INTERFACING BIM WITH BUILDING THERMAL AND DAYLIGHTING MODELING

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ABSTRACT

This paper presents our research and development of system interfaces between Building Information Modeling (BIM) and Building Energy Modeling (BEM), for supporting integrated architectural design and energy simulation. Our methods utilize the BIM authoring tools' Application Programming Interface (API) to translate BIM into Object-Oriented Physical Models (in Modelica) for building thermal simulation, and input files of ray-tracing software (Radiance) for daylighting simulation. Based on the methods, we have created two prototypes: *Revit2Modelica* and *Revit2Radiance*. Using these prototypes, when BIM (Revit models) are created for building design, multi-domain simulations (thermal and daylighting) can be conducted immediately. BIM becomes a common user interface for architectural design and building performance simulations.

INTRODUCTION

A lack of interoperability between architecture models and building energy models prevents the efficient use of simulation in the building design process. This paper presents our research and development of system interfaces between Building Information Modeling (BIM) and multi-domain simulations: solar thermal and daylighting. The objectives of the research are: (1) to enhance the interoperability between architecture modeling and energy modeling; (2) to enhance the coordination and interaction between thermal and daylighting models; (3) to enable more efficient and accurate simulation input, supporting an improved design process informed by simulation; and (4) to enable BIM as a common user interface for the multi-domain simulations.

Our research methods include: prototyping the system interfaces through BIM's Application Programming Interface (API); and comparative testing with benchmark energy models for validation, in which BIM is constructed for the energy models and results of BIM-based and the original simulations are compared. For thermal modeling, both BIM objects and the topology are mapped to Object-Oriented Physical Modeling (OOPM)-based models, through constructing OOPM-based BIM Package and OOPM-based BIM models. For daylighting, BIM's location data, geometry, and materials are exported to daylighting simulation tools.

We have created two corresponding prototypes demonstrating our methods: BIM to Thermal and BIM to Daylighting. The prototypes are created using the BIM authoring tool Autodesk Revit and its API, and simulation tools including Lawrence Berkeley National Laboratory (LBNL)'s Modelica Buildings library for thermal modeling and Radiance/DAYSIM for daylighting modeling. The results show that BIM models created in Revit can be converted into Modelica thermal models and Radiance/DAYSIM daylighting models through automated steps with high efficiency and accuracy.

The following sections will present details of the research methods, implementation, results, and validation, and discuss findings for interfacing BIM with building energy modeling. In this paper, based on context, BIM may refer to Building Information Modeling or a Building Information Model.

LITERATURE REVIEW

Buildings consume about one-third of the world's energy (NSF 2009). The use of electric power and heat in the building sector also accounts for about 40% of the world's greenhouse gas emissions (NSTC 2008). Sustainable buildings with efficient energy use and minimal environmental impact are in urgent and great demand. Solar technologies, integrated into buildings, help conserve energy and reduce greenhouse gas emissions significantly (Prasad and Snow 2005). The major uses of solar in buildings are across multiple domains, including thermal, daylighting, and building integrated photovoltaic (BiPV). When designing energy efficient buildings, it is necessary to integrate different technologies into a combination of systems (Hestnes et al. 2003). For example, in terms of the window-to-wall ratio, buildings' daylighting performance and thermal performance may have conflicting requirements to architectural design. In order to be most effective, a holistic and integrated approach to building design is necessary for optimizing solar energy utilization and reducing the consumption of energy in buildings (Hestnes et al. 2003).

Problems and Challenges

When considering design modeling and simulation tools, data exchange and interoperability problems exist, requiring acquisition of building geometry from computer-aided design (CAD) tools for energy simulation (Bazjanac 2001), geometry simplification for thermal modeling (Bazjanac and Kiviniemi 2007), and exchange of BIM data with thermal modeling. Similar to thermal simulation, daylighting simulation requires complicated building geometry and materials entered into simulation. Modeling of spaces and daylighting has special challenges, requiring characterizations of the resource and efficient methods of simulation (Carroll 1999). Participants of a survey on the use of daylighting simulations in building design named complexity of tools and insufficient program documentation as weaknesses of existing programs (Reinhart and Fitz 2006).

