INVESTIGATING BUILDING INFORMATION MODEL TO BUILDING ENERGY MODEL DATA TRANSFER INTEGRITY AND SIMULATION RESULTS

by

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A thesis
presented to Ryerson University

in partial fulfillment of the
requirements for the degree of
Master of Applied Science
in the Program of
Building Science

Toronto, Ontario, Canada, 2016

AUTHOR’S DECLARATION

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A THESIS

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ABSTRACT

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MASc. in Building Science, 2016

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Traditional energy modeling methods are usually time-consuming and labour-intensive, so energy simulation is rarely performed early in building design. If a Building Energy Model (BEM) can be seamlessly generated from a Building Information Modeling (BIM) model, the energy simulation process can be much more efficient and better integrated in design. The concerns about BIM to BEM data transfer integrity and the reliability of simulation results are preventing wider adoption of BIM-based energy simulation. This study aimed to address these two obstacles and increase energy modelers' confidence in using BIM for energy analysis. Green Building Studio (GBS) was used to simulate energy use and generate eQuest and EnergyPlus input files. Two building types were modeled in Revit with various iterations and BEM input files downloaded from GBS were compared line by line to identify and classify discrepancies. Simulation results from BIM-based and traditional modeling were compared to test reliability and showed unexpectedly good agreement across methods.

ACKNOWLEDGEMENTS

I sincerely thank my supervisor, Professor Jenn McArthur, for being such an inspiration. The dedicated one-hour meeting every week had helped me tremendously during the completion of my thesis. I am very lucky to have her as a mentor, who kept me on track and focused, and encouraged me to be more curious and adventurous with my research.

I also greatly appreciate the helpful feedback from my resourceful advisory committee, Dr. Mark Gorgolewski and Dr. Russell Richman, who helped with research scope and thesis refinement.

I would also like to thank my Building Science peers, who are all amazing people to study and work with. They have never failed to motivate me and provide me with endless support and encouragement.

Finally, I would like to thank my loving, caring and supporting family for always being there for me.

It has been a fun and rewarding journey.

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LIST OF ACRONYMS

ACRONYMS	FULL NAME
ACH	Air change per hour
AECOO	Architecture, Engineering, Construction, Owner, and Operations
AFR	Air film resistance
AIA	American Institute of Architects
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BCA	Building and Construction Authority
BEM	Building Energy Modeling
BEP	BIM Execution Plan
BIM	Building Information Modeling
BIN	eQuest weather file
bSc	BuildingSMART Canada
CAD	Computer-aided design
CIC	Construction Industry Council
CMU	Concrete masonry unit
COBIM	Common BIM Requirements
COP	Coefficient of performance
COP21	the 21st Conference of the Parties
CZ	Climate Zone
DB	Dry-bulb
DHW	Domestic Hot Water
DOE	Department of Energy
EAFR	Exterior air film resistance
EIFS	Exterior Insulation and Finishing System
GBS	Green Building Studio
gbXML	green building Extensible Markup Language
GHG	Greenhouse Gas
GLD	Ground Loop Design software
GSA	General Services Administration
GSHP	Ground Source Heat Pump
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation, and Air Conditioning
IAFR	Interior air film resistance
IBC	Institute for BIM in Canada
IBPSA-USA	International Building Performance Simulation Association
IDF	EnergyPlus input file
IES-VE	Integrated Environmental Solutions - Virtual Environment
INP	eQuest input file

LBNL	Lawrence Berkeley National Laboratory
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
MEP	Mechanical, Electrical, and Plumbing
NBS	National Building Specification (UK)
P3	Private-Public-Partnership
PDF	Portable document format
SEER	Seasonal Energy Efficiency Ratio
UNFCCC	UN Framework Convention on Climate Change
VAV	Variable air volume
WB	Wet-bulb
ZEB	Zero Energy Buildings

1 INTRODUCTION

As one of the participating nations of UN Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21), Canada has encouraged its provinces to establish greenhouse gas (GHG) reduction target and action plans. Ontario aims for an 80% GHG reduction by 2050 from the 1990 baseline (OMECC 2015). The buildings sector accounts for 34.7% of secondary energy consumption and over a quarter of overall GHG emissions in Ontario (NRCan 2015), but it is currently unregulated in carbon emission control (Canadian Energy Issues 2016, Wong, Li, et al. 2013). Among the various strategies and programs intended for GHG reduction, Building Information Modeling (BIM)-based Building Energy Modeling (BEM) have the potential to reduce energy demand – and associated GHG emissions – through sustainable design.

BEM is a tool used to predict building's energy consumption by inputting design climate conditions, orientation, massing, the envelope construction (including glazing systems), thermal bridging, internal loads, and systems (the mechanical, electrical, and plumbing systems, etc.) into the modeling software. BEM tools will be more effective if they are capable of parametric and optimization analysis to facilitate screening of multiple iterations. It is considered a key tool in meeting the 2030 Challenge target, which is to achieve carbon neutrality in new buildings, developments, and major renovations by 2030 (AIA 2015, Architecture 2030 2015).

BEM guides rational design decisions early on that can be very difficult to implement later in the design process (AIA 2015). However, a survey of 140 companies participating in the 2030 Commitment reported that 44% of building projects conducted energy modeling in the concept and schematic design stage (AIA 2015). This is very low given that average non-participants are expected to have a lower modeling rate. The lack of successful case studies showcasing energy modeling's positive impacts (AIA 2015) is partially responsible for the insufficient adoption, but the considerable amount of time and effort demanded by energy modeling using the traditional method is also a likely factor because it requires to re-create the geometry in a native BEM tool based on architectural drawings and define these properties in detail (Gane and Haymaker 2010). This is where BIM can improve the modeling efficiency because the BIM model already contains a good amount of information (e.g. geometry and construction) required by energy modeling and thus eliminates the time consuming and labour intensive remodeling process and facilitates repeated energy modeling as the design progresses (Ham and Golparvar-Fard 2015, Kim, et al. 2015). BIM has been adopted by an increasing number of designers for architectural/ structural/ mechanical design already; therefore, it is a missed opportunity not using BIM for energy analysis.

The **Research Objective** of this thesis is to fill a research gap by documenting the integrity of data transfer from BIM models to BEM input files and to provide insight on BIM-based energy modeling performance. The expected outcome is to increase designers and modelers' confidence in the wide adoption of BIM-based energy modeling.

The following **Research Questions** were developed to frame this research:

1. How accurately are building construction and system information transferred from BIM to energy modeling input files, such as gbXML (green building Extensible Markup Language), INP (eQuest input file), and IDF (EnergyPlus input file)?
2. How do the BIM-based simulation results compare with (a) a BIM-generated input file run using a BEM software for the same building inputs and simulation engine and (b) with the same building modeled directly in the BEM software?
3. Do particular climate zone effects, system types, or construction types, and geometric errors that introduce errors into results, and if so, why?

To answer these research questions and thus achieve the research objectives, a multi-phase research strategy was undertaken, including a comprehensive literature review (Chapter 2), followed by a series of semi-structured interviews with BIM managers and energy modeling experts (Chapter 3) to obtain further background. The case study models were generated (Chapter 4) for two building types and tested with several design options. The testing methodology and findings of data transfer integrity evaluation is presented in Chapter 5, simulation results comparison is discussed in Chapter 6, sources of error are evaluated in Chapter 7, and model geometric error resiliency in investigated Chapter 8. Finally, Chapter 9 presents a discussion of the conclusions of this research, informing the recommendations presented in Chapter 10.

2 CONTEXT OF RESEARCH

This section introduces the background and lays out the rationale for this research. It begins with an investigation of BIM adoption globally to demonstrate how starting from government projects, BIM is or will soon be heavily involved in the architectural design practice. Many countries have developed explicit goals and timelines for BIM implementation in building construction projects.

2.1 Worldwide BIM adoption

BIM is gaining popularity in the AECOO (architecture, engineering, construction, owner, and operations) community around the globe since it allows multidisciplinary collaboration, accommodates the increasing complexity of construction projects, and reduces project life cycle cost as well as shortens the construction time (Bryde, Broquetas and Volm 2013, Eastman, et al. 2011, Holland, et al. 2010). BIM, when implemented well, can be a powerful tool for design, analysis, integration, collaboration, visualization, and documentation for knowledgeable and trained users (Mohandes, Preece and Hedayati 2014).

Many countries have introduced the implementation of BIM into construction projects and attempted to accelerate BIM adoption by setting rigorous goals for government owned or procured projects (Cabinet Office 2015, Henttinen 2013). To facilitate BIM implementation, a BIM execution plan (BEP) is usually developed, which is a framework or a template that provides general guidance and standardized workflow to strategize BIM implementation in a holistic approach (CIC-Penn 2011, Wu and Issa 2015). It outlines the overall project vision, defines BIM uses, and maps the implementation processes. It also acts as an agreement among stakeholders in terms of their responsibilities, deliverables, and the time period they are involved in the project either as an owner or input provider (CIC-Penn 2011, Saluja 2009). The BEP is an effective tool to enhance interoperability and facilitate information sharing between diverse disciplines throughout the project lifecycle (Saluja 2009). To keep track of the project progress, the BEP requires regular reviews and updates; thus it is recognized as a “living document” (CIC-Penn 2011, NATSPEC 2016). BIM adoption is accelerated by setting the implementation targets complemented by the BEPs. The targets and BEP development of the following seven countries were investigated.

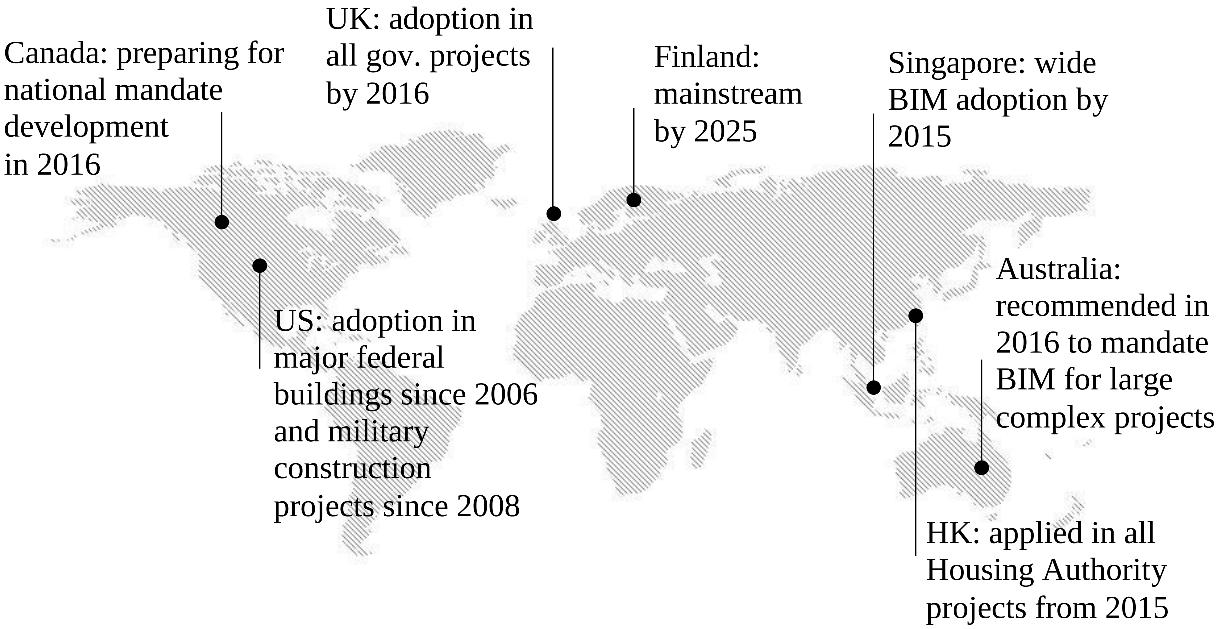

Figure 1. BIM implementation target around the world

US – The General Services Administration (GSA) required major federal building projects to be delivered using BIM from 2006, and the US Army Corps of Engineers required all military construction projects to adopt BIM from 2008 (Howell 2015). US has the largest number of BEPs (roughly 50% of existing BEPs) from varied developers; educational institutions take a considerable portion (BuildingSMART 2016).

Canada – There are three main organizations involved in BIM research, standard development, industrial education, and community building: CanBIM, BuildingSMART Canada (bSC), and Institute for BIM in Canada (IBC). They have developed BIM protocols and toolkits, but have not yet come up with a concrete timeline for BIM adoption. This calls for appropriate regulatory or policy framework that can accelerate the establishment of national BIM mandate, standard, and strategies (Tahrani, et al. 2015, Poirier 2016).

UK – BIM is recognized as one of the strategies to reduce construction project capital cost (Cabinet Office 2015) and improve design and construction efficiency (Cabinet Office 2012). The UK government committed to use BIM on all government procured public construction projects by 2016 (Cabinet Office 2015).

Finland –BIM is anticipated to be a mainstream practice around 2020 to 2025 (Henttinen 2013). BuildingSMART Finland published its Common BIM Requirements (COBIM) in 2012, which have improved the quality of BIM project delivery (Henttinen 2013).

Singapore – To cope with BIM adoption challenges, Building and Construction Authority (BCA) developed comprehensive BEPs and made the infrastructure available, which were key enablers for effective BIM implementation. By mid 2016, Singapore has published BIM Guide Version 2 and eight BIM Essential Guides to demonstrate good BIM practices. The content is prepared in a way so that beginners can easily follow as well. The electronic document submission platform, CORENET (COnstruction and Real Estate NETwork), for construction projects that seek for regulatory approvals has offered architectural BIM electronic submissions since January 2010 and the engineering BIM since April 2011 (Teo 2015). Starting from 2013, developments larger than 20,000 m^2 gross floor area have been required to submit the project in the BIM format. Mandatory BIM e-submission was enforced from July 2015 for new developments between 5,000 and 20,000 m^2 (Teo 2015). By putting these strategies into effect, Singapore has made a number of key achievements by 2014: 102 government procured projects has utilized BIM and 115 projects have been qualified for BIM e-submission (Lam 2014). The strategies have been constantly reviewed and evolved to push for faster and wider BIM adoption in the industry by 2015 (Lam 2014).

Australia – The current BIM uptake in Australia is rather limited. Considering the benefits of BIM in terms of efficiency improvement, Infrastructure Australia has recommended that the governments should mandate BIM for large complex infrastructure project design (Infrastructure Australia 2016).

Hong Kong – The Housing Authority and the Mass Transit Railway Corporation are early BIM adopters. The former started to experiment BIM in 2006 and targeted to apply BIM in its new projects from 2014/2015; the latter used BIM in some railway projects and aimed for its property projects and facility management (CIC-HK 2014).

2.2 BIM use cases

There are more than 25 identified BIM use cases that cover the building's lifecycle from design to facility management. To rank these BIM uses' popularity, 13 BEPs were investigated (shown chronologically in Figure 2) selected based on geographical diversity (North America, Europe, Australia, and Asia) and developer type variability (government, institutions, and the AEC community). One of the aspects that all BEPs investigated collectively agreed on was to define the BIM use cases early in the project. Through identifying BIM uses, all disciplines will have a better understanding in terms of how BIM will be used throughout the project and what information they are expected to input and in which format (CIC-Penn 2011). Therefore, this process is important for collaboration and handover.

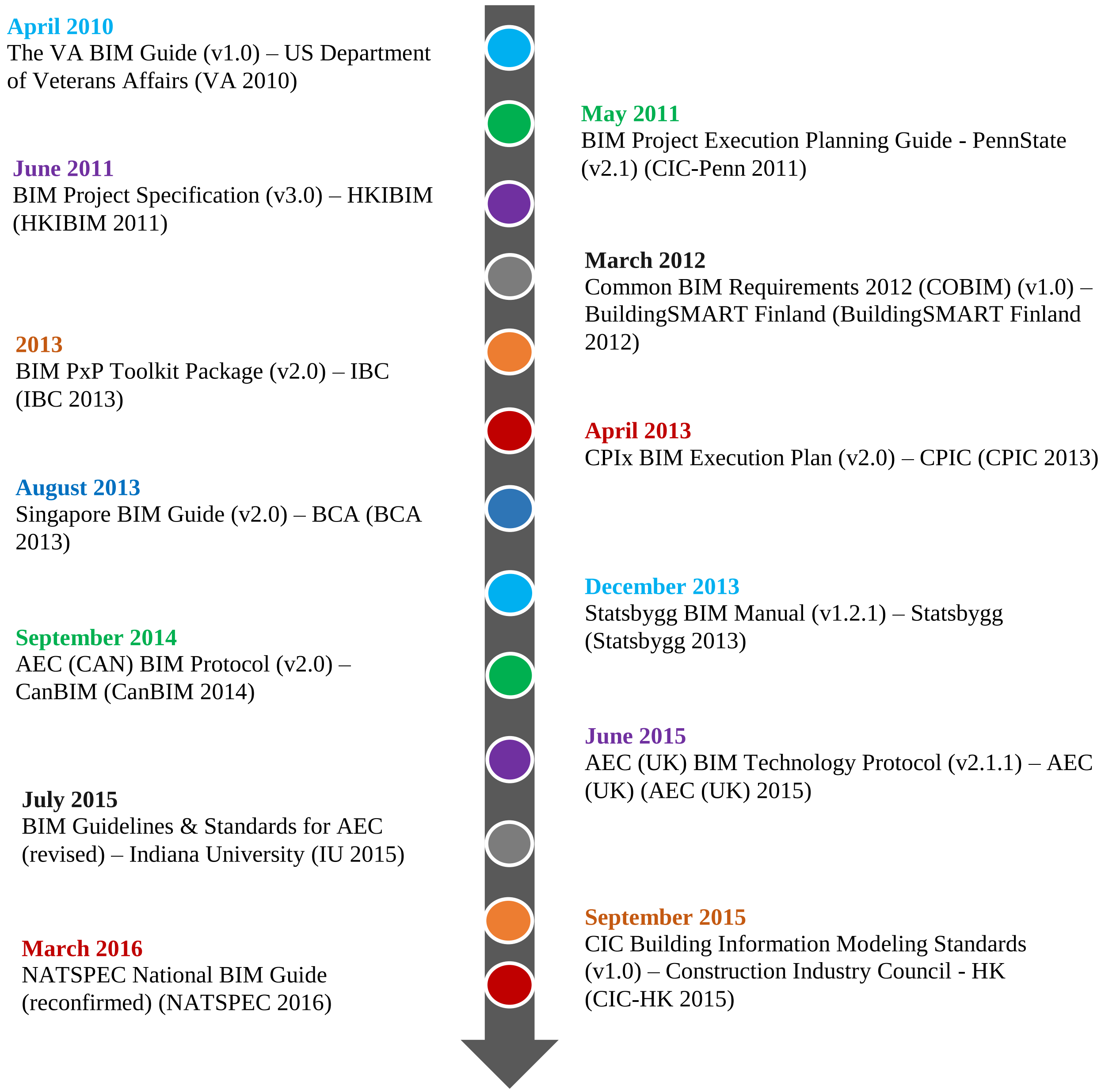

Figure 2. The global progress of BEP development

Review of these BEPs revealed that close to one quarter of the popular BIM uses were related to energy analysis (shown in **bold** text in Table 1) as described in their definitions. For example, even when *Facility energy analysis* was not selected as a use case by the project team, by choosing *Sustainability LEED evaluation*, the team had to conduct energy modeling as well.

Table 1. BIM use cases across 13 BEPs ranked in the descending order of mention

	BIM Use Cases Across BEPs	BIM Execution Plans												
		PennState	IU	VA	CANBIM	IBC-BIM	AEC(UK)	CPIx-UK	Statsbygg	COBIM	NATSPEC	HKIBIM	CIC-HK	SBCA-SG
All 13 BEPs	3D coordination (design)	●	●	●	●	●	●	●	●	●	●	●	●	●
	Space management/tracking	●	●	●	●	●	●	●	●	●	●	●	●	●
	Phase planning (4D modelling)	●	●	●	●	●	●	●	●	●	●	❍	●	●
	Engineering analysis	●	●	●	●	●	●	●	●	●	❍	●	●	●
	Design authoring	●	●	●	●	●	●	●	●	❍	●	●	●	●
	Building system analysis	●	❍	❍	●	●	●	❍	●	●	●	●	●	●
	Facility energy analysis	●	●	●	●	●	●	●	●	●	●	❍	●	●
12 BEPs	Design reviews	●	●	●	●	●	●		●	●	●	●	●	●
	Structural analysis	●	●	●	●	●	●	●	●	●	●	●		●
	Programing	●	●	●	●	●	●	●	●	●		●	●	●
	Other eng. analysis	●	●	●	●	●	●	●	●	●	●	●		●
	Mechanical analysis	●	●	●	●	●	●	●	●	●	●	●		●
	Cost estimation	●	●	●	●	●	●	●	●	●	●		●	●
	Building maint. scheduling	●		●	●	●	●	●	●	●	●	●	●	●
	Site analysis	●		❍	●	●	●	●	●	●	●	●	●	●
11	Existing conditions modelling	●	●	●	●	●	●		❍	❍	●		●	●
	3D coordination (construction)	●	●	●	●	●	●	●	●	●	●	●		
	Site utilization planning	●			●	●	●	●	❍	❍	●	●	●	●
	Lighting analysis	●		❍	●	●	●	●	●	❍	●	●		●
	Visualization	❍	●	●	●	❍	●		●	●	●	●		●
10	Construction system design	●	●	●	●	●	●		●	●	●	●		
	Code validation	●	●	●	●	●	●	●	●		●			●
	Sustainability LEED evaluation	●	●	❍	●	●	●	●	●		●		●	
9	Digital fabrication	●		●	●	●	●	●			●		●	❍
	4D modelling	●	●	●		●		●		❍	●	❍		●
8	Record modelling	●	●	●	●	●	●				●			❍
	3D control and planning	●			●	●	●		❍			●	●	●
7	Asset management	●			●	●	●		●		●		●	
5	Disaster planning	●			●	●	●				●			

Legend: ● = explicitly mentioned in the BEP, ❍ = indicated in the BEP

Although "energy analysis" is mentioned or indicated by all 13 BEPs, how it is integrated in the whole BIM project is not clearly described by most of the BEPs. Only three BEPs have a separate document dedicated to energy analysis:

1. *"Common BIM Requirements COBIM 2012 – Series 10 Energy Analysis"* (Laine, Backstrom and Jarvinen 2012) published in 2012 by BuildingSMART Finland
2. "*BIM Essential Guide – for transfer of BIM into building performance analysis tools*" (BCA 2015) published in late 2015 by Singapore Building Construction Authority
3. "*BIM guide – energy performance*" (USGSA 2015) published in mid 2015 by the US General Services Administration (GSA)

The COBIM document describes the potential use of energy analysis and data required in each stage of the project: conceptual design, schematic design, design development, building permit phase, detailed design, construction, commissioning, and operation and maintenance. It points out that there are serious deficiencies between information needed for energy modeling and the quality information provided by BIM. The guide also provides the minimal requirements for the architectural model in terms of architectural, MEP, and spatial air conditioning requirements.

The Singapore guide provides the gbXML export from BIM and import into several common building performance analysis tools: Trace 700, Integrated Environmental Solutions Virtual Environment (IES-VE), Carrier E20-II, DesignBuilder, and Ecotect. The guide also lists six main points for analytical model preparation and information needed to be communicated with other disciplines. This 21-page guide is not an extensive but an introductory document.

The GSA guide is a 76-page document that provides much more in depth information regarding different functionalities of energy modeling throughout the project lifecycle. It explores the feasibility of BIM-based energy modeling and compares it with traditional energy modeling. It also identifies the benefits, limitations, and future work of BIM to BEM data transfer in the aspects of geometry, construction and materials, mechanical systems, and internal gain items (lighting and equipment and occupants).

2.3 The benefits of BIM-based energy analysis

The fact that "sustainable design" has become more of a requirement than a voluntary initiative has urged early and repeated energy analysis to be integrated into the building projects. Energy modeling benefits the project at different design stages and enables the generation of a responsible design that is less dependent on primary energy. The European Union has been pushing for *Nearly Zero-Energy Buildings* (nZEB), demanding new public buildings achieve nZEB in 2019 and all new buildings meet this standard by 2021 (European Union 2010). BIM-based energy analysis is highly recommended to accomplish this target (Laine 2013)

Both the US GSA BIM guide and the COBIM 2012 note that energy analysis is beneficial *throughout* the project. During the preliminary or conceptual design stage, the impact of site, building orientation and massing, envelope types, and energy sources can be evaluated and improved using a simple energy model. Given that solar exposure varies depending on the building orientation and massing, early-stage energy modeling can identify the optimal orientation and massing and thus reduce energy demand and operational cost. As building envelope choices and mechanical options are explored in schematic design, these models can be further refined to test relative performance. Note that, at both the conceptual and schematic stage, the energy performance results should *only* be used for comparative purposes because there are a large number of building design variables still under development. During the design development stage, parametric analysis has the potential to add significant value to energy modeling because it facilitates exploring various design options and the resultant energy consumption and capital costs to help design teams select desirable design options. In some jurisdictions such as Toronto, Canada, a model created at this phase of design is used to support the site plan application. The final energy model is created during the construction documents stage to generate required documents for code compliance and certification application (USGSA 2015, Laine, Backstrom and Jarvinen 2012, Schlueter and Thesseling 2009).

There were a number of surveys investigating BIM practitioners' perspectives regarding BIM-based energy analysis. The 2009 survey of 145 US design and construction companies where participants agreed BIM-based energy analysis could lead to "some-to-significant" time and cost savings (Azhar, Brown and Sattineni 2010). Two industry surveys, one undertaken in 2010

(Kreider, Messner and Dubler 2010) and another in 2015 (McArthur and Sun 2015) found that BIM-facilitated energy analysis was perceived to be a beneficial use of BIM.

The main reason to integrate BIM with energy modeling is that the BIM models contain a library of information required for energy simulation, (e.g. geometry and construction), which eliminates the needs to create an energy model as required by the traditional modeling approach (Moon, et al. 2011). The reproduction of redundant information is an inefficient use of time and resources, and the influence of energy analysis on the design is minimal (Wong and Fan 2013). BIM-based energy analysis allows repeated simulations for a wide range of scenarios to be performed within a much shorter period of time, which better serves the purpose of energy modeling during design. Compared to traditional energy modeling process, BIM-based analysis possesses a number of other advantages:

1. The time saved from recreating the geometry could be better spent on alternative testing; therefore, value could be added to energy consulting (Moon, et al. 2011, Stumpf, Kim and Jenicek 2011).
2. Geometric changes made to the architectural building can be easily reflected in the energy model because the BIM program captures these changes and can generate a new energy model quickly.
3. BIM tools such as Revit allow inherent orientation and massing option investigation to optimize solar load (Wong and Fan 2013, Shoubi, et al. 2015).
4. The BIM model "acts as a single source of building information for all process" (Cheng and Das 2014): The geometric data transfer is repeatable and consistent (USGSA 2015) and can be potentially used by different analysis tools for detailed lighting or natural ventilation analysis.
5. By using BIM-based energy analysis (e.g. the combination of Revit and IES, which is a whole building analytical tool), the analysis required to inform up to 38 LEED points could be prepared directly or with minimal effort (Azhar, Carlton, et al. 2011)

The potential connection between BIM and sustainable design has begun to be realized (Bynum, Issa and Olbina 2013) as is evident in several case studies. Emory University's Psychology Building (Atlanta, USA), BIM was used as an early stage analysis tool to determine the optimal orientation (through daylighting study) and evaluate façade and window options, and shading (Azhar 2011). Sustainable solutions were successfully identified by taking the BIM approach, which resulted in reduction in operational energy use. In this case, a Revit architectural model was exported to Ecotect through gbXML for various analysis in Ecotect (Shoubi, et al. 2015).

