in their classified levels. The currently used LOD contains irrelevant, incomplete and additional information that cause errors, simplifications, modifications, and reworks in the BIM-BEM process. Accordingly, there was a need to develop a holistic, generic, applicable and easy to follow framework detailing the proper model integration method into an efficient process map for all BIM-BEM steps considering new appropriate LOD and IR for energy simulation during the design process.

The proposed framework presented in this thesis addresses the existing limitations in the current studies and provides the requirements of BIM-BEM execution. First, a generic template for BIM-BEM framework including the required elements during the design process has been proposed to clearly define the energy simulation scopes, the design procedures, the work and data flows, the relevant modeling and integration techniques, the IRs, the LOD, and the BIM-BEM interactions at each design phase. Thus, it is a reliable reference that can be generalized for different projects and execution plans in this area. In this way, the BIM-BEM steps and the requirements defined in the proposed framework template can be followed to match the different project specifications. In addition, the appropriate model integration method can be selected and followed based on the overview of technical solutions and model integration methods provided in the first article.

Accordingly, the central model integration method has been employed for the proposed BIM-BEM framework in the second article based on its characteristics and the current limitations of the building design industry (such as the professional knowledge, software limitations, and the type of design and execution process). In the proposed framework, both technical and process aspects are considered for BIM-BEM execution, where the modeling activities, work and data flows and the IR categories during the design process are detailed. Thus, it addresses all BIM-BEM steps (that were missing in the existing studies) such as BIM pre-processing, the interaction between the BIM and BEM tools, and completing the BEM detailing how to integrate the proposed approaches to the whole design process, but does not address design exploration. The proposed framework is presented in an easy to follow process map to be employed by all types of project members such as owner, BIM manager, design professionals and modellers. The IR categories, their property sets and the description of each property are provided to understand the general inputs and the data flow for each modeling activity during the design process. The IR categories have been advanced based on the proposed BIM-BEM activities and the design scopes to develop the LOD_{ES} in an information protocol, which is presented in the third article. The information protocol completes the existing LOD by adding the required levels and information to support the BIM-BEM framework during the design process.

In general, the entire proposed framework can fulfill the existing gaps by providing a generic, effective and usable BIM-BEM execution process that is not software-specific or developed only for specific project types. As described in the development and validation processes, different types of BEM tools (IES-VE, Sketch Up and OpenStudio) and data exchanger types (IFC and gbxml) were used to model different test cases (simple and complex projects).
Furthermore, the framework can be generalized by the BIM manager for a specific project type. In this way, the main BIM-BEM steps can be adapted and advanced for particular design activities, work and data flows. The supplementary IRs can be added based on the project specifications at each LOD_{ES}. Nevertheless, the basis of the framework and the main steps need to be preserved for any BIM-BEM execution plan.

The provided information in this thesis can also be used for different major studies such as the one promoted by the International Energy Agency Energy in Buildings and Communities (IEA EBC) for developing Model View Definition (MVD) to create IFC file for BEM purposes (Pinheiro, Wimmer et al. 2018). In this way, the proposed IRs, the essential activities, the required flow between these activities can be used as reliable information to develop IFC energy coordination view. As well, the proposed IRs cover the HVAC information that can be added to support expanding IFC through MVD.

It should be noted that the focus of the proposed framework is on transferring the architectural-BIM model for BEM, since there is a high lack of interoperability in transferring HVAC information using central model integration approach. This is due to the inappropriate modeling of the HVAC-BIM, the limitations of the current data exchangers to transfer the model, and incompatibility of BEM tools to import the model. In this case, using the distributed model integration method may allow transferring HVAC information from a BIM model to BEM tools by manipulating and adjusting the model through a proper middleware. The proposed framework can be more generalized by distributed model integration method. However, this involves aligning the culture of the design companies with the process of dynamic modeling and convincing them to use Visual Programing Language (VPL) in their design and simulation approach.

For this purpose, the BIM pre-processing for architectural design can be advanced for HVAC design following the same methodology for the proposed framework including all the process aspects such as design activities, flows, LOD_{ES}, and IRs. The main step that needs to be developed based on the distribution method is the BIM-BEM interaction step, which can be established based on the selected middleware (e.g. Dynamo) and its dialect of the schema.

Creating a BIM-BEM framework using distributed model integration requires further research in this area that is a future work to this study considering the needs and attitude of the design companies to use higher technologies. Albeit, following the BIM-BEM execution procedures, flows, requirements and the information protocol proposed in this study reduces the level of effort and time required in the previous BIM-BEM practices and supports the operationalization of previous frameworks; while increases the accuracy of their energy simulation results, which support the process of designing high-performance buildings.

CONCLUSION

In this thesis, a holistic and effective framework was developed to answer this question: how successfully and accurately BIM-BEM can be executed during the design process. This study aimed to address the existing problems and gaps in this area; such as no synergy between technical and process aspects, using incomplete BIM model for BEM, the difficulty of transferring accurate BIM model into BEM tools and inefficient BIM-BEM process. The proposed framework considers both technical and process aspects including proper model integration, technical solutions, work/data flows, the required activities based on design scopes and an information protocol to support modeling and sharing during the design process. The information protocol contains a new LOD_{ES} linked with appropriate IRs for an effective BIM-BEM execution that can be applied by the current industry at each design phase.

This framework was created based on Action Research (AR) that was a systematic multi-stages approach from diagnosing the problems to developing practical solutions to address them efficiently.

The main contribution of this research is to bridge technology and process in a unified BIM-BEM framework that supports the knowledge and practice in these ways:

- The contribution of this study to knowledge is a systematic literature review that identifies all technical and process approaches for BIM-BEM execution in a classified and streamline map which counts as a thorough reference in this area. The existing gaps highlighted in this map encourage the researchers to address them in their future work.
  Then, the developed information protocol in this study contributes to the science by providing a new LOD_{ES} that streamlines the BIM-BEM execution during the design process. It transforms the current procedures towards transparency, waste and interoperability error reduction, and better data management with potential positive results in practice. This allows using BIM-BEM to perform accurate energy simulation early in the process towards optimization of building design.

- The contribution of this thesis to practice is the generic and complete process map that considers all BIM-BEM steps during all phases of the design process. It encourages better use of a BIM model for energy simulation for designing high-performance buildings. Also, the information protocol support the creation of seamless BIM model using identified IR and in an appropriate LOD_{ES} using an applicable model integration approach to easily perform the energy simulation early in the design process.

In addition, this thesis is a resource to the scientist and developers getting the benefit of the classified approaches in all BIM aspects, and even the identified gaps within these approaches for further research and production in this area. More importantly, it can be used in developing MVD approach to creating a specific energy-related IFC coordination view for BIM-BEM. It should be noted, this framework focused on the most adaptable and acceptable model integration (central) approach for the current building industry and design process. However, the central model integration approach can not support transferring the HVAC system between BIM and BEM tools. In this regard, the HVAC modeling was not included in the BIM pre-processing of the framework and defined directly in the BEM tools.

Nonetheless, the framework represents a breakthrough for future work to advance it based on the distributed model integration approaches dynamically for transferring complex model including HVAC systems. The distributed approach makes possibilities to develop a BEM-BIM framework bi-directionally for an optimization process. Moreover, it may allow using the measured data in a real-time setting for optimizing the BEM and HVAC system in the operation phase.

