A BIM-based Interoperability Platform in Support of Building Operation and Energy Management

Yunjie Xiong

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Environmental Design and Planning

Georg Reichard, Chair

Tanyel Bulbul

Farrokh Karimi

Nazila Roofigari-Esfahan

Feb 21, 2020

Blacksburg, VA

Keywords: Building Information Modelling (BIM), energy simulation, operational data

Copyright © 2020 Yunjie Xiong

A BIM-based Interoperability Platform in Support of Building Operation and Energy Management

Yunjie Xiong

ACADEMIC ABSTRACT

Building energy efficiency is progressively becoming a crucial topic in the architecture, engineering, and construction (AEC) sector. Energy management tools have been developed to promise appropriate energy savings. Building energy simulation (BES) is a tool mainly used to analyze and compare the energy consumption of various design/operation scenarios, while building automation systems (BAS) works as another energy management tool to monitor, measure and collect operational data, all in an effort to optimize energy consumption.

By integrating the energy simulated data and actual operational data, the accuracy of a building energy model can be increased while the calibrated energy model can be applied as a benchmark for guiding the operational strategies. This research predicted that building information modeling (BIM) would link BES and BAS by acting as a visual model and a database throughout the lifecycle of a building. The intent of the research was to use BIM to document energy-related information and to allow its exchange between BES and BAS. Thus, the energy-related data exchange process would be simplified, and the productive efficiency of facility management processes would increase.

A systematic literature review has been conducted in investigating the most popular used data formats and data exchange methods for the integration of BIM/BES and BAS, the results showed the industry foundation classes (IFC) was the most common choice for BIM tools mainly and database is a key solution for managing huge actual operational datasets, which was a reference for the next step in research.

Then a BIM-based framework was proposed to supporting the data exchange process among BIM/BES/BAS. 4 modules including BIM Module, Operational Data Module, Energy Simulation Module and Analysis & Visualization Module with an interface were designed in the framework to document energy-related information and to allow its exchange between BES and BAS. A prototype of the framework was developed as a platform and a case study of an entire office suite was conducted using the platform to validate this framework. The results showed that the proposed framework enables automated or semi-automated multiple-model development and data analytics processes. In addition, the research explored how BIM can enhance the application of energy modeling during building operation processes as a means to improve overall energy performance and facility management productivity.

A BIM-based Interoperability Platform in Support of Building Operation and Energy Management

Yunjie Xiong

GENERAL AUDIENCE ABSTRACT

Building energy efficiency is progressively becoming a crucial topic in the architecture, engineering, and construction (AEC) sector, promising appropriate energy savings can be achieved over the life cycle of buildings through proper design, construction, and operation.

Energy management tools have been developed towards this end. Building energy simulation (BES) is a tool mainly used to analyze and compare the energy consumption of various design/operation scenarios. These instances include the selection of both new and retrofit designs and for building codes, building commissioning, and real-time optimal control, among others. The main challenge surrounding BES is the discrepancy between quantitative results and actual performance data. Building automation systems (BAS), or a part of BAS which is often referred to as building energy management systems (BEMS), works as another energy management tool to monitor, measure and collect operational data, all in an effort to optimize energy consumption. The key disadvantage to the more general tool of BAS in energy management is that the data sets collected by BAS are typically too large to be analyzed effectively.

One potential solution to the lack of effective energy management analysis may lie in the integration of BES and BAS. Actual operational data can be compared with simulation results in assessing the accuracy of an energy model while the energy model can be applied as a benchmark for evaluating the actual energy consumption and optimizing control strategies. The presented research predicted that building information modeling (BIM) would link BES and BAS by acting as a visual model and a database throughout the lifecycle of a building. The intent of the research was to use BIM to document energy-related information and to allow its exchange between BES and BAS. Thus, the energy-related data exchange process would be simplified, and the productive efficiency of facility management processes would increase.

More specifically, this research posits the framework of integrating BIM, BES, and BAS to produce a seamless and real-time energy-related information exchange system. The proposed framework enables automated or semi-automated multiple-model development and data analytics processes. In addition, the research explored how BIM can enhance the application of energy modeling during building operation processes as a means to improve overall energy performance and facility management productivity.

ACKNOWLEDGMENTS

Foremost, I would like to express my sincere gratitude to my advisor and dissertation chair, Dr. Georg Reichard for his patience, motivation, enthusiasm, and immense knowledge. His continuous support helped me in all the time of research and writing of this dissertation. Without his persistent help, the goal of this project would not have been realized. My sincere thanks also go to Dr. Tanyel Bulbul for providing me extensive personal and professional guidance and taught me a great deal about both research and teaching in general.

I would like to extend my thanks to the rest of my committee thesis committee: Dr. Farrokh Karimi and Dr. Nazila Roofigari-Esfahan, for their encouragement, insightful comments, and solid questions. I would like to recognize the invaluable assistance that they all provided during my research.

I am grateful to all of those with whom I have had the pleasure to work during this and other related research in the Virginia Tech Department of Building Construction. Special thanks to the Building Enclosure and Systems Technologies (BEST) Lab which provides me a chance to implement my experiment. I would especially like to show my gratitude to Dr. Ruben Avagyan who was in Virginia Tech Facilities for helping me collect the experiment data and providing important comments.

Finally, I wish to thank my parents, Guosheng and Yi, my husband, Kanshu, and my son, Michael who provide support, encouragement and unending inspiration throughout my life.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 Introduction

1.1 Background

Over the last several decades, energy conservation has become a growing global concern. One of the major challenges within energy conservation is energy consumption by buildings, as buildings use around 40% of the total energy consumption in developed countries. In fact, this number has typically exceeded the industrial and transportation sectors in the EU and the USA (Pérez-Lombard, Ortiz, et al. 2008). Furthermore, the absolute total building energy consumption is still predicted to grow. For example, the Energy Information Administration (EIA) predicts a 13% annual energy increase for the residential sector and 19.5% for the commercial sector from 2009 to 2035 in the U.S. (DOE 2009). The increase of building energy consumption is a result of the rising demand for various building types and their respective indoor environmental quality, especially for modern, large, and complex buildings. Thus, stakeholders in Architecture, Engineering, and Construction (AEC) have to seek a balance between the energy efficiency and indoor environmental quality of a building throughout the lifecycles of these buildings.

From an energy perspective, the design decisions greatly affect the actual life cycle costs of a building (Bogenstätter 2000). For instance, optimizing the shapes and orientations of buildings can reduce the future operating energy consumption by 30% to 40% (Brophy and Lewis 2011). Operating energy, which is influenced by the original design, is another significant contributor to the life cycle energy demand (80%–90%) of a building (Ramesh, Prakash, et al. 2010). As a result, energy analysis tools have been developed for optimizing both building design and operation.

1.1.1 Building Energy Simulation

Building energy simulation (BES) is an applicable energy analysis tool that can assist with all stages of a building project, from planning to operation. It is common to use BES to guide the design of large, complex buildings, in an effort to mitigate their normally high consumption of energy. BES can be implemented at the early design stage to determine the optimum combination of building shape, orientation, and floor layouts that minimize the load of mechanical systems (Clarke 2001). The energy simulation model can then be updated with more details throughout the design process, which can be used to compare the alternative design options. In turn, the option with the best cost-performance ratio, proper building components and equipment, and the most satisfactory indoor environmental quality with minimized energy consumption can be selected. BES can also evaluate the real energy performance of existing buildings, compare the potential renovation schemes, such as optimizing building control strategy, replace more efficient equipment to assist building commissioning, and increase the overall energy efficiency of the building. The brief roles and functions of BES during the lifecycle of a building project is summarized in Figure 1-1. The related parameters of an energy model are shown in Figure 1-2.

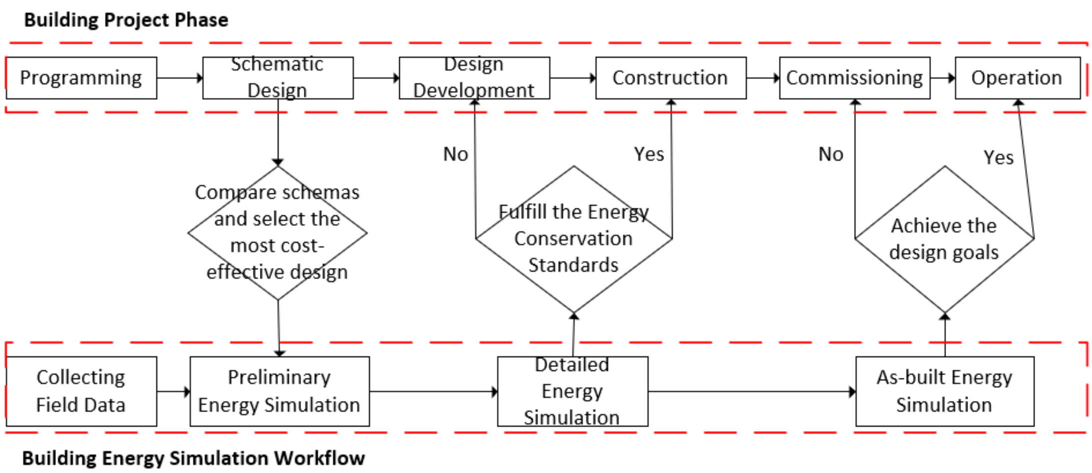


Figure 1-1 Building Project and BES workflow

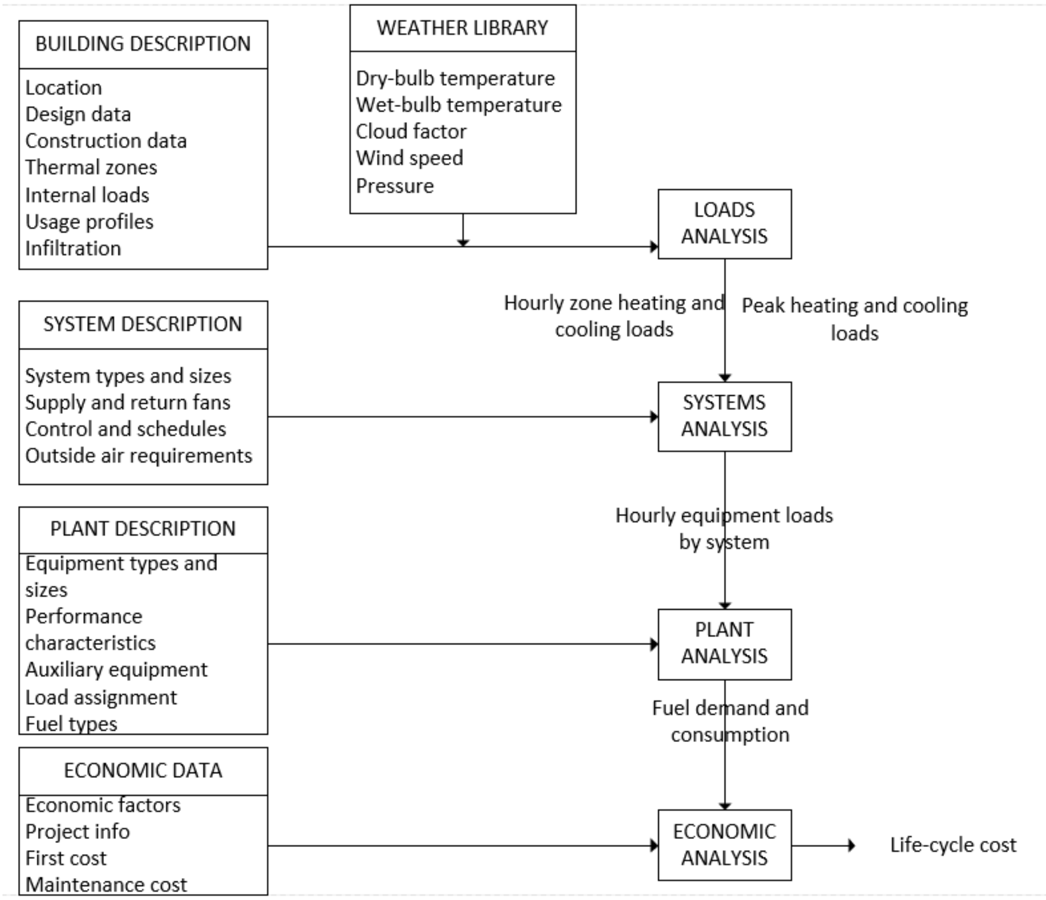


Figure 1-2 Flow Chart for Building Energy Simulation Program (Clarke 2007)

A whole-building energy simulation program is designed to develop an energy model of the entire building based on a few factors for predicting the annual energy consumption of the building. These factors include a series of heat and mass transfer equations and boundary conditions. The programs will calculate full- and part-loads, compare different design alternatives, and analyze system operating conditions (Trčka and Hensen 2010). Most building energy simulation programs consist of an engine that defines the mathematical and thermodynamic algorithms to calculate the energy performance. In addition, the engine also includes a graphical user interface (GUI) for its users to easily input variables and analyze output results. However, resulting details vary with the choice of thermodynamic equations, design of graphical user interfaces, and interoperability with other applications (Maile, Fischer, et al. 2007). Building energy simulation programs have been developed and popularized over the past 50 years due to the wide application of personal computers. Typical and popular whole-building energy simulation programs include Carrier HAP, Trane TRACE 700, DOE-2, eQUEST, EnergyPlus, ESP-r, IDA ICE, TRNSYS, HVACSIM+, VA114, SIMBAD, etc. (Trčka and Hensen 2010).

To achieve the best energy performance with minimal labor and cost, building energy simulation is recommended to be employed as early in the design process as possible. The MacLeamy Curve, which illustrates that when a project progresses, the cost of design changes increases while the ability to impact cost and functional capabilities decreases, implying that the most important design decisions are made during the early design phase (MacLeamy 2004). However, the detailed parameters, which a building energy model may need (e.g., building enclosure, HVAC system, lighting fixtures, building operating schedule and occupant behavior), are not available at the early design stage and, as such, must be estimated. Unfortunately, this can lead to possible inaccuracies. In some cases, building energy simulation is not even used for optimizing the conceptual design of the building. Rather, it is used for post-design validation. (Schlueter and Thesseling 2009, Jankovic 2013). During the operation phase, an energy model can be applied to assist the commissioning of existing buildings, in some cases, such as comparing potential operating configurations, optimizing controls, and replacing equipment responsible for the energy efficiency of the building. In ideal conditions, an energy model is updated in the whole-building life cycle for commissioning and the measurement and verification (M&V) processes to optimize the building schedule and control the setting of the operating status. This method can maximize building energy conservation, but the actual situation does not work ideally, as some issues remain.

1.1.2 Building Automation Systems

Building automation systems (BAS) are utilized to manage and control systems within a building, such as HVAC, lighting, fire alarms, and security, elevators, etc. The Association of German Engineers (Verein Deutscher Ingenieure) defines building automation as “the computerized measurement, control, and management of building services.” (Merz, H., Hansemann, T. & Hübner 2009). As a consequence of an increasingly digital society and the wide application of computer control and automation, building automation systems have been developed (Levermore 2000).

A BAS monitors the operating data, continuously manages the building plant and systems, and sends data to a centrally controlled computer, all to assist with energy management. Monitored data typically include actual indoor environmental conditions from sensors and energy consumption recorded by meters. Building operators analyze these recorded data to assess the operation status, find possible operation issues or faults, and develop energy-efficiency improvements. With respect to building energy management, this part of a BAS is often referred to as a building energy management system (BEMS). Energy management systems are important for large modern buildings, such as retail and high-rise buildings, as they usually contain multiple space functions that consume significant amounts of energy. The driving force behind BAS is the demand for indoor comfort and reduction of energy costs. Both of these conditions require a more effective method of controlling and managing all building systems.

The earliest building control method used individual modules running basic functions of building systems, such as temperature control, humidity control, light switching, system start/stop, power management, etc. The control system was a hard-wired, centrally-located system using conventional wires connected to an operator at the central console for monitoring various parameters. The operator could change control settings and times directly, without a working station and microcircuit(Clapp, M. D., & Wortham, R. H. 1989). These simple modules still work today for simple or old buildings (Moss 2006) (Harris 2012).

Modern, complex buildings with large energy consumption and flexible space functions raise the demand for cost-effectiveness, energy efficiency, indoor comfort, security, and system flexibility during operation. Simple modules are incapable of meeting these requirements. Instead, all of the building systems should be implemented by creating a proper building automation control strategy. A central automation control system alone is not able to satisfy the specific needs of the building occupants, like manual indoor temperature controls. Therefore, based on rapid advances in computerization and automation control technology since the 1960s, BAS has been developed to help overcome these challenges and has become widely applied for complex buildings today (Harris 2012). A typical building automation system is organized hierarchically with four levels. Figure 1-3 shows a general structure of a building automation system (Merz, Hansemann et al. 2009).

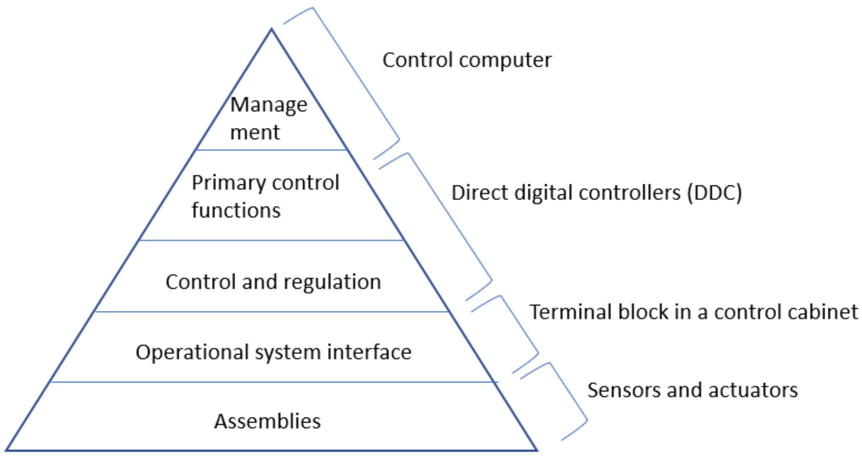


Figure 1-3 The Hierarchical Structure in Building Automation

The assemblies level contains sensors and actuators. Sensors collect the real-time operating parameters and send them to the upper levels for management. Actuators perform actions for controlling and regulating output commands from upper levels. All sensors and actuators work together to collect data and perform actions for several basic functions of a typical building, such as HVAC plant, zone comfort, lighting control, security, and fire hazard. Advanced functions (e.g. renewable energy systems) vary for different buildings. A list of common sensors and actuators for a typical modern building is found in Table 1-1. All sensors and actuators are physically connected by wires to direct digital controllers (DDCs), which consist of a microprocessor panel and its operating instructions that , into software for control. These work on primary control functions and control and regulation levels. The upper level is the management level in which a central control computer is applied to process all actual information and to control building systems automatically or manually by linking to the DDCs.

Table 1-1 Common Sensors for a Typical Modern Building

Functions	**Sensors/Actuators**
HVAC plant	Pressure/ Differential Pressure Transmitter
	Pressure/Flow Switch
	Flow sensor/ Flowmeter Detector
Hydronic system	Water Level Control/Switch
	Zone/control/Water Mixing Valves
	Flow Converter
	Water leak detector
Zone Comfort	Carbon Dioxide/Temperature/ Humidity Transmitter
	Sensor with thermometer
	Output transducer/controllers
Lighting control	Power Alert

	Current Transformer
	Lighting switch control
	Occupancy/Vacancy/outdoor motion/daylighting sensor
	Sensor Dimmer
Security and fire hazard	Fire Alarm & Detection
	Cameras

In short, building automation systems connect and coordinate all building systems within a building. Systems are linked with each other via DDCs and control systems, where large buildings with a huge amount of operating information typically have a central control computer connected to these DDCs and systems for management. These data are transferred via a bus system or network. Figure 1-4 shows the structure of a general building automation system, where the field level includes sensors and actuators; the automation level includes DDCs and automation devices, and the management level includes the central computer.

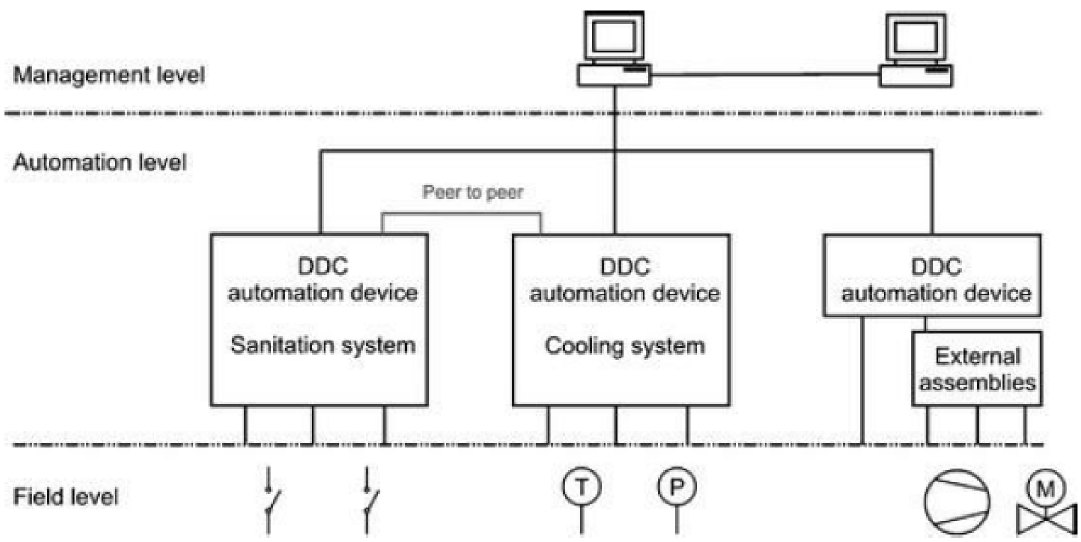


Figure 1-4 Structure Level of BAS

BAS manufacturers should have a common open protocol for their products to run a whole building automation system. Popular open protocols include LonWorks and Konnex, BATIbus, and EHS bus systems. (KNX Association 2017)(Merz, H., Hansemann, T., & Hübner 2009) (RTA 2017)(S. Wang et al. 2004). For an extensive building automation system with a central control computer, a data communication protocol called Building Automation and Control Network (BACnet) was developed by ASHRAE (Bushby 1997).

BACnet provides a common communication infrastructure for integrating products of different manufacturers and independent building services (Bushby 1997). In this protocol, the transmission pathway between devices or systems, messages containing real-time information such as binary input and output values, analog input and output values, and file messages are defined. Considering that devices from different manufacturers have different internal designs and configurations, BACnet defines a device as an “object” to communicate with other devices within a BAC network. A set of abstract data structures is used to describe the basic properties of the hardware, software, and operation of a device, and this set of data is called an object with certain properties (e.g., name and status) for being requested or set. This method allows the device information to be identified and accessed without knowing the internal design, and the concept of object is basic for interoperability. The latest ASHRAE 135-2008 defines 30 standard object-types for manufacturers to access which shown in Table 1-2.

Table 1-2 BACnet Standard Object Types

Accumulator	Device	Notification Class
Analog Input	Event Enrollment	Program
Analog Output	File	Pulse Converter
Analog Value	Group	Schedule
Averaging	Life Safety Point	Trend Log
Binary Input	Life Safety Zone	Access Door
Binary Output	Loop	Event Log
Binary Value	Multi-state Input	Load Control
Calendar	Multi-state Output	Structured View
Command	Multi-state Value	Trend Log Multiple

BACnet is currently the main open protocol in the U.S., as it allows devices made by different vendors to communicate with each other. This benefit saves time and expense, and as a result, almost all large building automation system manufacturers provide devices and systems supporting BACnet. A building automation market report shows that the top five manufacturers in this market are Honeywell International, Siemens, Johnson Controls, Schneider Electric, and United Technologies. Other companies with a main share of the market include Lutron, Bosch Security Systems, Control 4, Legrand, and Tyco (MarketsANDMarkets 2016). Major manufacturers, products, protocol, and export formats have been listed in Table 1-3.

Table 1-3 Main Manufacturers

Manufacturer	**System**	**Support Protocol**	**Support Export format**
Siemens	APOGEE	BACnet (field level network)	CSV (MS Excel), HTML, txt, XML
Johnson Controls	METASYS®	BACnet-compatible field controllers	XLS, CSV,txt, mdb (Microsoft Access) HTML, XML
Honeywell	EBI	HTML, LonWorks®, BACnet® OPC®, MODBUS™,	ASCII import/ export Microsoft Excel Data Exchange
Schneider	Andover Continuum	BACnet field bus TCP/IP, LonWorks®, Modbus®	CSV, Andover Continuum Archiver format

ABB	doMOOV	BACnet, LON, KNX	Data import of standard data bases (ETS for KNX, LNS for LON, EDE for BACnet) and MS Excel
KMCcontrols	Total Control Building Services applications	BACnet® protocol KMD Tier 1	Microsoft Excel Adobe Acrobat format
Carrier	i-Vu®	BACnet	XLS

1.1.3 Building Information Modeling

Project management processes of modern buildings are complex, and the demand for information exchange among stakeholders is at an all-time high. However, stakeholders from different domains have their own common file formats. As a consequence, building information modeling (BIM) has been developed as a standard digital representation and data management methodology to simplify the information exchange. A building information model represents "building information" in a comprehensive way, such as geographic information, building geometry, and spatial relationships, quantities and properties of building elements, cost estimates, material inventories, and even project schedules. Eastman defines BIM as "a modeling technology and associated set of processes to produce, communicate, and analyze building models" (Eastman, Teicholz, et al. 2011). BIM is useful for demonstrating the entire building life cycle including planning, design, construction, and operation of the building (Bazjanac 2004). All stakeholders, including owners, architects, engineers, contractors, subcontractors, and suppliers, can use a building information model as a single and virtual model to collaborate, update the details of design, construction, and operation due to different project stages, and visualize the designed building virtually for better understanding. By editing and updating the building information model, stakeholders exchange and share their related information like drawings, procurement details, submittal processes, and other specifications easily, which also streamlines the integrated project delivery (Glick and Guggemos 2009). In short, BIM increases productivity and working quality and saves on cost and delivery time of projects (Azhar, Nadeem et al. 2008). A typical BIM application area at different stages of the project life cycle is depicted in Figure 1-5 (Eastman2011).

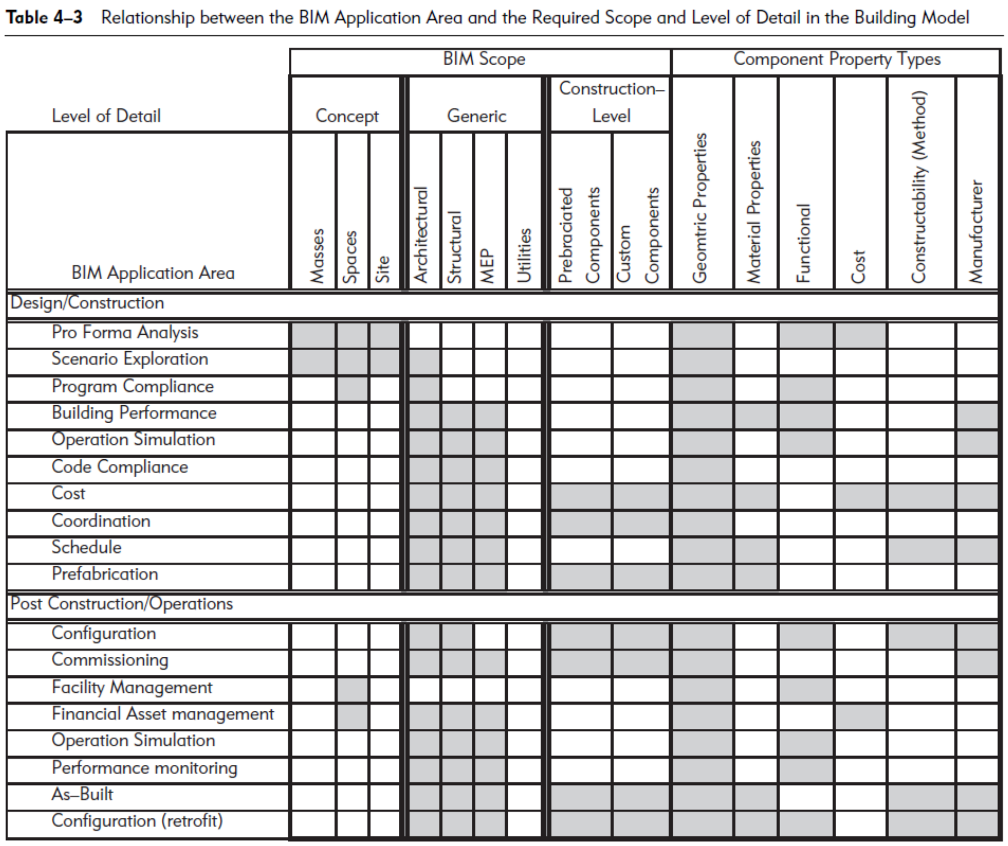


Figure 1-5 BIM Scope& Area (Eastman 2011)

A building information model contains building objects and relationships that are defined by open-source standards, allowing building information to be exchanged among different applications seamlessly to increase efficiency. One of the earliest efforts of describing building objects was ISO-10303 Standard for the Exchange of Product Model Data (STEP) in 1994 (Pratt 2001). EXPRESS and EXPRESS-G language were the main products of ISO-STEP (Schenck and Wilson 1993). Based on the ISO-STEP standard, several building data products are defined in the EXPRESS language, such as Building Elements Using Explicit Shape Representation (AP225), Industry Foundation Classes(IFC), CimSteel Integration Standard(CIS/2), and Generic Model for Life Cycle Support of AEC Facilities (AP241) (Eastman, Teicholz et al. 2011).

IFC is a neutral AEC product model based on the STEP standard, developed with the EXPRESS language by buildingSMART, formerly the International Alliance for Interoperability (buildingSMART 2017). The design goal is to develop an extensible set of consistent data representations of building information through the whole-building lifecycle for information exchange among AEC software. As an extensive framework model, IFC defines building objects and data in a general way to allow the building information to be exchanged over the whole-building life cycle, from planning, to design, construction, and building operation (Khemlani 2004). A few BIM applications even write and read IFC files directly as their native data model. The latest version of IFC is IFC 4 Addendum 2, and its data schema defines four conceptual layers with more than 800 entities (data objects). Figure 1-6 shows the schema architecture.

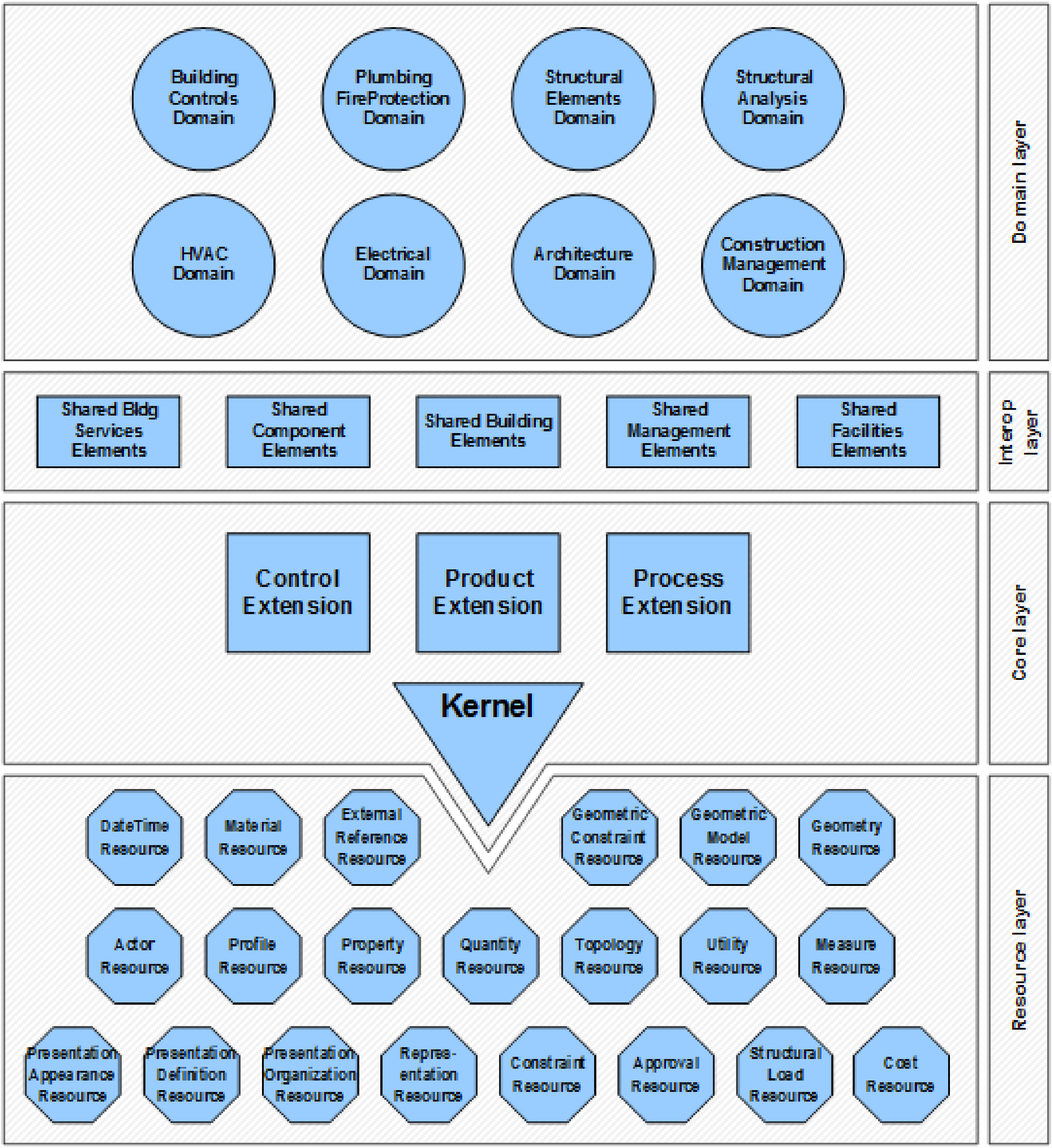


Figure 1-6 Data schema architecture with conceptual layers

The lowest resource layer includes 21 sets of reusable individual classes, such as material, geometry, actor, topology, utility, etc. All resources are individual business classes and may be referenced by other classes on high layers. For example, all information about the concept of topology is saved within the Topology Resource Schema as IfcTopologyResource and can be referenced by other models that include information of topology. Classes within this level are used to create commonly used objects and must be combined with a class from a higher layer in order to do so.

The core layer includes a kernel and three core extensions. Within this layer, the basic structure of a core IFC object model and more abstract concepts are defined as the object model foundation. The kernel may reference classes from the resource layer; provide all the basic concepts for IFC models, such as the provision of objects, relationships, and type definitions; and determine the fundamental model structure. As the base of a core model, a kernel is necessary for all IFC implementations but is not specific to the AEC/FM industry. To extend kernel constructs for the AEC/FM industry, three core extensions are developed: control extension, product extension, and process extension. Each core extension specifies classes defined in the kernel and primary relationships and roles. For example, the IfcControlExtension schema declares basic classes for control objects defined in the kernel (IfcControl, IfcPerformanceHistory). The interoperability layer includes a set of modules defining common objects and concepts across several domains and applications. For instance, IfcSharedBldgServiceElements schema defines basic concepts between different Building Service domain extensions as IfcHvacDomain, IfcElectricalDomain, and IfcBuildingControlsDomain. Basic type and occurrence definitions for flow and distribution systems are defined in this schema. The top domain layer specifies different modules for particular AEC industry domains or application types. Each is a separate model that may use or reference any class on lower layers. These modules may be products, processes, or resources specific to a certain AEC domain and are typically used for sharing of information among different AEC domains.

These layers of IFC are designed based on a "Ladder principle," in which a class is able to reference other classes at the same or lower layer but not at a higher layer. For the core layer, core extensions may reference or use classes in the kernel, but the reverse is not allowed. Considering the IFC hierarchical object subtyping structure, the defined objects are nested within a deep sub-entity definition tree.

As a set of open and individual data schemas, IFC represents numerous building components to ensure its comprehensiveness. For particular processes or special tasks in the AEC/FM industry, only a limited number of building objects are demanded. National BIM Standard (NBIMS) and

European companies developed a series of documents known as Information Delivery Manuals (IDM) and Model View Definitions (MVDs) to standardize the data sets required for exchanges and building lifecycle processes. These documents guide a special workflow using IFC in the AEC/FM industry, without losing their way in the numberless classes, datatypes, and property sets (Eastman, Teicholz et al. 2011).

Schemas other than IFC have been developed to meet special needs. Several schemas are based on eXtensible Markup Language (XML), a markup language designed to store and transport data for all kinds of "reading machines," including humans and machines. BACnet supports data representation in XML for building operating management. The XML-based schemas define their own entities, attributes, relations, and rules for implementing a special activity in AEC/FM areas, including gbXML (Green Building XML) (gbXML 1999) and CityGML (City Geography Markup Language). IFC also has a subset of schemas mapped to XML as ifcXML. Along the same lines, Construction Operations Building information exchange (COBie) is a performance-based specification for facility asset information delivery.

BIM applications are categorized as BIM tools, BIM platforms, and BIM environments (Eastman, Teicholz, et al. 2011). BIM tools are developed for a special task and produce special standalone outcomes, such as reports, drawings, and analysis results. The functions of BIM tools cover all AEC/FM areas, including model generation, clash and error detection, energy simulation, etc.. Sometimes, the outputs of tools may be exported to other tools, as well. A BIM platform is more integrated than a single BIM tool, whereas platforms often have the primary functions of design. The design model that hosts sufficient building information may then be used by other functions integrated with the platform, such as building analysis and clash detection. In addition, a user-friendly interface of multiple integrated tools is usually provided for interaction. Through this method, a BIM platform may manage a complete building project for its entire life cycle, depending on its integrated tools functionality. BIM platforms provide all-in-one solutions for various users in AEC/FM area. Popular BIM platforms include Autodesk Revit, Naviswork, Bentley Systems, and ArchiCAD. A survey from 2009 showed that Autodesk Revit controls 70% of the market, while Naviswork, a BIM platform, is second (Liu, Issa et al. 2010).The most common BIM platforms and the supported protocol are listed in Table 1-4.

Table 1-4 Common BIM Platform List

Revit(Autodesk)	Support Protocol	CAD formats: DGN, DWF™, DWG™, DXF™, IFC, SAT, and SKP Image formats: BMP, PNG, JPG, AVI, PAN, IVR, TGA, and TIF Other formats: ODBC, HTML, TXT, MDB, XLS, and gbXML
	Support Export format	CAD formats: DWG, DXF, DGN, ACIS SAT,DWF/DWFx, ADSK, FBX, NWC, gbXML, IFC ODBC Database: Microsoft® Access, Microsoft® Excel, Microsoft® SQL Server Images and Animations: AVI, JPEG, TIFF, BMP,TARGA,PNG Reports: Delimited text (.txt)
Naviswork(Autodesk)	Support Protocol	Navisworks:nwd nwf nwc CAD: dwg, dxf DWF/DWFx dwf dwfx MicroStation: dgn prp prw 3D Studio: 3ds prj BIM: FBX, IFC, IFC2X_PLATFORM, IFC2X_FINAL, Solidworks: prt, sld, asm STEP: stp, step STL: stl Binary only VRML: wrl, wrz ,VRML1, VRML2
	Support Export format	AutoCAD,3ds Max ,Revit Architecture / Structure / MEP ,Microstation,ArchiCAD
AECOsim Building Designer (Bentley)	Support Protocol	Bentley i-models, DGN, Revit Family File (RFA) RealDWG™, IFC, DXF, SketchUp SKP, PDF, U3D, 3DS, Rhino 3DM, IGES, Parasolid, ACIS SAT, CGM, STEP, STL, OBJ, VRMLWorld, Google Earth KML, COLLADA, Esri SHP…
	Support Export format	IFC2x3 Coordination View 2.0 files COBie spreadsheets gbXML, IFC 2x3, CIMsteel CIS/2 and SDNF
ArchiCAD (Graphisoft)	Support Protocol	ARCHICAD formats BIM:IFC,IFCXML,IFCZIP,NWC,SMC,BCF CAD: DXF,DWG,DGN Vector Graphics: DWF, PDF, EPS, PLT …
	Support Export format	ARCHICAD formats BIM:IFC,IFCXML,IFCZIP,NWC,SMC,BCF CAD: DXF,DWG,DGN Vector Graphics: DWF, PDF, EPS, PLT …

A BIM environment allows for “the data management of one or more information pipelines that integrate the applications (tools and platforms) within an organization” (Eastman, Teicholz, et al. 2011). It is often used to generate and manage multiple BIM tool data models and platforms within a firm. The actual demands of the firm may specify the functionalities of the BIM environment, while the BIM environments support various forms of information other than design models, such as videos, audio records, and emails for data management and coordination in managing a project. A BIM environment alone has difficulties in managing such diverse information. As such, BIM server applications, as a new technology, are produced to support BIM environments. A server used to integrate multiple BIM platforms and tools manages, distributes, and exchanges building information at an enterprise level for multiple users and is generally called a BIM server (Gu and London 2010).

1.2 Statement of Problem

1.2.1 Challenge for Building Energy Simulation

1.2.1.1 Inaccuracy

The main challenges for Building Energy Simulation (BES) are the rough estimation of input parameters and, consequently, the inaccuracy and unreliability of quantitative results compared to actual performance data. Other factors, such as data inconsistency and manual input errors, also cause inaccuracy in energy modeling. (Bazjanac, 2008. Maile, Fischer et al., 2010).

Building energy simulation is recommended to be employed in the design process as early as possible to achieve the best energy performance with minimal labor and cost. However, some parameters that building energy models need (e.g. building enclosure, HVAC system, lighting fixtures, building operating schedule and occupant behavior) are not available at the early design stage. Although these parameters could be estimated to develop a building energy model, the accuracy of results would be unreliable. Therefore, BES is popular for post-design validation (e.g. employed to specify HVAC equipment or to confirm compliance with regulatory codes) but fails to optimize the conceptual design of the building effectively (Schlueter and Thesseling 2009, Jankovic 2013).

Another issue is the reliability of the simulation results. Wider use of BES is complicated and relatively new to planners, building owners, architects, and traditional HVAC engineers. Currently, a building energy model could be developed by energy consultants, but the market lacks experienced and skilled energy consultants, causing distrust with clients (Tupper, Franconi et al. 2011). In addition, numerous detailed parameters, which are not defined at the early design stage, have to be estimated by building energy consultants subjectively. Thus, the quality and accuracy of a building energy model depend on the skill and experience of energy consultants to an extent. This can lead to inconsistent data, unreproducible results, and high labor and time costs (Maile, Fischer et al. 2010) (Bazjanac 2008). Furthermore, thermal and radiation processes in real buildings, as opposed to simulated buildings, are complex and not fully understood at this point. If the selected thermodynamic principles and assumptions do not approximate the real thermal processes correctly, the simulation results will be incorrect, and there is no way to compare actual measured data with simulation results at the design stage (Maile, Fischer et al. 2007), (Maile, Fischer et al. 2010).

1.2.1.2 Calibration

Several methods have been developed to improve the quality of energy simulations. These methods include energy model calibration, automated parameter transformation and input, and technical guidelines and training (Hong, Chou et al., 2000; Bazjanac, 2004, Hensen and Lamberts, 2012). Also, calibration ensures the accuracy of building energy models. Thus, when using a building energy model for evaluating the actual energy performance of an existing building, the results must be calibrated, since many studies claim that there are significant discrepancies between simulation results and the actual measured energy consumption of real buildings (Diamond, Opitz et al. 2006, Scofield 2009, Stoppel and Leite 2013). A large study of 121 buildings showed that the correlations between measured and simulated design consumption ranged between 0.25 and 2.5 (Newsham, Mancini et al. 2009). For this reason, calibration is utilized for building energy models in order to optimize building operation.

Calibration is defined by ASHRAE as "the process of comparing the output or results of a measurement or model with that of some standard, determining the deviation and relevant uncertainty, and adjusting the measuring device or model accordingly" (Guideline, A.S.H.R.A.E., 2002). In the calibration process, a building energy model of an existing building is created using a set of inputs. The simulated energy use is then compared with the actual operating energy bills to check if they can achieve a certain level of optimization. If the output is not as desired, the set of inputs will be adjusted, and the process repeated again until the simulated results are representative of the actual energy use.

A calibrated energy model is used in the monitoring and verification process (M&V) and the building commissioning process to provide an energy consumption benchmark for fault detection and diagnostics (FDD), to evaluate the possible energy conservation measures (ECM) and energy conservation opportunities (ECO), and to produce a model-based control method to maintain the building operation situation according to the design intent (Yoon, Lee et al. 2003) (Hensen and Lamberts 2012). Overall, calibration ensures the accuracy of energy models and provides an accurate estimation of the energy reduction of future ECMs (Costa, Keane et al. 2009).

Several standards of M&V define calibration simulation as one of the verification methods (Raftery, Keane, et al. 2009). ASHRAE Guideline 14 defines a calibration procedure using measured "pre-retrofit and post-retrofit data to quantify the billing determinants used for the calculation of energy and demand savings payments to energy service companies, utilities, or others" (Guideline, A.S.H.R.A.E., 2002). It also describes the procedures of a whole-building calibrated simulation approach but does not provide the detailed methodology of calibrating an energy model with the measured data (Agami Reddy 2006).

The International Performance Measurement and Verification Protocol (IPMVP) provided four basic options for preparing an M&V plan and determining the energy efficiency of existing buildings (IPMVP 2001). Calibrated simulation, one of the provided options, was recommended when the actual energy use data was incomplete or other options were not applicable. The Federal Energy Management Program (FEMP) Monitoring and Verification Guide cited these options and provided detailed processes (FEMP, 2015).

Although these standards defined their own calibration methods, the main issue of calibrated simulation is that calibration depends too much on the knowledge, experience, and personal judgments of the users. To calibrate a building energy model accurately, the user should have sufficient knowledge of both energy simulation and building operation, as well as the labor and time costs. Therefore, without enough experience on the part of the user, the quality of the calibration is doubtful. Furthermore, there are no recognized standards that define the calibration process using a detailed simulation program (Fabrizio and Monetti, 2015). Another problem is that the reporting simulation accuracy has a lack of uniformity, as normally, the user who calibrates an energy model does not report the hourly or daily error values (Agami Reddy 2006). Applying an energy model during the building operation phase can maximize the benefits of energy simulation in a building, but the actual situation is not ideal, as some issues remain.

Even with all the above issues, a BES still has its own potential opportunities for development. Complex and large modern buildings tend to be energy-intensive, which makes energy-saving design necessary. This also means the role of energy simulation as an assisting tool from the design phase is indispensable. BES tools are expected to be more integrated and intelligent to reduce the labor and time of all involved stakeholders and promote the progress of projects. To increase the accuracy of energy simulation, the process of calibrating a building energy model during the building operating phase is gaining more attention. Simulation results can be analyzed and compared with the real-time operating data to ensure the accuracy of the building energy model. Then, the calibrated building energy model could be applied for optimizing the building operating status and increasing energy efficiency as the design goal.

1.2.2 Building Automation System

A Building Automation System (BAS) monitors and controls the operating status of all systems within a building, including the HVAC system, lighting system, security and fire hazard system, etc., Energy consumption of building plants, systems, and related real-time data of sensors are collected to monitor indoor environmental conditions and energy consumption levels of the building. Building managers and technicians use these data journals to assess the operating status, decide controlling strategies, find possible operational faults, and develop the potential energy efficiency improvement schemes. Efficient energy management would save on labor and costs for energy-intensive buildings, such as commercial and industrial buildings. On its own, a BAS also monitors the plant and sends an alarm to the control system once an operational condition fails, allowing building managers to handle the faults quickly. A central control computer can monitor several buildings for facility management (e.g. an industrial park or campus). Through this method, a BAS enhances building maintenance and saves labor and time for building managers. Furthermore, the BAS assists in building energy audit services and system commissioning. Daily operating data, including indoor environmental conditions and actual energy consumptions collected by a BAS, could be a benchmark for retro-commissioning during the operating phase.

The application of BASs still faces several challenges. Huge volumes of operating data are collected daily by a BAS. Building managers should analyze these floods of data to identify the operating status and the energy consumption situation. Without considerable experience on the part of the manager and detailed guidelines, this large amount of data can confuse building managers. A survey of 50 buildings showed that 82% of the sample had a Building Energy

Management System (BEMS), but only 2% of building managers manipulated the recorded data to check and improve the energy performance of the systems in the building (Brendel, T. and Schneider, A., 1991). However, well-written BEMS manuals are rare and, as such, building managers require more on-site training (Levermore 2000).

In another respect, even experienced building managers must analyze the usable data carefully to assess the actual energy consumption and compare it with the energy benchmark based on design goals and the actual operating status of the system. A link between design and operating data must be developed to guide the decisions of the building manager. Furthermore, although compatibility is being solved by popular open protocols, such as BACnet and LonWorks, interoperability amongst different domains and the communication security of "user-aware" building systems will remain an issue for years to come (Kastner, Neugschwandtner, et al. 2005).

1.3 Challenges

As stated in the sections 1.1 and 1.2, a summary of advantages, disadvantages, and potential challenges of BES, BAS, and BIM has been listed in Table 1-5. The table shows that BES is applied to estimate energy consumptions of different design options and to provide a benchmark that guides building operating management. Simultaneously, BAS is used to capture and manage huge amounts of actual energy data of operation. This is likely because a BAS can manage and analyze these actual energy data based on the energy benchmark provided by the energy simulation. The energy model of a building can be calibrated with the actual energy data provided by a BAS to increase the accuracy of the energy model and vice versa. Therefore, an integration of BES and BAS may cover the energy management of entire life cycles of building projects by estimating, monitoring, and optimizing energy consumption at different stages. Another common challenge that both BES and BASs face is the growing complexity of large energy data volumes. Many parameters must be entered manually into energy models, which bring about labor and time costs with high error rates. A BAS collects huge amounts of actual energy data that must be analyzed and managed by experienced building managers. Unfortunately, the current number of energy experts is insufficient to meet the market demand. A user-friendly and automated method of energy information exchange and management is required to improve building energy efficiency. BIM offers an inherent new approach of sharing information amongst various applications and stakeholders related to AEC. Thus, it has the potential to be applied to integrate BES and BASs for easy energy-related information comparison, exchange, and management between various stakeholders, including planners, building owners, architects, and system engineers, throughout the entire life cycle of buildings. Figure 1-7 shows the data overlap between these three tools for building energy management. An ideal BIM-based platform could store and support all the related data, facilitate efficient energy information management, save unnecessary labor costs, and reduce manual and human input errors. This would all be in an effort to achieve optimal operation status while maintaining high building energy efficiency.

Table 1-5 Advantages and Disadvantages of Analysis

BES	PROs	Provide energy estimations of design options for decision-making. Provide an energy benchmark for building operating management. Assist in achieving energy savings targets.
	CONs	Inaccuracy. Numerous of input parameters. Limited training resources and limited experts.
	Challenges	Simplify the input process for modeling. Calibrate simulation results based on actual operating data.
BAS	PROs	Monitor and manage actual energy data and find operation faults. Provide historic data for developing benchmarks of building operating management.
	CONs	Huge data with no clear explanation. Design goals are not considered during building operation. Not all systems are compatible.
	Challenges	Collected data should be analyzed based on reliable methods. Collected data should be used for optimizing operation.
BIM	PROs	Provide a 3D model for better understanding. Store and share the building information among all stakeholders to reduce redundancy and manual error.
	CONs	All building information saved in a model causes to confuse. Applications are limited at the design stage. Limited training resources and limited experts.
	Challenges	Provide an integrated platform saving, sharing and managing all building information for the related stakeholders.