Inadequate interoperability has been estimated to cause $15.8 billion of unnecessary expense per year in the U.S. building industry (Gallaher et al. 2004). As computing power increases rapidly, simulation run times will likely be a less important concern, but data interoperability will remain a bottleneck in the design-simulation flow (Maile et al. 2007). Meanwhile, the difficulty of using state-of-the-art building simulation tools is overwhelming to most architecture users (Charron et al. 2005).

Currently, few energy simulation programs integrate BIM in the simulation process. Green Building Studio can be used with Autodesk Revit, while significant model preparation for simulation compliance is still needed after BIM is created.

In view of the complexity of sustainable building design and simulation, there's a significant need for a new integrated BIM, thermal, and daylighting modeling approach that can provide easy-to-use and accurate simulation at the early design stage, when design strategies have the major influence on the building performance. Existing multi-domain simulations, e.g. Hamdy et al (2011) has not integrated BIM in the process. Our research aim is to integrate BIM and multi-domain simulations.

Goal and Approach

The goal of this project is to enhance the use of simulation in sustainable building design. To achieve the goal, we developed an integrated modeling approach combining BIM, thermal, and daylighting modeling, named *Physical BIM* or *PBIM* – integrating physical simulation capabilities into BIM.

For BIM to thermal modeling, our new method is based on the emerging but currently separated technologies of BIM and Object-Oriented Physical Modeling (OOPM). While BIM supports 3-Dimensional (3D), semantically-rich, and parametric modeling for design and construction in a building's lifecycle, OOPM facilitates the simulation and analysis of both natural and artificial physical systems, with non-causal, object-oriented, and equation-based modeling (Fritzson 2004). Our novel method takes the advantages of the advanced features of both BIM and OOPM.

For daylighting, our method translates BIM geometry and material data into daylighting models. Based on literature review, our integration of BIM and multi-domain simulations (both thermal and daylighting) is a novel development towards simulation-driven design for sustainable buildings.

Our approach is to access BIM data in the BIM authoring tool's modeling environment through BIM's Application Programming Interface (API). This is an alternative approach to the use of the inter-exchangeable BIM data format - Industry Foundation Classes (IFC). With an acknowledgement of the benefits of IFC, the advantages of our method are as follows: (1) the method allows more seamless and direct design-simulation integration without the translation from BIM to IFC and to simulation models, which increases complexity and is error prone; and (2) our method preserves the parametric modeling capability that exists in the BIM tools, but not in IFC data. As design changes parametrically, objects modified in BIM can be updated automatically in the simulation models thus design options can be tested quickly with our approach.

From a design and simulation software user's point of view, both BIM and OOPM are object-based modeling approach, in which rich graphic and non-graphic representations allow direct manipulation of BIM and physical objects, and provide users with a common user interface metaphor. From a design and simulation software developer's point of view, similar object-oriented programming methods used in BIM and OOPM facilitate the development of system interfaces between the two representations.

Building Information Modeling

Building Information Modeling (BIM) is an emerging technology in the Architecture/ Engineering/ Construction (A/E/C) industry. As a product, BIM is a digital representation of physical and functional characteristics of a building that can serve as a shared knowledge resource for building information (NIBS 2008). As a process, BIM is the set of operations for constructing a digital model of the building to facilitate the exchange and interoperability of information (Eastman et al. 2008). BIM's semantically-based, object-oriented, and 3D modeling approach facilitates the access of comprehensive model data, including objects and their properties used in design, construction, and operation. In addition, BIM's parametric design capability enables quick, interactive, and real-time design changes (Lee et al. 2006). However, a lack of physical properties or the capability to modify them in BIM limits BIM's direct use in simulation. For example, in Revit 2013, materials' thermal properties are included in the building element material libraries, but there are missing parameters, such as solar and infrared absorptivities, which are needed for thermal simulation. Finally, the complexity of BIM requires simplification in order to form thermal envelopes and zones for thermal simulation (Bazjanac and Kiviniemi 2007). Research such as Geometry Simplification Tools (Bazjanac 2008) and

ASHRAE 1468 project (Clayton, et al. 2010) began to provide guidelines and methods for model simplification and translation from BIM to thermal modeling.