This requires using VPL and more complicated tools that involves changes in the culture, goals, constraints, skills, and trust of the current AEC industry. Thus, different approaches (e.g. action theory) can be proposed and advanced considering organization aspect to complete the BIM triangle (technology, process, and organization) for BEM. Considering the organization and people in the future framework containing the advanced technology in a design, construction and operation process provides a vast influence on the AEC knowledge and practice. Thus, the generalization of the proposed framework can be progressed as far as the technology and forward thinking can growth since its foundation is built on the main BIM pillars.

ANNEX I

EXISTING PROCESS MAPS IN THE LITERATURE

The existing BIM-based process maps that were developed by other researchers were assessed to evaluate whether they tackled all requirements for a complete BIM-BEM execution. Thus, an overview of the available process maps and their limitations is presented in this Annex.
In this regard, the process map developed by Crosbie et al. (2009) includes the work and data flow to create BIM model for BEM (Figure-A I-1). The identified missing requirements in this process map are:

- The different design phases are not represented and the flow between each phase is not clear;
- The BIM-BEM model integration approach and the procedures are not covered.
- The proper LOD and detailed IRs are not considered.

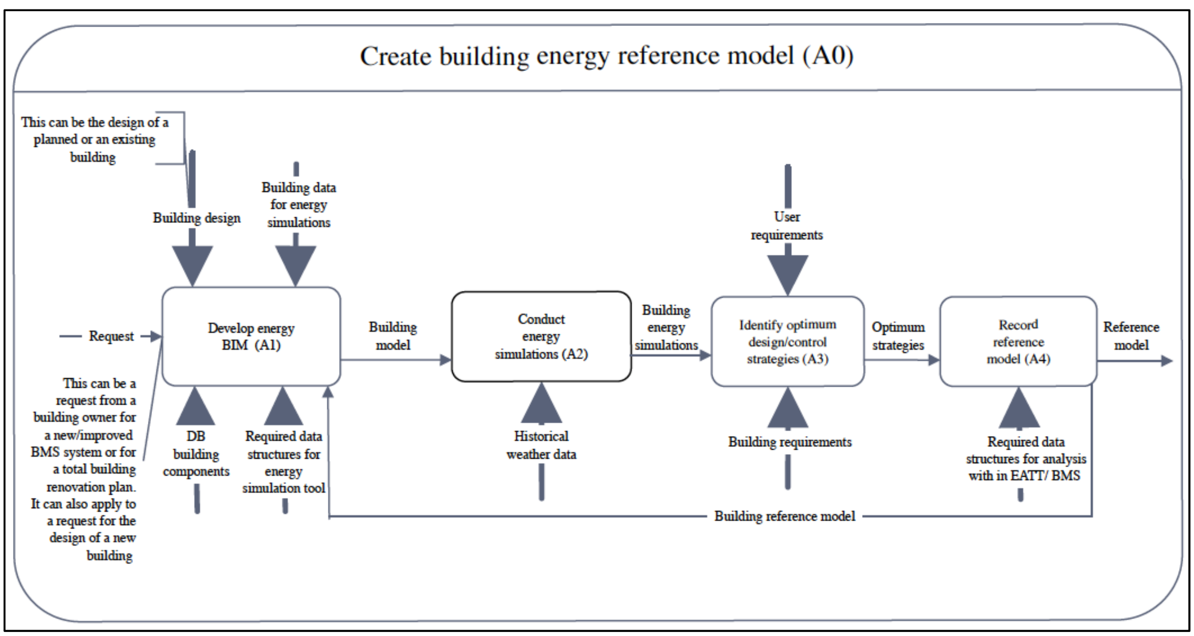


Figure-A I-1 The first stage process map for energy analysis
Taken from Crosbie et al. (2009)

The process map developed by Jeong et al. (2015) includes the work and data flow to transfer BIM model into Modelica (Figure-A I-2). The identified missing requirements in this process map are:

- The design activities at each design phase;
- It is applicable to other tools as it is developed for specific softwares, i.e., Revit to Modelica.

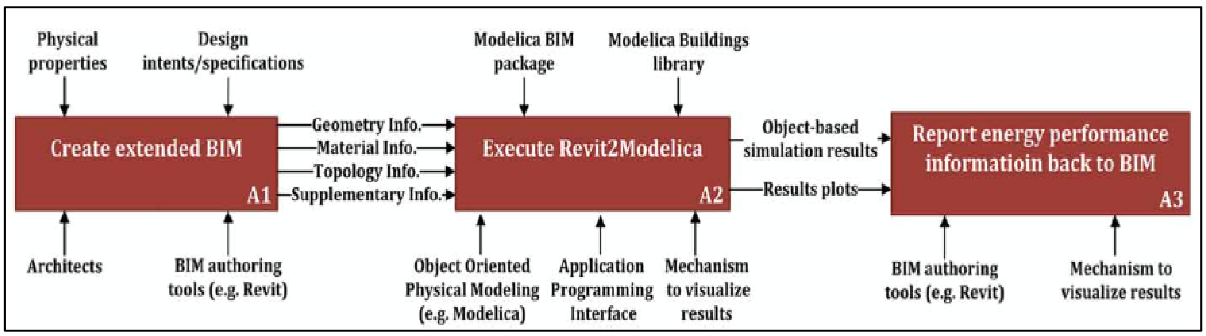


Figure-A I-2 Overall BIM to BEM process map for Revit to Modelica
Taken from Jeong et al. (2015)

The process map developed by Sald et al. (2016) as a part of the Design4Energy report proposes a guideline to transfer the BIM model into Design4Energy software for energy simulation (Figure-A I-3). Although this process map covers all design phases, it has some limitations:

- This process map is software-specific and not generic.
- The work and data flows that are required to be done in BIM and BEM tools are not presented;
- The proper LOD and relevant IRs are not considered.