2.4 Enabling tools

The industry has seen a fast growth in a variety of software, but to prepare for the shift to BIM-based analysis, collaborative efforts are required from BIM and BEM vendors and intermediate format developers as described in the following sections.

2.4.1 Prevalent BIM tools

There are a number of BIM tools on the market and Revit is the most used based on the surveys completed in the United Kingdom (UK) by National Building Specification (NBS) in 2014 (NBS 2014) and 2016 (NBS 2016), as well as a similar survey conducted in Canada by IBC in 2013 (IBC 2013). In UK, the tool used to produce drawings has shifted from Autodesk CAD/CAD LT to BIM tools, namely Revit, Graphisoft ArchiCAD, and Nemetschek Vectorworks; while in Canada, ArchiCAD and Vectorworks had very little adoption (Table 2). Although Bentley had very little adoption in both UK and Canada (3%), it was claimed to be a popular BIM tool by researchers in the USA (Stumpf, Kim and Jenicek 2011).

Table 2. Most commonly used tools to produce drawings

	UK (NBS 2016)	UK (NBS 2014)	Canada (IBC 2013)
Autodesk Revit	31%	27%	40%
Graphisoft ArchiCAD	19%	10%	0%
Nemetschek Vectorworks	15%	8%	6%
Autodesk CAD	12%	22%	43%
Autodesk CAD LT	12%	20%	3%
Other	5%	7%	6%
Bentley Microstation	3%	3%	3%
Trimble Sketchup	1%	3%	0%
Bentley Building Suite	1%	1%	0%

Revit, ArchiCAD, Vectorworks and Bentley AECOsim Building Designer all support Industry Foundation Class (IFC) import and export (BuildingSMART 2016) as well as Green Building Extensible Markup Language (gbXML) export (gbXML 2016) to communicate with other tools.

2.4.2 Prevalent intermediate formats and compatibility with BIM

Building information exchange has progressed from primarily geometric data transfer (first generation), to object-oriented data models that included information required for specific performance modeling (second generation), to the current third generation where models could potentially facilitate building information sharing throughout the building lifecycle (Dong, et al. 2007). This is enabled by creating compatible formats between BIM and other tools.

Currently, there are two primary building information exchange schemas to facilitate BIM to BEM data transfer: gbXML and IFC. IFC is object-oriented (Ahn, et al. 2014) and has a "top-down" structure, where data are presented in a relational and organized way, while gbXML is a "bottom-up" schema and is easy to understand (Dong, et al. 2007). They save time, reduce errors, and maintain consistency across different programs by avoiding reproducing information, such as geometry and construction (Cheng and Das 2014). They have also greatly increased the transparency of data transfer process (Bahar, et al. 2013) because the language is both machine-readable and human-readable. Acting as a bridge between BIM and BEM, both gbXML and IFC have significantly improved BIM-BEM interoperability. The fact that gbXML is more suitable for energy modeling has been indicated in academic research (Dong, et al. 2007, Cheng and Das 2014), industrial practice, and the software functionality for four key reasons:

1. Although IFC covers a wide scope of building information, which can be used for structural and mechanical analysis, it is not as comprehensive as gbXML in terms of transferring data required by energy modeling, such as ventilation and weather data (Cheng and Das 2014).

2. Communication with BEM tools is better with gbXML than IFC. While IFC translates complex building surfaces from the BIM model, BEM tools usually deal with simple surfaces and often fail to recognize those complex surfaces (Dong, et al. 2007). To accommodate this, Ahn et al. proposed an IFC-IDF interface that allowed IFC files generated by ArchiCAD 13 to be converted to IDF files for EnergyPlus simulation (Ahn, et al. 2014). This approach was not adopted elsewhere yet. Conversely, gbXML only transfers rectangular shapes (Dong, et al. 2007), making it very easy for BEM tools to

understand, although this poses a limitation when the building has curved surfaces, and this is an known issue with BEM that is not addressed in this thesis.

3. IFC transfers spaces as defined in an architectural model (Figure 3a) instead of an energy model (Figure 3b), so it takes account of the thicknesses of the elements. However, the energy models do not visualize thicknesses – the virtual thickness is just a numerical number listed under the thermal properties (Figure 4).

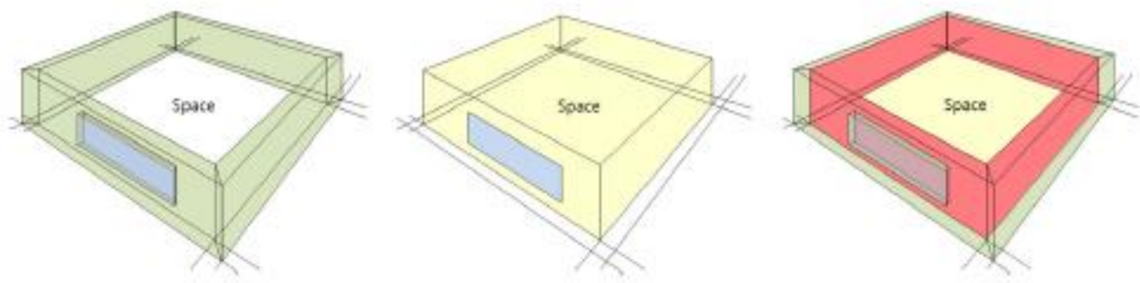

Figure 3. (a) Space and space boundary defined by a BIM architectural model (left), (b) energy model (middle), and (c) BIM energy model (right) (Ahn, et al. 2014)

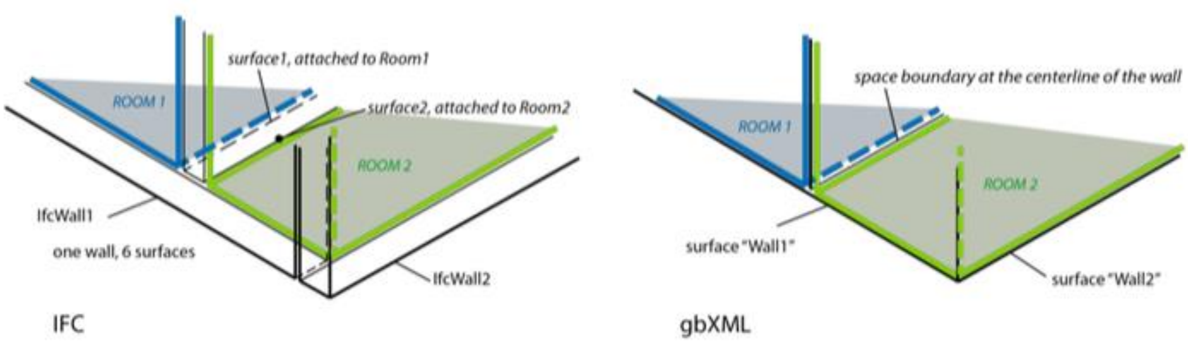

Figure 4. IFC actual thickness vs. gbXML virtual thickness (Shadrian 2015)

4. Because gbXML has been more widely embraced by the BEM community (Kim, et al. 2015, Cheng and Das 2014), the number of independent energy modeling programs supporting gbXML import is almost five times more than that of supporting IFC (gbXML 2016, BuildingSMART 2016).

gbXML enables users to describe buildings with more than 500 types of elements and attributes (Green Building XML Schema 2016). For the purpose of energy modeling information transfer, Revit supports 20 gbXML elements and their definitions were organized below (Autodesk Revit Help 2016, The Green Building XML Schema n.d.).

Table 3. gbXML structure and elements for energy modeling

Elements	**Description / Included Elements**
gbXML	Specifies default attributes, e.g., temperatureunit, lengthunit, etc.
Campus	Defines all physical objects with Location, Building, Surface, etc. elements.
- Location	Describes the building location by weather station, Zipcode, Longitude, Latitude, and Elevation.
- Building	Includes Area, BuildingStory, and Space elements
- Surface	Includes RectangularGeometry, PlanarGeometry, and Opening elements.
Opening	Contains attributes: id, Name, OpeningType, and ConstructionIdRef.
WindowType	Defines window U-value and SolarHeatGainCoeff.
Construction	Defines U-value, Absorptance, Roughness, LayerId, and Name.
Layer	Defines construction layers by MaterialId from outside layer to inside.
Material	Includes material's thermal properties, such as R-value, Thickness, Conductivity, Density, SpecificHeat, Permeance, Porosity, etc.
Schedule	Defines the year schedules
- WeekSchedule	Defines schedules from Monday to Sunday, Holidays, HeatingDesignDay, CoolingDesignDay, etc.
- DaySchedule	Defines 24-hour schedule
Zone	Defines DesignHeatT, DesignCoolT, OAFlowPerArea, AirChangesPerHour, etc.
DocumentHistory	Documents the creator/editors and programs that create/modify the file.
Space	Defines spaces, e.g. SpaceType, PeopleScheduleIdRef, LightScheduleIdRef, EquipmentScheduleIdRef, etc.
- SpaceBoundary	Contains attribute: SurfaceRef.
- ShellGeometry	Contains attributes: id and unit.
Lighting	Contains attributes: id, and LightingSystemIdRef.
- LightingSystem	Contains elements, e.g. Manufacturer, LumensPerLamp, Dimensions, etc.

2.4.3 Prevalent BEM software and compatibility with BIM

There are 133 BEM tools listed on Building Energy Simulation Tools web directory (BEST-D), which was hosted by the US Department of Energy (DOE) until late 2014 and is currently managed by International Building Performance Simulation Association (IBPSA-USA) (IBPSA 2016). Among these tools, IES-VE, DesignBuilder, Green Building Studio (GBS), Trace 700, EnergyPlus, and eQuest are a number of popular BEM tools in the industry that were repeatedly mentioned in academic research to have developed compatibility with BIM (Wong and Fan 2013, Azhar, Brown and Farooqui 2009, Attia, State of the art of existing early design simulation tools for net zero energy buildings: A comparison of ten tools 2011). There are a number of BIM plug-ins, which allow 3D models to be imported directly into native BEM programs with preliminary settings. Their compatibility with BIM is described as follows:

Table 4. BEM tools' compatibility with BIM

		Intermediate file		Plug-ins			References
		gbXML	IFC	Revit	SketchUp	Honeybee	
BEM tools	IES-VE	●	●	●	●	x	(Moon, et al. 2011)
	DesignBuilder	●	x	●	x	x	
	GBS	●	x	●	x	x	
	eQuest	x	x	x	x	x	
	EnergyPlus	x	x	x	x	●	
	Trace 700	●	x	x	x	x	(Stevenson and Dubowski 2012)
	OpenStudio	●	●	x	●	●	(OpenStudio 2016)

●: compatible x: not compatible

eQuest has not been considered an interoperable program with other tools as it only allowed 2D CAD import (Attia, State of the art of existing early design simulation tools for net zero energy buildings: A comparison of ten tools 2011), similarly with EnergyPlus. GBS has improved the compatibility of these two programs by providing INP and IDF file download. The investigation found that eQuest was the most interoperable tool when compared to EnergyPlus, Ecotect, and IES (Moon, et al. 2011). Honeybee assists building energy and daylighting simulation by connecting Grasshopper 3D with either OpenStudio, EnergyPlus, Daysim, or Radiance (Grasshopper 2016). SketchUp plug-ins allow models to be smoothly transferred into OpenStudio or IES; when using the OpenStudio plug-in, models can be exported as IDF for further analysis in EnergyPlus (OpenStudio 2016).

Two other BIM compatible energy analysis tools were considered: Autodesk Vasari and Ecotect, but both products have been discontinued and their features have been incorporated in Revit and GBS as summarized in Table 5.

Table 5. Features of Vasari and Ecotect transferred to Revit and GBS

	Revit	Green Building Studio (GBS)
Vasari (Vollaro 2015)	-Solar studies -Daylighting and lighting analysis	-Whole building energy analysis
Ecotect (Community Manager 2015)	-Solar analysis -Daylighting and lighting analysis -Sun and shadow studies	-Whole building energy analysis -Weather data -Thermal performance

Because Vasari and Ecotect had similar functionality, it is assumed the retirement of these programs was a strategy to focus development on Revit and GBS. GBS as a Revit in-house tool requires little model preparation and had no interoperability issues with the popular BIM tool – Revit (Azhar and Brown 2009). GBS takes advantage of the powerful cloud computing, which is insufficiently explored in green BIM tools (Wong and Zhou 2015). The cloud computing allows it to calculate the energy consumption and hundreds of alternatives within a short period of time (Wong and Zhou 2015). It calculates the carbon emissions and renewable energy potentials (Wong and Zhou 2015), which are important parameters to sustainable design (Lewis, et al. 2015). Similar to IES, GBS estimates life-cycle cost associated with each design so the simulation can be used to find the optimal design option, which balances cost effectiveness and energy efficiency (Stadel, et al. 2011). When importing a gbXML file to GBS online platform, GBS performed BIM model verification automatically and generated warnings to alarm users before exporting the gbXML file (Stumpf, Kim and Jenicek 2011).

Despite its advantages as a BEM tool, GBS is underused by the BEM community. The 2009 survey of 145 US design and construction companies mentioned revealed that GBS was the most used BIM-based energy analysis tools in the US: 15 of the 30 companies deploying BIM-based energy analysis used it. However, the percentage declined to 10% (15/145) when GBS adoption was calculated in the whole BEM community (Azhar and Brown 2009). This 10% was consistent with another study of 249 respondents where 27 respondents used GBS in the US architect's community who had a focus on sustainable design (Attia, Beltran, et al. 2009).

2.5 Barriers to BIM-based energy analysis

Leveraging the BIM model for energy analysis is often considered but is not common practice for a number of reasons, discussed in the following sections.

2.5.1 A lack of academic research support

Wong and Zhou reviewed the existing 84 papers on BIM use for sustainable analysis and found that while the concept of “green BIM” has gained great popularity in the past few years, the adoption rate is low because there is unsystematic and insufficient academic research to support its use in practice (Wong and Zhou 2015).

Further, there is limited literature on BIM-based energy analysis in terms of its reliability, which can be further broken down to (1) BIM to BEM data transfer integrity assessment and (2) simulation results evaluation.

2.5.1.1. BIM to BEM data transfer integrity assessment

There are a few examples of using BIM for sustainable design (Shoubi, et al. 2015, Azhar, Brown and Sattineni 2010), but they did not discuss either the challenges or verification measures for data transfer from BIM to BEM through either gbXML or plug-ins. Another study stated that GBS was capable of exporting geometrically accurate INP and IDF files (Stumpf, Kim and Jenicek 2011), but did not provide any validation measures.

Only two studies (Moon, et al. 2011, USGSA 2015) considered BIM-BEM data transfer integrity assessment. Moon, et al. (2011) evaluated the interoperability between Revit MEP and eQuest 3.64, EnergyPlus 5.0, Ecotect 2011, and IES 6.1 and investigated whether all the elements defined in Revit were transferred to BEMs, but did not discuss the consistency of the granular data transfer. This investigation concluded that eQuest was the most compatible format with BIM according to the following five areas (Moon, et al. 2011):

- Geometry: They examined geometric data transfer by visually checking the output models from these four BEM programs. All surfaces and openings were imported. The only issue was with EnergyPlus: windows were misplaced. They pointed out that there were no validation functions to check whether BEM was properly constructed based on the BIM model.
- Spaces and zones: eQuest identified multiple spaces that were assigned to one zone in Revit as one space; EnergyPlus and Ecotect identified each space as one zone; only IES supported both the “Spaces” and “Zones” elements.

- Construction: The constructions were defined by “Material”, “Layer”, “Construction” elements, which were compatible with eQuest and EnergyPlus. The glazing information stored under the “WindowType” element was only compatible with eQuest, but was not transferred to EnergyPlus. The construction and glazing information was not compatible with Ecotect and IES.
- Internal loads and operation schedule: eQuest and EnergyPlus were compatible but Ecotect and IES were not.
- The Heating, Ventilation, and Air Conditioning (HVAC): Since system information was assigned by GBS, only eQuest and EnergyPlus had this information.

The US GSA completed several pilot studies about BIM-BEM data transfer and summarized the challenges presented in geometry, construction and material, HVAC, and lighting, occupant, and equipment loads (USGSA 2015). In terms of the geometry, the US GSA Guide indicated that there was a good chance the building elements would be “missing, misplaced, and deformed” (Figure 5) and once the geometric errors occurred, it was very difficult to identify the sources. To improve geometric data transfer accuracy, they suggested to simplify the BIM model by deleting all surfaces that were not needed for energy simulation, such as the interior walls within one zone that do not separate different thermal conditions. Curved surfaces and curtain walls were two identified areas that need further investigation (USGSA 2015). They also suggested developing diagnostic tools for trouble shooting during export (USGSA 2015). Regarding the rest categories, US GSA found that although gbXML and IFC support those types of information, not many BEMs import it. There should be agreed protocols and organizational methodologies across the industry to enhance the accuracy of BIM export to gbXML/IFC, and BEM import (USGSA 2015).

Figure 5. Geometric errors found in US GSA case studies (USGSA 2015)

2.5.1.2. Simulation results evaluation

The BIM-based energy analysis simulation results were evaluated either by comparing the modeling results with the actual energy consumption or by comparing results obtained using different modeling tools. The case study of the DPR Construction headquarters building (Azhar, Brown and Sattineni 2010) illustrated the effectiveness of BIM-BEM geometry transfer and BIM-based analytical results: a BIM model was created for verification purposes after the building had been operated for several years. The geometry was imported into IES-VE and all the analytical properties were assigned directly within IES, and the modeled results were within 10% of actual energy consumption (Azhar, Brown and Sattineni 2010).

Although a number of journal articles mentioned GBS as an energy simulation tool (Wong and Fan 2013), the analysis and discussion about its application and reliability was mostly superficial, such as the study done by (Stadel, et al. 2011). They explored the lifecycle energy use and carbon emissions simulation results from GBS and IES plug-ins. A comparison of their results showed inconsistency: GBS results were 36% higher (Stadel, et al. 2011). They stopped exploring further when they found out the outputs were an aggregated estimation. The authors considered GBS and IES plug-ins as “black-box” calculations because they did not realize they could have compared the input files, which might indicate these two plug-ins made different assumptions based on the building type and HVAC system.

A more in-depth study (Stumpf, Kim and Jenicek 2011) developed a framework for early stage energy analysis using GBS and proposed a recommended process to export gbXML from BIM to GBS to perform analysis and design alternative evaluation. This framework and the process were demonstrated in the case study of Community Emergency Service Station in Fort Bragg, North Carolina, USA. Three building shapes and 12 orientations were tested at schematic design; 10 HVAC systems, 17 glazing options, 20 roofs, 15 walls, 4 lighting fixtures and 3 lighting controls were experimented at detail design. The final design was compared to a baseline model (ANSI/ASHRAE/IES Standard 90.1-2004) to quantify energy efficiency improvement. The energy results obtained following this GBS framework were validated with eQuest simulation results created by a different modeler. It was found that the 6% difference between the baseline models and 15.5% between the proposed design models resulted primarily from the thermal loads (Stumpf, Kim and Jenicek 2011). They suggested developing procedures to validate different energy models.

2.5.2 Software and the interoperability

Software venders are key players in the advancement of BIM-based energy modeling. Recently, software capacities have been greatly expanded; for example, Revit user today can easily assign construction, spaces and zones within Revit Architecture (Autodesk Knowledge Network 2016), while Revit Architecture 2011 had no such capacity (Moon, et al. 2011).

Software interoperability issues (e.g. transferring information between BIM and BEM) were commonly identified as one of main obstacles that have prevented the wider adoption of BIM-based analysis (Moon, et al. 2011, Bynum, Issa and Olbina 2013, El Asmi, et al. 2015). Although these difficulties have been improved along with the development of gbXML and IFC, there are still several BEM tools that do not support either format. Even when they support these intermediate schemas, not all the information exported from BIM can be imported into BEM tools as mentioned in Section 2.5.1, e.g. many BEM tools did not import the constructions and mechanical information (USGSA 2015). Another software-related challenge was that BIM did not have the capacity to verify model integrity and completeness, which could lead to false energy modeling (Stumpf, Kim and Jenicek 2011). In response to this issue, the US GSA BIM Guide proposed to develop software for model-checking purposes for early stage energy modeling and a joint effort of GSA, Lawrence Berkeley National Laboratory (LBNL) and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (USGSA 2015) is expected to develop predefined checklists/standards to guide this process.

2.5.3 Procedural difficulties

Given that several leading companies have successfully used BIM for sustainable projects with existing BIM technologies, software limitation is not the determining factor for unsuccessful implementing BIM in sustainable design, rather, the lack of proper standards and procedures is more likely to be the reason (Wu and Issa 2015, Häkkinen and Belloni 2011, El Asmi, et al. 2015) particularly because it can result in inaccuracy and errors (Bryde, Broquetas and Volm 2013, Lewis, et al. 2015).

The top “BIM construction firm” and “green building construction firm” Turner Corporation as ranked in *2013 Giants 300 Reports* (Building Design + Construction 2016) suggested that to achieve green BIM projects, BEP should be established early in the design phase and effectively implemented (Wu and Issa 2015). Thus, a project-specific and constantly updated BEP has a strong influence on the success of a sustainable project delivered using BIM (CIC-Penn 2011, Wu and Issa 2015). This is because the BEP could properly address the interoperability issues and coordinate BIM projects between multiple disciplines efficiently (Wong and Fan 2013).

As mentioned previously, it is not yet common practice to formally incorporate energy modeling in BIM project planning, but the industry has started the movement as seen in the recent Singapore BCA and US GSA publications. These documents set out a good start for energy modeling integration, but more work is needed to address the possible issues that could arise in model creation, preparation, and transition so that BIM project team without experience in BIM-based energy analysis could easily understand what goes into the planning and successfully apply energy modeling from the early design stage. It is anticipated that the results of this research will support the next generation of BEPs, particularly with regards to facilitating BIM-based BEM.

3 CURRENT PRACTICE IN BUILDING ENERGY MODELING

The industry has seen an increase BIM uses in energy-related analysis applications. To quantify and investigate this, the survey results of BIM use frequency obtained from a 2015 study focusing on Private-Public-Partnership (P3) projects (small target population) and a 2010 general study (much larger and more varied population) were considered. As shown **bold** in Figure 6, the BIM uses related to energy analysis all increased by at least 10%. However, P3 projects, driven by an energy target fulfillment requirement, are expected to have a higher adoption than conventional project delivery methods.

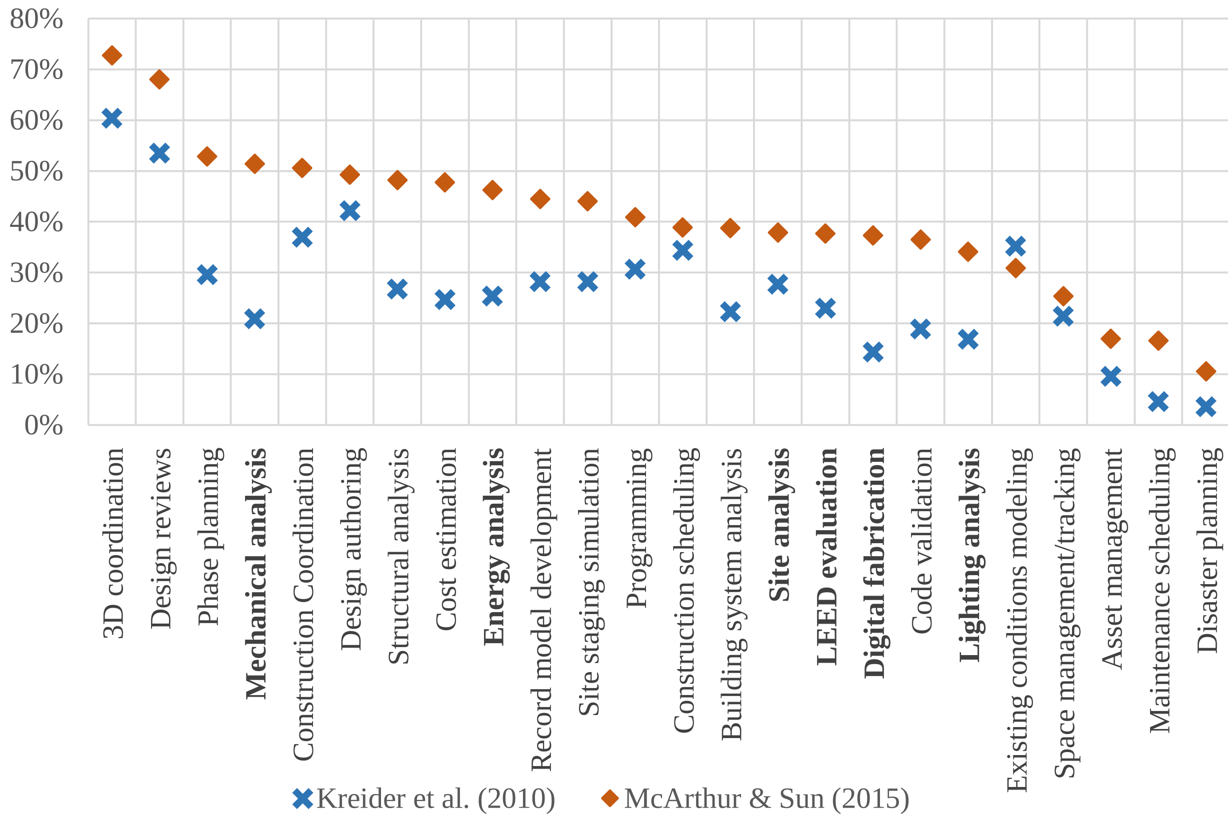

Figure 6. Comparison of BIM use frequency from 2010 and 2015 studies

A series of semi-structured interviews were undertaken in 2015 to better understand the current use of BIM-based energy modeling within the AEC industry generally and the key findings are summarized in this Chapter. Two groups of experts were involved in this industrial research: (1) five BIM managers from Canadian architectural and construction companies; and (2) ten highly-experienced energy modelers, who use energy modeling for diverse purposes (e.g. design assistance or compliance) and have different levels of BIM experiences.

The BIM managers interviewed recognized that BIM could be used for energy analysis but none of them had planned energy modeling in BIM execution. One of the interviewed architectural firms explained how energy modeling was involved in their projects: the architects established the orientation, massing, and glazing strategies and then brought energy consultants on board between schematic design and design development to perform a high level energy analysis and make suggestions about building performance. However, this was performed for the purposes of compliance rather than ongoing design-assistance.

The ten energy modelers were working primarily at engineering consulting firms (60%) while the remainder were from an architecture firm, a sustainable consulting firm, a software vender, and an interdisciplinary company. They either performed energy modeling and analysis on a daily basis or oversaw the modeling practice in the company.

The consolidated answers to the interview questions are presented in the following sections. Note that due to the small sample size and lack of randomization in interviewee selection, (this was an invited survey of recognized experts, not the general modeling population), the results presented cannot be considered representative of the general population, nor can generalizations be made. That said, this is expert energy modelers' input and provides valuable insight on best practices in the industry.

The recruitment script and interview questions as approved by the Research Ethics Board are included in Appendix A.

3.1 Software used for energy analysis

Key points regarding software used for energy modeling were that:

1. Revit was the BIM tool interviewees used if BIM-based energy analysis was performed.
2. The most used BEM tools by the interviewees were IES, followed by eQuest.
3. Although EE4 was being phased out for LEED compliance, it was still in use by 60% of the companies interviewed for a small amount of their work.

4. The adoption rate of GBS was consistent with the two surveys presented in Section 2.5.1, which is 10%, and it was only used for 5% of work.