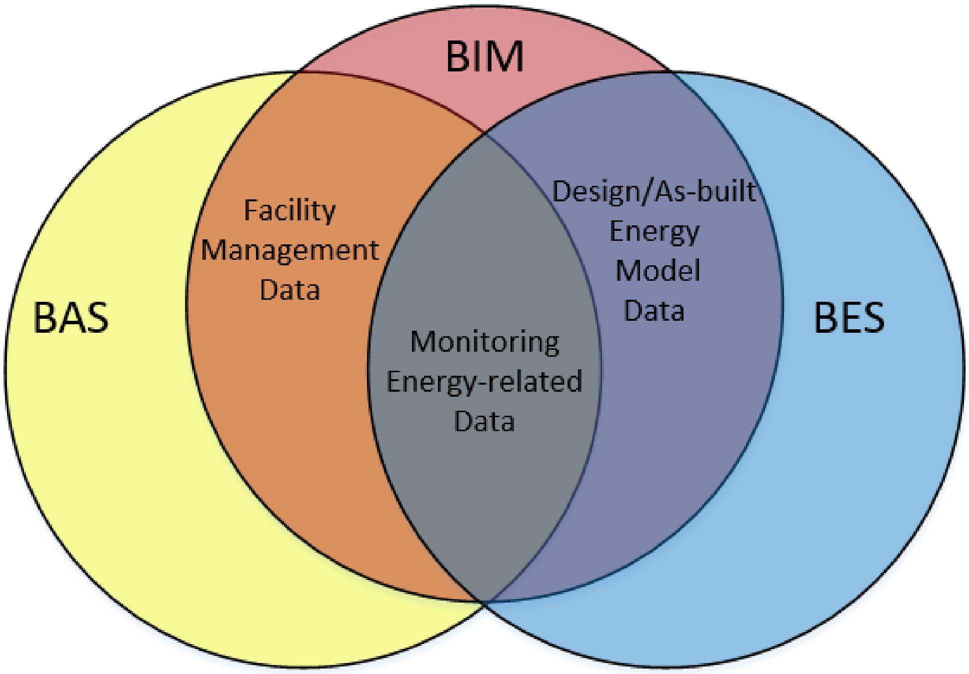


Figure 1-7 Data Overlap among BIM, BAS and BES

2 Literature Review

BIM is designed as an information handling system to collect, exchange, access, update and monitor all building information, and avoid several common flaws, e.g. recurrent and error-prone data replication, redundant data processing and storage conversion (Bazjanac, 2001). BIM, with its related functions, supports the requirements of information storage, exchange, and management, such as 3D modeling and construction management. However, BIM has to cooperate with other applications or systems to be able to implement these functions. For example, BIM may assist with the building energy modeling by exporting the related information to energy simulation tools at the design stage and manage the actual energy data at the operation stage by linking with BAS.

Since the BIM platform supports the whole life cycle of building projects, this literature review starts with the role of BIM and its interoperability with other tools throughout the life cycle of building projects. At the design and construction stages, BIM works with BES to assist the energy-saving design goal. Then, at the operation stage, BIM works with both BES and BAS to manage and analyze the recorded real-time data, sometimes using an energy model as a benchmark. The integration of BES and BAS is analyzed at the end of the review.

2.1 BIM Framework in Supporting Building Energy Performance

Supporting sustainable building analysis is one of BIM's main functions (Eastman, 2011) (Krygiel, Nies, and McDowell, 2008) (Arayici et al., 2011) (Barnes and Castro-Lacouture, 2009) (Cho, Alaskar, and Bode, 2010) (Sacks and Pikas, 2013). It is possible to develop a BIM conceptual design model that could be used for energy simulation directly, at an early design stage. Compared to a traditional design process, this BIM-based method saves time and costs and enhances the energy performance of the project. However, it requires that BIM integrates with other energy simulation tools, which is a challenge (Azhar 2010) (Annette, Kim, and Jenicek, 2009). Related research focuses on the integration of BIM and BES and claims that a building performance assessment has to be integrated into the design seamlessly (Schlueter and Thesseling 2009) (Cho, Alaskar, and Bode, 2010) (Annette, Kim, and Jenicek, 2009).

Several BIM building and facility frameworks have been developed to integrate BES tools with the BIM platform, supporting a sustainable building design assessment and the decision-making process at the design stage. A prototypical tool called the Design Performance Viewer (DPV), using a simple statistical method to perform instantaneous energy and exergy calculations with a building information modelling software, was developed by Schlueter and Thesseling. This method defined multi-disciplinary key energy indices for a conceptual building energy model only at the design stage (Schlueter and Thesseling 2009). Another methodology developed an automated energy simulation based on a building information model and used sensitivity analysis to evaluate uncertainty in the energy simulation of different design options (Sanguinetti, Eastman et al. 2009). A methodology was employed to exchange data between a system dynamics (SD) decision-making software model and a BIM software model. The data exported from the BIM model to the SD model was used for making decisions related to operations, maintenance and upgrades, then returned to the BIM model for assessment (Bank, McCarthy et al. 2010).

Generally, the number of BIM frameworks assessing building's operational status is limited and lacking in empirical studies. The BEMAC (Building Energy Monitoring Analyzing and Control) framework, based on IFC, was developed as a platform to combine a building product model with a building management system and other applied software tools. The framework assisted with the different stages to monitor, analyze and control building performance throughout the whole building life cycle, with energy usage a key performance metric (O'Sullivan et al., 2004). Another study identified key variables of operational and carbon emission performance through a building's operational stage and developed a consistent BIM approach to utilized these variables for monitoring a building's performance and supporting its energy management (Motawa and Carter 2013).

2.1.1 Interface and Model Developments for BIM

An applicable data exchange method has to be developed to conduct the interoperability between BIM and other software tools as energy analysis tools. While design data could be exported from a BIM tool to an energy simulation tool via IFC or gbXML schemas, research surrounding the interoperability of BIM and BES tools still has unresolved issues (Osello et al., 2011; Moon et al., 2011; O'Donnell et al., 2011). The two-way data exchange methods often need manual configuration, and to perform energy simulation based on a BIM platform, additional manual input and modification of energy simulation tools are necessary (Ferrari et al., 2008).

Current related research and case studies are disorganized, with no standard agreement of data collection, data exchange and model verification between BIM and BES. The details of building energy models are various due to the available data, external resources, skills of modelers and different project stages. Therefore, each building project has its unique data collection and modeling process and thus, varying accuracy of results.

The IFC schema has been identified as the "only public, non-proprietary and well-developed data model for buildings and architecture existing today" (Eastman et al., 2011). Many researchers used IFC schema because its scope is broader than gbXML's; even the latter is unique at energy simulation (Dong, 2007) (Cormier, Robert et al. 2011). The IFC building model is at the core of supporting a collaborative working environment; A study by O'Sullivan et al. developed a shared IFC building model that was saved on a STEP model server to establish a building object database on a central computer, supporting a collaborative decision-making process for the whole life cycle (O'Sullivan, Keane et al., 2004). Another study showed that IFC has several flaws, such as the robustness of the geometric model, the geometry concept and inconsistency amongst applications supporting IFC's version (Plume and Mitchell, 2007). Also, the current IFC schema lacks an energy domain (Cemesova, Hopfe et al. 2013). Another study selected ifcXML to save a BIM model and export it to DOE-2 as simulation files. The building information contained in ifcXML was parsed and mapped to an INP file, which worked for DOE-2.2. This framework was validated by a small case study that showed: manual inputs being necessary for conducting the energy model, the scalability of energy model may be an issue and few major BIM tools exported ifcXML easily (Kim and Anderson, 2013).

Another methodology, named Passive House Planning Package (PHPP), was proposed to exchange energy data between BIM and BES tools using the IFC schema. (Cemesova, Hopfe et al. 2012) (Cemesova, Hopfe et al., 2013). It created an extension describing thermal items, activities, and groups based on ifcXML, which is extendable without editing the original schema. The extended schema stored static data as geometry and behavior data in the same place. Then, the researcher used a Java tool to convert the extended schema into Java classes for further processing as heat demand calculation or other related tasks. Several cases were conducted to validate the accuracy of the geometry data transfer. Results differed by 4%, which had to be validated with a broader range of models. As a result, this methodology was deemed as successful for geometry extraction and annual heat demand calculation (Cemesova, Hopfe, and Rezgui, 2013).

The difference between a building energy model and a building physical model leads to the difficulties of data exchange. In 2009, the AECOO-1 (Architects, Engineers, Construction, Owners & Operators-1) Testbed was built to improve data exchanges between parties at the design stage, support construction cost estimation, and building performance energy analysis (BPEA) (OGC, 2009). BPEA defined the data exchange requirements of energy analysis at the concept design stage and formed an information delivery manual (IDM) and a model view definition (MVD), which standardized the critical building model data in energy analysis (IFC Solutions Factory, 2009). Furthermore, the AECOO-1 Testbed also developed a space boundary implementation guideline of energy analysis in an IFC-based BIM (Weise, Liebich et al. 2011). However, there is no consistent implementation of this MVD in real energy analysis and no reliable test method for assessing existing and future implementations (Robert J. Hitchcock, 2011).

SimModel was developed based on this MVD, and it remains to be seen if the SimModel ontology will unify all models, including IFC, gbXML, EnergyPlus, DOE-2, together into one centralized schema (J O'Donnell, 2011) (Pieter, Edward, and O'Donnell, 2014). An IDM framework has been presented for BIM-based energy analysis as part of Concept Design BIM, 2010 (IFC Solutions Factory, 2009). However, it does not consider the application of the IDM at the operation stage.

gbXML is another common data schema allowing software programs to communicate with little or no human intervention and is supported by many BIM tools, e.g., Revit, ArchiCAD, and energy simulation tools, e.g., Green Building Studio, Ecotect, VE. (Dong et al., 2007) (Moon et al. 2011). A study investigated the interoperability between a BIM-based architectural model and performance analysis programs, including EnergyPlus, eQUEST, Ecotect and IES<VE>, based on the gbXML protocol, and showed that different BIM tools would export gbXML in different levels of details. For example, EnergyPlus had trouble in converting the location of openings, while all the energy simulation tools were capable of importing building geometry information. Generally, both manual input and the modification of energy models are necessary after the data transfer (Moon, Choi et al. 2011). Although much time and cost of developing a building energy model can be reduced by exchanging information between BIM and BES tools, current software implementations are inadequate (Hitchcock and Wong 2011).

In a nutshell, interoperability is still not sufficient for energy data exchange between BIM and BES tools. Universal data schemas, such as IFC and gbXML, and several IDMs and MVDs have been developed to define the information exchange process at the design or construction stages for energy simulation or facility management, However, most of them focus on new buildings rather than the operation and deconstruction stages of building projects. Moreover, MVDs related to energy simulation are not supported by the actual IFC2×4 format yet (Volk, Stengel, and Schultmann, 2014). IFC does not represent detailed information of configurations of lighting and HVAC systems, such as controller and data interfaces, but contains material and geometric information of HVAC equipment, with new classes representing an HVAC system needing to be added into the new IFC version.

2.2 BIM Interoperability with BES

Even related schemas have not been fully developed; much effort in the application level has been made on the interoperability of BIM and BES tools to convert BIM data into energy models, automatically saving costs and avoiding manual errors (Eastman, Teicholz et al. 2011). Many studies focus on the data exchange between BIM and BES tools at the design stage (Clarke 2001, Augenbroe 2002, Hitchcock 2002, Eastman, Teicholz et al. 2011). It is still proposed that an energy simulation tool should have the ability to evaluate design options/actual building systems for decision-making at different stages (Tupper et al., 2011) (Attia and De Herde, 2011). Six stages of an ideal workflow, from BIM to BES tools, have been defined as 1) identify the building's location linked with weather data; 2) identify building geometry, construction materials and space types; 3) assign spaces as thermal zones; 4) assign space and lighting loads to spaces; 5) define the details of the HVAC system and related components; 6) run the energy model (Maile, Fischer et al. 2007). This procedure requires consistent data exchange and interoperability between BIM and BES tools, such as geometry modelling, HVAC design, energy analysis and facility management (Motawa and Carter 2013).

2.2.1 Application- Architectural Data Exchange

One barrier in transforming building information data into building energy models is the difference between the architectural view employed by BIM and the energy view employed by a building energy model. Architects see buildings as building physical objects e.g walls, floors and roofs in an architectural view, while energy analysts see buildings as thermal zones with volumes of consistent air, in an energy view. The difference leads to the drawbacks of data exchange between BIM and BES tools (Bazjanac 2008, Hetherington 2013).

A simple one-way model was developed in 2002. This IFC-compliant CAD tool exported the building model as an IFC file, then imported the geometry information, like walls and windows, into an energy simulation tool. This method saved the time of creating a new energy model by converting building objects into a building energy model, but it was only one way—from the IFC file into the energy model—and did not convert the thermal information (Hitchcock 2002). Lawrence Berkeley National Laboratory (LBNL) and Graphisoft developed a Geometry Simplification Tool (GST), renamed as Space Boundary Tool (SBT) later. This tool added space boundaries to IFC files, then converted the relevant building information (e.g. building materials and geometry) of the IFC file into other formats readable by energy simulation tools (Bazjanac and Kiviniemi, 2007). The current version of SBT can be downloaded online, but its further development has been suspended. A tool for building envelope performance evaluation was developed by Horvat and Fazio, which used the IFC schema as its data model, including material layers and building geometry, and linked with other simulation applications as MOIST 3.0 and HOT 2000, to evaluate thermal performance with pre-defined criteria for the building envelope. Its framework contains an IFC-compatible CAD application that converts CAD drawings into IFC files, an IFC processor that imports geometry data and edits IFC files with a user interface for inputting data, a material and weather database and other user interfaces for performance assessment. A prototype system and several case studies have been developed to demonstrate the functionalities of this framework (Fazio, He et al. 2007). DOE developed the Legacy OpenStudio Plug-in to establish and edit EnergyPlus zones and surfaces in SketchUp. This plug-in creates and edits building geometries, then adds an ideal HVAC system for simple load calculation in EnergyPlus. It is not capable of holding all key inputs which had to be added by a text editor manually (DOE, 2013). Green Building Studio (GBS) was developed based on gbXML as a standalone web service to support Autodesk Revit for energy analysis because gbXML is simple and ideal for quick implementation of schema extension (Dong, Lam et al. 2007). It was designed to read all building geometry data produced by a gbXML-based BIM tool and import a general HVAC system to perform thermal analysis and calculate building energy loads. However, the analysis types and file sizes are limited, so it did not allow the modification of the HVAC system or conduct detailed energy analysis. An application called RIUSKA was developed by Granlund and certified as IFC compliant, simplifying building geometry information in the IFC model and importing this data to the energy model for thermal simulation. RIUSKA's limitation is that it only has four different air-conditioning systems and did not simulate water loops serving the air loops. Besides, this application cannot import complex geometry correctly (Maile, Fischer et al. 2007).

2.2.2 MEP (Mechanical, electrical, and plumbing) Data Exchange

As early as 2004, an HVAC interface named "IFC HVAC interface to EnergyPlus" was developed by the Lawrence Berkeley National Laboratory (LNBL). HVAC equipment and schedule data were exchanged between EnergyPlus and IFC compatible tools (as HVAC design tools) via this interface. Users could define the HVAC system in EnergyPlus and export this information to IFC-based BIM tools. This was an attempt at another data transformation rather than building geometry data, but it only supported HVAC information related to a building directly. Besides, when this interface was used with an IFC to IDF utility, which converted building geometry data, some essential information (schedules and control parameters) would be lost during the transformation process, which then had to be added manually (Bazjanac and Maile 2004).

LNBL then developed a new methodology to avoid inappropriate human intervention in BES and support a semi-automated process of BES. Related data were defined by the IFC-based BIM tools and transformed under special rules into an energy model, with the transformation process itself being automatic and cover all the information of a building energy model (Bazjanac 2008). A geometry simplification tool (GST) and IDF generator, with embedded rules of data transformation between IFC and energy simulation tools as EnergyPlus, was developed to fulfill this purpose. The GST and IDF generator could read and convert building geometry and material data, and define space boundaries for energy simulation using EnergyPlus automatically, but the HVAC data had to be added to the IDF file with a text editor manually (Bazjanac 2008) (Bazjanac, Maile et al. 2011).

SimModel was developed as an interoperable XML-based data model for the building simulation domain and the overall AECOO industry. This model allowed integrated geometric and MEP (mechanical, electrical, and plumbing) data, related to EnergyPlus and other simulation tools with the DOE engine, to be exchanged by implementing an industry-validated terminology aligned with IFC. The model was compatible with the main BIM platforms used in the AEC industry, such as Autodesk Revit and ArchiCAD. It could translate data between input data dictionary (IDD) files, Open Studio IDD, gbXML, and IFC, and was employed by the EnergyPlus graphic user interface (GUI) as an internal data model. SimModel was expected to develop a new IFC MVD of HVAC design applications and support other data formats and simulations, such as daylighting and computational fluid dynamics (CFD) (O'Donnell 2013).

In addition, there are several other studies regarding data exchanges for other simulations. Wei Yan and Mark Clayton utilized an application programming interface (API) to transit BIM into Modelica and Radiance, for building thermal and daylighting simulation (Wei Yan, 2014). Apeksha Gupta presented a conceptual framework for developing IFC compliance into renewable energy simulation tools as RETScreen® and HOMER (Gupta, Cemesova et al. 2014). Although much work has been done on data exchange, there is no practical automatic tool supporting all energy-related data exchange between BIM and BES. Two approaches, one as a fully automated interface (FAI) and the other as a semi-automated interface (SAI), have been compared for transiting CAD (e.g., IFC) into an EnergyPlus input file and checking their efficiency and accuracy; the result indicating SAI as more reliable (Ahn et al. 2014).

2.3 BIM Interoperability with BAS for Energy Management

BIM has been integrated into facility management systems to assist with energy management in many areas, such as supporting energy analysis, visual 3D models and animations, management of equipment and fixtures, data tracking and recording (Motawa and Carter, 2013) (Becerik-Gerber, Jazizadeh et al., 2011) (Arayici, Onyenobi et al. 2012) (Volk, Stengel, and Schultmann, 2014). BIM, as a built model, is accurate and includes most information that building managers need at the operation stage and it can collect extra information from construction or the actual building operating data from BAS. This data may be imported using an open standard, such as COBie or IFC, into other tools as BES tools for further data analysis or used directly for a computerized maintenance management systems (CMMS) to reduce the manual input (Teicholz, 2013) (Volk, Stengel, and Schultmann, 2014). By managing the complex operation of information at commissioning and operation stages, BIM improves energy efficiency and building maintenance (Hwang and Liu, 2010) (Lu and Korman, 2010) (Singh, Gu, and Wang, 2011). The accuracy and completeness of building operating information would decide the quality of BIM implementation at the operation stage. For example, some input parameters for energy simulations provided by a BIM are estimated values, such as loads, airflows and heat transfer, which could be gathered as real data collected by a BAS (Crosbie, Dawood, and Dean, 2010). Thus, BASs can be applied for collecting data and monitoring systems to provide accurate and detailed building information data for BIM, with many studies working on integrating BIM and BAS.

The General Services Administration (GSA) has attempted to link BIM with facility management (FM) requirements (GSA, 2011). A guideline identified the work processes and information requirements for facility management, describing the requirements of a building information model and the technical issues of creating and using BIMs during facility management (FM). The GSA developed four data exchange options supporting the data flow during the FM process, which uses open standards such as IFC and COBie or other proprietary approaches to integrate with FM, computer-aided facility management (CAFM) and computerized maintenance management systems (CMMS) which is showed in Figure 2-1. The first option is that an Excel spreadsheet could be developed to capture the related operating data for FM, and entered into a CMMS, which is easy and fast but the structure is more prone to errors and not as formal as other options. The second option is that COBie is imported into a CMMS program directly without integrating the BIM, but it does not work for graphic data transfer, e.g., location, geometry. The third option is to create a two-way link between BIM tools and FM systems; an example of this being a software application, named EcoDomus, which integrates BIM with various BASs (Ecodomus, 2015). The fourth option is using a BIM API to integrate BIM tools and BAS directly; with this option, graphics data are saved and edited in the BIM, and FM data is represented by COBie or exported into the CMMS (Teicholz 2013).

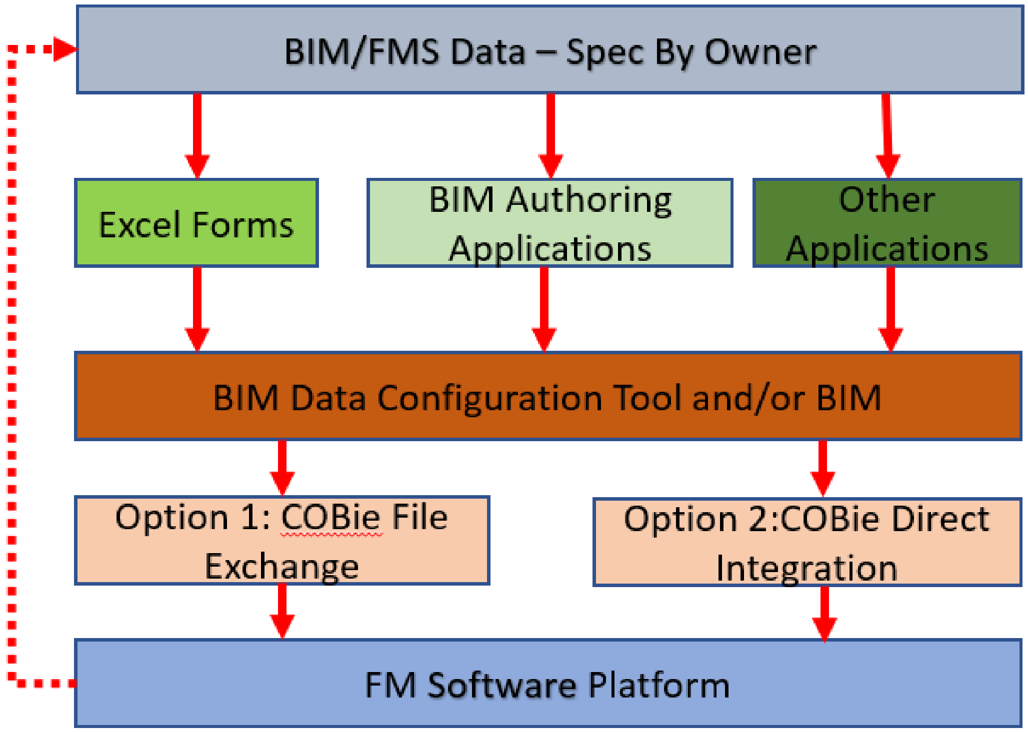


Figure 2-1 GSA Data Exchange Options (GSA 2011)

Other data transfer options include using IFC to represent the operating information in the building model and address facility-specific scenarios (i.e., International Alliance for Interoperability, IAI), using cloud-based servers to support the data exchange process. Several studies have focused on representing sensor information in BIM models; the Onuma Planning System could link with real-time sensors, lighting, and webcam data, using data acquisition technology (DAT) (Onuma, 2017) (Fares et al., 2013); Archibus is another FM system linking with BIM models, which could show building benchmark data for comparison (ArchiBus, 2017).

A BIM tool was developed as a data management framework for managing both real data from sensor networks and design data from different building service systems. The BIM model is based on the IFC schema, defining sensors using standard engineering definitions to assist with BAS, which only defined building control, and uses a data warehouse storing and analyzing long-term sensor data (Keller, O'Donnell et al. 2008). Another research analyzed the IFC schema to check if it represented the commissioning information and provided a potential extension (H. Wang et al. 2005). An approach of integrating the BIM information and sensor networks was proposed for supporting continuous commissioning (Ahmed et al., 2010). Current research focuses on extending the BIM schema for supporting necessary information of commissioning (Akin 2011). A case study showed that a 3D BIM model of building systems helped a commissioning team understand and utilize all data and documents together. This data was exported for simulation and analysis to assess the performance of building systems and detect possible faults. In addition, BIM data could be used for visualizing and managing systems, equipment and buildings, such as the Sydney Opera House (CRC, 2007; Mitchell, 2005) (Chen, Dib et al. 2011) and Maryland General Hospital (S. Russell-Smith, 2011).

While current BIM applications can classify and report actual operating data for energy management, related research is still limited and there are no automated integration solutions between BIM, BAS, and other AEC tools at the control and management level; most data have to be handled manually (Motawa and Carter, 2013). The main challenge is that BIM should be capable of updating real-time building operating data and any changes made to the actual building management in a building information model to reflect an accurate operating status for management. Moreover, not all data amenable to capture during actual operation and BIM has to handle such uncertain data and relationships, such as estimating values to assist the operating control (Volk, Stengel et al. 2014). In general, there is no substantial evidence surrounding successful BIM implementations in FM or energy management (Becerik-Gerber, Jazizadeh et al. 2011).

2.4 BES Interoperability with BAS for Energy Management

BES is commonly used for two purposes when improving energy management. One purpose is to assist with the commissioning process, which needs a calibrated energy model serving as the benchmark for determining savings. The other is to simulate the model-based control strategies of both manual optimization and automated optimization strategies (Claridge, 2004).

Many calibration methods were developed for comparing measured data with simulated data, focusing on a whole building and/or system level. Usually, a building energy model is calibrated by collecting data running off the initial model, together with the actual consumption of electricity and gas (Pan, Huang et al. 2006) (Tsubota and Kawashima, 2004). The errors generated by a whole-building energy model may be hidden by other compensating errors (Clarke, 2001) (Crosbie, Dawood et al. 2011). Thus, calibration at a component level, to identify possible compensation errors, is necessary and precise methods to detect differences between measured and simulated data are needed (Maile, Fischer, and Bazjanac, 2010). A method of identifying performance and measuring the data during the calibration process was developed by Maile (Maile, Fischer et al. 2010), with several case studies applying the comparison method at a general level without using too many details (Salsbury and Diamond, 2000), while other calibrated models focused on the component level or specific systems (Xu et al., 2005) (Salsbury and Diamond 2000). These simulation methods are usually for typical HVAC system configurations and not linked to design; additional works would need to be carried out for new or innovative HVAC systems (Maile, Fischer, and Bazjanac, 2010) (F. Wang et al., 2005) (Xu et al., 2005). Other studies have been carried out on using a building energy model to determine the optimized control methods of systems to minimize annual energy consumption and costs. Related case studies include optimal building control of a combination of a chiller, cooling tower and associated air handling units (Brandemuehl, Bradford, and Seaton, 1998) (Braunet al., 1989), predicative optimal building control of building thermal mass and chilled water storage, and mixed-mode building control (Costa, Keane et al. 2012) (Walker et al., 2004) (Spindler and Norford, 2009).

BASs are known to capture system performance data and measurements to evaluate energy-saving techniques (Cumali 1988, Clarke, Cockroft et al. 2001, Doukas, Patlitzianas et al. 2007, Doukas, Nychtis et al. 2009). The International Energy Agency (IEA) sponsored two projects in defining and applying performance evaluation and fault analysis methods based on typically available data in a real building energy management (BEM) systems (Hyvarinen and Karki, 1996) (Agency and Programme, 2006). These two documents developed the basic approaches for fault diagnosis and defined the key energy data from BAS for identifying potential operational problems and evaluating energy performance. Model-based control methods managing building subsystems should be embedded into BAS, to implement the real-time control strategies. Models cover many areas, such as low energy cost, carbon emissions, safety and maintenance, and indoor environmental conditions, as examples.

However, all the above research is on how to use the actual data to calibrate the energy model or manage the energy consumption, rather than linking the BES and BAS to achieve a fluent data exchange. Energy simulation tools often work for performance validation and building energy analysis with the whole building context, to increase the efficiency of energy management at a building's operation stage. A BAS is expected to monitor and supervise more comprehensive operating data for validating the simulation predictions, such as performance targets and energy analysis (Salsbury and Diamond 2000). Several researchers claimed that a perfect integration between a building energy simulation tool and a building energy management system should be capable of simulating actual buildings at different stages, coupled with intelligent systems that archive design intent and monitor actual building performance, and feed the results back to the simulation model to update it with better empirical data (Mills, 2004).

Only a few research projects integrated BES and BAS to assess and achieve the energy target of a building's design. For example, BES assists BAS for commissioning the energy improvement performance of HVAC systems (L. Wang et al., 2013) (Choinière and Corsi, 2003). A building energy management system based on aggregated BAS data and energy simulation was proposed to evaluate the operation status. Unlike other simulation-assisted control systems focusing on the optimum starting time of the facility, this system used simulation results to define inference rules, which would be accumulated automatically (Han, Jeong et al. 2011). Another common methodology of optimizing control strategies was based on the integration of calibrated building energy models and measured data collected by BAS. This methodology allows the building's energy manager to test the proposed control settings with the simulation model before they are implemented. A case study was discussed to demonstrate its applications (Costa, Keane et al. 2012).

Most functions of BES and BAS integration are based on the comparison between actual operating data and simulation data. Various appropriate sensor and equipment data has to be available from the BAS to make an accurate comparison (Claridge, 2004). PACRAT (Performance and Continuous Re-commissioning Analysis Tool) is a continuous commissioning program, recording meter and system operational data with an energy analysis to improve a building's energy management ("PACRAT - Fault Detection Diagnostics | Facility Dynamics", 2017). Also, Granlund Manager (formerly Taloinfo) was based on RIUSKA simulations to compare predicated data with actual measured data ("Home - Granlund Manager", 2017) (Maile, Fischer, and Bazjanac, 2007). Thus, data collection by BAS and interoperability between BAS and BES are the critical issues in this research area, which would simplify the utilization of energy simulation at the operation stage by connecting the actual operating status and the designed energy consumption targets.

2.5 Integration of BAS, BIM, and BES

There are only a few studies that utilized BIM in a building's operation stage, with a BAS collecting actual data and BES evaluating energy performance as an assisting tool for a building's operation management and decision-making process. The integration of BIM and BAS is often applied for a building's commissioning process, while calibrated energy simulation plays an irreplaceable role in building energy management. Although a few studies have been completed on integrating BIM and BAS, or BES and BAS, current studies of the integration of these three tools are still quite limited.

A framework and its related prototype were presented to utilize energy consumption feedback loops on facility management in a BIM environment. The prototype, with an interface of a BIM-enabled tool, linked BAS data to BIM by two approaches, a BIM energy analysis tool, BAS Link, and a BIM-energy consumption viewer plug-in link. These showed that the framework works in the whole life cycle of a building, but additional functions of information management, such as specifying, acquiring and processing of building performance data, are needed.

The integration of four information management tools may be the ultimate solution to evaluating a building's performance (Ozturk, Arayici et al. 2012). LBNL has developed an energy performance comparison methodology (EPCM) based on an interlinked building object hierarchy, describing the spatial and thermal objects and their relationships. EPCM allows the performance data to be compartmentalized from the bottom, as the control setpoints, to the top level, as total building performance data. This methodology does not use BIM directly but is based on the concept of the building object, with the building object hierarchy illustrated in EXPRESS (Maile, Fischer et al. 2010). Intelligent use of buildings' energy information (IntUBE) was proposed to collect dynamic operating data and integrate it into the optimization of building control, maintenance and retrofit strategies. The dynamic information of a building or a particular life stage could be saved in a "repository" of the Energy Information Integration Platform (EIIP). These repositories are linked to each other to exchange energy-related information between the different buildings, or stages, of a building's life cycle. BIM was assumed to be integrated for energy simulation (Dawood et al., 2011).

Another BIM-enabled information infrastructure for fault detection and diagnostics (FDD) has been developed and divided into four modules: an as-built building static information module, a building energy simulation module, a building operating data acquisition module, and an FDD module. A case study on FDD has been carried out based on this infrastructure. Its database was developed with EXPRESS and the BACnet module, based on Building Controls Virtual Test Bed (BCVTB), read BACnet data points based on an XML specification file (Wetter 2008). Device instances were defined with the signal type, then sent to an SQL statement block for implementation. A BIM platform was supporting all four modules, but the data exchange between BIM and BES was restricted to static data transformation (Dong, O'Neill et al. 2014).

A BIM server is another potential solution to integrate the actual operating information and building models. IFC files are transferred to a server, and dynamic sensor data are stored separately. Each sensor has a unique ID to correlate the data sets. BMS organizes these unique IDs to sensors in the IFC model and maps them onto hardware IDs; this method can save dynamic data (Borst et al., 2015). An existing open-source platform, named BIMserver.org, allows users to host their own BIM server to store building information of projects and build BIM tools. BIMserver integrates and saves this data as objects and provides numerous open interfaces and APIs to query, merge and filter the BIM data (Opensourcebim.org, 2016). An agent-based service-oriented approach of integrating facility life cycle information and supporting decisions during the entire facility life cycle was developed based on BIMserver.org (Shen, Hao, and Xue 2010). Singh et al. (2011) developed a theoretical framework of technical requirements for using BIMserver.org as a multi-disciplinary collaboration platform. However, a survey showed that the biggest obstacle for the effective use of BIMserver.org is client interface usability (Beetz, van Berlo et al. 2010). For daily work, Java code should be hidden from the standard users; a domain-specific query language is needed to encapsulate the Java code and be compatible with MVDs or (semi-)automatically composed based on the existing MVDs. (Jiang, Ming et al. 2012).

2.6 Research Gap

The actual obstacle to a successful implementation of BIM in information exchange is the interoperability between various applications and stakeholders in different phases of a building's whole life cycle. A summary of the literature is shown in Table 2-1, and a detailed gap analysis follows.

Table 2-1 Summary of Literature Review

	BIM/BES	BIM/BAS	BES/BAS	BIM/BAS/BES
Schema development	√√√	√	/	×
Envelope Interoperated	√√√	/	√	√
HVAC Interoperated	√	/	√	/
Sensor information exchange	/	√	√	×
Optimize control	/	/	√√	√
Retro-Commissioning	/	√	√	×

√√√: Major research area; √√: A certain number of researches; √: Limited research; ×:Almost no research;

/: not applicable;

2.6.1 Limitations of BIM and BAS Integration

Considering the complexity and diversity of activities during a building's life cycle, even with the help of IFC, it is too complicated to express all building objects uniformly and exchange them seamlessly between different applications 100% of the time (Plume and Mitchell 2007, Moon, Choi et al. 2011, Osello, Cangialosi et al. 2011, O'Donnell 2013). The first gap affecting the implementation of BIM in the operation phase is that there is no clear IFC schema and information exchange mechanism to represent the building operating information. Without a mature data representation scheme, BIM cannot save and exchange the building operating information fluently and correctly.

A modern BAS can monitor and collect a series of operating data, such as temperature, humidity, and air velocity. These data sets are recorded and analyzed to support the management's decision-making process and optimal control of the building's systems. Data exchange between BIM and BAS requires that BIM can read and integrate data from the recording datasets of BAS. Therefore, to save and manage these actual operating data, a BIM needs to have a standardized way to represent them. Although the newest IFC schema includes operating information, the applications of the IFC schema and BIM in actual operation management have not been widely applied (Berard and Karlshoej 2012). Some researchers work on representing sensor information in BIM-based models by IFC, but systematic research on this topic is limited. Amongst these studies, a small percentage work on saving sensor data as IFC format, to exchange them between BAS and BIM (Chen, Bulbul et al. , Liu and Akinci 2009, Chen, Bulbul et al. 2014). Without the ability to collect reliable operating data, the benefits of BIM in systems monitoring and operation are quite limited.

2.6.2 Limitations of BES in Operation

The second gap in research is that current BES implementations are insufficient for the operation phase. BES is mainly applied during the design phase to estimate future energy consumption and compare design solutions, providing a reference for decision-making. Simulation results are only used for comparing design solutions and there is no actual operating data collection with side-by-side comparisons to prove the accuracy of the simulation model. This is one of the primary reasons that the accuracy of energy models is doubted.

In an ideal situation, the original input parameters of an energy model are updated according to the process of the life cycle of a building and provide an energy consumption benchmark for a building's future operating status. However, the implementation of BES in the operation phase is limited at this point. A few studies work on comparing simulation data and operating data to calibrate energy models, but most of them collect or measure data manually and offline (Clarke, Strachan et al. 1993, Agami Reddy 2006, Pan, Huang et al. 2007). To improve optimal control and retro-commissioning, the core functions of energy management research attempts to integrate BES and BAS to provide an energy estimate for the building's operation phase (Han, Jeong et al. 2011, Costa, Keane et al. 2012). Although BAS can collect actual operating data for energy model calibration, there is no automated collection. Currently, there are no reliable methods to collect and compare the simulated data that BES provides with the actual operating data that BAS collects

2.6.3 Limitations of BIM and BES Integration

The third research gap is the lack of information exchange between BIM and BES. To integrate BIM and BES, the buildingSMART alliances have analyzed the IFC schema from an energy perspective and have developed several IFC extensions to support energy-related information exchange (Cemesova, Hopfe et al. 2013, O'Donnell 2013, Volk, Stengel et al. 2014). The data exchange between BES tools and 3D models of BIM has also been investigated, whereas most research focuses on automatic building data exchange between BIM tools and BES tools to reduce manual input and save time and labor. In this area, most of the building data exchange is limited to building geometry and construction materials (Fazio, He et al. 2007, Maile, Fischer et al. 2007, Bazjanac 2008, Hitchcock and Wong 2011). Currently, the primary transformation of building geometry has been achieved between BIM and BES, but relatively few studies have focused on converting HVAC system data from BIM tools into BES tools, without extra manual input work. (Bazjanac and Maile 2004, Bazjanac, Maile et al. 2011). Many energy analysis tools that claim they can transform HVAC data from BIM to energy analysis tools, only support limited types of HVAC systems and are used for energy estimation at the early design phase (Bazjanac and Maile 2004). Furthermore, BIM-integrated energy modeling tools cannot incorporate renewable energy systems. The seamless data exchange between BIM and simulation tools during the design phase is insufficient (J O'Donnell, 2011).

During the operation phase, the primary function of BES is to provide system analysis and energy benchmarks for building managers. Usually, BES is conducted with measured real-time data to analyze the building systems, but there is limited research on continuous information exchange between BIM and BES during the operation phase.

2.6.4 Lack of Total Integration of BIM/BAS/BES

This is the most significant gap in the research.The original goal of BIM was to provide uniform information storage and exchange platform, which required BIM to define a clear path for information exchange among various applications, for different activities to use different applications to collect and analyze this data. This approach monitors, analyzes and manages the operation status through a single BIM-based platform efficiently.

In an ideal case, a BAS collects actual data for analysis. Although building systems are nowadays extensive and complex, modern energy management systems, in conjunction with BAS, can continuously monitor and meter energy consumption, space conditions of rooms, and equipment status of HVAC systems. This rich information content provides a robust database that could be merged into BIM. Then, BES analyzes these data sets scientifically and effectively, optimizing building control, ensuring the operational status, and developing an energy consumption benchmark for building operators, to help them find their way through countless data. During this information collection and analysis process, the role of BIM is as a platform or a transit station to support all this information, save the original data, and provide a visible tool to control the energy consumption for building managers.

In summary, the current information exchange between BIM, BAS, and BES is quite limited, especially during the operation phase. Little research integrates BIM/BES/BAS to monitor and enhance the operation status. Several frameworks, for integrating the three to optimize operation, have been developed and some case studies and empirical research experiments have been conducted to prove the benefit of implementing BIM into building energy management (Dong, O'Neill et al. 2014). Currently, there is no openly documented, and fluent exchange for an information pathway between the three domains.

3 Research Design

3.1 Research Goal and Questions

According to the literature review in Section 2, few studies have been done on the topic of integration of BIM, BAS, and BES, especially with a focus on improving the building energy efficiency during operation. Unfortunately, operational energy consumption represents the largest part of the energy demand during a building's life cycle. To fill this gap, the main research question of this research is:

How can BIM be utilized as a facilitator to enhance the linkage between energy simulation data and energy-related real-time data and effectively support energy management during a building's operational phase?

BIM has been envisioned as a uniform information exchange gateway with a visible, 3D representation model, which can be shared by various stakeholders easily and fluently to help the construction and operation. The research investigates the opportunities of BIM for information capture and exchange and how BIM can be utilized to increase building energy efficiency while acting as an information hub to automate and reduce labor via simplifying the data management process. Ultimately, this prototype has the potential to impact the communication efficiency in the AEC industry and support various building stakeholders.

This research developed a framework and a prototype (proof of concept) of a BIM-based platform to support energy-related data exchange and management processes for facility management. With this platform, building operators are envisioned to have direct access to actual performance data and related energy simulation results. This will allow for the identification of possible system faults, improvement of model-based control, and assessment of potential energy-saving measures. Furthermore, researchers will be able to collect real-time data from various BAS and calibrate energy models to improve their accuracy. Ultimately, such a platform can also help to simplify the commissioning process and enhance the accuracy and quality of system installation and operation.

3.2 Research Objectives

This study describes the use of a theoretical framework to perform BIM-based data integration into BIM, BAS, and BES.

- **Objective A**

Development of integration strategies, mechanisms and a prototype of a BIM-based platform integrating BAS and BES towards applications in FM.

Research Methods: Systematic Literature Review, Framework, Prototyping

A systematic literature review was used to identify the existing research surrounding the current energy-related data exchange methods between the BAS/BIM, BIM/BES and BAS/BIM/BES combinations. It was expected to be used to decide which technology has the most potential, as well as to build a better data exchange method. Also, the outcomes decided what methods have been used, which data sets can be exchanged, and what the efficacy of these methods is. The following research, such as data exchanging methods and used tools, was found during the systematic literature review.

A BIM-based framework was developed to explain the major research findings graphically, and it defined the key factors, variables, and relationships using four modules that supported the general data exchange process among BAS, BIM and BES as a tool for facility management. The four modules are the BIM module containing static building information, the Operational database module containing the dynamic data from BAS, the Energy simulation module for energy simulation, and the Analysis and Visualization module for data analysis. The key exchanged dataset, including static building information, dynamic operating data, energy consumption data, and extra resource data for energy simulation, were identified using literature review and project investigation. Then, the identified data were analyzed and described using IFC schema, and the missing datasets in IFC schema for energy simulation and calibration were determined. The details are referred to in Section 5.

A developed prototype was coded to implement these proposed functions of the framework and serve as a tool to assess the applicability of the framework. To facilitate the data exchange process within the four modules, a GUI was coded and implemented using pre-developed tools, such as

Dynamo, OpenStudio, and MySQL Workbench. In general, the GUI extracts the dynamic information from the database module, translates the data into the BIM model, and then transfers the information into an energy model input file. Moreover, the GUI implements the functions of analyzing and visualizing data. This prototype assessed the applicability of the framework when applied to a case study to validate the functions of a prototype. The details are referred to in Section 6.

- **Objective B**

Application of the BIM-based prototype and analysis of the impact on Performance Monitoring as a result of integrating BAS/BES and BIM technologies in support of processes in FM.

Research Method: Case Study

The developed prototype was implemented to optimize building operational management in the form of a case study, which is an office with a fan coil unit (FCU) in the Bishop-Favrao Hall located in the Virginia Tech campus, Blacksburg, VA. A MySQL database was created to store the collected dynamic data, including actual weather data collected by National Oceanic and Atmospheric Administration (NOAA); indoor room temperature, room humidity, illuminance, and people activities collected by HOBO Web-Based Data Logging Systems; and indoor temperature, supply air temperature, and air flowrate collected by the BAS. These dynamic data were exported to the energy model by the GUI to calibrate the energy model using the parameter of zone air temperature as a calibration index. Then, the calibrated energy model was used to evaluate different operation scenarios to select the most efficient.

The GUI provided the following functions as a reference for the building managers: exchanging the weather data; building operating schedules, spot-measured data, and energy consumption data; comparing and analyzing the simulated data and measured data; visualizing the results; and reporting the possible operating faults. The case studies are expected to prove that BIM technology can be used to efficiently manage real-time dynamic and simulated data, evaluate operational energy performance, and optimize building energy management. The details are referred to Section 7.

3.3 Research Methodologies

This study describes the use of a theoretical framework to perform BIM-based data integration into BAS, BES, and BIM. A systematic literature review of data exchange functions between BIM and BES/BAS was conducted to support the first developmental stage of the theoretical framework. The framework was then applied across design modules to demonstrate how to classify, save, and exchange dynamic building information. Using this framework, related data, and parameters of a whole-building energy model were collected from literature reviews of industry guidelines and project reports. A prototype containing a GUI was coded to facilitate data exchange functions across the modules using pre-developed tools. This would assess the applicability of the framework when applied to several case studies.

The main research methods of this proposal are as follows: 1) Systematic literature reviews, 2) Framework development, 3) Prototyping, and 4) Case studies. The sub-research methods and validation methods are shown in Figure 3-1.

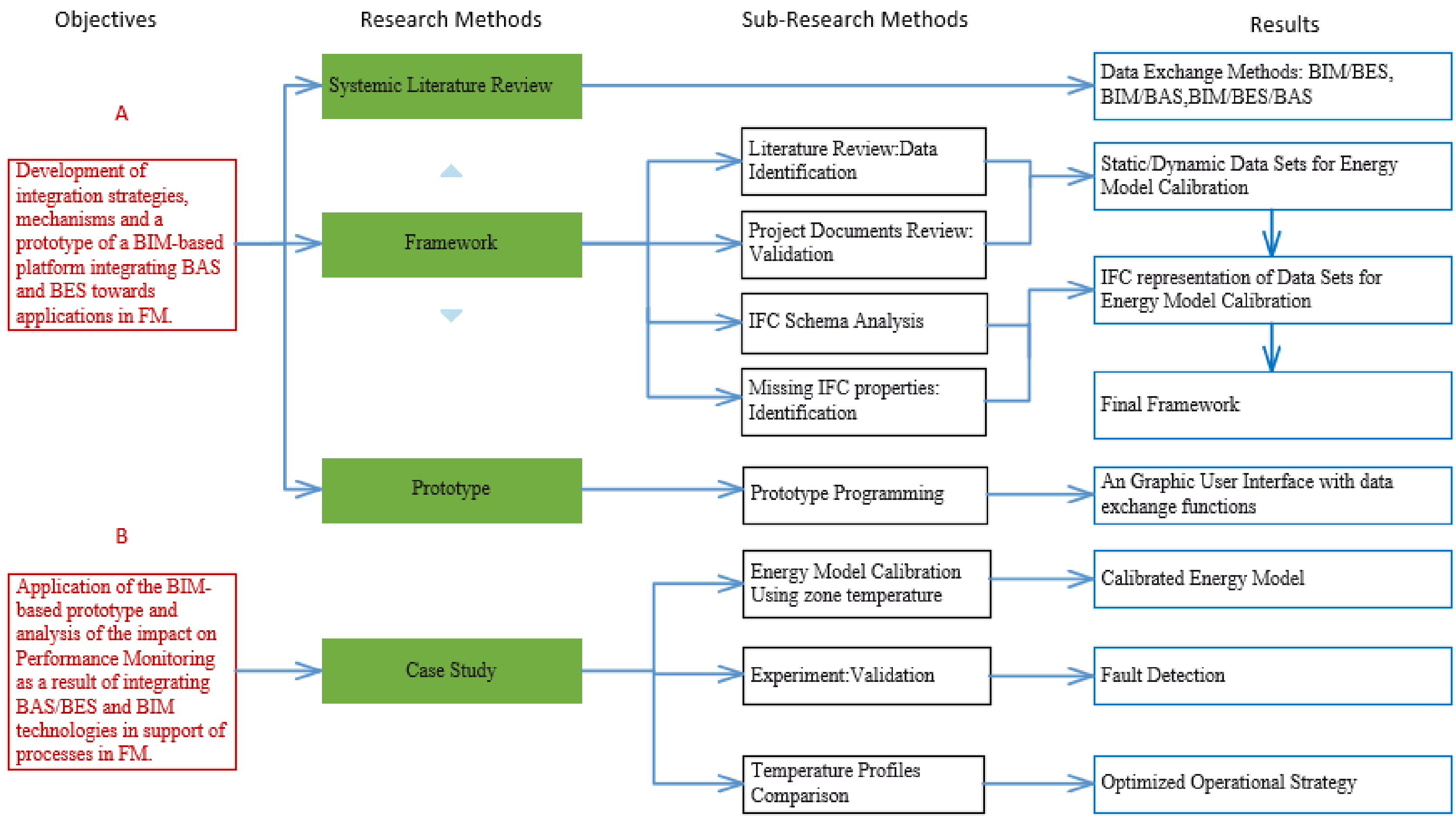


Figure 3-1 Research Methodologies

1. Systematic Literature Research

A systematic literature review is a methodology of searching, identifying, categorizing, and evaluating all relevant literature surrounding a particular research question or field. Compared to traditional narrative reviews, a systematic and quantitative literature review can identify and create new research evidence and minimize potential systematic error (biases) by reviewing all relevant studies. Systematic reviews comprehensively cover all the available literature of a specific research field, and then, they evaluate the quality of the research data and follow a clear, detailed approach for data production. This includes the use of documented, transparent, and rigorous extraction processes throughout (Robson and McCartan 2016).

The basic functions of the literature research include: 1) The identification of existing knowledge of the problem, 2) The background and basis for conducting this research, 3) The definition of methodological problems, 4) The identification of special knowledge or equipment required, and 5) The sourcing of relevant information for the preparation of research reports (Christensen, Johnson, et al. 2011).

A systematic review was applied herein to extract existing methods of dynamic data exchange amongst the BIM/BES, BIM/BAS, and BIM/BES/BAS. This review identified the most common data exchange solutions and functions, providing a reference for this study. Research papers, case studies, and technical manuals and guidelines were reviewed.

The practical guidelines for all systematic reviews can be summarized into three main phases. First, planning the review involves identifying the research question and developing the review protocol. Second, conducting the review involves performing a comprehensive literature search to select relevant studies. Data is then critically assessed, monitored, and extracted to create new research data. Third, reporting the review involves specification of the dissemination strategy and presentation of the findings (Keele 2007, Petticrew and Roberts 2008).

2. Framework Development

The development of the framework will complete the first study objective. The theory describing the study and why it is referred to as a conceptual framework was explained (Robson 2002). A framework typically explains the major research findings either graphically or literally. The main elements include research data, further theory, and appropriate methods/techniques of analysis (Fellows and Liu 2009). A framework also defines the key factors, constructs/variables, and their relationships (Miles and Huberman 1994). The benefit of a conceptual framework is that it allows the research to be selective, only choosing important features and relationships and defining that data for further analysis. Although some frameworks are narratives, they are most commonly presented as diagrams (Robson 2002).

This study proposed a framework that consists of four modules. These modules describe and explain a conceptual model that illustrates the flow of information and the processes for data exchange amongst the BIM/BAS/BES. The framework can potentially achieve three major functions: 1) Summarize all energy-related information exchange processes amongst BIM/BES/BAS, 2) Define the necessary quantitative and qualitative data and their relationships, and 3) Develop real-time dynamic information, simulated information exchange, and an analysis of procedures based on BIM to support building energy performance management. The four main modules are (1) the BIM module, (2) the Operation Database module, (3) the Energy Performance module, and (4) the Analysis and Visualization module. These modules are described in further detail in Section 5.

3. Prototyping

A prototype in system development was seen as an individual that exhibits the essential features of a later type. A prototype system is intentionally incomplete but can be modified, expanded, supplemented, or supplanted. Prototyping an information system is a four-step procedure, including 1) Identify the Basic Information Requirement of the User, 2) Develop a Working Prototype, 3) Implement and Use the Prototype System, and 4) Revise and Enhance the Prototype System. (Naumann and Jenkins 1982)

This study used a developed prototype to implement the framework and serve as a tool to assess the applicability of the framework in the form of a case study. To facilitate the data exchange process within different modules, a GUI was be coded. The GUI extracted the dynamic information from the database module, translated the data into the BIM model, and then transferred it into energy model input files.

The MySQL database was used as the Database Module due to its applicability and capabilities. The BIM tool, Autodesk Revit, and the interface were developed using Dynamo with python programming language. The energy simulation module was developed by SketchUp/Open studio, and Open studio supports whole-building energy modeling using EnergyPlus. The GUI collects information from the BIM model and the database. This was used to develop the input files for Open studio to perform energy simulations, to read the simulated results, and to analyze and visualize the data without manual intervention in the translation process. All of this was done after the BIM model and energy model are created and data are entered into the BIM and database.

4. Case study

The case study aims to validate the functions of a prototype building model. The case study is a typical research method in AEC field defined as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (Yin 2013). The purpose of the case study is to clarify a decision or set of decisions, including why the decisions were made, how they were implemented, and with what means were they implemented.

