An Object-Oriented Physical Modeling (OOPM) Approach Using Building Information Modeling to Support Building Performance Simulations

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Abstract
Diverse building performance analysis tools have been separately evolved relying on domain-oriented simulation engines. The segmented development has prevented practitioners from integrated analysis practice and has brought about the significant need for the integration of multiple domain simulations, which enables building performance analysis with a single building model. To overcome this problem, this paper introduces our research endeavor for adopting equation-based Object-Oriented Physical Modeling (OOPM) technique into building performance simulations. First, we investigate the capability of equation-based OOPM and employments in non-architectural domains including mechanic, electric, and control domain. We then demonstrate how to adopt the equation-based OOPM with BIM for multi-domain building performance simulations in an integrated fashion. It is argued which information need to be represented in OOPM models from BIM information for integrating multi-domain analysis process. The results show that the suggested methodology could facilitate current building performance analysis by linking diverse analyses with a single BIM model.

Keywords: Equation-Based Object-Oriented Physical Modeling, Building Information Modeling, Building Performance Simulation

1 Introduction
A variety of building performance simulation (BPS) tools have been separately evolved and design professionals and practitioners have utilized them to evaluate and analyze building projects. In traditional design process based on 2D drawings which designers created manually, architects and engineers have been challenged to effectively use them in the design process due to lack of integration among the BPS tools themselves and between design models and simulation models. For example, architects or designers are compelled to spend significantly more efforts obtaining simulation knowledge to better understand simulation processes to evaluate building performance analyses of their designed building (Maile et al. 2007; Attia 2011). Moreover, in order to provide valuable feedback from a single design model, each domain expert or practitioners need to create a separate building model consisting of required datasets for each kind of simulation. For instance, a thermal building model requires simplified geometry information and thermal material information such as conduction, whereas a daylighting model demands complicated building geometry information and material properties for daylight simulation such as reflectance and glazing transmittances. The term of BPS, as used in this paper, refers to various simulation tools for assessments and evaluations such as energy analysis, daylighting analysis, computational fluid dynamics for indoor air flow analysis, and so on.

Building Information Modeling (BIM)-based analysis tools have been emerged facilitating integrated building performance simulations with the design process (Aksamija 2010). BIM-based simulation tools facilitate directly use the building design data to create simulation building models. Therefore, the redundant process such as re-entering the building data already created by designers can be eliminated. Most of the tools utilize standard or common data format such as Industry Foundation Classes (IFC) and Green Building XML (gbXML) to link BIM and simulation models.

However, while the tools have been developed or modified from existing simulation tools to support the simulation model generation process using BIM, separated simulation models still need to be created to execute domain specific building performance analyses. Specifically, even the BIM-based energy simulation model creation tool facilitates the generation of an energy model from a BIM, a reliable energy model creation is time labor intensive, error-prone, and not explicit (O'Donnell et al. 2013). In order to efficiently provide whole-building performance analyses from a single BIM model, the integration of multiple domain simulations needs to be developed.

Recently, Object-Oriented Modeling (OOM) approaches have been researched to support the efficient use of multiple domains simulations (Wetter 2009). Object-Oriented Physical Modeling (OOPM) is emerging modeling and simulation approach based on the OOM methodology and provides a structured and equation-based modeling (Fritzson 2010). OOPM has been utilized in the complex physical system modeling and simulation in a diverse domains such as electric, mechanic, thermal, and control system. In this paper, we will describe our research endeavor to adopt the OOPM technique into BIM-based building performance simulations, which can facilitate multi-domain simulations with a single BIM model.

2 Background

2.1 Existing Building Performance Simulation Tools for Building Performance Analyses

Existing building performance simulation tools aims to support design decisions for energy efficient buildings (Attia et al. 2012). Given the variety of BPS tools, over four hundred BPS tools have been listed on the DOE website in 2014 and less than forty tools out of them are tailored for architects' uses in the early design phases (Attia 2011). In addition, among the tools, a few are widely used in education and industry (Aksamija 2012; Attia 2011; Crawley et al. 2008; Maile et al. 2007). For example, practitioners in the industry domain have widely used Ecotect, Energy-10, EnergyPlus, Green Building Studio, HEED, and IESVE in the United States (Attia et al. 2009). In the education domain, CONTAM, Ecotect, Energy-10, eQUEST, and Radiance have been widely used (Haberl 2008). Those BPS tools provide different building performance analyses;

