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BIM to BEM translation workflows and their challenges: a case study using a detailed BIM model

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Abstract: *This paper addresses the expedited translation process of a building information model (BIM) into a building energy model (BEM). Accurate systematic or automated translation of building geometry is the primary concern because it provides a faster and potentially more accurate alternative to recreating BEM geometry from floor plans. This BIM to BEM translation has been partially addressed by various efforts; however, obtaining a meaningful energy model geometry and extracting associated information from a detailed BIM still requires expertise and remains an elusive goal. This paper highlights currently available tools and workflows, identifies associated challenges and limitations, and suggests modelling techniques and potential software features for a better BIM to BEM integration. A net-zero energy commercial building was used in the case study, in conjunction with three energy simulation programs: OpenStudio, Virtual Environment, and Insight 360. This paper intends to provide industry professionals and researchers with modern BIM to BEM workflows.*

Keywords: *eSim, building performance simulation, model translation, energy modelling, BIM to BEM, interoperability*

INTRODUCTION

Building information model (BIM) promotes collaboration between disciplines by providing a multifaceted CAD model, containing relevant data throughout the building's life cycle, which can be exported to various function-specific software programs (Eastman *et al.*, 2011). BIM is a powerful tool that enhances multi-disciplinary collaboration, data management and integrated building design (Mayouf and Boyd, 2013). The ability to handle massive quantities of data and give rapid feedback during design provides an opportunity to integrate building performance simulation as a tool to guide design decisions. Seamless transition of information from BIM to building energy model (BEM) is expected to be a key driver for the broader adoption of building energy simulation in a project, one that would support energy-conscious building design processes.

Seamless integration between BIM and BEM, however, is still a research domain and is not yet ubiquitously adopted in industry. Thus, the manual BEM building process, described by O'Donnell et al. (2013) as "subjective, labor intensive, time intensive and error prone" that is "essentially reproducing already existing data", often leads to squandered efforts and modellers frustrated at the lack of suitable interoperability between programs. Motivations for achieving interoperability between BIM to BEM are substantial savings in time and effort, error reduction, and simulation model reproducibility over the current practice (Hitchcock and Wong, 2011).

In this paper, persistent challenges associated with automatic translation are explored, a sample of available software tools are introduced, and similar research efforts are presented. This literature review is limited to the broad understanding of BIM to BEM information flow and challenges, as well as an introduction for the three chosen energy modelling tools: OpenStudio, Virtual Environment, and Insight360. A case study is conducted using a detailed BIM from a 3-storey net-zero energy commercial building Sifton Center, and challenges and limitations of the workflow are discussed.

There were some issues that were foreseen to affect all modelling tools. The quality of the architectural BIM, level of geometrical inconsistencies, or completeness of space enclosures, would have an impact on the degree of success of the translation. The user's level of expertise on the BIM to BEM translation would also have an impact, as the process involves error-tracking, debugging, and manual adjustment.

CHALLENGES

The development and implementation of automated data exchange between BIM and energy simulation tools have been hampered by the industry culture of specialized practitioners being more comfortable with manual building data input than automated data exchange, the lack of available software programs that support a robust translation process (Hitchcock and Wong, 2011), and the technical expertise required.

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Many BIM models originate from design partners who are not familiar with the nuances necessary for energy modeling. They are often inconsistent and error-prone in creation, and are created with BIM tools whose objects and parameters significantly differ from the representation needed in performance simulation tools (Wetter and Van Treeck, 2017). These models translate poorly into energy modeling programs because they are aimed at construction documentation rather than performance simulation, often carrying architectural details irrelevant for an energy model while lacking the necessary details, such as clean space boundary, matching edges etc.

SmartMarket Report reported that surveys among practitioners had showed that the lack of tools, tools being too complicated or not having the required functionalities in current programs hinder the use of BIM for green projects and most users are 'frustrated' by the lack of a fully integrated approach (Bernstein, Jones and Russo, 2010). Automated BIM to BEM translation was in 2001 an "expensive and relatively rare solution" (Bazjanac, 2001), and unfortunately remains so today.

A successful translation will carry information related to the following domains: 1) building geometry, construction and material definitions, 2) HVAC systems, controls, and supporting systems, and 3) internal loads, building use, and operations (Bazjanac, 2009). This paper focuses on successful geometry translation.