In this study, the developed prototype was implemented to optimize building operational management. An office in the BFH Building located in the Virginia Tech campus was selected as the case study. The related MySQL database was created to store dynamic data, and a BIM model and whole-building energy model of BFH were created. The whole-building energy model was calibrated to provide an energy consumption baseline, which was driven by actual dynamic data using the GUI to obtain new simulated results. On the basis of these modules, different operation scenarios and interface functions were tested. The case study was expected to prove that BIM technology can be used to efficiently manage real-time dynamic and simulated data, evaluate operational energy performance, and optimize building energy management.

3.4 Research Assumptions and Limitations

This section presents the assumptions and limitations made within the scope of this research. The research scope will focus on the dynamic operating data exchange process between the BIM, BES and BAS, where the research goal is to provide a convenient BIM-based method of energy data exchange for integrating the energy simulation into the real building energy management process.

The assumptions are as follows.

a) The static data exchange between BIM and BES has been well-developed, and the prototype will implement a simple function updating several core static parameters as an example;

b) The key dynamic operating data for energy simulation has been uploaded into the Operational Database module from the BAS; and

c) The BIM and energy model exist before prototyping the framework, and the applied energy model has been calibrated manually offline to provide an energy consumption benchmark.

3.5 Proposed Framework and Contributions

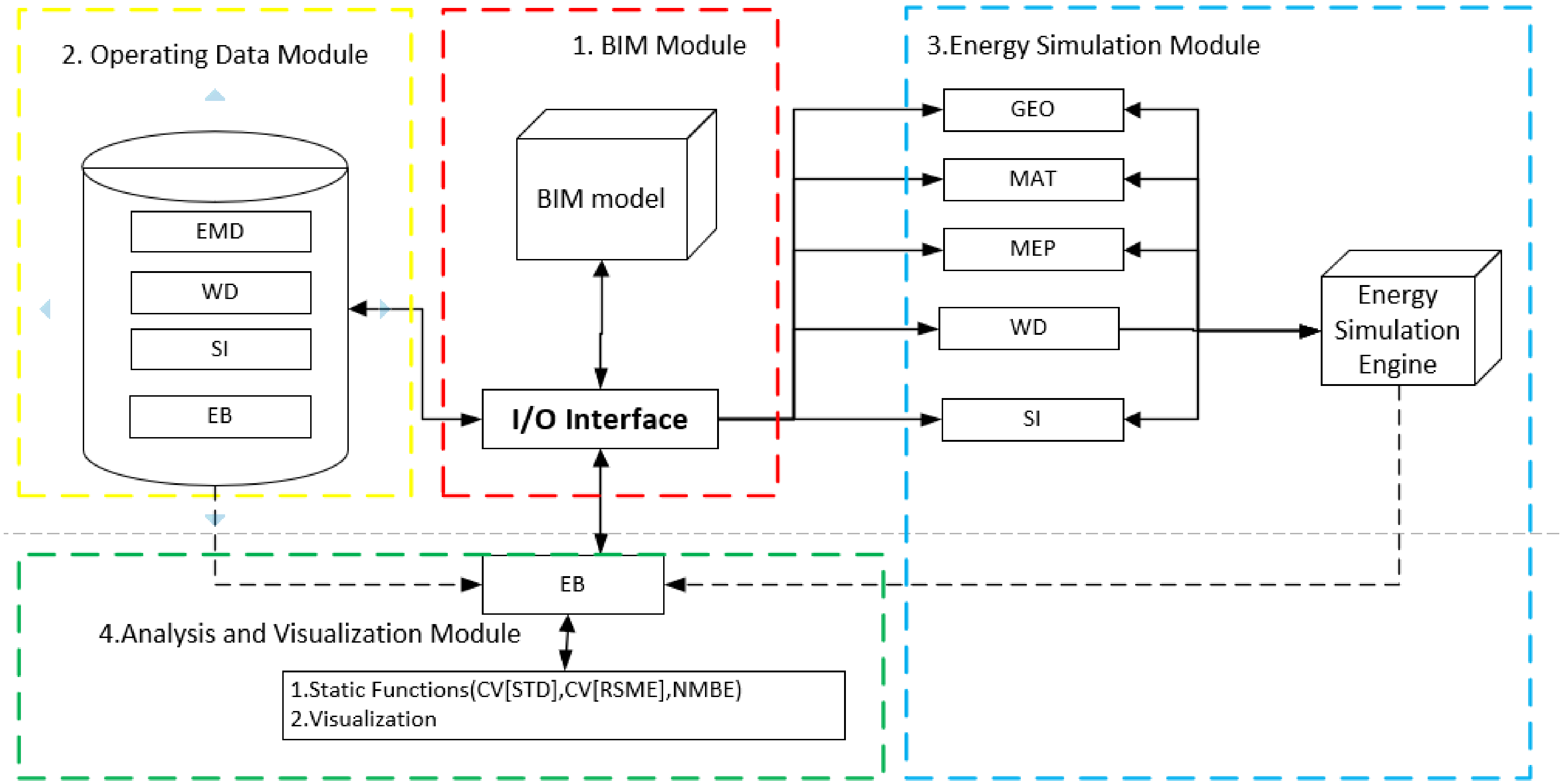
Figure 3-2 shows the complete framework for the research. A detailed explanation is referred to in Section 5. The main contributions of this research are:

a) This systematic literature review contributed to a general understanding of the existing static and dynamic data exchanging capabilities among BIM, BES and BAS. It also identified the commonly used data format and data exchange methods, which became a starting point for further research;

b) The research identified the IDR, classifying all the critical data sets for energy calibration and describing them using the IFC data model and an additional data set. This was a first attempt at defining the sub-dataset in IFC for energy simulation and calibration. Here, the IFC data sets not only serve as templates for the energy model calibration process but also as benefit methods that utilize both operational data and energy simulation output, such as model-based control.

c) The research develops a BIM-based framework that can be used as a standardized method for information exchange and management within the operational phase. An IFC-compliant dynamic data exchanging process and data management tool capable of conducting operational data and simulated data analysis was created. It demonstrated that

BIM, as an open, generic, and reusable data transfer and management platform, can serve as a tool to integrate an energy model into building energy management. The final developed framework was applicable not only to energy simulation but to other building performance simulations, as well.



EMD:Equipment Measured Data
WD:Weather Data
SI:Sensor Inventory
EB:Energy Benchmark

GEO:Geometry Data
MAT:Material Data
MEP:Mechanical,electrical and plumbing Data

CV[STD]:Coefficient of Variation of the Standard Deviation
CV[RSME]:Coefficient of Variation of the Root-Mean-Square Error
NMBE:Normalized Mean Bias Error

Figure 3-2 Framework (Detailed)

4 Data collection: Systematic Literature review

A systematic literature review has been conducted to investigate the required building blocks for a cohesive BIM/BES, BIM/BAS and BIM/BES/BAS integration. This research aims to investigate the current existing energy-related data exchange methods among building information modeling (BIM), building energy simulation (BES) tools and building automation systems (BASs). As shown in an earlier section, research about energy-related data exchange between BIM and BAS has been limited. Several studies defined a data exchange format; several researchers developed data exchange protocols, and others focus on software application and case studies. Researchers reviewed the current application of BIM in building operation phase, in which they try to use BIM to integrate the real-time data and design benchmark. Conclusively, a comprehensive assessment of this research is lacking. Thus, a systematic assessment has been conducted to decide which technology has the most potential as well as build a better data exchange method. Also, the outcomes decide what methods have been used, which data sets can be exchanged, and what is the efficacy of these methods. This section systematically analyses the literature on data exchange methods and processes among BIM, BES and BAS, and seeks to answer four research questions: (1) What are the prevalent data exchange methods among BIM, BES, and BAS? (2) What data sets can currently be exchanged among these parties? (3) What is the efficiency of these data exchanging methods? This review is considered to become a starting point for academics and practitioners, especially as research about using BIM into building management processes evolves.

4.1 Definition of Key Terms

Several key terms should be clarified to conduct the review. These definitions are used for defining the search protocol as well as developing the research quality review. Although a few studies have been done to exchange the data between energy models and BIM models, they have not defined the exchanged data sets. For the purpose of this paper, the target data are set to be energy-related and considered to impact building energy consumption. Two types of data sets are defined in this paper;

1) Static building information. This entails data that is not changed over time and can usually be applied for the energy model at the design phase: They are referred to as design parameters or design data. The main parameters of static building information include building geometry, enclosure material, designed internal load, etc. Different combinations of static parameters are compared and selected for running the energy model and getting the best design option, but these values are constant after they are decided.

2) Dynamic building information. The parameter values of this type of data set are anticipated to change over time and are usually collected by BAS for evaluating the actual operating energy consumption. They are possible to be referred to as building operating data, dynamic data, real-time data or actual operating data. A BAS typically collects a huge dynamic dataset, and the applied parameters with their values depend on the actual energy analysis goal. The operating data is collected from sensors or meters. e.g., real-time indoor environmental conditions from sensors, and energy consumption recorded by meters. So the dynamic information may also be referred to as sensor data or meter record.

Building energy simulation(BES). BES, sometimes known as building energy modeling (BEM), is defined as "building energy estimation using a computer simulation program"(ASHRAE 2018). The computer simulation program, known as building simulation tool or building simulation software, is capable of running these specific mathematical models and simulating the energy performance of building systems (ASHRAE 2018). There is no explicitly defined difference between building simulation tools and building simulation software.

Building Automation System(BAS). A BAS is utilized to manage and control building systems, such as HVAC, lighting, fire alarm, and security, elevators, etc. The Association of German Engineers (Verein Deutscher Ingenieure) defines building automation as "the computerized measurement, control, and management of building services." (Merz, H., Hansemann, T. & Hübner 2009). Therefore, building automation systems are developed owing to the digital revolution and wide applications of computer control & automation (Levermore 2000). Energy-related dynamic building information is supposed to be collected by BAS or a part of BAS which is often referred to as building energy management system (BEMS).

Building Information Modeling (BIM). The terms building information modeling (BIM) and building information model are often used interchangeably in practice, but BIM is defined as a modeling technology and associated set of processes to produce, communicate, and analyze building models, which is more like an IT-enabled, open standards-based deliverable and a collaborative process (NIBS 2008) (Eastman, Teicholz et al. 2011). To achieve a seamless data exchange among all AEC stakeholders, these building objects should be described or defined by a neutral AEC product data model to implement the interoperability among various applications. One of the most commonly applied and comprehensive building product data schemas is the Industry Foundation Classes (IFC) which is based on the ISO-STEP-developed data modeling language, EXPRESS (Schenck and Wilson 1994). Various BIM tools exchange their files through IFC as a shared neutral exchange format. Another large set of exchanges is supported by XML (eXtensible Markup Language) which is an extension to HTML and supports multiple handling of schemas. BIM applications in the AEC area are categorized as BIM tools, BIM platform and BIM environments whose definitions are referred to Section 1.1.3.

The methodology of data exchanging is classified in three main ways as 1) Direct links use the Application Programming Interface (API) of one system to extract data from that application and write the data using the receiving application's API. 2) A proprietary exchange format which is a file or streaming interface developed by a commercial organization for interfacing with that company's application. 3) The public product data model exchange formats involve using an open and publicly managed schema and language, such as XML or text file. Some product models support both XML and text file exchange (IAI 2010a).

4.2 Systematic Literature Review Questions

A systematic quantitative literature review was performed following a formal systematic literature review process that is being used in the social sciences and software engineering. This systematic literature review aims to summarize existing studies in data exchanging among BIM, BAS and BES. It also provides a background of current research activities as well as identifies any gaps to appropriately identify new research questions. A protocol has been developed as a plan for the review process, and its details are described in the following sub-sections.

The researcher is interested in using BIM to increase building energy efficiency. From this aspect, energy-related data are expected to be exchanged among BIM, the energy model based on BES, and the dynamic data collected by BAS or other external methods that can be integrated into a BAS. Considering only a few studies focusing on data exchange between two of the parties i.e. the energy-related design data exchange between BIM and BES, and their data exchanging methods are valuable for investigation as an example for future development. One main research question and four sub-questions are developed.

Main Question: What are the existing energy-related data exchanging methods among BIM, dynamic data collected by BAS or other system, and energy model data based on BES?

Sub-Question 1: What are the existing energy-related data exchanging methods between BIM and energy model data based on BES?

Sub-Question 2: What are the existing energy-related data exchanging methods between BIM and dynamic data collected by BAS or other equipment?

Sub-Question 3: What are the existing energy-related data exchanging methods based on BIM bridging energy model data based on BES and dynamic data collected by BAS or other equipment?

Sub-Question 4: What are the scopes and effectiveness of these existing energy-related data exchanging methods?

However, when conducting the review, it showed that very few of the studies reported any data exchanging methods between BIM and dynamic data collected by BAS or other equipment, but several researchers report how to integrate the dynamic data into BIM. Therefore, the research sub-question 2 and 3 are revised as "what are the existing energy-related data **exchanging methods/data integration platforms** between BIM and dynamic data collected by BAS or other equipment." And "What are the existing energy-related data **exchanging/integrating platforms** based on BIM bridging energy model data based on BES and dynamic data collected by BAS or other equipment?

4.3 Search Methods

4.3.1 Search Terms and Resources

4.3.1.1 Search Key Words

The strategy used to construct the search terms, in the review, was as follows:

a) Deriving major terms from the questions by identifying the population, intervention, and outcome;
b) Identifying alternative spellings and synonyms for major terms;
c) Using the Boolean OR to incorporate alternative spellings and synonyms
d) Using the Boolean AND to link major terms from sub-questions.

From Section 4.1, we select the following alternate spellings and synonyms. This resulted in the preliminary search string and keywords used in the search are listed as follows; every sub-question has one related searching term combination except No.4 sub-question.

Three short words combinations are defined as

- [A]: BIM OR Building Information Modeling OR IFC;
- [B]: BES OR energy simulation OR energy modeling OR energy model;
- [C]: BAS OR Building automation system OR building energy management system OR dynamic data OR sensor data OR real-time data OR operating data OR monitor data OR meter data;
- [D]: “Data exchange” OR “information exchange.”

These combinations were then searched together using the Boolean combinations AND as Search I, II, and III.

I. [A] AND [B] AND [D]

(BIM OR “Building Information Modeling” OR IFC) AND (“energy simulation” OR “energy modeling” OR “energy model”) AND (“Data exchange” OR “information exchange” OR interoperability OR integration)

II. [A] AND [C] AND [D]

(BIM OR “Building Information Modeling” OR IFC) AND (“Building automation system” OR “building energy management system” OR “dynamic data” OR “sensor data” OR “real-time data” OR “operating data” OR “monitoring data” OR “meter data” OR “actual data”) AND (“Data exchange” OR “information exchange” OR interoperability OR integration)

III. [A] AND [B] AND [C] AND [D]

(BIM OR “Building Information Modeling” OR IFC) AND (“energy simulation” OR “energy modeling” OR “energy model”) AND (“Building automation system” OR “building energy management system” OR “dynamic data” OR “sensor data” OR “real-time data” OR “operating data" OR "monitor data" OR "meter data") AND ("Data exchange" OR "information exchange" OR interoperability OR integration)

The search results from III. are included in the searching results from I. and II. To show the research trend from different data exchanging areas, the number of searching results is listed and all duplicate documents are removed in the next step.

4.3.1.2 Search Process

The systematic literature review was conducted using four scholarly electronic databases, namely as Google Scholar, ISI Web of Knowledge, Science Direct, and ProQuest. These key terms were searched in the title and abstraction of research publications. The searched terms and the number of search results are listed in Table 1 to show the general research focus in the related area. The 1st screening process was to review the title, abstract and conclusion, to determine whether this article is related to the research area, or to obtain the full article in the review. Google Scholar has no option to only search the key terms in title and abstract, so the key terms are searched in the full text, and the abstract is reviewed manually to decide if it is necessary to obtain the full article. This explains why Google Scholar has returned more articles than the other three databases. The other three databases provide the key terms' search in the title and the abstract. So each article's abstract is reviewed to select those discussing the energy-related data exchange between BIM and BAS, or BIM and BES, or BIM and BES and BAS. All the search process including the number of articles returned from searching and the number of articles after the first screening has been documented as in Table 4-1. The duplicate articles have been removed at the end, leads to the number of final selected articles as primary sources is 143. Details of the primary sources that were potentially relevant were stored as groups in Endnote software.

Table 4-1 Returned Results

Keywords Combination	**Google Scholar**		**Web of Knowledge**		**Science of Direct**		**ProQuest**		**Final Result**
	Search	1st	Search	1st	Search	1st	Search	1st	
I.	505	94	40	15	14	6	29	13	108
II.	605	44	30	9	24	5	19	5	51
III.	248	32	2	1	4	3	3	2	32
Total									143

After the first screening, a 2nd screening was done to evaluate against a set of inclusion and exclusion criteria to decide which studies should be contained in the review and extracted the research data into the database, while additional papers are added from the reference list of those selected research papers. The detailed study selection criteria and data extraction strategy are in the following sections.

4.3.2 Study Selection Criteria

4.3.2.1 Inclusion criteria

Studies that evaluated the data exchanging method among BIM, BAS and BES were of interest to the review. Therefore, the following inclusion criteria were applied:

1) Publications should be published in a journal or conference proceedings due to the applied peer review process that is expected to control quality;
2) The topic of publications should describe the energy-related data exchanging method among BIM data, dynamic data from BAS or other equipment, as sensor or meter, and energy model data developed by BES;
3) The method has been developed and described based on direct data exchange (mapping directly), or a proprietary/public exchange format, or integration among different applications (e.g. using a data ware);
4) If the research methodology is based on a proprietary/public exchange format, the original data type, the targeted data type and the used shared neutral format and the principle or mapping rules should be clarified for extraction.
5) If the research methodology is based on direct link/integration, the methods of data exchanging/data integration should be clarified.
6) The study should aim to energy-related issues as building energy simulation or building energy management. Topics about building facility management can be included if the author claimed that the research is related to building energy consumption.

4.3.2.2 Exclusion criteria

Studies that meet the following criteria were excluded from the review:

a) Studies that cannot provide a solid data exchanging method and its validation, e.g. a literature review, a theoretical publication, a case study evaluating related software importing and exporting without any technical improvement.
b) Studies are about some special topics other than directly building energy efficiency or a general facility management topic without indicating its application for energy

management, even investigate data exchange between BIM and BAS. E.g. construction safety, structure monitoring, the capture of BIM information from laser scanner data.

c) Publications for which only an abstract or a PowerPoint slideshows are available.

d) Books, reports, and dissertations are not included in this review, but the author's publication lists are searched to check if there is any related journal or conference paper.

e) Studies that are not focused on single building energy efficiency, e.g. urban-scale energy consumption.

f) Studies that focus on the sensor data integration with building energy management which is a data exchange between BAS and BES, but miss BIM.

g) Studies about integrating 3D thermal point cloud and BIM without energy simulation will be eliminated. Although the 3D thermal point is an actual monitored data, it is not a common data collection method in traditional building energy management system, but an innovative data-collecting technology with special data exchange method between 3D thermal point and BIM.

4.3.3 Included and Excluded Studies

After the 2nd screening, 12 studies were excluded because they compare or evaluate the existing software import/export methods and 2 studies are excludes because they just import/export data between applications, instead of developing new exchanging methods. 10 studies are excluded because of not giving enough details, such as only a general concept or a framework without any implement details. 15 studies were excluded because of no validation or weak case studies. And 13 studies were excluded because they are not a conference or journal paper, but the author's name has been searched to ensure their papers with similar topics are included. Other reasons for exclusion include the content is not about energy consumption(n=5), not about data exchange(n=5), not about single building energy consumption(n=2), duplicate papers(n=4), failed to find entire paper(n=4), review paper(n=2), and the language is not English(n=2). The result is 63, with added studies(n=9), the final result is 72 original peer-reviewed papers which have been listed and shown in Appendix A.

4.3.4 Data Extraction Strategy

Data is extracted from the selected studies to address each of the research questions described above. A data extraction form was developed and the following items of information were recorded in a Microsoft Excel database, the recording items are listed in Table 4-2. If a study contains the static data exchange and dynamic data exchange as two data exchange process, the related original and targeted data type, tools and exchange methods are recorded respectively.

Table 4-2 Recording Items

No.	Items	Content
1	Title of Publication	
2	Year of publication	
3	Authors	
4	Name of publication	
5	Data exchanged domains	BIM and BES, BIM and BAS, BIM/BES/BAS
6	Research goals	Energy simulation/ Renewable energy/FDD/Energy Management/Other simulation
7	Project Phase	Design/Construction/Operation/Life cycle
8	Research level	Method/Tool Development/Platform
9	Research content	Direct Link / Exchange format/Platform Integration
10	Exchanged Data Area(Static)	Geo/ Space/Material/MEP/Sensor Data/Dynamic Data from BAS
11	Exchanged Data Area(Dynamic)	Sensor Data/Metered data/ BAS data
12	Exchanged Direction	Record
13	Original Data Type	Record
14	Targeted Data Type	Record
15	Original Tool	Record
16	Targeted Tool	Record
17	Shared neutral data format	Record
18	Exchanged methods/tools	Record
19	Used tools (if applied)	Record
20	Citation times	
21	Other comments	

Based on data exchanged domains, extracted research papers were grouped by BIM and BES, BIM and BAS, and BIM/BES/BAS integration to classify the applied domains of data exchange methods answering the research questions. Research levels were classified as methods, which means the data exchange research is a methodology or a prototype level, a tool development producing research developed tools such as an API, or data exchanged software which can produce a standalone specific outcome for one goal, or simply exchange data between two stakeholders, and the platform which requires the study develops multiply tools and fulfill more than one goal. This item helps to classify the application of research methods. Research contents were classified as a direct link, shared exchange format and platform integration. The direct link means the original data format is mapped to the targeted data format using mapping methods or an algorithm without any shared data format. Shared exchange format refers to the data exchanging process using middleware or a shared data format, such as XML. Platform integration means the study uses multiple tools, e.g. database to achieve more than one goal.

4.4 Results

4.4.1 General Analysis: Timeline and Publication

4.4.1.1 Publication Timeline

The 72 original, peer-reviewed studies include 42 conference papers and 30 journal papers. These papers are published in 21 conferences and 20 journals. 18 conference papers are published in International Building Performance Simulation Association (IBPSA) conferences such as Building Simulation Conference and other regional simulation conferences, 4 published by International Council for Research and Innovation in Building Construction (CIB) W78, and 5 by European Conference on Product and Process Modelling (ECPPM). Among the 30 journal papers, 9 papers are published in Automation in Construction, and 3 in energy and buildings.

Based on the data exchanged domains, 43 studies are about BIM and BES integration which contains 25 conference papers and 18 journal papers. 9 conference papers are published in Building simulation/IBPSA, 5 published in other regional conferences hosted by IBPSA, 3 published in ECPPM, and 2 published in CIB W78. Among the 18 journal papers, 6 journal papers are published in Automation in Construction, and 2 published in Energy and buildings. the BIM and BAS integration, including 7 conference papers and 5 journal papers, and 2 conference papers are published in CIB W78, 1 is published in Building simulation/IBPSA. 1 journal paper is published in Automation in Construction, and 1 published in Energy and buildings. 17 papers are about BIM and BES and BAS integration, including 10 conference papers and 7 journal papers. shown conference papers are published in Building simulation and other regional conferences by IBPSA and 2 published in ECPPM. and 3 journal papers are published in Automation in Construction. All detailed results are shown from Table 4-3 to Table 4-5. The journal and conference paper published year and research categories are shown in Table 4-6 and Figure 4-1.

Table 4-3 Publication List: BIM/BES

Conference	**No**	**Journal**	**No**
International Conference on Sustainable Design, Engineering and Construction	1	Building Simulation	1
Building simulation/IBPSA	9	Journal of Computing in Civil Engineering	1
CIB-w78	2	Journal of Asian Architecture and Building Engineering	1
Computing in Civil Engineering (2011)	1	Automation in Construction	6

BAUSIM/IBPSA	3	The Scientific World Journal	1
SIMBUILD/IBPSA	1	Energy and Buildings	2
BSO/IBPSA	1	Journal of Building Engineering	1
11th International Modelica Conference	1	Engineering with Computers	1
International Conference CISBAT 2015	1	Journal of Building Performance Simulation	1
ECPPM	3	Energies	1
WSC	1	Computer Science-Research and Development	1
RESIDENTIAL BUILDING DESIGN & CONSTRUCTION CONFERENCE/ACEE	1	Energy	1
Total	25		18

Table 4-4 Publication List: BIM/BAS

Conference	**No**	**Journal**	**No**
CIB W78	2	Advanced Engineering Informatics	1
Buildingsim/IBPSA	1	INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING	1
PICMET '17: Technology Management for Interconnected World	1	Journal of Performance of Constructed Facilities	1
Computing in Civil Engineering	1	Automation in Construction	1
International Conference on Sustainable Synergies from Buildings to the Urban Scale,	1	Energy and Buildings	1
Linked Data in Architecture and Construction Workshop	1		
Total	7		5

Table 4-5 Publication List: BIM/BAS/BES

Conference	**No**	**Journal**	**No**
International Conference on Civil, Structural and Environmental Engineering Computing,	1	Journal of Computing in Civil Engineering	1
SIMBUILD/ibpca	1	Annals of the New York Academy of Sciences	1
ECPPM	2	Automation in Construction	3
ICT for Sustainable Place, 4th Workshop on eeB Data Models	1	Sustainable Cities and Society	1
International Joint Conference on Knowledge Discovery, Knowledge Engineering,	1	Building and Environment	1
buildingSimulation/IBPSA	2		
ASIM/IBPSA	1		
IEEE	1		
Total	10		7

Table 4-6 Timeline and Research Domains

	BIM+BES		**BIM+BAS**		**BIM/BES/BAS**	
	Conference	**Journal**	**Conference**	**Journal**	**Conference**	**Journal**
2007	1					
2008	1					
2009	2		1		1	
2010			1			
2011	3	1				
2012		2			2	
2013	2		1	1	3	2
2014	5	3			2	2
2015	6	4			1	1

2016	4	4		2		1
2017		1	3	2	1	1
2018	1	3	1			
Total	**25**	**18**	**7**	**5**	**10**	**7**

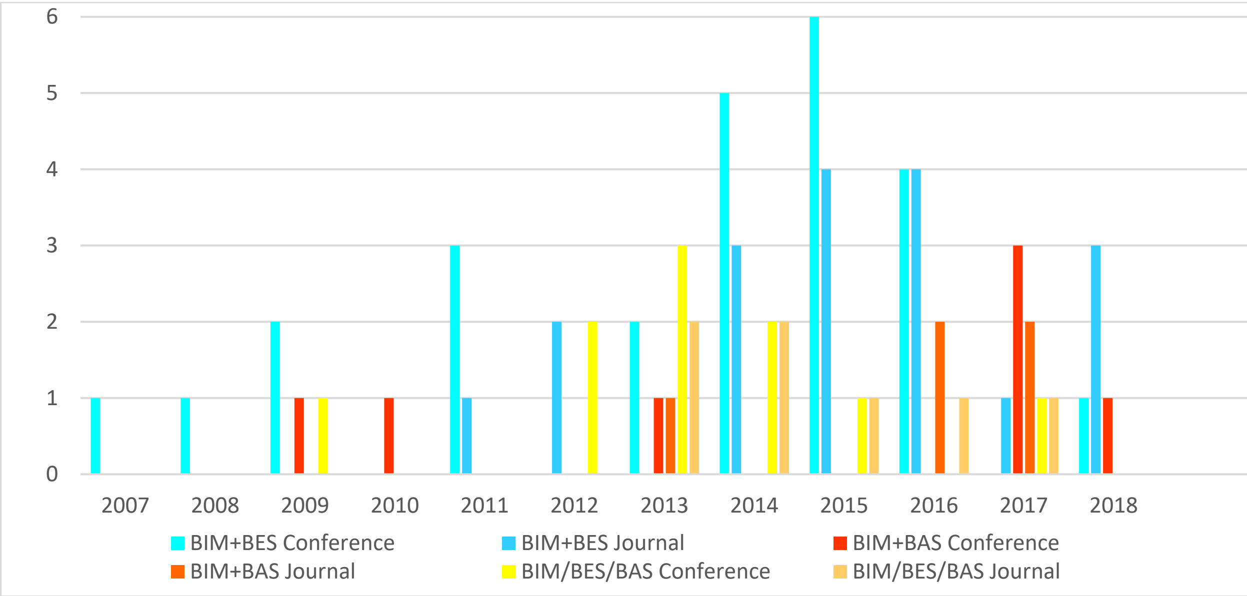


Figure 4-1 Research Domains and Year

4.4.1.2 Research Focus Areas

The research focus in terms of topic areas of studies on BIM and BES data exchange domain include energy simulation (n=39), thermal simulation and daylighting (n=2), as well as renewable energy (n=1) and daylighting (n=1). 42 studies focus on the design phase and only one study is for the operation phase which is a building retrofit project. The research goals of studies on BIM and BAS data exchange domain include energy management (n=7), with 4 conference and 3 journal papers as well as general FM and can be used for energy management (n=5) with 3 conference and 2 journal papers. Only one study covers the whole building lifecycle from design to operation, other studies are all about operation phase (n=11). For the BIM, BAS and BES integration studies, the research goals include energy management (n=11) with 7 conference papers and 4 journal papers, energy simulation (n=4), and FDD (n=2). 5 studies cover the whole life cycle with 4 conference papers and 1 journal paper, 12 studies focus on operation phase with 6 conference papers and 6 journal papers.

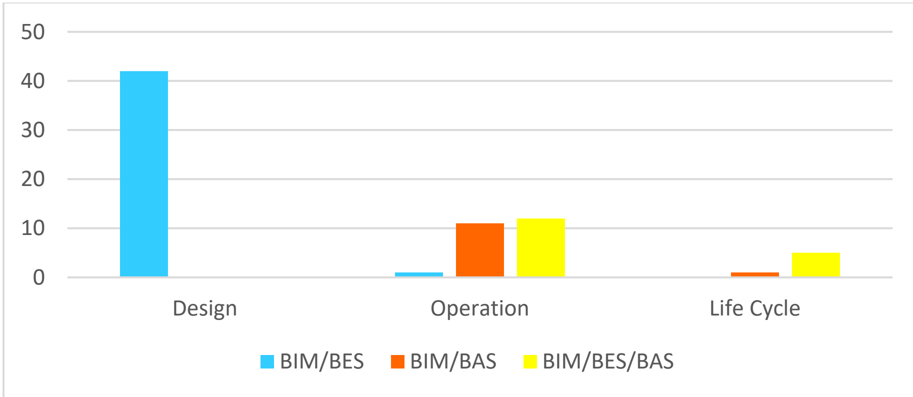


Figure 4-2 Phase Analysis

4.4.1.3 Produced Research Results

Among the 43 papers for BIM and BES, 28 studies are on method level, in which the content of 26 studies is about the direct link, and 2 are about the exchanged format. 13 studies are on tool development level and all of them use direct link. 2 studies are on a platform level in which one uses direct link and the other uses exchanged format. Among the 12 papers for BIM and BAS, 4 studies are on method level, in which three studies use direct link, and one uses platform integration. The other 7 studies are on a platform level with all platform integration. There are 17 papers of BIM/BES/BAS in which 13 studies are on the platform level with all platform integration, 1 uses tool development creating a direct link, and 3 studies are on the method level. The research method results are shown in Table 4-7.

Table 4-7 Results: Produced Research Results

	Method Only	**Tool Development**	**Platform**
BIM/BES	28	13	2
BIM/BAS	4	1	7
BIM/BAS/BES	3	1	13

4.4.2 Discussion of Systematic Literature Research Results

4.4.2.1 Sub-Question 1: What are the existing data exchanging methods between BIM and energy model data based on BES?

43 papers about the data exchange between BIM and BES were extracted to answer this question. Results show that most studies are about the data exchange between BIM and BES (n=42), which include 25 conference papers and 17 journal papers. Several institutions hold the main research shares, namely the Lawrence Berkeley National Laboratory(LBNL), the Community Research and Development Information Service (CORDIS), and the Scientific and Technical Center for

Building (CSTB). The related papers are published mainly on IBPSA as conference papers and on Automation in Construction as journal papers. Other small research papers are decentralized on several different resources. The earliest study was published in 2007, then the number of studies increased from 2011 onwards and achieved the highest point as 10 in 2015, and then decreased. Most studies are in design phase and focus on energy simulation.

To discuss the research method and level, most studies in this area are still on methodology phase (n=28) and 25 studies use a direct link and 3 studies use the shared exchange format. And 13 studies develop a tool to implement the data exchange process, 10 studies use a direct link, and 3 studies use exchange format. Also, 2 studies are designed as a platform integration level. About the data exchange method, 38 studies use direct link which means the original data and the targeted data are exchanged without any middle data format, and 5 studies use shared exchange format as a transfer mechanism.

Table 4-8 identifies the frequency of original data format and targeted data format for the 38 studies which used direct link without shared data format. If one study has two original data formats, the frequency is calculated respectively. The used methods or tools for data exchanging are recorded.

Table 4-9 shows the frequency of the original data format and targeted data format for the 5 studies which used a shared data format.

Table 4-10 shows the frequency of the relationship between the original data format and the targeted data format.

Table 4-8 File Format Analysis (Direct Link)

Original		**Target**		**Method/Tools**	
ifc	25	idf	10	MVD	6
IfcXML	3	modelica	11	Simmodel	5
gbXML	5	inp	3	Revit API	7
Revit model	5	xml	1	Mapping method	4
OSM	1	Software model	11	XML extension	4
		general geometry	1	Sever	4
		osm	1	EVEBIM	1
		ifcdoc	1	algorism	5
				ABEMAT	2

Table 4-9 File Format Analysis (Exchange format)

Original		**Target**		**Shared documents**	
ifc	4	Idf	3	XML	3
IfcXML	1	inp	1	ASC II format	2
		xml	1		

Table 4-10 Relationship Analysis

Relationship	**Frequency**
Ifc2idf	8
Ifc2modelica	8
Gbxml2idf	4
Revit2modelica	2
Ifcxml2inp	2
Ifc2E+	2
Ifc2GEO(General)	2
Other	18

The most common original data from BIM is IFC format (n=29), other 9 studies us ifcXML or gbXML as the original data, and 5 studies use the Revit model as the original model. The most common targeted data are Modelica and IDF (n=21), which are mainly from the SimModel research developed by LBNL(O'Donnell 2012). Other researches tend to use a model developed by software as the target model directly (n=11). Most studies use Revit API as the data exchange tools; MVD and SimModel are common methods too. Other exchange methods include algorism development, mapping method development, and XML extension. The most common data exchange relationships are ifc2idf and ifc2modelica(n=16), and gbXML2idf(n=4).

The data exchange between BIM and BES is only static data, which are classified as geometry, material, space (boundary), and MEP configuration. Among the 43 papers, 5 studies focus on geometry data exchange, 5 focus on geometry and space data exchange, 4 focus on geometry and materials exchange,16 focus on geometry, material, and space information exchange where one of them only can exchange part material information, and 13 studies focus on geometry, material, space information exchange and MEP where two of them are general data exchange. The paper publication year with the data exchange area information is shown in Table 4-11 and Figure 4-3. The earliest study was published in 2007 and only exchange geometry data, but most studies are published between 2014 and 2016.

Table 4-11 Data Exchange Type with Year

	GEO	GEO/MAT	GEO /SPACE	GEO/SPACE/MAT	GEO/SPA/MAT/MEP	General
2007	1					
2008				1		
2009				2		
2010						
2011		1		2	1	
2012	1		1			
2013		1		1		
2014	1	1		3	3	

2015		1	1	2	4	1
2016			3	3	2	
2017	1					
2018				2	1	1
Total	4	4	5	16	11	2

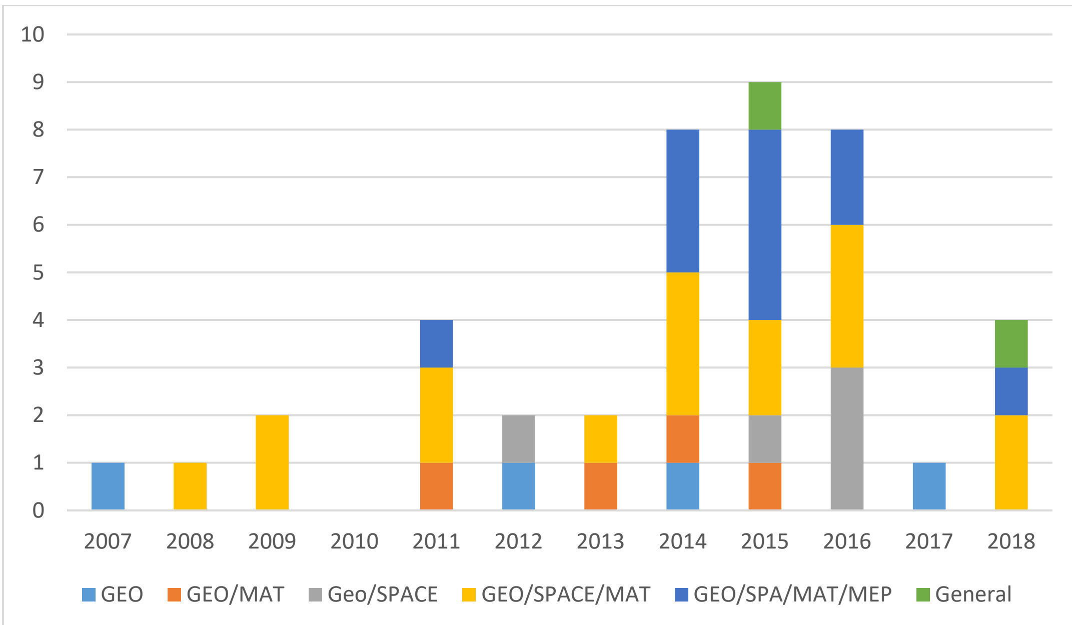


Figure 4-3 Data Exchange Type with Year

4.4.2.2 Sub-Question 2: What are the existing data exchanging methods between BIM and dynamic data collected by BAS or other equipment?

The review shows that there is no real data exchange between BIM and BAS. Researchers tend to link these two domains. There are 12 studies about the data exchange/integration between BIM and BAS; the first study was published in 2009, but the main time scope is from 2016 to 2017 when seven papers are published. There is no centralized research group or project in this research area. One reason for these results could be that the literature scope has been defined as should be related to energy efficiency. The searching results indicated that even studies of BIM and BAS integration are comprehensive, limited research focuses on integrating BIM and BAS to enhance building energy management. Among the 12 studies, seven studies are on the platform level, four studies are on a method level, and only one study is a tool development study. The main research goal in this area is energy management (n=7). Other studies integrate BIM and BAS data to facilitate general FM, including energy management. Eleven studies cover the operation phase while only 1 study covers the whole building lifecycle.

All studies link these two domains. More than half of the studies (n=7) link static data from BIM and dynamic data from BAS for management using middleware, including databases (n=6), APIs and BIM cloud(n=1) . Other studies link data from BAS and BIM models directly for better data visualization and management (n=5). 4 studies link geometry and space data and sensor data, 4 studies link architectural data without more details, and other studies do not specify BIM data type. Table 4-12 shows the research content and relationship. The static data format or model include IFC (n=6), Revit model (n=3), general BIM (n=2) and gbXML(n=1), and the dynamic data format include XML(n=2), CSV and XLS (n=3), SQL (n=2). Several studies transfer BIM data into other data formats to link with a database, but the methods and data types are various. For example, one study transfers IFC into XML which is linked to a Dataware and another study transfer IFC into RDF file, then uses the URL to link with the XML file of sensor data.

Table 4-12 Relationship Analysis

No	Static Data	Target Data	Link to	Dynamic data	File format	Link to	Type
1	ifc	xml	dataware	sensor	csv	dataware	
2	ifc	filter	database	sensor	xml	Database	
3	gbxml			sensor	xml		Direct link
4	ifc	rdf	url	Sensor			Direct link
5	BIM	wpm	html	BAS			Direct link
6	ifc		BAS	BMS/CMMS	xls		Direct link
7	ifc		database	sensor		Database	
8	revit		database	sensor	csv	Database	
9	revit	json	database	sensor	sql	as database	
10	revit	cobie		sensor	mysql	API	Direct link
11	BIM	cloud		BAS	cloud	cloud	
12	ifc	GUID	Database	sensor		Database	

4.4.2.3 Sub-Question 3: What are the existing data exchanging methods based on BIM bridging energy model data based on BES and dynamic data collected by BAS or other equipment?

There are 17 studies about BIM/BES and BAS integration. The earliest study was published in 2009, and the main publishing period is from 2013 to 2015. After 2015, the number of publications remained steady. Ten papers are published in conferences while seven papers are published in journals. This result shows a similar trend as the BIM/BES research. The exchanged static data is general data exchange (n=7), and geometry/space/material (n=1), geometry/space/material/MEP (n=7), one of them miss some thermal properties, geometry/space (n=1) and only material (n=1). The exchanged dynamic data are general BAS data (n=10), sensor data (n=2), sensor and thermographic graph(n=1), sensor and meter data (n=1), occupancy data (n=1), and actual thermal properties (n=1).

The research goals show differences from the studies of BIM/BES, the goal of 11 studies is energy management, 2 studies focus on FDD, and 4 studies focus on energy simulation with real-time data. To implement the data exchange process, 3 studies use a direct link to exchange data, while all other 14 studies use platform integration. 12 studies cover the operation phase, while the other 5 studies cover the whole life cycle.

Studies of BIM/BES/BAS integration are mostly in a platform level missing details of exchanging types. 7 studies exchange static data as general BIM data, and 7 studies aim to exchange geometry/space/material/MEP while one of them miss some thermal properties. Other studies exchange geometry, space, and material information. A similar situation happens to dynamic data where 10 studies only exchange general BAS data, 4 studies exchange sensor data, and other studies exchange thermographic graph, meter data, actual thermal properties, etc.

From a BAS view, 12 studies show the data exchange between a BAS and a database, and then the database links BIM or BES. The exchanged methods include sensor data to CSV/MySQL to database (7), sensor data to Building Controls Virtual Test Bed (BCVTB) to a database (3), and sensor data as thermal point link to a database (2). 4 studies show the data exchange between BAS and BES, using occupancy data to text (1), sensor to CSV (1) , sensor to BCVTB(1) and spreadsheet(1).

The data exchange methods in this area are complex. 6 types of relationships have been defined to review the exchange methods. Most studies use the database as a transfer tool (n=12). Type 1 of relationship describes BIM and BAS data are exported to a database, then to an energy model for managing the energy consumption(n=5), Type 2 defines that BIM data are exported to BES, then the simulated data and BAS data are exported to a database for data comparison (n=5). Type 3 links the BAS data into a database, then links the data to a BIM model, export to an energy simulation(n=2). Another choice is to export BIM data and BAS data to an energy model without a database (n=3). The last two studies use a BIM model to get BES data and BAS data for comparison and visualization. (Type 5 and 6). The general relationship is shown in Figure 4-4 and Figure 4-5.

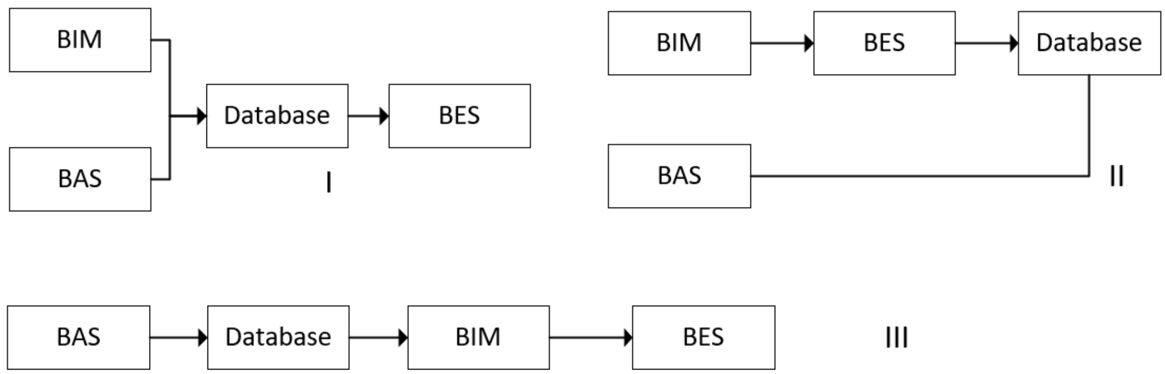


Figure 4-4 Data Exchange Type (Using Database)

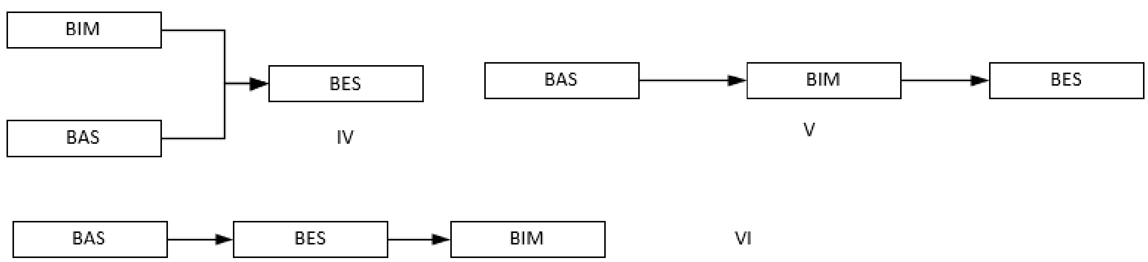


Figure 4-5 Data Exchange Type (No Database)

All studies allow for data exchange between BIM and BES. The static data original format are IFC (n=11), gbXML(n=3), and general BIM model (n=2).BIM data can be exported to a database(n=5) or BES, and the exchanged method includes using a MVD and XML (n=4), a IFC parser(n=1), a MVD and library(n=1), XML as shared format or extension(n=5), owl (n=1),ROM model(n=1) ,gbXML export directly(n=2) and BIM export directly(n=1). The applied energy simulation tools are various; Most simulation tools are developed by the researcher as energy calculators or FDD rules (n=7) while 3 studies use MATLAB to develop the model, other simulation tools include IESVE (n=2), Energy Plus(n=2) and DOE2(n=1). 3 studies identify general energy simulation tools without mentioning the name. 1 study uses a 3D point cloud model, and 1 uses the grasshopper Application Programming Interface (API).

To discuss BAS data, 5 studies just use BAS data for visualization and comparison, and 6 studies only export BAS data such as weather data and actual schedule into BES for simulation. Six other studies import and compare datasets. Among all these studies, only 5 studies use BIM as a transfer tool for the data exchange process between BAS and BES. The detailed list is shown in Table 4-13.

Table 4-13 Relationship Analysis (BIM/BES/BAS)

No	Model	Original data /software	Exchange Method	Targeted data/software	Energy Model	Relationship	Q1	1.1	Q2	2.1	Type
1	BIM	ifc	ifc parser	database		BIM2database					
	BAS	Sensor		database		BAS2database					
	BES	Database	Direct link (export to)	Simulation	FDD rules	Database2BES	Y	N	N		I
2	BIM	ifc	MVD, xml to	database		BIM2database2BES					
	BAS	Sensor	BCVTB	database		BAS 2 database					
	BES			BES	MATLAB, FDD	Database2BES (weather data) (Database compare and visualization)	Y	N	Y	N	I
3	BIM	ifc	XML	database		BIM2database					
	BAS	Sensor	csv	database		sensor 2 database					
	BES			database	Control module	database 2 control module	N		Y	N	I
4	BIM	ifc	MVD and Library	Middle Ware		BIM2MW					
	BAS	Sensor	csv	Middle Ware		BAS2MW					
	BES				Energy calculator	MW2energycalulation	Y	N	N		I
5	BIM	Ifc	MVD and xml , IES simulation	Database		IFC to simulation to database.					
	BAS	Sensor	csv	database		BAS 2 database.					
	BES			BIM2BES	IES	Database compare and visualization	N		Y	N	II
6	BIM	BIM	ROM model	MATLA		BIM 2 BES, sensitivity analysis to database,					
	BAS	BAS	BCVTB XML	database		BAS to database					
	BES	Sensitivit y analysis	to	Database	MATLAB	Database for visualization	Y		Y		II
7	BIM	IFC	OWL	Database		BIM2 Database					
	BAS	BAS	MySQL	Database		BAS2Database					
	BES	Database		Analysis	Search, Visualization and analysis tool	Database2BES tool (search, visualization and analysis)	Y	N	N		I
8	BIM	IFC	XML to inp	BES		BIM2BES					
	BAS	Occupan cy data	text	BES		BAS2BES					
	BES				DOE2		Y	N	N		IV
9	BIM	Ifc	MVD to XML	BES		BIM2BES,					
	BAS	Sensor	csv	BES		BAS2BES,					
	BES				Energy calculator	run energy calculator	Y	N	N		IV
10	BIM	GBXML	Extend XML	BES		BIM2BES, BES2BIM					
	BAS	Sensor	BCVTB-XML	BIM		BAS2BIM					
	BES				Energy Plus	Database compare and	N		Y	Y	V

						visualization					
11	BIM	Ifc/gbxml	XML	BES	use BES for FDD	BIM2xml					
	BAS	BAS	BCVTB 2 XML			BAS2xml					
	BES			MATLAB	FDD	Xml2MATLAB(use weather data)	Y	N	Y	N	IV
12	BIM	IFC	MVD to xml	IES		BIM2BES,					
	BAS	BAS	CSV	Database		BAS2CSV2 Database					
	BES	BES		Database	IES	BES2Database Database compare and visualization	N		Y	N	II
13	BIM	IFC	GUID link	BAS							
	BAS	BAS	to	Database		Database2BIM					
	BES	BIM	use real weather		Energy Plus	BIM2BES (real weather)	Y	Y	Y	N	III
14	BIM	GBXML (material)		BES		BAS2BIM2BES					
	BAS	thermal point cloud	Link	BIM							
	BES				Thermal Simulation	3D point cloud model	Y	Y	N		III
15	BIM					BAS2BES2BIM					
	BAS	BAS	Spreadsheets analysis	BES							
	BES	BES	2	BIM	General tools	Compare design and actual data	Y	N	Y	Y	V
16	BIM	BIM	2	BES		BAS2BIM2BES (4D thermal)					
	BAS	Sensor	BIM 4D thermal	BIM							
	BES				grasshopper API	Calculation and visualization	Y	Y	Y	N	II
17	BIM	gbxml	2 Energy Plus	database		BIM2BES2database,					
	BAS	BAS	2	Database		BAS2database,					
	BES				Comparison and visualization General tools	Database compare and visualization	N		Y	N	II
	Q1: Can the BAS data used in BES, such as weather data or actual schedule, to serve as simulation data? Q2: Can BAS data be compared with and visualized with BES?										

4.4.2.4 Sub-Question 4: What are the scopes and effectiveness of these existing data exchanging methods?

There is no clear evaluation standard about assessing the data exchanging methods. After the literature review, this study suggests "an ideal platform" that can be used for building operation energy monitoring and management should meet the following functions.

BIM and BES exchange

1) The system can transfer BIM information into BES to avoid the data errors and save labor as well as to achieve a seamless energy simulation.
2) BES settings can be updated or saved in BIM, to compare different schema and update building information, parameters in BES can be updated and run the simulation, sent back to the BIM model and select the best option for design. or renovation.

BIM and BAS exchange

1) BAS data can be shown, located, and managed through BIM.

BES and BAS exchange

1) The system can transfer the BAS data such as weather data or actual schedule into BES tools, to serve as assisting possible calibration requirements, using or not using BIM.
2) BES data as results can be compared with data from the BAS such as comparing the simulation results and actual consumption, using or not using BIM.

Based on the above principles, a rubric with four dimensions and credit form were developed to evaluate the identified studies in Table 4-14. The studies included in the review were assessed for exchanging efficiency based on the protocol. has been defined to achieve the following principles. An ideal platform has been designed above, and the rubric and results have been shown.

Table 4-14 Rubric of Assessing the Quality of the Literature

Question	**Answer**
How many types of BIM information can be transferred into BES?	GEO 1 GEO/SPACE:2 GEO/SPACE/MAT:3 GEO/SPACE/MAT/MEP:4 General: 2
Can the BES setting have updated to BIM?	Yes:4 No:0
How many types of BIM information can be linked with BAS?	GEO 1 GEO/SPACE:2 GEO/SPACE/MAT:3 GEO/SPACE/MAT/MEP:4 General: 2 Sensor 1, General BAS 2
Can the BAS data used in BES, such as weather data or actual schedule, to serve as simulation data?	Only applied for the BIM/BAS/BES integration (yes or no) One type, 1 score

If yes, does it use BIM?	
Can BAS data be compared with and visualized with BES?	Only applied for the BIM/BAS/BES integration (yes or no) Yes 2 No 0
If yes, does it use BIM?	