- Ecotect covers wide range of performance analyses including thermal, energy, lighting, shading, acoustics and cost aspects by providing a comprehensive 3D modeler with users (Crawley et al. 2008).
- Energy-10 is designed as a conceptual design tool suited to the architects and engineers for small building focusing on the integration of daylighting, passive solar design, energy-efficient equipment, and low-energy cooling into high-performance building (Balcomb & Crowder 1995; Crawley et al. 2008).
- EnergyPlus is based on two energy simulation engines DOE-2 and BLAST to predict heating and cooling energy consumption, and analyzing energy system performance and energy cost in buildings (Crawley et al. 2008; WBDG 2015).
- eQUEST is aimed at all design team members and available for all design phase enabling all functionalities of the DOE-2.2 simulation engine (Maile et al. 2007; Attia 2011).
- Radiance is an advanced and accurate daylighting simulation application using the ray-tracing method to predict illumination and visual environment (Oh 2013). Other BPS application such as IESVE can adopt the Radiance as a lighting or daylighting simulation engine.
- Green Building Studio is a web-based energy analysis tool based on DOE-2.2, which facilitates energy simulation within BIM environment (Autodesk Inc. 2015). Users can generate energy models from BIM models using Autodesk Revit models after manual preparation processes.
- IESVE consists of a series of application modules enabling multiple analyses and simulations including loads analysis, thermal, natural ventilation, components-based HVAC, shading visualization and analysis, 3D computation fluid dynamics, lighting design, model optimization, life-cycle energy and energy cost analysis, and building evacuation (Crawley et al. 2008). A common user interface links those different modules through a single data model (Crawley et al. 2008).

Such BPS tools consists of domain-specific simulation engines and graphic user interfaces (GUIs) (Clarke 2001; Crawley et al. 2008). As shown in the "Building Energy Software Tools Directory" in

(U.S. DOE 2014), the BPS tools differ in with regard to input, output, programming language, and computer platform. For instance, the traditional BPS tools such as DOE-2, ESP-r, and EnergyPlus (Clarke 2001; Crawley et al. 2001; Winkelmann et al. 1993) have developed their simulation engines using computer languages such as FORTRAN, C, and C++ to depict physical processes (Wetter 2009). All routines in the Energy-10 application are implemented using the C language (Balcomb & Crowder 1995). DOE-2.1E and EnergyPlus are basically based on input and output of text files for simulations (Crawley et al. 2008). To facilitate efficient translation of input, DOE-2.1E uses BDL Processor, and DesignBuilder provide a GUI for EnergyPlus (Good et al. 2008; DesignBuilder Software 2015). In case of IESVE, ModelIT are used for geometry creation and editing (IESVE 2014). The GUIs can support practitioners to avoid spending the amount of time needed in preparing input files and enable designers to assess the building performance of alternative designs (Crawley et al. 2008).

However, such domain-specific BPS engines and GUIs do not guarantee the availability of building performance analyses for practitioners due to their reliance on wide-ranging simulation knowledge and understanding of all building performance analyses process (Attia 2011; Maile et al. 2007; Attia et al. 2012). Architects and designers are required of the amount of significant time to better understand energy simulation to obtain meaningful feedbacks. In addition, there is a difficulty in using BPS tools to none BPS professionals due to the incompatibility with their working processes as well as the complexity of the tools (Gratia & Herde 2002) Even BPS professionals need to repeatedly input same information such as geometry or material information to execute multi-simulations due to the non-integrated simulation engines and GUIs.

Recently, to provide multi-domain simulation analyses efficiently, OOM approaches have been examined (Wetter 2009). In addition, BIM-based computational analysis tools have emerged to facilitate BPS analyses in the design phase (Aksamija 2010). Compared to the existing devoted GUIs and the related simulation process, BIM-based BPS tools can utilize the building data more efficiently because it can reduce the redundant activity of re-enter the building data into the BPS GUIs.

In order to support a more seamless integration with the design phase or BPS tools, BIM-based BPS tools and OOM-based simulation engine development would be required by providing an easy-to-use GUIs between BIM-based OOM BPS tools, and efficient and effective BIM-to-OOM-based-BPS system interface.