Object-Oriented Physical Modeling

Object-oriented physical modeling (OOPM) is a fast-growing area of modeling and simulation that provides a structured, mathematical, and equation-based modeling (Fritzson 2004). Modelica is a relatively new, unified OOPM language used for differential algebraic equation (DAE)-based simulation (Fritzson 2004). Existing Modelica authoring tools include Dymola (by Dassault Systèmes) and OpenModelica (by PELab, Linköping University), among others.

The topology of a component connection diagram in Modelica directly corresponds to the structure and decomposition of the modeled physical system (Fritzson 2004). This enables a natural mapping from the BIM structure to OOPM.

Lawrence Berkeley National Laboratory (LBNL)'s Buildings Library is a Modelica-based building thermal modeling and simulation system (Wetter 2009). The library is validated (Nouidui et al. 2012) and under continued development. The execution time of Modelica building system models can be comparable with TRNSYS if experimental controls are carefully made (Wetter and Haugstetter 2006).

However, with the existing LBNL's Modelica Buildings library, a user needs to write programming code to construct building models in Modelica and run the simulation. Our system automatically converts BIM (Revit) models into Modelica-based building models that can run thermal simulation using LBNL's Modelica Buildings library. This automatic method will reduce human errors when creating building energy models.

METHODOLOGY

Our methodology is to map BIM to physical modeling, prototype a Physical BIM modeling process and associated tools, and evaluate the process and tools with benchmark simulation results.

Preprocessing BIM

Before output energy models, BIM will need to be preprocessed by the following methods:

Addition: adding data that are missing in BIM but required by physical modeling, e.g. solar absorptivities of materials.

Translation: data translation between BIM and physical modeling, such as the translation of different semantics (e.g., rooms to thermal zones).

Calculation: values to be calculated based on other values in BIM, e.g. air volume needs to be calculated in BIM before passed to simulation, or splitting an exterior wall into multiple walls to satisfy energy modeling's required input of wall-window pairs).

While it is still needed, preprocessing may be reduced significantly due to the use of automatic translation between BIM and building energy models. For example, in the sample of BESTEST Case 600 in LBNL Modelica Buildings library, the two windows on the south wall need to be combined into one with an equivalent area in the simulation to satisfy the required wall-window pair definition. This preprocessing increases users' time and effort when manually creating the energy model. When we use automatic BIM to Modelica translation, our PBIM system will keep the two windows and split the wall hosting the two windows. The area ratio of the two walls equals to the area ratio of the two windows – this can be easily calculated by our program. This modeling approach (splitting the walls for multiple windows) helps deal with windows of different materials, in which case the combination of the two windows does not work. This example shows that some of the users' manual simplification/translation tasks are no longer needed if we use automatic BIM to energy modeling translation. The user modeling time is thus reduced, although the run time of the simulation may be increased. This way, the original design intent is maintained consistently in all the models and the energy performance of each building element (e.g. each of the two windows in the example above) can be examined separately.

Mapping building objects

Currently, PBIM system can map building elements that significantly influence energy performance, such as rooms, air volume, walls, roofs, floors, doors, and windows. For thermal simulation, BIM object classes are mapped to OOPM classes. For daylighting, BIM's geometry and material data are mapped into surface and materials models.

Mapping building topology

Connectivity of building components or model topology plays an important role in constructing energy models. To accomplish this, PBIM extracts the building topology from BIM and maps it into OOPM topology (through Modelica's *Connect* method) that directly corresponds to the structure and decomposition of the modeled buildings.

PROTOTYPING

We have created two prototypes demonstrating our methods: ***Revit2Modelica*** for BIM to thermal modeling translation, and ***Revit2Radiance*** for BIM to Daylighting translation. The prototypes are created using Autodesk Revit as a BIM authoring tool and its API, and simulation tools including Lawrence Berkeley National Laboratory's Modelica Buildings library, Radiance, and DAYSIM. Figure 1 shows the overall workflow of PBIM including BIM to multi-domain simulations (thermal and daylighting).

Currently Revit models do not contain complete thermal and daylighting parameters. Therefore, we added certain parameters to BIM through the use of external databases. For thermal modeling, the added parameters (including solar and infrared absorptivities, etc.) and Revit built-in parameters are passed from BIM to Modelica models. For daylighting, the added material roughness and specularity are passed from BIM to Radiance.

BIM to Thermal Modeling

Revit2Modelica is a BIM to thermal modeling framework including Revit API programs (written in C# programming language), *Modelica BIM package,* and *Modelica BIM Structure*.