Based on the rubric, if a study about BIM/BES exchange of all static data (GEO/SPACE/MAT/MEP) and the BES setting can be updated in BIM as a reference, it will get the full score which is 8. After scoring all the studies, the mode is 3 and the average score is 2.95. Most studies only exchange 3 types of static data, which are usually GEO/SPACE/MAT.

For BIM/BAS exchange, the highest score would 6 which requires the study to exchange 4 types of static data and general BAS data but the actual highest score is 4, and the mode is 3, with the average score of 2.95 in the real situation. Considering all studies that can exchange sensor data, this result indicates most studies only exchange 2 types of static data such as GEO/SPACE, or support general static data without details.

For BIM/BES/BAS integration, the highest score would be 14 which requires the study can exchange all types of static data and BAS data, BES data can be updated in BIM and BAS data can be utilized and compared in BIM. The actual highest score is 8 and mode is 8, with an average score of 6.7. Most studies exchange general static data and dynamic data which get 4 or 5 points, then at least fulfill with one function among the BAS data applied in BES or BAS data compared with and visualized with BES, which can get 2 points either way. Especially, among the 17 studies, 12 studies can use BAS data in BES for simulation but only 3 studies use BIM to implement the process. 11 studies compared BAS or visualized in BES, and only 2 studies use BIM to implement the process. The results show that many researchers realize the importance of using dynamic data for simulation, including applying actual data in simulation and comparing the simulated results and actual data but the potential of BIM is still underestimated.

Table 4-15 Evaluation Results

	No	**Highest Score**	**Lowest Score**	**Average**	**Mode**
BIM and BES	43	8	1	2.95	3
BIM and BAS	12	4	1	2.75	3
BBB	17	8	4	6.7	8

4.4.3 Discussion

4.4.3.1 BIM and BES

The analysis of data exchanging methods between BIM and BES shows that the earliest research about BIM and BES was in 2007, but the peak of research studies occurred from 2011 to 2015. The research about BIM and BES integration has developed at a certain level and there are several main groups working in this area. Almost all the studies serve the design phase and energy simulation. Most studies are on a methodology level (n=28) and use direct link method (n=38) to exchange the data.

The research between BIM and BES focuses on static data. 16 studies exchange geometry, material and space information exchange, with the earliest research in 2007, and 11 studies can exchange geometry, material, space, and MEP information, with the earliest research in 2011 (See, Haves et al. 2011). Although basic information of HVAC systems can be exchanged, there is still no mature data exchanging mechanism which supports all static data types (geometry, space, material, and MEP) between BIM and BES. This result shows that the researchers tend to exchange all related information, but the actual application level is still kept on the architected data exchange level. Ten studies exchange geo/space data and 4 studies exchange geo/material information.

The IFC schema is the most popular original data format from which BIM (n=29), ifcXML and gbXML are used also(n=9), and several studies use a Revit model (n=5) which exports a Revit model into other software. MVD(n=6), SimModel (n=5), Revit API(n=7), XML and XML extension (n=7) are popular exchanging methods. The most common targeted data formats are Modelica and IDF (n=24). The most common data exchange relationships are ifc2idf and ifc2modelica(n=16), then gbXML2idf(n=4). In the software side, Revit (BIM side) and EnergyPlus (simulation side) are two popular software.

In summary, the current data exchange research mainly focuses on architectural data exchange (GEO, SPACE, MATERIAL), and tend to exchange only static information (Architectural and MEP), but actual applications are limited. Researchers tend to use simple and direct data exchange methods in this area such as MVD and XML (SimModel is another kind of XML format) or use APIs to export information in Revit. Although there is no comprehensive data exchange format, the data types are classified with details, and there exist many studies on geometry, space and material. MEP information exchange is still limited.

4.4.3.2 BIM and BAS

The number of research studies between BIM and BAS integration is plenty, but the search protocol only chooses BIM and BAS integration research related to energy management in this review and the related research is relatively limited. 12 studies were selected for review when the first study was in 2009, but the peak time scope was from 2016 to 2017, later than the period of BIM and BES integration. The number of studies is steady which means this research trend is also steady, and no centralized project or research group works in this area.

One result is that there is no real data exchange between BIM and BAS, which is due to the huge data sets from these two parties. All 12 studies link BIM data and BAS data, with the main goals of energy management (n=7) and general FM that includes energy management(n=5). Most studies cover the operation phase (n=11), which is in contrast to the various BIM/BES studies that cover the design phase.

The results of research levels show that 7 studies are implemented on a platform level, 4 studies are method level, and only 1 study is a tool development study. The related research is on a general level which is reflected from the data type. 4 studies specify the linked static data including geometry and space from BIM, 4 studies link architectural data without more details, and others just describe the static data as a general BIM data. 9 studies link sensor data from BAS and 3 studies link general data from BAS. It shows that related research is still on a general methodology level without a detailed technical solution. Most researchers describe a blueprint of data exchanging framework or mechanisms without going to the technical details to implement the actual data exchanging process. It can be explained that data from BIM and BAS are huge and general. The general solution shows that an integrated platform is necessary to conduct the data exchange between BIM and BAS but the development of applicable solutions and data exchanging principles are missing, contrary to the integrated research of BIM/BES ,which has started to develop basic data exchanging algorithms and principles.

Without detailed exchange data types, 7 studies link the static data from BIM and dynamic data from BAS for management using middleware, including databases (n=6) and BIM cloud(n=1). Utilizing databases is a popular linking method(n=6). Other studies (5) link data from BAS and BIM models which all are used for better data visualization and management.

The most popular static data format or model include IFC (n=6), Revit model (n=3), general BIM (n=2) and gbXML(n=1). The most common formats for dynamic data include XML(n=2), CSV, and xls (n=3), SQL (n=2). Several studies transfer BIM data into other data formats to link them with databases, but the methods and data types are various. Using databases is a common solution in the integration of BIM and BAS, and researchers usually aim to use BIM to manage such as filtering and querying, comparing valuation. The related research is still limited due to the high volume of datasets and the complexity of systems.

4.4.3.3 BIM/BAS/BES

The earliest study was published in 2009 and the publication period is from 2013 to 2015, which is almost as same as the BIM/BES core period. But the number of papers decreased from 2015 and remained steady. There are 17 studies together, 12 serve the operation phase and 5 serve the entire life cycle. The research goal includes energy management(n=11), FDD(n=2), and energy simulation with real-time data (n=4). The common function of the integration of BBB is still energy management, and fewer studies aim to increase the precision of energy simulation for management. About the goal of integration, we can identify 5 studies that just use BAS data for visualization and comparison and 12 studies can export BAS data such as weather data and actual schedules into a BES for simulation.

All studies in this area are at an early development level and most of the research is about platform integration, only 3 studies use a direct link to integrate the three parties and no study is about tool development.

The identification of data exchanging types is weak in the area, 7 studies only exchange static data as general BIM data, and 7 studies aim to exchange geometry/space/material/MEP, one of them missing some thermal properties. Other studies exchange geometry, space, and material information. The same situation happens in dynamic data where only 10 studies exchange general BAS data, 4 studies exchange sensor data, and other studies exchange thermographic graph, meter data, and actual thermal properties, etc. Research tends to implement the BIM/BAS/BES integration in a comprehensive way.

When examining data exchanging methods, 6 types of data transferring mechanisms have been defined in Section 4.4.2.3. Type I, II and III all use databases as the transferring mechanism(n=12). 5 studies export BIM and BAS linkage to a database, then export to the energy model. 4 studies export BIM information directly to an energy model, then export the simulated results and BAS data to a database. 3 studies link BAS data to a database, then link the database to BIM and export to the energy model. All studies using databases apply BAS data to database for energy management. Type IV, V, VI do not use database, just exchange the data among the three parties in various ways, but related studies are scattered and limited.

The most common BIM original format is IFC (n=10). 3 studies use GBxml and 3 studies use a general BIM model. Other formats include ifcXML and 3d cloud points. The most common exchanged method is using in MVD with XML or library (n=5) or using XML as the shared format(n=5). Dynamic data exchange methods are using mostly the CSV/MySQL format to export sensor data to databases (n=8), or use BCVTB (n=3) to export BAS data. Other linking methods include text, GUID link, or 3D cloud points.

About the energy simulation tool, the studies tend to use their own developed model or program for special needs including FDD, system control and energy calculators (n=10). Other studies use existing energy simulation tools such as IES, EnergyPlus, and DOE2 (n=5).

4.4.3.4 Summary

The research area about data exchanging between BIM/BES has been most developed, which started earliest and attracted more attention than the other two areas. Some researchers focus on detailed data exchange principles. Special detailed data types have been investigated, and several important projects or simulation tools have been developed. Architectural data exchanging processes have been studied to a certain level and all data types (geometry, space, material) have been covered, but studies are continuing to optimize the data exchange process. MEP data exchanging method support only basic and standard HVAC system information because MEP data is complex and hard to be simply summarized into several categories as architectural data. Most of the studies in this area serve for the design phase with a simple goal of energy or thermal simulation, which shows single energy simulation is still used for design benchmark and is less applied for the operation phase, the accuracy is still a challenge.

The research of BIM/BAS has got less attention but the numbers of studies are steady over the years, which shows a moderate interest in this topic. Researchers tend to use database and platform integration in this research area, maybe due to the complex of datasets. Research goals are common energy management, such as data comparing and visualization, as filtering and querying, and comparing, valuation. Most studies are at the methodology or framework level, without an applied and useable platform. Not like BIM/BES, all studies link BIM and BAS data together, so there is no real data exchange method and no detailed linked data type identification. Most studies describe the data as architectural data or general BIM data. BAS data is commonly sensor data and general BAS data without details. Studies cover mainly the operational phase; only one mentioned the whole lifecycle.

The research area of BIM/BAS/BES shares some common features as the other two research areas. The earliest publication year is in a little later than that of BIM/BES, and the peak year is from 2013 to 2015. The common data exchanging methods in this area are still about platform integration and database. The identification of data type is less detailed than BIM/BES, but several studies are based on the BIM/BES integration, add data link or export process from BAS, so the data exchanging method about static data type is more advanced. Studies expect to exchange all static data (geometry/space/material) for simulation. Most users develop their energy tools to test special functions. In general, the related studies are in early development, new ideas and frameworks emerge without any applicable technical tools, and current traditional energy simulation tools fail to support enough for the energy management goals.

To discuss the technical details about static data exchanging, IFC is no doubt the most applied data format for BIM export, gbXML and general BIM model which is usually for import and export between software is also used. Modelica and IDF are popular choices for the BIM/BES area and MVD with XML extension or libraries to define the MVD and add missing information is the common method. However, the researchers tend to develop their own simulation tools or API for BIM/BAS/BES area and integrate a platform or database. Several studies link BIM data into a database directly.

To discuss the technical details about dynamic data exchanging which happens in BIM/BAS and BIM/BES/BAS area, a database is the main solution in integrating these parties. The common dynamic data format describing sensor data or BAS data is CSV/MySQL which can be used for the database. BCVTB is another choice but only works for BIM/BAS/BES. The detailed data analysis is limited. Table 4-16 summaries all the information.

Table 4-16 Summary

	BIM/BES/BAS	**BIM/BES**	**BIM/BAS**
Research Level	Concept phase	Advanced phase	Concept phase
Serving phase	Operation	Design	Operation
Goal	Energy management,	simulation	Energy management, visualization
Main BIM format	ifc	ifc	Ifc
Main BAS format	General, FDD, more specified.		general
Simulation tools?	developed	Existing	N/A
1st year			
Peak year			

4.4.4 Conclusion

The review shows that the research of the BIM/BES area is more advanced than the other two integration areas. The data exchange between BIM and BES has created several tools and mature exchanging mechanisms, and static data including architectural and MEP can be changed, but the research has still potential in enhancing exchanging methods and algorism. Furthermore, MEP information exchange is still a challenge and there has not been a main and widely accepted solution in this area. The research is always applied only for the design phase.

The research about BIM/BAS in energy management is limited and more at a concept level. An integrated platform or a framework is a common solution of exchanging data without going to the data details and technical details. The research goals are often about simple energy management such as data comparing, filtering, querying, and visualization. Considering that BIM and BAS both handle a huge amount of dataset even simple data management tools work0 effectively, more advanced management tools are expected. The related research is only applied for the operation phase.

BIM/BES/BAS integration has similar features as BIM/BAS, but its research is more advanced and energy simulation is expected to provide an energy benchmark. In summary, the related research is in an early stage, and the platform integration with a database is a popular solution. This platform integration works for the whole building lifecycle, but most studies only aim for the operation phase.

About the technical details of data exchange, IFC is the most popular choice for BIM data, ` follows. The main data exchange method between BIM and BES is MVD with XML extensions or libraries, Simmodel is the second option. No real data exchange between BIM and BAS, but they link each other using database mainly, and the common BAS data format is CSV or MySQL for a database. In the BIM/BAS/BES integration, BCVTB is used in several cases for sensor data. The target data format in BES is Modelica and IDF.

The following research is based on these results. My research aims to integrate BIM/BES/BAS; therefore, a platform and MySQL database is used in the case, and the BIM data format is IFC which can use MVD and XML extension to define, the BAS data will be CSV format, and the BES data is used EnergyPlus or MATLAB and Openstudio to implement. The details are referred to as Section 6.1.

5 Framework

This framework aims to involve BIM as the central data model to link the BES, BAS and BIM as models and information repositories, support the information exchange process. The exchanged data requirements of a calibrated energy model are listed as the foundation of the whole framework, and IFC schema is selected as the central data format, analyzed and extracted relevant exchanged data to implement the information exchanging process. The involved data models and repositories, data requirements and exchanging process are summarized as the framework, which provides a prototype of integrating BIM, BES and BAS, and demonstrate a BIM application during building operation phase.

5.1 Process Modeling for the Framework

The process modeling method is used to model the behavior of database applications (Elmasri and Navathe 2010). This study used a process model to identify the key required information, object relationships, and the sequence of activities. Unified Modeling Language (UML) has been used to model the system in structural modeling and behavior modeling. The proposed framework concept is shown in Figure 5-1. The concept of the framework includes a BIM model involving dynamic data from Dynamic database, and static data from building design, and an energy model providing the simulated results as energy consumption report. An interface exchanges the energy-related information among BIM model, BAS database and BES. The final detailed framework is presented in Section 5.5.2.

A sequence diagram as a “behavioral diagram” presents the actors’ interactions with each other and describes the workflow in Figure 5-2. An energy manager initiates the interface and inputs the selected parameter name and time range. The interface uses the input information to search the database and return the required data, updates the value in BIM model, and sends the value to the energy model, then reads the simulated results from energy model, compares the actual energy consumption data and the simulated results. Likewise, a use case is shown to explain the actual execution process in Figure 5-3. BAS updates the actual operational data to the database, and BES provides the simulation results, while the BIM with interface implements other functions such as getting data, updating parameter values, sending data to energy model, read and visualize the results.

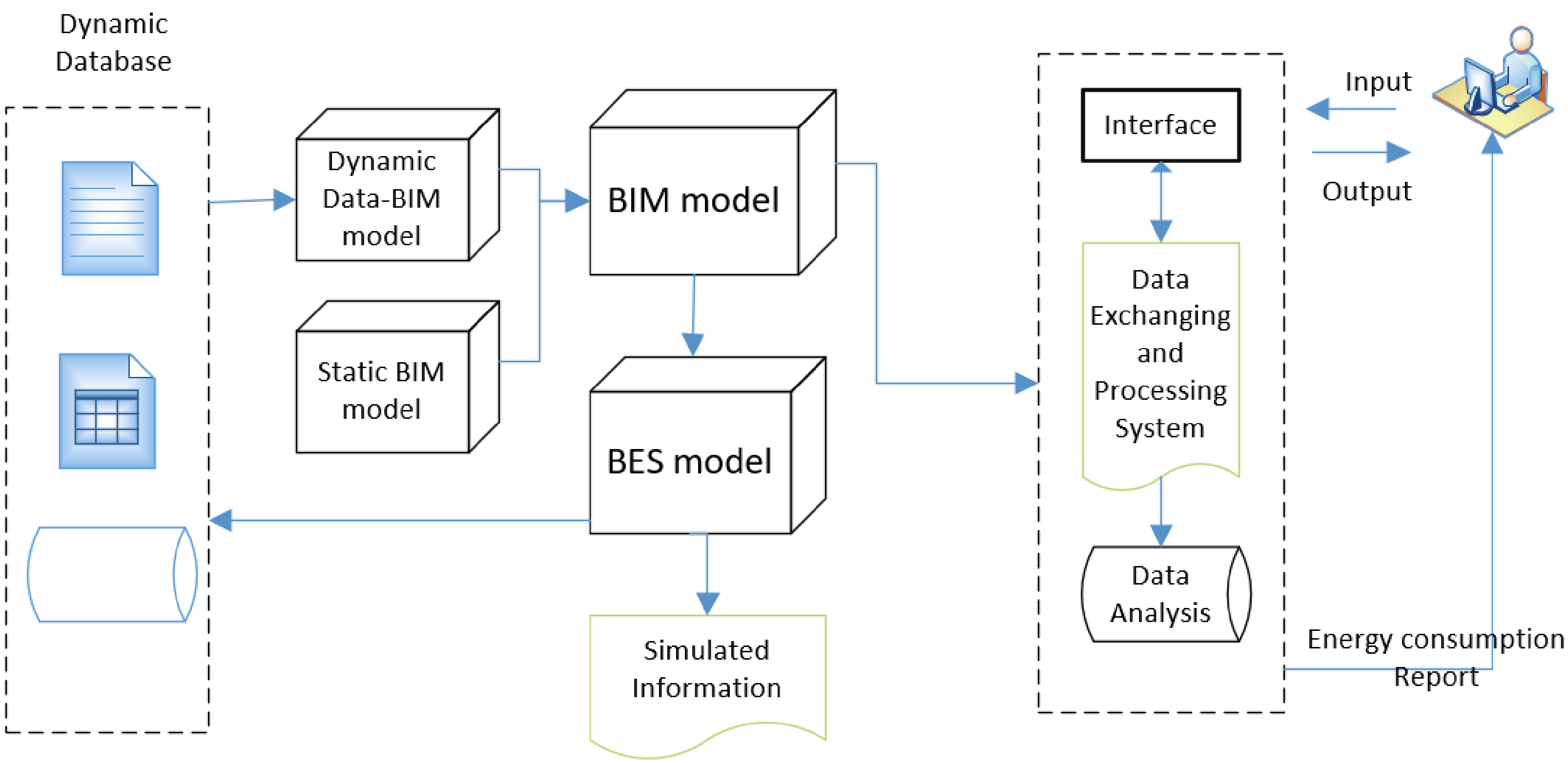


Figure 5-1 Framework (Concept)

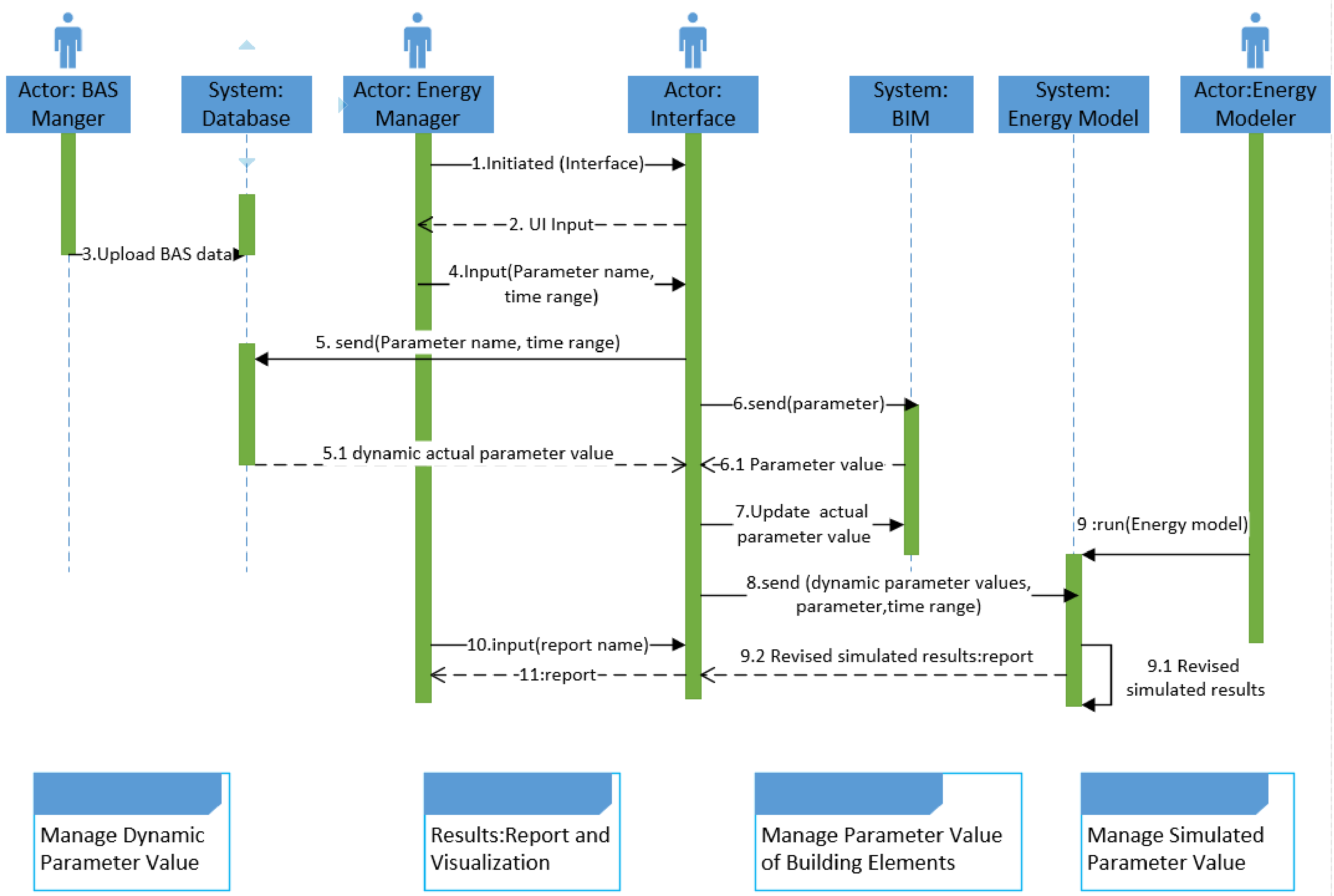


Figure 5-2 Sequence Diagram (Detailed)

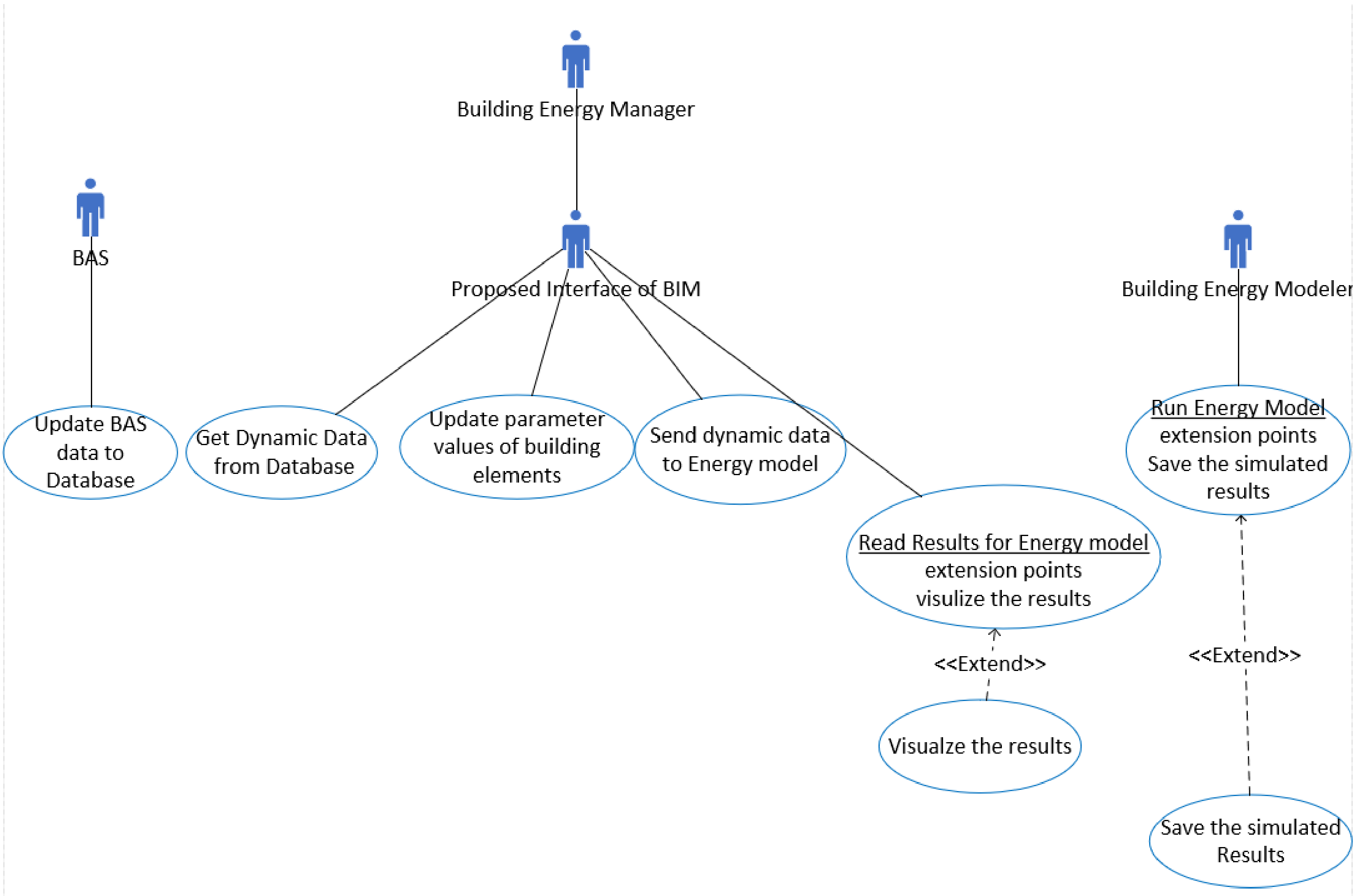


Figure 5-3 User Case

5.2 Data Identification

The exchanged data in this framework has been identified to develop the platform as the first step. A typical BIM model serving for the design and construction phase provides a significant amount of input data for energy simulation; however, some parameters applied during building operations may be missed in an early-phase of the BIM model. This study considers the entire process of developing and calibrating the whole building energy model to identify the key datasets.

Calibrated simulation is commonly used for building measurement and verification, especially while a baseline of building energy consumption is hard to be established (e.g. new construction, unavailable performance period energy data for major renovation). These data are collected to calibrate the energy model against actual measured energy, demand, or water consumption data. The collection of other more detailed data depends on the actual determination, such as the desired tolerances of the calibration and the building characteristics.

There are various ways of calibrating a building energy model. A common calibration method has been developed as the Measurement and Verification (M&V) option D in ASHRAE 14 (ASHRAE 2014) and described in detail in IPMVP(IPMVP 2001) and M&V Guidelines developed by FEMP (Webster, Bradford et al. 2015). This research investigated the entire standard process of M&V option D to identify key static and dynamic parameters and reviewed 5 M&V reports from 5 LEED projects to validate the results. These M&V reports of LEED project were used to apply for the EA C5: Measurement, and verification of LEED for New Construction Rating System.

The following data contents were suggested in the above standards. It should be noted that the particular datasets necessary to collect vary widely depending upon the desired tolerances of the calibration and the individual building characteristic. As such, they are not be fully covered in the list.

5.2.1 Static Data Identification

Static data are defined here as the data values that won't change after being set or recorded. The investigation showed that the most relevant building information for energy simulations in this category are the geometry defining the design zone and space, the material information defining the thermal properties of the envelope, and MEP information describing the designed equipment parameters.

Table 5-1 Static Building Information (Architectural)

Category	Parameter	Content	Unit
Building Location		Latitude/ Longitude	
Building Geometry	Building Shape/ Dimensions	Description	
	Orientation	Description	
	Levels	Description	
	Zoning	Description	
Building Envelope: Opaque Material	External/Interior Wall /Door/Floor/Roof/Ceiling	Material Type and Thickness	Ft or cm
		Area	(sq.ft or m^2)
		U-value	($W/m^2.c$) or (Btu/ (hr. ft^2.F))
Building Envelope: Non-Opaque Material	Windows/Curtain Wall/Skylight/Door	Material Type and Thickness	Ft or cm
		Area	(sq.ft or m^2)
		U-value	$W/m^2.c$) or (Btu/ (hr. ft^2.F))
		VT and IT (Visible and Infrared Transmittance)	
		SC (Shading Efficient)	
		Description: Spacing of Framing Materials and Shading from Nearby Objects.	
Building Space	Type	Description (Office, Corridor, etc)	
	Infiltration *	Air Changes Per Hour	
	Internal Load *	lighting, Plug, HVAC, Elevator,	(w/m^2) or (w/sq.ft)
	Occupancy *		m^2/person or sq.ft/person
	Occupied Hours *		am-pm
* Design value, which means it should be assigned with a constant for running energy model during the design phase, but the actual value will change as the real building operating data during the operation phase.			

Table 5-2 Static Building Information (MEP)*

Category	Parameter	Content	Unit
Heating Appliances and Related Parameters	Heating Source	Description	
	HVAC Heating Loads	Description	
	Boiler	Fuel Type	
		Capacity (Tons)	
		Rated Efficiency and Part Load Efficiencies	
		Hot water temperature	°*F* or °C
	Hot water pump	Flowrate	(GPM)
		Rated efficiency and part load efficiencies	
		Inlet and outlet temperature	°*F* or °C
		Power	(HP or Watt)
Cooling Appliances and Related Parameters	Cooling Source	Description	
	Cooling Load	Description	
	Chiller	COP	
		Inlet and Outlet Temperature	°*F* or °C
		Capacity	(Tons)
		Flowrate	(gpm)
		Power	(HP or Watt)
		Rated Efficiency and Part Load Efficiencies	
	Cooling Tower	Inlet and Outlet Temperature	°*F* or °C
		Water Flow Rate (GPM)	
		Air Flowrate	(m^3/s or CFM)
		Fan Power	(watt)
		Type and Capacities	
		Rated Efficiency and Part Load Efficiencies	
Ventilation	Terminal System	Description, System Types	
		Water Loop: Inlet and Outlet Water Temperature	°*F* or °C

		Air Loop: Inlet and Outlet Air Temperature	
		Heating/Cooling Setpoint Per Zone	
		Ventilation Rate Per Zone	CFM
		Minimum Fresh Air Percentages Per Zone	
	Fan	Power	kW
		Efficiency	
		Air Flowrate (m^3/s or CFM)	
MEP Schedule	Lighting Schedules	Description	
	Fan Schedules	Description	
	Equipment Operating Schedules	Description	
*All data in this table is design value and usually be updated in the actual operating phase.			

The static data exchange mechanism between BIM and BES has been well-developed by many studies; the framework implements a simple function updating several core static parameters as an example. The main dataset categories consist of geometry, space, material, and MEP. The IFC 4.2 schema was used to describe these static parameters and their relationships for energy simulation. Static parameters and their relationships are shown using a schema representation in Figure 5-4.

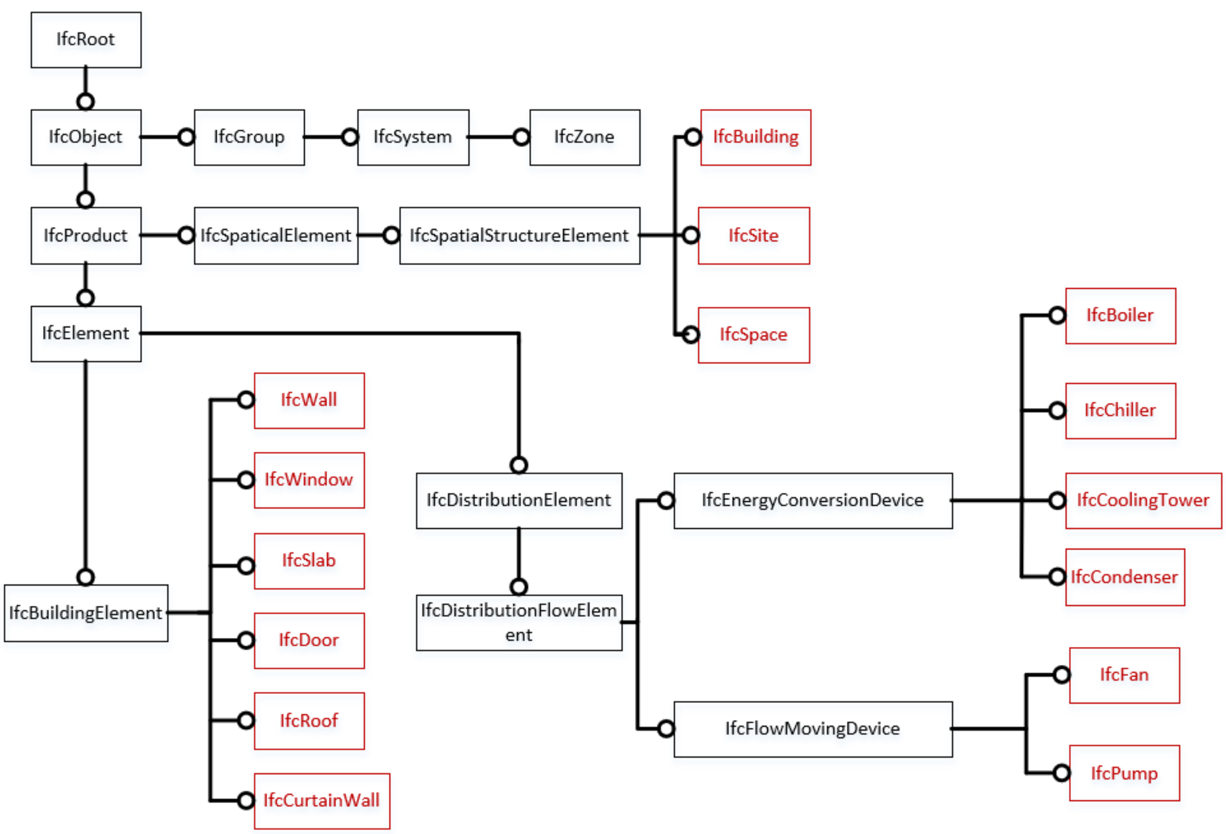


Figure 5-4 Schema Representation of Static Data

Figure 5-5 explains how to assign the thermal transmissions as a set of property values (name, value, unit) to an *IfcObject* (*IfcDoor*).

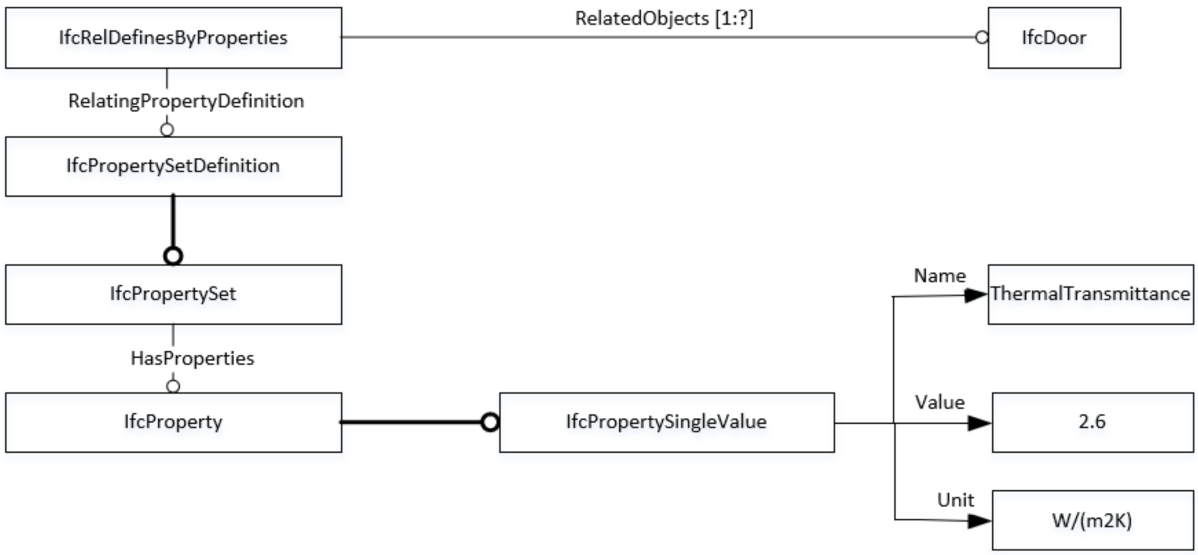


Figure 5-5 Assign Properties to an IfcObject

Figure 5-6 is an example of a fan coil unit (FCU) entity in the IFC schema. An FCU is delivered as a complete package, but the information can be dealt with at a component-based level for various purposes. Fan, coil, and motor are connected using *IfcRelConnectsPortToElement* and *IfcRelConnectsPorts* relationship, and the completed aggregation is achieved using *IfcRelAggregates*.

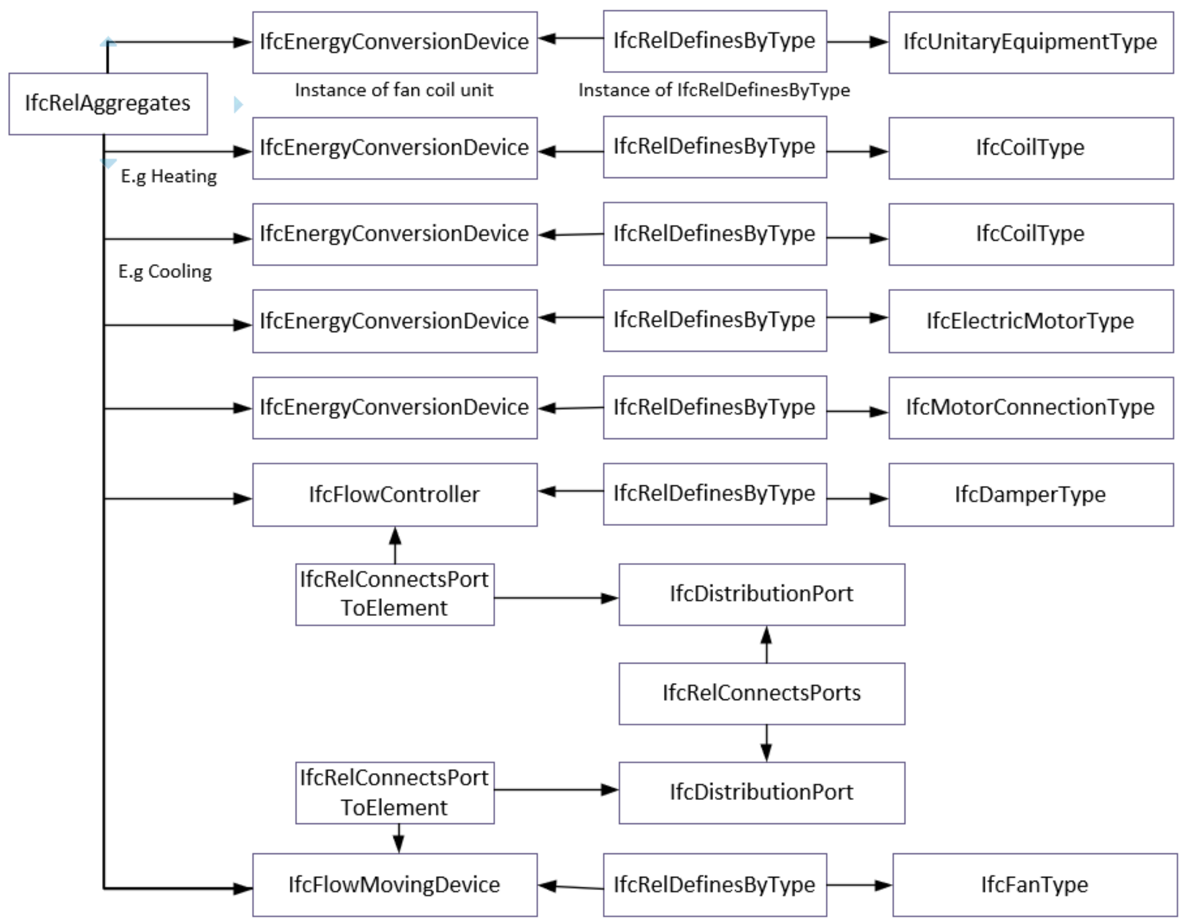


Figure 5-6 Schema of Components in FCU

Figure 5-7 depicts how to connect a fan, a sensor, and space in a building model using the IFC schema. The sensor and fan are connected using *IfcRelConnectsElements*, and space can use *IfcRelcontainedInSpatialStructre* to contain the sensor.

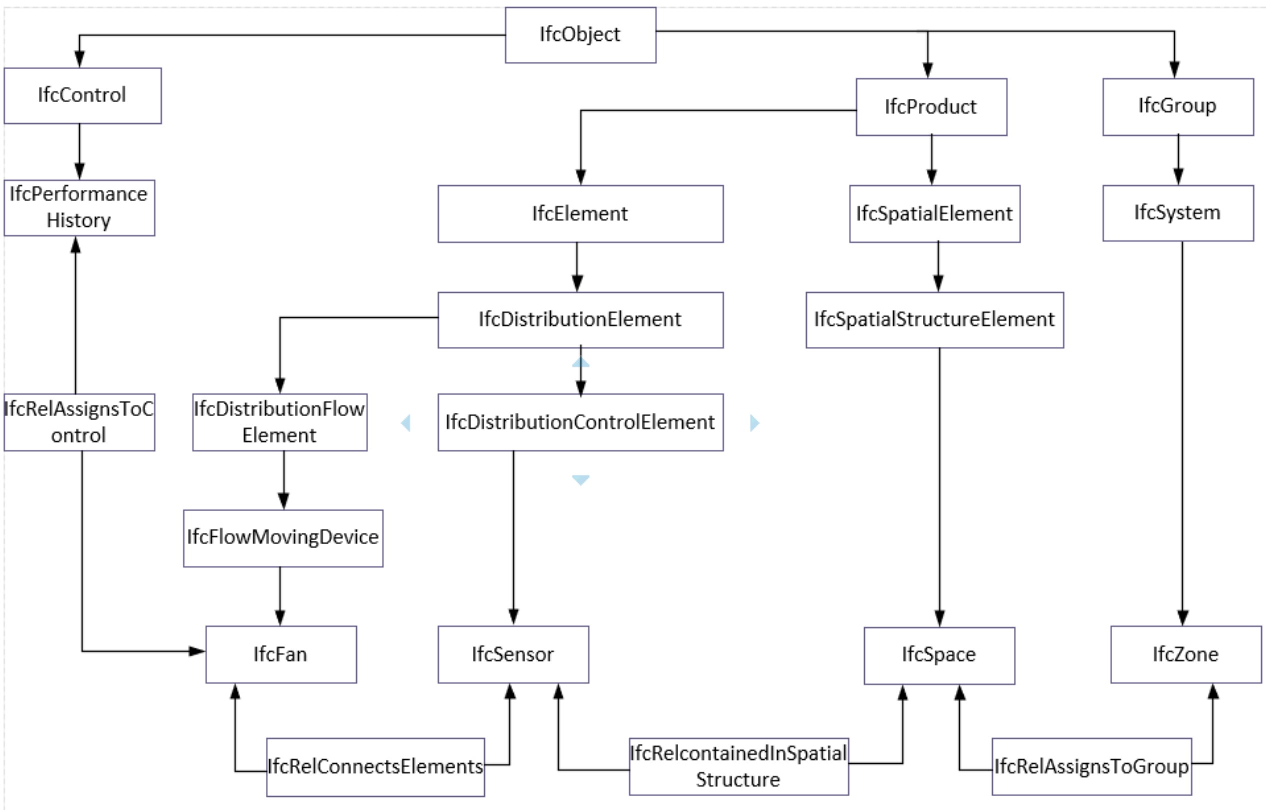


Figure 5-7 Sensor to Space and an FCU

These cases explain the basic principles of expressing static building objects and their relationship using complex entities and property sets in IFC schema. Many studies have proved that there are several challenges in transferring IFC data about geometry or space information into an energy model (Bazjanac 2010, Hitchcock and Wong 2011, Lilis, Giannakis et al. 2017). For example, an energy model defines the interior partition as a simple surface while an architectural BIM model defines it as an interior wall with thickness. These issues have not been analyzed in the research.

5.2.2 Dynamic Data Identification

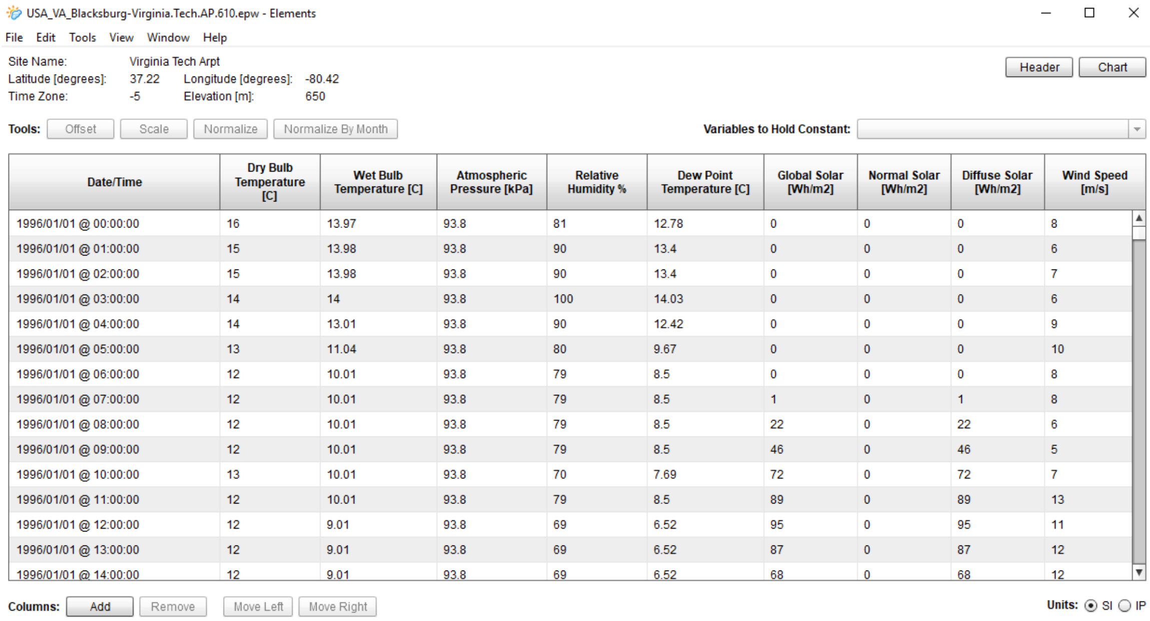
The dynamic data identification has been extracted from the general energy model calibration process, as suggested by M&V option D from ASHRAE 14, and includes the following main categories.

5.2.2.1 Weather Data

Weather Data (WD) is the actual weather data obtained from the nearest local station or site weather station. The typical parameters of weather data are *outdoor air temperature* (dry-bulb and wet-bulb), *relative humidity, wind speed and direction, cloud cover, precipitation,* and *solar radiation* at the site location. These data, which are usually measured hourly, are achieved from local weather stations and should be collected during the simulated period to calibrate the energy model. Two types of weather data can be used in the building energy simulation as *actual weather data* (measured hourly) and *typical meteorological year* (TMY). Table 5-3 shows the critical parameters of weather data. Figure 5-8 is a screenshot of the common weather data file for energy simulation.

Table 5-3 Weather Data

Classification	Measurement items	Measurement point	Time Period	Resource
Weather Data	Outside Air Temperature Dry-bulb	Hourly Measured Data and Typical Weather Data	Simulated Period or A Whole Year	NCDC or Onsite Station
	Outside Air Temperature Wet-bulb			
	Humidity			
	Solar Radiation			
	Cloud Cover			
	Precipitation			
	Wind			


USA_VA_Blacksburg-Virginia.Tech.AP.610.epw - Elements

File Edit Tools View Window Help

Site Name: Virginia Tech Arpt
Latitude [degrees]: 37.22 Longitude [degrees]: -80.42
Time Zone: -5 Elevation [m]: 650

Header Chart

Tools: Offset Scale Normalize Normalize By Month

Variables to Hold Constant:

Date/Time	Dry Bulb Temperature [C]	Wet Bulb Temperature [C]	Atmospheric Pressure [kPa]	Relative Humidity %	Dew Point Temperature [C]	Global Solar [Wh/m2]	Normal Solar [Wh/m2]	Diffuse Solar [Wh/m2]	Wind Speed [m/s]
1996/01/01 @ 00:00:00	16	13.97	93.8	81	12.78	0	0	0	8
1996/01/01 @ 01:00:00	15	13.98	93.8	90	13.4	0	0	0	6
1996/01/01 @ 02:00:00	15	13.98	93.8	90	13.4	0	0	0	7
1996/01/01 @ 03:00:00	14	14	93.8	100	14.03	0	0	0	6
1996/01/01 @ 04:00:00	14	13.01	93.8	90	12.42	0	0	0	9
1996/01/01 @ 05:00:00	13	11.04	93.8	80	9.67	0	0	0	10
1996/01/01 @ 06:00:00	12	10.01	93.8	79	8.5	0	0	0	8
1996/01/01 @ 07:00:00	12	10.01	93.8	79	8.5	1	0	1	8
1996/01/01 @ 08:00:00	12	10.01	93.8	79	8.5	22	0	22	6
1996/01/01 @ 09:00:00	12	10.01	93.8	79	8.5	46	0	46	5
1996/01/01 @ 10:00:00	13	10.01	93.8	70	7.69	72	0	72	7
1996/01/01 @ 11:00:00	12	10.01	93.8	79	8.5	89	0	89	13
1996/01/01 @ 12:00:00	12	9.01	93.8	69	6.52	95	0	95	11
1996/01/01 @ 13:00:00	12	9.01	93.8	69	6.52	87	0	87	12
1996/01/01 @ 14:00:00	12	9.01	93.8	69	6.52	68	0	68	12

Columns: Add Remove Move Left Move Right

Units: SI IP

Figure 5-8 A Weather File for Simulation

Table 5-3 shows that the weather dataset includes various data points, such as *temperature* and *humidity*, though they have similar properties. The following parameters are extracted to define a type of weather data in Table 5-4 and shown in Figure 5-9 as a UML class example.

Table 5-4 Weather Data Extraction

Data Description	Description (Outside Air Temperature Dry-Bulb and Wet-Bulb, Humidity Solar Radiation, Cloud Cover, Precipitation, Wind)
Data Origin	Actual Data and Typical Data
Measured Timestep	Hourly
Schedule Value	Double
Schedule Period	Start: End:

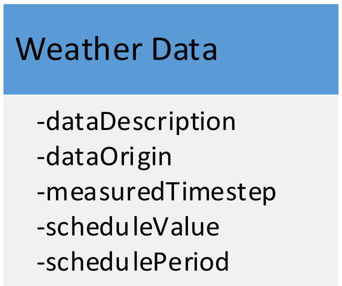


Figure 5-9 Weather Data Class

5.2.2.2 Utility Consumption Data

Energy consumption and demand data of the whole building and main sub-systems have to be measured to calibrate the simulated results of the energy model. All necessary data are listed in Table 5-5. The related parameters include *energy consumption system*, *energy type*, *measured and simulated results*, and *measured timestep*. Furthermore, a baseline model without energy conservation measures (ECM) and a retrofitted model with ECMs are needed for model comparison, such that the *model stages* are classified as a baseline period and post-installation period.