The percentage use of different BEM tools by the ten interviewees is presented in Table 6, followed by the advantages and disadvantages of each main modeling software based on user experience. Interviewees indicated that BEM programs had their strengths and weaknesses, so instead of investing in different BEM programs, it was more important to understand software capabilities and develop tools to overcome the disadvantages. Because they spent most of the time working with the software they were familiar with, they usually had a good understanding of their software's pros and cons, but their comments on other software's disadvantages should be taken carefully because the information might be outdated or simply not accurate for lack of familiarity. Some companies indicated they used several modeling programs because they could take advantage of different programs' functionalities or the modelers on the team specialized in different programs. Since the modeler interviewed might not be directly using certain software that was used in the company, they could not comment on it.

Table 6. BEM software used by interviewees

Interviewee Number	IES	eQuest	EE4	DOE 2	Energy Plus	Design Builder	TRACE 700	Carrier HAP	GBS
1	75%	10%	15%	25%	0%	0%	0%	0%	0%
2	0%	0%	0%	0%	0%	100%	0%	0%	0%
3	0%	0%	0%	0%	100%	0%	0%	0%	0%
4	60%	10%	0%	0%	0%	0%	30%	0%	0%
5	80%	0%	0%	0%	15%	0%	0%	0%	5%
6	90%	5%	5%	0%	0%	0%	0%	0%	0%
7	0%	70%	30%	0%	0%	0%	0%	0%	0%
8	20%	75%	2%	0%	3%	0%	0%	0%	0%
9	50%	35%	5%	0%	10%	0%	0%	0%	0%
10	75%	10%	15%	0%	0%	0%	0%	0%	0%

IES was used by 70% of the interviewees and over half of them used it for more than 70% of their projects. They considered IES to have wider functionalities while other simulation tools were very limited. Apart from thermal analysis and lifecycle analysis, several interviewees indicated that they used IES because it had strong thermal comfort, daylight, natural ventilation analysis, as well as a LEED module that helped with obtaining material and site credits for

LEED certification. Although IES was interoperable with SketchUp, it was better suited for Revit. It was easy to export data to Excel, so it provided a very simple way to exchange information back and forth with other tools. One of the interviewees also found it easier to use and manipulate IES data than many other tools, such as OpenStudio.

eQuest was used by 50% of the companies interviewed and two of them used it for more than 70% of their projects. One interviewee mentioned that eQuest did not have a nice user interface (primarily textual input and limited visualization) and modeling could be quite time consuming. One advantage was that parametric analysis could be conducted relatively easily. It was widely adopted mainly because it was one of the programs designated for LEED compliance.

EnergyPlus was used by three companies interviewed. One company used it for 100% of their energy simulation for whole building modeling and the other two used it for detailed studies, such as modeling green roofs. The energy modelers thought EnergyPlus was more versatile than other BEM tools because it allowed programing through its text editor and thus it was possible to copy and paste contents, which was especially beneficial and time saving when there were a large number of similar zones. One modeler gave an example of a 500,000 square feet hospital that had 500 thermal zones. By creating EnergyPlus templates for schedules, wall assemblies, and glazing performance, the energy modeler could easily plug information from template files into new projects. The modelers also mentioned that EnergyPlus could be used for parametric studies. Given the context of these responses – particularly the exclusive use of EnergyPlus by one interviewee – there is an element of bias in these comments and the comparison made with other BEM tools.

DesignBuilder and **Trace 700** were each used by one company. The interviewee used Trace 700 indicated that it was not the easiest tool to use because it had no visualization. Since it was number input, it was hard to check if anything was missing or wrong. DesignBuilder used the EnergyPlus simulation engine, but it was not superior to other tools in any notable area, so most modelers were not familiar with it.

3.2 Current workflow

Energy analysis is commonly brought into the project late in the design stage to generate documents for building permit, sustainable building certifications, (e.g. LEED®), or incentive programs (e.g. High Performance New Construction). The energy consultant at the architectural firm observed that when the modeling was done primarily for compliance purposes, the architects spent very little time trying to understand those energy reports or used them for performance improvement. Energy analysis has not been used enough in the design process mainly due to the considerable amount of effort required to create an energy model using the traditional approach. Therefore, an improved modeling approach as well as BIM-based energy analysis was developed to accelerate the geometry creation process. The three current workflows are described below.

3.2.1 Traditional energy modeling approach

Half of the energy modellers interviewed were using this traditional approach for 75% to 100% of their projects because their attempts of BIM-based energy analysis were not successful for various reasons or because they did not trust that BIM tools could import the geometry correctly. Two interviewees were very interested in exploring more about BIM because their current approach took too long to create the geometry and it was not easy to make modifications once the geometry was created. Since geometry would be different for every project, there was no way to speed up this process by developing a template.

To provide feedback to the architects without a complete model at the early design stage, most modelers would make suggestions based on previous experience or stand-alone tools. For example, the energy modelers working at the sustainable consulting company used FramePlus Online to model thermal bridging for windows. The architectural firm’s in-house energy consultant used DesignBuilder to model the concerning elements, such as a solar chimney and double-skin façade, to analyze the impact on lighting and energy consumption. Sometimes Ecotect and Radiance were used for daylighting simulation. These visualization tools helped architects better understand the building science behind their design.

3.2.2 Improved energy modeling approach

20% of the energy modelers had adopted an improved approach where instead of using the native BEM tools to input geometry, they used SketchUp IES plug-in or OpenStudio plug-in. They either redrew the whole building directly in SketchUp or traced the PDF drawings provided by the architects and transferred the model to IES or EnergyPlus for energy analysis. This was to take advantage of SketchUp's 3D visualization. The modelers also simplified the model while building it to have the correct representation in BEM and reduce simulation processing time. Once the building was recreated, they defined boundary conditions to surfaces, assigned zones and space types, and assigned material properties. The energy modeler claimed that this approach had significantly reduced the time spent on energy model creation from several months to a few days for large projects. The only disadvantage with this approach as pointed out by several interviewees was that it took significant time to respond to major architectural changes whenever they occurred.

3.2.3 Existing BIM-based energy analysis workflow

30% of energy modelers had explored the BIM approach to accelerate modeling efficiency. All who had this experience in BIM had adopted a semi-automated approach, meaning they rebuilt a BIM model based on the architectural model and exported that BIM model to third party BEM tools. They did not utilize the architectural Revit model directly because it was not built with the specific intent of energy modeling integration; therefore, to understand how architects created the model and clean up the excessive information takes a lot of time. On the other hand, an energy model can be very simple with envelope definition and interior zoning, so it could be created very quickly (Stumpf, Kim and Jenicek 2011).

This approach is a significant step forward from modeling directly in the BEM programs but requires the rebuilding of this model and rarely were constructions, internal gains, etc. defined in BIM. The Revit model did facilitate the geometry rebuilding in that (1) the underlay of a Revit model or CAD/PDF files was traced in Revit using simple families, or (2) the Revit architectural model was linked to the MEP model and the energy model was built using the MEP model.

A fully automated approach would instead use the BIM model created by architects directly for energy analysis. The major challenge of this approach is that the BIM model needs to be set up very carefully with the intent of energy analysis integration. One firm had begun to explore this approach and were using it for less than 5% of their work. They had started to train their architects on how to setup the Revit model so that it would allow energy modelers to use it without substantial cleanup or rework.

3.3 Strategies to improve modeling efficiency, accuracy, and flexibility

Companies have developed in-house tools/templates and workflows to minimize input time and expand the modeling tools' functionality, and quality assurance protocols to improve accuracy. A summary of all the best practices obtained from the interviews is listed below.

Modeling efficiency improvement:

1. If EnergyPlus is used, reuse previous projects information (e.g. similar mechanical systems) by simply copying and pasting into the new project.
2. Verify the model to ensure it is working properly before performing parametric analysis.
3. Create a parametric tool to examine the sensitivity of assumptions thoroughly and efficiently.
4. Use a targeted lighting power density instead of doing specific takeoff of equipment that was still flexible to eliminate the time spent on estimation and assumptions.
5. Use macros in Excel to spot discrepancies between the different files.

Modeling accuracy improvement:

1. Hold energy modeling reviews with more experienced staff to collect feedback and discuss alternative approaches.
2. Develop internal quality assurance checklists and multiple matrix to verify the model from different perspectives.
3. Use accurate weather file is important to energy simulation, particularly in Public-Private-Partnership projects. Stakeholders will be financially rewarded if actual consumption is lower than modeling prediction and they will be penalized if the actual utility bills are higher than simulation results. Since this verification is done on a yearly basis, the weather file used by the energy model is updated with previous year weather data. The new results will be compared to the previous year's consumption.

BIM-based energy analysis:

1. Use the tool in Revit to add all the spaces automatically and name all the mechanical spaces that match with the room names of the underlay architectural model. This was said

to be the cleanest way to prepare for a BEM model and it was time saving compared to and retyping all the room names.

2. Allocate extra time to make sure the curtain walls are set up and defined correctly or simplify them before exporting.
3. Modify the gbXML file before importing to the BEM programs to ensure smooth transition.
4. Use tools (e.g. spreadsheets) to facilitate data communication both ways between Revit and BEM programs. For instance, one energy modeler used one Excel spreadsheet for data transfer from Revit, a second Excel spreadsheet for calculations (e.g. specified supply airflow), and a third Excel spreadsheet to import the data back to Revit.

Because BIM model creation requires significant quality control effort every step of the way, a couple of studies (Maile, et al. 2015, O'Donnell, et al. 2013) concluded that standards should be in place to verify geometry translation when conducting BIM-based energy analysis especially with complex geometry.

3.4 Preferred energy modeling input format

Most modelers indicated a preference for a combination of the BIM model and spreadsheet because some information could be too buried in the model and it was very easy to be lost in the spreadsheet if looking at them separately. The best format for geometric information was the Revit model with correctly defined families, while construction information could be provided through Revit construction definition or spreadsheet and the internal gains and HVAC specifications were preferred in spreadsheet format. Several specific strategies were identified to obtain and track information required for the energy model:

1. Make a list of information they required to easily navigate through the massive information obtained from the designers (2 interviewees).
2. In-person communication with designer to acquire a better understanding of the design than by reading everything from drawings (2 interviewees).
3. Compile a document with updated questions that was sent to designers on a weekly basis (1 interviewees).

4. Review documentation regarding major changes to the architectural model and determine whether this should result in energy model modification (1 interviewees).

3.5 Opinions on BIM-based energy analysis

Some of the interviewees were not convinced that the BIM approach would save time and maintain the same level of accuracy. They also expressed concerns towards extremely simplified BIM-based energy analysis, which were related to the gbXML export and GBS simulation results.

One interviewee gave an example to demonstrate that BIM analysis was not necessarily time-saving once errors occurred:

"One example is unclosed roof or wall – once imported into the energy modeling tool, there's an opening in the geometry and the heating load will go through the roof because of high infiltration. Finding out what is wrong and where usually takes longer."

One interviewee had tried Revit to BEM conversion either with direct Revit gbXML export or IES plug-in, but did not have much success. He/she also mentioned the difficulty of trying new approaches at a consulting company: because fees are really tight, they do not have time to do experiment. If they tried it once and it did not work, they would go back to the old approach. The following quotes the interviewee's statement:

"[I] Do not really trust [BIM-based energy modeling tools] right now and this ties back to the gbXML issues, which are caused mainly by the architectural model that is not developed properly. I also noticed that at least for Revit, the libraries for wall types and systems are somehow lacking, so you end up doing a lot of work. More than anything else, it is mainly the lacking of familiarity."

Two interviewees that had successful experience with exporting geometry from BIM to BEM pointed out the similar reason why they did not trust BIM-based energy analysis results: the available design options were too conceptual and high level. The following was quoted from one of them:

“[I] Do not trust [BIM-based energy analysis]. I have tried some of the plug-ins. The amount of time we spend inputting details into our models is to lead to the accuracy we need. So now you take a plug-in where it only asks you 3-4 quick questions about your HVAC systems, you will never get the accuracy you need. People are trying to push to do things faster and get results quicker, so these simplified program where from drop-down menus, you say it is a fan coil system, curtain wall, lighting is LED and that is your energy model. There are so many variables. If you dumb down all these details, the results would not be close."

The only interviewee that had experience in GBS considered it to possess great potential but its gbXML export was inadequate:

“The number one benefit of GBS is the integration with Revit. […] Currently the functionality is very good for early stage, such as the dropdown menu for HVAC system types and envelope characteristics. It is more of an early stage tool and it is seamless. I think it will be a great tool once they […] do a little bit more work on geometry creation. For example, the gbXML from GBS is a little messy: it is a little bit excessive and triangular for no apparent reason. The large percentage of my time for models is spent on recreating the geometry, so if Revit GBS can some sort of eliminate that, that is huge potential.”

3.6 Barriers to BIM-based energy analysis

Several interviewees mentioned that BEM tools were not intelligent and adaptable enough to recognize complex BIM models, particularly curved surfaces and curtain walls. Software interoperability is also an issue as interviewees mentioned that the constructions and materials defined in Revit could not be exported to IES.

Another barrier is regarding the fully automated BIM-based energy modeling approach. It is rarely used due to the extra time and effort required to transform the architectural model into a suitable model than modeling directly in BEM software. According to several interviewees, the architectural model was often not ready to be effortlessly transitioned to a BEM model. They claimed that compared to the SketchUp plug-in approach, the BIM-based approach was not extremely time saving. BIM modelers were more inclined to model and analyze directly in BEM tools or use the non-BIM workflow because of familiarity and previous investment. The followings are a few issues associated with the architectural BIM model:

- Improperly modeled with unbound or undefined spaces.
- Inadequate data in BIM model: no construction or materials properly assigned.
- The use of (Revit) families does not reflect actual constructions: e.g. sometimes architects used a floor family for a roof or did not define door as internal or external. They look similar but the correct family and boundary definition interferes with energy model creation.

These issues could be addressed with a well-planned BEP and training so the architects could take account of the needs for the BIM model while they develop it.

Finally, one of the key non-technical issues is that early and repeated energy analysis during design is not usually required by the owner (whose requirements are typically prioritized in a project), especially when there are conflicting needs. However, when energy is a key performance indicator, the energy modelers and their suggestions would have significant influence in the design process. Therefore, the owners need to be better educated about energy modeling's benefits, and the interviewees revealed the best way to convince them is through operational cost or payback period.

3.7 The development of research objectives and methodology

A number of challenges were identified through literature review and interviews regarding BIM-based energy simulation and the feasibility for this research is also discussed considering the time frame and resources availability:

1. BIM-to-BEM adoption was perceived as requiring more effort because the architectural models were not intended for energy simulation.
2. BIM-based energy simulation was perceived less reliable because of the limited system options and the lack of flexibility in system definition.
3. Software interoperability was one of the major obstacles mentioned in many literature and most interviewees, but this is more likely to be solved by software venders, which is out of the scope of this research.
4. There was a lack of proper standards and procedures to guide design teams to incorporate energy simulation in the BIM process. This requires a sophisticated understanding of BIM projects and energy simulation processes ideally from working experience.

5. There was a lack of systematic academic research on data transfer integrity evaluation and simulation performance validation to sufficiently meet industry needs.

The fifth challenge was selected to frame the research objectives and research questions because the verification of BIM-to-BEM data transfer will provide insight on good practices to prepare architectural models for smooth transition to energy simulation. This part of the investigation is the stepping stone for BIM-based energy analysis process development. The validation of simulated results by comparing with native modeling results will suggest how the BIM approach is different from traditional approach, which can potentially improve modelers' confidence in using BIM simulation. Case studies were considered the best methodology for the investigation because models can be manipulated based on research purposes and a wide range of tested can be conducted as described in the next chapter.

4 CASE STUDY METHODOLOGY

A number of challenges have been identified in the previous chapters that prevent the wide adoption of BIM-based energy analysis. Of these, the lack of systematic research on BIM-BEM data transfer integrity and simulation results compared with native format BEMs has limited modelers' confidence in the use of BIM tools for energy modeling and forms a significant barrier to adoption. To address this issue, the following four steps were taken:

1. Two complete models (a small office building and a single-family house) were created in BIM and run in GBS to generate BEM input files
2. The input files generated for BEM were verified with the BIM input for data transfer integrity
3. BIM-based energy modeling results were compared with conventional modeling results
4. Simulation results variation resulted from geometric errors, constructions, different climate files, and HVAC systems were tested to determine causes of analysis inaccuracy

The BIM models were created using Autodesk Revit 2016 and represented early-stage schematic models suitable for massing option testing. Each model consisted of external walls, windows and doors, floor slabs, ceilings, partition walls and roofs as room bounding elements. Located in Toronto (ASHRAE Climate Zone 6A), the models were constructed with high performance envelopes and systems that meet or exceed the ANSI/ASHRAE 90.1-2010/90.2-2007 baseline.

There are an increasing number of BIM-based energy analysis tools could have been considered, e.g. Revit IES plug-in, Revit DesignBuilder plug-in, or SketchUp OpenStudio (EnergyPlus) plug-in, but due to time limitations, only GBS was investigated for the following three reasons:

1. GBS eliminates the challenge of software interoperability issues:
    - It is integrated within Autodesk Revit, which is the most widely-used BIM software across all disciplines;
    - It generates three BEM input files and thus offers the most flexibility in testing data transfer across platforms: (1) gbXML, which is used by an increasing number of BEM tools, (2) INP for eQuest, and (3) IDF for EnergyPlus.

2. GBS uses the DOE-2 engine, which is also used by eQuest, a very widely used building energy modeling software in practice.
3. GBS' online platform has expanded functionalities, such as a wide variety of HVAC systems, hundreds of parametric analysis options, and carbon emission and renewable energy potential calculation. This resolves the energy modelers' concerns regarding the over simplicity of BIM-based energy analysis.

4.1 Case study 1: Office building

The south-facing two-storey office building has a floor area of 1,022 m^2. The building has a uniform geometry (Figure 7). It was constructed with concrete masonry units (CMUs) and 52 high performance double pane windows.

4.1.1 Model construction

To create an energy-simulation-ready-model, correct Revit families were used and all building components were interconnected to make sure there were no gaps or overlaps. Revit provides a number of default constructions for each building component, but it also allows users to define their own assemblies with desired materials, thermal properties and thicknesses. These construction details and material information of this model were defined in Revit as summarized in Table 7.

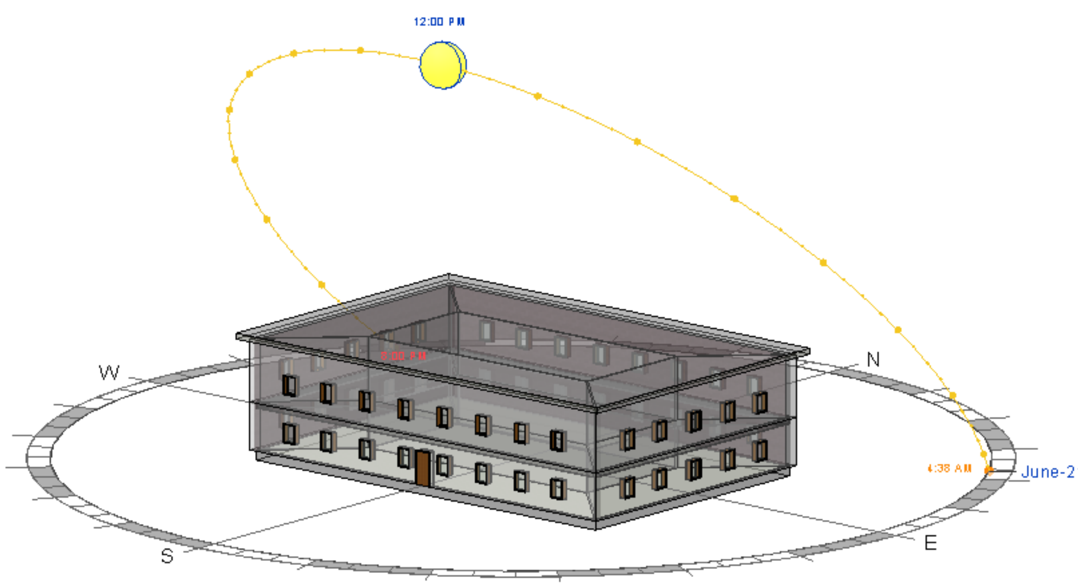

Figure 7. Small office building Revit model

Table 7. High performance office building construction and thermal resistance values

	ASHRAE 90.1-2010 Requirements		
	Assembly Max U	Insulation Min R	User defined construction in Revit
Roof	U0.27	RSI-3.52 c.i.*	RSI-4.51 Precast concrete roof
Ext. wall	U0.45	RSI-2.34 c.i.*	RSI-4.76 CMU exterior wall
Int. wall	-	-	RSI-3.7 123mm partition (1hr)
Floor	-	-	RSI-3.35 Wood frame floor
Slab	F4.88**	RSI-2.64	RSI-4.76 Cast-in-place concrete slab
Door	U3.97	-	U1.93 Wood frame, triple glass with glass storm door
Window	U1.99	-	U1.99 Double glazing, low-e coating, clear glass window

Units: U: W/m^2•K; R: m^2•K /W
*c.i.: continuous insulation
**F factor: the perimeter heat loss factor for slab-on-grade floors, expressed in Btu/h·ft^2·°F (ASHRAE 2010)

4.1.2 Energy model preparation

To simply energy modeling process for architects, GBS can automatically assign zones if they are not defined in Revit. However, it is recommended to define spaces and zones before simulation in GBS to meet design requirements. As a typical office building, this model was zoned core/perimeter to accommodate the different weather conditions due to sun movement and wind on four sides of the building. In total, there were two core zones and eight perimeter zones.

When defining the spaces, if export category “Rooms” is selected, Revit default assumptions of the spaces are used based on the building type, so they do not differentiate based on space properties. However, when export category “Spaces” is selected, it allows modelers to specify and export user-defined loads and schedules for each space. To test both export categories, the office model was exported by “Rooms” and the house model was by “Spaces”. The parameters for office energy analysis were set in the “*Energy Settings*” dialogue (Table 8).

Table 8. Revit "Energy Settings" for the office building

Parameter	Value	Notes
Common		
Building Type	Office	Number of occupants: 4 people/100m^2 People heat gain: 131.88 W/person Lighting density: 9.68 W/m^2 Equipment power density: 14.42 W/m^2 Infiltration flow: 0.4 ACH OA flow per area: 2.5 m^3/h/m^2 Office occupancy schedule Assumptions comply with ASHRAE 90.1
Location	Pearson Airport	
Ground Plane	Level 1	
Detailed Model		
Export Category	Rooms	
Export Complexity	Simple	No shading surfaces or mullions exported
Include Thermal Properties	Yes	
Project Phase	New construction	
Sliver Space Tolerance	304.8 (Default*, mm)	Definition: "narrow areas bounded by parallel interior room-bounding components" (Autodesk Knowledge Network 2015)
Building Envelope	Use function parameter	
Energy Model		
Analysis Model	Use building elements	
Analytical Space Resolution	457.2 (Default*, mm)	Defines the minimum gap between elements that will be ignored in creating the analytical model spaces; the maximum is two times of the setting
Analytical Surface Resolution	304.8 (Default*, mm)	Resolution smaller than this value will not be considered as a surface
Energy Model – Building Services		
Building Operating Schedule	12/5 Facility	
HVAC System	Central VAV, Hot Water Heat, Chiller 5.96 COP, Boilers 84.5 efficiency	VAV: variable air volume COP: coefficient of performance
Outdoor Air Information	Outdoor air per person 8L/s	

*Default values were recommended for a balance of simulation accuracy and processing time (Autodesk Revit 2016).

4.2 Case study 2: Single-family house

A one-storey two-bedroom bungalow has a footprint of 96 m^2. It was constructed with super insulated EIFS (exterior insulation and finishing system) exterior walls, wood-joist slab, and wood rafter roof. There were 13 double glazed windows and a door on the south façade (Figure 8). It had six zones: the living room, kitchen, bedrooms, bathroom, circulation area, and the attic.

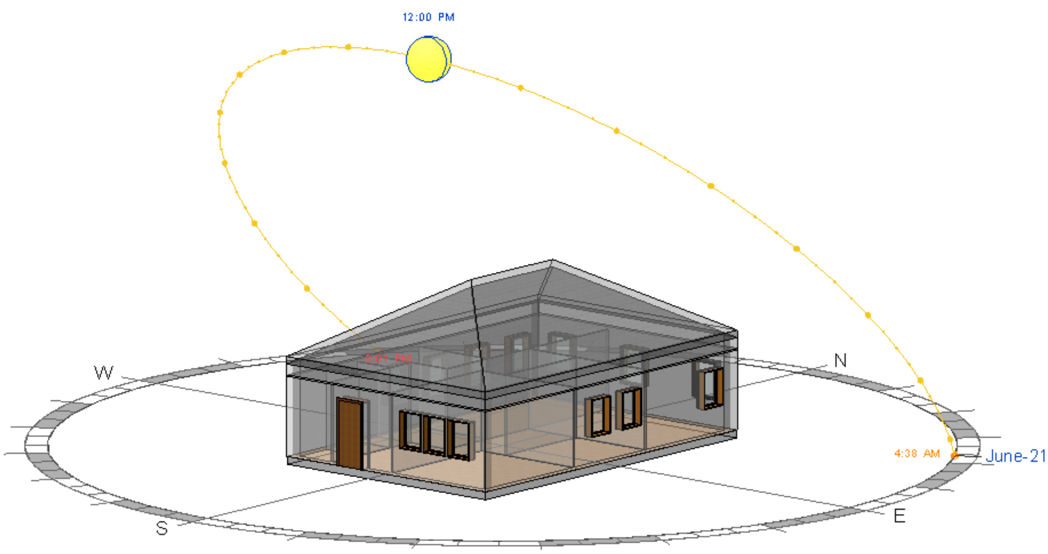

Figure 8. Single-family house Revit model

4.2.1 Model construction

The envelope construction and corresponding thermal resistance values well exceeded ASHRAE 90.2-2007 as presented in Table 9. Slightly different from the office model, the house model was set to export by "Spaces" and the energy settings were defined as shown in Table 10.

Table 9. Single-family house construction and thermal resistance values

	ASHRAE 90.2-2007 Requirements		
	Assembly Max U	Insulation Min R	User defined construction in Revit
Roof	U0.12	RSI-8.63	RSI-9.85 Wood rafter/Asphalt shingles roof
Ext. wall	U0.46	RSI-3.7, RSI-1.76 c.i.	RSI-11.43 EFIS on metal studs
Int. wall		-	RSI-1.74 79mm partition (1-hr)
Slab	U0.22	RSI-6.69, RSI-4.4 c.i.	RSI-9.05 Wood joist/Wood finish floor
Door	U2.21	-	U1.65 Solid core wood storm door
Window	U1.99	-	U1.99 Double glazing, low-E coating, clear glass window

Units: U: W/m^2•K; R: m^2•K/W (ASHRAE 2007)

4.2.2 Energy model preparation

When creating spaces and zones on the Revit model, the upper and lower boundaries bound to level surfaces, so creating a space and associated zone to model the attic under the pitched roof on the house model was challenging. To resolve this, a new level datum was created, as described in Appendix B. Because the generated analytical model had imperfections, particularly in the roof as illustrated in Figure 9, the space resolution was adjusted from 457.2 mm (the default value) to 155 mm (close to minimal resolution value) and the surface resolution was modified from 304.8 mm (the default value) to 100 mm. In contrast with the office model, the house model was set to export by "Spaces" to investigate whether this impacted the data export and simulation results. The remaining energy settings are presented in Table 10.