2.2 Building Information Modeling for Building Performance Simulation

2.2.1 Building Information Modeling

Building Information Modeling (BIM) can be described as two major aspects: product and process. As a product, (NIBS 2011) defines that BIM is "a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition." As a process, BIM is the set of operation in order to create a digital building model to enable the exchange and interoperability of related information (Eastman et al. 2008). The features of BIM's semantically-based, object-oriented, and 3D modeling capability enable the access of comprehensive model data consisting of objects and their properties during a building's life cycle (Yan et al. 2013) and facilitate a single model to superimpose multi-disciplinary information (Azhar et al. 2010). Such BIM's capabilities can support data integration between the design phase and building performance analyses.

2.2.2 Integrating Building Performance Simulation tools with BIM

BIM authoring tools' vendors have developed private interfaces such as Green Building Studio between design and BPS tools to enhance data integration. However the interfaces are not integrated, also often resulting in creating multiple simulation building models. Model translation by using the interfaces between a design model and BPS tools has been a little better than the traditional manual model creation approach (Sanguinetti et al. 2012). For instance, the Green Building Studio enable designers to translate a BIM model to the gbXML format for the energy analysis (Autodesk Inc. 2015; GBXML 2015); however, the BIM design model needs to be modified to convert BIM data into energy simulation model requirement such as zoning information and surface information with physical properties instead of solid object information. Although the manual data inquiry process has been replaced with model-based data modification and translation by using BIM, each BPS tools' GUIs external to a BIM authoring tool has their own information requirements which are not straightforwardly integrated (Integrated Environmental Solutions 2009; U.S. GSA 2009). The various and frequently conflicting requirements cause to develop similar but distinct building models to execute each analysis. The model translation and development to generate separate analyses models can be done by designers thorough BIM-based BPS tools' GUIs; however, the BPS experts or practitioners more likely conduct the model translation or development similar to the traditional process (Sanguinetti et al. 2012). To enhance efficient and effective data translation between BIM and BPS tools may be accomplished through the same modeling method such as an object-oriented Modeling approach enabling direct data mapping between them.

2.3 Object-Oriented Physical Modeling

In order to facilitate easy-to-use of multi-domain simulations through a single analysis model and enable efficient reuse of models, Object-Oriented Modeling (OOM) approaches have been studied (Wetter 2009). Based on the OOM approach, Object-Oriented Physical Modeling (OOPM) has been emerging providing structured and equation-based modeling techniques (Fritzson 2010). Modelica is an object-oriented language for modeling of large, complex, and heterogeneous physical system (Tummescheit 2002), and developed to represent OOPM including dynamic behaviors using differential algebraic equation (DAE)-based calculations (Fritzson 2010). A lot of physic-based domains including mechanic, electric, thermal, and control system has used the Modelica-based modeling method to design the complex physical system. The component-connection representation using Modelica in OOPM can present physical system topology of simulation models (Fritzson 2010; Fritzson & Bunus 2002). An intuitive data mapping between object-based design models (BIM) and OOPM may be achieved using the object-oriented modeling approach compared to between traditional design models and BPS tools. In this section we investigate the capability of current OOPM in non-architectural domains.

2.3.1 The capability of Modelica-based OOPM and adoption in non-architectural domains including electric, mechanic, and control domain

Modelica has been developed for hierarchical object-oriented physical modeling merging and generalizing previous OOM languages (Fritzson & Bunus 2002). The Modelica language allows Modelica simulation environment tools such as Dymola (Dassault Systèmes 2015) to generate simulation codes automatically which facilitates exchange of models and Modelica libraries. One of the main features of Modelica-based OOPM is the capability of multi-domain simulations; it enables the same application model to combine model components from multiple domains including electrical, mechanical, thermodynamics, control system, and so on. (Fritzson 2010; Fritzson & Bunus 2002) describes four key features of Modelica as follows;

- Modelica is primarily based on equations rather than assigning statements. This capability allows Modelica-based OOPM to perform acausal modeling which enables better reuse of classes due to the non-defined data flow direction.
- Modelica enables multi-domain modeling in resulting that model components representing physical objects from multiple domains such as electrical, mechanical, thermodynamic, hydraulic, and control applications enable to be described and connected.
- Modelica is an object-oriented language which enables a single construct to unify classes, generics, and general subtyping. This capability allows reuse of components and easily models development.
- Modelica includes a software component model such as constructs to create and connect components. Thus, Modelica-based OOPM is ideally appropriate for modeling of an architectural description to represent complex physical systems.