Table 5-5 Utility Data

Content	Data Origin	Energy Type	Measured Timestep	Model Stage	Comments
Whole-Building Energy Use	Measured Energy Use	Electricity/Gas/Steam	Monthly/ Hourly	Baseline Energy Use/ Post-installation Energy Use	1 year at least (12 valid meter readings)
	Simulated Energy Use	Electricity	Hourly	Baseline Energy Use/ Post-installation Energy Use	Energy Use Predicted by the Model
Whole Energy Demand	Actual Demand and Peak /Off-Peak Demand	Electrical and Gas	Monthly and hourly Demand	Baseline Energy Use/ Post-installation Energy Use	kW-months
	Simulated Demand and Peak/Off Demand	Electrical and Gas	Monthly and Hourly	Baseline Energy Use/ Calibrated Energy Use/ Post-installation Energy Use	Consumption kWh
Sub-system Energy Use	The Actual Energy Use of Specific Systems	Sub-system Type e.g VAV power log	Specific systems. bills from submeters	Baseline Energy Use/ Post-installation Energy Use	
	The Simulated Energy Use of Specific Systems	e.g VAV power log		Baseline Energy Use/ Calibrated Energy Use/ Post-installation Energy Use	
Rate		Electricity/Gas/Steam/Water			

Table 5-6 simplified that these utility data applied in the energy model calibration process, and shown by a UML class diagram in Figure 5-10.

Table 5-6 Utility Data Parameters

Data Content	Energy Use and Energy Demand
Data Origin	Actual Data and Simulated Data
Energy System	Whole Building/Subsystem Name
Energy Type	Electricity/Gas/Steam/ etc.
Energy Rate	Cost
Measured Timestep	Monthly and Hourly
Schedule Value	Double

Schedule Period	Start: End:
Model Stage	Baseline Energy Use/ Calibrated Energy Use/ Post-installation Energy Use
Unit	kWh/kW

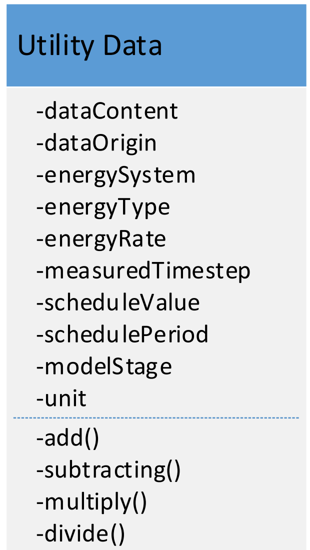


Figure 5-10 Utility Data Classification

5.2.2.3 Zone Related Data

Zone related datasets are classified into two categories as *indoor environment parameters* and *zone loads*. *Indoor environment parameters* are spot-measured, such as carbon dioxide levels and indoor temperatures. *Zone loads* represent another comprehensive dataset with four main types of loads: occupancy load, *lighting load*, *plug-in device load*, and *other equipment load*. Although several parameters related to a load type can be classified as indoor environment parameters (e.g. occupancy density), they are classified under the related load type to simplify the data management. Table 5-7 listed the related data.

Table 5-7 Zone Related Datasets

Classification	**Date Content**	**Measurement point**	**Time Period**
Zone Parameter	Temperature Setpoints	Per Interior Zone	
	Control Setpoints	Per Zone	
	Terminal Heating Coil Valve Position	Per Zone	
	Carbon Dioxide Levels	Spot Measured, per Zone	Calibrated Period
	Interior Space Temperature	Spot Measured, per Zone	Calibrated Period
	Humidity Data	Spot Measured, per Zone	Calibrated Period
	Air and Water Flows	Spot Measured, per Zone	Calibrated Period
	Static Pressures	Spot Measured, per Zone	Calibrated Period
	Duct Leakage	Spot Measured, per Zone	Calibrated Period
	Equipment Schedules (e.g. zone temperature setpoint cold deck temperature, hot deck	Per zone	

	temperature, and economizer setpoint),		
	Infiltration Rates through Outside Air Ducts and Building Pressurization	Tracer Gas Tests	Calibrated Period
Occupancy Load	Occupancy Schedule	Per Zone	Weekday/Weekend/Holiday
	Occupancy Density	Per zone	
	Activity Levels	Per zone	
Lighting Load	Lighting Fixture Counts	Per Space	
	Fixture Types	e.g. Lamps and Ballasts	
	Fixture Power	Nameplate Data	
	Characteristics of Fixtures		
	Lighting Load	Per Zone	Calibrated Period
	Lighting Schedule	Per Zone (Indoor/Outdoor)	Weekday/Weekend/Holiday
	Illuminance Measurement	Per Zone	
	Diversity of Operation	Per Zone	Can be Calculated
Plug Devices Load	Major and Typical Plug Loads	Per Zone	Calibrated Period
	Plug-in Device Counts		
	Plug-in Device Power	Nameplate Data	
	Plug Load Schedule	Per Zone	Weekday/Weekend/Holiday
	Power Factor	Per Circuit	
	Diversity of Operation	Per Zone	Can be Calculated
Other Major Energy Using Loads.	Special Loads and Energy Use	e.g. air compressors, water heaters, industrial process, vertical transportation, outdoor lighting etc.	

Indoor environment parameters and loads can be simplified as a series of different schedules, such as interior space temperature, lighting, thermostatic controls, occupancy activity, and temperature setpoints. These data can be expressed in a spot-measured schedule format, including a time series. Schedules are related directly to a zone or related to a single building system object, such as an air terminal related to a zone. More than describing zone parameters, schedules describe other system activities such as the inlet and outlet water temperature or the damper/valve position of hot- and cold-water loop in a building. The general parameters of a schedule which apply in an energy model calibration are extracted as Table 5-8.

Table 5-8   Schedule Description

Schedule Name	Temp-air, Temp-water, Air speed, water flowrate, load, pressure, status(on/off), etc
Zone ID	Reference (e.g 410A)
Equipment ID	Reference (e.g Terminal, Boiler, Fan etc.)
ConnectionPort ID	Reference (e.g Inlet/Outlet, Terminal)
Schedule Type	Spot-measured, Load, Controlled Schedule
Schedule Data Type	Value, On/Off, Fraction
Data Origin	Design/Actual
Measured Timestep	Hourly
Schedule Value	/
Schedule Period	Start: End:
Model Stage	Baseline Energy Use/ Calibrated Energy Use/ Post Installation Energy Use

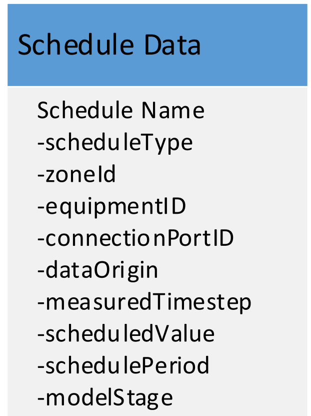


Figure 5-11 UML Class Diagram of a Schedule

The main load datasets have more parameters than the schedule datasets because several static parameters are related to the special type of load (e.g., the lighting load should include the power density of the lighting system). The detailed parameters are listed in Table 5-9.

Table 5-9 Load Data

Data Content	**Occupancy**	**lighting**	**plug-load**	**Other-system**
Zone ID				
Data Origin	Designed Schedule/Actual Schedule			
Measured Timestep	Hourly			
Schedule Value				
Schedule Period				
Item Counts				
Diversity Factor	/		/	/
Power Density	/			
Illuminance	/		/	/

All of these loads include the same parameters as schedule datasets, such as *value* and *schedule* period. Other parameters include *item counts* (fixture, occupancy, device number per zone), and *power density* (activity levels related to occupancy), *diversity factor*, and *measured illuminance*. A UML class diagram is in Figure 5-12 to describe these parameters of the load and show.

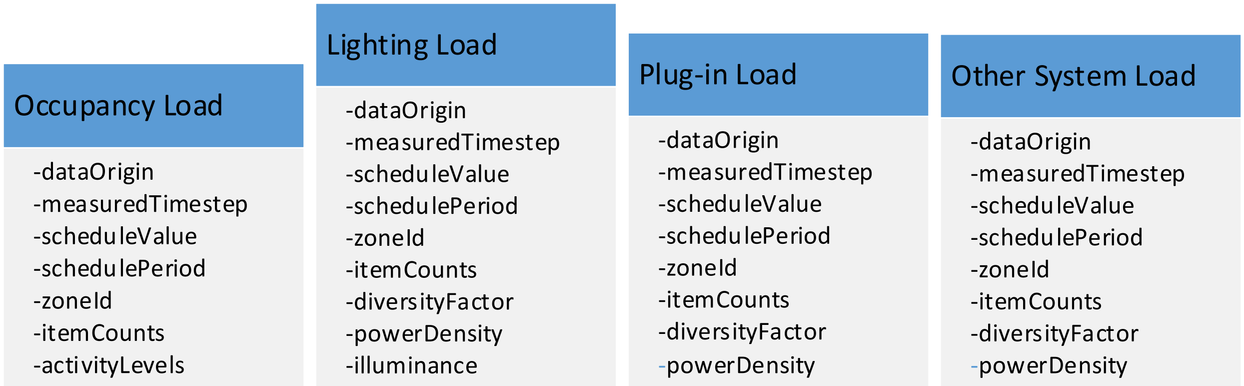


Figure 5-12 UML Class Diagram of Loads

5.2.2.4 HVAC System Data

HVAC system data are complex. Key datasets are classified into the following categories. *Primary Equipment General* parameters include the common parameters for primary equipment, as capacities, model and serial numbers from the nameplate, and performance curves. *Primary Equipment Special* parameters refer to the special parameters of the equipment, such as the boiler efficiency of a boiler. *Coil and Loop* parameters refer to the parameters of heating and cooling loop, which are difficult to assign to a single zone (e.g. heating water supply and return temperatures). *Secondary Equipment* includes air distribution equipment and water distribution equipment, such as the fan, pump, and motor. *Special Systems* include AHU, heating pump, air conditioning, and so forth. *Controls* include control types, economizer schedules, and setpoints schedules. Table 5-10 lists the detailed data entries under these categories.

Complex HVAC system data are simplified into two types of datasets, one type being a single value of measured parameters, without time changes, such as the capacity of a boiler, which are derived from the nameplate or measured, but nothing to do with time. The other type is a schedule of different objects, such as occupancy density, lighting, thermostatic controls and occupancy activity, which can be summarized as in Section 5.2.2.3. This solution provides a method of simplifying HVAC system data in calibration, the detailed explanation of which is provided in Section 5.4.

Table 5-10 HVAC Equipment System

Parameter Classification	**Parameter**	**Measurement Point**
Primary Equipment (e.g: Boiler/Condenser/Cooling	Capacity	Nameplate
	Model/Serial Numbers	Nameplate

Tower) General	Number of Equipment	Counts
	Default Performance Curves	Default Performance Curves of the Various Systems and Plant Equipment
	User-Definable Part-Load Performance Curves	(Efficiency vs Load);
	User-Definable Capacity qnd Efficiency Correction Curves	
	Performance Data Thermostat Settings	
Primary Equipment Special	Boiler	Boiler Efficiency
		Supply and Return Ducting
		Economizers
	Cooling Tower	VFD Speed
	Chiller	Chiller Power
		Efficiency of Constant and Variable Load Motors
		Variable Frequency Drive Operation
		Chiller Efficiency at Variable Loads
		Cooling Load
		Air and Water Economizer
		Air Distribution Static Pressures
		Ventilation Air Volumes
Coil and Loop	Heating/Cooling Coil	Sensible Heating Factor
		Temperatures of the Air Leaving The Coils
	Hot Water Loop	Heating Water Supply and Return Temperatures
	Hot Water Loop: Pump	Pump Status
		Differential Pressure between Supply and Return
		Water Flow Rate
		VFD Speed
	Chilled Water Loop	Chilled Water Supply and Return Temperatures
	Chilled Water Loop: Pump	VFD Speed
		Water Flowrate
	Condenser Water Loop	VFD Speed
		Condenser Water Supply and Return Temperatures
		Condenser Water System Load
	Secondary Loop Pump	Water Flow Rate
		Differential Pressure between Supply and Return
		Heat Exchanger Entering and Exiting Water Temperatures
Secondary Equipment	Terminal Boxes	Discharge Air Temperature, Mixed Air Temperature, Return Air Temperature
		Mixed Air Damper Position, Return Air Damper Position, Exhaust Air Damper Position, Minimum and Main Outside Air Damper Positions
		Supply and Return Fan VFD Speed
		Duct Static Pressure
		Chilled Water Valve Position
		Hot Water Valve Position
		Total Supply Airflow, Total Return Airflow, Entering Outside Airflow
		Cooling Coil Entering and Leaving Temperatures
		Heating Coil Entering and Leaving Temperatures
		Raised Floor Plenum Static Pressure
	Motor	Motor Sizes
		Efficiency
		Location
	Fan	Fan Sizes and Types, (e.g, Forward Curved, Backward Curved),
		Fan Flow CFM, Design-Flow Rates and Static Pressures
		Fan Curve
		Fan Power

	Pump	Water Flow Rate
		Differential Pressure between Supply and Return
		VFD Speed
		Entering and Exiting Water Temperatures (Cooling or Heating)
Special System	AHUs	Peaking Cooling Load Tons
		Peak CHW Pump Demand(kW)
		Infiltration and/or Ventilation Rates
		Overall Plant Efficiency
		Metered Electrical/Gas Consumption
		Equipment Run Time
	HRU	Supply Enthalpy Difference, and Exhaust Enthalpy Difference across the Heat Exchanger
		Supply and Exhaust Airflow and HRU (Heating Recovery)
	AC	Unit Power, Run Time, Space Set Points, Airflow, Supply Temperatures, Equipment Run Time
Controls	Airflow Control	Airflow Control Types (Discharge Damper, Inlet Vanes, VSD);
		Economizer Operation
		Type of Controls
		Economizers
	HVAC Control	Locations of Zones,
		Temperature Set-Points,
		Control Set-Point and Schedule
		Any Special Control Sequence

To extract the data listed in Table 5-10, four main types of datasets were defined, namely *general equipment parameters, performance curves, special equipment parameters, and control types*. *General Equipment Parameters* listed in Table 5-11 showing the basic collected parameters of equipment during the calibration process.

Table 5-11 General Equipment

EquipmentName	Description
EquipmentID	Reference
ZoneID	Reference
Overall Efficiency	
Loads Efficiency	Efficiency at Different Loads
Power Capacity	
Model Number	
Number of Equipment	
Data Origin	Design/Actual

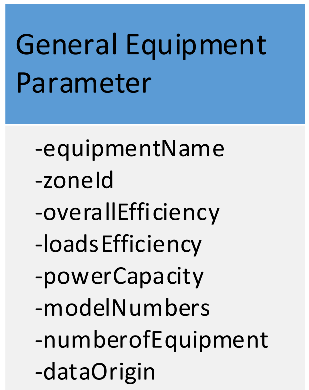


Figure 5-13 UML Class Diagram of General Equipment Parameter

The *Performance Curve* shows the correlation between two variables (data A and data B). The calibration process requires three types of performance curves defined as *default system curves*, *user-definable part-load performance curves* (efficiency vs load), and *user-definable capacity and efficiency correction curves*. The related properties are suggested in Table 5-12.

Table 5-12 Performance Curve

EquipmentName	CO2, Internal Temperature, Static Pressure for Terminal, Infiltration per Duct/Door…
EquipmentId	
Curve Type	Default System Curves, User-Definable Part-Load Performance Curves (Efficiency VS Load); User-Definable Capacity and Efficiency Correction Curves
scheduleNameA	
scheduleNameB	Spot-measured, Load, Controlled Schedule
scheduleAvalue	
scheduleBvalue	
dataClassification	Design/Actual
measured Timestep	
Schedule Period	

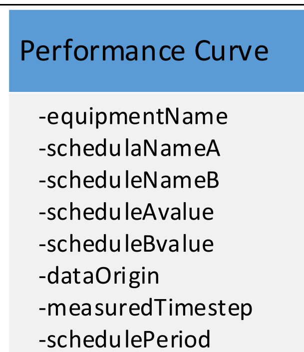


Figure 5-14 UML Class Diagram of a Performance Curve

Special equipment parameters vary with different equipment. An example of a fan is used to describe the dataset in Table 5-13. Another type of HVAC system data is the controller data, which is usually an element such as a damper or a valve, with control type and methods. The controller usually follows a schedule, so it can link with the schedule using the "*schedule name*" property. The related parameters are summarized in Table 5-14. Figure 5-15 shows the UML class diagram.

Table 5-13 Special Equipment Parameter:Fan Example

EquipmentName	Fan
ZoneID	Reference
Overall Efficiency	
Loads Efficiency	
Power Capacity	
Economizer Status	
Model Numbers	
Number of Equipment	
Data Origin	Design/Actual
Fan Types	e.g. Forward Curved, Backward Curved
CFM	
Static Pressures	

Table 5-14 Control Type

EquipmentID	
ZoneID	
Control Type	Discharge Damper, Inlet Vanes, VSD
Controller Set-point	
Control Schedule Name	

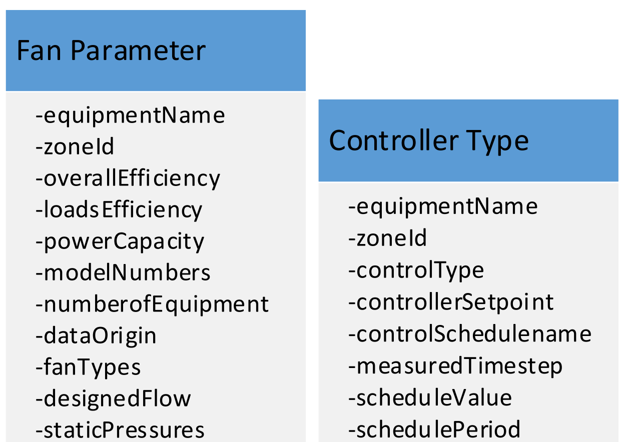


Figure 5-15 UML Class Diagram of Special Equipment and Controller

5.2.2.5 Final Class diagram

Figure 5-16 summarizes all class diagrams from above and shows a schema representation of these dynamic data using entities and property sets. An entity of the whole building and an entity of thermal zone were used to show the relationship among these classes. All dynamic datasets were classified using UML class diagrams and were assigned to the actual building objects as space, equipment, or a system. In this figure, the only class which is not related to schedule is the *general* *equipment parameters,* which values are measured. Other data can be simplified as S*chedule Data*, represented through a series of values with time stamps.

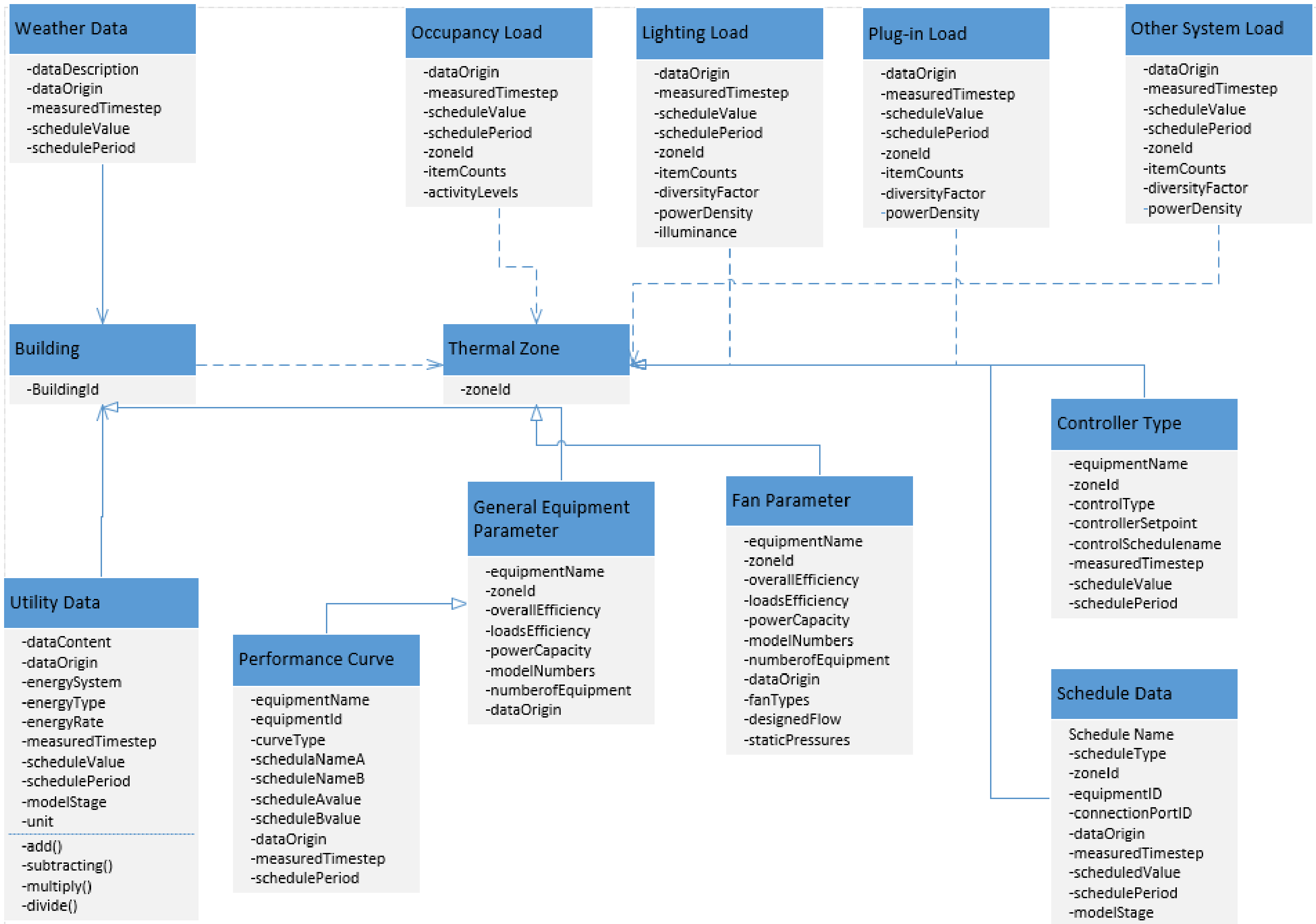


Figure 5-16 Final UML Class Diagram

5.3 Data Validation

This research utilized 5 M&V plans from 5 LEED projects for validation. All of these projects applied for EA C5: Measurement and Verification using option D. In these reports, the engineers described the planned collected parameters in a calibration process. Therefore, these submitted reports are reviewed to validate the selected data information in Section 5.2.2.

Table 5-15 lists the project information. Project size and climate zone are taken from the EA P2 Minimal Energy Performance credit form. Snapshots of these reports are presented in Appendix B.

The actual or expected monitored data were selected from the M&V plans as Table 5-16. All plans have common collected parameters, such as energy consumption of general equipment. Particular collected parameters depend on the actual MEP system of projects, and all of the particular data can be described using the general data description in Section 5.2.2. For instance, one project monitors operating time and status of the heating recovery system, which is the secondary equipment running schedule in Table 5-8.

The review results of M&V reports showed that most of the selected data have been included in the result of Section 5.2.2: Dynamic Data Identification, which indicated the correctness and quality of these dynamic datasets. Partial data, such as water consumption or carbon dioxide level are rarely included in energy simulations. Moreover, the data identification part did not include renewable energy systems, and one project with a solar water system required a measure of the amount of solar hot water, which was achieved by measuring the system capacity or pump flowrate.

Table 5-15 Project Information

Pseudonym	LEED System	Credit	Completed Time	Project Type	Project Size (sq.ft)	Climate zone
Project I	CS	EA 5.1	2013	Commercial	2850975	2A
Project II	NC	EA 5	2013	Manufacture	577445	3A
Project III	CS	EA 5.1	2012	Office	388164	3A
Project IV	NC	EA5	2013	Office	41090	2A
Project V	NC	EA 5	2013	Manufacture	375182	2A

Table 5-16 Collected Data

Category	Specify System	Included?	Comments
Electricity Consumption(kw) Meter or Submeter	Chiller system	Y	
	Cooling tower	Y	
	Space heating and cooling	Y	

	Main circuit	Y	
	Plug loads/ Plug socket/ Receptacle equipment	Y	
	AHU/FCU/AC units	Y	
	Water Heater/ Service water heater	Y	
	Interior and exterior Lighting power	Y	
	Fans (independent fan, exhaust fan, supply fan, etc.)	Y	
	Pumps (chilled water, solar water system, domestic hot water, cooling tower, etc.)	Y	
	Refrigeration system	Y	
	Fresh air unit	Y	
	Process equipment	Y	
	Kitchen appliance	Y	Special loads and energy use
	Auxiliary system: rolling door	Y	Special loads and energy use
	Auxiliary system: dock leveler	Y	Special loads and energy use
Water Temperature	Chilled water temperature (supply & return)	Y	
	Condensing water temperature (supply & return)	Y	
Water Flow Rate	Chilled water flow rate (supply & return)	Y	
	Condensing water flow rate	Y	
Airflow Rate	Outdoor air flowrate for Ventilation demand control	Y	
	Supply air flowrate for Ventilation demand control	Y	
Air Temperature and RH	Outdoor air temperature and RH for various systems (Heating recovery system, Air Economizer, Ventilation demand control)	Y	Weather data
	Exhaust air temperature and RH for Heating recovery system?	Y	HRV system
	Indoor air temperature and supply for Ventilation demand control	Y	
System Operating Time/Status	Chiller system	Y	schedule
	Heating recovery system	Y	schedule
	Air Economizer	Y	schedule
	Ventilation demand control	Y	schedule
Damper Operating Status	Heating recovery system	Y	schedule
	AHU	Y	schedule
	Air Economizer	Y	schedule
	Ventilation demand control	Y	schedule
Sensors Operating Status	CO2 sensor	Y	Not applied in simulation
	Lighting sensor	Y	schedule
Water Consumption	Make-up water for a chiller	Y	Not applied in simulation
	Cooling tower	Y	Not applied in simulation
	Solar hot water consumption	Y	
	Flushing/hand-washing	N	Not applied in simulation
	Stormwater collection	N	Not applied in simulation
	Process lines and laboratory	Y	Not applied in simulation
Natural Gas Consumption	Cooking devices	Y	Special loads and energy use
	Utility system: air compressor	Y	Special loads and energy use
	Fire pump system	Y	Special loads and energy use
	Forklift recharge system	Y	Special loads and energy use

5.4 Dynamic Data Schema in IFC

5.4.1 Data Schema and Property Sets

The IFC 4.2 schema allows users to assign various properties, including single properties and a series of data history to an entity such as zone or equipment. Figure 5-16 lists the key dynamic parameters in the complete energy simulation and calibration process. This section reviewed IFC schema to select the related IFC entity and property sets which are applied to describing identified datasets of energy model calibration and used a series of figures to explain how to express the related building objects and their relationships through the IFC 4.2 schema.

Figure 5-17 shows how to assign related IFC property sets to an *IfcZone*, and Figure 5-18 shows how to assign the related IFC property sets to devices. The choice of devices and property sets are made according to the actual dynamic data in Section 5.2.2. Related property sets, including the identified datasets are listed, but only partial properties in the sets are used to express the identified dynamic data. These selected property sets are listed in Table 5-17. A completed related IFC entities and common property sets about an energy model, including static data and dynamic data, is documented in Appendix C.

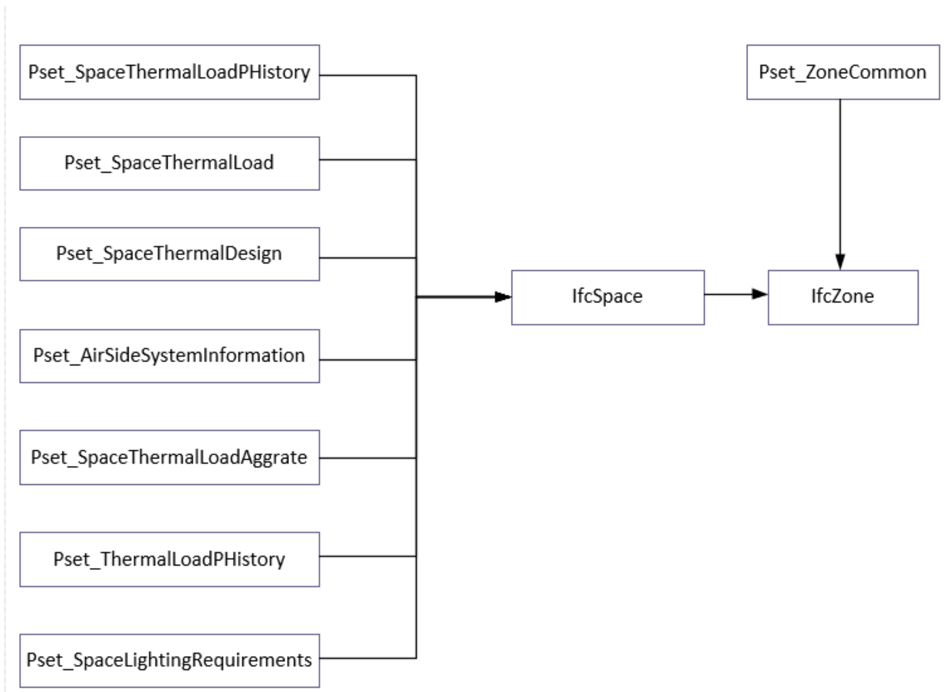


Figure 5-17 Parameters of a Zone

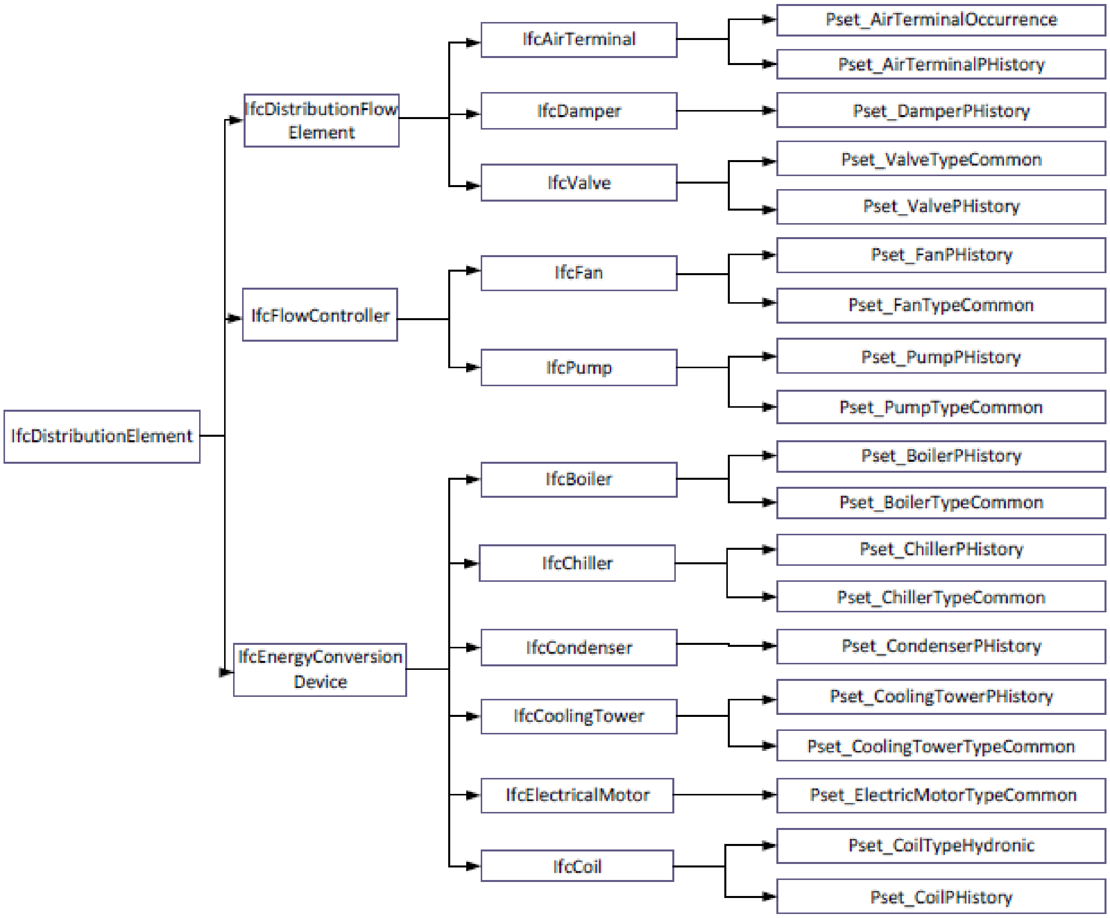


Figure 5-18 Parameters of Equipment

Table 5-17 Selected IFC Parameters

	Attribute/Property Set	**Property**	**Data Type**
IfcBuilding	Pset_OutsideDesignCriteria	WeatherDataStation	IfcText
		WeatherDataDate	IfcDateTime
	Pset_UtilityConsumptionPHistory	Heat	P_REFERENCEVALUE / IfcTimeSeries / IfcEnergyMeasure
		Electricity	P_REFERENCEVALUE / IfcTimeSeries / IfcEnergyMeasure
		Water	P_REFERENCEVALUE / IfcTimeSeries / IfcVolumeMeasure
		Fuel	P_REFERENCEVALUE / IfcTimeSeries / IfcVolumeMeasure
		Steam	P_REFERENCEVALUE / IfcTimeSeries / IfcMassMeasure
IfcSpace	Pset_ThermalLoadDesignCriteria	OccupancyDiversity	P_SINGLEVALUE /IfcPositiveRatioMeasure
	Pset_SpaceThermalLoadPHistory	People	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		Lighting	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		EquipmentSensible	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		VentilationIndoorAir	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		VentilationOutdoorAir	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		RecirculatedAir	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		ExhaustAir	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		AirExchangeRate	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		DryBulbTemperature	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		RelativeHumidity	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure

		InfiltrationSensible	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		TotalSensibleLoad	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		TotalLatentLoad	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		TotalRadiantLoad	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
	Pset_SpaceOccupancy Requirements	OccupancyNumber	P_SINGLEVALUE /IfcCountMeasure
	Pset_SpaceLightingRe quirements	Illuminance	P_SINGLEVALUE / IfcIlluminanceMeasure
	Pset_AirSideSystemIn formation	TotalAirflow	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
		LightingDiversity	P_SINGLEVALUE / IfcPositiveRatioMeasure *
		InfiltrationDiversitySu mmer	P_SINGLEVALUE / IfcPositiveRatioMeasure *
		InfiltrationDiversityWin ter	P_SINGLEVALUE / IfcPositiveRatioMeasure *
		ApplianceDiversity	P_SINGLEVALUE / IfcPositiveRatioMeasure *
		HeatingTemperatureDel ta	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		CoolingTemperatureDel ta	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		Ventilation	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
Equipment			
IfcAir Temin al	Pset_AirTeminalType Common	AirFlowrateRange	P_BOUNDEDVALUE /IfcVolumetricFlowRateMeasure
		TemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasu re
	Pset_AirTeminalPHist ory	AirFlowRate	P_REFERENCEVALUE / IfcTimeSeries /IfcVolumetricFlowR ateMeasure
		SupplyAirTemperature Heating	P_REFERENCEVALUE / IfcTimeSeries /IfcThermodynamic TemperatureMeasure
		SupplyAirTemperature Cooling	P_REFERENCEVALUE / IfcTimeSeries /IfcThermodynamic TemperatureMeasure
		PressureDrop	P_REFERENCEVALUE / IfcTimeSeries /IfcPressureMeasure
		CenterlineAirVelocity	P_TABLEVALUE /IfcLinearVelocityMeasure /IfcLengthMeas ure
	Pset_AirTerminalOccu rrence	AirflowType	P_ENUMERATEDVALUE / PEnum_AirTerminalAirflowType / PEnum_AirTerminalAirflowType
		AirFlowRate	P_SINGLEVALUE / IfcVolumetricFlowRateMeasure
IfcDa mper	Pset_DamperTypeCo mmon	MaximumAirFlowRate	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
		TemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasu re
		MaximumWorkingPress ure	P_SINGLEVALUE /IfcPressureMeasure
		TemperatureRating	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		NominalAirFlowRate	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
	Pset_DamperPHistory	AirFlowRate	P_REFERENCEVALUE / IfcTimeSeries /IfcVolumetricFlowR ateMeasure
		DamperPosition	P_REFERENCEVALUE / IfcTimeSeries /IfcNormalisedRatio Measure
IfcVal ve	Pset_ValveTypeComm on	TestPressure	P_SINGLEVALUE /IfcPressureMeasure
		WorkingPressure	P_SINGLEVALUE /IfcPressureMeasure
		FlowCoefficient	P_SINGLEVALUE /IfcReal
	Pset_ValvePHistory	PercentageOpen	P_REFERENCEVALUE / IfcTimeSeries / IfcPositiveRatioMe asure
		MeasuredFlowRate	P_REFERENCEVALUE / IfcTimeSeries / IfcMassFlowRateM easure
		MeasuredPressureDrop	P_REFERENCEVALUE / IfcTimeSeries / IfcPressureMeasure
IfcFan	Pset_FanTypeCommo n	MotorDriveType	P_ENUMERATEDVALUE / IfcLabel /PEnum_FanMotorCon nectionType
		CapacityControlType	P_ENUMERATEDVALUE / IfcLabel /PEnum_FanCapacityC ontrolType

		NominalAirFlowRate	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
		NominalTotalPressure	P_SINGLEVALUE /IfcPressureMeasure
		NominalStaticPressure	P_SINGLEVALUE /IfcPressureMeasure
		NominalRotationSpeed	P_SINGLEVALUE /IfcRotationalFrequencyMeasure
		NominalPowerRate	P_SINGLEVALUE / IfcPowerMeasure
		PressureCurve	P_TABLEVALUE /IfcVolumetricFlowRateMeasure /IfcPressureMeasure
		EfficiencyCurve	P_TABLEVALUE /IfcVolumetricFlowRateMeasure /IfcNormalisedRatioMeasure
	Pset_FanPHistory	OverallEfficiency	P_REFERENCEVALUE / IfcTimeSeries /IfcNormalisedRatioMeasure
		FanPowerRate	P_REFERENCEVALUE / IfcTimeSeries / IfcPowerMeasure
		DischargeVelocity	P_REFERENCEVALUE / IfcTimeSeries / IfcLinearVelocityMeasure
IfcPump	Pset_PumpTypeCommon	FlowRateRange	P_BOUNDEDVALUE /IfcMassFlowRateMeasure
		NetPositiveSuctionHead	P_SINGLEVALUE /IfcPressureMeasure
	Pset_PumpPHistory	MechanicalEfficiency	P_REFERENCEVALUE / IfcTimeSeries / IfcNormalisedRatioMeasure
		OverallEfficiency	P_REFERENCEVALUE / IfcTimeSeries / IfcNormalisedRatioMeasure
		PressureRise	P_REFERENCEVALUE / IfcTimeSeries / IfcPressureMeasure
		Flowrate	P_REFERENCEVALUE / IfcTimeSeries / IfcVolumetricFlowRateMeasure
		Power	P_REFERENCEVALUE / IfcTimeSeries / IfcPowerMeasure
IfcBoiler	Pset_BoilerTypeCommon	WaterInletTemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasure
		PartialLoadEfficiencyCurves	P_TABLEVALUE /IfcPositiveRatioMeasure /IfcNormalisedRatioMeasure
		OutletTemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasure
		NominalEnergyConsumption	P_SINGLEVALUE / IfcPowerMeasure
		EnergySource	P_ENUMERATEDVALUE / IfcLabel /PEnum_EnergySource
	Pset_BoilerPHistory	EnergySourceConsumption	P_REFERENCEVALUE / IfcTimeSeries /IfcEnergyMeasure
		OperationalEfficiency	P_REFERENCEVALUE / IfcTimeSeries /IfcNormalisedRatioMeasure
		WorkingPressure	P_REFERENCEVALUE / IfcTimeSeries /IfcPressureMeasure
		PartLoadRatio	P_REFERENCEVALUE / IfcTimeSeries /IfcNormalisedRatioMeasure
		Load	P_REFERENCEVALUE / IfcTimeSeries /IfcPowerMeasure
		PrimaryEnergyConsumption	P_REFERENCEVALUE / IfcTimeSeries /IfcPowerMeasure
		AuxiliaryEnergyConsumption	P_REFERENCEVALUE / IfcTimeSeries /IfcPowerMeasure
IfcChiller	Pset_ChillerTypeCommon	NominalCapacity	P_SINGLEVALUE / IfcPowerMeasure
		NominalEfficiency	P_SINGLEVALUE /IfcPositiveRatioMeasure
		NominalCondensingTemperature	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		NominalPowerConsumption	P_SINGLEVALUE / IfcPowerMeasure
		CoefficientOfPerformanceCurve	P_TABLEVALUE /IfcThermodynamicTemperatureMeasure/ IfcReal
		FullLoadRatioCurve	P_TABLEVALUE /IfcPositiveRatioMeasure /IfcNormalisedRatioMeasure
	Pset_ChillerPHistory	Capacity	P_REFERENCEVALUE/ IfcTimeSeries /IfcPowerMeasure
		EnergyEfficiencyRatio	P_REFERENCEVALUE/ IfcTimeSeries / IfcReal
		CoefficientOfPerformance	P_REFERENCEVALUE/ IfcTimeSeries /IfcPositiveRatioMeasure

IfcCoolingTower	Pset_CoolingTowerPHistory	Capacity	P_REFERENCEVALUE / IfcTimeSeries /IfcPowerMeasure
IfcElectricalMotor	Pset_ElectricalMotorTypeCommon	MaximumPowerOutput	P_SINGLEVALUE /IfcPowerMeasure
		ElectricMotorEfficiency	P_SINGLEVALUE /IfcPositiveRatioMeasure
IfcCoil	Pset_CoilTypeCommon	OperationalTemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasure
		AirflowRateRange	P_BOUNDEDVALUE /IfcVolumetricFlowRateMeasure
	Pset_CoilPHistory	AtmosphericPressure	P_REFERENCEVALUE / IfcTimeSeries /IfcPressureMeasure

5.4.2 Additional Data Expression

Most of the identified datasets can be described using IFC schema, while some limitations exist in the current IFC schema for describing energy model calibration datasets. This section discusses the limitations and provides a possible solution.

5.4.2.1 Weather and Utility Data Representation

IFC 4.2 can express the weather station and date of the building location using the properties *WeatherDataStation* in *Pset_OutsideDesignCriteria*. Considering weather data are large and complex, the full weather dataset with data points is saved in a database. To link and import the actual weather data into an IFC schema, the *IfcTimeSeries* can be used to describe the weather data type, actual value, and time. Attribute *HasExternalReferenc*e links an external reference e.g. the weather station location. The suggested property sets *Pset_WeatherDataStationPHistory* in Table 5-18 can be assigned to *IfcSite*. The typical weather yearly data can be achieved based on the weather data station property. Figure 5-19 shows how to assign the *IfcPropertySet* with a timestamp and list values to an object using *IfcTimeSeries*. In this case, the *IfcLable* of *IfcTypeObject* can be *weather station* and the name of *IfcRegularTimeSeries* can be *dry-bulb temperature*.

Table 5-18 Weather Data Extraction

Property Name	Property	Type
Pset_WeatherDataStationPHistory	Dry-bulb Temperature	P_REFERENCEVALUE / IfcTimeSeries / IfcThermodynamicTemperatureMeasure
	Wet-bulb Temperature	P_REFERENCEVALUE / IfcTimeSeries / IfcThermodynamicTemperatureMeasure
	Humidity	P_REFERENCEVALUE / IfcTimeSeries / IfcRatioMeasure
	Solar Radiation	-
	Cloud Cover	-
	Precipitation	-
	Wind Speed	P_REFERENCEVALUE / IfcTimeSeries /IfcLinearVelocityMeasure

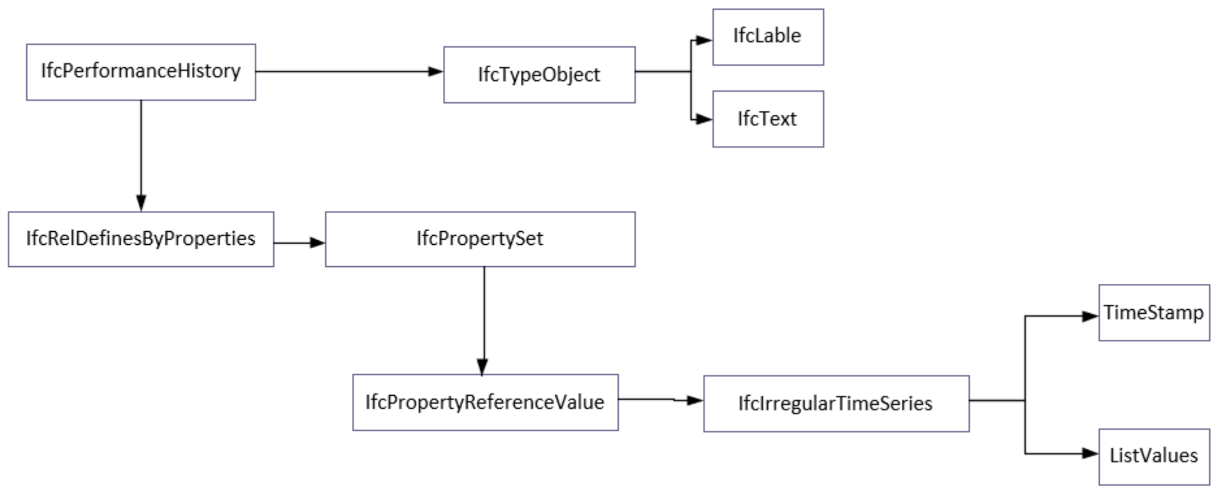


Figure 5-19 IfcPerformace History Relationship

The IFC schema only uses *UtilityConsumptionPHistory* in Table 5-19, which describes the amount of energy consumed during the period specified using time series. The set of parameters shows the consumption (heat, electricity, water, fuel, steam) history, and applies for *IfcBuilding* without indicting the difference between measured energy use and simulated energy use, related system and calibration period. The following properties in Table 5-20 are suggested to be added for the energy model calibration in the IFC 4.2 schema.

Table 5-19 Existing Parameters for Utility

Object	**Property Name**	**Data Type**
Pset_UtilityConsumptionPHistory	Heat	P_REFERENCEVALUE / IfcTimeSeries / IfcEnergyMeasure
	Electricity	P_REFERENCEVALUE / IfcTimeSeries / IfcEnergyMeasure
	Water	P_REFERENCEVALUE / IfcTimeSeries / IfcVolumeMeasure
	Fuel	P_REFERENCEVALUE / IfcTimeSeries / IfcVolumeMeasure
	Steam	P_REFERENCEVALUE / IfcTimeSeries / IfcMassMeasure

Table 5-20 Additional Parameters for Utility

Object	**Property Name**	**Data Type**	**Definition**
IfcBuilding / UtilityConsumptionInformation	Data Content	IfcLable	Energy Use and Energy Demand
	Data Origin	IfcDataOriginEnum	Actual Data and Simulated Data
	Energy System		Whole Building/Subsystem Name
	Energy Type		Electricity/Gas/Steam/etc.
	Measured Timestep		Monthly and Hourly
	Model Stage	IfcLifecycle	Baseline Energy Use/ Calibrated Energy Use/ Post-installation Energy Use
	Unit		Kwh/kw

5.4.2.2 Load Data and Zone Data Representation

Main load data and their history are expressed in the IFC schema directly by *Pset_SpaceThermalLoad* and *Pset_SpaceThermalLoadPHistory*. Most related zone parameters can be described in IFC using a rather complex way. For example, EnergyPlus defines the infiltration relating to *ZoneInfiltration* object, which defines the unintended flow of air from the outdoor environment into a thermal zone. Infiltration is due to the operation of doors, windows, and air leaks in building elements such as walls or ducts. When infiltration is expected to be an important issue, a blower door test and trace gas test can measure the air changes per hour (ACH) and use the results in the energy model. Energy consumption of ACH changes are based on the temperature difference and pressure, where EnergyPlus uses an infiltration schedule to express the various ACH and calculate the infiltration load.

The IFC 4.2 schema defines the infiltration of doors and windows, *AirFlowLeakage* of ducts, *InfiltrationDiversitySummer* of the airside system per zone, and the *AirExchangeRate* load per zone. The measured infiltration of the components can be aggregated to get the final infiltration per zone, which can be expressed as infiltration diversity. For simulation, the measured infiltration can be used with a fraction schedule in the simulation model. The relationship of *IfcRelAggregates* is used to describe the zone infiltration in IFC in Figure 5-20. The related parameters are listed in Table 5-21. The value of measured actual infiltration assigned to door and window operation or air leakage of ducts can be measured and be added as a zone infiltration named *InfiltrationDiversity* for actual simulation. Applied infiltration in the energy model is related to the HVAC schedule and depends on the selected mathematical model; however, the final infiltration load is saved as infiltration sensible load as a property of space.

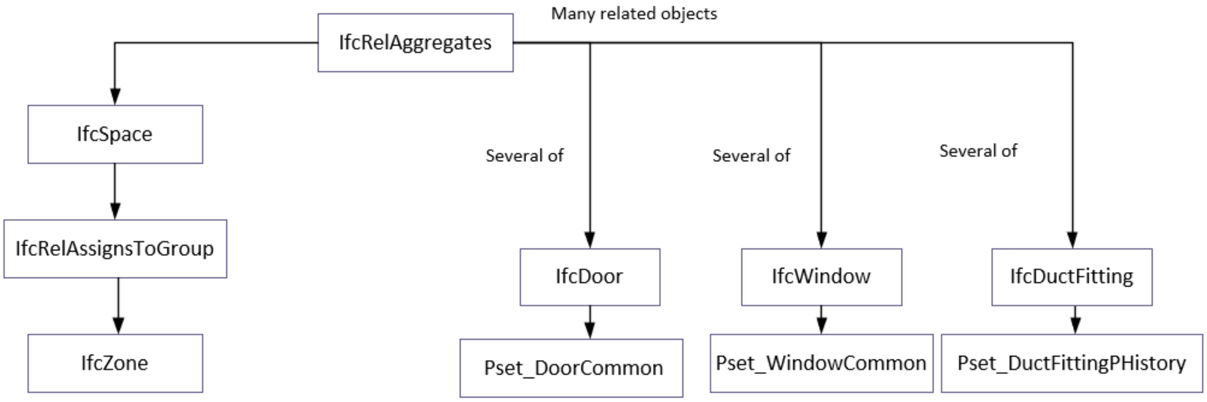


Figure 5-20 Assign Infiltration Property to a Zone

Table 5-21 Related Infiltration Existing Properties in IFC

Object	Property Name	Property	Data Type	Definition
IfcDoor	Pset_DoorCommon	Infiltration	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure	Infiltration flowrate of outside air for the filler object based on the area of the filler object at a pressure level of 50 Pascals. It shall be used, if the length of all joints is unknown.
IfcWindow	Pset_WindowCommon	Infiltration	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure	
IfcDuctFitting	Pset_DuctFittingPHistory	AirFlowLeakage	P_REFERENCEVALUE / IfcTimeSeries /IfcVolumetricFlowRateMeasure	Volumetric leakage flow rate.
IfcZone	Pset_AirSideSystemInformation	InfiltrationDiversitySummer	P_SINGLEVALUE / IfcPositiveRatioMeasure	Diversity factor for Summer infiltration.
	Pset_AirSideSystemInformation	InfiltrationDiversityWinter	P_SINGLEVALUE / IfcPositiveRatioMeasure	Diversity factor for Winter infiltration.
IfcSpace	Pset_SpaceThermalLoad	InfiltrationSensible	P_BOUNDEDVALUE /IfcPowerMeasure	Heat gains and losses from infiltration.
	Pset_SpaceThermalLoadHistory	InfiltrationSensible	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure	Heat gains and losses from infiltration.

5.4.2.3 Schedule Representation

The IFC 4.2 schema does not define the operating schedule accurately and directly. The entity *IfcPerformanceHistory* can be assigned with extra property sets such as *IfcTimeSeries* of performances and is used to document the actual performance.