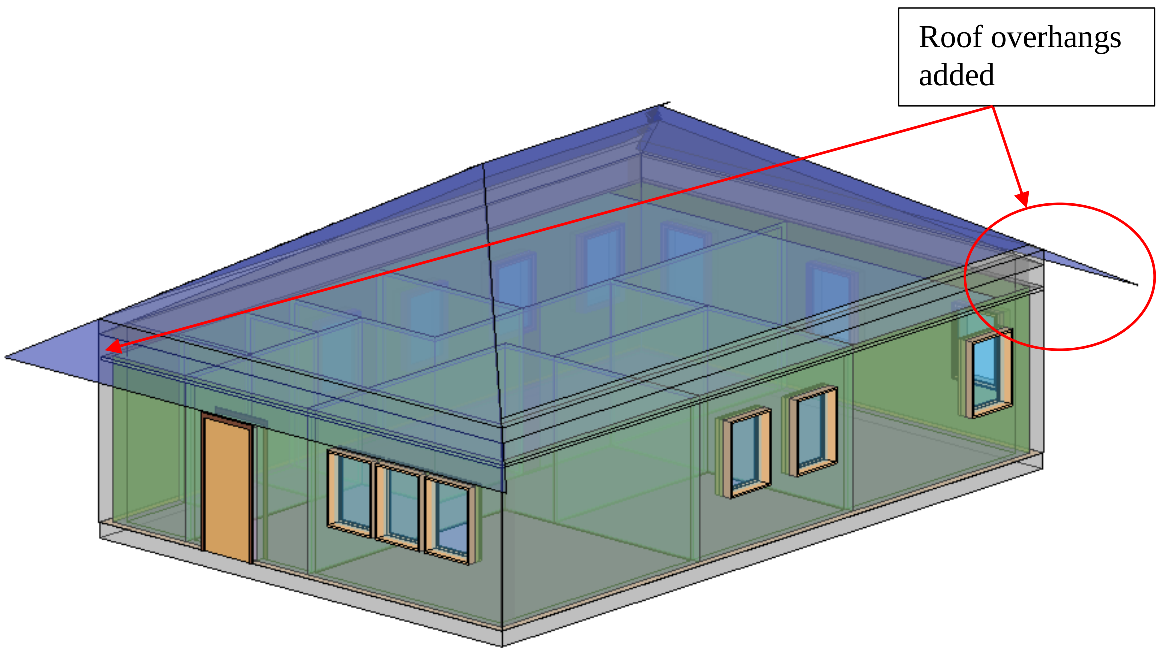

Figure 9. Automatically-generated analytic energy model with added overhangs

Table 10. Revit "Energy Settings" for the single family house

Parameter	Value	Notes
Common		
Building Type	Single family	Revit Space assumptions: Number of occupants: 0.95people/100m^2 People heat gain: 132 W/person Lighting density: 10.867 W/m^2 Equipment power density: 10.867 W/m^2 Infiltration flow: 0.5 ACH Residential occupancy schedule
Location	Pearson Airport	
Ground Plane	Level 1	
Detailed Model		
Export Category	Spaces	
Export Complexity	Simple	
Project Phase	New construction	
Sliver Space Tolerance	100 (mm)	
Building Envelope	Use function parameter	
Building Service	Split system with mech. ventilation	Overridden by *Energy Model – Building Services*
Building Construction	<Building>	Uncheck the "Override" boxes of "Analytic Constructions" to analyze with the constructions assigned in Revit
Building Infiltration Class	None	
Export Default Values	Yes	
Report Type	Standard	
Energy Model		
Analysis Model	Use building elements	
Analytical Space Resolution	155 (mm)	
Analytical Surface Resolution	100 (mm)	
Energy Model – Building Services		
Building Operating Schedule	Default	
HVAC System	Residential 17 SEER/9.6 HSPF Split Heat Pump < 5.5 ton	SEER: seasonal energy efficiency ratio HSPF: heating seasonal performance factor
Outdoor Air Information	Outdoor air per person 8L/s	

5 DATA TRANSFER INTEGRITY EVALUATION

If an energy model could be seamlessly generated from a BIM model with as much information as BIM could provide, the efficiency of repeated energy modeling would be substantially improved. As identified by interviewees, uncertainty regarding data transfer integrity is one of the major concerns preventing the adoption of BIM-based energy analysis. This section presents an evaluation completed by comparing the elements and the details of BIM-generated BEM input files with BIM model element definitions.

5.1 Testing methodology

Three BEM input files were generated using GBS for each of the case study models: the gbXML open format, and the native files for eQuest 3-65 (INP) and EnergyPlus 8.3.0 (IDF). These files, along with a second gbXML file exported directly from Revit (which only includes climatic, geometric and construction information, and thus is only compared in these three categories), were compared with the input in the Revit architectural model. Discrepancies were identified by comparing both gbXML files, INP and IDF against BIM inputs. To obtain all the files for evaluation, the following procedure was taken as illustrated in Figure 10:

1. Create the model in Revit 2016, set up “Energy Settings”, and simulate the model
2. Export gbXML from Revit; Open GBS online platform and go to “Download” tab to download all three types of files
3. Compare these files with Revit input

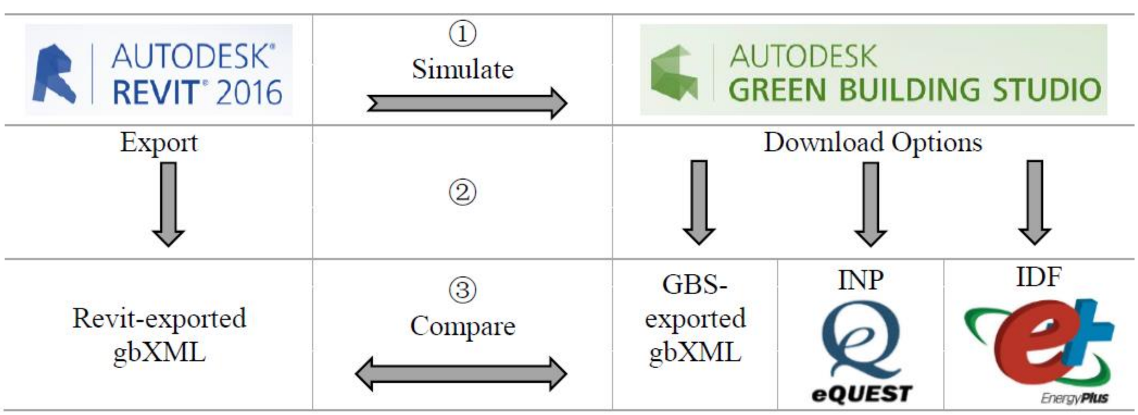

Figure 10. Illustration of data transfer integrity evaluation methodology

The line-by-line file comparison considered climatic data, geometric data (including surfaces and openings), construction layers and material thermal properties, mechanical systems, internal loads, and schedules. The evaluation was completed for both case studies and the comparative results of both buildings are presented in the following sections.

5.2 Climatic data

Selecting the correct location and climate file is very important for energy simulation since heating and cooling loads are determined largely by the design conditions. Therefore, data transfer integrity started with climate data verification. The two modeled buildings were located near Toronto Pearson International Airport. The geographic and climatic data transfer from BIM to BEM is summarized in Table 11. Note that Revit-exported gbXML does not contain climatic data and is excluded from this table.

Table 11. Geographical and climatic data discrepancies between BIM and translated BEM files

		Input	GBS Output				ASHRAE 90.1-2010
		Revit 2016	gbXML	INP	IDF1	IDF2	
Location	Location	Mississauga, Canada	Mississauga	-	Niagara Falls, US	Toronto Pearson	Toronto Downsview
	Latitude	43.688N	43.688N	43.688N	43.10N	43.67N	43.75N
	Longitude	79.622W	79.622W	79.622W	78.95W	79.63W	79.48W
Climate	Cooling DB*	30ºC	28.7ºC	28.7ºC	31.0ºC	29.4 (1%)	28.9ºC (1%)
	Cooling WB*	21ºC	20.9ºC	20.9ºC	22.7ºC	21.2 (1%)	21.1ºC (1%):
	Wind speed				5.7 m/s	5.8 m/s	
	Heating DB*	-20ºC	-19.9ºC	-19.9ºC	-16.4ºC	-18.8ºC (99.6%)	-20ºC (99.6%)
	Wind speed				4.7 m/s	4.3 m/s	

*DB: dry-bulb, WB: wet-bulb

The location comparison showed that exported INP files use opposite longitude coordination from gbXML (west is positive whereas in gbXML, it is negative), but after checking the INP file in eQuest, it was confirmed that its location was the same as gbXML.

The GBS-exported IDF file showed different design conditions because it could not detect non-USA locations; thus the closest USA location (Niagara Falls, NY) was assigned as seen in column “IDF1” (run in January 2016). This was flagged to Autodesk Building Performance

Analysis team and a recent test (in June 2016) found that this issue had been resolved as shown in the column "IDF2". Seven other Canadian locations were also tested and confirmed that these locations could be identified by the IDF file as well.

Although the locations (latitude and longitude) were consistent across the four platforms, the design conditions were slightly different between GBS and IDF. The GBS weather data is based on a period of a 30 year record (Autodesk Knowledge Network 2014), while EnergyPlus uses Canadian Weather for Energy Calculations (CWEC), which are based on hourly weather data from 1953-1995 period of record in Canada (EnergyPlus n.d.). The design conditions in GBS-exported gbXML, INP, and IDF files were very close to the Revit weather data and ASHRAE 90.1 design conditions.

5.3 Geometric data

As discussed in literature review and interviews, there is no effective method to verify geometric data other than visual inspection in BEM tools. In order to review thoroughly, this study conducts 3D model visual inspection as well as line-by-line file inspection.

5.3.1 3D model visual inspection

The 3D representations of the Revit analytical models, the eQuest models, and the EnergyPlus models are compared in Figure 11. It was found that the eQuest and EnergyPlus models' envelope components (roofs, exterior walls, slabs, windows, and doors), interior partitions, and floors/ ceilings were in their correct locations. The issues mentioned by (Moon, et al. 2011) that windows were misplaced in EnergyPlus visualization tool have thus apparently been resolved. However, the exterior walls were much more complicated than the Revit energy model and both EnergyPlus models appeared to have surfaces missing.

To identify the cause of the missing surfaces in the EnergyPlus model, the house model polygons were redrawn in AutoCAD using the IDF node coordinates. The south façade appeared to have two missing surfaces: one near the door and the other near the window (Figure 12a white spaces). The façade redrawn from IDF coordinates indicates a complete façade with no overlap surfaces found (Figure 12b), thus indicating that this was a display error and that the exported IDF file had the correct geometry for energy simulation.

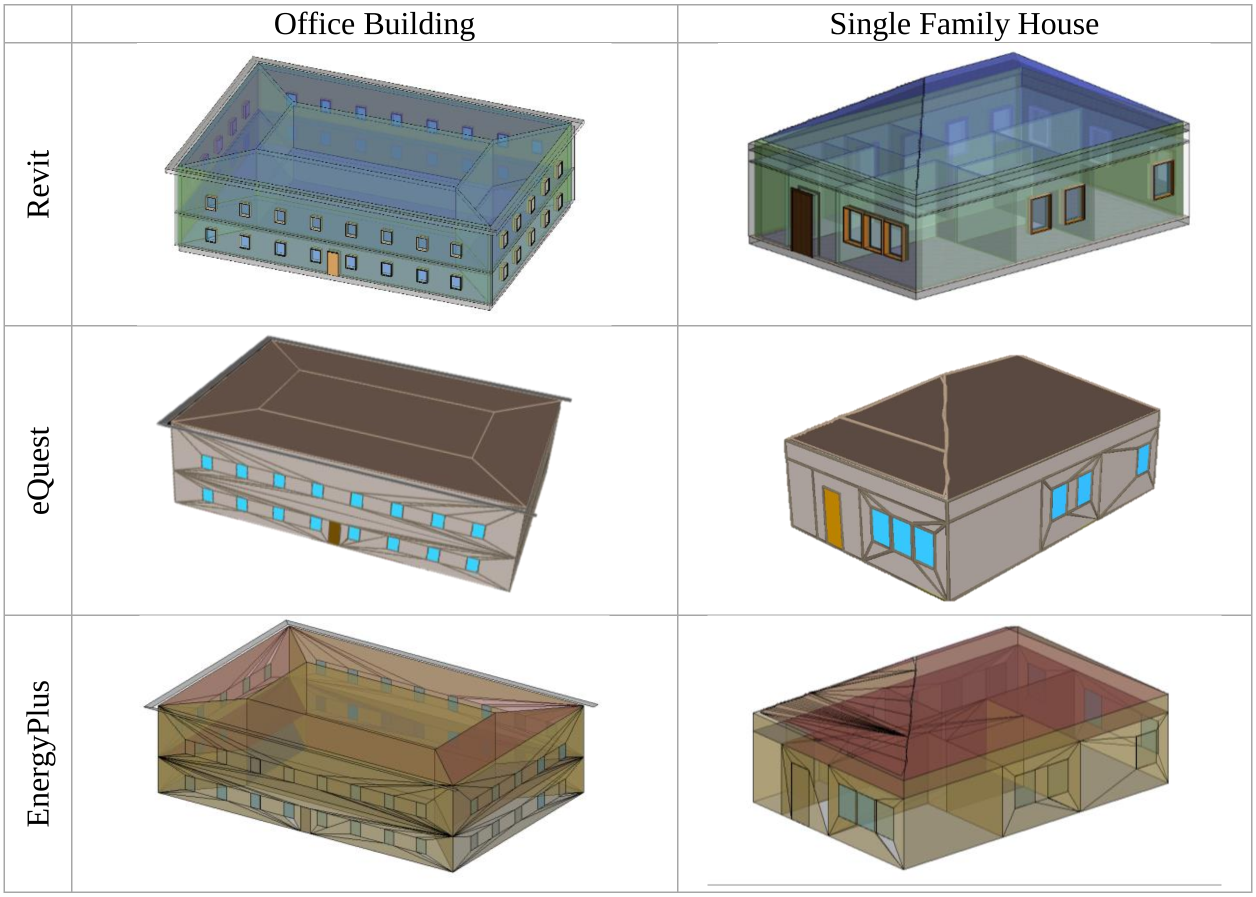

Figure 11. Office and house energy models as displayed in Revit, eQuest, and EnergyPlus

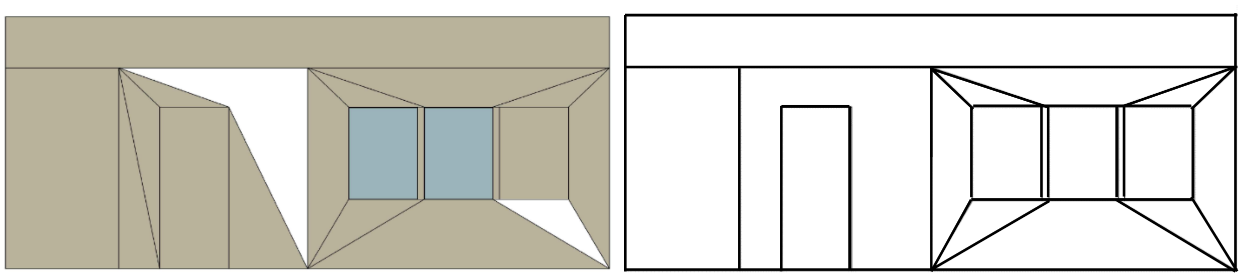

Figure 12. (a) South facade obtained through GBS plug-in (left), (b) South facade drawn from IDF coordinates (right)

The surface components are much simpler in gbXML file exported directly from Revit. To investigate whether the rendering issue would still exist with a simpler gbXML instead of using the GBS plug-in, the file was exported from Revit and uploaded to GBS online platform for simulation. The IDF file was then downloaded and imported in EnergyPlus. Figure 13 is the 3D model obtained, which shows that the surfaces are much simpler and the envelope is intact These results suggested that the EnergyPlus visualization tool is not able to properly display complex surfaces.

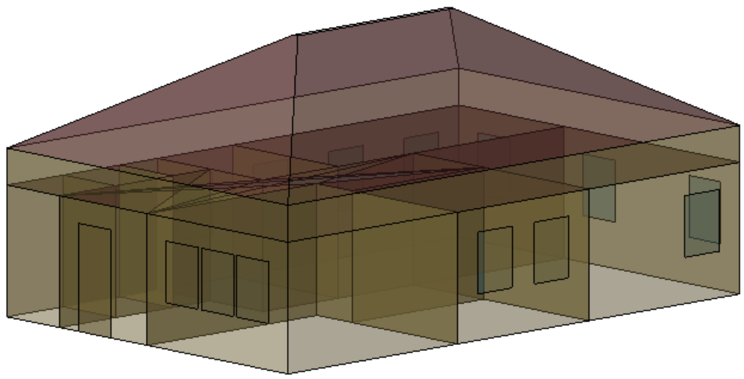

Figure 13. EnergyPlus model created by using the gbXML file exported directly from Revit

5.3.2 BIM and BEM file inspection

In addition to visual inspection, the gbXML, INP, and IDF files were examined to count the number of surfaces and calculate the floor areas. The floor area in each file was the same and the number of slab surfaces, doors and windows were well maintained. The surface counts of the office building and the house are presented in Table 12 and 13, respectively. The discrepancies found between BIM input and GBS output files are discussed below.

Table 12. Number of surfaces of BIM and translated BEM files (office)

	Input	Revit Export	GBS Export		
	Revit 2016	gbXML	gbXML	INP	IDF
Exterior Wall	8	8	173	173	173
Interior Wall	16	16	16	16	32
Roof	5	5	5	5	5
Slab	5	5	5	5	5
Ceiling	4	*not explicitly modeled*	*not explicitly modeled*	*not explicitly modeled*	5
Floor	5	5	5	5	5
CMU Addition	N/A	N/A	53	53	53
Door	1	1	1	1	1
Windows	52	52	52	52	52
Total	96	96	310	310	331

Table 13. Number of surfaces of BIM and translated BEM files (house)

	Input	Revit Export	GBS Export		
	Revit 2016	gbXML	gbXML	INP	IDF
Exterior Wall	17	17	56	56	56
Interior Wall	17	17	17	11	34
Roof	5	4	5	5	5
Slab	9	9	9	9	9
Ceiling	9	9	1	1	9
Floor	9	-	8	8	9
Wood Frame Addition	N/A	N/A	14	14	14
Door	1	1	1	1	1
Windows	13	13	13	13	13
Total	60	70	115	109	150

5.3.2.1. GBS-introduced discrepancies

Two discrepancies resulted from GBS processing are added surfaces around all openings (including windows and doors) and subdivided exterior wall surfaces. First, GBS adds extra surfaces (the “CMU Addition” and “Wood Frame Addition” as shown in Table 12 and 13) that make the openings 5mm smaller all four sides. While the gbXML exported directly from Revit organizes the openings as child elements of the exterior wall, the GBS-exported gbXML lists the openings as child elements of these new structures (relevant gbXML file context is included as Appendix C).

Second, the gbXML, INP, and IDF define a larger number of exterior wall surfaces because GBS subdivides the surfaces, which are then exported in the INP and IDF files. As illustrated in Figure 11, wherever there is an opening, the surface around the openings consists of several polygons in the eQuest and EnergyPlus models as opposed to a complete surface in the Revit energy model. Despite these subdivisions, the total area does not change.

The cause of these two issues remained unknown after reviewing the previous literature and software manuals, the interviews, and the communication with Autodesk GBS developers. The excessive triangular exterior wall surfaces were also noted by one of the interviewees but he/she had no answer as to why this happened or how this could be resolved. However, since there are no gaps or overlaps between surfaces, this should not impact energy simulation accuracy, only computation time.

5.3.2.2. eQuest missing interior walls

The INP file has 20 surfaces identified as "Interior-Wall", but only 11 surfaces' construction is "Basic Wall: Interior – 79mm Partition (1-hr)". As demonstrated in Table 14, nine surfaces are tilt 180 degrees and eight of them are carpeted floor and one is ceiling construction. The rest 11 interior wall surfaces in the INP file can be found in the gbXML file (**bold text**) as well.

To investigate the possibility that gbXML might have excessive surfaces (as the exterior wall does), the interior walls were recreated in AutoCAD with gbXML "Surface" coordinates. The recreation process found no overlap surfaces and the layout and dimension of interior wall surfaces (Figure 14a) were identical with the Revit model as seen in the floor plan (Figure 14b). However, six interior wall surfaces were missing because they were not separating different thermal zones (highlighted in red thicker lines). Therefore, these missing surfaces would have a negligible impact on energy simulation results. As previously discussed in literature review, US GSA recommended deleting all surfaces not necessary in energy simulation, including interior walls that are within one thermal zone to simplify the model and lower the chances of geometric errors.

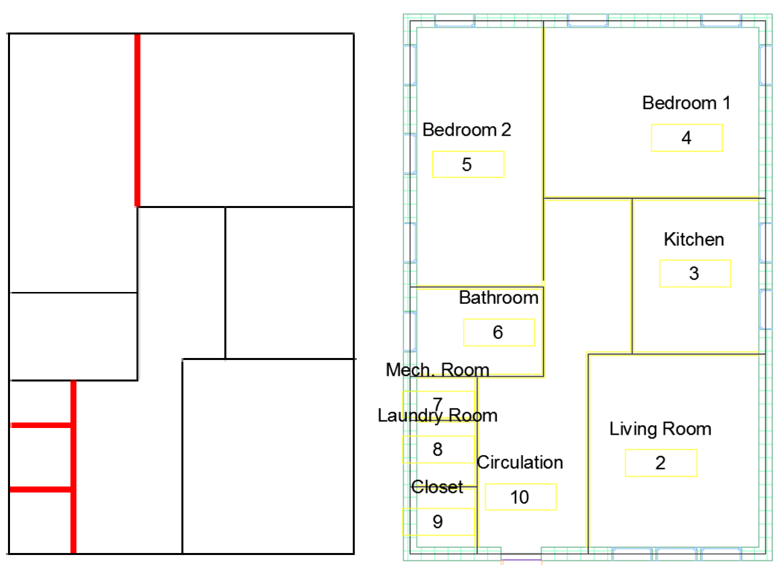

Figure 14. (a) Interior wall surfaces drawn with gbXML coordinates (left) compared with (b) Revit floor plan (right)

Table 14. Surfaces INP identified as "Interior-Wall"

Construction	Location	Next to	Space type	Tilt	Azimuth	Surface
Construction-23 R0 wood frame carpeted floor	Bottom	Space_1	Roof	180	90	aim3603 aim3519 aim3557 aim3683
					180	aim3721 aim3759 aim3645 aim3481
Construction-33 interior drop ceiling tile	Bottom	Space_1	Roof	180	180	aim3797
aim0126 basic wall: interior – 79mm partition	-	Space_2	Living Room	90	180	**aim4500** **aim4538**
	-	Space_7	Circulation	90	90	**aim4842** **aim4880**
					180	**aim4956** **aim4994** **aim4424**
					270	**aim4576** **aim5032**
	-	Space_3	Kitchen	90	180	**aim4462**
aim0155 basic wall: interior – 79mm partition	-	Space_6	Bathroom	90	180	**aim4804**

5.3.2.3. Revit-exported gbXML missing one roof surface

It was found that the gbXML exported directly from Revit has four roof surfaces, while other files have five. The missing surface (Figure 15a) was identified through redrawing the roof in AutoCAD based on the coordinates in Revit-exported gbXML, which was the peak of the pitched roof (highlighted in red): the rectangle piece (0.13mm x 4.13m) sized 0.5m^2. Because it was a very narrow strip, depending on the energy simulation tools and their surface resolution settings, this gap will most likely be ignored in energy simulation.

To verify that the five roof surfaces in the GBS-exported gbXML were interconnected without gaps or overlaps, the roof was drawn in AutoCAD with coordinates from GBS-exported gbXML. However, instead of five pieces of roof surfaces that were fully enclosed, it only had three complete surfaces and the south facing roof was made of triangular pieces that were grouped into two "Roof" surfaces. EnergyPlus has the same representation of the roof (Figure 15b).

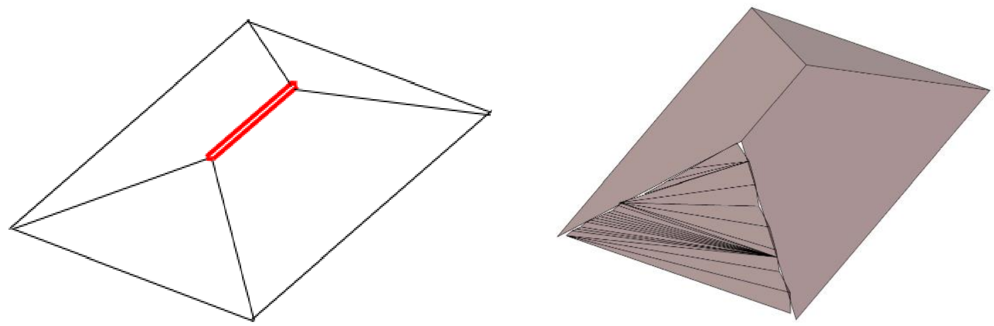

Figure 15. (a) Roof drawn from Revit-exported gbXML coordinates(left); (b) GBS-exported gbXML & EnergyPlus roof (right)

5.3.3 Model simplicity and discussion

In summary, GBS-exported files added extra surfaces around openings and have more exterior wall surfaces than BIM models in both cases. The IDF files double interior wall surfaces and have a matching surface number for ceilings and floors because EnergyPlus runs a surface-matching process to obtain the correct convection coefficients of each surface (NREL 2016); ceiling surfaces are not exact matching in other files. Since the total area of the façade and the floor is consistent with the BIM model, the complex surface composition due to GBS processing is expected to have minimal impact on energy simulation. Overall, the house model has presented more discrepancies than the office model because of the pitched roof (not a horizontal or 90-degree vertical surface) and the zone definition (multiple spaces were grouped in one zone), but as discussed, these discrepancies are expected to have negligible impact on energy simulation as well.

The case study models had a very simple geometry with regular walls, floors, roof, etc., and mostly rectangular surfaces either vertical or horizontal. The issues occurred in geometry export from the US GSA report (Figure 5) did not appear in the case study models and the excessive surfaces created by GBS plug-in did not cause simulation problems. However, in complex models where there are shadings, irregular surfaces, curtain walls, multiple roofs at different levels, or exterior walls with different above grade and below grade thicknesses, etc., the complexity is expected to cause exporting errors. This is the reason that US GSA had suggested simplifying the BIM model to improve geometric data transfer accuracy after they tested diverse geometry exports.

By comparing the geometric representations in the two exported gbXML files, it was found that the Revit-exported file was much cleaner than the GBS plug-in. The simpler geometry is also beneficial for model verification and validation. Therefore, when a complex building is created in Revit, it is suggested that the gbXML (geometry and materials only) be exported directly from Revit instead of using GBS export. The loads, schedules, and systems can then be assigned by uploading the gbXML to GBS online and entering them on that platform, exporting from GBS online to a 3rd party BEM software, or – as this becomes more widely available – importing the resultant gbXML into a 3rd party BEM software.

5.4 Construction and material data

Four aspects of data transfer integrity for construction and material information was examined: (1) whether all the layers were transferred, (2) whether layers were in the correct order either from interior to exterior layer, (3) whether thermal property values were transferred accurately, and (4) whether the assembly heat transfer coefficient values were consistent across different platforms.

5.4.1 Construction

All construction layers were exported except for the membranes (weather barriers), which had zero thickness in Revit. These were omitted in gbXML because materials with no thickness have negligible thermal resistance values.

Three main discrepancies in construction were noted: exterior wall layer order, door properties, and the added parent structures for openings. The remaining envelope elements, i.e. the roof and slab were constructed with correct layers; no construction layer was specified for windows – only a construction description was available.