GBXML AND IFC

Two data formats commonly facilitate BIM to BEM interoperability: Green Building XML Schema (gbXML) and Industry Foundation Class (IFC). Both data formats are capable of extracting and transferring geometrical information from BIM models (Ivanova, Kiesel and Mahdavi, 2015).

gbXML format was originally developed by Green Building Studio in 2000 to facilitate the transfer of building information stored in CAD-based BIM, enabling interoperability between disparate building design and engineering analysis software tools (GbXML Inc, 2018). It contains geometry and construction information, divided into three categories: ShellGeometry, SpaceBoundary and Surface. Each BEM software may import a single gbXML file differently because each program does not use all three categories to reconstruct the model but instead uses a combination of information to obtain the geometrical information (gbXML, 2013).

IFC, developed by buildingSMART, promotes and provides the only specifications for open-BIM throughout the building life cycle (O'Donnell *et al.*, 2013). Open-BIM is a universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows (buildingSMART, 2016). IFC format has an object-based data structure, and is able to share additional information to geometry and construction, such as space internal loads and HVAC systems (Wetter and Van Treeck, 2017).

AVAILABLE TOOLS

This section is not intended to be an exhaustive list of available tools, but an overview of three prominent tools chosen for the case study: OpenStudio, Virtual Environment (VE), and Insight360. Each tool represented respectively a freely available tool, a commercial grade package, and a BIM integrated web-based analysis tool.

In addition to the applications introduced below, relatively newer efforts such as Simergy, launched in 2012 by Digital Alchemy (Digital Alchemy, 2018), as well as BIM server platforms like EDMmodelServer (Singh, Gu and Wang, 2011) are actively pursuing enhancement of BIM to BEM workflows.

OpenStudio

OpenStudio is an open-source tool that supports whole-building energy modelling, developed by the National Renewable Energy Laboratory (NREL). The OpenStudio suite of tools includes the SketchUp Plug-in, stand-alone application, ResultsViewer and Parametric Analysis Tool. EnergyPlus is the thermal balance engine and Radiance is the daylight engine (OpenStudio, 2018). SketchUp Make 2017 was used for this paper.

Pros

A strength of OpenStudio is the output of EnergyPlus Input Data Files (IDF), which can be directly accessed and modified by the user. Directly editing IDFs affords configurability and transparency, including control over the detail aspects inaccessible through the OpenStudio interface. Being an open-source software allows users to script "measures" to automate repetitive tasks, and even share these measures with other users (OpenStudio, 2018). OpenStudio can import both gbXML and IFC formats and allows model creation from scratch within the user-friendly SketchUp environment. It includes construction templates and building activity schedules for a number of building types, vintages, and climate zones (The American Institute of Architects, 2012), providing an accelerated data input with EnergyPlus.

Cons

OpenStudio often experiences software errors, many of which are unexplained to the user and lead to crashes. When an imported file results in an incomplete or

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disjointed geometry, OpenStudio provides a cryptic non-comprehensive error report; finding and troubleshooting errors is manual, difficult, and time-consuming. Importing an IFC file follows a roundabout multi-step process involving a BIMserver. While the OpenStudio uses the SketchUp plug-in to provide access to OpenStudio geometry, it cannot read and convert the native SketchUp files nor export back into SketchUp (The American Institute of Architects, 2012). Some BIM elements, e.g. ground-level floor or roofs made with floor elements, are lost upon gbXML import. While OpenStudio's biggest strength is the direct access to EnergyPlus's input data files (IDFs), subject expertise is required to work directly with IDF files. Moreover, Trimble's SketchUp recently moved to a web-only interface (Trimble, 2018), leading to questionable longevity of OpenStudio as an off-line plug-in for SketchUp, as the software may no longer be actively developed further. Meanwhile, BigLadder software has taken on the legacy version of the program and is continuing the development independently under the name Euclid (Big Ladder Software, 2017).

Virtual Environment

Integrated Environmental Solution's Virtual Environment is a proprietary whole-building performance simulation tool. Analyses include thermal and comfort solutions, daylighting, solar studies, egression, and carbon emissions code compliance (Leaman, et al., 2007)

Pros

In contrast to OpenStudio, VE's platform is relatively stable and experiences fewer crashes. The report provided upon importing a gbXML file is detailed and informative, telling the user what the issue was and what actions the program had taken to address the problem. VE also offers an optional automatic geometry-correction functionality upon gbXML imports, reducing the chances of simulation errors caused by incomplete model geometry, consequently reducing the labour of manually correcting model inconsistencies (Carriere, 2017).