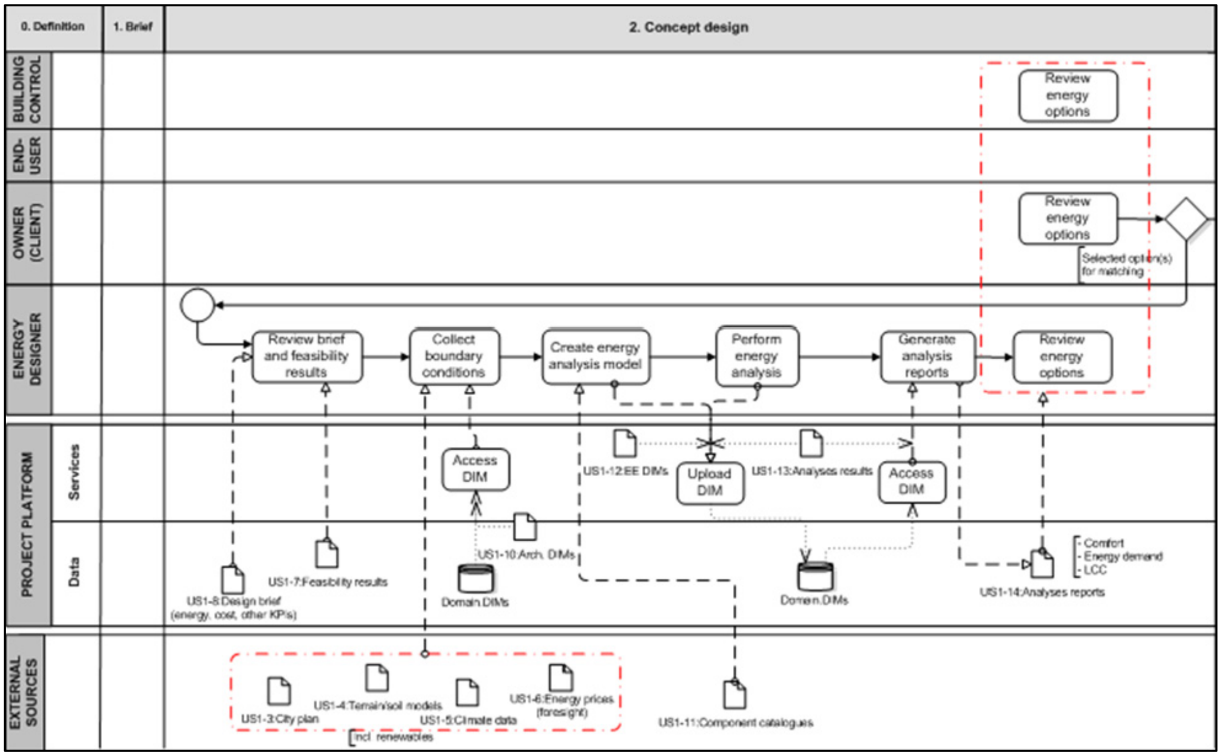


Figure-A I-3 BIM to Design4energy process map
Taken from SALD et al. (2016)

The process map developed by Wu and Issa (2016) is one of the most completed maps for BIM-based sustainable design (Figure-A I-4). However, there are some missing elements in this process map that are required for general BIM-BEM execution as listed below:

- The work and data flow is only developed for LEED projects and are not generic for whole design projects;
- The work and data flow that are required to be completed in BIM and BEM tools are not clear.
- The BIM-BEM integration process is not considered in this process map;
- Using proper LOD is suggested, but it is not developed for BIM-BEM.

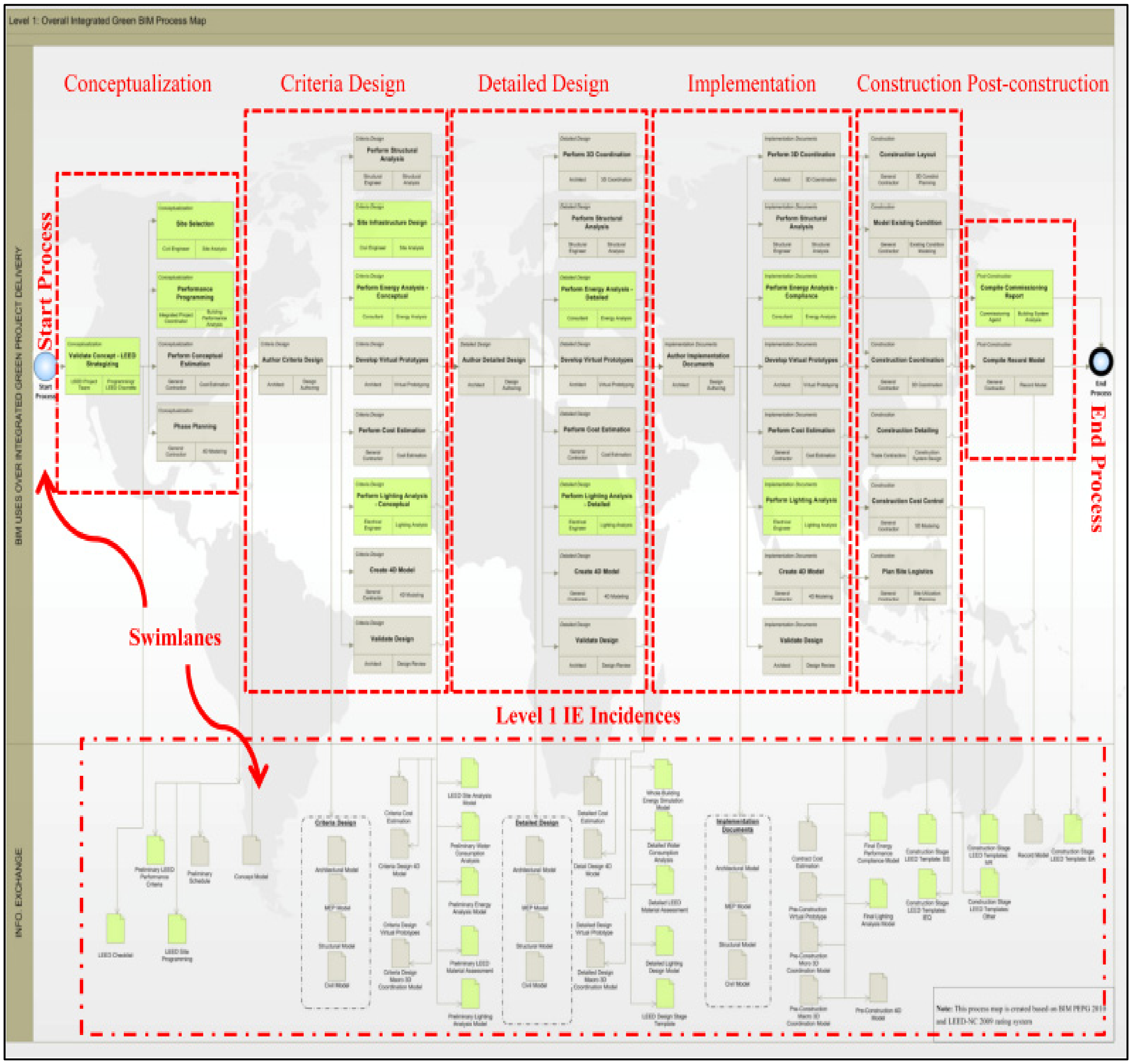


Figure-A I-4 Overall process map for BIM-based sustainability design

Taken from Wu and Issa (2016)

The process map developed by Zanni et al. (2016) presents the procedures to use BIM for sustainable design (Figure-A I-5). Some of the requirements for BIM-BEM execution are presented in this process map; however, the limitations are as follows:

- The process map is developed in three levels; however, the required design activities at each phase are not clear;

- The work and data flow for BIM-BEM interaction and the technical aspects of this step are not established.
- The LOD is introduced, but is not defined for BEM and energy simulation.