5.4.1.1. Exterior wall construction layers

The exterior wall construction layers, when input in Revit, started from the exterior layer, and gbXML, eQuest, and EnergyPlus had the same layer definition. However, all exported files, no matter whether exported directly from Revit or through GBS, assigned the layers in the reverse order.

Table 15. Exterior wall construction discrepancies between BIM and translated BEM files

	Input	Revit Export	GBS Export		
	Revit 2016	gbXML	gbXML	INP	IDF
From outermost layer to innermost layer					
Office	Brick veneer	Gypsum board			
	Air cavity	CMU			
	Rigid insulation	Rigid insulation			
	Air barrier	Air cavity			
	Vapour retarder	Brick veneer			
	CMU				
	Gypsum board				
House	EIFS	Gypsum board			
	Air cavity	Metal stud layer			
	Air barrier	Plywood sheathing			
	Plywood sheathing	Air cavity			
	Metal stud layer	EIFS			
	Vapour retarder				
	Gypsum board				

To investigate the impact of this inverted construction on simulation results, the construction layers were fixed in eQuest and the model was re-simulated.

Table 16. eQuest result comparison between imported and corrected construction layers (office)

	Imported construction	Corrected construction	% difference (kWh)
Annual energy use			
Electricity	128,970.00	128,890.00	-0.1% (-80.00)
Fuel	72,192.20	71,922.57	-0.4% (-269.63)
Energy use: Fuel			
Hot water	7,842.58	7,842.58	-0.0% (-0.00)
Space heating	64,349.61	64,079.99	-0.4% (-269.62)
Energy use: Electricity			
Space heating	2,560.00	2,550.00	-0.4% (-10.00)
Heat rejection	280.00	280.00	0.0% (0.00)
Pumps & Aux	7,340.00	7,350.00	-0.1% (10.00)
Fans	7,480.00	7,440.00	-0.5% (-40.00)
Space cooling	16,130.00	16,090.00	-0.2% (-40.00)
Exterior loads	3,370.00	3,370.00	0.0% (0.00)
Misc. Equipment	56,030.00	56,030.00	0.0% (0.00)
Lights	35,790.00	35,790.00	0.0% (0.00)

The results above showed that the energy consumption breakdown had a deviation within 0.5%. The "Space Heating" had the largest value difference, which was 269.62 kWh/year. The total of the remaining categories was within 100 kWh annually. Therefore, the inverted construction did have a slight impact on energy results.

5.4.1.2. Door construction

The door construction and thermal properties were both overridden by the GBS plug-in with a "R5 Door". Since Revit-exported gbXML was able to display the user defined door construction and thermal properties correctly (Table 17), the GBS plug-in was the cause of this issue and these construction and analytical properties were also assigned in the generated INP and IDF files. The fact that user-assigned doors were not reflected by GBS was a known issue to *Autodesk Green Building Studio* developers (Autodesk Corporation 2016).

Table 17. Door construction discrepancies between BIM and translated BEM input files

	Input	Revit Export	GBS Export		
	Revit 2016	gbXML	gbXML	INP	IDF
Office	Wood frame, double glass door: RSI-0.52 m^2•K/W (R3)		"R5 Door": 4in Wood: RSI-0.838 m^2•K/W (R4.76)		
House	Solid core wood, wood storm: RSI-0.61 m^2•K/W (R3.46)				

It is noteworthy that although the door's construction and analytical properties assigned in Revit could be found in the gbXML and IDF files' *construction, layers, and material* section, the "R5 Door" was actually placed on the surface where the door was located as written in the following gbXML text (**bold** added for emphasis):

*<Opening interiorShadeType="Operable"exteriorShadeType="Fixed"openingType= "NonSlidingDoor" id="aim0822" constructionIdRef="**construction-86**">*
[…]
*<Construction id="**construction-86**">*
<LayerId layerIdRef="layer-86" />
*<Name>**R5 Door**</Name>*
<Description>R5 Door</Description>
<U-value unit="WPerSquareMeterK">6.4164338</U-value>
[…]
</Construction>

A variety of tests were run to investigate whether the GBS plug-in would always override the door construction: (1) changing door construction to below or over ASHRAE requirements, (2) modifying building types, (3) exporting either by “Rooms” or “Spaces”, and (4) changing the building locations to apply different weather files. These tests found that only the weather condition had an impact on the default door assigned by GBS: a “R2 Default Door” was used in Climate Zone 1-3 and “R5 Door” in Climate Zone 4-8.

To circumvent the GBS default door, the modeler must export by “Spaces” and override the door construction with desired analytic construction in the “Building Construction” - <Building> dialogue (Figure 16). There are 28 doors of different construction and thermal properties in the selection. Also as mentioned above, it is possible to export user-assigned doors when exporting the gbXML from Revit directly, which circumvents this issue.

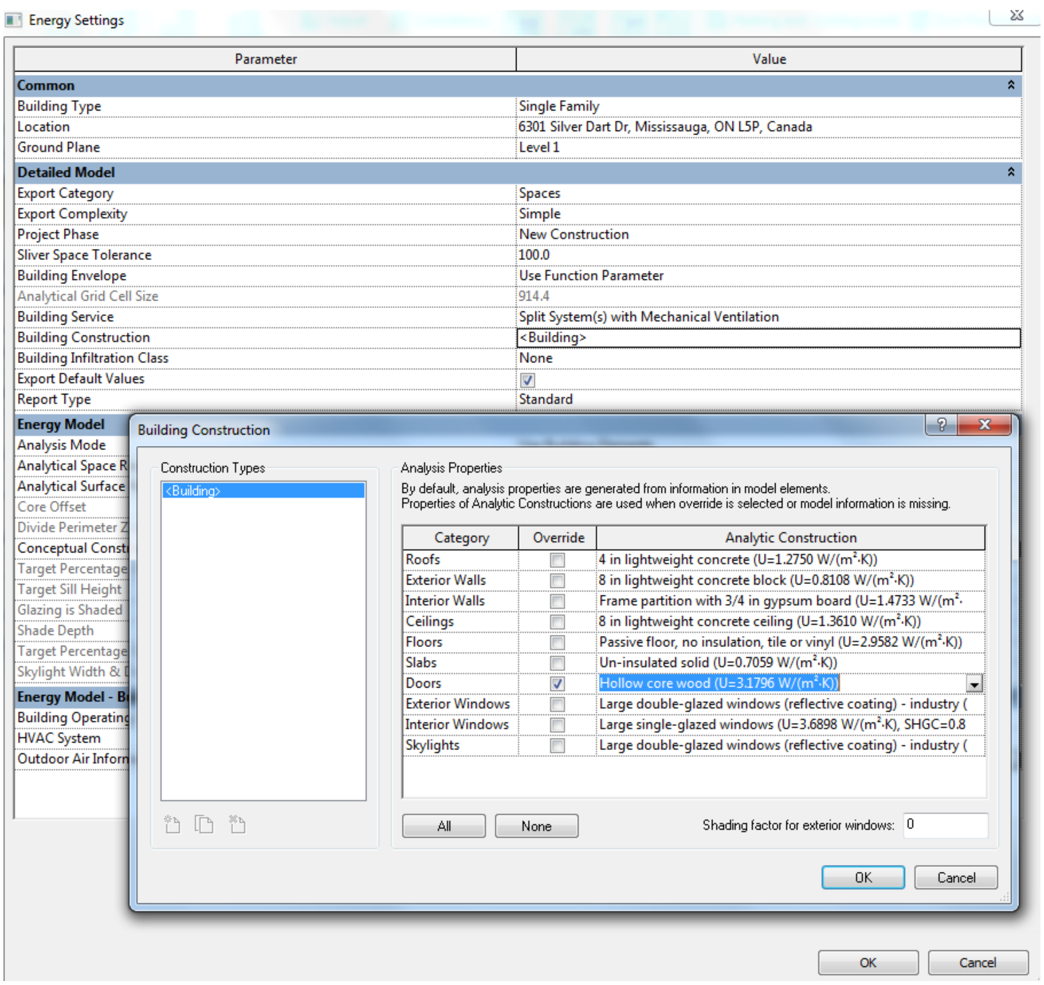

Figure 16. Screenshot illustrating how to avoid default R-value assignment

5.4.1.3. Additional exterior wall construction

As previously discussed, GBS created additional exterior wall constructions to wrap around all openings. These were defined within GBS gbXML as "ASHRAE compliant" constructions, which were assigned to best match the user-defined exterior wall types, but the thermal properties were quite different as illustrated in Table 18. In the office building constructed with CMUs, GBS added a CMU parent structure, while in the single family house constructed with EIFS on metal studs, GBS added a wood frame wall as the parent element for all openings. These constructions consistently appeared in INP and IDF files generated with GBS.

Table 18. Opening parent element and thermal properties

	Input	Revit Export	GBS Export		
	Revit	gbXML	gbXML	INP	IDF
Office	CMU with ext. insulation U-value: 0.21 $W/m^2 \cdot K$		ASHRAE 90.1 compliant concrete or block wall: U-value: 0.5 $W/m^2 \cdot K$		
House	EIFS on metal stud U-value: 0.0876 $W/m^2 \cdot K$		ASHRAE 90.1 compliant Wood frame wall U-value: 0.284 $W/m^2 \cdot K$		

Since the "Door construction" section suggests that by changing the climate file, GBS-assigned constructions were modified, the added wall constructions were also checked for construction variations. It was found that the insulation value increased as the climate condition became colder as shown below:

Table 19. GBS-assigned construction varied with climate

Climate Zone	Office	House
1: Miami, FL	8in concrete wall hollow	ASHRAE 90.1 R13 wood frame
2: Houston, TX	R5.7 8in concrete	ASHRAE 90.1 R15 wood frame
3: Atlanta, GA	ASHRAE 90.1 R7.6 concrete	
4: Seattle, WA	ASHRAE 90.1 R9.5 concrete	R15+5 continuous insulation wood frame wall
5: Vancouver BC		
6: Toronto, ON	ASHRAE 90.1 R11.4 concrete	ASHRAE 90.1 R21 wood frame
7: Edmonton, AB	ASHRAE 90.1 R15.2 concrete	R21+10 continuous insulation wood frame wall
8: Yellowknife, NT		

When there are a large number of openings in the building model, these constructions are expected to make a difference in the simulation results. Therefore, the gbXML exported directly from Revit is recommended to export the geometry.

5.4.2 Thermal properties

Revit allows users to input up to nine thermal properties and two analytical properties for materials as listed in Table 20. The other three analytical properties, i.e. thermal transfer coefficient, thermal resistance, and thermal mass are calculated by Revit and could not be modified (properties in *italic*). Four key thermal properties, including material conductivity, specific heat, density, and thickness were well maintained across the files except for doors as discussed previously. In addition to these four properties, gbXML also included R-values for each material based on thickness and conductivity. For "no mass" materials where conductivity, specific heat, density, and thickness were not available, the R-values were consistent between gbXML, INP, and IDF.

Table 20. Thermal property transfer integrity

<table>
<tr><th></th><th>Revit Input</th><th>gbXML</th><th>INP</th><th>IDF</th></tr>
<tr><td rowspan="9">Material thermal</td><td>Conductivity</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>Specific heat</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>Density</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>Thickness</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>Emissivity</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Permeability</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Porosity</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Reflectivity</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Electrical resistivity</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="6">Analytical properties</td><td>Heat transfer coefficient (U)</td><td>Appeared in Revit inherent constructions</td><td>-</td><td>-</td></tr>
<tr><td>Thermal resistance (R)</td><td>●</td><td colspan="2">Presented when other properties were not available</td></tr>
<tr><td>Thermal mass</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Absorptance</td><td>●</td><td>●</td><td>-</td></tr>
<tr><td>Roughness</td><td>●</td><td>●</td><td>●</td></tr>
<tr><td>Note</td><td>GBS-assigned constructions added reflectance, transmittance, and emittance</td><td></td><td>All materials had the following three properties:
Thermal absorptance (0.9)
Solar absorptance (0.75)
Visible absorptance (0.75)</td></tr>
</table>

Legend: ● = exported; - = not exported

Constructions in the exported files were categorized into two types: (1) Revit-inherent constructions (user-defined in Revit, e.g. exterior walls and slab); (2) GBS-assigned constructions (e.g. the construction wrapping the openings).

In gbXML, Revit-inherent constructions included the heat transfer coefficient (U) under the "Construction" element, while GBS-assigned constructions specified the inside air film resistance (IAFR) instead of assembly U-values. The INP had no U-value property, but similar to gbXML, it had no IAFR in Revit-inherent constructions and had the same IAFR as gbXML in GBS-assigned constructions. Neither the U-value nor IAFR was explicitly defined in IDF.

Table 21. gbXML and eQuest surface film coefficient and assembly U-value comparison (house)

		IAFR (m²•K/W)		Calculated U (W/m²•K)		Reference U (W/m²•K)	
		gbXML	eQuest	gbXML	eQuest	w/a IAFR*	IAFR
Revit-inherent constructions	Exterior wall		0.12	0.088	0.085	0.088	0.085
	Slab		0.12	0.110	0.108	0.110	0.108
	Roof		0.12	0.102	0.102	0.102	0.102
	Interior wall		0.12	0.575	0.539	0.575	0.539
	Window			1.987	1.987	-	-
GBS-assigned constructions	Wood Frame Wall	0.12	0.12	-	0.284	0.282	0.284
	Wood Frame Floor	0.162	0.162	-	1.158	1.156	1.155
	Interior Drop Ceiling Tile	0.0162	0.162	-	2.601	2.605	2.589
	R5 Door	0.109	0.109	6.416	1.056	1.056	1.056

*w/a IAFR: with available interior air film resistance

By exporting the INP file in eQuest, it was found that a default IAFR value of RSI-0.12 m²•K/W was assigned to construction layers wherever not otherwise defined; in this case, the default value was used in Revit-inherent constructions. U-values were also calculated for each construction (Table 21). These IAFR and calculated U-values were compared against gbXML values to verify consistency. Table 21 showed very close results for all Revit-inherent constructions except for interior walls, which had a 6% difference. One significant difference was found in the R5 door, whose U-value in gbXML was six times of that in eQuest.

To verify GBS and eQuest heat transfer algorithm: whether those mostly minor differences between gbXML and eQuest U-values mentioned above were caused only by the default IAFR or there was hidden exterior AFR (EAFR), the following options were tested:

1. Without surface film resistance;

2. With both exterior and interior surface film resistance;
3. With only interior surface film resistance.

The best matching algorithm for GBS and eQuest were found as shown in the "Reference U" column. It was certain that GBS calculated Revit-inherent constructions without taking account of any surface film resistance because this property was not available in Revit; eQuest took account of IAFR and not EAFR for both Revit-inherent and GBS-assigned constructions (Taitem Engineering 2008). It was unknown whether GBS would calculate the U-value with the surface film resistance when it was available as in GBS-assigned constructions. Therefore, attempts were made to back calculate the GBS-assigned constructions' U-value by checking the *heating and cooling loads from* these constructions, but GBS and eQuest did not break down any of these constructions.

With or without surface film resistance, the door constructed with R4.76 wood should not have a U-value of 6.416 $W/m^2 \cdot K$ as currently appeared in the gbXML file. If only IAFR was counted as eQuest did, the U-value would be 1.056 $W/m^2 \cdot K$; if both surface film resistances were calculated (RSI-0.03 $m^2 \cdot K/W$ on the outside and RSI-0.109 $m^2 \cdot K/W$ on the inside), the resistance value would be 1.024 $W/m^2 \cdot K$. It was believed that the extremely high assembly U-value written in gbXML was most likely a typo in the text. The "R2 Default Door" used in Climate Zones 1-3 also had extremely high U-value (16.13 $W/m^2 \cdot K$), which was not reasonable. However, if the BEM tools used do not import U-values property, such as eQuest and EnergyPlus (which import RSI-values), this would not be a problem; only when the U-value was also imported, it needed to be verified before running the simulation.

It is noteworthy that for doors, such as a French door with glass panels and a wood component, the construction layers where imported into BEM programs correctly and the thermal properties of each material were correct, but the assembly U-values were different because these two components are layered out in two layers instead of glass panel embedded in the wood.

The investigation of construction layers and material thermal properties had revealed a number of areas where attention is required when using GBS as an intermediate tool to export BEM input files:

1. Exterior wall construction layers were inverted but other envelope components were correctly laid out.
2. Added structures were created by GBS to wrap around all openings, including windows and doors, as parent elements. Although they were assigned to best match the user-defined envelope structure, their thermal properties varied significantly and depended on the assigned location.
3. The door construction despite Revit definition, it would be overridden by GBS with either R2 or R5 doors.
4. The constructions exported from Revit did not have surface film resistance, so this property must be modified in the BEM tools.
5. The main thermal properties, including material conductivity, specific heat, density, and thickness were consistent across the gbXML, INP, and IDF files. These values were maintained well from BIM to BEM, except for the door as described in #3 above.

5.5 Mechanical systems

The mechanical systems were defined through the "*Energy Setting*" dialogue within Revit. There was a very limited number of systems that users could select from because during the early stage design, the systems were mainly used to compare energy consumption for different iterations rather than obtaining the exact numbers. To verify mechanical system data transfer integrity, the systems used by GBS and the systems transferred to INP and IDF were compared with Revit assumptions as shown in Table 22 for the office building and Table 23 for the house.

The office building was set to export by "Rooms" in the "*Energy Settings*" dialogue. This was an easy way to set up mechanical systems, as well as internal loads and schedules because default assumptions of the spaces were made based on the building type, so users were not required to input any parameters other than selecting the systems from a drop down menu. The main disadvantage of this option was the lack of diversity factor: it did not allow users to modify system parameters and it did not differentiate based on space properties. However, this would be sufficient for informing early stage design, such as weighing massing and orientation options if the same HVAC system was consistently assigned across design options. The house was set to export by "Spaces", which allowed GBS to perform energy simulation based on specific settings made in each space, so this option would be more beneficial in the later design stage.

In the office building, the HVAC system consisted of a static pressure variable air volume (VAV) system with reheat boxes, which was heated by an 88.4% efficient gas-fired hot water boiler and cooled by a COP 5.96 chiller. The chiller was further connected with an open cooling tower. The domestic hot water (DHW) was provided by a 0.575 energy factor DHW unit, using natural gas per Revit 2016 default settings.

Table 22. Mechanical systems consistency between BIM input and translated BEM files (office)

<table>
<tr><th>Input</th><th colspan="3">GBS Export</th></tr>
<tr><th>Revit “Office”</th><th>gbXML</th><th>INP</th><th>IDF</th></tr>
<tr><td>Infiltration flow (ACH): 0.4</td><td colspan="2" rowspan="4">Matches input</td><td>Matches input</td></tr>
<tr><td>Outside air flow/Area:
28.8 m^3/h/person
plus 2.5 $m^3/h/m^2$</td><td>28.8
m^3/h/person</td></tr>
<tr><td>Economizer present</td><td>No economizer</td></tr>
<tr><td>Ventilation system:
VAV with reheat boxes</td><td rowspan="3">Ideal loads air system: Max heating supply air temp=50 ºC, Min cooling supply air temp=13 ºC; humidification setpoint: 30%</td></tr>
<tr><td>Heating:
Gas-fired hot water boiler with draft fan > 2500kBtu, 84.5% combustion efficiency</td><td>Matches input.
Adds: Max temp: 87.8ºC, Min temp: 71.1ºC, Design temp: 82.2ºC</td><td>Matches input.
Adds: Heat input ratio =1.179 (84.8% eff.), electrical input ratio = 0.022</td></tr>
<tr><td>Cooling:
Water cooled centrifugal chiller (COP 5.96)</td><td>Matches input.
Adds: Max temp: 10ºC; Min temp: 5.6ºC; Design temp: 6.7ºC</td><td>Matches input.
Electrical input ratio=0.1678 (results in COP 5.96)</td></tr>
<tr><td>Domestic hot water system
(Energy Factor: 0.575)</td><td>Matches input.
Adds: Max temp:60 ºC, Min temp: 43.4 ºC, Design temp: 48.9 ºC; AFUE=0.8</td><td>Matches input.
Adds: gas; heat input ratio=1.25 (equals 80% eff.)</td><td>No domestic hot water system was included</td></tr>
</table>

The single family house used a high efficient (17.4 SEER/9.6 HSPF) packaged air source heat pump with a 0.85 energy factor on-demand tank-less DHW system (Autodesk Revit 2016 2016).

Table 23. Mechanical systems consistency between BIM and translated BEM files (house)

	Input	GBS Export		
	Revit "Single Family"	gbXML	INP	IDF
ZONE CONDITIONs				
Infiltration flow	0.5 ACH	Matches input		Matches input
Cool Design	23 ºC			Not specified
Heat Design	21 ºC			Not specified
Outside air flow/Area	28.8 m^3/h/person, 1.08 $m^3/h/m^2$	1.08 $m^3/h/m^2$	1.097 $m^3/h/m^2$	1.08 $m^3/h/\ m^2$
HVAC SYSTEMS				
Air source heat pump	17.4 SEER / 9.6 HSPF <5.5 ton			Ideal loads air system
Cooling COP	Not specified	5.43	Same as gbXML EIR*: 0.1842	Not specified
Heating COP		3.75	Same as gbXML EIR*: 0.2667	Not specified
Min supply temperature		48.89 ºC	Same as gbXML	50 ºC
Max supply temperature		11.11 ºC	Same as gbXML	13 ºC
Fan power	2" water gauge	Matches input	2.6" water gauge	
Humidification	-	Min: 10% Max: 90%	Min: 0 Max: 100%	Setpoint: 30%
DOMESTIC HOT WATER SYSTEM				
Domestic hot water system	On-demand, tank-less water heater; Energy factor: 0.85	Matches input	Matches input	No domestic hot water system included

*EIR: electricity input ratio

The gbXML file provided explicit specifications for the system and the information was well transferred into INP. The significant discrepancy of mechanical system data transfer came from the IDF file (the simulation results (in Section 6.2) have reflected this), which used an ideal loads air system that took advantage of district heating and cooling, and did not export domestic hot water system.

Due to limitations in GBS regarding system type selection, it is recommended based on these results that the energy modeler review and manually update the mechanical system characteristics as the design progresses. For early-stage designs when such details are unknown, the same system type should be used for all models to allow a consistent basis for comparison.

5.6 Internal loads

The internal loads in each file are presented in Table 24 for the office and Table 25 for the house. In the office building, GBS added equipment: a 12kW elevator and four 0.8kW vending machines, which were not listed in Revit building type “Office”. The INP file was able to capture this additional information while the IDF file did not. In both cases, the people heat gain, and lighting and equipment load density could be well maintained with input regardless of the exporting category (“Rooms” or “Spaces”) and building types. The occupancy was more consistent in the office than in the house because it had much lower occupant density. A more significant rounding issue was noted in the IDF file.

Table 24. Internal loads consistency between BIM input and translated BEM files (office)

	Input	GBS Export		
	Revit “Office”	gbXML	INP	IDF
External equipment	Not explicitly defined	12kW elevator	Same as gbXML	No elevator specified
Occupancy	4/100m^2 (40.88 people)	Matches input	Matches input	44 people
People heat gain	Lat: 58.61 W/person Sen: 73.27 W/person Total:131.88 W/person	Matches input		
Lighting load density	9.7 W/m^2 (per ASHRAE 90.1)			
Equipment load density	14.4 W/m^2 (per ASHRAE 90.1)			
Vending machines	Not specified	4 vending machines: 0.8kW	Same as gbXML	No vending machines

Table 25. Internal loads consistency between BIM input and translated BEM files (house)

	Input	GBS Export		
	Revit “Single Family”	gbXML	INP	IDF
Occupancy	0.951/100m^2 1.67 people	0.933/100m^2 1.79 people	0.99/100m^2 1.9 people	0.52/100m^2 1 person
People heat gain	Lat: 58.61 W/person Sen: 73.27 W/person Total:131.88 W/person	Matches input		
Lighting load density	10.867 W/m^2			
Equipment load density	10.867 W/m^2			

5.7 Schedules

Since Revit provided very limited scheduling information – only an occupancy schedule and a general operating schedule – the specific schedules for each element were assigned by GBS. The schedule data transfer integrity was well maintained across GBS-exported files except that GBS had no infiltration schedule, while INP and IDF had default infiltration schedule. It was further observed that while the IDF file did not include the elevator or vending machines as described previously, the schedules for these two types of equipment were still imported.

Table 26. Schedule consistency between BIM input and translated BEM files (office)

<table>
<tr><th rowspan="2"></th><th>Input</th><th colspan="3">GBS Export</th></tr>
<tr><th>Revit “Office”</th><th>gbXML</th><th>INP</th><th>IDF</th></tr>
<tr><td>Occupancy</td><td>12/5 schedule</td><td>Applied Revit weekday schedule to 7day/week</td><td colspan="2" rowspan="9">Same as gbXML</td></tr>
<tr><td>Lighting</td><td>12/5 schedule</td><td>Applied different weekday schedule to 7day/week</td></tr>
<tr><td>Equipment</td><td rowspan="9">Not defined</td><td>Applied lighting schedule instead of equipment schedule</td></tr>
<tr><td>Vending machines</td><td>12/5 schedule;
Phantom load: 0.2 fraction (weekend schedule)</td></tr>
<tr><td>Elevator</td><td>12/5 schedule;
Phantom load: 0.01 fraction (weekend schedule)</td></tr>
<tr><td>Fan</td><td>“FanSch-44”
12/5 fan schedule</td></tr>
<tr><td>Heating</td><td>“Heatsched-7”
12/5 schedule</td></tr>
<tr><td>Cooling</td><td>“Coolsched-7”
12/5 schedule</td></tr>
<tr><td>Domestic hot water</td><td>12/5 schedule</td></tr>
<tr><td>Infiltration</td><td>Not specified</td><td>Perimeter zones: 12/5 schedule; core zone: off</td><td>Same as INP</td></tr>
</table>

Table 27. Schedule consistency between BIM and translated BEM files (house)

	Input	Revit Export	GBS Export		
	Revit "Single Family"	gbXML	gbXML	INP	IDF
Occupancy	Home occupancy – 24 hours	"aim0067" Matches input	"aim0193" Matches input		
Lighting	Residential – All day	"aim0061" Matches input	"aim0187" Matches input		
Equipment	Residential – All day	Not defined	"aim0187" Matches input		
Fan	Not defined		"FanSch-12" ON all day	Same as gbXML	
Heating			"Heatsched-9" 20 ºC		
Cooling			"Coolsched-9" 25.5 ºC		
Domestic hot water			"DHWSchedule-80"		
Infiltration			Not specified	"FanSch-12INF" ON all day	Same as INP

Although the GBS exported files had a very high level of consistency (horizontal comparison), there were two main discrepancies: (1) The equipment used the lighting schedule, and (2) the office building schedule was set to a "12/5 Facility", but GBS did not differentiate weekdays and weekends schedules for occupancy and lighting. This latter issues is discussed in Section 5.7.2.