Revit API programs include the classes that assist in adding data to BIM and those that can access BIM data and output Modelica code. The Modelica BIM package contains wrapper classes of building element classes in LBNL Modelica Buildings library. For example, our Room class is a wrapper of the MixedAir class in LBNL Modelica Buildings library. The need of the wrapper classes is to create similar object semantics and structures as in BIM to facilitate the mapping from BIM object classes to Modelica energy object classes. Modelica BIM Structure uses the Modelica BIM package to construct building thermal models whose structures are in between (or a hybrid of) BIM and the building models in LBNL Modelica Buildings library, to facilitate the mapping from BIM to Modelica energy models.

Based on BIM (geometry, materials, location, etc.), the prototype will output a building energy model file in Modelica following the Modelica BIM Structure, and immediately call Dymola to start the simulation and produce results including heat flow of each building element, room temperatures, and annual heating and cooling loads. Figure 2 shows the workflow diagram of Revit2Modelica.

BIM to Daylighting Modeling

Revit2Radiance is a BIM to daylighting prototype written in C# programming language using Revit API. Based on BIM (geometry, materials, location, date / time, a camera view, and sensor points), the prototype extracts the building surfaces in triangle meshes and other data needed to generate input files of Radiance and DAYSIM. Once the input files are created, Revit2Radiance will immediately call Radiance and DAYSIM to run daylighting simulations. The results include: Radiance-generated illumination images, human sensitivity images, and isolux contour plots, and DAYSIM-generated annual illumination data. Figure 3 shows the workflow diagram of Revit2Radiance.

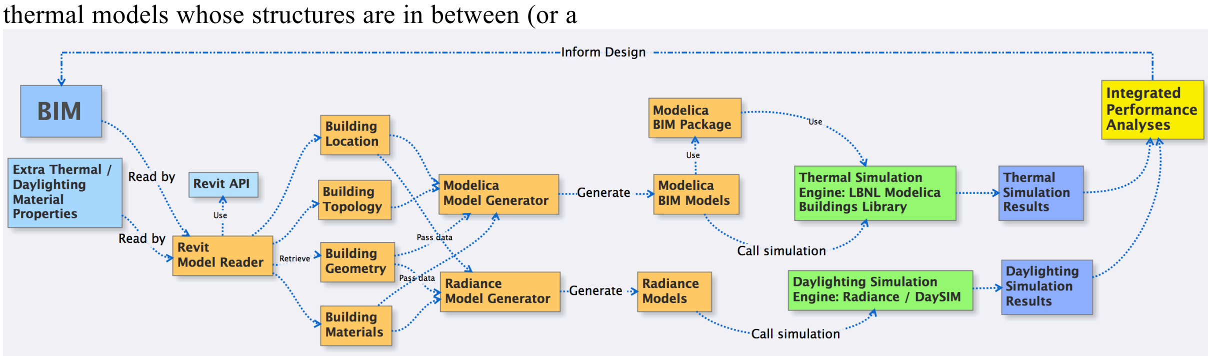

Figure 1. Workflow of PBIM: BIM to multi-domain (thermal and daylighting) simulations. In the diagram, the components of Integrated Performance Analyses to Inform Design will be implemented in the future. The gold color components represent our PBIM prototype components.