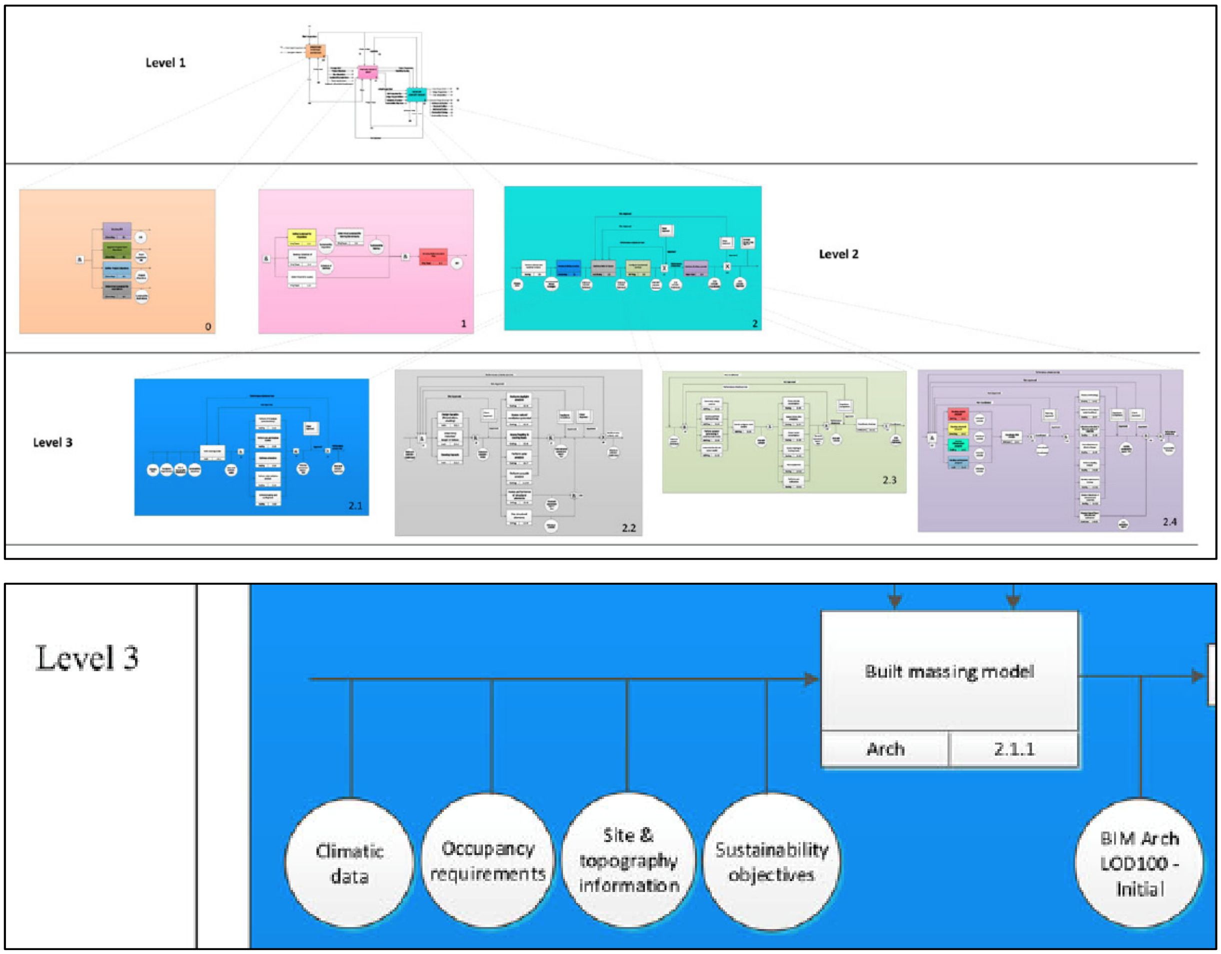


Figure-A I-5 Overall process map for BIM-enabled sustainable design
Taken from Zanni et al. (2016)

ANNEX II

FIELD INVESTIGATION

In the action planning, one of the important actions to establish the targets was identifying the real-based process map for BIM-BEM execution. To realize this process, field investigations and observations were completed in architectural and engineering firms to reflect the specificities of both disciplines in the proposed process map.

The activities for model creation at each design phase were used to develop the preliminary process map to better understand the existing procedures. The sequences and the flow between each activity to achieve different design scope were documented in the preliminary process map. The data entry and the source of information to model each element of were collected and documented in table formats to extract the IRs. The IRs were investigated in both BIM and BEM models for all used tools. The general overview of the preliminary design process map is illustrated in Figure-A II-1, which presents the current work and data flow for energy analysis.

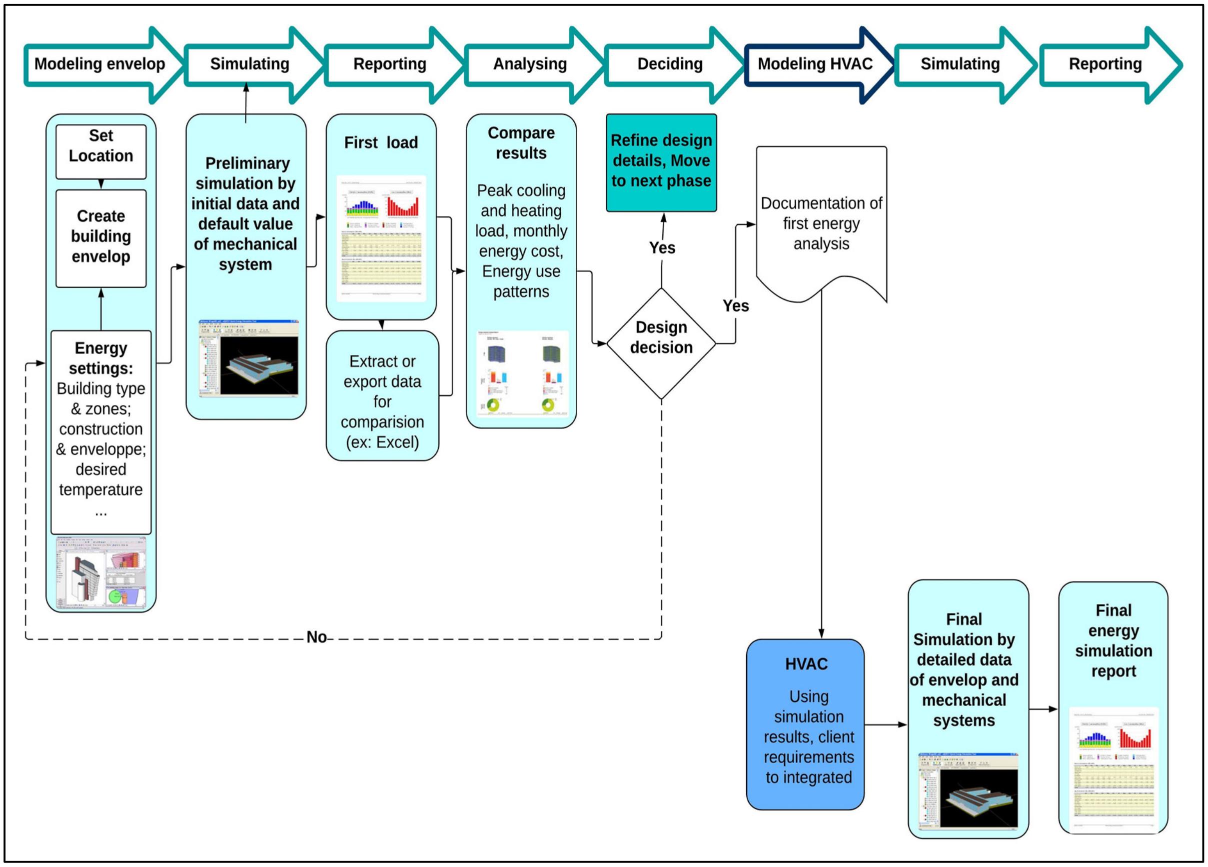


Figure-A II-1 Macro scale of preliminary process map

The more detailed and complete process was mapped in Figure-A II-2. The process map presents the existing work and data flows in the available BIM and BEM tools, the data exchangers used to transfer the data, and the IRs for preliminary and final energy simulation. The process map was the basis for the proposed and more simplified process map in this study. In addition, the LODs and sharing points for energy simulation at each phase were investigated and assessed to define the range and degree of IRs. The observations and assesments showed that many simplifications and remodelings were required, which is very time consuming and inefficient.