5.7.1 Schedule conflicts

Among all schedules, the equipment schedule was most deceiving. Usually in gbXML, the schedule of an element would be defined as one of its attributes, so "EquipSched-50" was the schedule of "Equip-4" as shown in the following gbXML text.

```
<IntEquip id="Equip-4" type="GeneralPlugload" scheduleIdRef="EquipSched-50">
   <Name>Loads 4.63 W/area</Name>
   <Description>Receptacle Loads 4.63 W/area</Description>
</IntEquip>
```

"EquipSched-50" defined the year schedule, which identified week schedule id. The week schedule then associated each day with a day schedule as shown below:

Table 28. The detailed schedule for "EquipSched-50"

Schedule id:	<Schedule id="EquipSched-50" type="Fraction"> <Name>LtgEquip - RES</Name>
Year schedule:	<YearSchedule id="EquipSched-50-ys-82"> <BeginDate>1997-01-01</BeginDate> <EndDate>1997-12-31</EndDate> <WeekScheduleId weekScheduleIdRef="ws-79-Equip" /> </YearSchedule>
Week schedule:	<WeekSchedule id="ws-79-Equip" type="Fraction"> <Name>LtgEquip - RES</Name> <Day dayType="Weekday" dayScheduleIdRef="ds-374-Equip" /> <Day dayType="Sat" dayScheduleIdRef="ds-375-Equip" /> <Day dayType="Sun" dayScheduleIdRef="ds-376-Equip" /> <Day dayType="HeatingDesignDay" dayScheduleIdRef="ds-376-Equip" /> <Day dayType="CoolingDesignDay" dayScheduleIdRef="ds-374-Equip" /> <Day dayType="Holiday" dayScheduleIdRef="ds-376-Equip" /> </WeekSchedule>
An example of the day schedule:	<DaySchedule id="ds-374-Equip" type="Fraction"> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.45</ScheduleValue> <ScheduleValue>0.45</ScheduleValue> <ScheduleValue>0.45</ScheduleValue> <ScheduleValue>0.45</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> <ScheduleValue>0.6</ScheduleValue> <ScheduleValue>0.8</ScheduleValue> <ScheduleValue>0.9</ScheduleValue> <ScheduleValue>0.8</ScheduleValue> <ScheduleValue>0.6</ScheduleValue> <ScheduleValue>0.3</ScheduleValue> </DaySchedule>

The confusion of equipment schedule came in because eQuest used lighting schedule "aim0187" instead of "EquipSched-50" for equipment, but had the same equipment end use result as GBS. To find out why GBS and eQuest had different schedules, "EquipSched-50" and "aim0187" were checked to determine if they were referring to the same *day schedule*. As Table 29 showed, the lighting and equipment schedules were different in both cases.

Table 29. Office and house lighting and equipment schedules

	Office			House	
	Lighting	Equip weekday	Equip weekend	Lighting aim0187	Equipment EquipSched-50
1	0	0.2	0.2	0.1	0.3
2	0	0.2	0.2	0.1	0.3
3	0	0.2	0.2	0.1	0.3
4	0	0.2	0.2	0.1	0.3
5	0	0.2	0.2	0.1	0.3
6	0	0.2	0.2	0.3	0.3
7	0.1	0.2	0.2	0.45	0.45
8	0.3	0.2	0.2	0.45	0.45
9	0.9	0.3	0.2	0.45	0.45
10	0.9	0.9	0.2	0.45	0.45
11	0.9	0.9	0.2	0.3	0.3
12	0.9	0.9	0.2	0.3	0.3
13	0.8	0.9	0.2	0.3	0.3
14	0.9	0.8	0.2	0.3	0.3
15	0.9	0.9	0.2	0.3	0.3
16	0.9	0.9	0.2	0.3	0.3
17	0.9	0.9	0.2	0.3	0.3
18	0.5	0.9	0.2	0.3	0.3
19	0.3	0.5	0.2	0.6	0.6
20	0.3	0.3	0.2	0.8	0.8
21	0.2	0.2	0.2	0.9	0.9
22	0.2	0.2	0.2	0.8	0.8
23	0	0.2	0.2	0.6	0.6
24	0	0.2	0.2	0.3	0.3

Next, the equipment schedule was changed to "EquipSched-50" in eQuest as indicated by gbXML and rerun the model. The annual equipment electricity demand changed and no longer matched GBS results. Calculations were also done manually, and it was found that to get the

GBS and eQuest original results, the lighting schedule “aim0187” had to be used. To verify whether this was due to a glitch in gbXML text, the file was checked again, and this time, the spaces where the equipment was located was examined. Finally, it was found that the equipment schedule was set to “aim0187” in the “Space” attributes as shown in the gbXML text below:

<Space zoneIdRef="aim5042" lightScheduleIdRef="aim0187" ***equipmentScheduleIdRef=***
"aim0187" *peopleScheduleIdRef="aim0193" conditionType="HeatedAndCooled"*
id="aim0176" buildingStoreyIdRef="aim0013-Storey-0">
[…]
*<IntEquipId intEquipIdRef=****"Equip-4"*** */>*
[…]
</Space>

Since this schedule was defined by the “Space” element, it had higher priority when it came to equipment load calculation. However, this was believed to be an error in GBS schedule definition for “Space”: it would be more reasonable to use the equipment schedule for equipment because there would be a certain level of phantom load even when equipment was shut but not unplugged.

5.7.2 Schedule assumption concerns

Although defined as a “12/5 Facility” in Revit, the office occupancy, lighting, and equipment (because equipment used lighting schedule instead of equipment schedule) used weekday schedules throughout the year in the exported files. However, in Revit operating schedule assumptions (Autodesk Revit 2016 2016), a “12/5 Facility” operates five days a week. Figure 17 compares the Revit operating schedule with the corresponding GBS schedule: weekdays are shown in the first 24 hours, Saturday in the second 24 hours and Sunday in the third 24 hours. In addition to the excessive operating days, the GBS weekday schedule did not aligh with Revit assumptions. In the house model, as it was to 24/7, the occupancy schedule matched with Revit assumption, but similar to the office model, GBS created its own operational schedule, which differed from Revit assumptions.

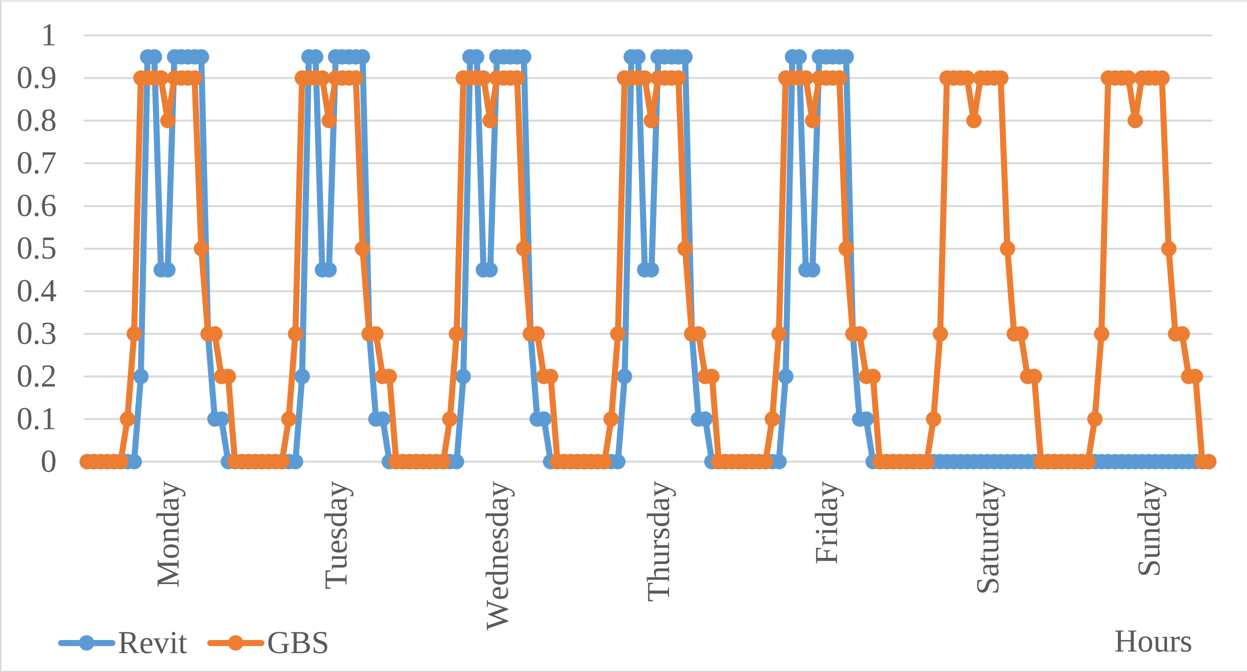

Figure 17. Revit vs. GBS operating schedules for office - weekly

Similar to the operating schedule, excessive occupancy could be found in GBS occupancy schedule, but the weekday occupancy schedule matched up well with Revit schedule (Autodesk Revit 2016 2016) (Figure 18).

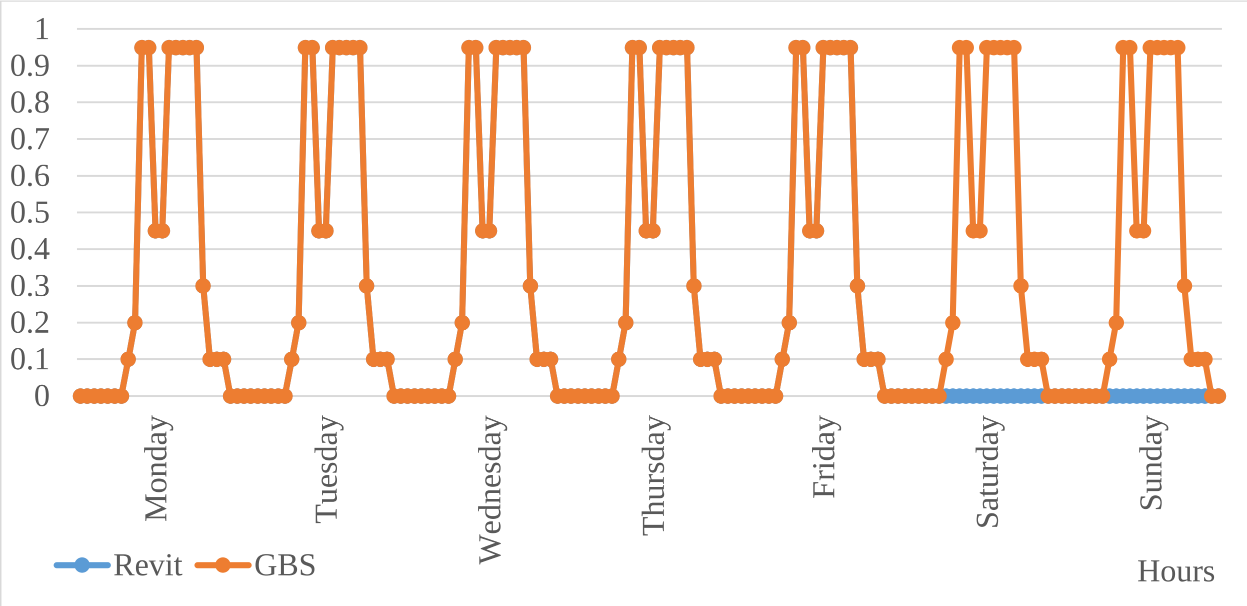

Figure 18. Revit vs. GBS occupancy schedule for office - weekly

The following are the key lessons learned from the scheduling investigation:

1. Users need to be aware that the lighting schedule will most likely be used for equipment (as it was in both office and house cases), so the “Space” element’s attribute: schedule id need verification.

2. The GBS schedules can be different from Revit assumptions and result in unrealistic energy end uses. This can either be kept consistent or be removed from the model in the third-party software to get more realistic results and a better ability to identify the impact of massing and other decisions on energy performance.

6 COMPARISON OF SIMULATED RESULTS

The line-by-line investigation of data transfer integrity of climate, geometry, construction and material thermal properties, mechanical system, internal loads, and occupancy and building operating schedules has revealed a number of discrepancies between BIM input and translated BEM files and also among the GBS-exported files (gbXML, INP, and IDF). Simulation results were compared as a second layer of verification to data transfer integrity. This investigation will reflect whether or not those discrepancies are critical.

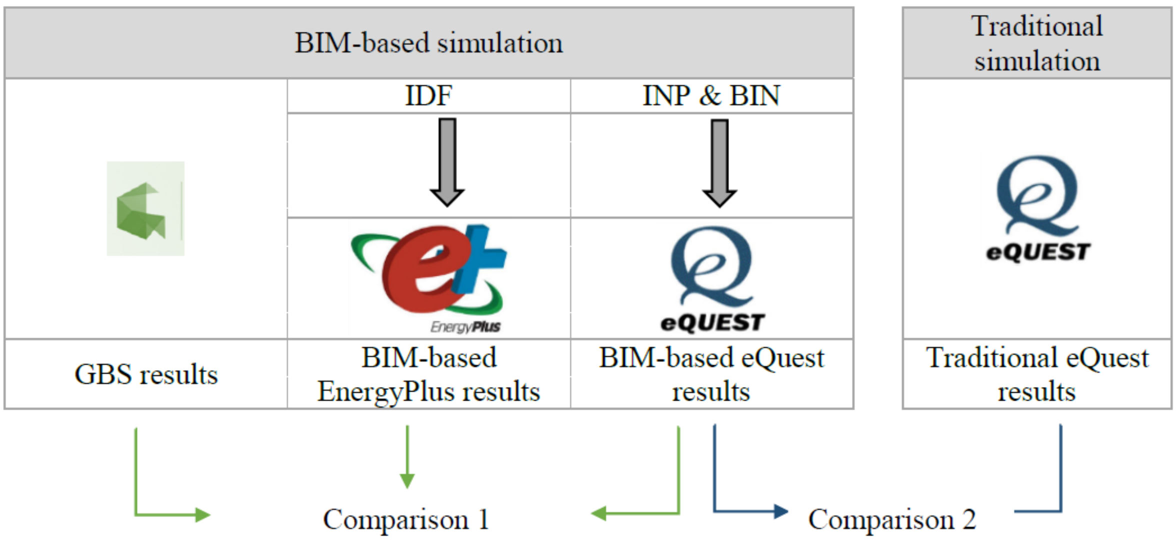

Figure 19. Illustration of results comparison process

As illustrated in Figure 19, the comparison is divided into two parts: The comparison between BIM-exported file results and the comparison with native BEM model results.

The consistency of BIM-based energy analysis was evaluated by comparing GBS, eQuest, and EnergyPlus simulation results as follows:

- **GBS results**: obtained using GBS plug-in within Revit. However, the GBS results appear within Revit are rounded numbers, so they are not as accurate. The results section of the gbXML file downloaded from GBS online platform should be used.
- **BIM-based eQuest results**: obtained by importing the INP file and BIN file (DOE weather file format) downloaded from GBS into eQuest. Simulate the model without changing anything to the model.

- **BIM-based EnergyPlus results**: obtained by importing the IDF file into EP Launch and running the file without any modifications.

The comparison of BIM-based energy simulation results with traditional building energy simulation results was investigated by manually re-producing the energy models with geometry and construction information from Revit (i.e. consulting the architects) and MEP specifications from gbXML (i.e. consulting the engineers). Because eQuest has the same calculation engine as GBS, it was selected to create the same model using the traditional approach and the simulated results were compared with BIM-based eQuest results. The comparison will thus reveal whether GBS simulation gives similar results to native eQuest models.

6.1 BIM-based energy analysis results

The office has very high relative energy consumption of lighting and miscellaneous equipment. As illustrated in Figure 20, their load is almost half the office's total energy use. This is resulted from a combination of three reasons: (1) GBS assumption for miscellaneous equipment included four vending machines in addition to general plug loads; (2) the lighting and equipment schedules are seven days/week instead of five and the phantom load of vending machines are high; and most importantly (3) the extremely high-performance envelope defined resulted in relatively low lower-than-average space heating and cooling loads.

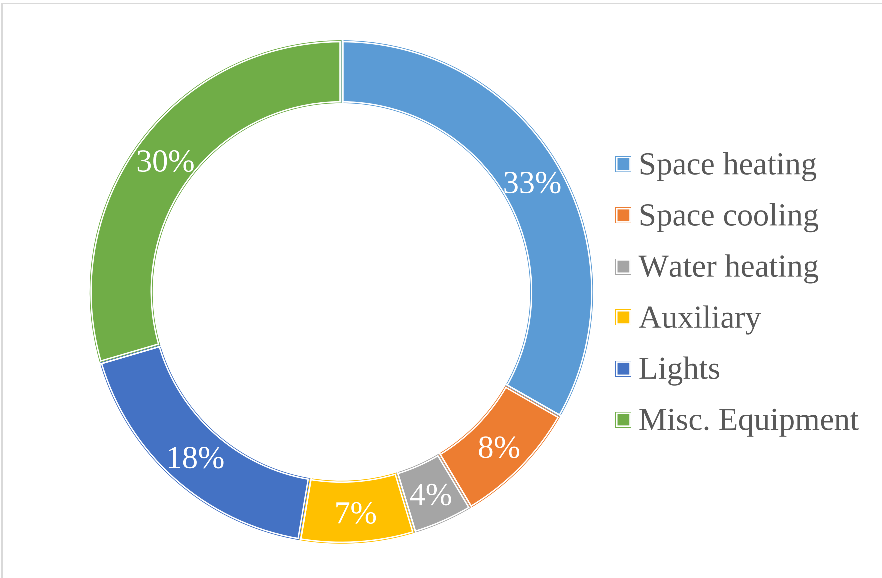

Figure 20. Office energy end use breakdown

6.2 BIM-based energy analysis result comparison

BIM-based eQuest results were very close to GBS simulation results – the largest percentage difference was 1.2% on heat rejection with the actual value difference of 3.39 kWh per year. The eQuest and GBS results were almost identical for the single family house. BIM-based EnergyPlus, on the contrary, presented significantly different results. This was expected due to the findings from data transfer integrity investigation. Key findings are as follows:

- EnergyPlus ran on a different HVAC system, resulting in district heating and cooling, which was quite different from GBS and eQuest's heating and cooling output.
- EnergyPlus' DHW was blank because the IDF file did not specify a DHW system.
- The miscellaneous equipment was 2,762 kWh lower in the office model because IDF did not have the vending machines.
- Lighting was the only category that was consistent with GBS as IDF had the same lighting load density and lighting schedule for both models.

Table 30. High-performance office energy use comparison (% (kWh) difference from GBS)

		GBS results	BIM-based eQuest results	% (kWh) difference from GBS	BIM-based EnergyPlus results	% (kWh) difference from GBS
Total	Electricity	128,970.16	128,970	0.00% (-0.16)	89,058.33	30.9% (-39,911.83)
	Fuel	72,191.67	72,192.20	0.00% (0.53)	-	
Fue	Hot water	7,841.78	7,842.58	0.01% (0.08)	-	-
	Space heating	64,350.09	64,349.61	0.00% (-0.48)	-	-
Electricity	Space heating	2,556.21	2,560.00	0.15% (3.8)	-	-
	Heat rejection	283.39	280.00	1.2% (-3.39)	-	-
	Pumps & Aux	7,339.50	7,340.00	0.01% (0.5)	-	-
	Fans	7,475.03	7,480.00	0.07% (4.97)	-	-
	Space cooling	16,126.65	16,130.00	0.02%(3.35)	-	-
	Exterior loads	3,370.43	3,370.00	0.01% (-0.43)	-	-
	Lights	35,787.00	35,790.00	0.01% (3)	35,788.89	0.00% (1.89)
	Misc. equipment	56,031.78	56,030.00	0.00% (-1.78)	53,269.44	4.93% (-2,762.34)
	District heating	-	-	-	45,633.33	-
	District cooling	-	-	-	38,900.00	-

Table 31. High-performance single family house energy use comparison – BIM approach (kWh)

	GBS results	BIM-based eQuest results	% (kWh) difference from GBS	BIM-based EnergyPlus results	% (kWh) difference from GBS
ANNUAL ENERGY USE					
Electricity	25,740.11	25,740.00	0% (-0.11)	13,577.78	47.25% (-12,162.33)
Fuel	2,904.00	2,903.98	0% (-0.02)	-	-
ENERGY USE: FUEL					
Hot water	2,904.00	2,903.98	0% (-0.02)	-	-
ENERGY USE: ELECTRICITY					
Space heating	926.98	927.00	0% (0.02)	-	-
Space cooling	1,049.92	1,050.00	0% (0.08)	-	-
Pumps & Aux	881.31	881.00	0% (-0.31)	-	-
Fans	7,918.28	7,918.00	0% (-0.28)	-	-
Heat pumps	1,385.58	1,386.00	0% (0.42)	-	-
Lights	6,788.99	6,789.00	0% (0.01)	6,788.89	0% (0.00)
Misc. equipment	6,788.99	6,789.00	0% (0.01)	6,788.89	0% (0.00)
District heating	-	-	-	5,647.22	-
District cooling	-	-	-	4,444.44	-

Table 32. Monthly electricity and natural gas comparison between GBS and eQuest (office)

	Monthly electricity consumption			Monthly gas consumption		
	GBS	eQuest	% difference	GBS	eQuest	% difference
Jan	11852.66	11850	0%	26577.13	26516.5	0%
Feb	8801.633	8800	0%	12614.12	12543.33	1%
Mar	9514.812	9510	0%	7001.27	6961.68	1%
Apr	9216.551	9220	0%	3341.063	3319.69	1%
May	10583.39	10570	0%	1144.447	1139.77	0%
Jun	11655.58	11640	0%	612.546	612.37	0%
Jul	13135.4	13130	0%	550.353	550.84	0%
Aug	12998.93	12990	0%	561.613	562.56	0%
Sep	11933.43	11920	0%	492.896	492.24	0%
Oct	9861.421	9860	0%	1545.49	1535.32	1%
Nov	9220.236	9220	0%	3666.159	3641.99	1%
Dec	10196.12	10180	0%	14084.8	14025.91	0%
Total	128970.2	128890	0%	72191.89	71902.2	0%

To more thoroughly compare the eQuest and GBS simulation results, monthly electricity and gas consumption were compared (Table 32). The results also demonstrated a very high level of consistency between eQuest and GBS results.

6.3 BIM approach vs. traditional approach

To evaluate the performance of GBS as a simulation tool, the case study models were also created in native eQuest software using the same building inputs. The native eQuest model was developed by first using Design Development Wizard and then modifying the model in the Detailed Mode. The areas and volumes of each space and zone and both locations and sizes of all openings were checked to best match the BIM model's geometry. Matched to the gbXML properties, the native modeling results were compared with the BIM-generated eQuest results, which were nearly identical to GBS but provide more directly comparable output files.

To best compare between BIM-based eQuest and traditional eQuest results, inputs related to gbXML discrepancies were duplicated in eQuest exactly as presented in gbXML except for the added constructions wrapping openings, which were not created in native eQuest. The modeled issues include (1) 7-day occupancy and lighting schedules, (2) wrong equipment schedule (which copied the lighting schedule), and (3) overridden door thermal property as previously mentioned. In addition, the initial runs for this comparison found that eQuest default Toronto weather condition differed from GBS-exported BIN file as illustrated in Table 33; therefore, the GBS-exported BIN file was used for simulation.

Table 33. Percentage/kWh difference between eQuest BIN file and GBS BIN file (office)

	GBS .BIN	eQuest .BIN	% (kWh) difference	
Annual energy use				
Electricity	128,970.00	127,670.00	1.01%	1,300.00
Fuel	72,192.20	74,457.64	-3.14%	-2,265.44
Energy Use: Fuel				
Hot water	7,842.58	7,948.09	-1.35%	-105.51
Space heating	64,349.61	66,509.55	-3.36%	-2,159.94
Energy Use: Electricity (kWh)				
Space heating	2,560.00	2,760.00	-7.81%	-200.00
Heat rejection	280.00	260.00	7.14%	20.00
Pumps & Aux	7,340.00	7,260.00	1.09%	80.00
Fans	7,480.00	7,220.00	3.48%	260.00
Space cooling	16,130.00	14,980.00	7.13%	1,150.00
Exterior loads	3,370.00	3,370.00	0.00%	-
Misc. equipment	56,030.00	56,030.00	0.00%	-
Lights	35,790.00	35,790.00	0.00%	-

The overall energy simulation for the office model presents 1.31% difference between BIM-based eQuest and traditional eQuest results, while the house model presents a slightly larger difference (4.6%). Compared to previous studies, these are much smaller discrepancies because a number of issues with GBS simulation were eliminated. The comparison of energy end uses is summarized in Table 34 and 35. The finding is consistent with (Stumpf, Kim and Jenicek 2011) where larger discrepancies stemmed from the thermal loads.

- **The office model**: a good number of end uses are within 10% differences except for pumps & auxiliary devices (overestimated by 16.5%) and heat rejection (overestimated by 366.7%, 220kWh/year);
- **The house model**: space heating (underestimated by 30%), fans (overestimated by 29%), and heat pumps (underestimated by 20.7%).

Upon inspection of the output files and the comparison with GBS-exported INP files, these more significant differences can be attributed to a combination of slightly different space volumes and the elimination of the constructions wrapping the openings. It was also found in the office model that the BIM exported chilled water loop had a secondary loop while the native eQuest did not automatically generate a secondary loop, but this did not make a significant difference in simulated cooling, which showed a 4% difference.

Table 34. BIM-based eQuest vs. traditional eQuest simulation results comparison (office)

	BIM-based eQuest	Traditional eQuest	% difference
ANNUAL ENERGY USE			
Total	**201,162.20**	**203,824.44**	**-1.31%**
Electricity	128,970.00	126,990.00	1.56%
Fuel	72,192.20	76,834.44	-6.04%
ENERGY USE: FUEL			
Hot water	7,842.58	7,772.24	0.91%
Space heating	64,349.61	69,062.20	-6.82%
ENERGY USE: ELECTRICITY			
Space heating	2,560.00	2,820.00	-9.22%
Space cooling	16,130.00	15,500.00	4.06%
Pumps & Aux	7,340.00	6,300.00	16.51%
Fans	7,480.00	7,170.00	4.32%
Heat rejection	280.00	60.00	366.67%
Exterior loads	3,370.00	3,360.00	0.00%
Lights	35,790.00	35,770.00	0.06%
Misc. Equipment	56,030.00	53,250.00	0.05%

Table 35. BIM-based eQuest vs. traditional eQuest simulation results comparison (house)

	BIM-based eQuest	Traditional eQuest	% difference
ANNUAL ENERGY USE			
Total	**28,643.98**	**27,383.80**	**4.60%**
Electricity	25,740.00	24,701.00	4.21%
Fuel	2,903.98	2,682.80	8.24%
ENERGY USE: FUEL			
Hot water	2,903.98	2,682.80	8.24%
ENERGY USE: ELECTRICITY			
Space heating	927.00	1,327.00	-30.14%
Space cooling	1,050.00	1,086.00	-3.31%
Pumps & Aux	881.00	815.00	8.10%
Fans	7,918.00	6,145.00	28.85%
Heat pumps	1,386.00	1,747.00	-20.66%
Lights	6,789.00	6,786.00	0.04%
Misc. Equipment	6,789.00	6,786.00	0.04%

7 ITERATION TESTING FOR SOURCES OF ERROR

Three parameters (climatic data, HVAC systems, and constructions) were varied and the GBS results and BIM-based eQuest results were compared to further determine the consistency and reliability of BIM to BEM data transfer integrity and simulation results. These tests were undertaken for both case study models to identify consistency or model-specific differences in the impacts of such changes.

Climatic data was chosen because the previous investigations had revealed that GBS-assigned constructions (exterior doors and the parent structures of the openings) changed accordingly. Therefore, by changing the climate files, multiple variables are changed in each test. This is very efficient for data transfer integrity evaluation. HVAC system iterations were selected because eQuest and GBS occasionally needed different pieces of information to define one equipment, and thus tests of HVAC systems might determine whether this could cause a problem in particular systems.

7.1 BIM model iteration testing: climatic data

Eight locations representing eight ASHRAE climate zones (four USA locations and four Canadian locations) were tested (Table 36), and the percentage difference between GBS and BIM-based eQuest results were presented in Table 37 and 38 for the office model and Table 39 and 40 for the house model.