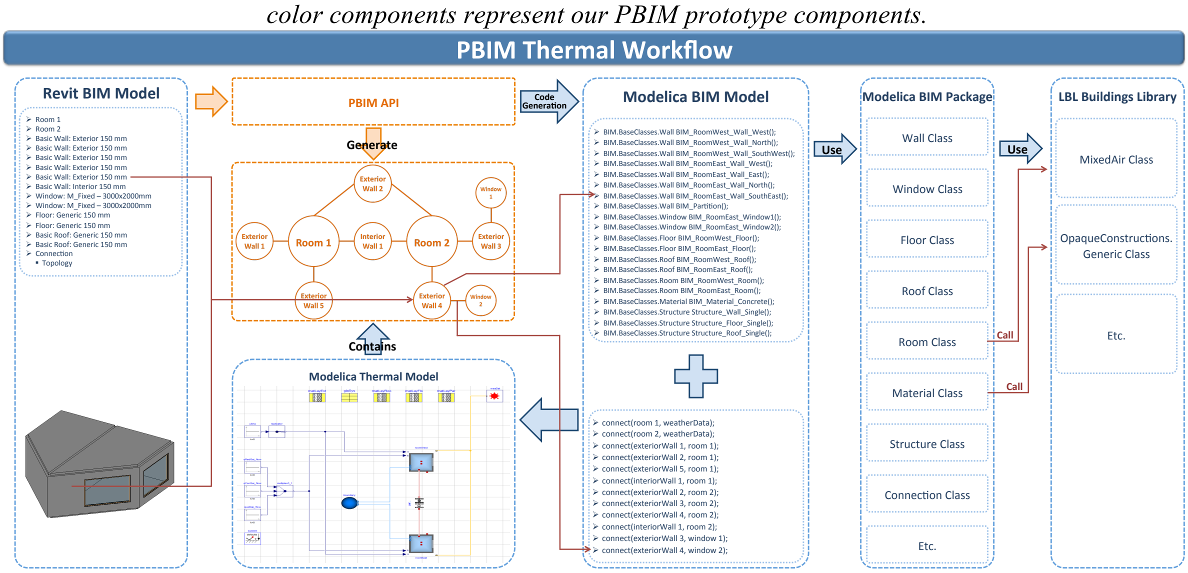

Figure 2. Revit2Modelica workflow

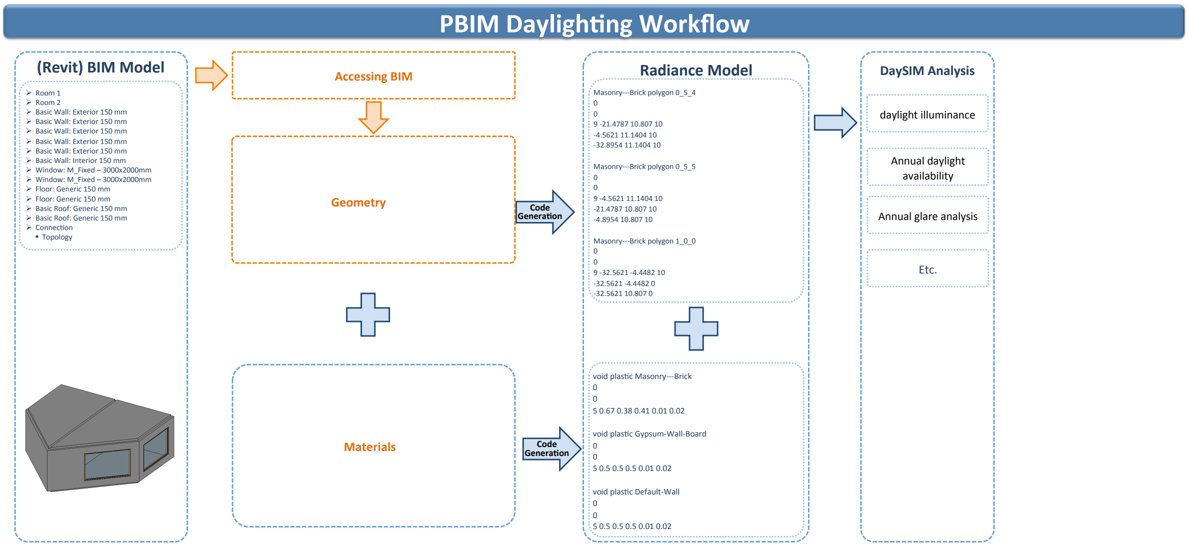

Figure 3. Revit2Radiance workflow

VALIDATION

In terms of thermal modeling, Revti2Modelica-generated Modelica models have different code structures and different components compared to the LBNL Modelica models for the same buildings. To validate PBIM results, we have conducted a series of experiments to compare simulation results. Each experiment includes two models: one is automatically generated from BIM by Revit2Modelica, using the PBIM's Modelica BIM package and Model Structure (that use LBNL's Modelica Building's Library as a simulation engine), and the other is manually created following the structure of LBNL Modelica Buildings library's sample models. The experiments yielded identical simulation results from paired models of each test case.