The capabilities of Modelica-based OOPM enables simulations in a broad range of scientific and engineering area (Fritzson & Bunus 2002). To enhance the usability of the Modelica-based OOPM, Modelica association (Modelica Association 2015a) has disseminated and informed Modelica-based libraries including commercial and non-commercial libraries. We briefly present some of the model libraries for electronics, mechanics, and control system.

- Modelica Standard Library (Modelica Association 2015b): Modelica standard library is a free library from the Modelica Association, which enables to model mechanical (1D/3D), electrical (analog, digital, machines), thermal, fluid, control system and hierarchical state machines as show in Figure 1. The library provides model components and standard components interfaces from many engineering domains.

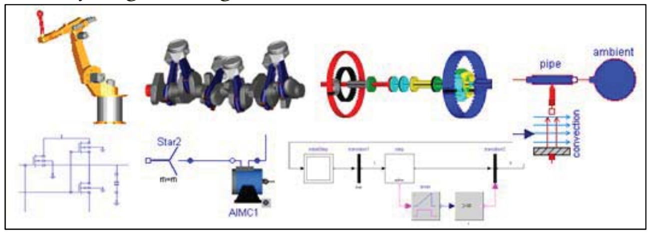

Figure 1 Modelica standard library to model mechanical, electrical, thermal, fluid, control system and hierarchical state machines (Modelica Association 2015b).

- IDEAS (KU Leuven & 3E 2015): The IDEAS Modelica library allows simultaneous transient simulation of thermal and electrical systems at both building and feeder level.
- Modelica_Quasistationary (Modelica Association 2015c): Modelica_Quasistationary library demonstrates the analysis of electrical circuits with purely sinusoidal voltage and currents.
- Vehicle Dynamic Library (Modelon 2015): Vehicle Dynamic Library from Modelon is a commercial library and allows optimizing and verifying the design of vehicle systems from the early design stages by using control design and implementation (Figure 2). The library provides whole multi-body, multi-domain simulation with real-time performance, and model export capabilities.
- Industrial Control Systems (Bonvini & Leva 2015): Industrial control system is a non-commercial library and provides a set of continuous and discrete control systems (Figure 3). This library enables modelers to set up or replicate the majority of industrial controllers.

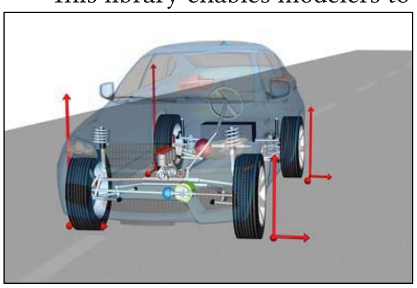

Figure 2 Vehicle dynamics library to model, simulation, and analyze full vehicles (Modelon 2015)

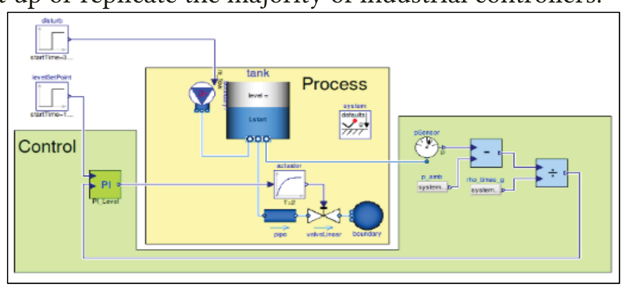

Figure 3 The Diagram view of a Modelica-based OOPM model using Industrial control systems library (Bonvini & Leva 2015)

These libraries are mainly intended to modify Modelica toward a specific domain by providing modelers with common model elements and terminology. Under Modelica authoring tools including Dymola (Dassault Systèmes 2015) and OpenModelica (OpenModelica 2015), these libraries allows an integrated Modelica-based OOPM model to simulate various simulations offering model components and solvers for the specific simulation.