Table 36. Eight airports situated in eight climate zones

ASHRAE CZ*	Country	City	Airport Address	Revit Weather Station No.
1	USA	Miami, FL	2100 NW 42nd Ave	59260
2	USA	Houston, TX	2800 Terminal Rd N	59269
3	USA	Atlanta, GA	6000 N Terminal Pkwy	59283
4	USA	Seattle, WA	17801 International Blvd	59421
5	Canada	Vancouver BC	3211 Grant McConachie Way	6993
6	Canada	Toronto, ON	6301 Silver Dart Dr.	45277
7	Canada	Edmonton, AB	1000 Airport Rd, Nisku, AB	15772
8	Canada	Yellowknife, NT	1 Yellowknife Hwy	17111

*CZ: Climate Zone

The percentage difference of overall fuel and electricity use was very close to 0%. The value difference of fuel end use remained within +/- 1 kWh/year. The electricity end use breakdown showed minor discrepancies (percentage difference larger than 0.5% were highlighted in ***bold italic***) in space heating and more significant in heat rejection. The outlier results were associated with low energy consumption values where the differences were within a trivial 5 kWh/year. The greater variations (larger than 2%) usually occurred for heating estimates in cooling-dominant climates and cooling estimates in heating-dominant climates.

Table 37. Office model % (kWh/yr) differences of eQuest results from GBS results in CZ1-4

		CZ 1 Miami		CZ 2 Houston		CZ 3 Atlanta		CZ 4 Seattle	
	Electricity	0.0%	(-3.4)	0.0%	(-3.7)	0.0%	(0.3)	0.0%	(2.3)
	Fuel	0.0%	(-0.1)	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.2)
Fuel	Hot water	0.0%	(-0.1)	0.0%	(-0.1)	0.0%	(-0.1)	0.0%	(0.0)
	Space heating	-	-	0.0%	(0.1)	0.0%	(0.0)	0.0%	(0.1)
Electricity	Space heating	-	-	***2.2%***	***(2.6)***	***1.1%***	***(-4.7)***	0.4%	(-2.8)
	Space cooling	0.0%	(4.6)	0.0 %	(4.3)	0.0%	(3.2)	0.0%	(4.5)
	Heat rejection	0.3%	(-4.7)	0.2%	(3.1)	0.1%	(-0.9)	***4.3%***	***(4.5)***
	Pumps & Aux	0.1%	(4.3)	0.0%	(4.8)	0.0%	(3.7)	0.0%	(2.4)
	Fans	0.0%	(1.9)	0.0%	(1.0)	0.0%	(-1.7)	0.0%	(2.9)
	Lights	0.0%	(3.0)	0.0%	(3.0)	0.0%	(3.0)	0.0%	(3.0)
	Misc. equipment	0.0%	(-1.8)	0.0%	(-1.8)	0.0%	(-1.8)	0.0%	(-1.8)
	Exterior loads	0.0%	(-0.4)	0.0%	(-0.4)	0.0%	(-0.4)	0.0%	(-0.4)

Table 38. Office model % (kWh) differences of eQuest results from GBS results in CZ 5-8

		CZ 5 Vancouver		CZ 6 Toronto		CZ 7 Edmonton		CZ 8 Yellowknife	
	Electricity	0.0%	(7.3)	0.0%	(-0.2)	0.0%	(-4.0)	0.0%	(1.0)
	Fuel	0.0%	(0.3)	0.0%	(0.5)	0.0%	(-0.3)	0.0%	(0.1)
Fuel	Hot water	0.0%	(-0.1)	0.0%	(0.8)	0.0%	(-0.7)	0.0%	(-0.3)
	Space heating	0.0%	(-0.1)	0.0%	(-0.5)	0.0%	(0.4)	0.0%	(0.2)
Electricity	Space heating	***0.6%***	***(-4.2)***	0.1%	(3.8)	0.1%	(-3.6)	0.0%	(0.9)
	Space cooling	0.1%	(7.5)	0.0%	(3.4)	0.0%	(-4.4)	0.0%	(-2.5)
	Heat rejection	***0.6%***	***(-1.1)***	***1.2%***	***(-3.4)***	***2.7%***	***(-2.5)***	***7.0%***	***(-3.8)***
	Pumps & Aux	0.0%	(-0.4)	0.0%	(0.5)	0.1%	(-4.8)	0.0%	(1.9)
	Fans	0.1%	(4.9)	0.1%	(5.0)	0.0%	(0.5)	0.1%	(3.6)
	Lights	0.0%	(3.0)	0.0%	(3.0)	0.0%	(3.0)	0.0%	(3.0)
	Exterior loads	0.0%	(-0.4)	0.0%	(-0.4)	0.0%	(-0.4)	0.0%	(-0.4)
	Misc. equipment	0.0%	(-1.8)	0.0%	(-1.8)	0.0%	(-1.8)	0.0%	(-1.8)

Table 39. House model % (kWh) differences of eQuest results from GBS results in CZ 1-4

	CZ 1 Miami		CZ 2 Houston		CZ 3 Atlanta		CZ 4 Seattle	
ANNUAL ENERGY USE								
Electricity	0.0%	(0.2)	0.0%	(-0.4)	0.0%	(-0.2)	0.0%	(0.2)
Fuel	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)
ENERGY USE: FUEL								
Hot water	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)
ENERGY USE: ELECTRICITY								
Space heating			0.3%	(0.1)	-0.3%	(-0.4)	0.1%	(0.1)
Space cooling	0.0%	(-0.4)	0.0%	(0.2)	0.0%	(-0.0)	0.0%	(-0.2)
Pumps & Aux	***3.4%***	***(0.5)***	-0.1%	(-0.3)	0.0%	(-0.1)	0.0%	(0.4)
Fans	0.0%	(0.1)	0.0%	(0.4)	0.0%	(0.2)	0.0%	(0.4)
Heat pumps			***10.7%***	***(0.3)***	***1.6%***	***(0.3)***	***6.7%***	***(0.4)***
Lights	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)
Misc. equipment	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)

Table 40. Office model % (kWh) differences of eQuest results from GBS results in CZ 5-8

	CZ 5 Vancouver		CZ 6 Toronto		CZ 7 Edmonton		CZ 8 Yellowknife	
ANNUAL ENERGY USE								
Electricity	0.0%	(-0.4)	0.0%	(-0.1)	0.0%	(-0.3)	0.0%	(0.0)
Fuel	0.0%	(0.0)	0.0%	(-0.0)	0.0%	(0.0)	0.0%	(0.1)
ENERGY USE: FUEL								
Hot water	0.0%	(0.0)	0.0%	(-0.0)	0.0%	(0.0)	0.0%	(0.1)
ENERGY USE: ELECTRICITY								
Space heating	0.4%	(0.4)	0.0%	(0.0)	0.0%	(-0.2)	0.0%	(0.1)
Space cooling	0.0%	(0.2)	0.0%	(0.1)	0.0%	(0.1)	0.1%	(0.4)
Pumps & Aux	0.0%	(0.0)	0.0%	(-0.3)	0.0%	(-0.1)	0.0%	(0.2)
Fans	0.0%	(-0.0)	0.0%	(-0.3)	0.0%	(-0.2)	0.0%	(-0.4)
Heat pumps	0.0%	(-0.0)	0.0%	(0.4)	0.0%	(0.2)	0.0%	(-0.3)
Lights	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)
Misc. equipment	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)	0.0%	(0.0)

7.2 BIM model iteration testing: HVAC systems

Two additional HVAC systems were randomly selected for the office model, while the only three options for residential HVAC systems were used for the house model. These are summarized in Table 41.

Table 41. HVAC systems options

	Office	Single Family
Base option	Central VAV, HW Heat, Chiller 5.96 COP, Boilers 84.5 eff	Residential 17 SEER/9.6 HSPF Split HP < 5.5ton
Alternative 1	12 SEER/0.9 AFUE Split/Packaged Gas, 5-11 Ton	Residential 14 SEER/8.3 Split/Packaged Heat Pump
Alternative 2	4-Pipe Fan Coil System, Chiller 5.96 COP, Boilers 84.5 eff	Residential 14 SEER/0.9 AFUE Split/Packaged Gas < 5.5 ton

Very high consistency has been found in the HVAC system tests for both the office model (Table 42) and the house model (Table 43). The outliers (larger than 0.5% difference) are highlighted in ***bold italic***. This suggests that HVAC systems are consistently exported from BIM to BEM.

Table 42. Office model (eQuest-GBS)/GBS %/kWh differences using different HVAC systems

	Central VAV		12 SEER gas furnace		Four-Pipe Fan Coil	
Annual energy use						
Electricity	0.0%	-0.16	0.0%	4.90	0.0%	1.50
Fuel	0.0%	0.53	0.0%	0.37	0.0%	0.07
Energy Use: Fuel						
Hot water	0.0%	0.80	0.0%	0.80	0.0%	0.80
Heating	0.0%	-0.48	0.0%	-0.43	0.0%	-0.74
Energy Use: Electricity						
Heating	0.1%	3.80			-0.1%	-2.30
Cooling	0.0%	3.35	0.0%	1.34	0.0%	-2.00
Heat rejection	***-1.2%***	***-3.39***			***0.6%***	***1.72***
Pumps	0.0%	0.50	-0.2%	-4.55	0.0%	-0.62
Fans	0.1%	4.97	0.0%	-2.69	0.0%	3.93
Lights	0.0%	3.00	0.0%	2.96	0.0%	2.96
Exterior loads	0.0%	-0.43	0.0%	-0.43	0.0%	-0.43
Misc. equipment	0.0%	-1.78	0.0%	-1.78	0.0%	-1.78

Table 43. House model (eQuest-GBS)/GBS %/kWh differences using different HVAC systems

	17 SEER ASHP		14 SEER HP		14 SEER gas furnace	
ANNUAL ENERGY USE						
Electricity	0.0%	-0.11	0.0%	-0.53	0.0%	0.46
Fuel	0.0%	-0.01	0.0%	0.11	0.0%	0.11
ENERGY USE: FUEL						
Hot water	0.0%	-0.01	0.0%	0.11	0.0%	0.11
Space heating					0.0%	0.00
ENERGY USE: ELECTRICITY						
Space heating	0.0%	0.02	0.0%	0.25		
Space cooling	0.0%	0.08	0.0%	-0.48	0.0%	0.09
Pumps & Aux	0.0%	-0.31	0.0%	-0.35	0.0%	0.25
Fans	0.0%	-0.28	0.0%	-0.11	0.0%	0.09
Heat pumps	0.0%	0.42	0.0%	0.20		
Lights	0.0%	0.01	0.0%	0.00	0.0%	0.00
Misc. Equipment	0.0%	0.01	0.0%	0.00	0.0%	0.00

7.3 BIM model iteration testing: Construction

As introduced, both of the case study models are highly insulated, which resulted in relatively low heating and cooling loads. The simulation results discussed previously in Section 7.1 showed higher percentage discrepancies between GBS and BIM-based eQuest simulations in extreme climate zones where either heating or cooling loads were extremely small. To investigate the interference of a high insulation envelope with simulation results, a code compliance model (Figure 21 and Table 44) was evaluated.

Because GBS provides automatic parametric simulation, the “ASHRAE 90.1-2010” option was initially used; however, a cursory review of the new gbXML files showed that only the HVAC system was updated to ASHRAE 90.1 standard while the constructions remained the same. This does not properly reflect an ASHRAE 90.1 baseline case necessary for energy modeling. Therefore, the BIM model was manually modified to match the office model’s envelope insulation with ASHRAE baseline as demonstrated in Table 44. For the simulation, all “*Energy Settings*” were kept consistent as for previous highly insulated office model. The simulated GBS results were compared with BIM-based eQuest results and found similar high consistency between results, as illustrated in Table 45.

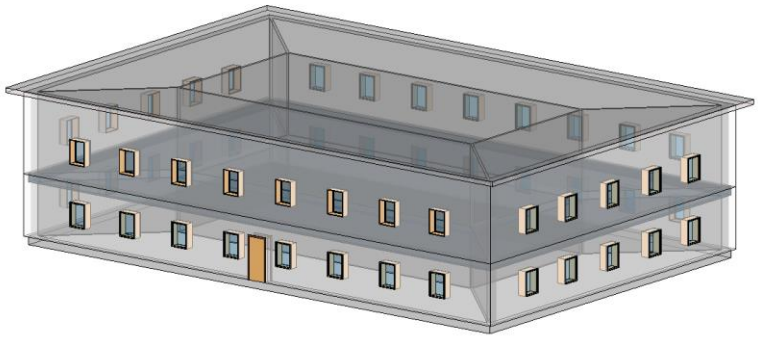

Figure 21. ASHRAE baseline office model

Table 44. ASHRAE baseline office building construction and thermal resistance values

	ASHRAE 90.1-2010 Requirements (Toronto)		
	Assembly Max U	Insulation Min R	User defined construction in Revit
Roof	U0.27	RSI-3.52 c.i.	R20.21 Precast concrete roof
Ext. wall	U0.45	RSI-2.34 c.i.	R13.75 Metal stud exterior wall
Int. wall	-	-	R2.3 79mm partition (1hr)
Floor	-	-	R0 Generic floor
Slab	F4.88**	RSI-2.64	R15.2 Cast-in-place concrete slab
Door	U3.97	-	U0.65 Metal door
Window	U1.99	-	U0.35 Double glazing, low-e coating, clear glass window

Units: U: $W/m^2 \cdot K$; R: $m^2 \cdot K/W$

Table 45. ASHRAE baseline office energy use comparison %/kWh

	GBS	BIM-based eQuest	% difference	kWh difference
ANNUAL ENERGY USE				
Electricity	126,651.10	126,650.00	-0.001%	-1.10
Fuel	100,134.14	100,133.59	-0.001%	-0.55
ENERGY USE: FUEL				
Hot water	7,841.78	7,842.58	0.010%	0.80
Space heating	92,292.36	92,291.00	-0.001%	-1.36
ENERGY USE: ELECTRICITY				
Space heating	3,712.36	3,710.00	-0.064%	-2.36
Space cooling	14,201.78	14,200.00	-0.013%	-1.78
Heat rejection	251.53	250.00	-0.609%	-1.53
Pumps & Aux	6,470.33	6,470.00	-0.005%	-0.33
Fans	6,825.90	6,830.00	0.060%	4.10
Lights	35,787.04	35,790.00	0.008%	2.96
Exterior loads	3,370.43	3,370.00	-0.013%	-0.43
Misc. equipment	56,031.78	56,030.00	-0.003%	-1.78

The comparison of GBS and BIM-based eQuest results difference between the ASHRAE baseline model with the high performance model simulation shows very high consistency as well: the largest difference of 0.587% is for heat rejection in Toronto. In the ASHRAE baseline model, eQuest slightly underestimated results and in the high performance model, eQuest mostly overestimated.

Table 46. BIM-based energy analysis consistency (%/kWh) between ASHRAE baseline and high performance models

	(eQuest-GBS)/GBS (%)		eQuest-GBS (kWh)	
	ASHRAE baseline model	High performance model	ASHRAE baseline model	High performance model
Annual energy use				
Electricity	-0.001%	0.000%	-1.10	-0.16
Fuel	-0.001%	0.001%	-0.55	0.53
Energy Use: Fuel				
Hot water	0.010%	0.010%	0.80	0.80
Space heating	-0.001%	-0.001%	-1.36	-0.48
Energy Use: Electricity				
Space heating	-0.064%	0.148%	-2.36	3.80
Space cooling	-0.013%	0.021%	-1.78	3.35
Heat rejection	-0.609%	-1.196%	-1.53	-3.39
Pumps & Aux	-0.005%	0.007%	-0.33	0.50
Fans	0.060%	0.067%	4.10	4.97
Lights	0.008%	0.008%	2.96	3.00
Exterior loads	-0.013%	-0.013%	-0.43	-0.43
Misc. equipment	-0.003%	-0.003%	-1.78	-1.78

8 MODEL RESILIENCY TO GEOMETRY ERRORS

A common geometric error concerning energy modelers interviewed was unconnected surfaces, which were a common issue in early BIM-based energy simulations. This section investigates GBS tolerance of unconnected surfaces to better understand its potential impact on a model.

The “Analytical Space Resolution” in “*Energy Settings*” is the key control of gap tolerance according to Autodesk. Whether the gap is ignored or not when creating spaces is stated below (Autodesk Revit 2016) (X = Analytical Space Resolution):

1. Gaps < X will be ignored and spaces will be created
2. Gaps > X and < 2X may or may not be ignored
3. Gaps > 2X will not be ignored and spaces will not be created

8.1 Testing methodology

To verify the relationship between surface gaps and the space resolution, and also to investigate what other factors will influence gap’s impact on simulated results, a range of gaps were created on case study models for three scenarios:

1. Two gap locations: (1) incomplete roof – unconnected roof and exterior wall and (2) incomplete exterior wall – unconnected slab and exterior wall as illustrated below;

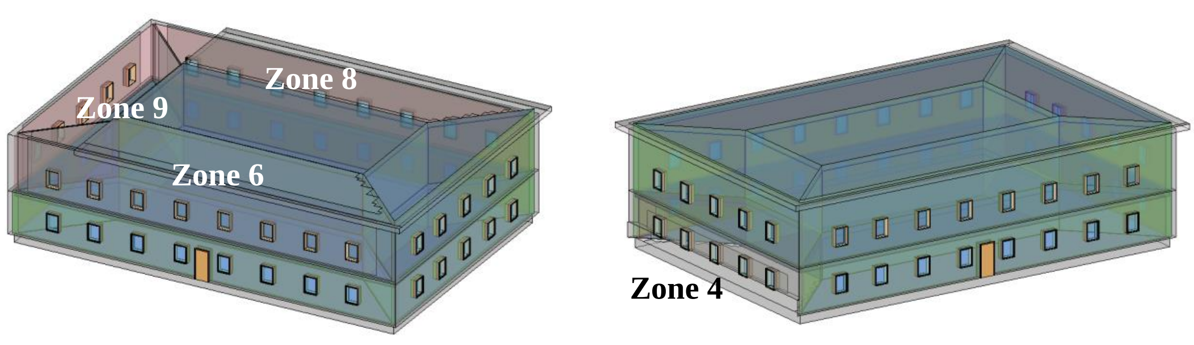

Figure 22. Modified office models: (a) incomplete roof (left); (b) incomplete exterior wall (right)

2. Two space resolutions: (1) 0.457m (default setting) and (2) 0.155m (minimal setting);
3. Two building types: (1) office and (2) house as demonstrated below.

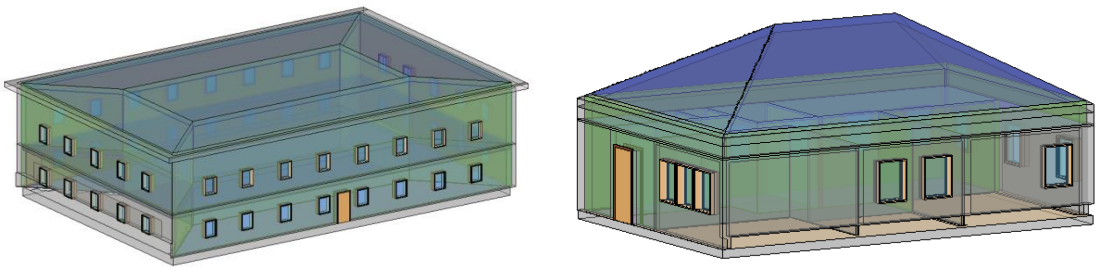

Figure 23. Exterior walls gaps on the office model (left) and the house model (right)

All existing rooms, spaces and zones were deleted and reassigned to eliminate the impact of the previous assignment. Revit generates warnings for unconnected building components either when gaps are created (Figure 24) or when the rooms (spaces) are redefined after gaps are created (Figure 25). Either way, no fatal errors occurred when performing energy simulation within Revit. New simulation results were compared with those from the complete model to evaluate the gaps' impact on simulation results as presented in the following sections.

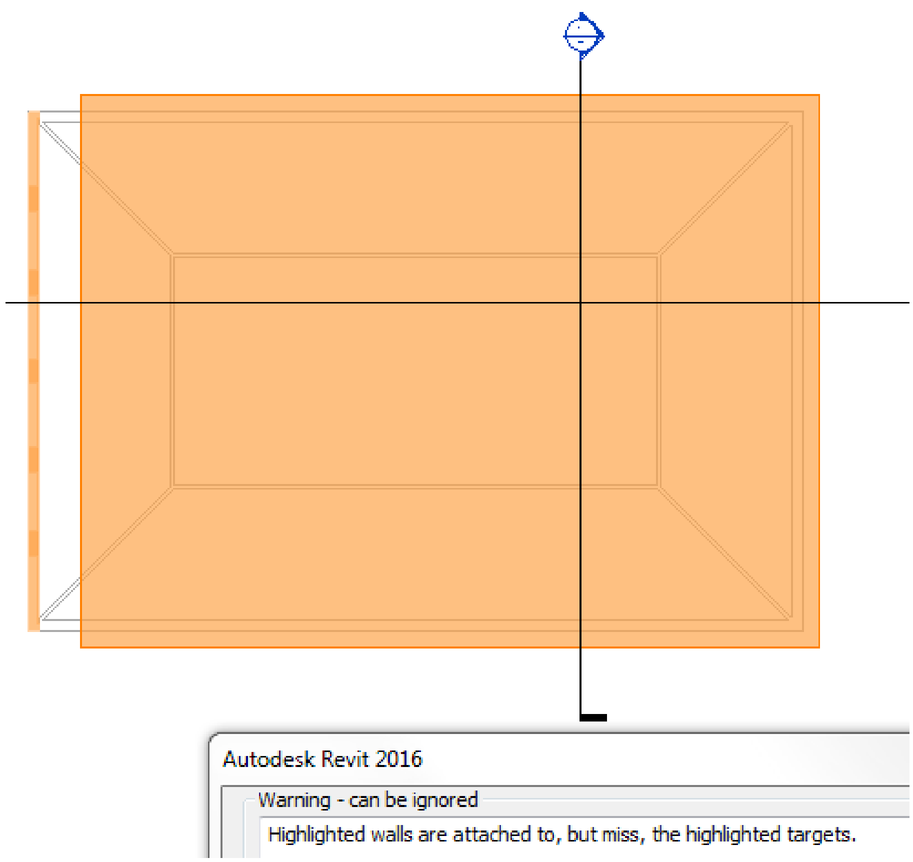

Figure 24. Revit-generated warning in the office model

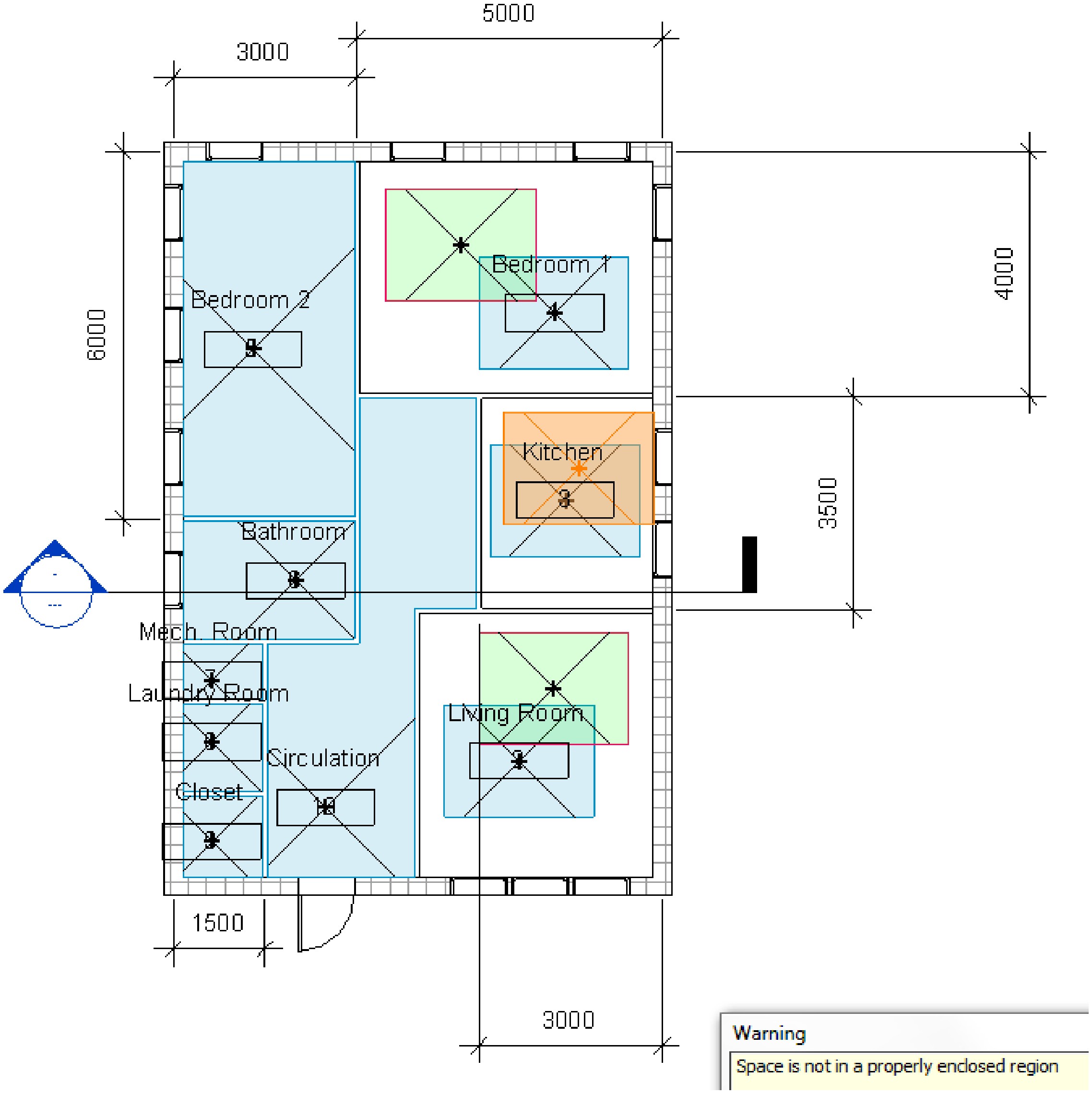

Figure 25. Revit generated warnings when elements are not connected

8.2 The comparison of simulation results variation

The energy consumption results obtained from the modified models were compared with those of the original model. This section discusses the simulated results variation due to roof gaps and exterior wall gaps with different space resolution settings on different building types. Figure 26 compares the simulated energy end uses of a range of gaps on the roof and the exterior wall at 0.457m and 0.155m space resolution respectively.