Cons

VE uses a proprietary simulation engine APACHESIM and does not allow users to access the simulation input source file for a possible inspection or manual modification. Many embedded hidden default values for simulation cannot be accessed (Attia, 2011), model viewing capabilities are limited (Azhar, Brown and Farooqui, 2009), and the model must be modified in a plan view or an isometric view rather than in a full 3-D view. Refining details in the later process requires expertise in the program (The American Institute of Architects, 2012).

Insight 360

Autodesk's Insight 360 program, launched in November 2015, is a fairly new energy analysis tool. It was a progression of Autodesk's Green Building Studio and was created to integrate BIM and BEM into the same software platform, in this case FormIt or Revit, to provide an easier transition between the two models. Insight 360 automatically converts BIM models into BEM models, and simulates the BEM using EnergyPlus and DOE2. A manipulatable web viewing portal is rendered through DOE2 information. The EnergyPlus file is provided for download. For now, it is meant for an early stage energy analysis and not detailed energy modelling due to the rough analysis resolution pre-set at the whole building level instead of each thermal zone, non-customizable operation schedule and HVAC systems, etc. It aids designers as a marketing tool that easily and visually conveys the broad energy impacts of the client's decisions (Butts, 2016).

Pros

From Insight's online portal, those who are given access can view high level energy results without needing the model or the Autodesk program. It is easy to catalog model history and the impacts of high level energy parameter changes. Such energy parameters are associated with photovoltaics, orientation, window shading, general construction types, infiltration, lighting efficiency, daylighting and occupancy controls, general HVAC (heating, ventilation, and air conditioning), operating schedules, and plug loads. When the energy parameters are changed, the EUI (energy use intensity) automatically updates a dynamic color-coded building benchmark that depicts ASHRAE Standard 90.1 and Architecture 2030 performance levels. The mean energy cost also automatically updates. The summary reports and analytical spaces and surfaces per room can be viewed in Revit. Construction values can be exported and edited as XML files (Butts, 2016).

Cons

The program, while stating to have the accuracy of VE, Trace, or SEFAIRA, does not provide enough detail to aid in the documentation needed for sustainability programs such as LEED, with the possible exception of lighting reports. Thus, if the energy model is to be used for compliance purposes, another energy modelling program must used (Butts, 2016).

By creating a BEM through Insight 360, a separate 3D view of the BEM will be created in the same Revit file. If changes are made to the BIM, the changes will not automatically update into the BEM, even though both the BIM and BEM are in the same file. A new BEM needs to

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be generated which would overwrite the previous BEM. Workflow is hence uni-directional, in which the online interface does not allow making changes to the model itself, but rather serves as a viewer window for pre-run energy analyses.

If the BIM model is incomplete or has geometrical inconsistencies, Insight360 will be unable to run energy simulations, though graphical BEM representation may be displayed. If a simulation is not run, a EnergyPlus file will not be generated. To retrieve the input data file, a separate login into Green Building Studio, instead of the Insight 360 web portal, is required.

RELATED WORK

There have been similar studies regarding geometry extraction from BIM, though mostly with basic building shapes. Ivanova et al. (2015) compared gbXML against IFC formats in their capabilities of extracting and transferring spatial and geometrical information from BIM. Petrushevski et al. (2015) integrated a collaborative mapping solution into generating a simplified BEM geometry, and compared the simulation results produced by the automated approach, semi-automated approach, and manual approach. O'Donnell et al. (2013) used Solibri Model Checker and Space Boundary Tool-1 to semi-automatically transform a detailed BIM of an institutional building, however a rebuild of the BIM was required due to the geometrical inconsistencies and errors in the original BIM.

Other BIM to BEM integration efforts such as IFCtoIDF Transformation Utility, RIUSKA, AECOO-1 Testbed, Space Boundary Implementation Guideline, IFCtoEnergyPlus Utility and CES BESM, Curtain Wall for Energy Analysis MVD, and ASHRAE RP-1468 are introduced in paper by Hitchcock and Wong (2011).

RESEARCH METHODOLOGY

This paper aimed to explore state-of-the-art practices in BIM to BEM translation, and to suggest modelling techniques and software features that would help support such interoperability.

Literature review was conducted on relevant topics including persistent challenges related to BIM to BEM integration, import/export file formats, related work, and available tools. A case study was then conducted emulating a common scenario for a practitioner. Three BEM tools were tested in the case study, each representing respectively a freely available software, a commercial grade package, and an integrated web energy analysis platform. Primary objectives of the case study were: 1) to assess the effectiveness of translating a complex BIM into BEM, 2) to compare time consumed on translation efforts versus creating BEM from scratch, 3) to assess the geometrical integrity of the imported model. And 4) to assess the effectiveness of Virtual Environment's automatic geometry correction functionality. Focus was placed on geometry translation, prevention and resolution of model translation errors, rather than on model calibration.