For daylighting, we use the same Revit models to generate Radiance and DAYSIM models, in order to demonstrate that BIM can be a common user interface for multi-domain simulations. Because the test models are created for benchmark thermal simulation cases, there are no standard daylighting results to compare for validating our Revit2Radiance. Therefore, currently we only visually examine the Radiance rendering results and compare them with the Revit models (to validate the geometry and materials). More validation study for Revit2Radiance will be conducted in the future.

The LBNL Modelica Buildings library has been validated using ANSI/ASHRAE Standard 140-2007 (ANSI/ASHRAE 2007). The simulation results of LBNL Modelica Buildings library are within the range specified in the Standard (Nouidui, et al. 2012). We compared the results generated by Revit2Modelica to the results of LBNL's Modelica models for the same test cases. Here we use BESTEST Case 600 as a test case for explaning our validation method and results. Case 600 is a one-zone design with light weight constructions. It has two windows on the south facing wall without shading devices. Its simple HVAC system is operated with 20°C heating and 27°C cooling temperatures. We created a corresponding BIM model for BESTEST Case 600 (Figure 4) and processed it with Revit2Modelica and Revit2Radiance. During the development process, we used conventional manual methods to create the BESTEST Case 600 Modelica model following our Modelica BIM Structure (Figure 5) in order to calibrate Revit2Modelica. However, our final Modelica model used for the following comparisons was produced automatically by Revit2Modelica.

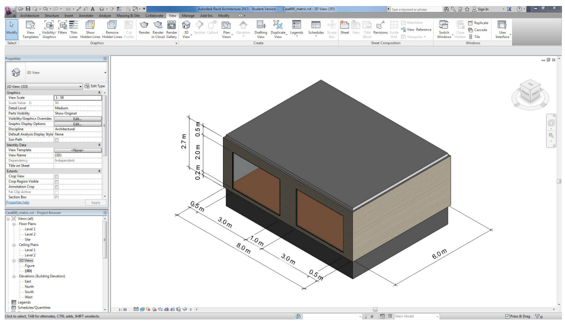

Figure 4. BESTEST Case 600 Revit model

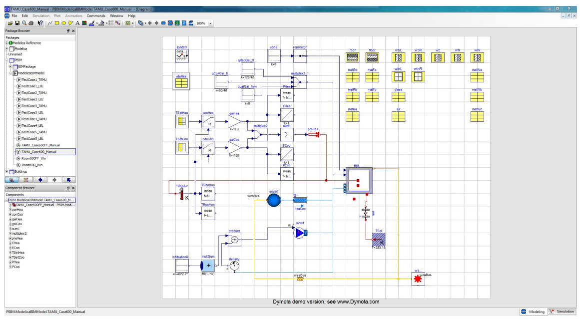

Figure 5. BESTEST Case 600 Modelica model following Modelica BIM Structure (manually

created in Dymola during the development of automatic Revit2Modelica).

Revit2Modelica

We performed a one-year simulation for BIM-generated Case 600 Modelica model for: (1) annual heating and cooling loads and (2) peak heating and cooling loads. Figure 6 shows the annual heating and cooling loads simulation based on Revit2Modelica.

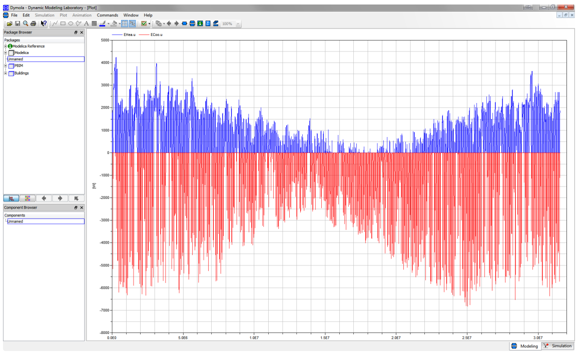

Figure 6. Results of annual heating and cooling loads of BESTEST Case 600 (shown in Dymola through Revit2Modelica).

While our major comparison is between LBNL Modelica Buildings library and PBIM's Revit2Modelica, to be more complete, we also juxtapose results of five other tools documented in ANSI/ASHRAE Standard 140-2007 in the comparison chart and tables below.

Figure 7 shows the results of annual heating and cooling loads across simulation tools. Our PBIM system produces the following results: 5.474 MWh of heating loads and 6.941 MWh of cooling loads. The results are similar to those of LBNL Modelica Buildings library (5.44 MWh of heating and 6.97 MWh of cooling loads), which are also comparable with the results of other tools in ASHRAE Standard 140-2007.

