SimBuild
2024

Eleventh National Conference of IBPSA-USA
Denver, Colorado
May 21 – 23, 2024

Evaluating the Feasibility of a Workflow for Following the ASHRAE Standard 90.1 Performance Rating Method Using Building Information Modeling

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Abstract

This paper explores the integration of building information modeling (BIM) into energy code compliance modeling and uncovers both the opportunities and challenges associated with workflow automation solutions across the three traditional design phases: schematic design; design development; and construction document. A workflow was established that leverages Autodesk Revit, OpenStudio, and the OpenStudio Standards performance rating method (OSSTD-PRM). Three BIM models of the Department of Energy prototype medium office building, representing distinct design phases, were created in Revit. The BIM models were converted into OpenStudio models using the Revit Systems Analysis tool. Baseline energy models were created from the OpenStudio models for each design phase by using the OSSTD-PRM. Opportunities and challenges associated with this proposed workflow were analyzed by comparing the geometry, internal loads, and heating, ventilation, and air conditioning systems across the generated baseline models. Although BIM technologies were found to be feasible for automating PRM generation, some challenges that may limit full marked adoption were also identified. These findings encourage the development of an automated and streamlined modeling and simulation framework that tightly integrates building design with performance path energy code compliance, paving the way for designing sustainable and energy-efficient buildings on a nationwide scale.

Introduction

In the United States, commercial and residential buildings collectively account for a significant 40% of total energy consumption and contribute to 30% of carbon emissions (U.S. Environmental Protection Agency, 2022). Building energy codes play a pivotal role in reducing energy consumption within buildings (U.S. Department of Energy, 2022a), and are crucial regulatory instruments for working toward the goal of achieving net-zero emission by 2050.

Building energy codes have evolved to incorporate a performance path compliance approach, which is viewed favorably by industry stakeholders as the key to achieving low energy consumption and ultimately net-zero energy buildings. Building energy modeling (BEM) tools are required to estimate building energy consumption and demonstrate compliance.

The use of BEM tools has grown from traditional design evaluation and optimization (Ramesh et al., 2010; Xu et al., 2016) to retrofit analysis (Heo et al., 2012; Sun et al., 2016) and code compliance. Despite the recognition by designers of its value in supporting high-performance design, its application is frequently hampered by the labor-intensive, time-consuming, and error-prone process of manually creating the building model in the BEM tool of choice. Typically, BEM models must be created from scratch based on the design information available when compliance analysis is performed. In addition, the modeling strategies shaped by the intricate modeling rules often lead to challenging situations, demanding days or even weeks of effort from both design teams and the rating authorities (Niemeyer & Rao, 2020).

Building information modeling (BIM) is intended to serve as a shared knowledge base offering a dependable foundation for informed decision making. It continues to gain popularity among design professions due to its potential to enhance project efficiency, reduce errors, and improve decision-making processes (Eastman et al., 2011). The commercial market for BIM tools has many competitors, including but not limited to Autodesk Revit, Graphisoft Archicad, and Bentley OpenBuildings Designer. The broad use of these tools creates opportunities for improving upon the traditional manual process of creating an energy model. The Industry Foundation Class and the Green Building XML (gbXML) data models define how information can be exchanged between BIM and BEM. Several open-source tools that leverage these data models have been developed to support BIM-to-BEM workflows (Bazjanac & Maile, 2004; Xu et al., 2019). In recent years, multiple commercial tools that claim some ability to support BIM-to-BEM workflows have been updated or released (Autodesk, 2024) (Pollination, 2023).

Automated workflows for code compliance have also been widely offered by BEM software developers. Tools such as DesignBuilder and Trace 3DPlus provide automation solutions for demonstrating compliance with the performance rating method (PRM) in ASHRAE 90.1 Appendix G (ANSI/ASHRAE/IES, 2019). The PRM outlines a performance-based approach for meeting the ASHRAE 90.1 standard requirements. These tools guide users through a "wizard" to generate a proposed and baseline energy model. The process significantly reduces the workload for code compliance modeling. In contrast, a fully automated model generation and PRM compliance tool was developed as part of the OpenStudio-Standards (OSSTD) (PNNL, 2023). Although some rule implementations are planned for future releases, the tool can automatically adjust geometry, internal loads, and heating, ventilation, and air conditioning (HVAC) transformations as well as support mixed-use buildings. The measure supported by the tool can be accessed through application programming interface function calls or through the OpenStudio Command Line Interface, which makes it appealing to BEM tool and simulation workflow developers.