IfcTimeSeries including *IfcIrregularTimeSeries* and *IfcregularTimeSeries* with their properties refer to Table 5-22. Properties of *IfcTimeSeries* sets can be assigned with *IfcPerformanceHistory* by the objectified relationship *IfcRelDefinesByProperties*, defining the relationships between property set definitions and objects. *IfcPerformanceHistory* can be aggregated with

IfcWorkCalendar, which is defined by a set of work times and exception times using *IfcWorktime* and *IfcRecurranceParteen*, to define the “on/off” status throughout the year with predefined patterns. Then, as a subtype of *IfcControl*, entities *IfcPerformanceHistory* can be related to *IfcSensor*, a subtype of *IfcFlowDistributionElement*, via the *IfcRelAssignsToControl* relationship. *IfcSensor* can be assigned to *IfcRelFlowControlElements*, which declares the *IfcEnergyConversionDevice* and can be located with *IfcObjectPlacement* to show the sensor location. Types of *IfcSensorTypeEnum* define the basic sensor types. Other sensor types that are not included in the IFC 4.2 schema (e.g. occupancy sensor) can be defined by users. Figure 5-21 shows the relationship.

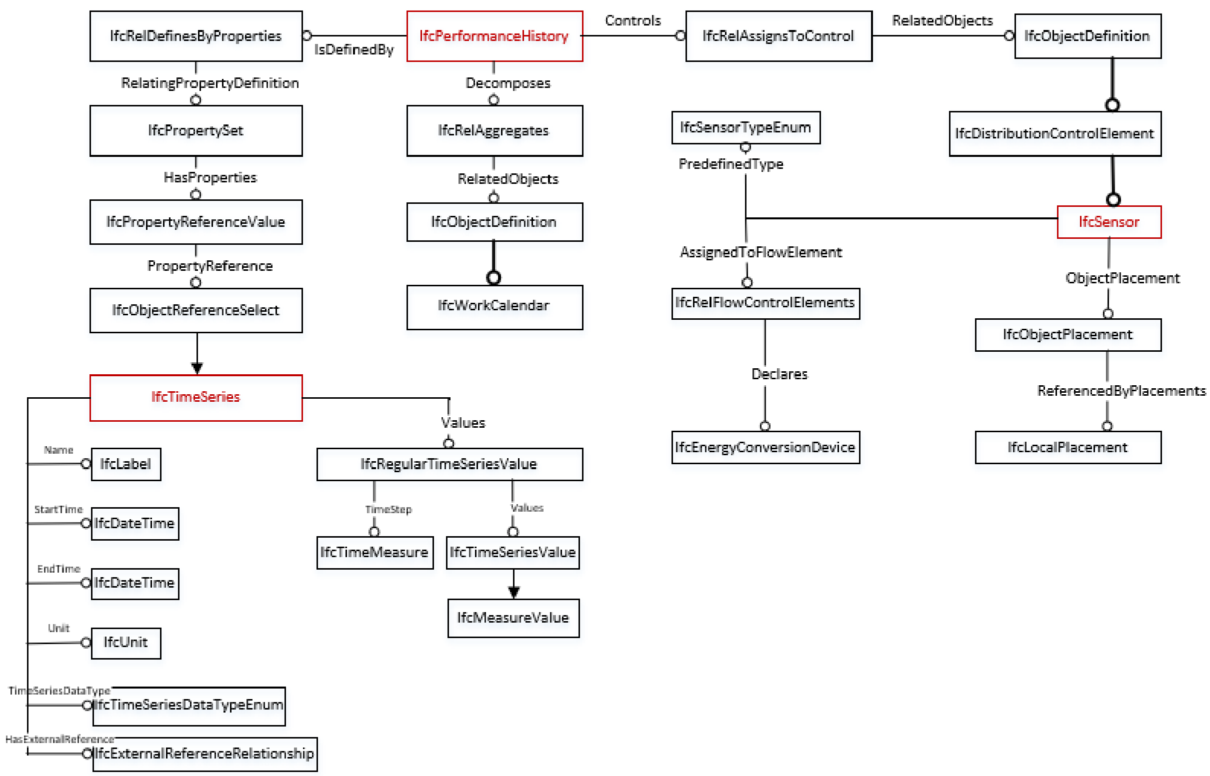


Figure 5-21 IfcPerformanceHistory Assigned with a Sensor

Table 5-22 Existing Properties of TimeSeries

Object	**Property Name**	**Property Data Type**	**Description**
IfcTimeSeries	Name	IfcLabel	A unique name for the time series.
	Description	IfcText	A text description of the data that the series represents.
	StartTime	IfcDateTime	The start time of a time series.
	EndTime	IfcDateTime	The end time of a time series.
	TimeSeriesDataType	IfcTimeSeriesDataTypeEnum	The time series data type.

	DataOrigin	IfcDataOriginEnum	The origin of a time series data.
	UserDefinedDataOrigin	IfcLabel	Value of the data origin if DataOrigin attribute is user-defined
	Unit	IfcUnit	The unit to be assigned to all values within the time series.
	HasExternalReference	IfcExternalReferenceRelationship @RelatedResourceObjects	Reference to an external reference
IfcIrregularTimeSeries	Values	IfcIrregularTimeSeriesValue	The collection of time series values.
IfcRegularTimeSeries	TimeStep	IfcTimeMeasure	A duration of time intervals between values.
	Values	IfcTimeSeriesValue	The collection of time series values.

Building operational information was classified as all sensor data with continuous values, command signals, and control setpoints (Dong, O'Neill et al. 2014). Therefore, the related schedules were classified as shown in Table 5-23 including *types of values*, *on/off* and *fractions*, where "*value schedule*" is a particular value assigned to a related timestamp. E.g. the setting point of temperature is 75 °F from 9-12 am, "*fraction schedule*" assign only the percentage to the related timestamp, e.g., the lighting load is 30% at 9 am. If the schedule only provides start/stop functions, it may be an *On/Off schedule*, with the value of 0 or 1. IFC fails to express these schedule types using *TimeSeries*, so *ScheduleDatatype* is suggested to be added in IFC. Based on Table 5-8, another two parameters that should be defined are model stage (as Baseline energy use, calibrated energy use and post-installation energy use) and *DataOrigin* (as design/actual). The data classification can use *DataOrigin* to be defined. The model stage can be assigned with the parameter "lifecycle" of *IfcPerformanceHistory* and defined as baseline energy use, calibrated energy use, and post-installation energy use. The summary of data was listed in Table 5-20.

Table 5-23 Schedule Data Type

Schedule Name	Lower Limit	Upper Limit	Example
Value	User Define	User Define	Occupancy Number, Temperate Setting
On/Off	0	1	Start/Stop of Fans, Two-position Dampers
Fraction	0	1	HVAC Equipment Schedule, Lighting Schedule

Table 5-24 Additional Parameters for Schedule

Object	Property Name	Data Type	Definition
IfcTimeSeries	DataOrigin	IfcDataOriginEnum	Actual Data and Simulated Data
IfcPerformanceHistory	Lifecyclephase	IfcLable	Baseline Energy Use/ Calibrated Energy Use/ Post-installation Energy Use
	Schedule Data Type	IfcTimeSeriesDataTypeEnum	Value, On/Off and Fraction

5.4.2.4 Performance Curve Representation

Calibration requires achieving the *default performance curves* and *user-definable part-load performance curves* (efficiency vs load or capacity and efficiency correction curves) for mechanical equipment. Furthermore, the performance should be identified as a manufacturer's manual performance curve and the measured performance curve.

Performance curves are polynomial curves that are used to describe the specific behavior of an HVAC component at varying conditions (e.g. pump curve is the function of flow and head). IFC 4.2 does not have a systematic description of this characteristic but has described several parameters such as *CapacityCurve* using *P_TABLEVALUE*. EnergyPlus provides 10 types of performance curves, including linear and quadlinear. Essentially, two variables are in an equation to expressing the performance curve. *IfcPropertyTableValue* can be used to express the two variables. The equation names can be defined in IFC, while the detailed simulation process is conducted by the energy model. Therefore, the following parameters are suggested in Table 5-25. The related properties can be assigned to other objects via the entity *IfcRelDefineByProperties*.

Table 5-25 Additional parameters for Performance Curve

Object	**Property Name**	**Data Type**	**Definition**
IfcPerformanceCurve	DataOrigin	IfcDataOriginEnum	Actual data and simulated data
	Lifecyclephase	IfcLable	Baseline Energy Use/ Calibrated Energy Use/ Post-installation Energy Use
	DefiningValuesNameA	IfcLable	
	DefiningValuesNameB	IfcLable	
	DefiningValuesNameC	IfcLable	
	DefinedValuesName	IfcLable	
	DefiningValuesA	IfcValue	List of defining values, which determine the defined values. This list shall have unique values only.
	DefiningValuesB		
	DefiningValuesC		
	DefinedValues	IfcValue	Defined values which are applicable for the scope as defined by the defining values.
	Expression	IfcText	
	DefiningUnitA	IfcUnit	
	DefiningUnitB	IfcUnit	
	DefiningUnitC	IfcUnit	
	DefinedUnit	IfcUnit	
	CurveInterpolation	IfcCurveInterpolationEnum	Interpolation of the curve between two defining and defined values that are provided. if not provided a linear interpolation is assumed. in under define, should add more types and define related coefficients

5.5 Data Module and Final Interface

5.5.1 Data Classification in Framework

Static Data are not included in this research; they are assumed to be saved in a BIM model as a design model and classified traditionally as geometry (GEO), material (MAT), and MEP. Section 5.2 and 5.4. classified the main dynamic/measured datasets for energy model calibration as the following main categories and saved in different modules.

5.5.1.1 Weather Data

Weather Data (WD) is the actual weather data obtained from the local station or site weather station that is updated in the database. Section 5.2.2.1 identified the typical parameters of weather data as *outdoor air temperature* (dry-bulb and wet-bulb), *humidity*, *wind speed*, *cloud cover*, *precipitation* and *solar radiation* at the site location. Although two types of weather data exist in the building energy simulation, defined as *actual weather data* (measured hourly) and *TMY*, the framework database only includes actual weather data because an energy simulation software can usually import TMY data automatically.

5.5.1.2 Energy Benchmark (Utilities)

The energy benchmark (EB) contains the utility consumption data. The energy model calibration uses the actual bills to refine the simulated results. Therefore, the types of energy benchmarks include *measured energy consumption* which is the actual measured energy consumption as EB(ME), *simulated or calibrated energy consumption* as EB(SE), which are the simulation results from the calibrated building energy model, and *baseline energy consumption* as EB(BE). The related timestep, energy type, and building/systems have been defined as the attributes according to Section 5.2.2.2. With new dynamic datasets and project goals, other relevant benchmarks such as designed energy saving targets or energy efficiency required in a sustainable building rating system can be added in the database when necessary.

5.5.1.3 Sensor Inventory

Sensor Inventory (SI) or monitored series data are based on datatype classified as a *value, on/off*, and *fraction*. All of these continuous time series are summarized as schedules with properties such as name and data origin. These properties are assigned to a zone or equipment according to Section 5.2.2.3. For example, a temperature sensor of chilled water should be identifiable by the room and equipment ID. With these attributes, users can identify the sensor location within the BIM model and update the real-time values over time with relative ease.

Common schedules include the occupancy schedule, lighting schedule, and HVAC schedules. Schedules saved in the database can be identified using data origin as the actual schedule and the defined schedule. In some cases, users define and insert different schedules into the database manually, then test various operational scenarios. For example, a user defines different HVAC schedules and runs them to select the optimized schedule with the assistance of the energy model.

5.5.1.4 Equipment Measured Data

Equipment Measured Data (EMD) saved in the database are the spot-measured data that are not related to time, such as pump efficiency. Usually, this type of data is saved in the BIM model as a design parameter of MEP, but the actual value can be also obtained by a BAS, which can be exported to the database or determined by the building manager, and then updated in BIM for management. Performance curves are saved in a two-column data format as a table. The detailed definition is according to Section 5.4.2.4.

5.5.2 Data Module and Interface

The framework consists of four modules which are (1) *the BIM module*, (2) *the Operation Database (OD) module*, (3) *the Energy Simulation (ES) module*, and (4) *the Analysis and Visualization (AV) module*. These modules describe and explain a conceptual model that illustrates the flow of information and the processes for data exchange amongst the BIM/BAS/BES. The framework can potentially achieve three major functions: 1) Summarize all energy-related information exchange processes supporting energy model calibration amongst BIM/BES/BAS; 2) Define the necessary quantitative and qualitative datasets and their relationships; 3) Develop real-time dynamic information, simulated information exchange, and an analysis of procedures based on BIM to support building energy performance management. The detailed information is as follows.

5.5.2.1 BIM Module

The BIM module is a critical module with a Graphic User Interface (GUI) in the framework, which is utilized as a database management tool in this study. The BIM module supports all related building model information. A typical BIM model serving for the design and construction phase includes a significant amount of static data which can be saved and exported for energy simulation. Some parameters must be added or updated to the model during the construction and operation phase to express the actual building situation; BIM is used to manage these design values and actual values.

The BIM model in this study is assumed to have all key static parameters for an energy model, but the actual model may miss several parameters that should be added manually. The static data sets in the BIM model are geometry (GEO), materials (MAT), and MEP data. The actual measured value of a parameter can be updated in the BIM model manually or from the BAS using the GUI for better performance tracking. The related dataset is equipment measured data (EMD).

For this research, the GUI based on the BIM module was developed to manage the flow of information exchange across the modules and allow for the ability to reuse and exchange building information in an interoperable environment throughout the information flow process. The detailed description of the GUI is discussed in Section 6.3.

5.5.2.2 Operational Database Module

The OD module is the basic module for supporting the whole data exchange process, and it connects with the BAS to save dynamic data in the database. The actual measured points as EMD run by a BAS or other equipment can also be saved in the database. Another function is that the database saves the actual energy consumption (e.g. monthly bill) and the simulated results from the ES module for comparison and calibration. The BIM module contains sufficient building information, but the actual operating data as time series are massive datasets, and it is not realistic to save them in a BIM model. Therefore, a database is necessary to store all datasets. The main data sets saved in the OD module include weather data (WD) and sensor inventory (SI) which are continuous data series with time stamp, and the equipment measured data (EMD) (e.g. an actual pump efficiency). These data can be referenced and updated in the BIM model, but it is suggested to have a backup in the database with tracking history. Another type of data is the energy benchmark (EB) data including the actual measured energy consumption (EB(ME)), simulated/calibrated energy consumption (EB(SE)), and baseline energy consumption (EB(BE)).

5.5.2.3 Energy Simulation Module

The ES module runs the energy model and retrieves simulated results instead of saving data in this framework. Static building information is extracted from the BIM module into a standardized format that can be interpreted by the Energy Simulation module using the GUI. The physical properties of the building, such as the heat transfer coefficient of the material, indoor temperature set-point, for example, can be inserted in the BIM module manually and then updated in the Energy Simulation module automatically. Dynamic data including SI, EMD, and actual WD are extracted from the OD module and inserted into the ES module to update the energy model.

The main function of the ES module is to export simulation results such as simulated energy consumption or the parameters of indoor thermal environment (e.g. indoor temperature). These simulated results, which are data of time series, are exported to the OD module for comparison and to optimize the design or operation status. The ES module includes a calibrated energy model, a design energy model, and baseline energy model. The related simulated results are exported to the database.

Another function of the ES module is to compare scenarios and save the settings. For example, different temperature setpoints are simulated to get the most efficient system setting; then the value of setpoint are sent back to the BIM module as the final design/operating scenario. If the case needs a baseline energy model, the baseline model set is saved in the BIM model, and the baseline energy consumption is saved in the database for reference.

5.5.2.4 Analysis and Visualization Module

The AV module allows for optimization of the design model and operational status. The Energy Simulation module exports the simulated results (e.g. the monthly electricity consumption) to the BIM module. The GUI works as a tool for comparing the simulated results with actual energy consumption from the OD module, analyzing them statically, and visualizing the curves in a new window for intuitive expression. The module provides a simple comparison function and three indices that represent how well a mathematical model describes the variability of the measured data from ASHRAE 14-2014. The indices are the coefficient of Variation of the Standard Deviation (CV [STD]), the Coefficient of Variation of the Root-Mean-Square Error (CV [RMSE] and the Normalized Mean Bias Error (NMBE). A calibrated energy model should have NMBE within ± 10% and CV(RMSE) within ± 30% when using hourly data, or 5% MBE and 15% CV(RMSE) for monthly data (ASHRAE 2014). The equations are as follows.

$\mathrm{y} = \text{depend variable of some functions of the independent variables}$

$\bar{\mathrm{y}} = \textit{arithmetric mean of the sample of n observations}$

$\hat{\mathrm{y}} = \textit{regression model's predict value of y}$

$$\mathrm{CV(STD)} = \frac{\sqrt{\frac{\sum(y_i - \bar{y})^2}{(n-1)}}}{\bar{y}}$$

$$\mathrm{CV(RMSE)} = \frac{\sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{(n-1)}}}{\bar{y}}$$

$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{(n-1) \times \bar{y}}$$

5.5.2.5 Interface

The GUI enables (1) the export of BIM data to the other modules, (2) the import of data into the BIM module from other modules, and (3) the selection of different scenarios and the execution of the user's orders for data analysis. The interface structure which shows the 4 modules and their relationships is presented in Figure 5-22, and a process map is shown in Figure 5-23.

The static data including GEO, MAT, and MEP data of the BIM module and the dynamic data including EMD, WD, and SI data of the OD module are extracted into the Energy Simulation module from the OD module. The EMD data can be updated into the BIM module to update the related parameter value, which is expressed by dotted lines.

The OD module exports measured energy consumption data (EB(ME)) while the Energy Simulation module exports simulated/baseline energy consumption (EB(SE/BE) to the AV module for analysis. EB(SE/BE) data are sent back to the OD module as a backup.

The parameters of different scenarios in the energy model are updated and saved in the BIM module or the OD module depending on the characters of the setting. For example, if different thermal parameters are compared among scenarios, the value of the static thermal parameter can be updated in the BIM module. If comparing different schedules, the schedule can be saved in the OD module for further use.

Because the static data exchange mechanism is well-developed, this research focusses on the dynamic data exchange process and only updates several static parameters to demonstrate functionality.

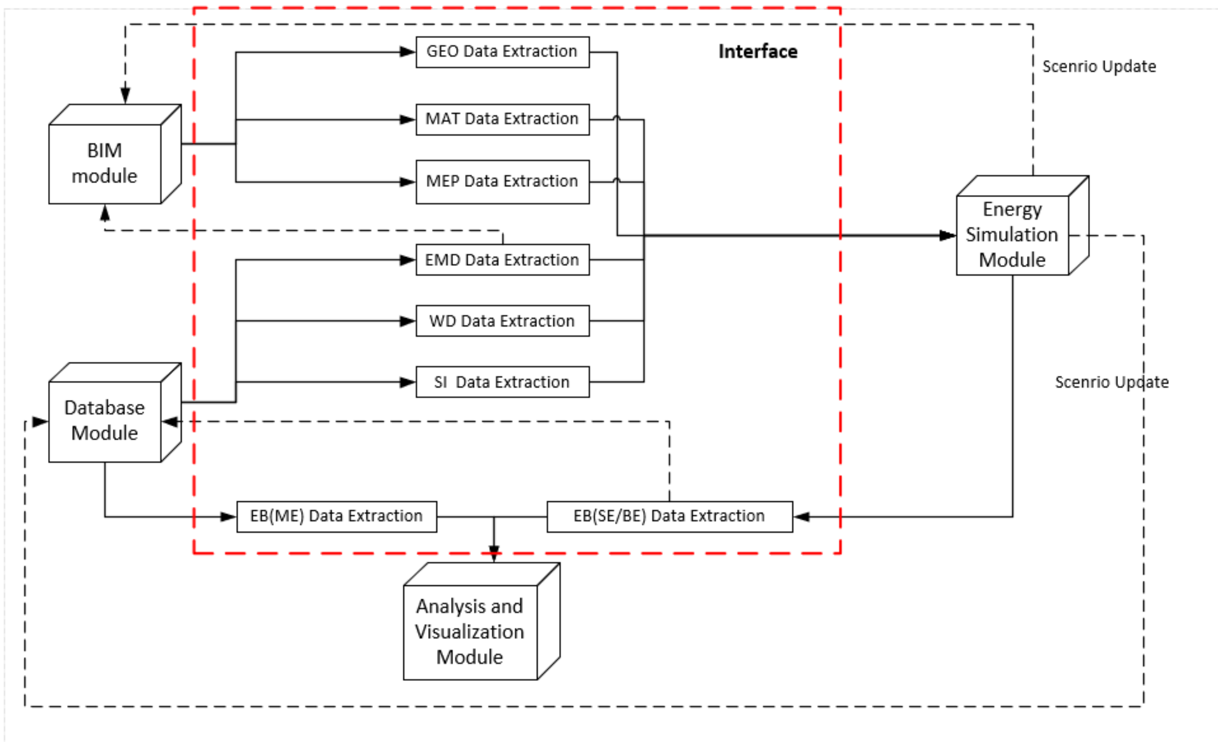


Figure 5-22 Overview of the Interface Structure

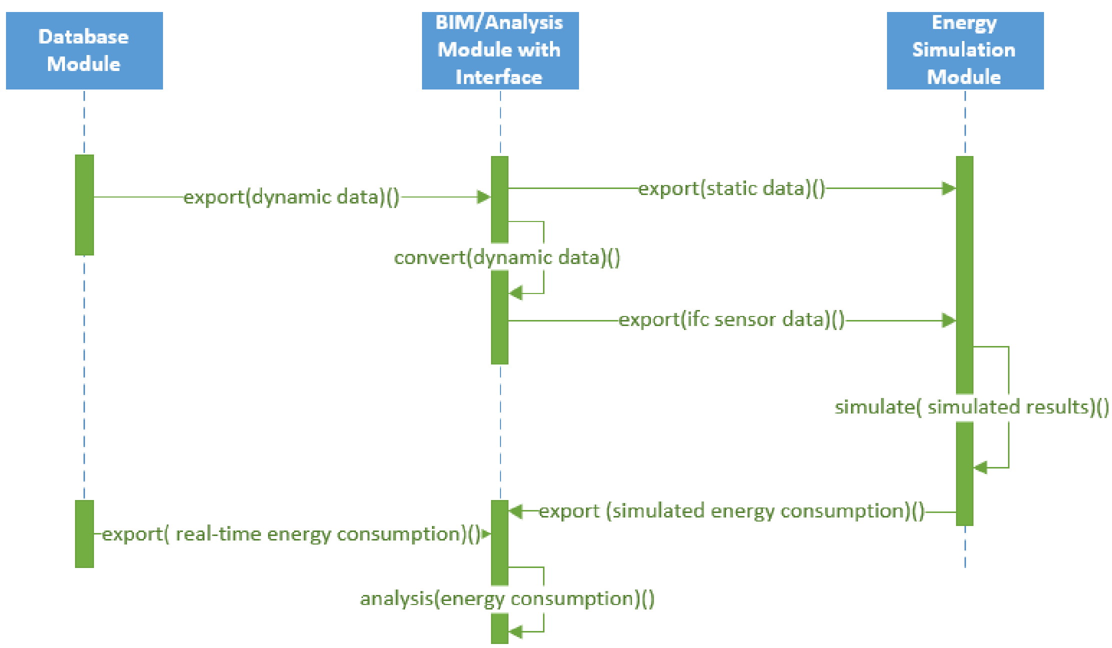


Figure 5-23 Process Map of the Interface Structure

The final framework is shown in Figure 5-24.

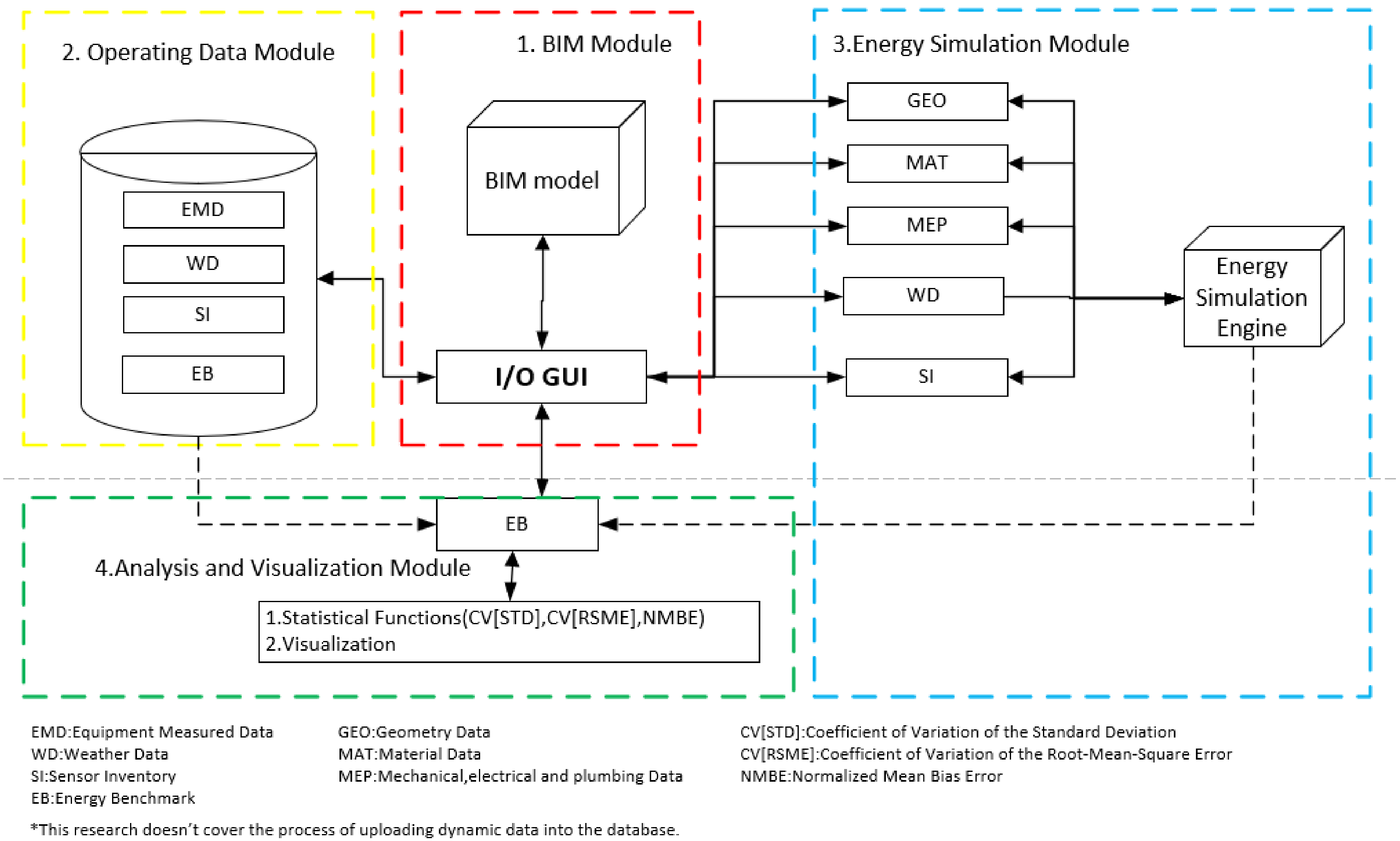


Figure 5-24 Framework (Detailed)

6 Prototyping

A prototype environment has been developed as a proof of this concept to implement the framework and serve as a tool to assess the framework's applicability in the form of a case study. The prototype allows to extract the dynamic information from the database, insert part of the data into the BIM model, and export part of the data into energy model input files. The following four steps were used to develop the prototype.

6.1 Tool selection

A MySQL database is used in the OD Module because of its applicability and achievability. The selected BIM tool was Autodesk Revit, and the interface has been developed using Dynamo with Python as the programming language. The Energy Simulation module was developed through OpenStudio, which offers an open-source software development kit (SDK) with a graphical interface, supports whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. It allows users to create geometries for an energy model and program their own "measures" to transform, query and run a model and its simulation results. OpenStudio measures are small programs or scripts that can create or make changes to an OpenStudio model (.osm). (Guglielmetti, Macumber et al. 2011).

The prototyped GUI collects information from the BIM module and the OD module, then develops the input files for OpenStudio to perform energy simulations, reads the simulated results and analyzes the data without manual intervention in the translation process after the BIM model and energy model have been created, and data have been entered into the BIM module and the OD module.

6.2 Parameters Selection

The exchanged parameters, including the static and dynamic data of a whole building energy simulation and calibration, have been defined in Section 5.2. The selected parameters in this prototype are listed as follows.

- Static Data from BIM

A BIM model contains comprehensive building information while an energy model only requires a sub-set of building information. The detailed critical static data for an energy model have been listed in Section 5.2.1. Although this research does not cover the data exchange methods of the static parameters between the BIM module and the ES module, the parameter of a fan overall efficiency was selected to conduct the demonstration of the data exchange process. The fan efficiency was exported to the BIM model from the database and then transferred to the energy model for setting as EMD data. The geometry and space data exchange between BIM and energy models are still a significant research challenge, but not the focus of this research.

- Dynamic Parameters from BAS

The dynamic data of the BAS contains weather data, sensor data, and energy consumption data. The selected parameters were the dry-bulb temperature of weather data as WD, indoor lighting schedule data as SI, which were exported to the energy model, and the final electricity consumption bills per month, which were shipped to BIM from the MySQL database and compared to the simulated results.

- Simulated Values List

Using static data from the Revit model and dynamic data from the OD module, the building energy model runs and obtains simulated values. For the energy model to be calibrated, simulated results were sent back to the GUI for data analysis. In this case, the simulated indoor air temperature was selected as the demonstration parameter.

6.3 Prototyping

The prototype was coded using Dynamo within Revit. The primary function of the GUI is to extract data, including static data, from the BIM module, dynamic data from the OD Module, and simulated results from the ES Module. Static, designed parameters with no time constraints were manually inputted directly into the Revit model. The dynamic data sets were classified as EMD, WD, SI and EB datasets as in Section 5.2.2, saved in the OD module, and corresponding functions were developed.

EMD data is the spot-measured data without a timestamp, which can be measured by a BAS and updated in the database, then the actual value could be extracted into the BIM module to replace the designed value. The related data include equipment efficiency and overall capacity. Reference IDs from the BIM module are used to select the related equipment and extract the value of parameters in the OD module. The other three types of datasets (WD, SI, and EB) include a series of values and timestamps that are used to define the time-scope within the database. Users could select the required data type and time-scope to extract target data, then insert them into the BIM and ES modules respectively. The exchanged data and tested functions are shown in Figure 6-1 using red solid lines.

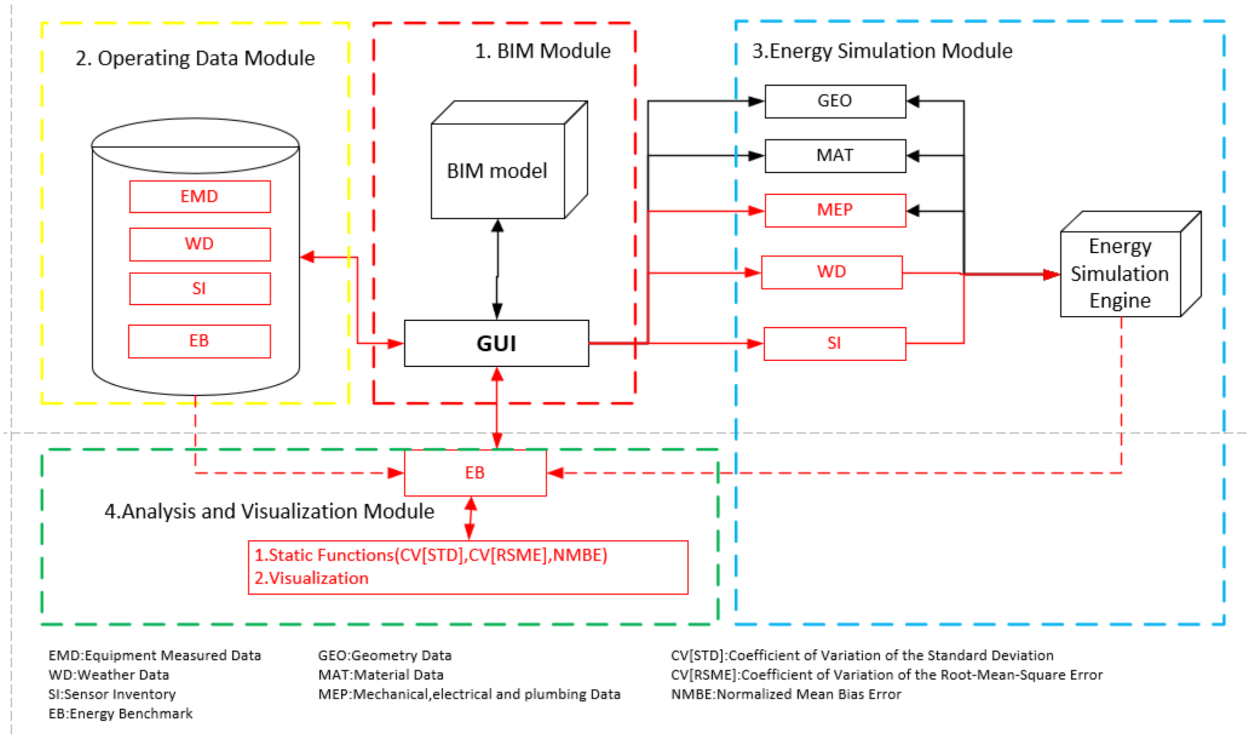


Figure 6-1 Tested Functions and Data

The following elements were developed and tested using the GUI. While this section explains them in summary, a detailed implementation is presented in Section 7.7.1.

1) A User Interface (UI) form has been developed to select the time period of dynamic data (e.g. weather data), and extract the required data from the database, insert them into the BIM module. The UI form is shown in Figure 6-2. In this UI form, the users can select the starting and ending year, month, date and hour of the time period for searching. Furthermore, the UI form is expected to select a list of building elements in BIM model as searching keywords (e.g. *FCU 13*), then return the element information by searching table names (e.g. *equipment_name)* and column names (e.g. *overall_efficiency*) in the database to choose the required dynamic data.

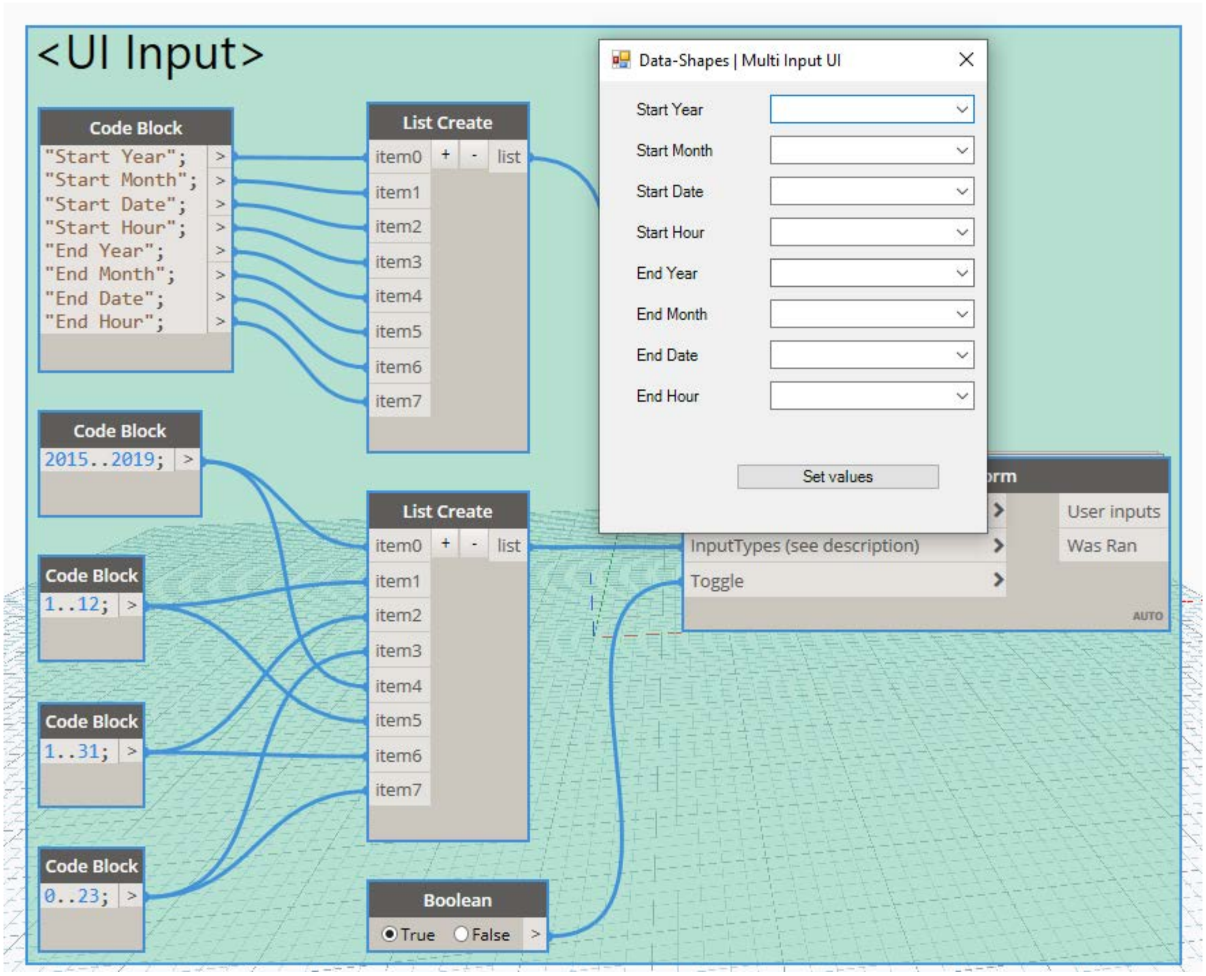


Figure 6-2 UI Input by Dynamo

2) Dynamic data exchange

The dynamic data represents the value changes over time, which includes the weather data (e.g. hourly dry-bulb temperature), schedule (e.g. measured illuminance) and energy benchmark data (e.g. monthly electricity consumption). All these dynamic data were saved in the MySQL database and used a unique id (e.g. zone id) to link the related objects of the BIM model, and the GUI developed by Dynamo connected the MySQL database, selected the time period and returned the required data. The extracted data such as a lighting schedule can be linked with the related object (e.g. a lighting sensor) of the BIM model and can be assigned with the used object in the simulation file. In this prototype, the schedule was exported as .csv file which could be used by OpenStudio. Figure 6-3 shows the function of getting weather data from the database. The GUI connected a MySQL database named *Operational 410 Database* and searched the item as

HourlyDryBulbTemperature in the table *weather_data_45240*, returned a list of 2856 data points and exported them as .csv file for OpenStudio use.

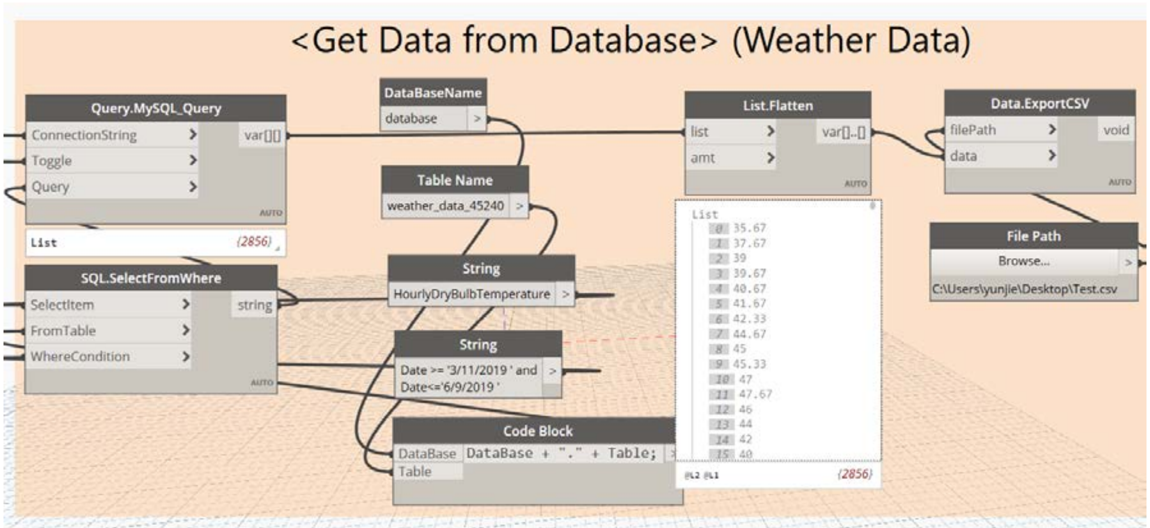


Figure 6-3 Get Weather Data from Database

3) EMD Exchange

The GUI updates the EMD (e.g. overall efficiency of an FCU) in the BIM using the equipment name and ID as a link. Figure 6-4 shows the GUI collects the *measured overall efficiency* of an FCU from the database, then update the value of overall efficiency with the related FCU in the BIM model. The value can be sent to a .idf file for EnergyPlus directly, or written into a measure which OpenStudio model uses.

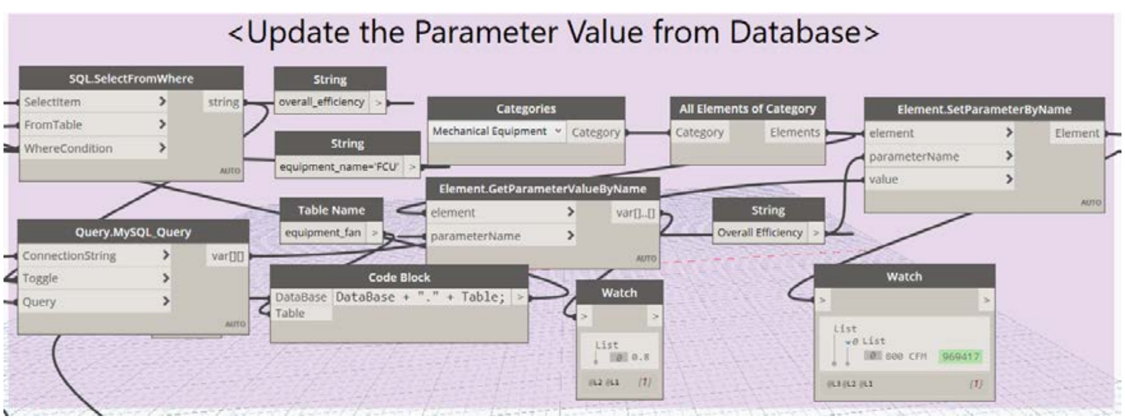


Figure 6-4 Get the Fan Efficiency from Database

4) Data Analysis

Basic statistical functions have been developed in Dynamo. Users can use the interface to compare the simulated data and measured data, then calculate the NMBE, CV(RMSE), and CV(STD). The measured data were extracted from the database and the simulated results were exported by the OpenStudio model, where the GUI read both data types. Figure 6-5 shows the calculation process of CV(STD) and R correlation coefficient between the measured data and simulated data.

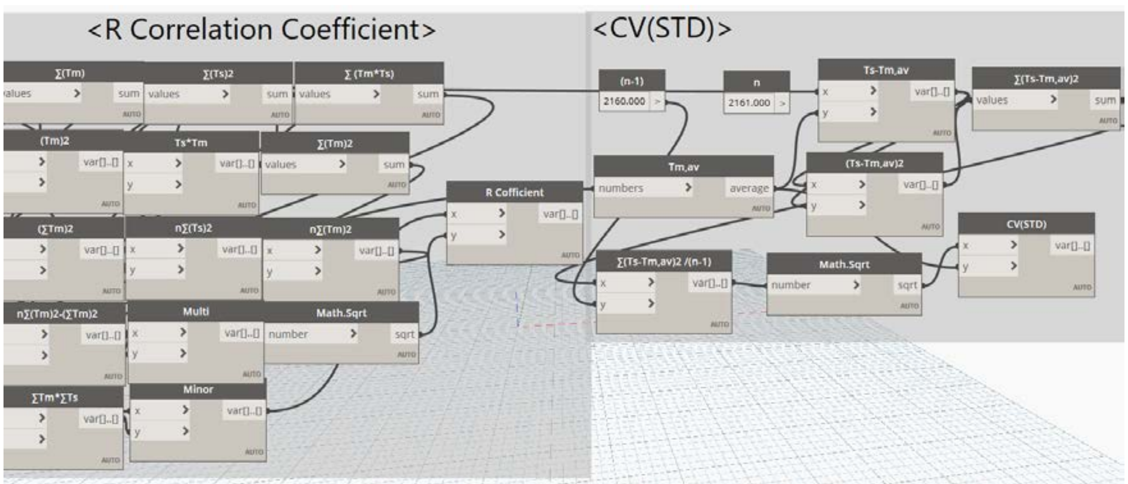


Figure 6-5 R Collection Coefficient between the Measured Data and Simulated data

5) Visualization

The actual test showed that the ability of visualizing huge hourly data sets, such as 8760 hours per year, is limited in Dynamo. Therefore, two groups were developed in Dynamo to visualize the data. The *Diagram Developing Group* can visualize the continuously measured hourly data value and simulated hourly data value for several days (e.g. one week) directly using dynamo. Another option is the GUI exports the huge dataset as XML file, then use MATLAB to read the file and draw the line chart, export the results as images, which a *Diagram Reading Group* in Dynamo can read the external resource directly. Figure 6-6 shows how to read a 3-month simulated/measured hourly results from an external resource using the *Diagram Reading Group* and how to compare a 5-days simulated/measured hourly results (120 points) using the *Diagram Developing Group*.

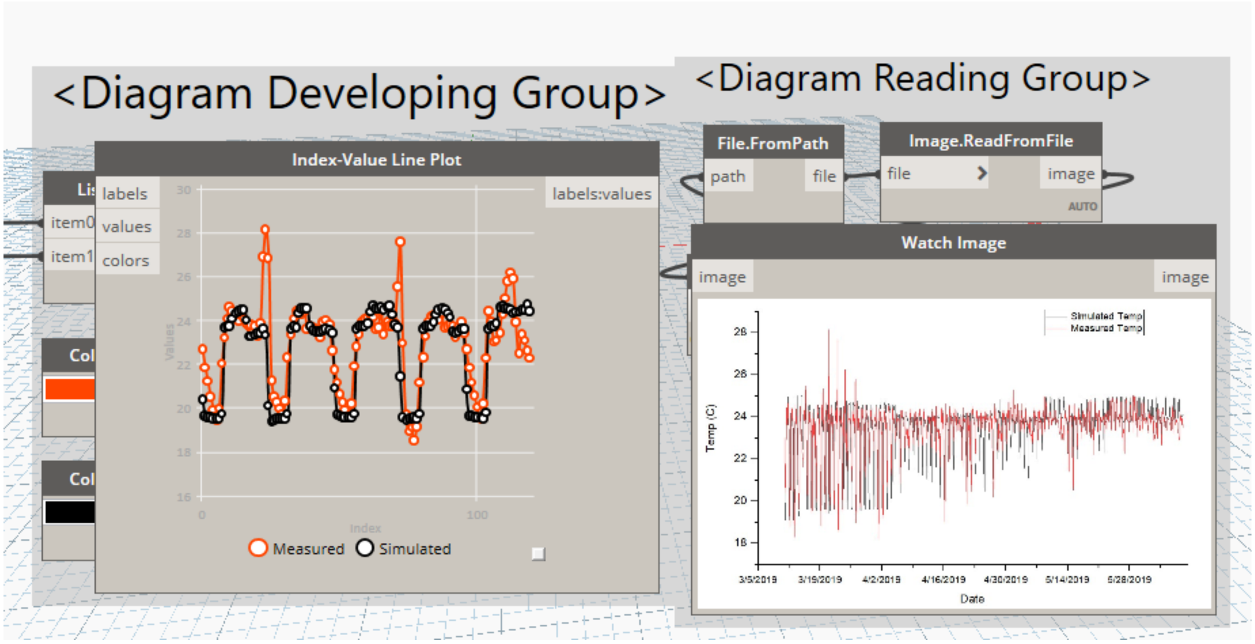


Figure 6-6 Data Visualization

6.4 Final Interface

The final interface is shown in Figure 6-7. Further coded modules can be added to implement the more developed and detailed functions, but the main categories of functions have been shown in the final interface.

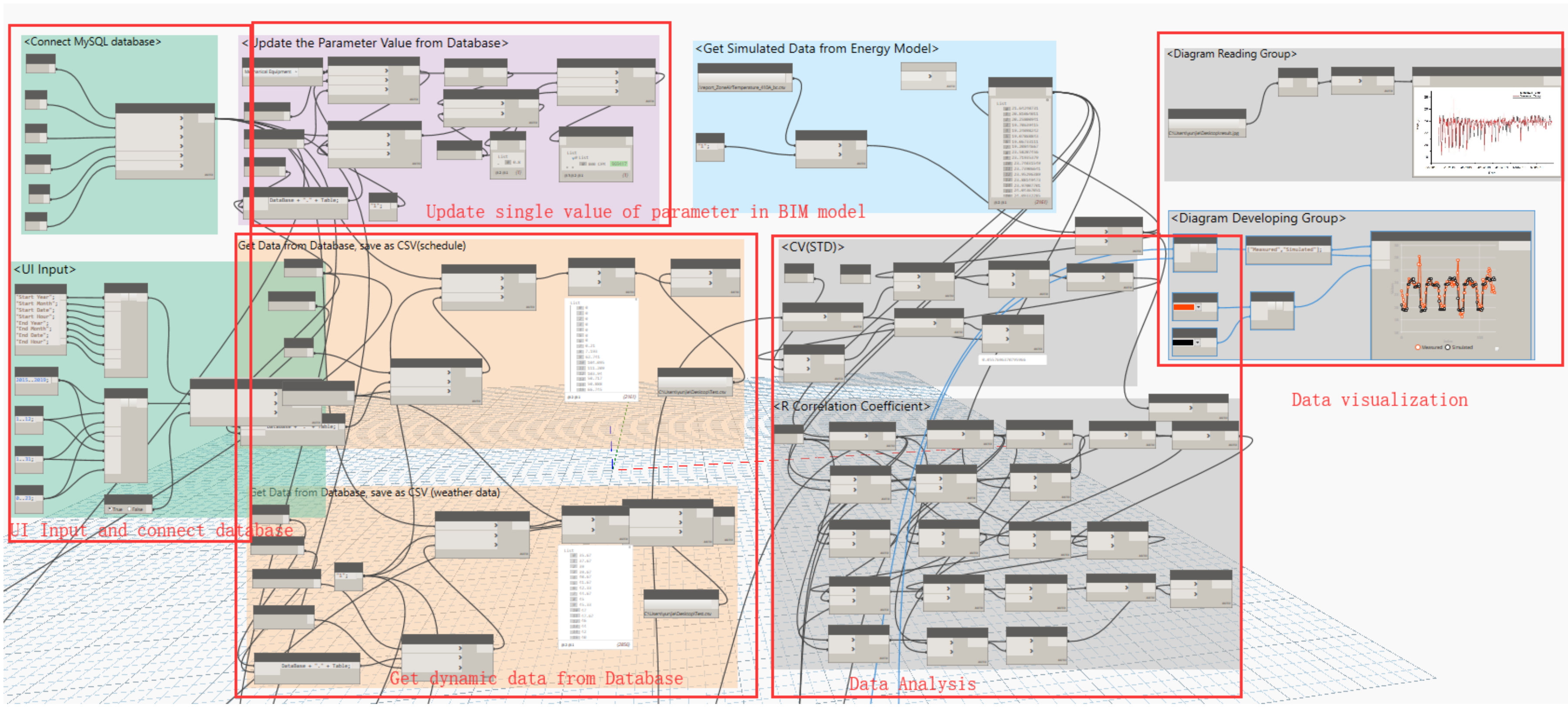


Figure 6-7 Final Interface

7 Case Study

This study uses a case study to implement the developed prototype to optimize building operational management for validation of the developed integration structure and processes. The selected case is an office zone within Bishop-Favrao Hall, a university building located at the Virginia Tech campus in Blacksburg, VA. The zone spans three faculty offices and is served by a single fan coil unit (FCU) for temperature control to meeting the environmental thermal loads of the spaces.