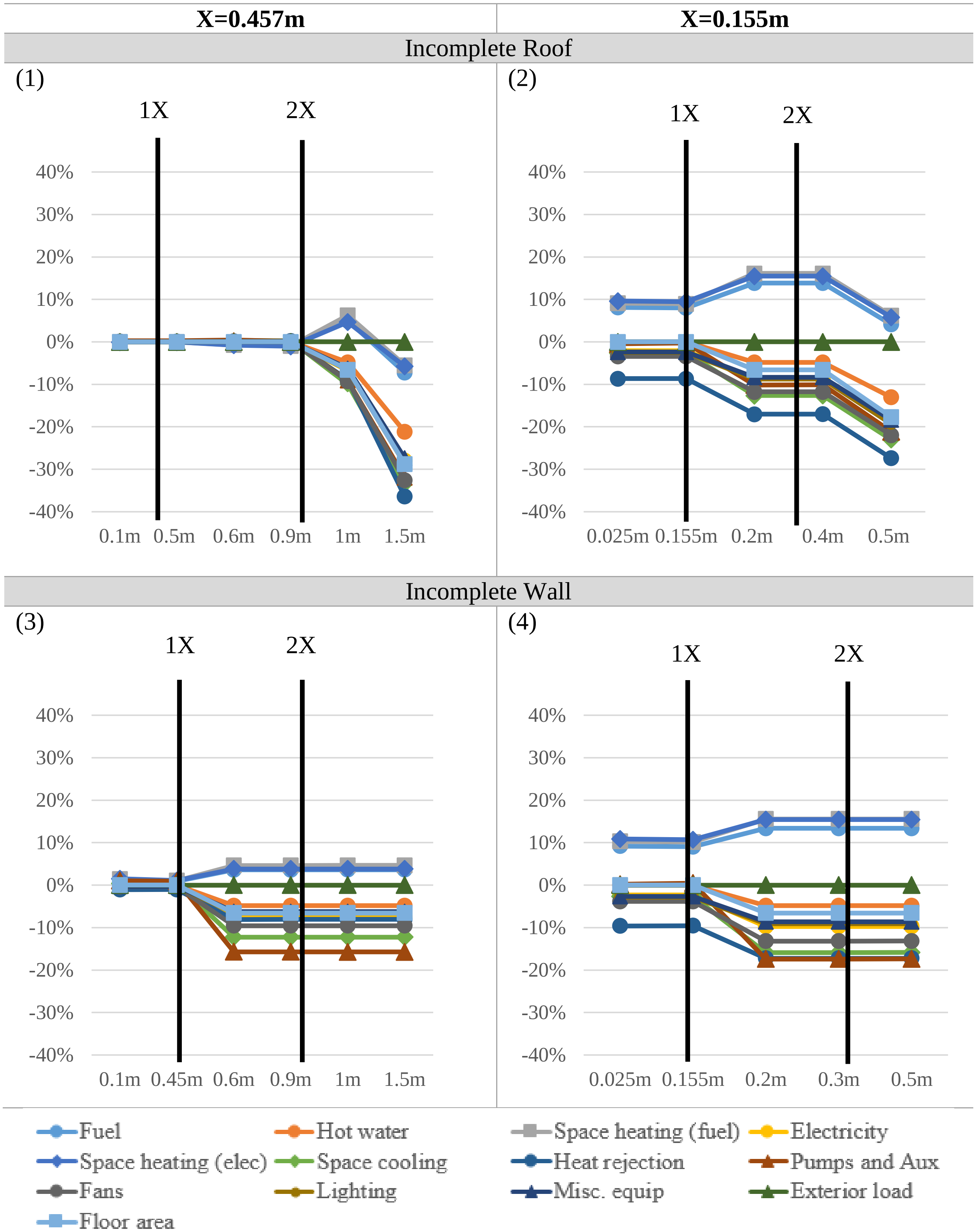

Figure 26. Simulate results variation with incomplete roof (above) and incomplete exterior wall (below) for the office model

It was observed in these four tests that once the gaps were large enough to make a significant impact, they led to an increase in the space heating consumption (resulted from fuel and electricity use) and total fuel consumption and a decrease in the other energy end uses. This is because the spaces were not created so the floor area shrunk and the interior walls were exposed and treated as exterior surfaces. An example is demonstrated below where Space 9 was no longer created when the gap was enlarged to twice of space resolution.

Table 47. The change in space creation with roof gap distances (m^2) at X=0.457m (office)

Space Name	Original model, 0.1m – 0.9m gap	1.0m gap
Space 1	113.45	113.45
Space 2	67.30	67.30
Space 3	113.45	113.45
Space 4	67.30	67.30
Space 5	149.66	149.66
Space 6	113.45	113.45
Space 7	67.30	67.30
Space 8	113.45	113.45
Space 9	67.30	-
Space 10	149.66	149.66
Total	1022.31	955.02

8.2.1 Comparison of different gap locations

By comparing the simulation result variations due to roof gaps (Figure 26 (1) and (2)) with wall gaps (Figure 26 (3) and (4)), it was noticed that at 1.5m gap (when X=0.457m) and at 0.5m gap (when X=0.155m), the roof gaps led to a different trend, while the results variations due to wall gaps stayed the same. A number of gaps larger than 1.5m were also tested and the percentage difference continued to increase. This can be attributed to from a combination of three exposed zones (zone 6, 8, and 9) created by the gap on the roof, as opposed to one exposed zone (zone 4) due to the gap on the wall.

(1) and (3) align well with Autodesk's three rules regarding gaps and analytical space resolution settings previously mentioned. When the gaps were smaller than analytical space resolution (X), the results had minimal variations, all within 1%. When gaps were larger than X, the two cases

started to show different patterns: the gaps on the roof continued to have a minimal impact on results but the gaps on the wall had a more significant impact, up to 16%.

When comparing (2) and (4) where the minimum resolution value was applied, it was found that even a 25mm gap (smaller than X) was not ignored and its impact on the simulated results was up to 10%. When the gaps were enlarged to X, the results variations became larger.

8.2.2 Comparison of space resolutions

Comparing the patterns of (1) and (3) with (2) and (4), it was found that a relatively large resolution setting (e.g. 0.457m) may result in different patterns while a very small resolution setting (e.g. 0.155m) can result in similar patterns up to twice of the resolution setting (Figure 26). The patterns also suggest that regardless of gap locations, whenever the gap is large enough to make a significant impact on simulation results, the impact is very similar to all simulated energy end uses as demonstrated in the following table. At space resolution 0.457m, the differences of gaps' impact on results variation were within 2%, except for "pumps and auxiliary", which was 6.6%. Similarly, at space resolution 0.155m, "pumps and auxiliary" was again the outlier, which resulted in a 7% difference.

Table 48. Space resolution greatly influences gaps' impact on simulation results

	X=0.457m			**X=0.155m**		
	Roof gap > 0.9m (2X)	Wall gap > 0.45m (X)	Difference	Roof gap > 0.155m (X)	Wall gap > 0.155m (X)	Difference
Fuel	5.06%	3.60%	1.46%	13.86%	13.37%	0.49%
Hot water	-4.83%	-4.83%	0.00%	-4.83%	-4.83%	0.00%
Space heating	6.26%	4.63%	1.63%	16.13%	15.59%	0.55%
Electricity	-6.77%	-7.47%	-0.69%	-8.61%	-9.74%	-1.13%
Space heating	4.66%	3.79%	0.87%	15.48%	15.44%	0.04%
Space cooling	-9.98%	-12.25%	-2.26%	-12.63%	-15.89%	-3.26%
Heat rejection	-8.91%	-8.08%	0.83%	-17.03%	-17.23%	-0.20%
Pumps and Aux	-9.11%	-15.71%	**-6.60%**	-10.14%	-17.40%	**-7.26%**
Fans	-9.25%	-9.56%	-0.32%	-11.76%	-13.18%	-1.41%
Lighting	-6.58%	-6.58%	0.00%	-8.75%	-9.08%	-0.33%
Misc. equip	-6.26%	-6.26%	0.00%	-8.32%	-8.63%	-0.31%
Exterior load	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Floor area	-6.56%	-6.55%	0.00%	-6.56%	-6.56%	0.00%

8.2.3 Comparison of different building types

A range of gaps between the exterior wall and slab were created on both the office and the house model at the minimal space resolution setting. The simulation results deviated from the complete model were compared to that of the office model.

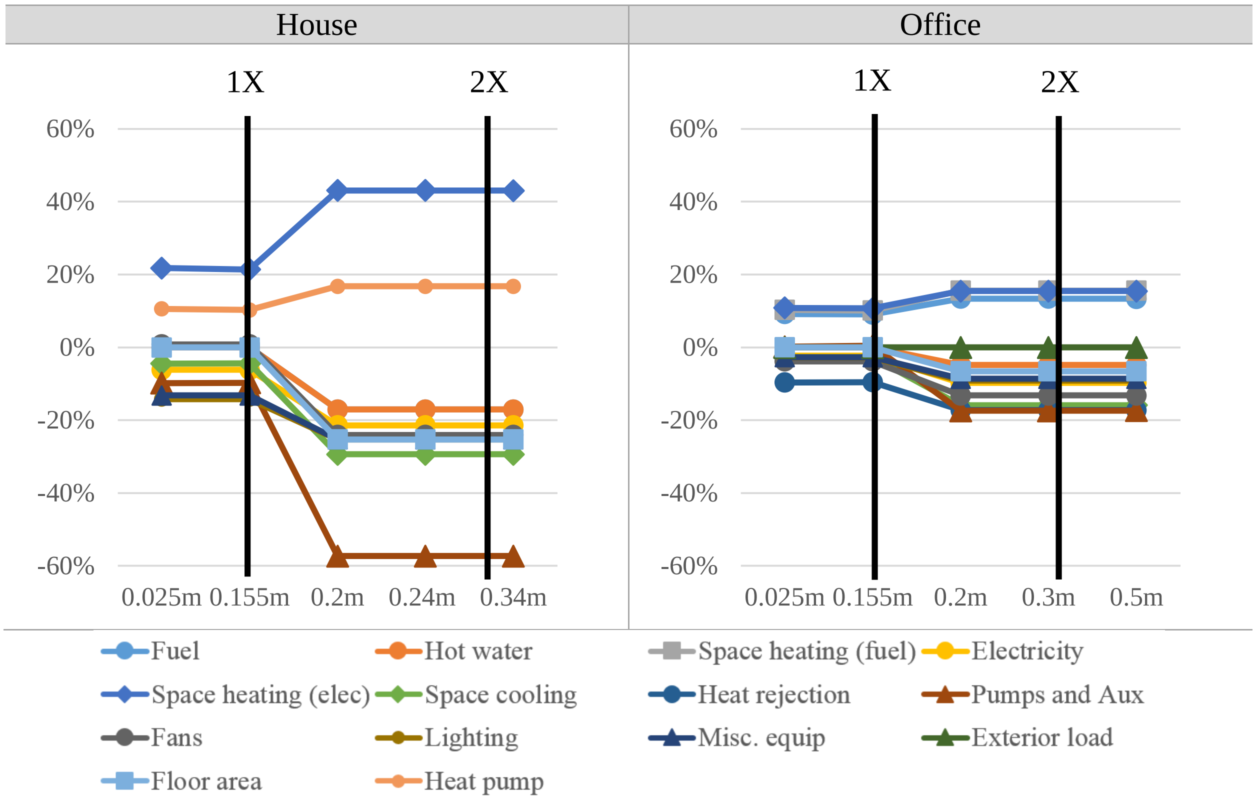

Figure 27. The comparison of results variation between the house model and the office model

Similar to the office model with exterior wall gaps at X=0.155m, the house model presents significant result variations from the complete model even when the gaps were smaller than the resolution setting. The percentage variations were much larger than the office model, up to 22% as shown in Figure 27. Since there are a number of variables between these two models, such as different building type definitions, HVAC systems, and footprints, more tests with controlled variables are needed to identify the determinant factor for this more significant results variation.

As the gaps were enlarged to the resolution setting, the results were driven further away from the complete model simulation because the relevant spaces (the living room, kitchen, and bedroom 1) were no longer created (Table 49).

Table 49. The change in space creation with gap distances (m^2) (house)

Room Name	Original model, 0.025 – 0.155m gap	0.20 – 0.34m gap
Roof	96.00	96.00
Living room	20.00	-
Kitchen	10.50	-
Bedroom 1	18.00	-
Bedroom 2	17.50	17.50
Bathroom	6.00	6.00
Mech. room	1.50	1.50
Laundry room	2.25	2.25
Closet	2.25	2.25
Corridor	18.00	18.00
Total	192.00	143.50

8.3 Geometric error results comparison summary

The key findings of the investigation are that (1) gaps smaller than the space resolution setting are not always ignored; (2) gap locations and building types may influence the gaps' impact on simulation results. The above conclusions were drawn from very limited testing; therefore, to generalize the determinant factors for gaps' impact on simulation results, a larger number of more diversified tests are required.

Depending on the designers' comfortable working scale in BIM, it is assumed that the noticeable gap sizes differ. As discussed above, for a lower space resolution setting, energy simulation has lower tolerance of gaps. Therefore, modelers are recommended to verify the completeness (including the number of spaces, space areas, and space volumes) of the spaces through the following methods instead of looking at the 3D model with bear eyes. There are at least three methods to inspect rooms, spaces and zones (listed below). Cross checking using two methods is recommended to ensure accuracy.

1. Go to Revit export option – gbXML, and spaces whether created properly or improperly will be displayed under "Details" tab
2. Within Revit, go to "View" menu, create schedules for rooms, spaces, and zones
3. Check the gbXML file downloaded from GBS online

9 CONCLUSIONS

As BIM is becoming increasingly popular in the AEC industry, leveraging the BIM model for energy analysis is often considered but currently not common practice. One of the main reasons for this is the lack of research on BIM-BEM data transfer integrity and simulation results validation, resulting in low user confidence, which has hindered its widespread adoption.

The objective of this study has been to address this research gap by undertaking an in-depth evaluation on this issue through two case studies. For each case study, a schematic level BIM model was created and the Green Building Studio (GBS) energy simulation was run in Autodesk Revit 2016. This was undertaken in four sub-studies: (1) line-by-line comparison of generated files with the BIM input, (2) comparison of BIM-based energy simulation results, (3) comparison of BIM-based energy simulation results with native BEM models, and (4) parametric investigations into the impact of geometric errors and other potential sources of errors in model development.

The resultant exported gbXML, INP, and IDF files with BIM input were compared line by line to evaluate the data transfer from BIM inputs to automatically-generated BEM input files. Overall, the GBS-exported files generally remain a high degree of consistency with each other except for mechanical systems, but present a few discrepancies when compared with BIM input. The following are the key findings from this investigation:

1. The geometry is exported with a high degree of accuracy from the BIM model.
2. Revit-exported gbXML contains less information (climatic, geometric and construction information) but has a much cleaner geometry.
3. The material thermal properties are generally correctly exported, except that assigned doors are overridden with GBS default R2/R5 doors depending on the climate zone. The U-value property of these default door is wrong as well.
4. The constructions are well maintained except that the exterior wall construction is inverted in all exported files, and that GBS assigns additional construction around openings and assigns ASHRAE 90.1 default values to this construction.
5. Systems and internal loads are mostly consistent between gbXML and INP, while IDF does not import vending machines.

6. GBS uses the lighting schedule for equipment, and the occupancy and lighting schedules are seven days per week instead of facility operation setting. Additional schedules and loads are assigned by GBS based on ASHRAE 90.1 defaults for the occupancy type.

Second, GBS simulation results were compared with BIM-based eQuest and EnergyPlus results (both obtained by running the GBS-exported input files in the relevant software) to identify any discrepancies in the simulated results. To further evaluate GBS simulation consistency, a number of variables were also tested: climate files, system types, and building constructions. Key findings of these investigations are that:

1. GBS and eQuest results agreed within a 1% error margin in a series of iterations of climatic zones, HVAC systems, and envelope constructions for both case studies. The few outliers are due to low energy consumption values where the differences are minimal, within 5 kWh/year.
2. EnergyPlus results were not comparable with either the GBS or eQuest results due largely to the inaccurate system and missing elements (such as vending machines in the office model) export in the automatically-generated IDF file.

Third, native BEM models for each case study were created in eQuest and compared with the BIM-based energy simulation results. This provided insight on potential discrepancies in underlying assumptions inherent in the GBS-generated model data. This investigation found that overall, the difference between BIM-based eQuest and traditional eQuest results was within 5% for both models; the house model presented a larger disagreement. The extremely high discrepancy for heat rejection (337%) and a few significant discrepancies (10-30%) could be a result of slightly different space volumes and the elimination of constructions wrapping around openings. Due to the limited number of models tested, the trend of whether BIM-based simulation was consistently under or over estimating could not be found.

Finally, the resiliency of BIM-based energy analysis to geometric errors was evaluated. Unconnected envelope components of varied gaps were created in both case studies and simulation results were compared to the complete models. The findings are classified into the following three scenarios:

1. The Autodesk Revit rules regarding gaps and space resolution setting are mostly correct except that when gaps are smaller than the space resolution setting, they are not always ignored despite that the spaces are created;
2. The gap locations and potentially the building footprint influence the gaps' impact on simulated results.

The key contributions of this research include the following:

1. Filled the research gap for lack of systematic academic research on data transfer integrity evaluation and simulation results verification through case studies;
2. Compared the BIM-generated BEM input files line-by-line for data transfer integrity evaluation, which was never done before, and found discrepancies that highlighted key areas need checking while adopting the BIM approach for energy simulation;
3. Inspected the model geometry through visualization models and BEM input files, and concerning building components were further investigated by re-creating them using coordinates, which provided a more confirmative verification;
4. Compared BIM simulation results (GBS results and BIM-based eQuest and EnergyPlus results) to further verify data transfer integrity and found high levels agreement between GBS and eQuest;
5. Compared BIM simulation with native modeling and obtained smaller discrepancies in total energy consumption comparison than previous studies because a number of known issues with GBS default settings were incorporated in native modeling;
6. Investigated BIM energy simulation resiliency to geometric errors and found discrepancy in Autodesk manual.

A number of limitations of this research are noted below:

1. The number of interviews performed was small, so generalizations cannot be made;
2. There are a number of BIM energy simulation tools, but due to time limitation, only GBS was reviewed in detail;
3. The building models were very simple with unified geometry and zones, and thus may have missed issues arising with more complex geometry;
4. Limited model iterations were tested, and additional iterations are required to answer outstanding questions (e.g. to find critical space resolution value where errors occur).

10 RECOMMENDATIONS

The following sections provide specific recommendations for BIM model development arising from interviews and the case study investigations. These relate to BIM model preparation as well as BEM model preparation. Section 10.4 provides insight on future studies that would enhance this research.

10.1 Checklist for preparing the BIM model

While creating BIM models, architects are recommended to do the following:

- Use correct families (note that special attention is required for curtain wall and curve shapes, which are historically problematic with gbXML)
- Be attentive to Revit warning and enclose all spaces
- Properly define construction and material properties
- Assign all rooms

As a quality assurance check, before handing over the BIM model to the energy modelers, the designers should confirm that all the rooms are tagged properly by using Revit menu "Export" – "gbXML" option, checking both the "Rooms" and "Spaces" options, and recording any warnings or errors so they can be fixed before exporting to the third-party analytical tools.

When the energy modelers take over the BIM model, it is suggested by the interviewed modelers that regular communication with the designers is necessary to gain a better understanding and resolve questions about the model. When the energy model is created (especially when it requires significant effort to make the geometry), it will be more efficient if architects document major geometric changes, allowing energy modelers to make intelligent decisions as to whether or not to update these changes manually in the BEM software or to re-import the BIM model.

10.2 Checklist for creating the BEM model

Based on the investigation of data transfer integrity, if GBS is used for energy simulation and to generate BEM input files, energy modelers are recommended to do the following:

- Review the weather file.
    - Check the location and design conditions as it is indicated that different programs could have different design conditions even for the same location

- Review the material properties assigned and modify thermal properties if required.
    - Check particularly for doors and constructions hosting openings.
    - Check construction layers.
- Review HVAC system assumptions and modify to match known system design details.
- Review assumed equipment loads and modify if necessary to avoid these loads dominating the results and rendering alternative design comparisons difficult.
- Confirm that the assigned schedules and occupancy rates are realistic for the building.

The following recommendations were summarized from literature review, the interviews with experienced energy modelers, and the modeling experience accumulated from the case study investigations. These strategies are likely to improve model creation efficiency and accuracy:

- Add spaces automatically using the tool in Revit and name them to match the room names.
- Use model checking tool (such as the one US GSA is currently developing) when available because they will greatly improve model verification efficiency.
- Select GBS-exported files or Revit-exported gbXML wisely to transfer information from BIM depending on the compatibility of BEM tools used.
- Select the "Export Category" based on information availability. At the very beginning of the project when information is mostly undetermined, export by "Rooms" to take advantage of Revit/GBS system and schedule assumptions; when more information is available, export by "Spaces", to define and export project- specified occupancy and lighting schedules and basic zone information.
- Minimize the number of elements exporting, e.g. the interior walls that are not separating different thermal zones should be deleted because the risk of exporting error increases with the complexity of the model (USGSA 2015).

10.3 BIM-to-BEM workflow

This research has found that depending on the software the designers and energy modelers are used to using, there are a few workflows to allow data transfer between the BIM and BEM programs. Here present several workflows that use Revit as the BIM tool.

The data integrity investigation has revealed that the gbXML file exported directly from Revit has a cleaner geometry than the gbXML file downloaded from GBS and the door construction defined in Revit could be exported correctly. Revit-exported gbXML contains less information than the GBS-exported file – only geometric and construction information is available. Therefore, for BEM software that only imports geometric data, the Revit-exported gbXML is sufficient.

To import BIM information to eQuest, the modeler can either (1) use GBS plug-in or (2) export gbXML from Revit and upload it to GBS online platform where more HVAC system options are available. The first workflow option is easier but the resultant geometry in the gbXML file is more complex (due to surface triangulation), suggesting that the latter approach is preferable for more complex geometry. Since the INP file (eQuest) has a very high-level compatibility with BIM, it is worth assigning all the construction information, system specifications and schedules in BIM.

The investigation has found that EnergyPlus does not import mechanical systems and its visualization tool is not capable of rendering complex geometry, so it is recommended uploading the Revit-exported gbXML file to GBS online platform and download the IDF file. The geometric and construction information should be imported well but other information will need to be updated in EnergyPlus directly.

When IES or DesignBuilder is used, the Revit plug-ins can be used to easily import the BIM model into the corresponding program for further simulation. These plug-ins only transfer the geometric information into the BEM software. The construction and system information defined in Revit are not imported; they use the information selected from several drop-down menus.

10.4 Future work

Due to time limitation, there are a number of areas that could not be explored further and warrant future research:

1. Building upon the findings of this study, develop a comprehensive BIM-based energy analysis guide as an integral part of the BEP to specify how architectural models should be setup and modeled, and explain the integration process in detail, such as the input required from different disciplines at different stages of the project.

2. Determine the best practice to create curved surfaces and curtain walls in BIM so that they can be seamlessly export to BEM tools.
3. Test data transfer integrity and simulation evaluation of other BIM plug-ins, such as Revit IES or DesignBuilder plug-in.
4. Test more variables, such as more complicated building geometry (e.g. shading, exterior walls with uneven thicknesses), different geometric gap shapes, more space resolution settings, and more gap locations, etc.
5. Investigate into the breadth and depth of GBS parametric models. Because GBS automatically runs hundreds of parametric analyses, there is value in identifying whether or not the data transfer integrity from the parametric models is properly exported. As previously discussed, the "ASHRAE 90.1-2010" option is misleading because only HVAC system is updated to code.

APPENDIX A. INTERVIEW RECRUITMENT SCRIPT AND QUESTIONS

Recruitment Script

Dear <name>,

I am Stacy (Xi) Sun, candidate for MASc in Building Science under the supervision of Professor Jenn McArthur at Ryerson University. I am writing to invite your participation in a research study regarding BIM-based energy analysis. The goal of this research is to investigate current energy modeling practice and whether BIM-based energy analysis is adopted and trusted. I am conducting this study in partial fulfillment for my degree.

As you are recognized as an experienced energy modeller, your input and experience would be valuable should you be willing to participate. Please see the attached interview questions that we are planning to use and advise of your availability for a telephone or in-person (Toronto area) interview. The interview will last maximum 1 hour. Conversely, if you are unavailable for an interview but would be willing to respond to these questions via email, we would welcome that input. Please note that participation is optional and only consolidated results will be presented.

Best regards,

Stacy (Xi) Sun
Candidate for MASc Building Science
Ryerson University

Interview Questions
Review consent form with the interviewee

1. Could you please describe your role in the company and your background using BIM and/or energy analysis?

2. Could you check the software you usually use for BIM? If there are more than one software you usually use, could you indicate the percentage of use of each?

☐ Autodesk Revit
☐ Bentley Architecture
☐ SketchUp
☐ Graphisoft ArchiCAD
☐ Nemetschek Allplan Architecture
☐ Nemetschek Vectorworks Architect
☐ Softtech Spirit
☐ RhinoBIM
☐ CADSoft Envisioneer
☐4MSA IDEA Architectural Design (InterlliCAD)
☐ Gehry Tehcnologies – Digital Project Designer

3. Could you check the applications/software you use for energy modeling and analysis? What are the advantages and disadvantages of the chosen software? Are any of them particularly well-suited to BIM projects?

☐ IES
☐ Trane-trace
☐ eQUEST
☐ EnergyPLUS
☐ Bently HevaComp
☐ Carrier HAP
☐ EE4
☐ Green Building Studio
☐ Ecotect
☐ DesignBuilder
☐ DOE-2.2
☐ Bentley TAS Simulator
☐ CAN-QUEST
☐ Graphisoft EcoDesigner

4. In order to obtain an energy model, what approaches do you most commonly take?

☐ Conduct energy analysis in BIM software
☐ Export directly for use in a 3rd party software

☐ Build a Revit energy model, which is simplified from the architectural model, and import to a 3rd party analysis software

☐ Take advantage of Revit worksets

☐ My approach: ____________________

5. What are the major advantages and disadvantages/flaws of your current practice?

6. What strategies do you take to shorten the time needed and enhance the accuracy when creating an energy model?

7. How would you most prefer to obtain the necessary inputs for your energy models – (prompt: *for example, would you like them in a spreadsheet format, or built into the BIM model that could then be used with a plug-in*?) Why is this the case?

8. How much influence do you believe you have on the design? How are recommendations from the energy analysis considered by the wider team?

9. What are the major challenges or issues have you encountered regarding the use of BIM model as input for energy analysis? Anything else we are missing?

☐Software incompatibility

☐Lack of suitable plug-in or information exchange format (IFC, gbXML)

☐Improperly modeled (e.g. unbound or undefined) spaces

☐Inadequate data in BIM model

☐Poor material assignments

☐Use of typical Software (e.g. Revit) families do not reflect actual materials

☐The outputs are not reasonable

☐It is not a software/process I am familiar with and do not have time to learn it

10. Have you used gbXML or IFC to transfer information from the BIM model into the energy analysis software?
    a) If yes, what lessons have you learned to improve this process?
    b) If no, why have you not used these tools?

11. How do you simplify (clean up) BIM (Revit) model (what are the steps)? How long would it take for the model to be ready for energy modeling?

12. To what extent do you trust BIM-based energy modeling tools? Why?

13. Does the BIM Execution Plan guide the BIM model development to allow early analysis and/or repeated analysis?

14. Do you perceive any value to BIM-based analysis tools for schematic or detailed design and construction stage? Why?

15. Have you compared the energy modeling results with actual post-occupancy consumption? Have you found that the BIM-based tools were more, less or equally accurate in predicting actual consumption?

APPENDIX B. STEPS TO CREATE ZONES TO ATTIC

It was a challenge to create a zone for attic as the top surface was not automatically defined by a horizontal level datum. By consulting Autodesk Knowledge Network, the following steps were recommended using to place zones up to the roof.

1. Open the floor plan view in the project browser
2. Create a section view and make sure the section line intersects the roof
3. Activate the section view by double clicking on it
4. Add one level above the roof: “Architecture” tab → “Datum” panel → “Level”
5. Make sure “Areas and Volumes” is checked by opening “Architecture” tab → “Room & Area” panel → “Area and Volume Computations”
6. Activate spaces visibility in the floor plan view and the section view: enter “v” “g” on the keyboard → find “Spaces” from the dialogue and expand → check “Interior” and “Reference”
7. Place “Room” in the attic and drag room boundary down to fill between the ceiling and the roof
8. Assign “Space”: “Analyze” tab → “Spaces & Zones” panel → “Space”
9. At the level where roof locates, set the “Upper Limit” the level above and “Offset” 0mm

APPENDIX C. EXTRACTED GBXML TEXT

Extracted text from gbXML file related to the additional constructions around openings:

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