Currently BEM software tools often incorporate a wizard approach to gather additional design data from users, like space type, to ensure accurate code compliance modeling (DesignBuilder, 2021).While BIM inherently contains these design details, many existing BIM-to-BEM workflows focus on supporting early-stage design decision making, neglecting in-depth modeling details required for code compliance (Pollination, 2023). This study is motivated by the hypothesis that BIM-to-BEM automation has the potential to improve performance path energy code compliance accuracy and reduce execution time.

This paper evaluates the feasibility of using existing tools to develop a workflow that leverages BIM for energy code compliance modeling and verification. Workflow challenges are identified, and improvements are suggested for streamlining the workflow to support the automated generation of a proposed and baseline model following PRM rules such as those found in ASHRAE Standard 90.1 Appendix G. An ideal workflow is envisioned that a) ensures accurate rule implementation and eliminates unintentional errors and intentional "cheating", and b) facilitates automatic updates to PRM compliance status as designs change and allow the modelers to spend more time and project budget evaluating energy-efficiency design and operation strategies.

Methodology

The evaluated workflow for this study consists of two main components:

1. Development of the BIM model and translation to a BEM model.
2. Implementation of the ASHRAE Standard 90.1 PRM on the generated BEM models using an automated approach.

Step 1: BIM models and export routes

Four different export routes to translate BIM-to-BEM were explored. Autodesk Revit 2024 was used to create BIM models and the OpenStudio was chosen as the target BEM file format.

The target building is based on the Department of Energy Prototype Medium Office building (U.S. Department of Energy, 2022b) assumed to be located in Denver, Colorado. The prototype building model was further developed via the addition of interior architecture, office furniture, and a lighting layout to support the evaluation of lighting design decisions and the development of semantic interoperability standards. Details of this "high-fidelity" prototype medium office building can be found elsewhere (Collier et al., n.d.). The building is rectangular with a footprint measuring 161 ft by 108 ft, where the longer perimeter sides have a north-south orientation and contains 17,420 ft^2 per floor. The building was created in Revit, following three levels of details requirements: schematic design (SD); design development (DD); and construction documents (CD). Although PRM requires fully detailed design specifications, SD was included in consideration of industry needs for compliance evaluation in early design stages.

Schematic design

The schematic design is a shoe-box model that was created using the conceptual masses option in Revit. It implies that there are no actual envelope elements such as walls, roofs, or windows. Figure 1 shows a typical building floor plan in Revit (top) and the generated OpenStudio model (bottom). The following inputs were implemented:

- Geometry shape is a simple shoe-box model representing a three-story office building.
- Envelope elements including roofs, exterior walls, and slabs are modeled using the Revit conceptual massing feature.
- Windows are modeled as a percentage of exterior wall area.

- Generic assemblies from the Revit built-in library are used as the default envelope construction.
- Revit default internal loads are assigned based on building typology according to various standards and databases (e.g., ASHRAE 90.1, ASHRAE 62.1 and CBECS data) (Autodesk, 2024).
- A single thermal zone per floor is defined.
- No actual HVAC systems are modeled, but an ideal load air system is automatically generated in the export process.

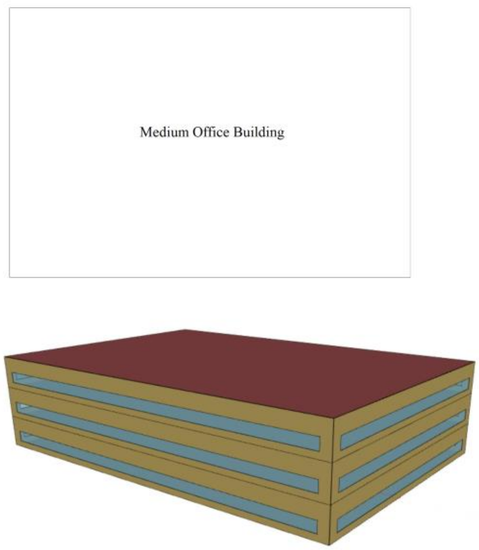

Figure 1. The SD phase typical floor plan (top) and generated OpenStudio Model (bottom).