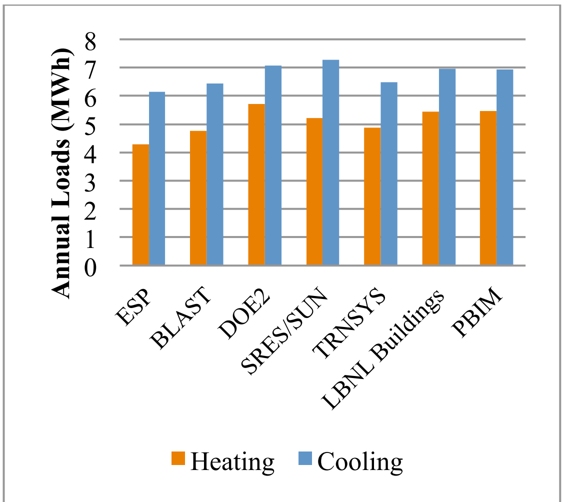

Figure 7. Annual heating and cooling loads of BESTEST Case 600 through Revit2Modelica.

Table 1 and 2 show the comparison of annual peak loads of heating and cooling, respectively. PBIM's Revit2Modelica results in 4.248 kW peak heating loads and 6.816 kW peak cooling loads, which are comparable with the corresponding results of LBNL Modelica Buildings library.

Table 1
Annual hourly integrated peak heating loads of Case 600

TOOLS	LOADS(KW)	DATE	HOUR
ESP	3.437	4-Jan	5
BLAST	3.940	4-Jan	5
DOE2	4.045	4-Jan	5
SRES/SUN	4.258	4-Jan	2
TRNSYS	3.931	4-Jan	6
LBNL Buildings	4.229	4-Jan	5
PBIM	4.248	4-Jan	5

Table 2
Annual hourly integrated peak cooling loads of Case 600

TOOLS	LOADS(KW)	DATE	HOUR
ESP	6.194	17-Oct	13
BLAST	5.965	16-Oct	14
DOE2	6.656	16-Oct	13
SRES/SUN	6.827	16-Oct	14
TRNSYS	6.486	16-Oct	14
LBNL Buildings	6.821	17-Oct	13
PBIM	6.816	17-Oct	13

Overall, our PBIM's Revit2Modelica produces similar results as LBNL Modelica Buildings library. Figure 7 and Table 1 and 2 are adapted from the corresponding figure and tables in (Nouidui, et al. 2012, Figure 2 and Table 1 and 2), with our PBIM results added.

There are slight differences between our results and LBNL's, which are expected due to the reasons below:

(1) Our model structure is not the same as LBNL's. For example, there is a difference between the two structures in terms of the order of building enclosure elements as arguments in Modelica thermal calculation functions. Reducing model tolerance (in Dymola) can reduce errors.

(2) We have different building components generated for our Modelica model than the manually created Modelica model from LBNL Modelica Buildings library. For example, as mentioned in Methodology, the two windows on the south wall are combined into one window with an equivalent area in LBNL's model but our algorithm splits the wall into two walls each having one of the windows (reason explained in Methodology).

Revit2Radiance

Using the same BIM of BESTEST Case 600, we ran our Revit2Radiance program and produced Radiance and DAYSIM daylighting analyses. Since there is no standard daylighting results of BESTEST Case 600 for comparison, we visually examined the results including the Radiance illumination and rendering results (Figure 8) and DAYSIM annual illumination results for selected sensors (Figure 9). The results demonstrate that the same BIM can be used in different simulations.

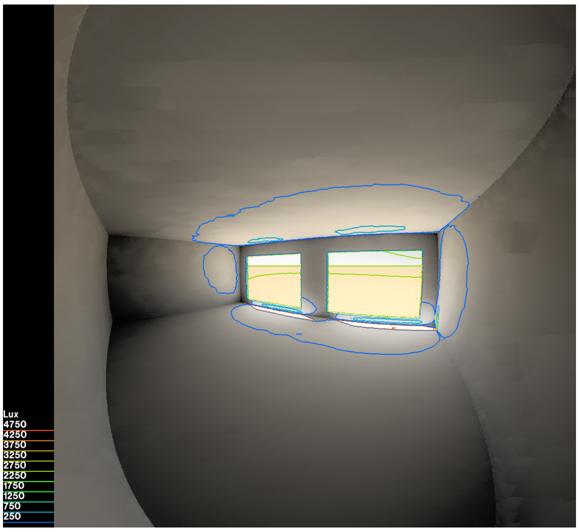

Figure 8. Radiance illumination result and rendering of BESTEST Case 600 (through Revit2Radiance)