CASE STUDY

Using the three prominent BEM tools (e.g. OpenStudio, Virtual Environment (VE), and Insight 360), each representing different BEM environment, a detailed BIM of Sifton Centre was translated into BEM.

This paper was limited to only using gbXML format due to an error in OpenStudio that prohibited importing IFC files. Insight 360 operated directly from Revit, and thus did not need extracted data to operate.

Sifton Centre

The Sifton Centre of the West 5 Net Zero Community in London, Ontario, Canada was used as the subject of this case study. The Sifton Centre is an approximately 5,800 m^2 building with ground floor retail and two storeys of office space. The structure was finished in late spring of 2017 and was not yet fully occupied at the time of this study. The West 5 Net Zero Community is under active construction (West Five, 2017).

All case study methods used an architectural model with the mechanical and structural models linked in. The model files of all three were provided in Revit 2015, in which the architectural model was then modified as described in the below sections. The only modifications to the structural and mechanical models were those necessary to update the model to Revit 2018 and resolve any errors preventing the updating process.

OpenStudio and Virtual Environment

As the gbXML import of the original BIM resulted in disjointed and incomplete geometry in both OpenStudio and VE, the BIM had to be simplified and refined. A systematic manual modification approach proposed by Carriere (2017) was largely adopted. The translation effort could be categorized into four parts: 1) planning and setup, 2) simplifying the model geometry, 3) creating complete enclosures for spaces, 4) post-processing in BEM tools (Carriere, 2017). The model was repeatedly brought into both BEM tools during modification to confirm progress, and to determine when to stop modifying BIM and address the remaining geometrical inconsistencies within OpenStudio or VE. Some minor inconsistencies were difficult to trace or address in Revit, but more easily mended within OpenStudio or VE. About 90% of the issues

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were addressed by modifying BIM and 10% in energy modelling tools.

Of the four parts of translation process, geometry simplification was the most laborious and time-consuming. Once the detailed model had been linked and bound to a new Revit project file, floorplans and elevation views were created with a task-specific view template to de-clutter the view of annotations, architectural details, etc. The focus of simplification followed the order of multi-storey shafts, exterior walls, interior walls, and the miscellaneous. The elements irrelevant to thermodynamic simulation, such as furniture, columns, beams, stairs, railings, etc., were removed. Generic walls throughout the model were replaced with walls of uniform thickness. The thickness was set to match the curtain wall mullion thickness to ensure vertical and horizontal alignment. The replacement walls were color-coded to designate that the particular wall had been replaced, and the new wall names retained the construction information of the original wall. The wall names would later serve as references when re-assigning the correct wall construction in BEM tools. Where applicable, single-storey walls across multiple floors were replaced by one wall vertically spanning the floors to ensure alignment. Curtain walls were not modified, but generic walls above and below mid-height curtain wall systems were replaced. The original location of the core walls and exterior walls were preserved, while the locations of the interior walls were adjusted to remove sliver spaces. Floors and roofs were replaced using the same method. Elements that protruded out of the space enclosure, e.g. roof overhangs capped with walls or intricate parapets, have also been replaced by a simple wall or floor slab to retain the same shape of the shadow being cast. Figure 1 shows a stage in the model simplification process. The 3D view and floorplan view, often with other floors showing as underlay, were used alternatingly to understand the location of walls and other features over different floors, or to trace space boundaries below with space separation line (e.g. for the 3-storey lobby space).

Once the geometry was sufficiently simplified, "Spaces" were assigned to each enclosed area, including elevator shafts, stairwells, and small spaces. Multi-story spaces were assigned to the enclosures that vertically span over more than one floor.

In BEM tools, space adjacency is what later informs the software program of the wall type: exterior, interior, or shading. Leaving an enclosure within the building interior without space assignment leads the BEM program to define "exterior" walls inside the building around the unassigned space (Maile *et al*, 2013). For this reason, it was important that Revit spaces filled in the whole enclosure volume in

Figure 1: Revit screenshot during model simplification process. The replacement walls are color-coded and have uniform thickness, but still retain original construction information in their names.

the Sifton Centre. Level 3 was the only storey with ceiling plenums, which were defined as separate spaces.