Design development

The DD model was created using actual building elements in Revit. Figure 2 shows the first-floor plan in Revit (top) and the generated OpenStudio model (bottom). The following inputs were implemented:

- Geometry that separates some spaces by their functions is defined.
- Actual building envelope elements are modeled including walls, roofs, floors, and windows.
- Schematic construction types in the Revit built-in library are assigned as the assemblies for envelopes.
- Internal loads are assigned on a space-by-space basis according to various standards and databases.
- Thermal zones are defined with a core/perimeter layout. A single thermal zone may encompass several spaces.
- A variable air volume (VAV) reheat packaged rooftop unit is modeled with one system serving each floor.

Construction document

The CD model was created using actual building envelope elements and detailed floor layouts. Figure 3 shows the first-floor plan in Revit (top) and the generated OpenStudio model (bottom). In the CD model, the following inputs are considered:

- More detailed architectural, structural, and lighting layouts are defined.
- Actual building envelope elements are modeled including walls, roofs, floors, and windows.
- Actual constructions are assigned as the assemblies for envelope elements.
- Internal loads other than lighting are assigned on a space-by-space basis according to various standards and databases. Lighting loads are assigned based on the actual modeled luminaires.
- Thermal zones are defined with a core/perimeter layout. A single thermal zone may encompass several spaces.
- Plenum spaces are defined.
- A VAV reheat packaged rooftop unit is modeled with one system serving each floor.

Export routes

Four export routes were explored for transferring data from a BIM tool (i.e., Revit) to a BEM tool (i.e., OpenStudio).

1. Revit native gbXML
2. Revit Systems Analysis OpenStudio model
3. Revit Systems Analysis gbXML
4. Autodesk Insight gbXML.

The gbXML models generated by export routes 1, 3, and 4 differ in terms of their content. All gbXML models include essential information such as geometry, construction, internal gain definitions, and schedules. The gbXML exports made via Revit Systems Analysis and Autodesk Insight contain additional information, but particularly related to HVAC objects. Notably, the basic OpenStudio import method (i.e., user interface) only translates a limited set of gbXML contents, including geometry, constructions, thermal zones, and schedules. The translation of the remaining contents can only be achieved using OpenStudio measures.

The Revit Systems Analysis (routes 2 and 3) offers a streamlined workflow that effectively translates most of the gbXML content into BEM using OpenStudio measures. Various export modes are available in Systems Analysis, including “Use Conceptual Masses and Building Elements,” which was used for the SD model, and “Use Rooms or Spaces,” which was employed for the DD and CD models.

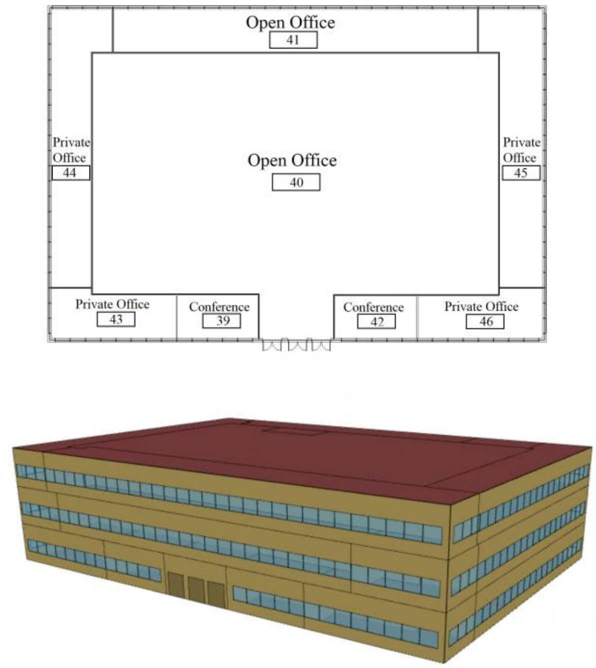

Figure 2. The DD phase first floor plan (top) and the generated OpenStudio Model (bottom).