2.3.2 Modelica-based Object-Oriented Physical Modeling for Building Performance Simulation

The existing Modelica authoring tools such as Dymola and OpenModelica facilitate the topology representation through a component-connection diagram to support the complex physical system design. The topology representation directly matches the structure and decomposition of the physical system topology of BPS models (Fritzson 2010; Fritzson & Bunus 2002). In order to facilitate natural mapping between object-based design modeling (BIM) and OOPM-based BPS modeling (Modelica-based OOPM), the development of easy-to-use Modelica libraries for BPS has been driven (Nytsch-Geusen et al. 2013; Nytsch-Geusen et al. 2013; Wetter et al. 2013). We briefly describe the Modelica-based BPS libraries as follows;

- BuildingSystems (Nytsch-Geusen et al. 2013): This library is developed at UdK Berlin as open source development. The library allows integrated modeling and simulation of buildings and complex energy supply systems, and supports the transient calculation of transformation, transportation and storage of thermal energy (Höger & Nytsch-Geusen 2012). As shown in

Figure 4, it supports the topology representation of BPS model by using designed components and their connections.

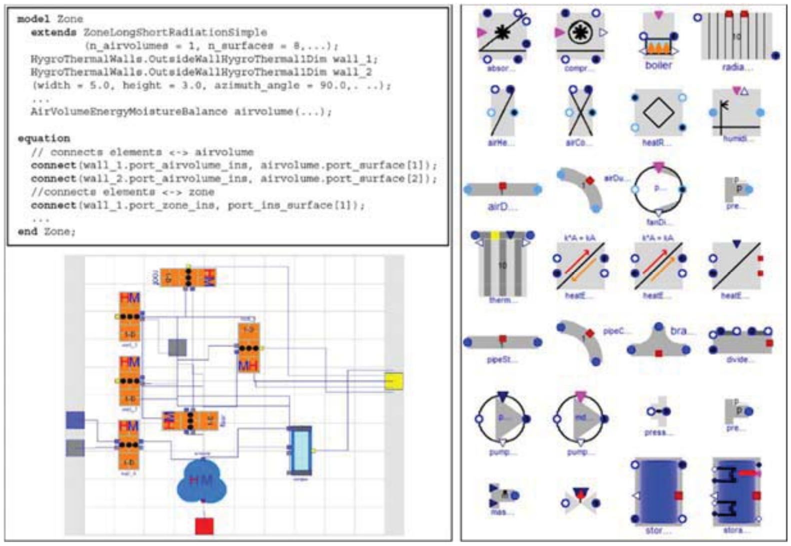

Figure 4 The topology representation of a thermal model (left) by using designed Modelica-based components (right) (Höger & Nytsch-Geusen 2012)

- Modelica Buildings Library (Wetter et al. 2013): the Buildings library is a free open-source library implemented in Modelica. The library supports rapid prototyping and design and operation of building energy and control systems. The library convers various building performance analyses including heating, ventilation and air-conditioning system, multi-zone heat transfer and mulita-zone air flow and contaminant transport. More details regarding the utilization with the design phase will be discussed in the following section.

2.4 Challenges in Model Translation between BIM and Modelica-based OOPM

The same modeling concept between BIM and the Modelica-based BPS libraries can support the intuitive model translation for Modelica-based OOPM. However, there is significant challenges in the model translation between BIM and Modelica-based OOPM using Modelica-based BPS libraries: *inconsistent object relationships and semantics*. Object relationships and semantics of BIM are mostly abstracted when such model information is translated into Modelica-based OOPM to correspond each libraries' specific requirements. For example, building components such as walls, floors, and roofs are abstracted as surfaces to correspond the heat transfer simulation. To overcome such an abstraction issue, consistent object classifications and semantics between BIM and Modelica-based OOPM need to be implemented.

3 Development

To facilitate using the Modelica-based BPS libraries with BIM for multi-domain simulations, we have been investigating an intermediate class packages, BIM-OOPM library, enabling the creation of Modelica-based OOPM models from BIM and the libraries. To develop the BIM-OOPM library, we use LBNL Modelica Buildings library (Wetter 2015) as a simulation solver for building energy analysis. We will expand the coverage of the BIM-OOPM library by adding more libraries in future researches.