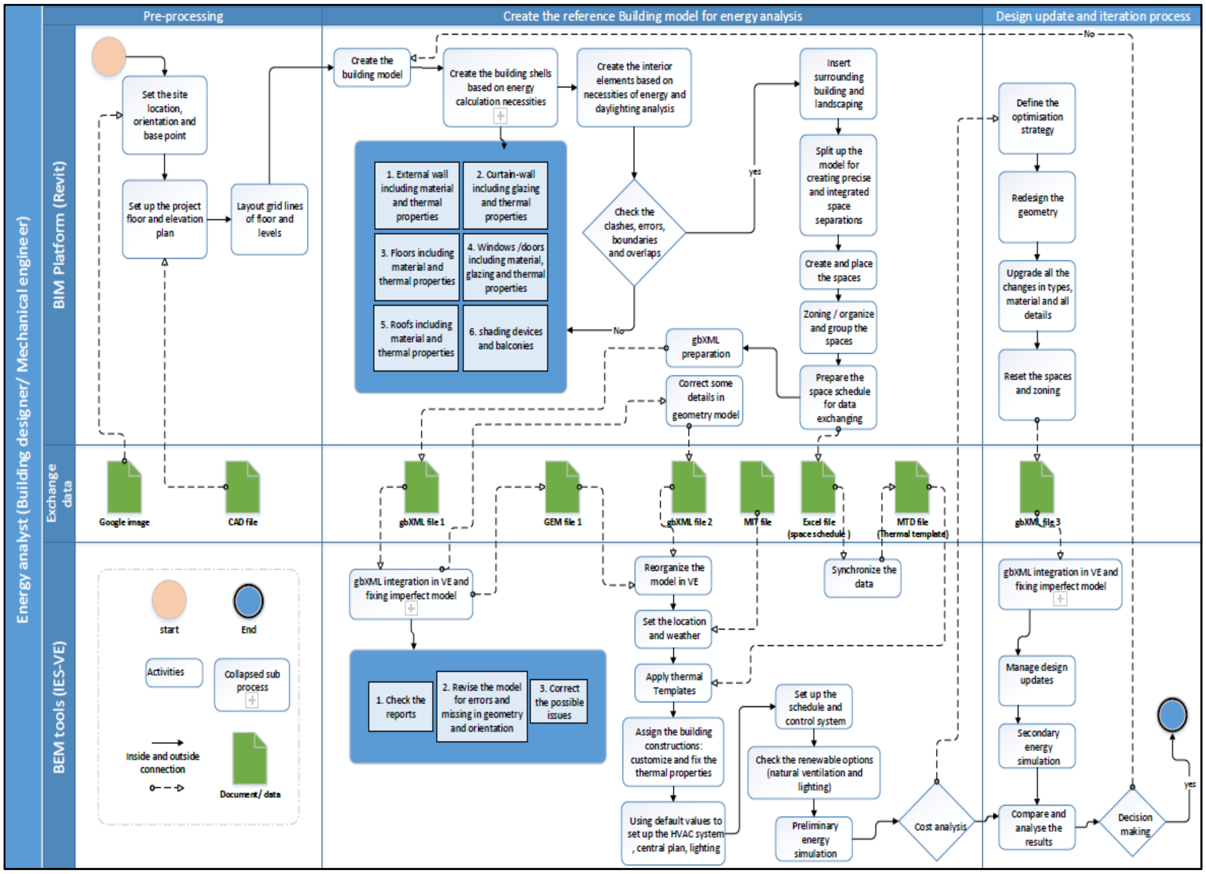


Figure-A II-2 Preliminary process map extracted from field investigation

The preliminary process map and the existing LOD used provided the basis of the proposed framework in this thesis. Also, the needs, limitations and practical challenges identified in the field investigation were employed as targets in the action taking step to be resolved in the proposed process map.

ANNEX III

PROPOSED IRs

The proposed IRs are classified in five levels based on the developed LOD_{ES} in this thesis, which are listed in Table-A III-1. In this table, the IRs are detailed based on design phase, subject type, and units. In addition, the reference of each IR is indicated in this table that shows the source of collected data.

The references are shown by numbers as follow:

- BIM references: [1] Messner, Anumba et al., (2010), [2] BCA (2015), and [3] Reinhardt, (2017);
- BEM references: [4] ASHRAE 90.1 (2016a), [5] ASHRAE 62.1 (2016b), and [6] Title 24 CA (2016).

Table-A III-1 Proposed IR

		IR 100		
		Subject type	**Unit**	**Reference**
Preliminary concept design		**Climate conditions**		
	Specifications	Zone letter (location type definition)	A, B, or C	[1,3]
		Zone number (verity of location)	1, 2, 3	[1,4]
		Climate data		[4,6]
		Heating design temperature	°C	[4-6]
		Cooling design temperature (dry and wet bulb)	°C	[4-6]
		Heating degree day		[4-6]
		Cooling degree data		[4-6]
		Humidity	%	[4-6]
		Solar radiation	W/m^2	[4,5]
		Cloud cover		[4,5]
		Wind speed	m/s	[4,5]
		Direction from representative climate data	Degree	[4,5]
		Annual data set		[4-6]
		Peak data set		[4-6]
		Building site and topology		
	Specification	City (longitude and latitude)	N, S, W, E	[1,3]
		Location constraint	N, S, W, E	[1,3-4]
		GPS position		[2,3]
		Orientation	Degree	[1-6]
		Adjacent building masses	m^3	[2,3]
		Building massing and form		
	Specifications	Form	x, y, z	[1,3-4]
		Different geometry block	m^3	[1,3]
		Typology standard (wall)	m	[1,3]
		Name		[1,2]
		Overall length	m	[1-4]
		Overall width	m	[1-4]
		Overall height	m	[1-4]
		Overall area	m^2	[1-4]
		Overall volume	m^3	[1-4]
		Layout (roof area)	m^2	[1-4]
		Layout (floor area)	m^2	[1-4]
		Building orientation		
	Spec.	Orientation	x, y, z	[1-6]
		Proximity to adjacent buildings	m	[2,3]
		Solar radiation in each direction	Degree	[4-6]