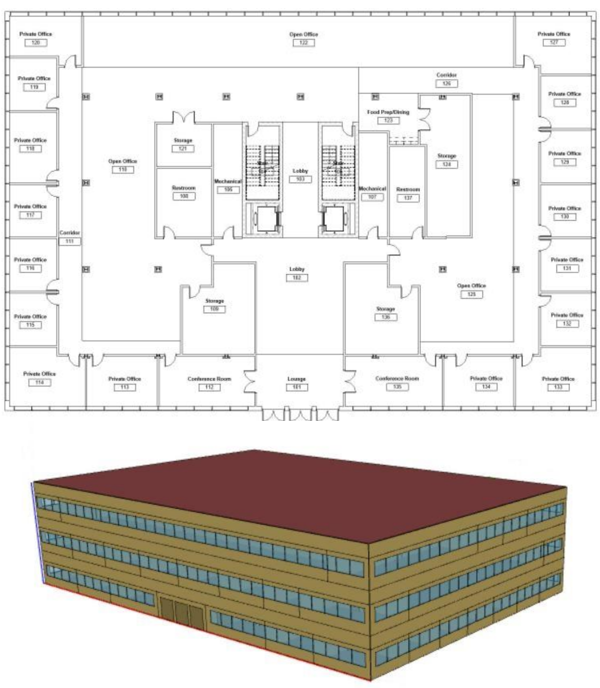

Figure 3. The CD phase first floor plan (top) and the generated OpenStudio Model (bottom).

The BEM model will inherit all rooms and will incorporate the preassigned thermal zoning from the BIM model. In the BIM model, multiple spaces can be associated with the same thermal zone indicating that they are controlled by a single thermostat, and this is reflected in the BEM model.

In Step 2, only the Systems Analysis export route (route 2) is evaluated to showcase the ASHRAE 90.1 PRM capabilities and limitations of OSSTD-PRM.

Step 2: Apply 90.1 performance rating method

The exported BEM-compatible model was used to generate a baseline model according to the PRM compliance rules. PRM was implemented by OSSTD Ruby Gem. This gem extends the OpenStudio SDK (NREL, 2023b) and offers a collection of measures and resources that, for example, automate the construction of typical BEMs in the OpenStudio format from existing geometry via high-level methods (NREL, 2023c), and performs the transformations associated with PRM. Its primary function is to automate the generation of a proposed model and baseline model from a user model following a set of modeling rules. To fully implement the PRM rules, OSSTD-PRM requires data that cannot be captured in an OpenStudio model. The OSSTD-PRM uses utilities to collect this information from the user.

The method in OSSTD-PRM was accessed through the OpenStudio Command Line Interface (NREL, 2023a). The OSSTD-PRM utilities were used to input the building area types for window-to-wall ratio (WWR), HVAC system selection, and service hot water (SHW) system. Two flags were added to the input to allow users to experiment with turning off the baseline rotation and unmet load hours requirements. The PRM measure inputs are summarized in Table 1.

Table 1. PRM measure input data.

Variable	Value
Building area type for WWR	Office 5,000 to 50,000 ft^2
Building area type for HVAC	Other nonresidential
Building area type for SHW	Office
Is exempted from rotation?	No
Is exempted from unmet load hours	No
Climate Zone	ASHRAE 169-2013-5B

Model Preparation

The OpenStudio model obtained through the Revit Systems Analysis typically needs some additional processing for PRM automation. More specifically, details about standard space type, as well as HVAC and other building service systems, need to be checked and sometimes defined.

Standard space type

In the PRM, space types play a pivotal role in determining parameters like lighting power density, while building types dictate factors such as WWRs, SHW systems, and the HVAC systems. The space types used by the PRM are defined in the same ASHRAE 90.1 document and referred to as “standard space types.” However, these space types are not always used by designers, thus creating a mapping challenge.