A MySQL database was created to store dynamic data, including actual weather data, indoor temperature, relative humidity, illuminance, occupancy, and supply air temperature. A BIM model and an energy model of the office zone were then created using Revit and OpenStudio. Without knowing the electricity consumption from sub-meters, this study uses actual indoor temperature as a calibration index and then applies different operation scenarios to compare energy consumption results and test the GUI functions. The case study is conducted to prove the concept that BIM technology can be used to manage real-time dynamic and simulated data efficiently, evaluate operational energy performance, and help optimize building energy management. The functions the case study is supposed to validate include 1) WD data exchange;2) SI data exchange;3) EMD data exchange 4) EB data exchange and comparison.

7.1 Model Description

The case study is comprised of a 645 sq. ft office suite labeled BFH410 in Bishop-Favrao Hall (BFH), a campus building in Blacksburg VA. The entire office suite is separated into three small offices labeled as rooms 410A, 410B, and 410 C. The floor plan and 3D model are shown in Figure 7-1. The detailed drawing can be found in Appendix D. The heating and cooling supply is provided by a single FCU (FCU-13) with a designed constant volume flow of 760 CFM. The heating and cooling sources for the unit are the hot and chilled water delivered from a central chiller and steam plant on campus. Outdoor air is provided by a Makeup Air Unit (MAU) with a designed 80 CFM for the offices. Each office has an individual supply diffuser and a return grill connecting back to the FCU, and a supply diffuser delivering fresh air from the MAU. A single thermostat in Office 410A controls the demand for the FCU and monitors the indoor temperature.

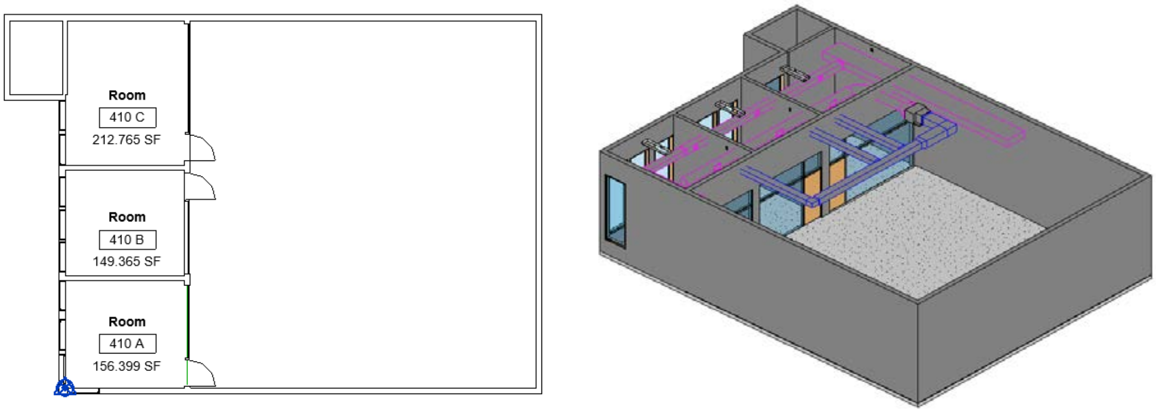


Figure 7-1 410 Office BIM Model

The energy model has been developed in OpenStudio and includes the office with envelope and mechanical systems. The geometry of the model is shown in Figure 7-2, and the detailed model setting is presented in Appendix E. The thermal properties of envelope materials were taken from design drawings, and are listed as follows.

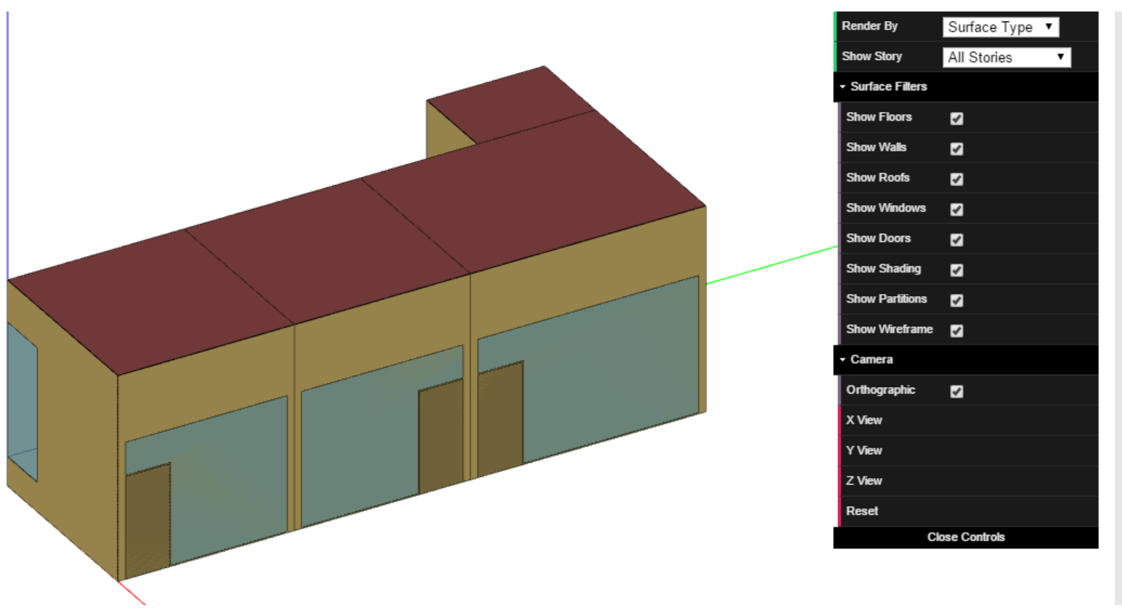


Figure 7-2 410 Office Energy Model

Table 7-1 Thermal Properties of Envelope

Envelope	**Material**	**Thickness (mm)**	**Conductivity W/M.K**	**Visible Transmittance**
Roof	Roof Membrane	10	0.16	/
	Rigid Insulation	75	0.049	/
	Metal Decking	13	45.006	/
Ceiling	Lightweight Concrete	100	0.53	/
	Acoustic Tile	20	0.06	/
Exterior Wall	Stone	130	1.9	/
	Rigid Insulation	50	0.049	/

	CMU	200	1.311	/
Interior Wall	GWB	16	0.16	/
	Sound Attenuation Blankets	90	0.0432	/
	Studs-16 in.OC	92	0.121467	/
Floor	Poured Concrete	250	0.44	/
Door	Plywood-Douglas Fir	45	0.12	/
Curtain Wall	Theoretical Glass	25	0.016	0.319
Interior Window	Indoor Glass	25	2.107	0.25

7.2 Exchanged Data Principle

The exchanged data in this case study include WD (dry bulb temperature), SI (lighting load), EMD data (fan efficiency) and EB (simulated energy consumption benchmark), all related properties are extracted from the identified dynamic data information in Section 5.2.2, and an object diagram is developed to present the properties with values in Figure 7-3.

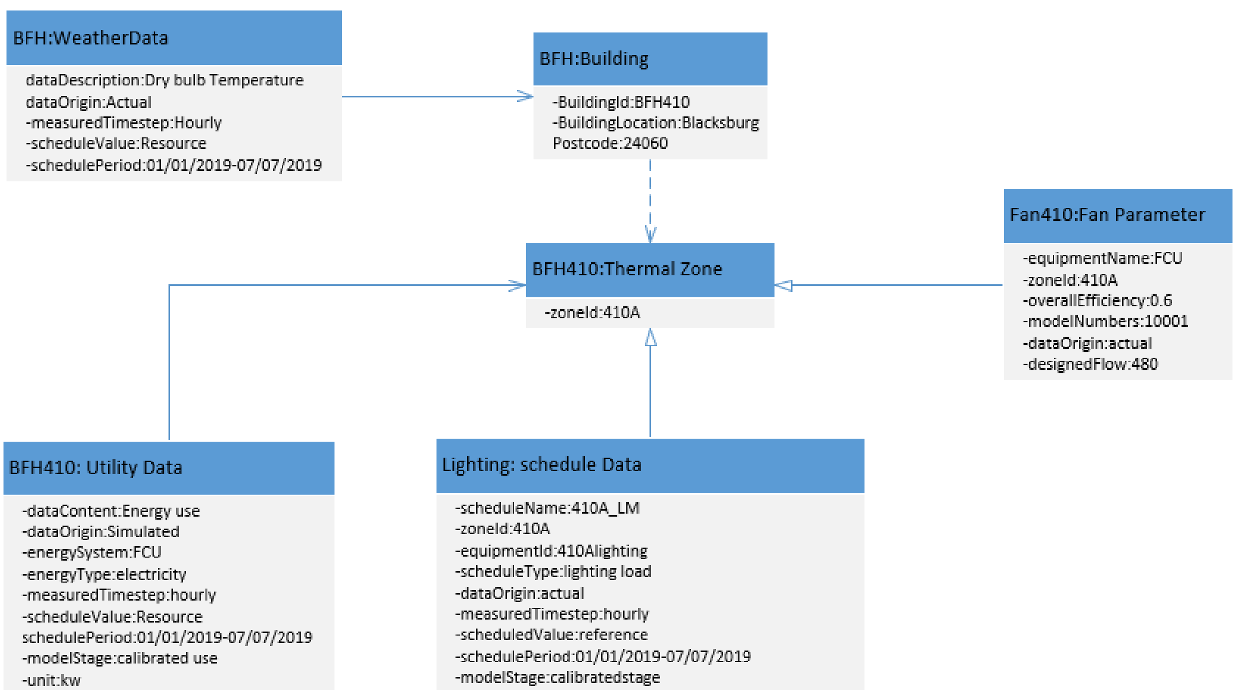


Figure 7-3 Object Diagram for 410 Office

WD is assigned to the BIM model using the *BuildingId* (BFH410) and *weather station ID*. The *Weather station ID* is the search keyword in a global weather database. The prototyped GUI can select the data description (dry bulb temperature) and pick a period to return the related schedule value.

The class diagram of *lighting loads* has several unique properties such as *item counts* and *power density*, but the exchange process focuses on the schedule itself so that a *general schedule* class can express the *lighting schedule*. Schedule value lists are saved in the database and linked to the BIM model using the zone id and equipment id. The GUI conducts the search, defines the time scope, and returns the value as a list.

The selected *EMD* data is the *overall fan efficiency*. This study does not measure the *overall fan efficiency* but sets it as 0.8 in the database; the BIM model uses the *equipment id* and *data origin* to identify and extracts the value of overall fan efficiency from the database and then writes the value as an object into the .osm file.

Energy consumption data with timestamps are stored in the database. The common entities being measured for energy consumption data are the *whole building energy consumption* data and *system/sub-system energy consumption* data. This BIM model uses the *building id* (BFH410) and *system type* (FCU) to export the *simulated electricity consumption* data from the energy model (.osm file), read the name, and the value as a list, then save it to the database for comparison. In this case, several simulations can be run based on different indoor temperature setting point profiles to compare all the simulated data and validate the functions. The measured and simulated data are then analyzed statistically and visualized using the GUI for fluent data management.

7.3 BIM Parameter

The related properties are defined in the BIM model as a reference to link and query the associated data. Detailed settings are explained here. The parameter of the *project name* defined as “BFH 410” under the project information panel and the *weather station id* is 45240. Figure 7-4 shows the weather station ID in Revit.

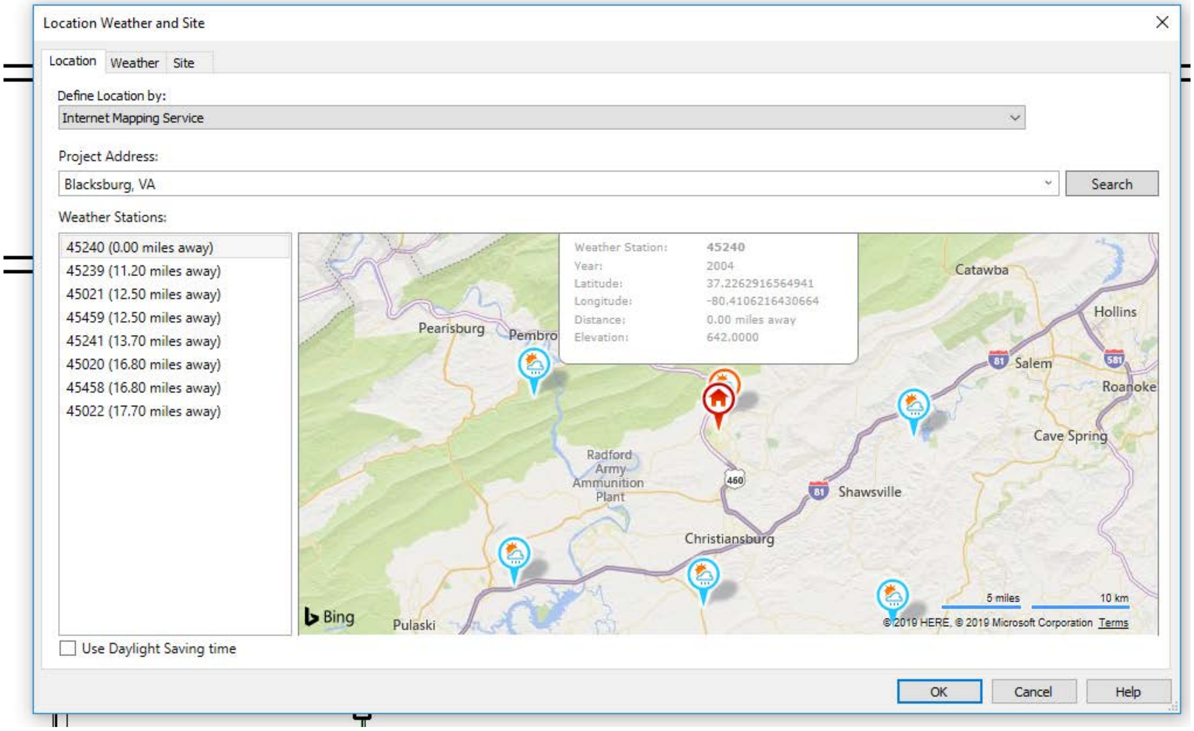


Figure 7-4 Project Location with Weather Station

The properties, include *equipmentID, equipmentName, modelNumbers* and *overall efficiency*, were created and defined for the FCU as shown in Figure 7-5.

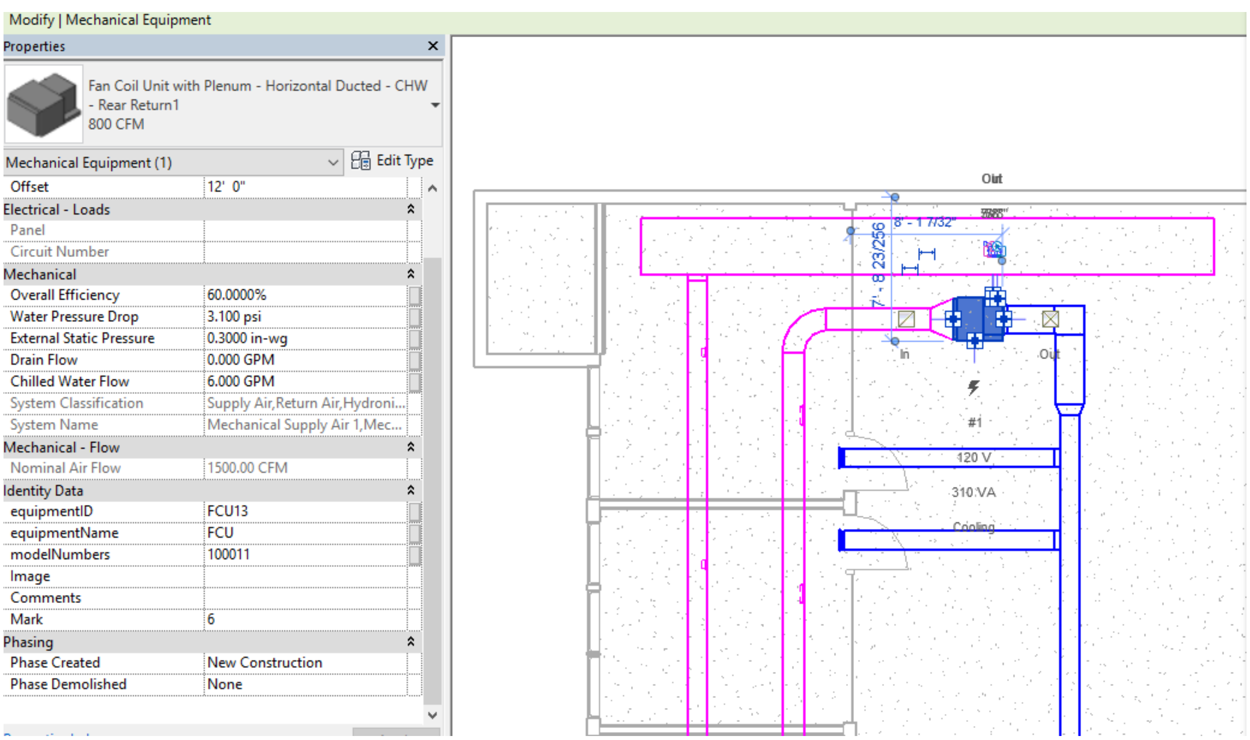


Figure 7-5 Defined Parameters for FCU

Four zones defined as zone *410A*, *410B*, *410C*, and *410D* were developed. Revit does not allow to add customized parameters to zones and spaces. Therefore, lighting sensors and occupancy sensors were created in the model to link the respective schedules. The properties, including *schedule name*, *schedule type*, *zone ID*, and *sensor ID*, were defined as shown in Figure 7-6.

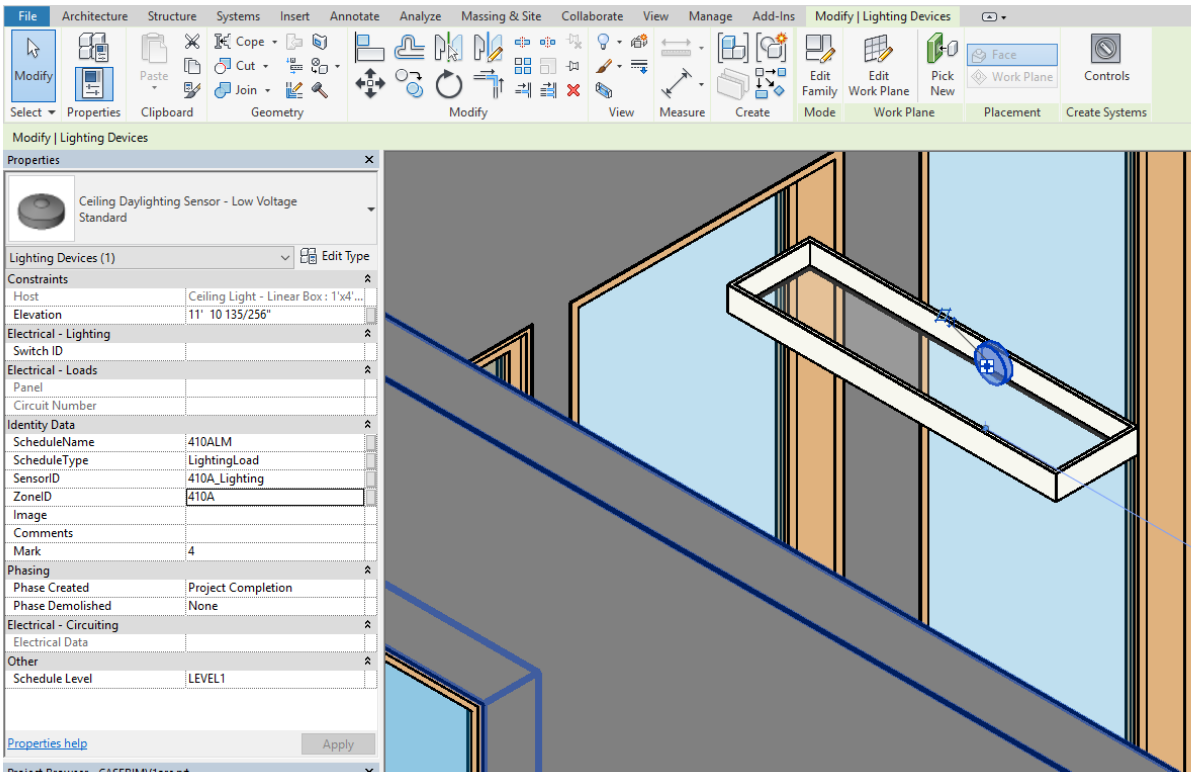


Figure 7-6 Defined Parameters for Sensor

The parameters of *utility data* were assigned to an electrical meter, including *energy system*, *schedule name*, and *data origin*, which are shown in Figure 7-7. The proposed GUI uses these values to link the schedule.

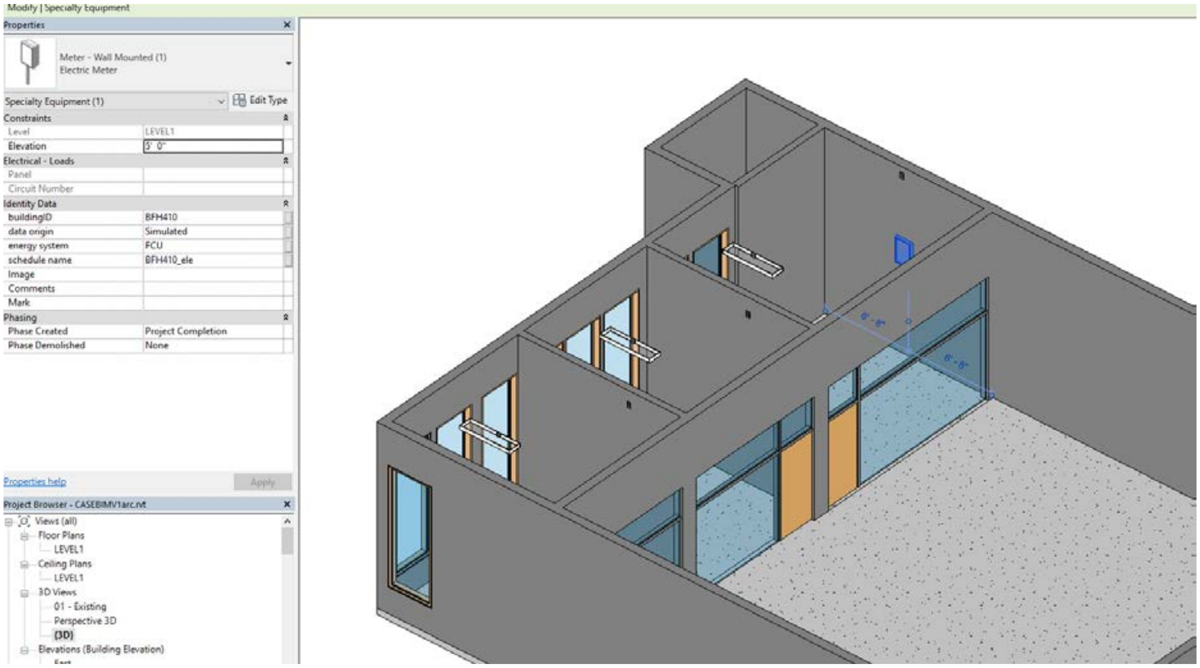


Figure 7-7 Defined Parameters for Utility Data

7.4 Dynamic Database Data Collection

7.4.1 Weather Data

The actual weather data was pulled from Climate Data Online (CDO) developed by the National Oceanic and Atmospheric Administration (NOAA). CDO provides free access to NOAA's National Climatic Data Center’s archive of global historical weather and climate data with station history information. A dataset named Local Climatological Data was used to collect the necessary weather data. Figure 7-8 shows the weather station name as Blacksburg Virginia Tech Airport, VA, US. and the Network ID as 53881.

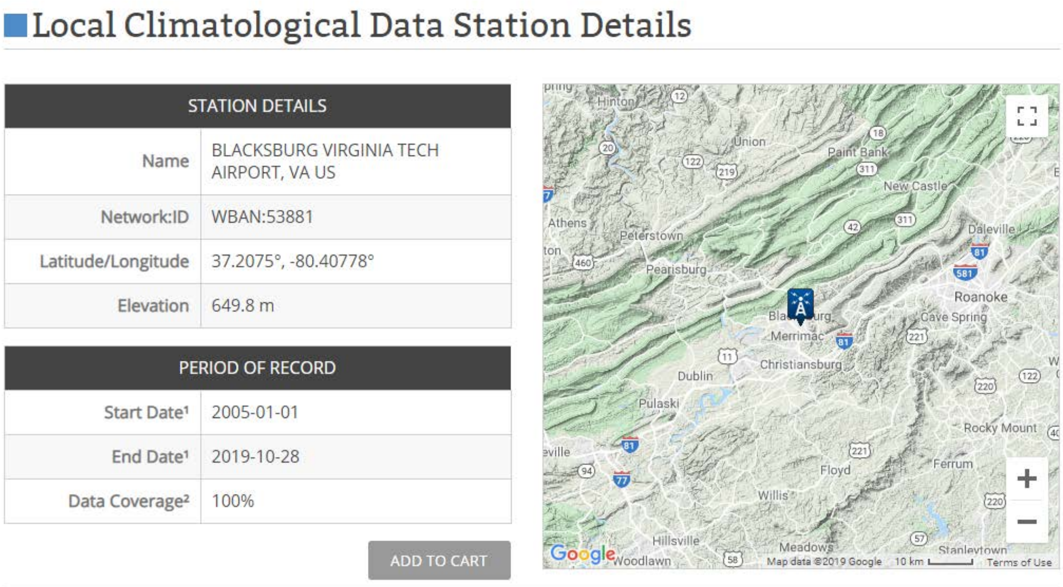


Figure 7-8 Local Weather Data Station

The collected historical weather data were the hourly output of the local weather data from 01/01/2019 to 07/06/2019. Downloaded data was .csv format, and the actual measured points were three points per hour (15 min, 35min, 55 min). Consequently, missing increment values were cleaned and hourly averaged values are calculated. Several measured data points are missing as zero. The missing values were estimated manually to reduce the error rate. The final datasets examples are shown in Figure 7-9, and the detailed datasets are listed in Appendix F. *Dew Point Temperature*, *dry bulb temperature*, *hourly relative humidity*, *hourly wet bulb temperature*, and *wind speed* were used as the actual weather data for energy simulation.

	A(Y)	B(Y)	C(Y)	D(Y)	E(Y)	F(Y)	G(Y)
Long Name	Date	HourlyDewPointTemperatur	HourlyDryBulbTemperature	HourlyRelativeHumidity	HourlyStationPressure	HourlyWetBulbTemperature	HourlyWindSpeed
Units							
Comments		reduce every 3 points with Av	reduce every 3 points with Avera	reduce every 3 points with Averag	reduce every 3 points with Average	reduce every 3 points with Avera	reduce every 3 points with Av
F(x)=							
1	1/1/2019 00:00:00	56.00	61.33	83.67	27.71	58.00	8.00
2	1/1/2019 01:00:00	56.00	59.67	86.33	27.73	57.67	5.67
3	1/1/2019 02:00:00	56.33	59.33	89.33	27.74	57.67	6.67
4	1/1/2019 03:00:00	57.00	58.00	98.33	27.73	57.00	5.67
5	1/1/2019 04:00:00	54.33	56.67	92.00	27.74	55.33	9.00
6	1/1/2019 05:00:00	49.00	54.67	81.67	27.76	51.67	9.67
7	1/1/2019 06:00:00	47.00	54.00	77.33	27.80	50.00	8.00
8	1/1/2019 07:00:00	47.00	54.00	77.00	27.82	50.00	8.00
9	1/1/2019 08:00:00	47.00	54.00	78.33	27.84	50.00	6.00
10	1/1/2019 09:00:00	47.00	54.00	76.33	27.86	50.00	5.00
11	1/1/2019 10:00:00	46.33	55.00	74.00	27.88	50.33	7.33
12	1/1/2019 11:00:00	44.67	54.33	69.33	27.88	49.33	13.00
13	1/1/2019 12:00:00	44.67	54.00	69.67	27.86	49.00	11.33
14	1/1/2019 13:00:00	44.00	54.00	68.00	27.85	49.00	12.33
15	1/1/2019 14:00:00	42.67	54.00	66.00	27.87	48.00	11.67
16	1/1/2019 15:00:00	42.33	54.00	66.00	27.88	48.00	8.33
17	1/1/2019 16:00:00	42.33	53.33	67.33	27.90	48.00	7.33
18	1/1/2019 17:00:00	41.33	51.33	69.00	27.92	46.33	7.33
19	1/1/2019 18:00:00	41.00	49.33	72.33	27.94	45.33	7.00
20	1/1/2019 19:00:00	40.67	47.67	77.00	27.96	44.67	7.33
21	1/1/2019 20:00:00	40.00	45.33	81.67	27.96	43.00	2.00
22	1/1/2019 21:00:00	39.67	44.67	83.00	27.96	42.67	3.67
23	1/1/2019 22:00:00	40.00	44.67	84.00	27.96	42.67	6.33
24	1/1/2019 23:00:00	39.67	44.00	85.67	27.95	42.00	3.00
25	1/2/2019 00:00:00	39.67	42.67	89.00	27.96	41.33	1.67
26	1/2/2019 01:00:00	39.33	40.67	96.00	27.98	40.33	0.00
27	1/2/2019 02:00:00	39.33	40.33	97.33	27.99	40.33	0.00
28	1/2/2019 03:00:00	38.67	39.00	99.00	27.98	39.00	0.00
29	1/2/2019 04:00:00	38.00	38.00	99.33	27.97	38.00	0.00
30	1/2/2019 05:00:00	38.67	38.67	100.00	27.97	38.67	0.00
31	1/2/2019 06:00:00	39.33	39.33	99.67	27.99	39.33	0.00

Figure 7-9 Weather Data (Example)

7.4.2 BAS Data

The BAS data were collected from the Campus Building Automation System of Virginia Tech, which is a Siemens Apogee system and controls all significant campus facilities. BFH has its own branch of Campus building automation system, which makes collecting the running data of FCU 13 possible. The collected data points include the *supply air temperature of FCU*, *day/night model*, *on/off fan working status*, *setting temperature* and *actual room temperature*, and various *valves and switch positions*. The *outdoor air temperature*, *setting room temperature*, *humidity*, and *temperature of fresh supply air* for the building were recorded as reference. The detailed data points are shown in Table 7-2.

Hourly data points were collected from 02/21/2019 to 07/08/2019, but several weekly data points were missing. The final used data set runs from 03/11/2019 to 06/09/2019, and covers about three months. The information was reviewed, and several missing data points were bridged with adjacent averages to reduce the error rate. The detailed data reviewing process is documented in Appendix F, and an example is presented in Figure 7-10.

Table 7-2 Measured Data Point

Number	**Name**	**Comment**
Point_1:	BFRM410A.FC:AUX TEMP	FCU Supply Air Temperature
Point_2:	BFRM410A.FC:DAY.NGT	Day/Night Mode
Point_3:	BFRM410A.FC:FAN	Fan On/Off Mode
Point_4:	BFRM410A.FC:HEAT.COOL	Heat/Cool Mode
Point_5:	BFRM410A.FC:RM STPT DIAL	Room Setting Temperature
Point_6:	BFRM410A.FC:ROOM TEMP	Room Thermostat Temperature
Point_7:	BFRM410A.FC:VLV 1 COMD	Valve position
Point_8:	BFRM410A.FC:VLV 1 POS	
Point_9:	BFRM410A.FC:VLV 2 COMD	
Point_10:	BFRM410A.FC:VLV 2 POS	Valve position
Point_11:	BFRM410A.FC:WALL SWITCH	Wall Switch On/Off
Point_12:	BF01OAT	Outdoor Air Temperature (BFH)
Point_13:	BF01SAH	Supply Air Humidity
Point_14:	BF01SAS	Supply Air Setting Temperature
Point_15:	BF01SAT	Supply Air Temperature

	A(Y)	B(Y)	C(Y)	D(Y)	E(Y)	F(Y)	G(Y)	H(Y)	I(Y)	J(Y)	K(Y)	L(Y)	M(Y)	N(Y)	O(Y)	P(Y)
Long Name	Time	FC AUX TEMP	Day/Night	ON/OFF	Heat/Cool	Room Setti	Room Tem	VLV1 COM	VLV1 POS	VLV2 COM	VLV2 POS	WALL SWI	OAT	SAH	SAS	SAT
Units																
Comments																
F(x)=																
1	3/11/2019 00:00:00	74.29167	NIGHT	OFF	HEAT	75.25	74	0	0	0	0	NO	63.26	23.62	67	70.19
2	3/11/2019 01:00:00	71.95833	NIGHT	OFF	HEAT	75.25	73.75	0	0	0	0	NO	63.2	23.53	67	70.27
3	3/11/2019 02:00:00	70.91667	NIGHT	OFF	HEAT	75.25	73.75	0	0	0	0	NO	63.13	23.37	67	70.42
4	3/11/2019 03:00:00	69.875	NIGHT	OFF	HEAT	75.25	73.5	0	0	0	0	NO	63.03	23.26	67	70.62
5	3/11/2019 04:00:00	69.5	NIGHT	OFF	HEAT	75.25	73.5	0	0	0	0	NO	62.88	23.21	67	70.71
6	3/11/2019 05:00:00	69.04167	NIGHT	OFF	HEAT	75.25	73.5	0	0	0	0	NO	62.74	23.24	67	70.79
7	3/11/2019 06:00:00	69	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.61	23.13	67	70.96
8	3/11/2019 07:00:00	81.125	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.42	22.99	67	71.07
9	3/11/2019 08:00:00	84.75	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.35	23.12	67	71.09
10	3/11/2019 09:00:00	85.33333	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.23	23.11	67	71.08
11	3/11/2019 10:00:00	83.70833	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.05	23.04	67	71.19
12	3/11/2019 11:00:00	80.41667	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	61.86	22.99	67	71.26
13	3/11/2019 12:00:00	75.33333	NIGHT	OFF	HEAT	75.25	73	0	0	0	0	NO	61.8	22.97	67	71.27
14	3/11/2019 13:00:00	74.08333	NIGHT	OFF	HEAT	75.25	73	0	0	0	0	NO	61.58	22.81	67	71.42
15	3/11/2019 14:00:00	77.16667	NIGHT	OFF	HEAT	75.25	73	0	0	0	0	NO	61.41	22.79	67	71.47
16	3/11/2019 15:00:00	79.45833	NIGHT	OFF	HEAT	75.25	72.75	0	0	0	0.4	NO	61.27	22.49	67	71.5
17	3/11/2019 16:00:00	78.08333	NIGHT	OFF	HEAT	75.25	72.75	0	0	0	0.4	NO	61.12	22.39	67	71.57
18	3/11/2019 17:00:00	75.33333	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.93	22.44	67	71.66
19	3/11/2019 18:00:00	74.66667	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.78	22.47	67	71.65
20	3/11/2019 19:00:00	74.04167	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.68	22.81	67	71.57
21	3/11/2019 20:00:00	73.16667	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.53	22.19	67	71.64
22	3/11/2019 21:00:00	72.125	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.39	22.51	67	71.66
23	3/11/2019 22:00:00	71.33333	NIGHT	OFF	HEAT	75.25	72.25	0	0	0	0	NO	60.24	22.79	67	71.58
24	3/11/2019 23:00:00	70.95833	NIGHT	OFF	HEAT	75.25	72.25	0	0	0	0	NO	60.07	22.8	67	71.59
25	3/12/2019 00:00:00	70.04167	NIGHT	OFF	HEAT	75.25	72.25	0	0	0	0	NO	59.92	22.83	67	71.66
26	3/12/2019 01:00:00	70	NIGHT	OFF	HEAT	75.25	72	0	0	0	0	NO	59.85	22.83	67	71.62
27	3/12/2019 02:00:00	70	NIGHT	OFF	HEAT	75.25	72	0	0	0	0	NO	59.64	22.66	67	71.64

Figure 7-10 BAS Data Example

7.4.3 Measured Data

Besides the collected data from BAS, additional sensors were installed to achieve a more detailed indoor environment information, these spot-measured data were monitored and collected through a wireless HOBO ZW sensor network system. HOBOware Pro was used for launching, reading out, and plotting data from data loggers and sensors to monitor the indoor environmental condition of the three office spaces. Onset Computer Corporation develops data logger and weather station products. In our case, temperature, illuminance[1], occupancy[2], humidity, and airflow sensors were selected to measure the actual indoor environmental conditions. The monitor interface of HOBOnode Manager is presented in Figure 7-11, which shows the real-time monitoring of sensor data.

[1] Lighting sensor are not directly provided or supported by the ZW logger series and were developed and calibrated in house.
[2] Occupancy sensors were developed in-house with a binary information signal obtained from an IR sensor in 10-min intervals.

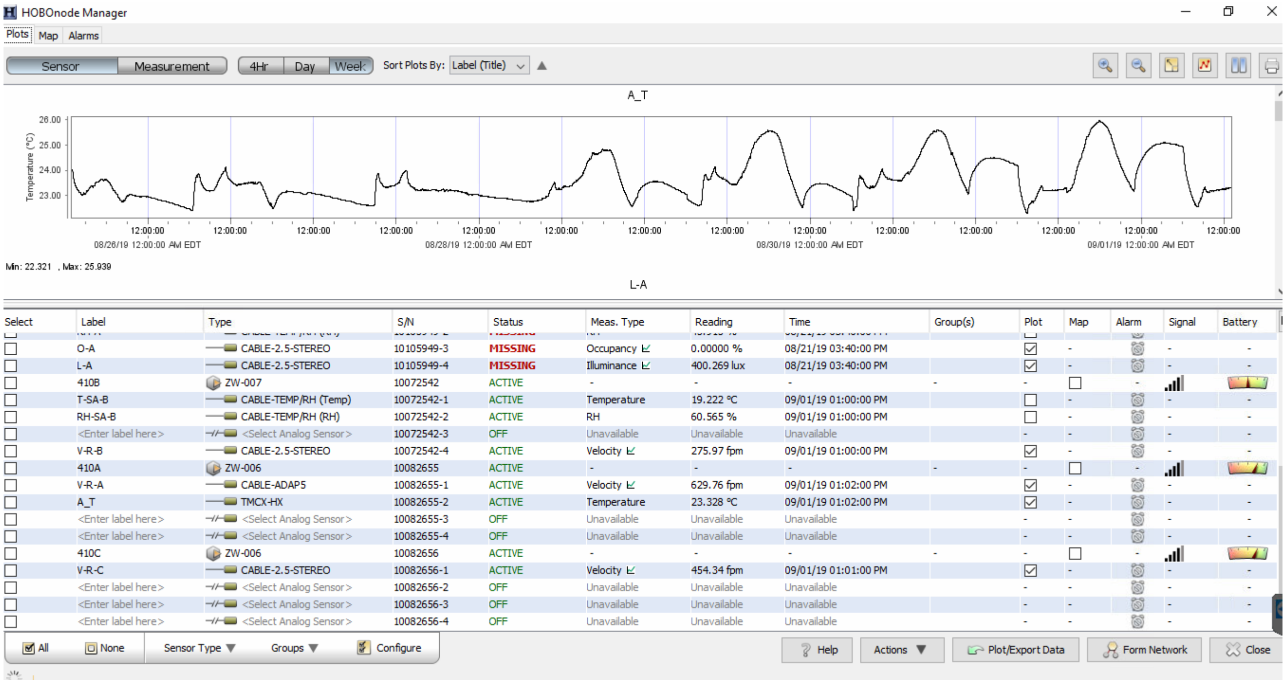


Figure 7-11 HOBO Data Manager (Screenshot)

The *indoor air temperature*, *humidity*, *illuminance*, *occupancy*, and *supply air CFM* were measured for all three offices from 3/11/2019 to 7/6/2019. The lighting sensor, occupancy sensor, room temperature and humidity sensors were attached under the lighting fixture, at about 6.7 feet height. The air flowrate sensors were attached to the return air grill in every office, and the supply air temperature and humidity of FCU were measured by a temperature and humidity sensor attached to the supply grill located in 410 B office. Figure 7-12 shows all the sensor locations and types. Data were cleaned and reviewed to ensure there were no missing data. The original data measurement and process is included in Appendix F, and a data example is shown in Figure 7-13.

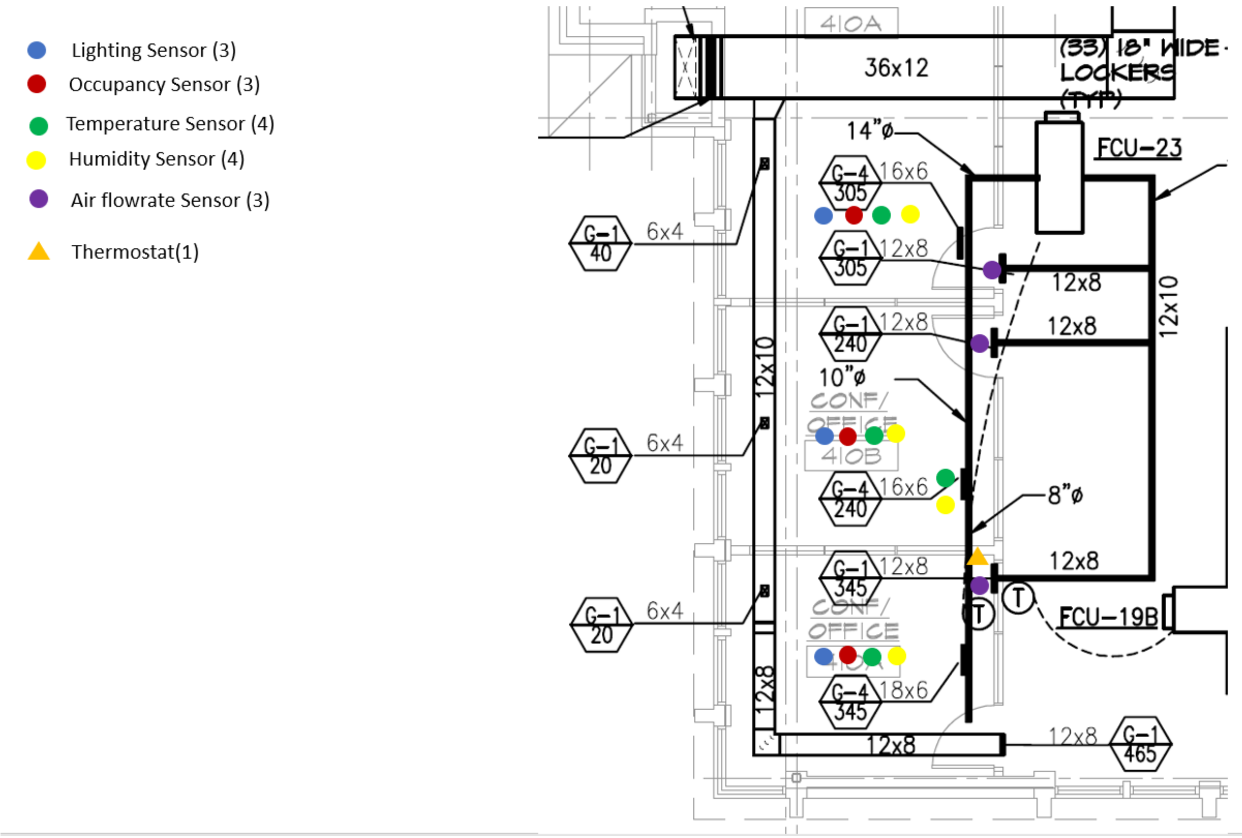


Figure 7-12 Sensor Protocol

	A(Y)	B(Y)	C(Y)	D(Y)	E(Y)	F(Y)	G(Y)	H(Y)	I(Y)	J(Y)	K(Y)	L(Y)	M(Y)	N(Y)	O(Y)	P(Y)	Q(Y)	R(Y)
Long Name	Time	410B	410 B	410B	410B	410C	410C	410C	410C	410A	410A	410A	410A	Supply Air	Supply Air	410B	410A	410C
Units																		
Comments		Temp	RH	illuminanc	Occ	Temp	RH	Occ	illuminan	Temp	RH	Occ	illuminan	Temp	RH	Velocity	Velocity	Velocity
F(x)=																		
1	3/11/2019 00:00:00	22.571	25.421	0.000	0.000	22.457	25.867	0.033	0.000	22.044	27.023	0.000	0.000	22.796	24.922	9.310	19.680	9.910
2	3/11/2019 01:00:00	22.151	25.908	0.000	0.000	22.174	26.148	0.000	0.000	21.499	27.746	0.000	0.000	22.241	25.718	9.310	19.680	9.910
3	3/11/2019 02:00:00	21.766	26.264	0.000	0.000	21.939	26.351	0.000	0.000	21.035	28.286	0.000	0.000	21.825	26.190	9.310	19.680	9.910
4	3/11/2019 03:00:00	21.406	26.566	0.000	0.000	21.722	26.520	0.000	0.000	20.610	28.742	0.000	0.000	21.461	26.643	9.310	19.827	9.910
5	3/11/2019 04:00:00	21.089	26.814	0.000	0.000	21.532	26.689	0.017	0.000	20.222	29.190	0.000	0.000	21.134	27.064	9.310	20.172	9.910
6	3/11/2019 05:00:00	20.779	27.036	0.000	0.000	21.354	26.861	0.000	0.000	19.845	29.594	0.000	0.000	20.832	27.245	9.310	22.632	10.065
7	3/11/2019 06:00:00	20.492	27.262	0.000	0.000	21.197	27.027	0.000	0.000	19.492	29.993	0.017	0.000	20.558	27.361	9.310	25.912	10.080
8	3/11/2019 07:00:00	22.665	24.879	0.567	0.000	22.181	25.620	0.017	0.055	21.031	28.020	0.017	0.210	27.186	19.718	434.338	831.054	581.513
9	3/11/2019 08:00:00	23.889	23.280	10.611	0.000	23.000	24.445	0.000	2.789	22.595	25.824	0.000	7.193	29.107	17.449	442.135	843.272	589.840
10	3/11/2019 09:00:00	24.391	22.533	42.648	0.000	23.439	23.681	0.000	13.678	23.445	24.561	0.017	62.741	29.401	17.016	444.116	847.289	587.669
11	3/11/2019 10:00:00	24.376	22.020	58.447	0.000	23.556	23.009	0.067	20.050	24.139	23.158	0.000	104.095	28.541	17.408	445.921	848.258	587.504
12	3/11/2019 11:00:00	23.934	21.540	65.832	0.000	23.339	22.175	0.000	28.726	24.232	22.018	0.000	111.209	26.774	18.322	443.140	851.259	582.834
13	3/11/2019 12:00:00	23.060	21.651	97.208	0.000	22.734	21.837	0.000	41.409	23.625	21.751	0.000	103.940	23.959	20.585	440.500	849.538	580.388
14	3/11/2019 13:00:00	22.659	21.280	64.944	0.000	22.330	21.401	0.000	23.227	22.827	21.608	0.000	50.717	23.199	20.696	439.994	849.504	580.703
15	3/11/2019 14:00:00	23.142	20.045	65.851	0.000	22.625	20.460	0.000	24.158	22.997	20.732	0.000	50.888	25.117	18.026	441.995	848.306	583.285
16	3/11/2019 15:00:00	23.697	18.805	89.151	0.000	23.001	19.496	0.000	31.103	23.555	19.537	0.000	66.745	26.201	16.362	442.555	847.503	579.321
17	3/11/2019 16:00:00	24.109	17.938	337.528	0.000	23.273	18.700	0.017	115.997	24.162	18.492	0.000	228.537	25.524	16.536	442.505	848.733	581.114
18	3/11/2019 17:00:00	24.625	17.887	157.138	0.000	23.194	18.936	0.000	47.235	24.779	18.579	0.000	94.962	24.368	17.961	16.497	33.964	19.534
19	3/11/2019 18:00:00	24.083	19.473	182.321	0.000	22.760	20.093	0.000	24.850	24.147	20.384	0.000	71.973	24.073	19.312	9.310	19.680	9.910
20	3/11/2019 19:00:00	23.814	20.349	50.327	0.000	22.513	20.737	0.000	5.646	23.833	21.338	0.000	19.174	23.813	20.168	9.310	19.680	9.910
21	3/11/2019 20:00:00	23.080	21.393	0.000	0.000	22.148	21.365	0.000	0.000	23.004	22.437	0.000	0.000	23.251	20.794	9.310	19.680	9.910
22	3/11/2019 21:00:00	22.519	22.074	0.000	0.000	21.835	21.888	0.000	0.000	22.326	23.161	0.000	0.000	22.644	21.501	9.310	19.680	9.910
23	3/11/2019 22:00:00	22.031	22.596	0.000	0.000	21.554	22.298	0.000	0.000	21.757	23.660	0.000	0.000	22.096	22.128	9.310	19.680	9.910
24	3/11/2019 23:00:00	21.600	22.982	0.000	0.000	21.307	22.650	0.000	0.000	21.244	24.097	0.000	0.000	21.656	22.669	9.310	19.680	9.910
25	3/12/2019 00:00:00	21.200	23.283	0.000	0.000	21.079	22.973	0.000	0.000	20.754	24.547	0.000	0.000	21.278	23.106	9.310	22.369	9.910
26	3/12/2019 01:00:00	20.823	23.559	0.000	0.000	20.857	23.318	0.017	0.000	20.283	24.962	0.000	0.000	20.918	23.560	9.310	34.899	10.000
27	3/12/2019 02:00:00	20.459	23.801	0.000	0.000	20.637	23.677	0.017	0.000	19.823	25.406	0.000	0.000	20.569	23.951	9.310	42.444	12.459
28	3/12/2019 03:00:00	20.095	24.042	0.000	0.000	20.432	23.931	0.000	0.000	19.357	25.852	0.000	0.000	20.223	24.274	9.310	49.840	14.261
29	3/12/2019 04:00:00	19.729	24.275	0.000	0.000	20.236	24.155	0.033	0.000	18.891	26.297	0.000	0.000	19.878	24.463	9.310	53.545	15.311
30	3/12/2019 05:00:00	19.364	24.464	0.000	0.000	20.047	24.390	0.000	0.000	18.431	26.724	0.000	0.000	19.536	24.682	9.310	61.795	19.550
31	3/12/2019 06:00:00	19.042	24.696	0.000	0.000	19.872	24.747	0.000	0.000	18.013	27.261	0.000	0.000	19.246	25.114	9.310	72.782	27.081
32	3/12/2019 07:00:00	20.868	22.602	2.435	0.000	20.615	23.336	0.000	0.732	19.236	25.599	0.000	1.550	25.557	18.329	324.202	637.222	446.094
33	3/12/2019 08:00:00	23.287	19.277	21.982	0.000	22.110	20.648	0.000	7.077	21.864	21.625	0.000	17.993	30.310	12.974	441.730	845.075	592.113
34	3/12/2019 09:00:00	24.039	18.189	42.767	0.000	22.822	19.551	0.000	12.915	23.001	20.038	0.000	52.014	30.810	12.331	444.166	847.979	593.634
35	3/12/2019 10:00:00	24.465	17.322	64.725	0.000	23.142	18.734	0.000	22.442	23.810	18.722	0.000	83.896	30.602	12.115	444.027	846.568	593.478
36	3/12/2019 11:00:00	24.680	16.666	88.956	0.000	23.382	17.967	0.000	36.813	24.339	17.706	0.000	105.667	30.001	12.161	444.456	844.568	591.031

Figure 7-13 Collected HOBO Data (Example)

7.5 Database Design

MySQL workbench was used to design the database system. The monitored values of sensors with time stamps were saved in table *sensor_id*, then other parameters of a sensor were saved in table *sensor_list*. One piece of equipment may contain several sensors and several performance curves, and connect to one zone. One building includes several zones, but only connects one weather data station using *weather_station_id*. The Entity Relationship Diagram is presented in Figure 7-14.