Final concept design – Specifications					
IR 200					
Subject type	**Unit**	**Ref.**		**Unit**	**Ref.**
Building geometry, spatial configuration, layouts					
Building common			**Floor common**		
Net planned area	m^2	[1-6]	Element		[1-3]
Number of storeys	N	[1-6]	Family and type		[1-3]
External wall common			Top offset	Level	[1-3]
Element		[1-3]	Base offset	Level	[1-3]
Family and type		[1-3]	Overall length	m	[1-4]
Location constraint		[1-4]	Overall width	m	[1-4]
Rotation angle	Degree	[3-4]	Overall height	m	[1-4]
Top offset	Level	[1-3]	Overall area	m^2	[1-4]
Base offset	Level	[1-3]	Overall volume	m^3	[1-4]
Overall length	m	[1-4]	Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
Overall width	m	[1-4]	Thermal flow	W/m^2	[4-6]
Overall height	m	[1-4]	**Roof common**		
Overall area	m^2	[1-4]	Element		[1-3]
Overall volume	m^3	[1-4]	Family and type		[1-3]
Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]	Level		[1-4]
Thickness	m	[1-6]	Base offset from level		[1-3]
Thermal flow	W/m^2	[4-6]	Overall length	m	[1-4]
Adiabatic wall		[4-5]	Overall width	m	[1-4]
Interior wall common			Overall height	m	[1-4]
Element		[1-3]	Overall area	m^2	[1-4]
Family and type		[1-3]	Overall volume	m^3	[1-4]
Location constraint		[1-4]	Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
Top offset	Level	[1-3]	Thermal flow	W/m^2	[4-6]
Base offset	Level	[1-3]	Element		[1-3]
Overall length	m	[1-4]	Family and type		[1-3]
Overall width	m	[1-4]			
Overall height	m	[1-4]	**Openings**		
Overall area	m^2	[1-4]			
Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]	**Window common**		
Thickness	m	[1-6]	Element		[1-3]
Thermal flow	W/m^2	[4-6]	Level		[1-3]
Curtain wall common			Rotation angle	Degree	[3-4]
Element		[1-3]	Location constraint		[1-4]
Rotation angle	Degree	[3-4]	Overall area	m^2	[1-4]
Location constraint		[1-4]	Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
Family and type		[1-3]	Thermal flow	W/m^2	[4-6]
Top offset	Level	[1-3]	Percentage of glass in wall	%	[4-6]
Base offset	Level	[1-3]	**Door common**		
Overall length	m	[1-4]	Element		[1-3]
Overall width	m	[1-4]	Level		[1-4]
Overall height	m	[1-4]	Rotation angle	Degree	[3-4]
Overall area	m^2	[1-4]	Location constraint		[1-4]
Overall volume	m^3	[1-4]	Overall area	m^2	[1-4]
Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]	Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
Thermal flow	W/m^2	[4-6]	Thermal flow	W/m^2	[4-6]
Size and percentage of glass	%	[4-6]	Percentage of glass in wall	%	[4-6]

		IR 250					
		Subject type	**Unit**	**Ref.**		**Unit**	**Ref.**
Final concept des		**Spaces**			**Chiller**		
	Specifications	Space name		[3]	Type		[3-4]
		Number		[1-3]	Nominal condensing temperature	°C	[4-6]
		Space adjacency		[3-4]	Nominal capacity	kW	[4-6]
		Space type/Category		[3-4]	Nominal evaporating temperature	°C	[4-6]
		Level		[1-3]	**Coil**		
		Area	m^2	[1-4]	Type		[3-4]
		Volume	m^3	[1-4]	Nominal sensible capacity	kW	[4-6]
		Ceiling finish	m	[3]	Nominal latent capacity	kW	[4-6]
		Wall finish	m	[1-3]	Airflow rate	L/s	[4-6]
		Floor finish	m	[1-3]	**Cooling tower**		
		Limit offset	Level	[1-3]	Type		[3-4]
		Upper limit	m	[1-3]	Ambient design wet bulb temperature	°C	[4-6]
		Thermal zones			Number of cells	N	[3-4]
	Specifications	Zone name		[3]	Operation temperature range	°C	[4-6]
		Zone number		[3]	**Fan**		
		Zone adjacency		[3]	Type		[3-4]
		Level		[1-4]	Nominal air flow rate	L/s	[4-6]
		Area	m^2	[1-4]	Nominal total pressure	Pa	[4-6]
		Volume	m^3	[1-4]	Nominal power rate	kW	[4-6]
		Ceiling finish	m	[3]	**Boiler**		
		Wall finish	m	[3]	Type		[3-4]
		Floor finish	m	[3]	Nominal part load ratio	%	[4-6]
		Limit offset	Level	[3]	Outlet temperature range	°C	[4-6]
		Upper limit	m	[1-3]	Water inlet temperature range	°C	[4-6]
		Primary HVAC and central			Energy resource	Type	[4-6]
	Specifications	**Space thermal load**			**Pump**		
		Ventilation outdoor air	L/s	[4-6]	Type		[3-4]
		Recirculate air	L/s	[4-6]	Flow rate	L/s	[4-6]
		Exhaust air	L/s	[4-6]	Capacity	kW	[4-6]
		Total sensible load	W	[4-6]	**Control system**		
		People		[3-6]	Occupant time schedule	Time range	[4-6]
		Estimated HVAC load per area	W/m^2	[4-6]	HVAC system operation time	Time range	[4-6]
		Estimated other load per area	W/m^2	[4-6]	Heating setpoint temperature	°C	[4-6]
		Lighting	W	[3-6]	Cooling setpoint temperature	°C	[4-6]
		Total radiant load	W	[4-6]	Heating design temperature	°C	[4-6]
		Total latent load	W	[4-6]	Cooling design temperature	°C	[4-6]
		Air side system information					
		System type		[4-6]			
		Ventilation airflow	L/s	[4-6]			
		Energy loss	J	[4-6]			
		Energy gain total	J	[4-6]			
		Heating temperature delta	°C	[4-6]			
		Sensible airflow	L/s	[4-6]			
		Fan power	kW	[4-6]			
		Sensible energy gain	J	[4-6]			
		Total airflow	L/s	[4-6]			

		IR 300					
		Subject type	**Unit**	**Ref.**		**Unit**	**Ref.**
		Building geometry, spatial configuration, layouts					
Detailed design	**Specifications**	**Building common**			**Curtain wall common**		
		Net planned area	m^2	[1-6]	Element		[1-3]
		Number of storeys		[1-6]	Family and type		[1-3]
		External wall common			Top offset	Level	[1-3]
		Element		[1-3]	Base offset	Level	[1-3]
		Family and type		[1-3]	Storey number		[1-6]
		Location constraint		[1-4]	Floor total height	m	[1-6]
		Top offset	Level	[1-3]	Nominal size	m^2	[1-4]
		Base offset	Level	[1-3]	Rotation angle	Degree	[3-4]
		Storey number		[1-3]	Total length	m	[1-6]
		Floor total height	m	[1-6]	Total width	m	[1-6]
		Nominal size		[1-4]	Total height	m	[1-6]
		Rotation angle	Degree	[3-4]			
		Final length	m	[1-6]	Total area	m^2	[1-6]
		Final width	m	[1-6]	Total volume	m^3	[1-6]
		Final height	m	[1-6]	Wall material layer types		[1-4]
		Final area	m^2	[1-6]	Wall interior finish		[1-6]
		Final volume	m^3	[1-6]	Wall exterior finish		[1-6]
		Material layer types		[1-4]	Wall thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
		Interior finish		[1-4]	Wall R-value	$m^2 \cdot K/W$	[4-6]
		Exterior finish		[1-4]	Absorption coefficient		[4-6]
		Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]	Total radiation	W/m^2	[4-6]
		R-value	$m^2 \cdot K/W$	[4-6]	Thermal flow	W/m^2	[4-6]
		Absorption coefficient		[4-6]	Air infiltration	L/s	[4-6]
		Radiation	W/m^2	[4-6]	Gazing type		[1-6]
		Thickness	m	[3-6]	Total glass area	m^2	[1-6]
		Interior wall common					
		Thermal flow	W/m^2	[4-6]	Glass layers		[1-4]
		Air infiltration	L/s	[4-6]	Glass inside gas		[4-6]
		Adiabatic wall		[4-6]	Glass thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
		Element		[1-3]	Glass R-value	$m^2 \cdot K/W$	[4-6]
		Family and type		[1-3]	Glass absorption value	%	[4-6]
		Location constraint		[1-4]	Glass radiation	W/m^2	[4-6]
		Top offset	Level	[1-3]	Low-e glazing		[4-6]
		Base offset	Level	[1-3]	Frame material		[1-4]
		Storey number		[1-3]	Frame thickness	m	[1-6]
		Floor total height	m	[1-4]	Frame width	m	[1-6]
		Nominal size	m^2	[1-4]	Frame thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
		Rotation angle	Degree	[3-4]	Frame R-value	$m^2 \cdot K/W$	[4-6]
		Final length	m	[1-6]	Frame absorption coefficient		[4-6]
		Final width	m	[1-6]	Frame radiation	W/m^2	[4-6]
		Final height	m	[1-6]	Mullion material		[1-4]
		Final area	m^2	[1-6]	Mullion thickness	m	[1-4]
		Material layer types		[1-4]	Mullion width	m	[1-4]
		Interior finish		[1-4]	Mullion thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
		Exterior finish		[1-4]	Mullion R-value	$m^2 \cdot K/W$	[4-6]
		Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]	Mullion absorption coefficient		[4-6]