The intricacy of this challenge for automating BIM to PRM is exacerbated when cross-validating different building area types. In PRM, there are three building type categories used to determine the baseline WWR, HVAC, and SHW system types. For instance, a section of a building model that is categorized as an “Office (<=5,000 ft^2)” building type to determine the baseline model WWR should not be classified as a “Multifamily” building type to determine the baseline model SHW system. Similarly, spaces designated as “Dormitory” building type should not be mistakenly tagged as “Non-Residential” building type to determine the baseline model HVAC system.

In the Revit model creation process, default space types are assigned, and sometimes designers do not modify the defaults until later design phases. In either case, space types need to be checked against the standard space type list and modified, if necessary, for the PRM to deliver accurate results. However, despite the availability of these default space types in the exported models, there is an essential need for an additional mapping step to align them with the space type names listed in the PRM. The space type misalignment issue was consistently observed in all models generated during this study. To ensure successful model generation, the team had to manually map the space names from Revit to those used in PRM prior to using the OSSTD-PRM. This manual effort presents a significant challenge, especially in later design phases where the number of spaces increases.

Ideally, designers would assign standard space types to Revit models in all phases of design, and a validation tool would be incorporated as part of the export process to ensure that that model does not contain any space type assignments that are not in the standard list. If assigning space types from the standard list is not possible or suitable, then the export process might facilitate a semi-automated mapping sequence, where users select a standard space type to map to each space found in the model that is not in the standard list, thereby preserving the model but ensuring correct PRM and avoiding repetitive manual work.

HVAC and other building service systems

During the SD phase, an ideal-load HVAC system is commonly defined, given that energy modeling at this stage primarily focuses on load reductions, and thus a complete HVAC system is not typically deemed to be necessary. However, the PRM requires the definition of a comprehensive HVAC system due to specific requirements, such as space conditioning definitions and transformation rule logics that rely on the definition of details like fan power distribution ratios.

In addition to using ideal-load air systems, several export routes face challenges when it comes to translating the design HVAC system into energy models. For instance, the native gbXML export feature in Revit does not export HVAC system information. On the other hand, Insight 360 does export a complete HVAC system in the gbXML file, but OpenStudio is unable to import the HVAC data from a gbXML file using the basic import feature. Revit Systems Analysis appears to provide the best support for HVAC system export. It generates a complete OpenStudio model using a gbXML-based schema developed internally by Autodesk. The resulting OpenStudio model includes a comprehensive HVAC system description that can be directly used for OSSTD-PRM baseline model generation without modification.

Several other vital building systems are not fully supported by the various BIM-to-BEM export processes, including SHW, heating, renewables, and system controls. The absence of data related to these systems can significantly impact the OSSTD-PRM baseline model generation process, potentially leading to inaccuracies.

Table 2 presents the HVAC and SHW systems added to the exported BEM model. Both systems were created using the OpenStudio default settings. For all models, the HVAC system was modeled with one air handling unit per floor, while the SHW was modeled with one system for the entire building.

Table 2. HVAC and SHW systems.

System	SD	DD	CD
HVAC	Packaged Rooftop Unit	Packaged DX Rooftop VAV with Reheat	Packaged DX Rooftop VAV with Reheat
SHW	Single SHW Loop	Single SHW Loop	Single SHW Loop

Discussion

Building geometry

The generated baseline models were compared across design phases to identify and validate any discrepancies. Figures 4, 5, and 6 provide perspective views of the generated baseline models for each design phase. Visual inspection confirms that the OSSTD-PRM successfully captures the evolution of the building’s geometry as the design progresses. Examples include the adjustment of windows in each space to meet the target WWR specified by PRM. Additionally, constructions are correctly replaced based on the climate zone and assembly type according to ASHRAE Standard 90.1-2019, Appendix G. Table 3 lists the performance of these constructions.

Table 3. Construction performance.