VE's "geometry correction" function was used on every import instance to test the capacity of the algorithm. The algorithm follows "ABC" approach, where it will A) attempt to import space from the complete shell, B) if A fails, optionally extrude from floor, and C) if B is not performed or fails, import raw shell (IESVE, 2017). Importing raw shell means that openings and unmatched edges associated with the space will carry over to the energy model. In the case study, Shell Import Settings were left in default, allowing the VE to attempt to fix shell surface orientations, and attempt to heal bad geometry by adding surfaces to close the shell, when in Option A. The first setting automatically flips surface so that those facing outwards from the room are assigned the correct orientation (IESVE, 2017). Having incorrect surface orientation in BIM files can lead to incorrect room volumes, additional unmatched edges and missing surface area being detected, floor and ceilings being misidentified, and adjacencies being incorrectly determined (IESVE, 2017). Revit warnings or model inconsistencies spotted during gbXML imports were numerous and were addressed to the best effort by the order of significance.

Insight 360

A different approach was used for simulating through Insight 360. Three models were created for testing workflows in Insight 360. All three models were based from the same original architectural file and saved as three separate files. This was to ensure that all models used the same thermal properties for construction elements. This also saved time by removing the need to start a new project, create new views, create new import links, etc. Because all the construction was finished, an audit was performed on the original model to reduce file size. An audit removes any

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unused families and construction elements loaded into Revit. Generally, model audits should be performed by the designer creating the BIM (e.g. engineer or architect) so that model families are not removed from the project prematurely. Note that the Sifton Centre BIM was created in Revit 2015. Insight 360 was first released as an update in Revit 2016. The 2018 version of Revit and Insight 360 were used for this experiment.

Model 1 was the complete architectural model as provided. Before modifying the BIM for BEM purposes, a BEM was generated to establish a baseline. While the BEM generated, the analysis of the model failed. An error log stated "Error: Issue: An error has occurred related to the DOE-2 simulation…. Cannot simulate LAYERS aim0037 as given. The wall is too thin or U-VALUE CONSTRUCTION," along with two similar layer errors. The layers referenced in the error log were not found in the IDF file of the model. In an attempt to clear errors, all warnings produced by the Revit model were resolved. Some of these errors included overlapping walls and floors, gaps in building construction, and walls of negligible depth and/or thermal resistance. Please see Figure 2 for reference. Because Insight 360 is a young product, there is a shortage of formal documentation and support. However, Autodesk provided recommendations to troubleshoot errors on helpdesk pages and employee supported forums.

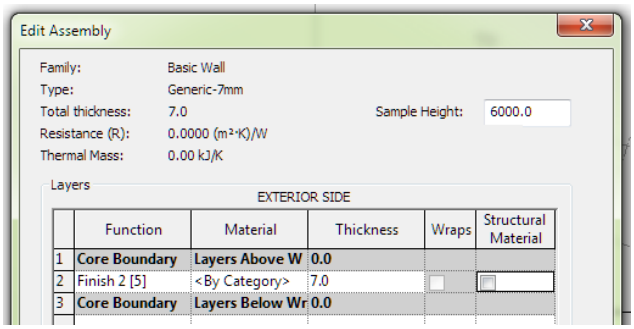

Figure 2: Example of a wall of with no thermal mass or thermal resistance.

Settings were changed to analyze building masses and thermal building elements, and the model was geometrically tidied. Heating and cooling loads were unable to be run successfully, returning a remote internal server error.

To successfully run a heating and cooling analysis, some background energy settings were changed. This included changing the location from Canada to the United States, changing the energy analysis from combined 'conceptual masses and building construction elements', to each 'conceptual masses' and 'building construction elements' individually. A heating and cooling analysis was still not successfully run for Model 1.

Model 2 started as the complete architectural model, but had all interior features removed, such as walls, stairwells, columns, etc. A BEM was attempted several times, following the same procedure as Model 1. However, a BEM was not successfully created, and therefore could not be analyzed.

Model 3 was the shell of the building redrawn from scratch. Layered walls (e.g. a "construction" wall paired with a "finish" wall) were combined into one wall that represented the depth and thermal properties. Some geometrical definitions, e.g. the targeted window-to-wall ratio, were input into the settings of Revit instead of directly modelled. After ensuring that there were no gaps in the façade of the building, Model 3 successfully generated an energy model, ran an energy analysis, and heating and cooling load model.

RESULTS

Despite extensive efforts invested in manually simplifying and correcting the original BIM model, none of the three BEM platforms successfully ran an energy simulation with it. The BIM was visually clean (Figures 3 and 4), but the imported geometry still contained numerous gaps and unmatched edges. Upon the first import of the BIM the VE reported 10609 unmatched edges in the imported geometry, which on the 10th iteration has been reduced to 3855. Though the number of inconsistencies significantly decreased after such manual effort, understanding and addressing the persistent issues in the already-simplified model became more difficult. It was concluded that a more systematic and rigorous approach was necessary; otherwise creating the BEM from scratch would be more efficient. Note that by creating BEM from scratch, the potential savings from automated model translation are lost. Because the translation approach did not generate satisfactory BEM geometry, the time difference against creating BEM from scratch was not assessed.