		IR 300					
Detailed design		**Subject type**	**Unit**	**Ref.**	**Subject type**	**Unit**	**Ref.**
	Building geometry & spatial configuration				Final height	m	[1-6]
	Specifications	**Floor common**			Final area	m^2	[1-6]
		Element		[1-3]	Position type		[3-4]
		Family and type		[1-3]	Location constraint		[1-4]
		Top offset	Level	[1-3]	Air infiltration	L/s	[4-6]
		Base offset	Level	[1-3]	Total thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
		Storey number		[1-3]	Total glass area	m^2	[1-6]
		Floor total height	m	[1-6]	Glass thickness	m	[1-6]
		Nominal size	m^2	[1-4]	Glass layers		[1-4]
		Rotation angle	Degree	[3-4]	Glass inside gas		[4]
		Final length	m	[1-6]	Glass thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
		Final width	m	[1-6]	Glass R-value	$m^2 \cdot K/W$	[4-6]
		Final height	m	[1-6]	Glass absorption coefficient		[4-6]
		Final area	m^2	[1-6]	Glass radiation	W/m^2	[4-6]
		Final volume	m^3	[1-6]	Low-e glazing		[4-6]
		Material layer types		[3-4]	Frame material		[3-4]
		Floor finish		[3-4]	Frame thickness	m	[1-6]
		Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]	Frame width	m	[1-6]
		Total floor R-value	$m^2 \cdot K/W$	[4-6]	Frame thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
		Total floor absorption coefficient		[4-6]	Frame R-value	$m^2 \cdot K/W$	[4-6]
		Total floor radiation	W/m^2	[4-6]	Frame absorption coefficient		[4-6]
		Roof common			Frame radiation exposure	W/m^2	[4-6]
		Element		[1-3]	Mullion material		[3-4]
		Family and type		[1-3]	Mullion thickness	m	[3-6]
		Level		[1-3]	Mullion width	m	[3-6]
		Base offset from level		[1-3]	Mullion thermal transmittance(U-value)	$W/m^2 \cdot K$	[4-6]
		Storey number		[3]	Mullion R-value	$m^2 \cdot K/W$	[4-6]
		Floor total height	m	[1-6]	Mullion absorption coefficient		[4-6]
		Nominal size	m^2	[2-4]	Mullion radiation	W/m^2	[4-6]
		Rotation angle	Degree	[3-4]	**Door common**		
		Material layer types		[1-4]	Element		[1-3]
		Roof finish		[1-4]	Family and type		[1-3]
		Final height	m	[1-6]	Rotation angle	Degree	[3-4]
		Final area	m^2	[1-6]	Position type		[3-4]
		Final volume	m^3	[1-6]	Location constraint		[1-4]
		Thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]	Level		[1-3]
		Total roof R-value	$m^2 \cdot K/W$	[4-6]	Final length	m	[1-6]
		Total roof absorption		[4-6]	Final width	m	[1-6]
		Total roof radiation exposure	W/m^2	[4-6]	Final height	m	[1-6]
		Percentage of skylight	%	[4-6]	Final area	m^2	[1-6]
	Openings				Final volume	m^3	[1-6]
	Specifications	**Window or skylight common**			Material layer types		[3-4]
		Element		[1-3]	Frame material		[3-6]
		Level		[1-3]	Air infiltration	L/s	[4-6]
		Family and type		[1-3]	Total thermal transmittance (U-value)	$W/m^2 \cdot K$	[4-6]
		Nominal size	m^2	[3-4]	Total R-value	$m^2 \cdot K/W$	[4-6]
		Rotation angle	Degree	[3-4]	Absorption coefficient		[4-6]
		Final length	m	[1-6]	Radiation	W/m^2	[4-6]
		Final width	m	[1-6]	Thermal flow	W/m^2	[4-6]

		IR 350					
		Subject type	**Unit**	**Ref.**	**Subject type**	**Unit**	**Ref.**
Detailed design		**Spaces**			Lighting	W	[3-4]
	Specifications	Space name		[3]	Total radiant load	W	[4-6]
		Space number		[1-3]	Total latent load	W	[4-6]
		Space adjacency		[3-4]	Ventilation indoor air	L/s	[4-6]
		Space type/Category		[3-4]	**Air side system information**		
		Location		[1-4]	System type		[3-4]
		Rotation angle	Degree		Sizing ratio		[4-6]
		Length	m	[1-6]	Ventilation	L/s	[4-6]
		Width	m	[1-6]	Humidifier type		[4]
		Height	m	[1-6]	Max humidity	%	[4-6]
		Area	m^2	[1-6]	Energy loss	J	[4-6]
		Volume	m^3	[1-6]	Energy gain total	J	[4-6]
		Ceiling finish		[1-4]	Heating temperature delta	°C	[4-6]
		Wall finish		[1-4]	Sensible airflow	L/s	[4-6]
		Floor finish		[1-4]	Fan type		[3-4]
		Limit offset	Level	[1-3]	Fan power	kW	[4-6]
		Upper limit	m	[1-3]	Total efficiency	%	
		Level		[1-4]	Sensible energy gain	J	[4-6]
		Occupancy number		[3-4]	Total airflow	L/s	[4-6]
		Area per occupant	m^2/person	[4-6]	Cooling temperature delta	°C	[4-6]
		Occupancy type		[3-5]	**Heating equipment**		
		Humidity	%	[4-6]	Type		[3-6]
		Radiant heating	J	[4-6]	Quantity of equipment		[3-6]
		Air circulation	L/s	[4-6]	Power of each unit	kW	[4-6]
		Temperature range	°C	[4-6]	Energy resources		[4-6]
		Thermal zones			**Chiller**		
	Specifications	Zone name		[3]	Type		[3-6]
		Zone number		[3]	Design CHW temperature	°C	[4-6]
		Zone adjacency		[3]	Loop design temperature	°C	[4-6]
		Space type/category		[1-3]	Loop pump		[4-6]
		Length	m	[1-6]	Number of pump		[4-6]
		Width	m	[1-6]	Nominal capacity	kW	[4-6]
		Height	m	[1-6]	Refrigerant type		[4-6]
		Area	m^2	[1-6]	Evaporator type		[4-6]
		Volume	m^3	[1-6]	Evaporator flow rate	L/s	[4-6]
		Ceiling finish		[1-3]	Compressor type		[4-6]
		Wall finish		[1-3]	Condenser flow rate	L/s	[4-6]
		Floor finish		[1-3]	Capacity	kW	[4-6]
		Limit offset	Level	[1-3]	**Coil**		
		Upper limit	m	[1-3]	Type		[3-6]
		Level		[1-4]	Nominal sensible capacity	kW	[4-6]
		Occupancy	Number	[3-4]	Nominal latent capacity	kW	[4-6]
		HVAC and central systems			Airflow rate		[4-6]
		Space thermal load			**Cooling tower**		
		Ventilation outdoor air	L/s	[4-6]	Type		[3-4]
		Recirculate air	L/s	[4-6]	Ambient design wet bulb temperature	°C	[4-6]
		Exhaust air	L/s	[4-6]	Number of cells		[3-4]
		Total sensible load	W	[4-6]	Operation temperature range	°C	[4-6]
		People	Number	[3-4]	Motor power	kW	[4-6]