	Constructions Performances in SD, DD, and CD
Slab on grade (F-Factor)	0.73
Roof (U-Factor)	0.063
Wall (U-Factor)	0.084
Window (U-Factor)	0.57
Window (SHGC)	0.39
Door (U-Factor)	0.7

The consistency in results demonstrates that the variations in geometry among the three design phases has little impact on the application of transformations in PRM. However, it is important to note that among the list of export routes, the Systems Analysis is the only one capable of producing a clean CD OpenStudio model with minimal manual clean up. Applying PRM to models with unclean geometry can lead to unexpected behaviors, as shown in Figure 7, where the baseline model generation process removed windows on the first and second floor and increased window sizes on the third floor. The causes of these behaviors could be attributed to the presence of floating surfaces, which are common in some export routes.

Internal loads

The internal loads generated in the different design phases varied significantly, with the maximum difference reaching as high as 60% for occupancy. Notably, all internal loads increased during the DD phase but slightly decreased in the CD phase. This result is primarily due to the diversification of thermal zones. In the SD phase, internal loads were estimated at the building level. However, in the DD phase, more detailed floor plans were defined, incorporating spaces like conference rooms and open offices, resulting in higher internal loads.

As the floor plans became even more detailed in the CD phase, additional space types, including corridors and lobbies, were introduced, leading to a reduction in the internal loads. These results underscore the significant impact of thermal zoning on internal loads. A comparison of values between the user model and the baseline model (Table 4) indicates that the OSSTD-PRM effectively captures the trend in changes of lighting power density as the design progresses.

HVAC system

The OSSTD-PRM effectively generates a packaged VAV with reheat system (System Type 5 from the ASHRAE 90.1-2019 PRM) for the baseline models, with minimal variations in heating and cooling efficiencies due to relatively small differences in calculated capacity (ANSI/ASHRAE/IES, 2019; Goel et al., 2017). However, the most significant issue observed in this study relates to the fan performance curve.

Table 4. Internal loads comparison between the user and baseline models.

User	SD	DD	CD	Max.V
Plug Loads (W/ft2)	0.540	0.678	0.598	25%
Occupancy (ppl/ft2)	0.0050	0.0080	0.0075	60%
Lighting (W/ft2)	0.9	1.0	0.93	11%
Baseline	**SD**	**DD**	**CD**	**Max.V**
Plug Loads (W/ft2)	0.540	0.678	0.598	25%
Occupancy (ppl/ft2)	0.0050	0.0080	0.0075	60%
Lighting (W/ft2)	1.0	1.11	1.03	11%

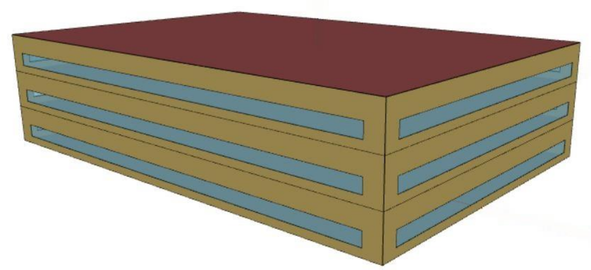

Figure 4 SD baseline model.

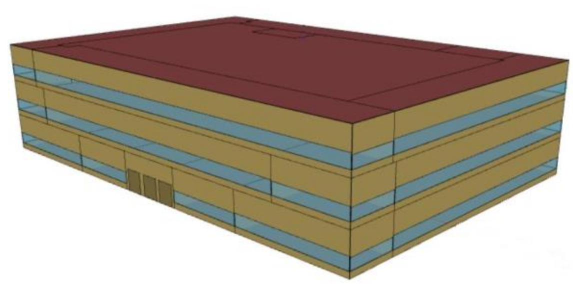

Figure 5 DD baseline model.

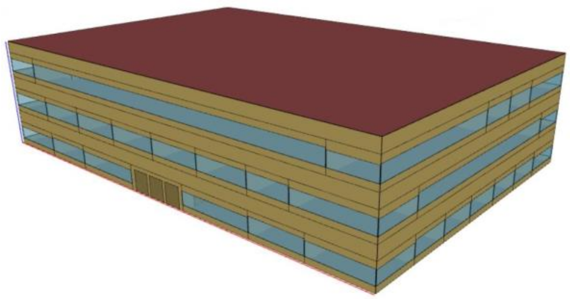

Figure 6 CD baseline model.