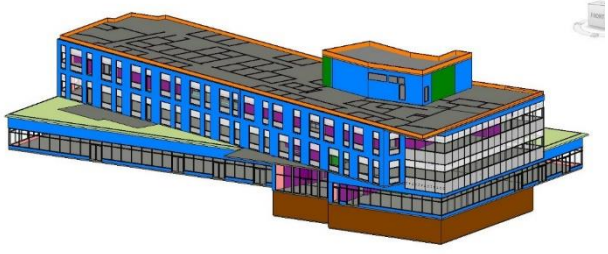

Figure 3: Manually simplified BIM for gbXML export. Walls were replaced to achieve uniform thickness across the whole model.

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Figure 4: Basement floorplan of the manually simplified BIM.

OpenStudio Results

OpenStudio proved to be unstable upon gbXML imports. The program handled earlier imports, but later iterations of import appeared without surfaces, as if in the wireframe mode. Users were left with no way to continue with the model, and no error report to indicate possible problems. This error was discussed in online forums and may originate from surface intersections. Other difficulties included malfunctioning of the "undo" button, and cryptic warning messages upon imports that were difficult to understand, and to locate and address the problem with.

Virtual Environment Results

The VE proved more stable upon gbXML imports, and produced an informative report outlining the automatic corrections applied to each space within the imported geometry. However, the "geometry correction" function was unable to bring the model up to a desired level of integrity, where the imported model would be a few minor corrections away from being simulation-ready. On the contrary, the geometry correction mechanism often added arbitrary surfaces, as shown in Figure 5, incorrectly representing the building's thermal characteristics. Geometry correction also left the model still showing gaps, missing walls and floors, and other geometrical errors, which required further manual intervention. The automatically added surfaces further complicated the following manual corrections. Thus, even when the correction algorithm reportedly drastically reduced the number of unmatched edges on the 10th and last import instance from initial 3855 down to 121, the model was still not deemed close to geometrical completeness, and no further imports were attempted. Another reported drawback to the correction algorithm is that it assigns default construction to the added surfaces, necessitating extra manual intervention (Carriere, 2017).

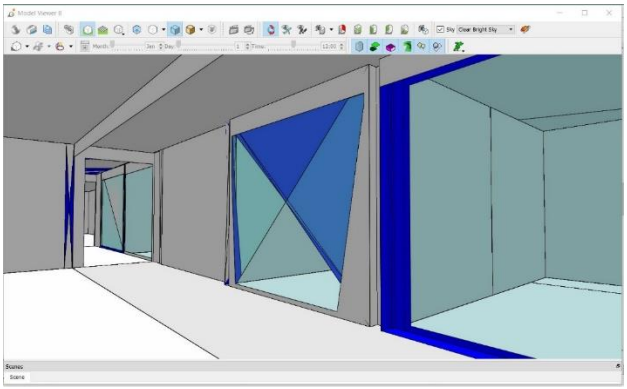

Figure 5: Arbitrary diagonally defined surfaces created by VE's "geometry correction" functionality. BEM geometry after automatic correction is still incomplete, and now more complicated to manually correct.

Insight 360 Results

Models 1 and 3 were able to successfully produce an energy analysis for 'building elements' and for 'conceptual masses and building elements'. Only the 'conceptual masses' setting led to BEM creation failure. Model 1 was unable, and Model 3 was able to successfully to generate a heating and cooling load report. Models 1 and 3 both successfully generated daylighting analyses, and lighting load analyses. Model 2 failed to successfully generate a BEM and was therefore unable to procure any further analyses.

While not being able to calibrate the models against metered data, it was somewhat possible calibrate Models 1 and 3 through Insight 360's online portal by changing the setting ranges. Settings include several window settings, wall and roof constructions, HVAC and operational settings, etc. When the energy analysis was run, the full range of the setting was considered in the reported EUI. Based on information given, the user was able to narrow the setting range. Figure 6 is the Energy Analysis Setting for Wall and Roof Construction of Model 1, in which 'BIM' designated the value selected from the BIM. Note that Wall Construction was much more detailed than Roof Construction in the provided architectural model. The setting range was not restricted to the 'BIM' value, which may help avoid incorrect modelling in instances such as shown in the Roof Construction without negating the effort of correctly modelled assemblies.