3.1 LBNL Modelica Buildings Library

The LBNL Modelica Buildings library is a Modelica-based library with dynamic simulation models for building energy and control systems (Wetter 2015). The library includes various models for building energy analyses: air-based HVAC systems, chilled water plants, water-based heating systems, controls, heat transfer among rooms and the outside, multi-zone airflow, sing-zone computational fluid dynamics, data-driven load prediction, and electrical DC and AC systems with two- or three-phases (Wetter 2015). Recently, the library added some new features in the version 2.0 including a Computational Fluid Dynamics model (Figure 5) and an electrical package allowing buildings to electrical grid integration.

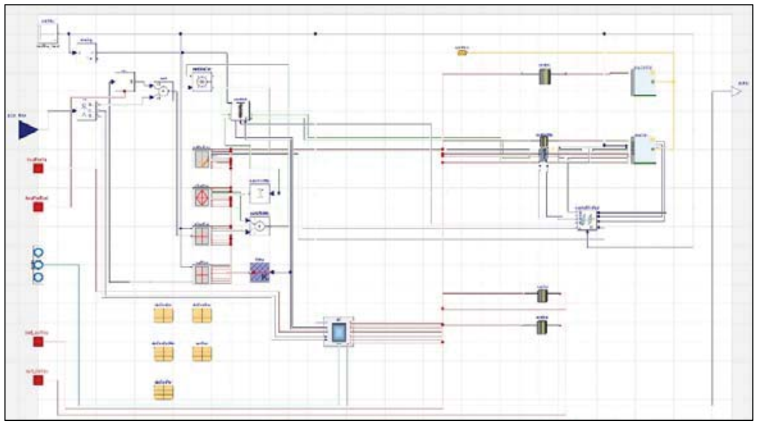

Figure 5 Computational Fluid Dynamics model diagram implemented in Rooms package (Wetter 2015)

To construct a building energy model using the Buildings library, users need to manually retrieve building's data and prepare a Modelica-based OOPM model by writing a Modelica codes using Modelica authoring tools. To efficient use the Buildings library with BIM models, a system interface is needed to support automatically converting BIM models into Modelica-based OOPM models. In order to overcome the inconsistent object relations and semantics between BIM and the Buildings library, an intermediate package is also needed, which allows object mapping between them.

3.2 BIM-OOPM Library for BIM-based OOPM

To implement object mapping between BIM and Modelica-based OOPM libraries, we have been developing BIM-OOPM library containing parameter information and BIM structure represented by Modelica as shown in Figure 6.

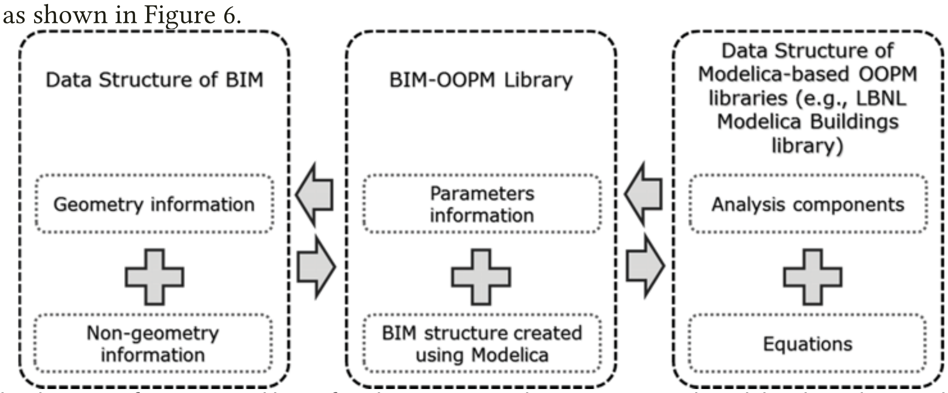

Figure 6 The diagram of BIM-OOPM library for object mapping between BIM and Modelica-based OOPM libraries

To define the object mapping, we have identified required information and a structure of the libraries. Currently, we have been identifying the data structure of BIM focusing on the Revit BIM authoring tool and the LBNL Modelica Buildings library (Figure 7). Based on the clarification of each data structure, we have been developing wrapper classes which allow BIM-based OOPM model creation. The BIM-based OOPM model follows data structures and semantics of BIM and use the Modelica library for the simulation engine. For example, the Room class in the wrapper classes is a wrapper class of the MixedAir class in the Buildings library. The instance from the Room class contains parameter information of required information defined in the MixedAir class and specific values came from a BIM model. The BIM-OOPM library includes primary building component classes for building design and a wrapper class which will be expanded by adding more libraries for multiple domains simulations.