		Estimated HVAC load	W/m^2	[4-6]	Motor efficiency		[4-6]

		IR 350		
Preliminary concept design		**Subject type**	**Unit**	**Reference**
		HVAC and central systems properties		
	Specifications	**Fan**		
		Efficiency		[4-6]
		Boiler		
		Type		[3-6]
		Nominal part load ratio		[4-6]
		Outlet temperature range	°C	[4-6]
		Water inlet temperature range	°C	[4-6]
		Fuel type		[4-6]
		Burner type		[4-6]
		Burner fuel rate		[4-5]
		Burner rated efficiency		[4-5]
		Main fuel rated flow rate	L/s	[4-5]
		Main fuel rated pressure	Pa	[4-5]
		Efficiency		[4-6]
		Pump		
		Type		[3-6]
		Flow rate	L/s	[4-6]
		Capacity	kW	[4-6]
		Power per equipment	kW	[4-6]
		Load	kW	[4-6]
		Motor power	kW	[4-6]
		Efficiency		[4-6]
		Height	m	[4-5]
		Domestic hot water loop		
		Type		[4-5]
		Design temperature	°C	[4-6]
		Set point temperature	°C	[4-6]
		Tank capacity	kW	[4-6]
		Process flow	L/s	[4]
		Process load	kW	[4]
		Heat input ratio		[4-6]
		Control system and schedules		
		Occupant time schedule	Date range/Day/hr	[3-6]
		HVAC system operation time	Date range/Day/hr	[4-6]
		Heating setpoint temperature	°C	[4-6]
		Cooling setpoint temperature	°C	[4-6]
		Heating design temperature	°C	[4-6]
		Cooling design temperature	°C	[4-6]
		Setpoint control type	eg. Fixed	[4-6]
		Operation control mode	eg. Standby	[4-5]

ANNEX IV

IRs FOR THE TEST CASE

Table-A IV-1 General Model information

Building type	Office
Localisation	Montreal
ASHRAE climate zone	Quebec - CZ6A
OpenStudio - Building type	Office
OpenStudio - Construction type	90.1-2010 - CZ7 - Office

Table-A IV-2 Building envelope

Wall	**ASHRAE 90.1-2010 ExtWall Mass CZ 6**				
Type of material	**Thickness (m)**	**Conductivity (W/m-k)**	**Thermal resistance**	**Thermal conductivity**	
			SI (m^2-k/W)	SI (W/m^2-k) without air film	SI (W/m^2-k) With air film
1IN Stucco	0.0253	0.6918	0.037		
8IN CONCRETE HW Ref-Bldg	0.2032	1.311	0.155		
Mass Wall Insulation R-10.11 IP	0.087256	0.049	1.781	0.487	0.454
1/2IN Gypsum	0.0127	0.16	0.079		
		Total thermal resistance	**2.05**		
Roof	ASHRAE 90.1-2010 ExtRoof IEAD CZ 2-8				
Type of material	**Thickness (m)**	**Conductivity (W/m-k)**	**Thermal resistance**	**Thermal conductivity**	
			SI (m^2-k/W)	SI (W/m^2-k) without air film	SI (W/m^2-k) With air film
Roof membrane	0.0095	0.16	0.06		
IEAD roof insulation R-19.72 IP	0.170137	0.049	3.47	0.283	0.273
Metal decking	0.0015	45.006	0		
		Total thermal resistance	**3.53**		
Ceiling	ExtSlab Carpet 4in CZ 1-8				

Type of material	Thickness (m)	Conductivity (W/m-k)	Thermal resistance	Thermal conductivity	
			SI (W/m²-k)	SI (W/m²-k) without air film	SI (W/m²-k) With air film
MAT-CC05 4 HW Concrete	0.1016	1.311	0.077	5.634	2.945
CP02 Carpet pad	Nomass material		0.1		
		Total thermal resistance	**0.177**		
Fenestration TYPE I					
Window	ASHRAE 90.1-2010 ExtWindow metal CZ 4-6		Fixed window 3.12/0.40/0.31		
Thermal conductivity "U"	3.123045	W/m²-k	Simple glass		
	17.73	btu/ft²-°F			
Solar Heat Gain Coefficient "SHGC"	0.4				
Transmissivity of the visible spectrum	0.31				
Surfaces II					
Wall	ASHRAE 90.1-2010 ExtWall Mass CZ 6				
Type of material	Thickness (m)	Conductivity (W/m-k)	Thermal resistance	Thermal conductivity	
			SI (m²-k/W)	SI (W/m²-k) without air film	SI (W/m²-k) With air film
G05 Wood 25 mm	0.0254	0.15	0.169	0.458	0.428
8IN CONCRETE HW RefBldg	0.2032	1.311	0.155		
Mass wall insulation R-10.11 IP	0.087256	0.049	1.781		
1/2IN Gypsum	0.0127	0.16	0.079		
		Total thermal resistance	**2.18**		
Fenestration II					
Window	Fix-Window-TYPE II		Fixed window 3.12/0.40/0.31		
Thermal conductivity "U"	3.6886	W/m²-k	Simple glass		
Solar Heat Gain Coefficient "SHGC"	0.78				
Transmissivity of the visible spectrum	0.9				

HVAC systems

The HVAC system is a variable air volume (VAV) multizone system with baseboard heaters. The cooling is provided by a chiller via a cold-water loop with a COP of 5.5. An electric coil provides the main heating, while all spaces are equipped with at least one electric baseboard to provide additional heating.

Table-A II-3 Principal HVAC information of the model

Principal HVAC equipment	Capacity (W)
HEATING COIL (ELECTRIC)	226,303.40
COOLING COIL WATER	500,118.58

Table-A IV-4 Zoning information of the model

Thermal Zones number	Capacity of electric baseboard (W)
1	7264.09
2	6551.56
3	126.78
4	4267.83
5	4071.35
6	1992.55
7	620.14
8	52.34
9	92.78
10	2466.55
11	3300.0
12	7162.07
13	4914.79
14	5463.21
15	2395.33
16	25091.41
17	6182.67
18	11854.74
19	9386.25

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