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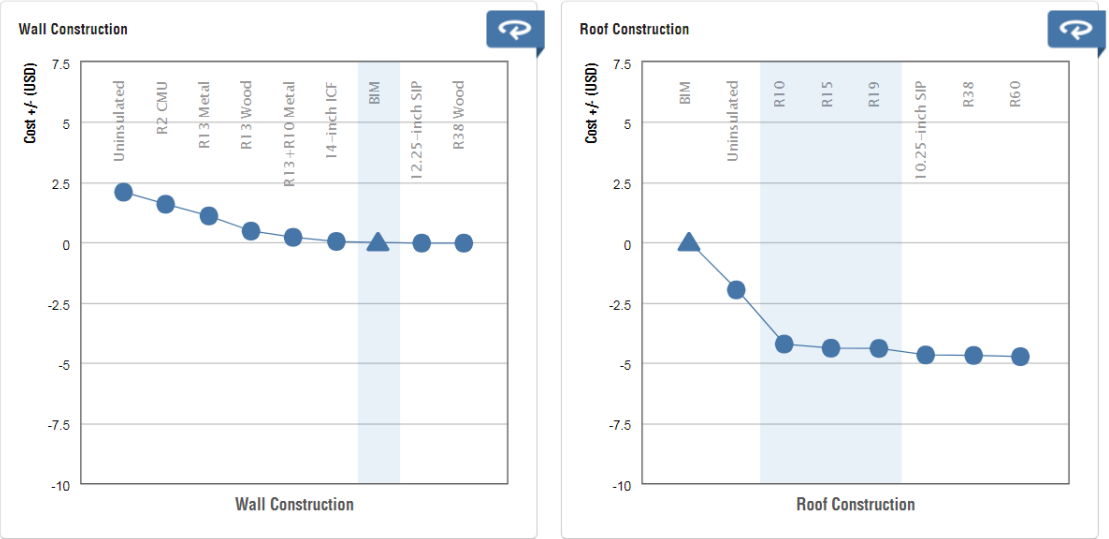

Figure 6: An example of the option range selected for Model 1 from Insight 360's online portal.

Key Similarities and Differences

Both OpenStudio and VE are designed for detailed energy modelling applications with options of importing BIM geometry, or starting from scratch within the program. The VE's software platform proved to be more stable than that of OpenStudio, but OpenStudio's modeling interface inside SketchUp is more intuitive to the user. The VE's automatic "geometry correction" algorithm only partially addresses geometrical inconsistencies.

It was found that a single gbXML file will result in slightly different geometries in OpenStudio and VE, e.g., curtain wall mullions will import as shading devices in OpenStudio but entirely omitted in VE.

Unexpectedly, OpenStudio also demonstrated a degree of built-in automatic geometry correction upon gbXML import: short interior walls were raised to meet the ceiling; curtain wall systems were aligned with the generic walls above and below in spite of the intentional misalignment in the BIM; and small gaps in the wall joins were closed, except when created by the *split wall* tool.

Insight 360 provides team members with an instantaneously dynamic and visual metric to see how high-level changes can affect the gross EUI of a building without necessarily needing an in-depth understanding of energy flows or energy analysis programs. However, Insight 360 does not provide detailed analyses.

DISCUSSION

As shown by the case study, moving information from BIM to BEM today requires a large amount of manual coordination, which is inherently resource-intensive, error-prone, and irreproducible. Part of the difficulty is that BIM is built in a discipline-specific manner, typically for architectural representation or construction documentation. BIM modellers should consider that the model may later be used to serve the other disciplines; thus, a standardized modelling approach is called for. Also, BIM software tools can be better equipped to support BIM's translation into the energy performance domain. For a more profound solution for achieving multidisciplinary interoperability, BIM-server is expected to play a key role.

Creating BIM with BEM in mind

When constructing a BIM with later BEM translations in mind, apply the following modelling guidelines to minimize errors and inconsistencies. Before drawing features in the model, establish the correct framework to design the building. To help establish this framework in Revit, area and volume calculations should be enabled, predefined space types should be reviewed and edited for the project, material thermal properties should be reviewed and edited for the project, decide if the energy model will be based on conceptual shapes and masses or use building elements to construct the model geometry, the zone depth division should be set if using conceptual shapes and masses, detailed building elements settings should be reviewed and edited if using detailed building elements, decide if the energy model needs to be done over multiple construction phases or only once, and decide if spaces or rooms will be used (Butts, 2016; Abdelalim, O'Brien and Shi, 2017).