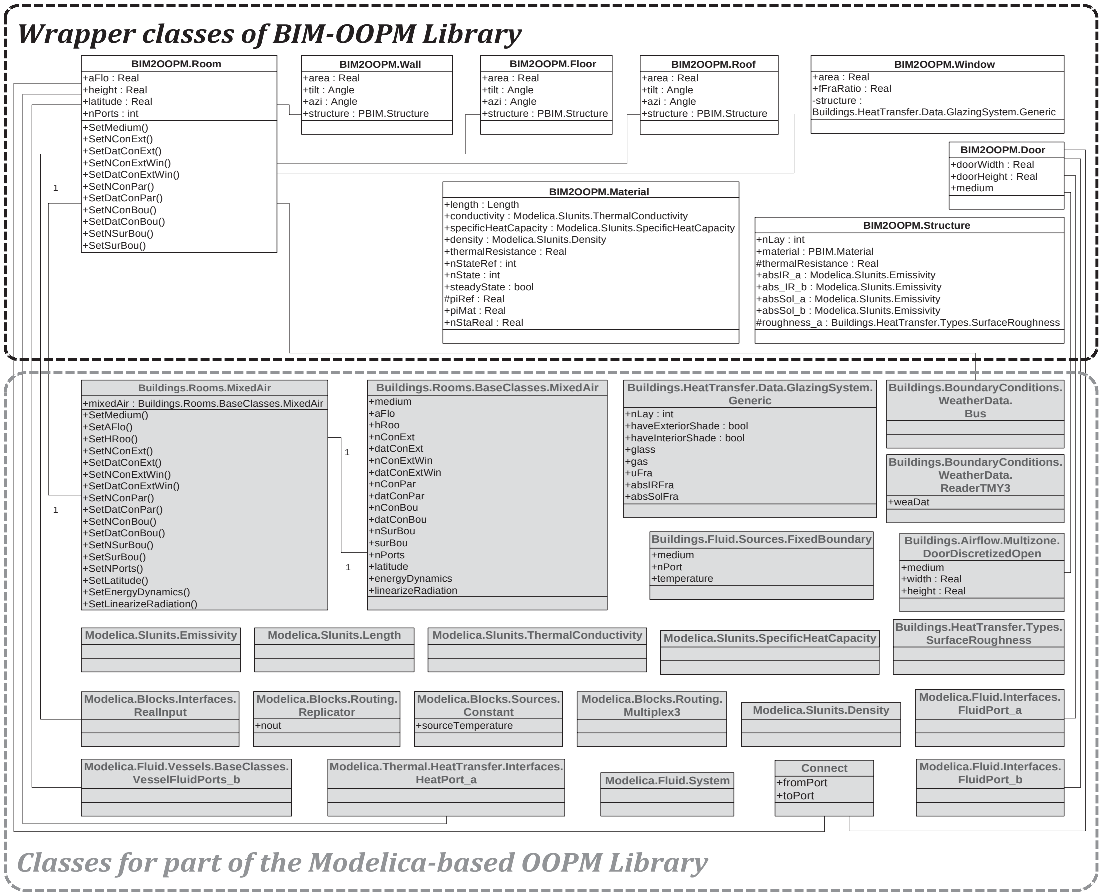

Figure 7 The class diagram of the wrapper class and related classes of the Modelica-based OOPM library (LBNL Modelica Buildings library)

4 Conclusions

Our research demonstrates a new method to integrate various BPS analyses into BIM-based OOPM. To investigate our methodology, we explored the current BPS tools and their limitations regarding the data integration issue, and then introduced various Modelica-based OOPM libraries in non-architectural domains. Base on the investigation of the adoption trend in non-architectural domains, we suggested BIM-based OOPM technique by providing object mapping methodology and current class diagram development. Our suggested methodology could facilitate current BPS analyses by linking divers Modelica-based OOPM libraries with BIM-based OOPM models.

This research is a part of ongoing research regarding the integration of BIM and OOPM for multi-domain simulations. We expect to further investigate the integration of more OOPM libraries into our BIM2OOPM intermediate class package. Furthermore, we plan to implement the intermediate class package with Modelica to execute multiple simulations by using BIM information.

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