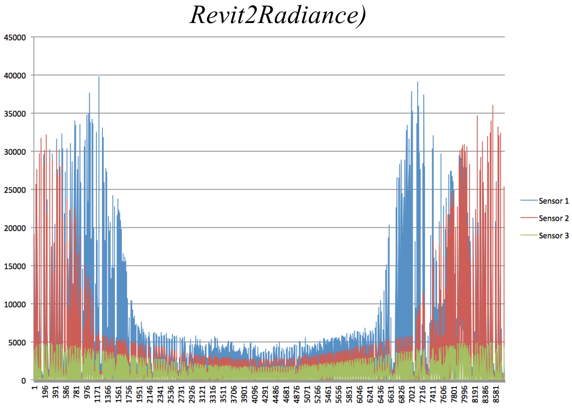

Figure 9. DAYSIM annual illumination results of BESTEST Case 600 (through Revit2Radiance)

CONCLUSIONS

Significance: The significance of the project lies in the following: our research demonstrates a new method for reducing the interoperability problem that exists between architectural design models and energy simulation models. The project is expected to benefit sustainable building design by integrating BIM and multi-domain simulations (thermal and daylighting presented in this paper). BIM becomes a common user interface for architectural design, thermal simulation, and daylighting simulation. The advantages of using BIM as the common user interface for simulations include: it helps maintain data integrity among different models; BIM's interactive 3D modeling environment is easier to use for creating simulation models than creating building description files through coding (e.g. in Modelica) or through other inter-exchangeable file formats (e.g. converting BIM to CAD models and then converting CAD models to Radiance models). After BIM is created, both thermal and daylighting simulations can be completed quickly. Furthermore, our approach enables each building element's thermal performance be examined separately. Architects can then be better informed to improve their design.

Major findings: BIM models created in Revit can be converted into Modelica thermal models and Radiance/DAYSIM daylighting models, through automated steps with high efficiency and accuracy.

Based on the different input requirements for simulations, we used different strategies for mapping BIM to simulation models. The mapping from BIM (Revit) to OOPM (Modelica) is proved to be a successful strategy for interoperability between architectural models and thermal models. Compared to legacy thermal modeling libraries written in procedural programming languages (e.g. *ASHRAE Toolkit for Building Load Calculations* that we also investigated and experimented for BIM to thermal translation), object-oriented thermal modeling (LBNL's Modelica Buildings library) facilitates better interoperability with BIM.

The more direct mapping from BIM (Revit) to daylighting modeling (Radiance/DAYSIM) is also proved to be successful, and it becomes the first direct translator between Revit and Radiance (based on our literature review).

There are differences in data representation of the building geometry and materials between BIM and thermal/daylighting modeling, which needs to be addressed based on research such as ASHRAE RP 1468 (Clayton, et al. 2010).

Discussions: From the point of view that design is about change, a BIM authoring tool with parametric change capabilities is essential for the architectural design process. Our approach provides a very easy to use interface for almost seamless operation during the design process. Though IFC uses relational data representation, it is complex to program and implement in software (Dong, et al. 2007). It is therefore a reasonable choice to include BIM authoring tools in the BIM to simulation process. Nonetheless, IFC's benefit of supporting interoperability among different BIM applications and different simulation tools enables IFC to play an important role in the translation from BIM to energy simulation (Bazjanac 2008). The IFC approach has an advantage in that our prototype does not work with other BIM authoring tools than

Revit. However, the same API method can be applied to major BIM authoring tools supporting API programming.

FUTURE WORK

An integrated analysis of thermal simulation and daylighting simulation can inform architectural design towards an optimized design option. Since our method enables BIM to multi-domain simulations, we expect to further investigate the inclusion of the integrated analysis into the BIM-to-simulation process. We also plan to include BIM to BiPV integration into the PBIM framework in the future.

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