Other parameters that should be set, but not necessarily before adding features, include project information such as the location and energy settings, the ground plane, the building space type settings such as occupancy and lighting

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and power schedules, the space boundaries to be defined by interior surfaces, the analytical surface and space resolutions, and inclusion of nearby buildings (e.g. simply as analytical masses) (Butts, 2016; Abdelalim, O'Brien and Shi, 2017).

Once features that are added into Revit the model should be kept simple and geometrically accurate, with no gaps at building joints (e.g. wall corners). A wall should not overlap with another wall; such segments should be modelled as one wall with the full assembly. Correct wall orientation needs to be assigned. Curtain walls should be modelled as one non-space bounding element or as a large window of the same thermal and visual properties of the curtain wall. Similar widows should be lumped as one if possible. Analysis planes should be set to the height representing the widest area of a room. Levels should be created at ceiling plenum heights. All rooms and spaces should be defined with the height set between the current level and the above level rather than using default offset from level, with the exception of sloped roof spaces. The enire building should be defined as a space or a room both horizontally and vertically including plena and shafts, with no nested spaces. All applicable Revit warnings should also be resolved (Butts, 2016; Abdelalim, O'Brien and Shi, 2017).

Note that frequent constructive communication between BIM and BEM personnel can provide clarity, reduce confusions and duplicate works between modellers, and help ease the translation process, regardless of the progress of standardization.

Improved support from BIM tools

BIM authoring tools could better support BIM to BEM interoperability by considering the following features:

- Extended warning capabilities to include Insight360 analysis domain. Currently there are no pre-analysis warnings or troubleshoot dialogues provided before or after an Insight360 analysis, and the user is left to decipher a vague error log.
- Optional model checking capability against gbXML or IFC export, possibly activated upon Space or Zone assignment. Ideally BIM authoring tools will suggest default remediation options to fix the geometrical or other issues, to which the user can respond immediately or later, depending on the severity of the issue.
- An option to view Space volumes in a standard 3-D view for an easier Space assignment and inspection.
- Default height setting for new Spaces set between current floor to the floor above with zero level offset, when "Compute area and volume" option is selected.
- An option to directly assign ASHRAE Standard 90.1 Space types, in addition to Revit space types.

BIM-server

A prominent solution to achieving integration between BIM and BEM, as well as with many other AEC disciplines, is through using a BIM-server. A BIM-server is a collaboration platform that maintains a repository of the building data, and allows native applications to import and export files from the database for viewing, checking, updating and modifying the data (Singh, Gu and Wang, 2011). The BIM-server consists of a Database Management System (DBMS) in which BIM data is stored, the Server Manager that supports multiple access for project participants, and the Server Access Control to control data accessibility by users (Oh *et al.*, 2015). BIM-servers are expected to allow exchange of information between the various applications involved in a building project life cycle including design tools, analysis tools, facility management tools, document management systems, etc. (Singh, Gu and Wang, 2011). BIM-server's potential at centralizing the fragmented communications in the complex design process as well as its readily acceptance by the design partners is shown in an experiment conducted with a simple BIM collaboration platform by Léon van Berloa and Thomas Krijnen (2011). Singh et al., (2011) has developed a theoretical framework of technical requirements for a comprehensive BIM-server.

CONCLUSION

The intent of this study was not an exhaustive comparison of BEM tools of their import capabilities, but rather an attempt to assess the feasibility of translating detailed BIM into BEM using the tools readily available in the market today. A detailed BIM of a three storey Net Zero Energy building was attempted for translation into BEM using gbXML format through the three energy modelling platforms: OpenStudio, Virtual Environment, and Insight 360. Much of the manual model simplification and correction effort was made to the original BIM to fix the prevalent geometrical inconsistencies; however, a functional translation was not achieved in the end. It was concluded that a more systematic and thorough approach to model correction and debugging was required. Presently, as shown through the case study, the amount of time and effort invested into attempted translations null the intention of saving time against creating anew. The only reliable way to create a useable BEM from the BIM was to redraw key aspects of the geometry, typically by extruding up the model from the floor plans. Naturally, the quality of the original BIM plays a significant role in the success of translation; hence BIM needs to be created with an eventual translation into BEM in mind. Specific BIM modelling techniques with such considerations, as well as the

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potential features within BIM authoring tools that would help support the translation process, are suggested. BIM server is introduced as a more holistic solution for BIM interoperability with performance simulation platforms, as well as with other disciplines in architecture, engineering, and construction industry.

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