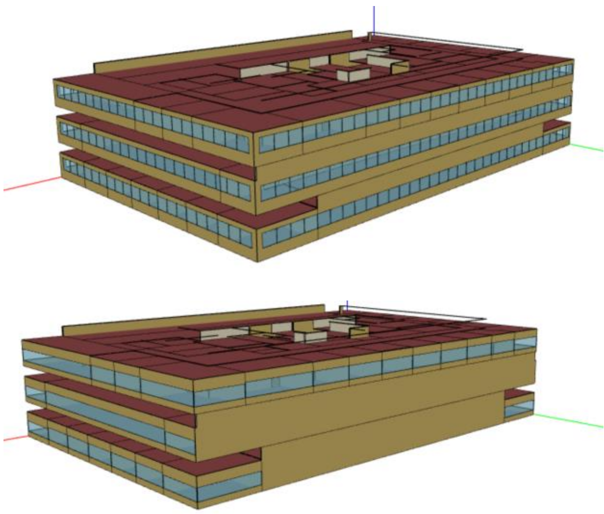

Figure 7 Demonstration of unclean user model (top) and generated baseline model (bottom).

Table 5. VAV fan performance curve.

	SD	DD	CD
Fan Power Coeff 1	0.027828	0.0013	0.0013
Fan Power Coeff 2	0.026583	0.1470	0.1470
Fan Power Coeff 3	-0.087069	0.9506	0.9506
Fan Power Coeff 4	1.03092	-0.0998	-0.0998
Min flow fraction	0.1	0.2	0.2

The OSSTD-PRM determines a fan performance curve according to various factors, such as zone configuration. A fan serving a single zone operates differently than one serving multiple zones. In the SD phase, only one zone is defined for each floor. This results in the generation of one HVAC system serving the single zone in the baseline model, leading the OSSTD-PRM to select a single-zone VAV fan. In the DD and CD phases, with more detailed zoning, the PRM created a multizone VAV fan with a variable speed drive and a fixed static pressure setpoint, which performs significantly differently (Table 5) (Goel et al., 2017). This difference results in fan energy consumption variances and consequently affects both cooling and heating energy use in the baseline model. The results indicate that a simplified one-zone-per-floor layout from a mass model may not be the most suitable floor layout for the OSSTD-PRM. Instead, a recommended approach would be to define a minimum core-perimeter zone layout to improve modeling accuracy.

Conclusion

This study investigated the feasibility of integrating BIM, BEM, and PRM using existing software tools. Three distinct Revit models were created to represent the traditional design phases: SD, DD, and CD. Revit Systems Analysis was used to convert the BIM models into OpenStudio models, which were then used to create BEMs. When comparing these baseline models, it was evident that the building external geometry complexity has minimal impact on OSSTD-PRM generation; however, the thermal zone layout significantly influences internal load gains and HVAC systems. Furthermore, it is important to note that the workflow can demand a substantial amount of manual effort, including tasks like editing space types and defining or modifying HVAC systems in the exported BEM model for all design phases. For the evaluated software tools, the DD phase appears to be the most suitable level of detail for automating the BIM-to-PRM workflow, given the existing BIM-to-BEM export routes. Although design explorations during the SD stage are one of the most frequent uses of BIM-BEM workflows, the SD BIM models lack essential energy performance details (e.g., information related to the HVAC system), and the generated baseline model is highly influenced by its simplified zoning assumptions. The use of BIM at the SD stage to generate a baseline model can potentially result in incorrect compliance outcomes. Further, the use of CD models can, depending on the export route chosen, lead to geometry issues that result in unexpected behaviors from the OSSTD-PRM measure.

Future work will explore other commercial BIM-to-BEM methods to identify options that are best suited for use with the PRM. Another interesting avenue for future work could involve comparing the simulation results of the baseline models among the three design phases and exploring potential use cases of the BIM-to-PRM workflow.

Acknowledgment

The authors would like to thank the support from Dr. Amir Roth, the technology manager for BTO's Building Energy Modeling subprogram.

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