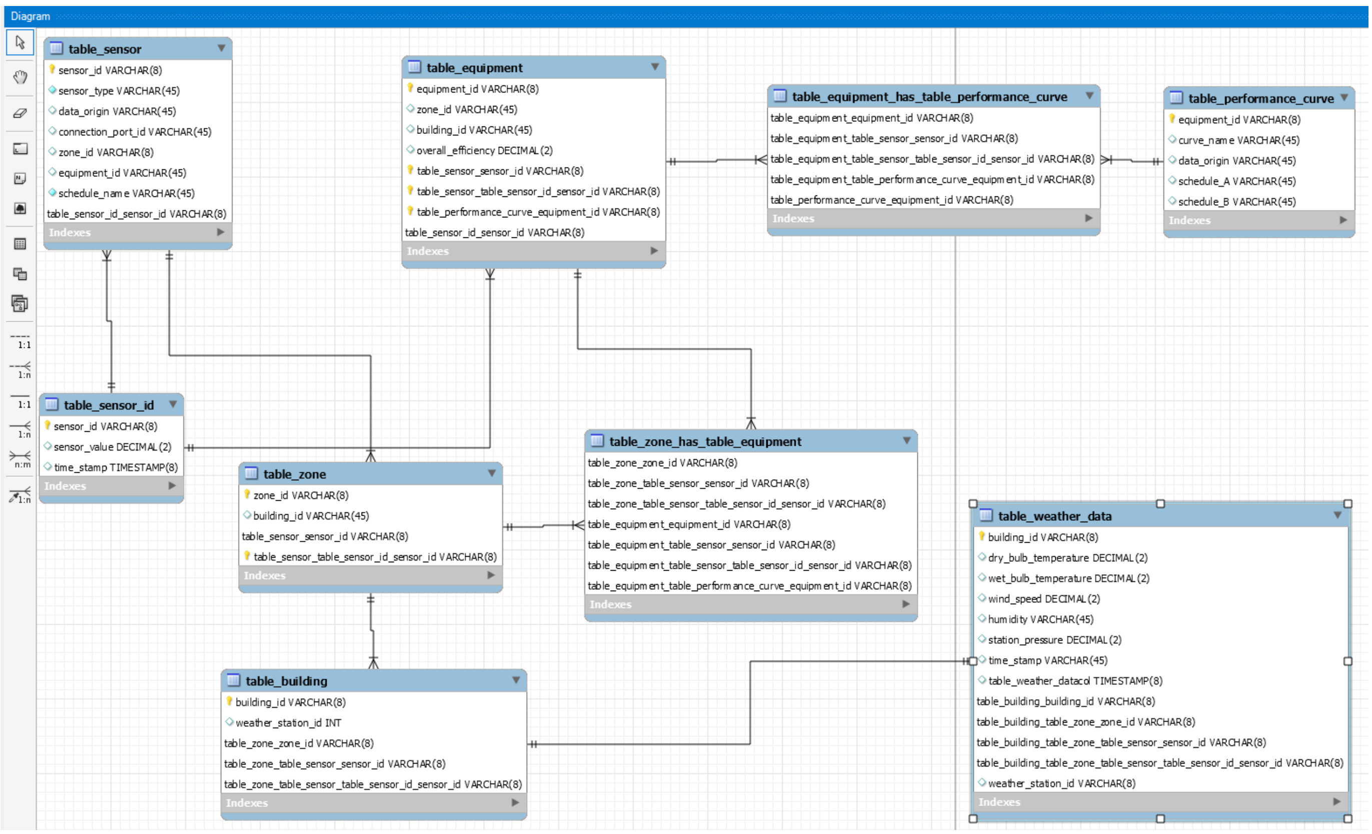


Figure 7-14 ERR Diagram

To implement the data exchange of 1) weather data (dry bulb temperature); 2) schedules (lighting load); 3) EMD data (overall fan efficiency); 4) EB (simulated energy consumption benchmark), the following tables were created in MySQL database. The related weather data table was named *weather_data_45120*. The value of lighting sensor data and related time stamp were saved in table *lighting_sensor_id*; other parameters defining a sensor were stored in table *sensor_list*. Other sensors including occupancy sensors, airflow rate sensor and indoor temperature sensors were created as individual tables. Overall fan efficiency was saved in the *equipment_fan* table. The whole schema example is presented in Figure 7-15.

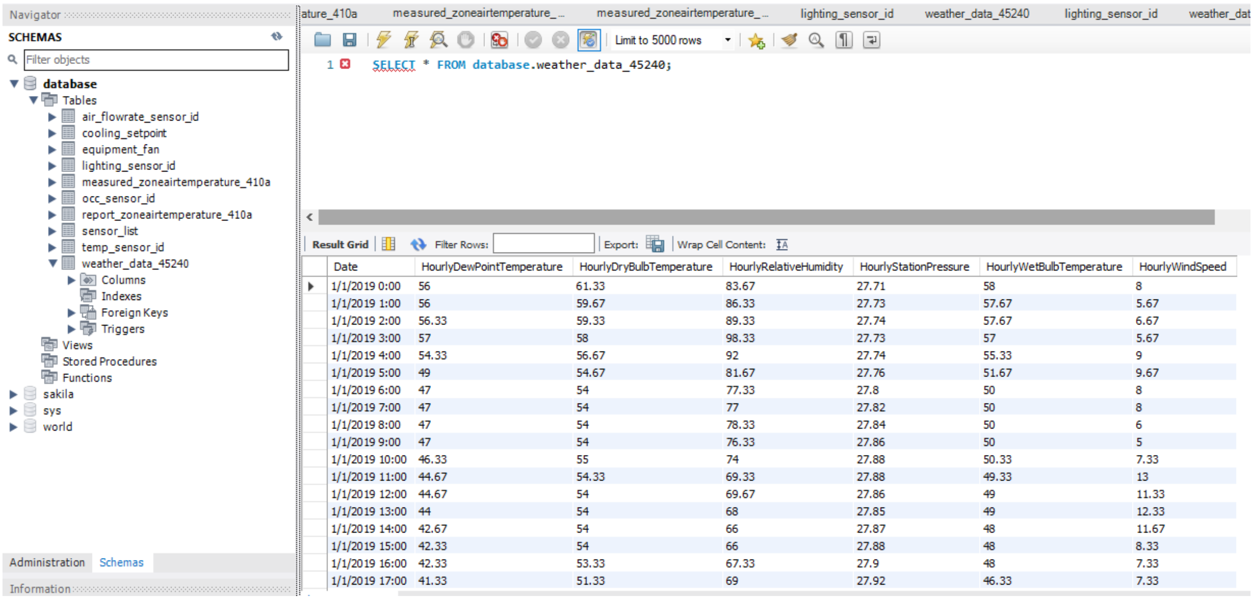


Figure 7-15 Database Schema and Table Example

7.6 Energy Model Setting

The study utilized OpenStudio as an energy simulation platform. OpenStudio uses EnergyPlus as the building energy modeling (BEM) engine but presents the EnergyPlus model as a structural, dynamic and object-oriented data model with an application programming interface (API). Furthermore, EnergyPlus allows the user to edit the EnergyPlus Input Files (IDF) using text editors or a developed IDF editor. However, OpenStudio does not recommend manipulating the .osm file directly because OpenStudio requires every new object with a new unique UUID, and OpenStudio does not import all EnergyPlus objects, especially not all available HVAC systems.

Thus, an alternative solution is to apply an OpenStudio measure, which is a program or script that can create or make changes to existing OSM files using the OpenStudio API. Measures are written in Ruby but can be edited by a text editor or a proper IDE such as RubyMine. One benefit of the application of measures is that the simulated results could be saved with the different applied measures for tracking. This study required functions of measures: 1) can input schedules into an energy model; 2) can update a special parameter value (*fan overall efficiency*) in an energy model; 3) can read weather data as .epw file using a unique location.

Zone ID, *schedule name*, and *equipment name* were used as the reference to link these data. The simulated results were exported for the proposed GUI reading, linking the used building ID and energy type. The detailed energy model and calibration process data are attached in Appendix G.

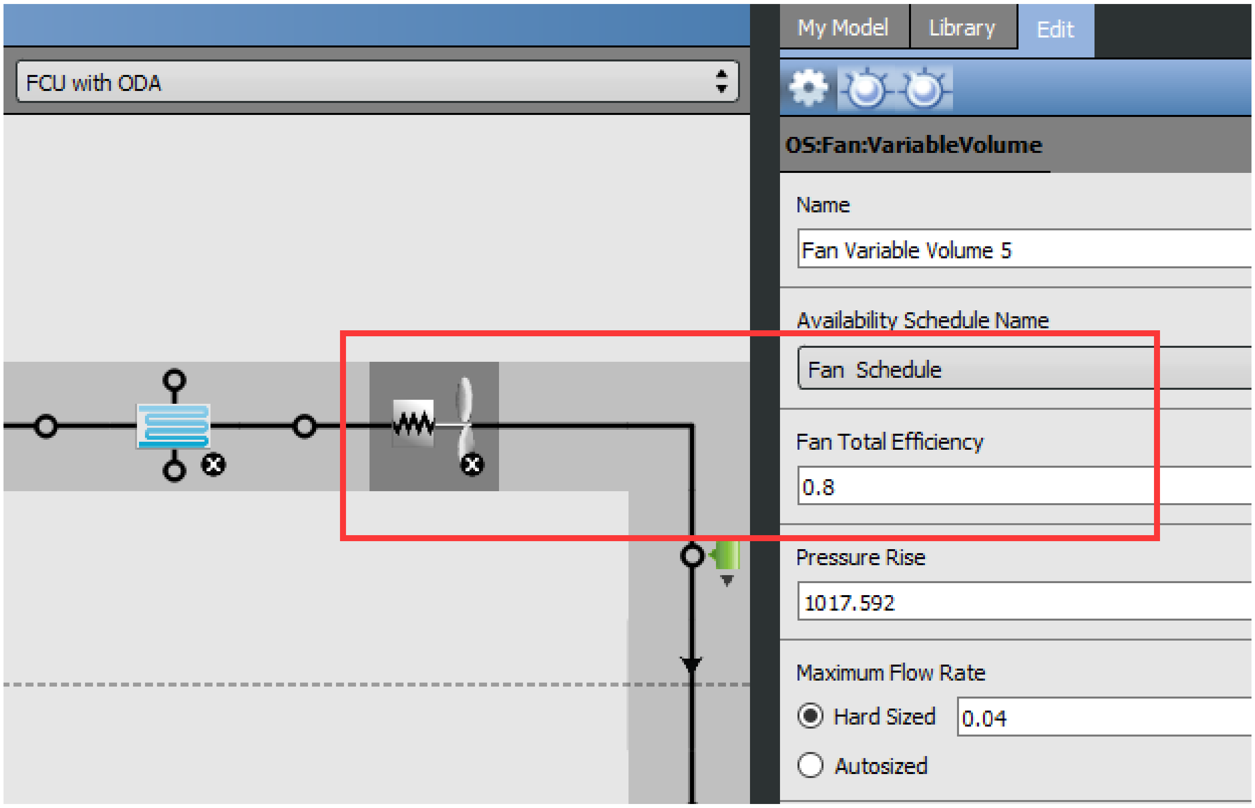


Figure 7-16 Fan Efficiency Setting (Example)

7.7 Part I: Temperature Calibration

7.7.1 Dynamic Data Input and Data Exchange Process

1. Actual Weather Data Input

The developed GUI uses the weather station id (45240) in the BIM model to link the OD module, select the *weather data* table, return the value of critical parameters in the selected time period, export them as a list, and write into a .csv file, and save them as a .epw file for OpenStudio to read. The period is from 3/11/2019 to 6/10/2019, as in Figure 7-17. The table name and column name are shown in Figure 7-18.

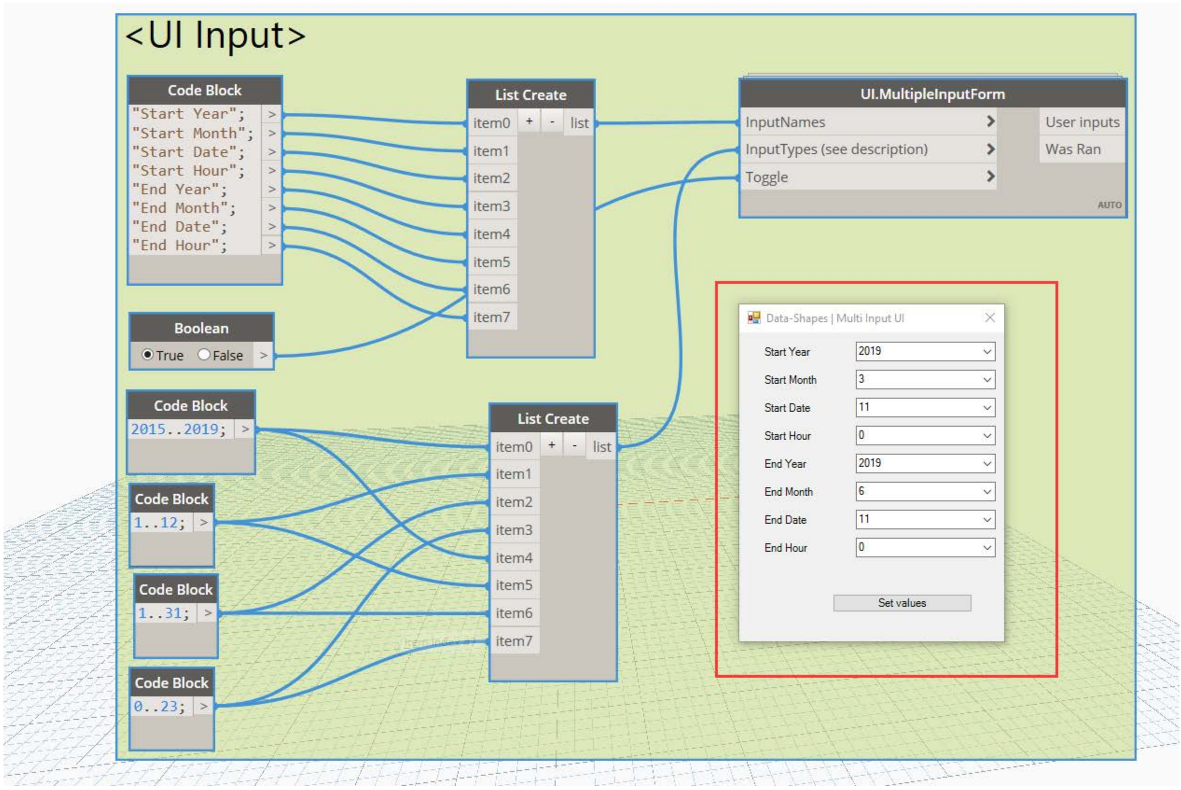


Figure 7-17 Time Period Selection

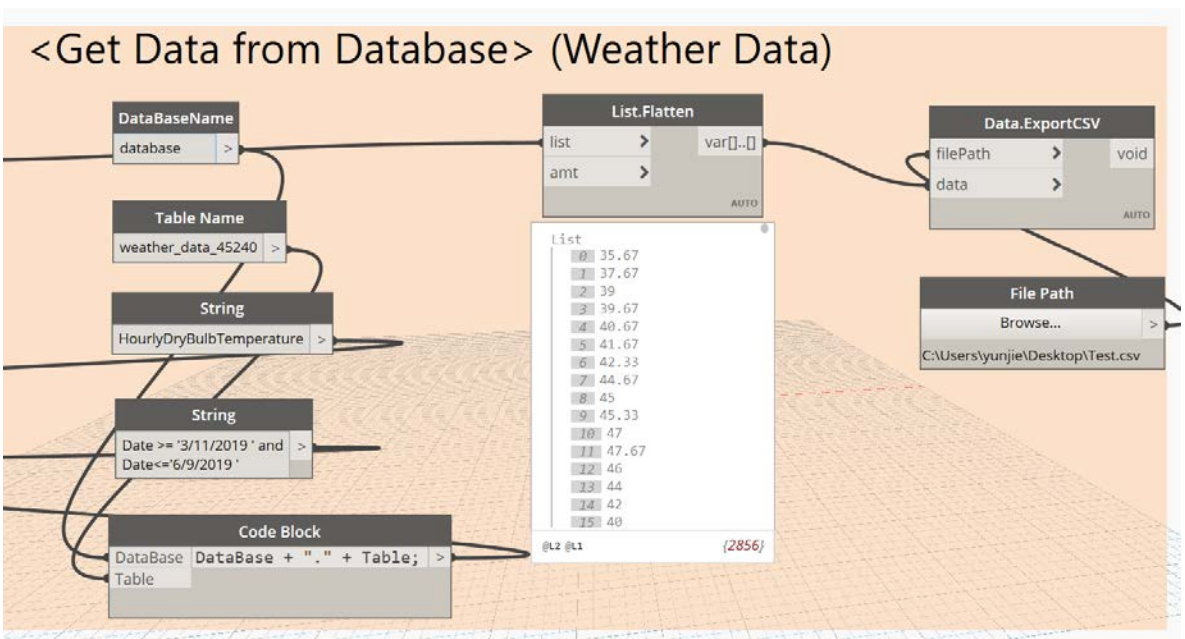


Figure 7-18 Search Weather Data Table

2. Schedule data exchange

The GUI allows the operator to select a sensor, then reads its sensor ID and type to search the table, returns the value of critical parameters in the chosen period, exports them as a list, and saves them in a .csv file for later use. In this case, lighting sensors monitored the actual illuminance in Office 410A, B, and C, the values were saved in the database. The GUI reads the table *lighting_sensor_id* in the database, returns the value of *410A_LM* (which is the schedule name of the sensor as a parameter in BIM model), and then save it as .csv file for OpenStudio model. Figure 7-19 shows the process.

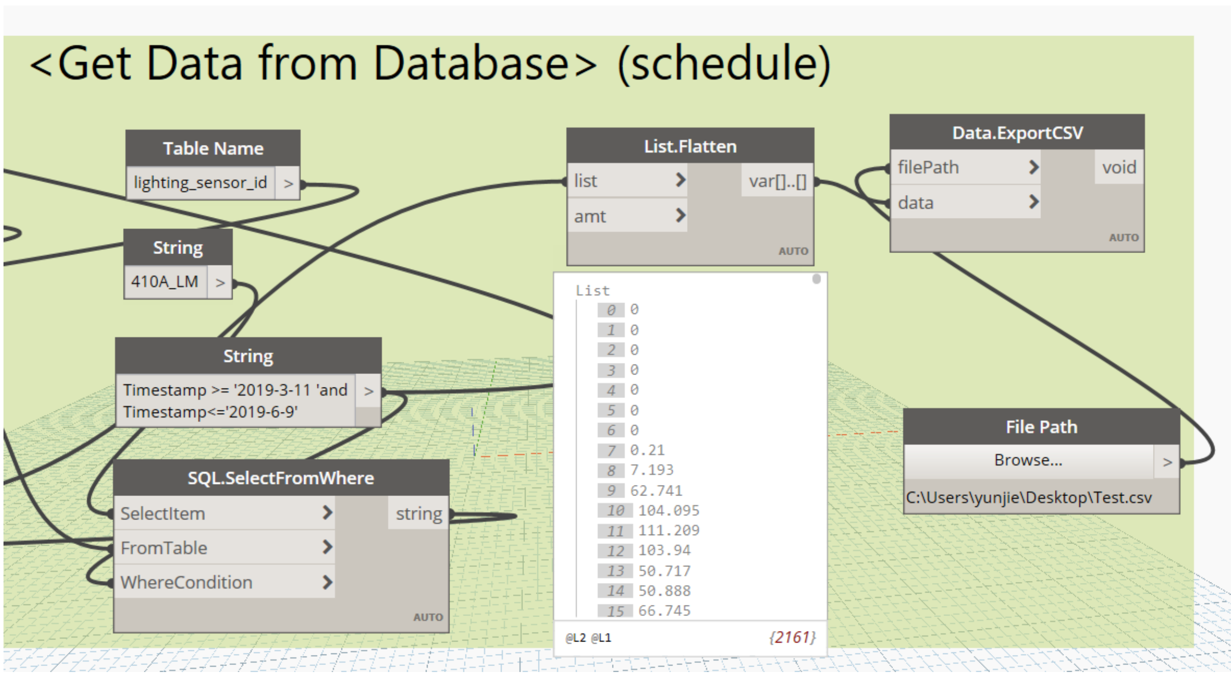


Figure 7-19 Get Lighting Schedule Data from Database

Another function of the GUI is to read EMD data, such as overall fan efficiency. In this case, the *equipmentID* was used to search the related value and update the value in the BIM model and energy model. The table *equipment_fan* was searched to select the value of *fan overall efficiency* and set the value to the FCU 13 in the BIM model. Figure 7-20 shows the process and the final overall efficiency as 0.8.

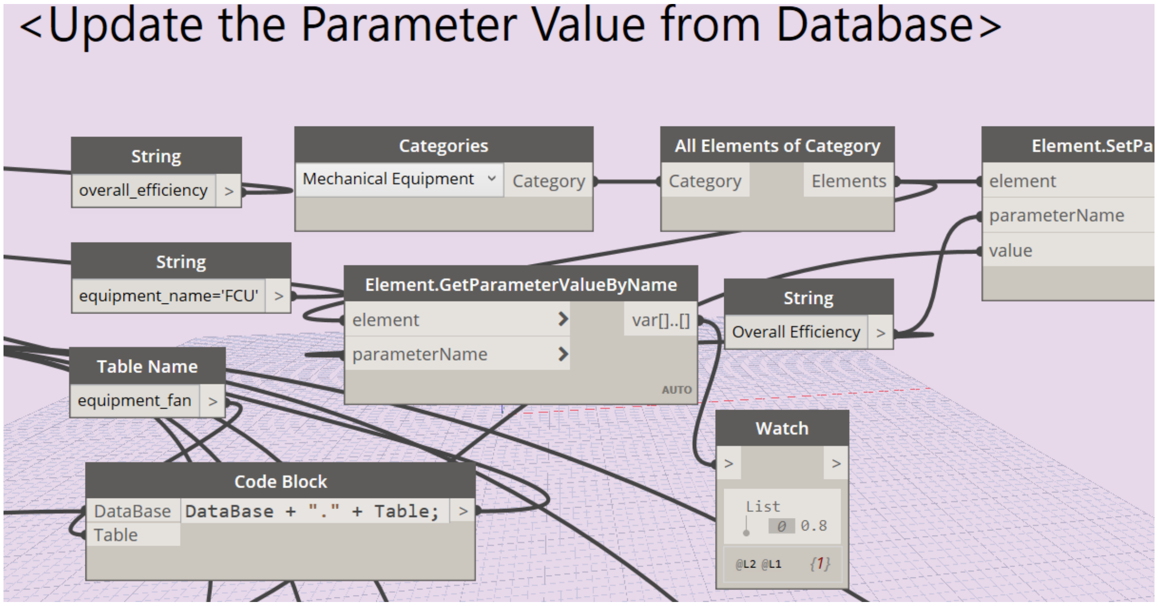


Figure 7-20 Example of Updating the Related EMD Data (Single Value)

3. EB data send back

OpenStudio can export the simulated results file as a .csv file. The GUI reads the data series as a list, then compares them with the existing energy benchmark in the MySQL database. In this case, the simulated indoor temperature of 410 A was exported from energy model and read by the GUI, shown in Figure 7-21. The actual room temperature collected by BAS were saved in the database and the GUI could read them with the chosen time period, the process is shown in Figure 7-22.

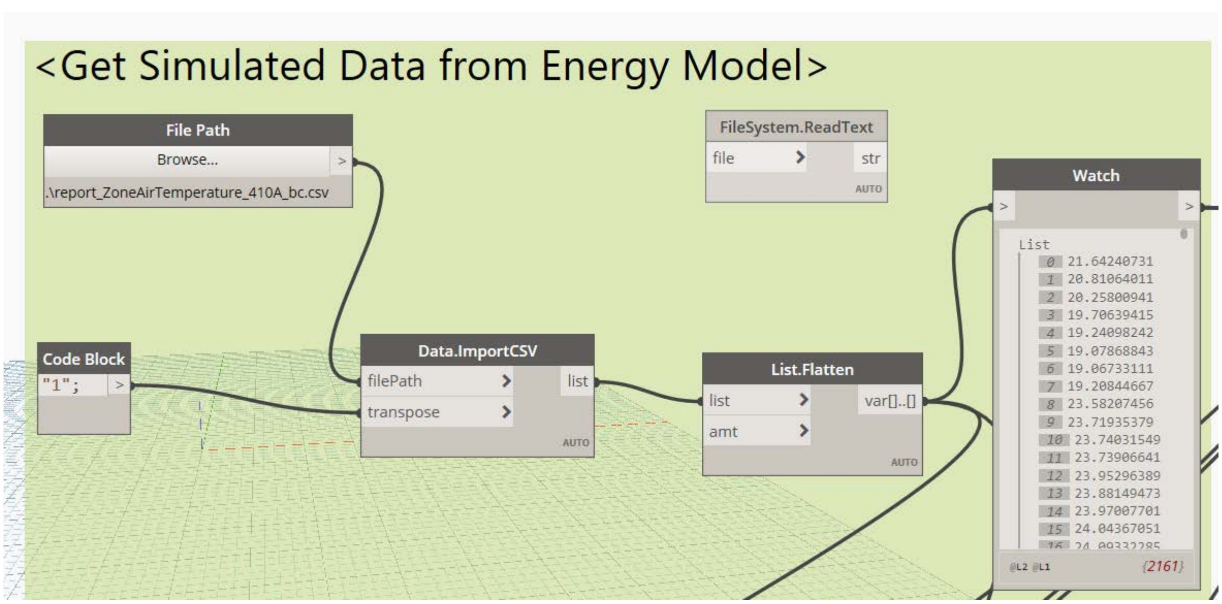


Figure 7-21 Read Simulated Zone Air Temperature of 410 A

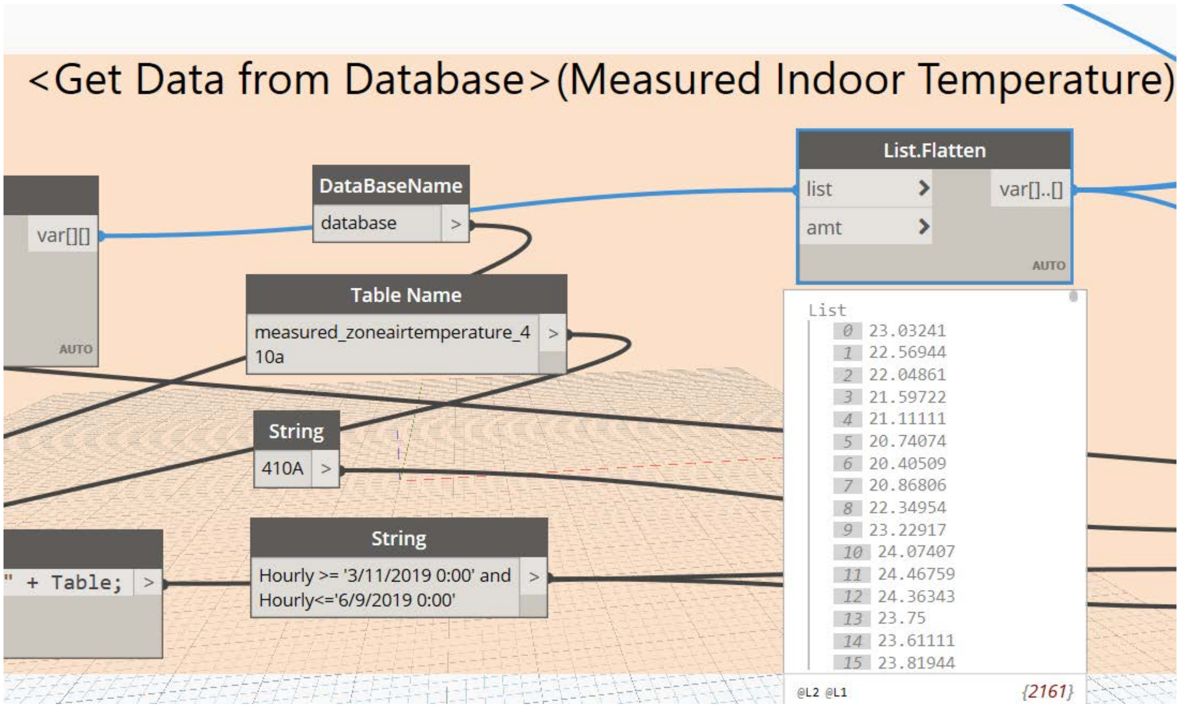


Figure 7-22 Read Measured Zone Air Temperature of 410 A

4. Results Comparison and Visualization

The simulated zone air temperature was then read by the GUI, and the measured zone air temperature was collected from the database by the GU; both data sets were compared and visualized as plots. The GUI runs two functions of calculating CV(STD) and R correlation coefficient, shown in Figure 7-23 and Figure 7-24. The CV(STD) between the simulated and measured zone air temperature was 5.57%, and the R was 0.774. The detailed calibration process is presented in Section 7.7.3.

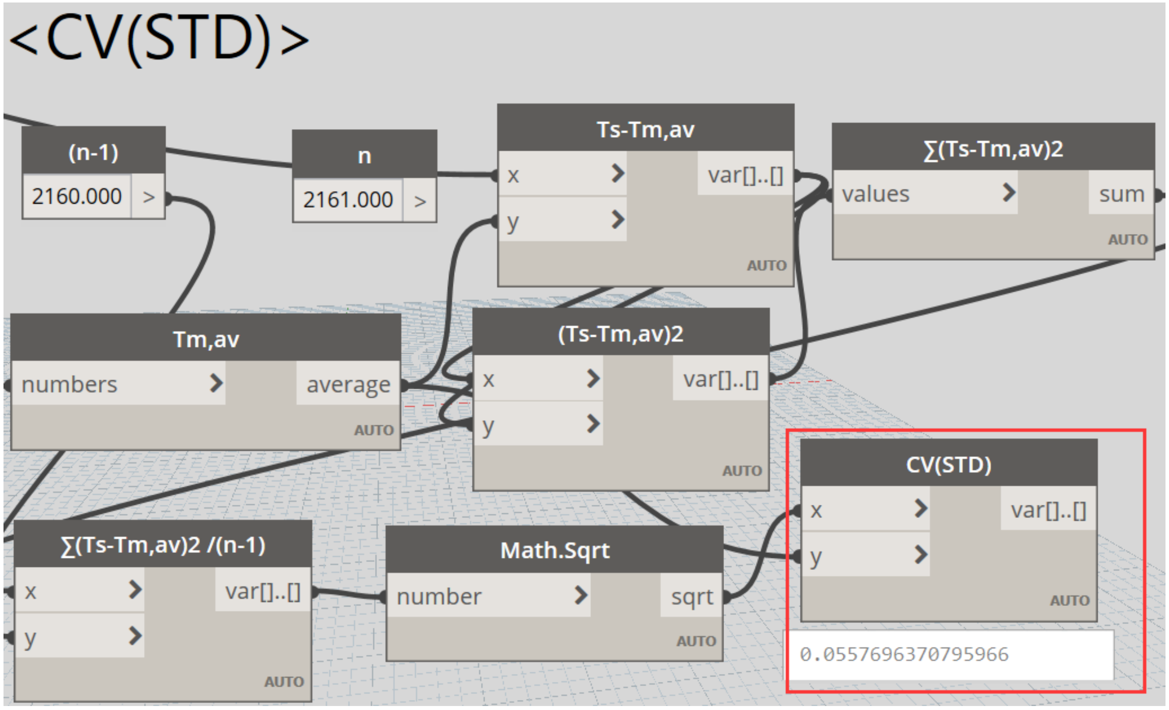


Figure 7-23 CV(STD) Calculation

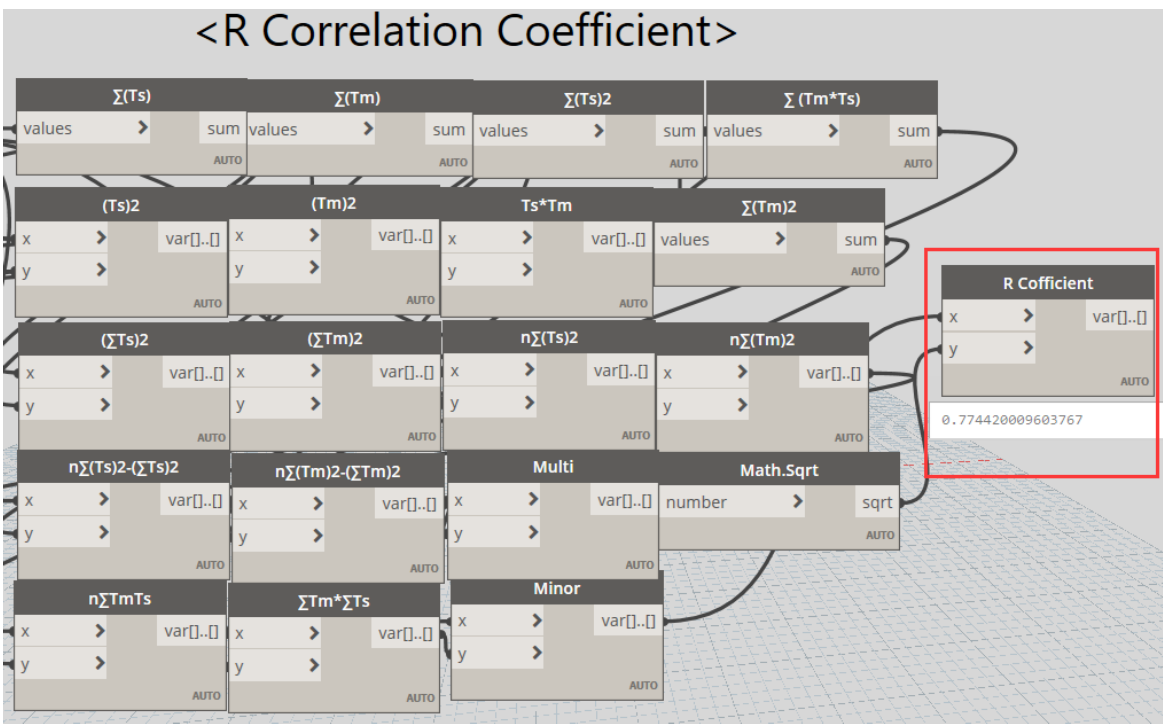


Figure 7-24 R Correlation Coefficient Calculation

The GUI can visualize the two hourly data series as a line chart. Figure 7-25 shows the measured hourly temperature and simulated hourly temperature from 3/20/2019 to 3/25/2019.

Figure 7-26 shows the measured hourly temperature and simulated hourly temperature results from March 2019 to June 2019 from an external resource (MATLAB).

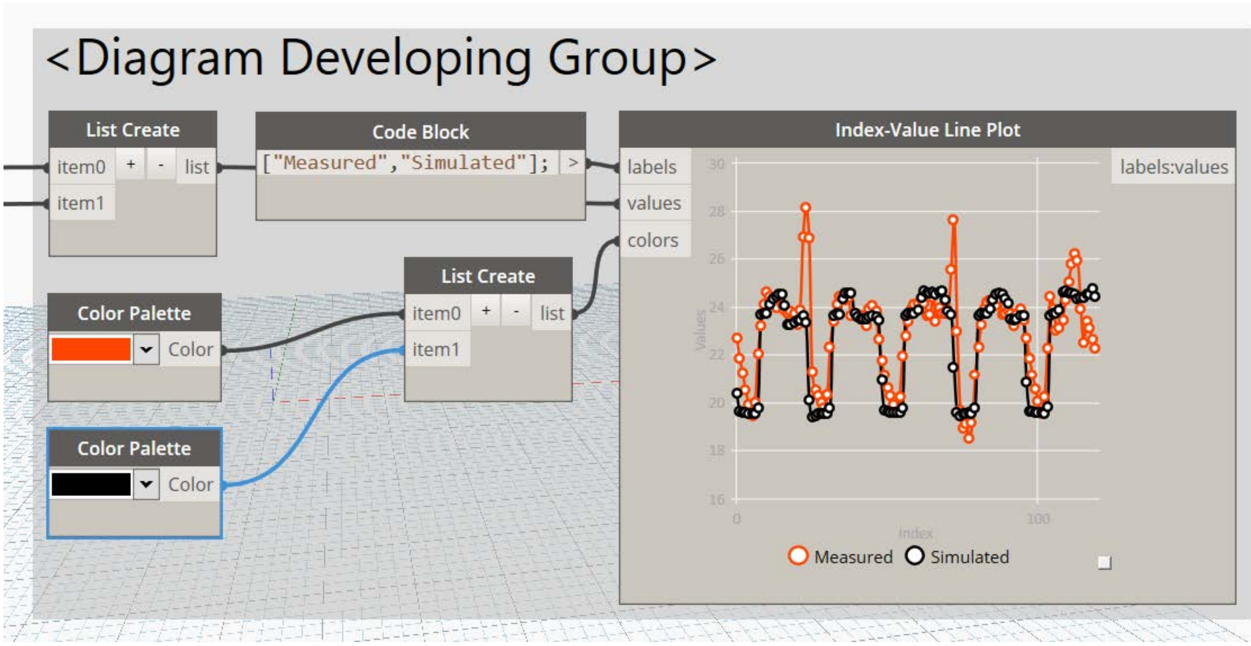


Figure 7-25 Indoor Temperature for 5 Days

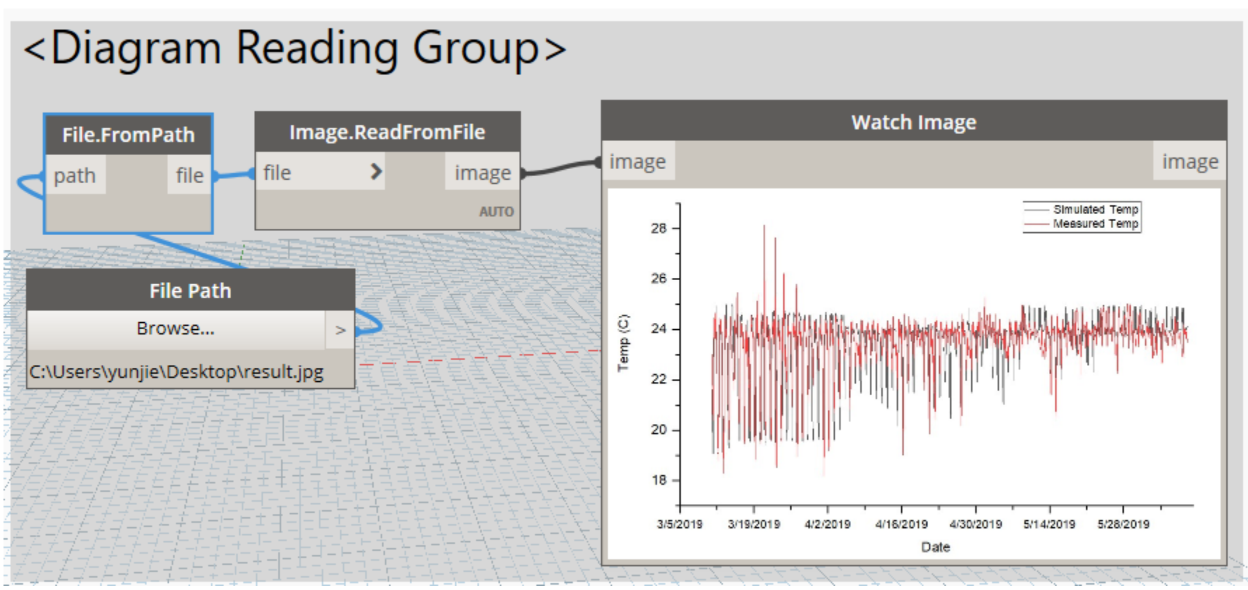


Figure 7-26 Indoor Temperature for 3 Months

7.7.2 Simulated Results

The detailed calibration process is further documented in Appendix F and includes all data collection processes, simulation rounds, model editing details, and results analysis. The final calibrated model and results are as follows, the measured data using for simulation include actual weather data, lighting and occupancy schedule, FCU working schedule, and supply air temperature. The simulated period runs from March 11, 2019, to June 10, 2019.

This study used a simulated indoor temperature to calibrate the energy model. Therefore, the export variable as 410A zone temperature was used to compare with the BAS collected "room temperature." The room temperature from the BAS was collected by the thermostat connected to the FCU, which was installed in office 410A. Furthermore, the spot-measured data collected the room temperature of 410A as a reference. The compared temperature results are in Figure 7-27. The detailed data are referred to Appendix F. The comparison of BAS collected room temperature data, and HOBO measured room temperature data is shown in Figure 7-28. The electricity consumption (kWh) and zone conditions are presented in Figure 7-29 and Figure 7-30, the electricity consumption is 1259.8 kWh, and the number of unmet hours is 8, which 2 hours happened during occupancy time. The zone temperature distributes from 74 °F (23°C) to 76°F (24°C).

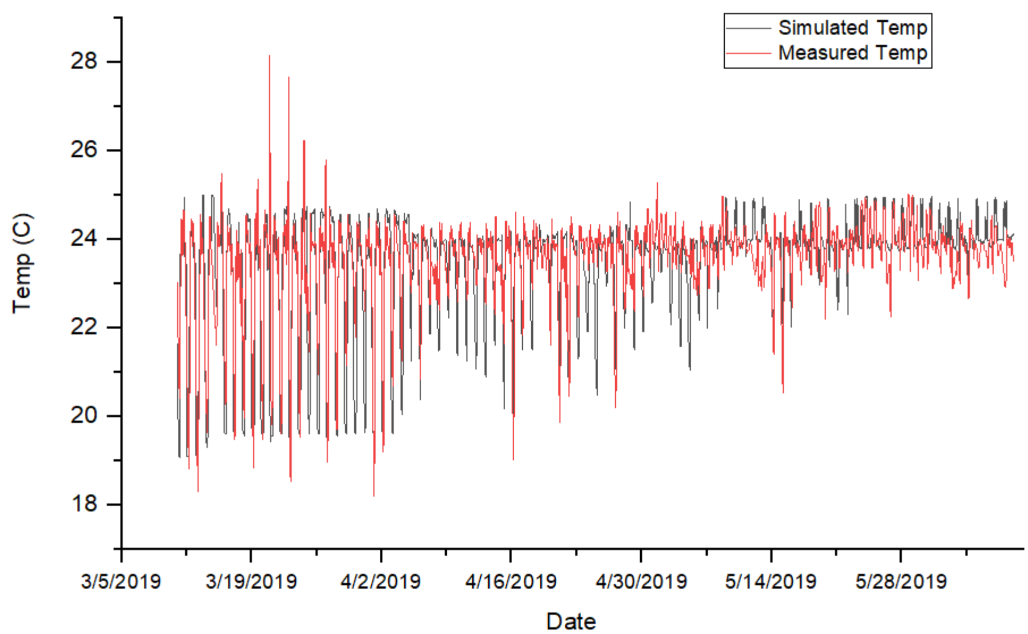


Figure 7-27 Calibrated Result and Measured result

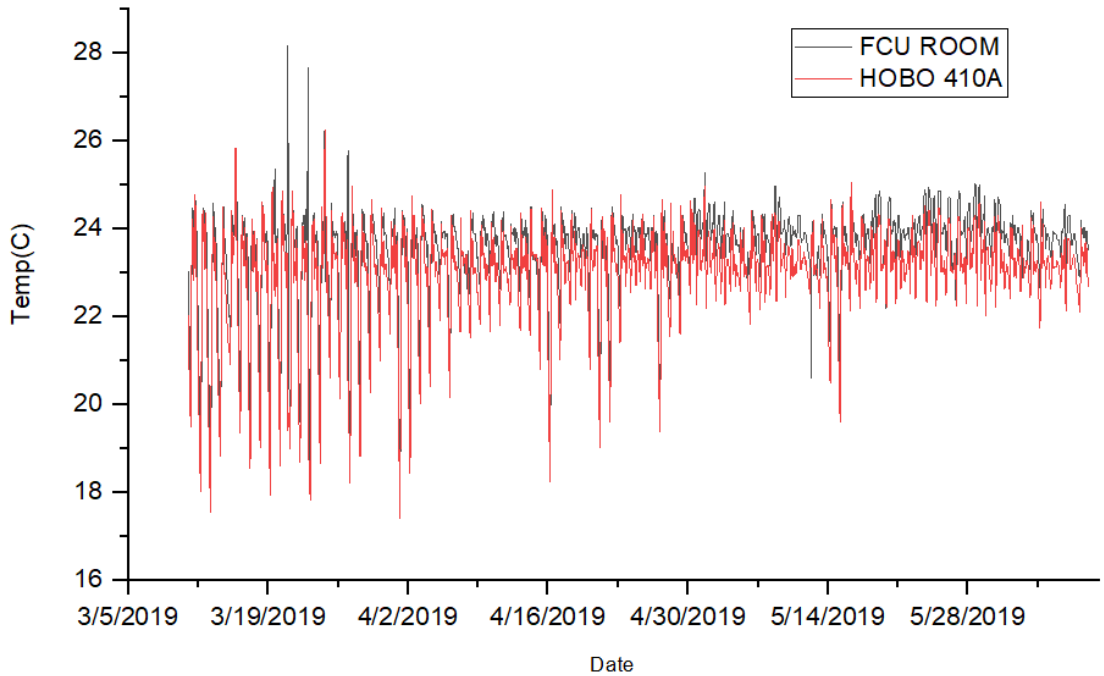


Figure 7-28 BAS data and HOBO data

Electricity Consumption (kWh) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Heating													
Cooling													
Interior Lighting			45.51	63.04	214.62	78.54							401.71
Exterior Lighting													
Interior Equipment			81.61	113.17	117.68	34.04							346.5
Exterior Equipment													
Fans			121.51	158.49	163.77	52.83							496.61
Pumps			1.5	4.69	6.38	2.4							14.98
Heat Rejection													
Humidification													
Heat Recovery													
Water Systems													
Refrigeration													
Generators													
Total			250.13	339.39	502.46	167.81							1259.79

Figure 7-29 Electricity Consumption(kWh)

Temperature (Table values represent hours spent in each temperature range)

Zone	Unmet Htg (hr)	Unmet Htg - Occ (hr)	< 56 (F)	56-61 (F)	61-66 (F)	66-68 (F)	68-70 (F)	70-72 (F)	72-74 (F)	74-76 (F)	76-78 (F)	78-83 (F)	83-88 (F)	>= 88 (F)	Unmet Clg (hr)	Unmet Clg - Occ (hr)	Mean Temp (F)
410A	4	0	0	0	0	152	75	123	168	1501	237	0	0	0	32	7	74.1 (F)
410B	2	1	0	0	0	152	74	111	203	1291	324	88	13	0	174	89	74.4 (F)
410C	2	1	0	0	0	105	77	109	248	1548	169	0	0	0	0	0	74.1 (F)
410D	0	0	245	366	231	199	164	118	106	89	129	451	158	0	0	0	69.3 (F)

Figure 7-30 Zone Conditions

All the detailed indoor temperature and simulated results were saved in the MySQL database for further analysis.

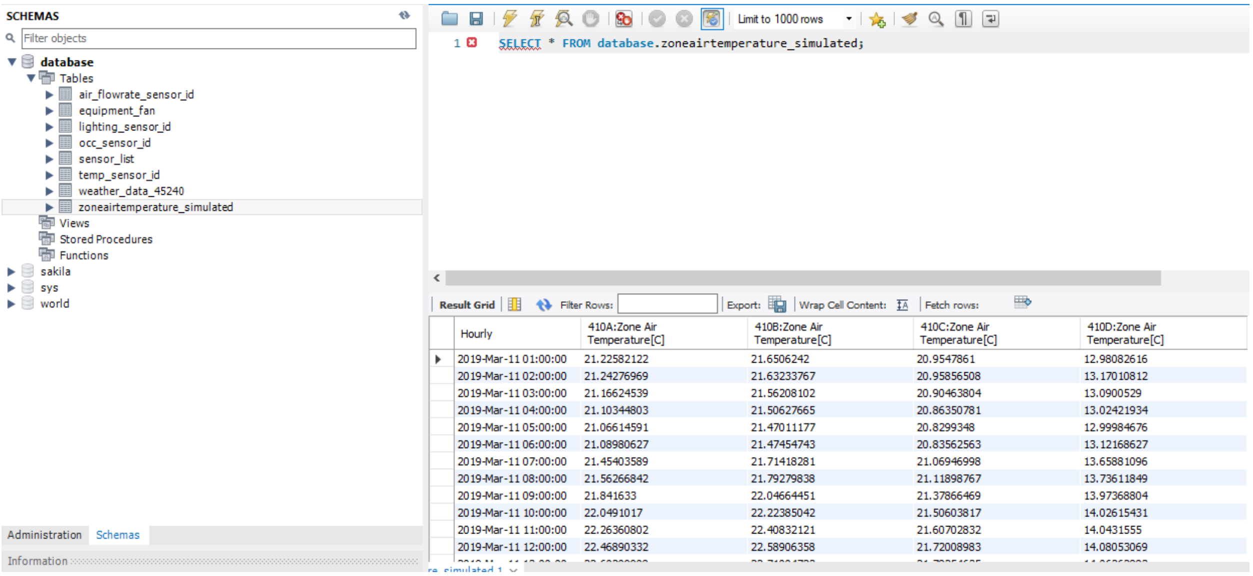


Figure 7-31 Database Example (Zone Air Temperature)

7.7.3 Statistical Analysis

Monitored indoor temperatures and simulated indoor temperatures were compared with two analyses. The first method is a linear correlation (R) analysis between the hourly simulated and monitored indoor temperatures. The second method is an error analysis that intends to check the deviation of simulated hourly temperatures from the monitored data, including the NMBE, CV(RMSE), and CV(STD). Equations (1), (2) (3) present the formulas employed, where n is the number of observations, p is 1, $T_{m,av.}$ is the average of the monitored indoor temperature data for n observations, T_s is the simulated data for n observations, and T_m is the monitored data for n observations.

$$\text{CV(STD) (\%)} = \frac{1}{Tm,av} \times \left[\frac{1}{(n-1)}\sum (T_s\text{-}T_{m,\,av})^2\right]^{0.5} \quad \textbf{(1)}$$

$$\text{CV(RMSE) (\%)} = \frac{1}{Tm,av} \times \left[\frac{1}{(n-p)}\sum (T_s\text{-}T_m)^2\right]^{0.5} \quad \textbf{(2)}$$

$$\text{NMBE (\%)} = \sum_{i=1}^{n}(Tm - Ts)/[\,(n\text{-}p) \times T_{m,\,av}] \quad \textbf{(3)}$$

According to the calibration criteria of ASHRAE Guideline 14, the computer model shall have an NMBE of 5% and a CV(RMSE) of 15% relative to monthly calibration data. If hourly calibration data are used, these requirements shall be 10% and 30%, respectively. The simulated indoor temperature of the calibrated model fulfills these criteria with 3.97% RMSE, 0.7% MBE, 0.17◦C absolute average error (Eav), and 0.774 correlation coefficient (R). The study also investigated the comparison between HOBO sensor data and FCU data, which shows these two series of measured indoor temperatures from different sources have a better linear correlation (0.89), and other indicators are similar or better than the simulated indoor temperature.

Table 7-3 Statical Analysis

RUNs	Indoor Temperature Calibration				
	CV(RMSE)	CV(STD)	NMBE	Eav	R
Final Simulation	3.6%	5.74%	0.48%	0.113	0.78
HOBO vs FCU	3.21%	5.39%	2.3%	0.543	0.89

7.7.4 Validation

Two experiments were set up to validate that the abnormal situation during operating can be detected using the significant difference between simulated operating status and the actual running status.

A portable heater was put close to the thermostat in Office 410A to heat indoor air. The fan of an FCU works from 06:00 am to 11:00 pm daily, and when the thermostat detected an increase in temperature, it opened the chilled water valves flowing through the cooling coil. The first test was conducted at 9:30 pm on 3/20, while the FCU was working in heating mode and supposed to be off at 11 pm. After turning on the heater, the FCU switched to cooling mode and kept running until the time the heater was set to switch off, which is at 0:45 am on 3/21. The second test was conducted at 11:35 pm on 3/22. The fan was off due to the regular night setback schedule, but when the heater was on, the fan started in cooling mode and kept running until the heater switched off at 1:05 am on 3/23. Figure 7-32 shows the thermostat value during the experiment. The detailed data are presented in Table 7-4.

Figure 7-32 Thermostat Value

Table 7-4 On/Off Time

	Time		**Average Heating temperature**	**Result**		
	Heater On	Heater Off	F	Fan On	Fan Off	Mode
Run 1	3/20 21:30	3/21 0:45	85 F	3/20 21:35	3/21 0:46	Cooling
Run 2	3/22 23:35	3/23 1:05	85 F	3/22 23:40	3/23 1:06	Cooling

The BAS data report showed these two abnormal high-temperature points and matched the experiment time. Meanwhile, the simulated results kept normal; there were two significant differences in the comparing diagram.

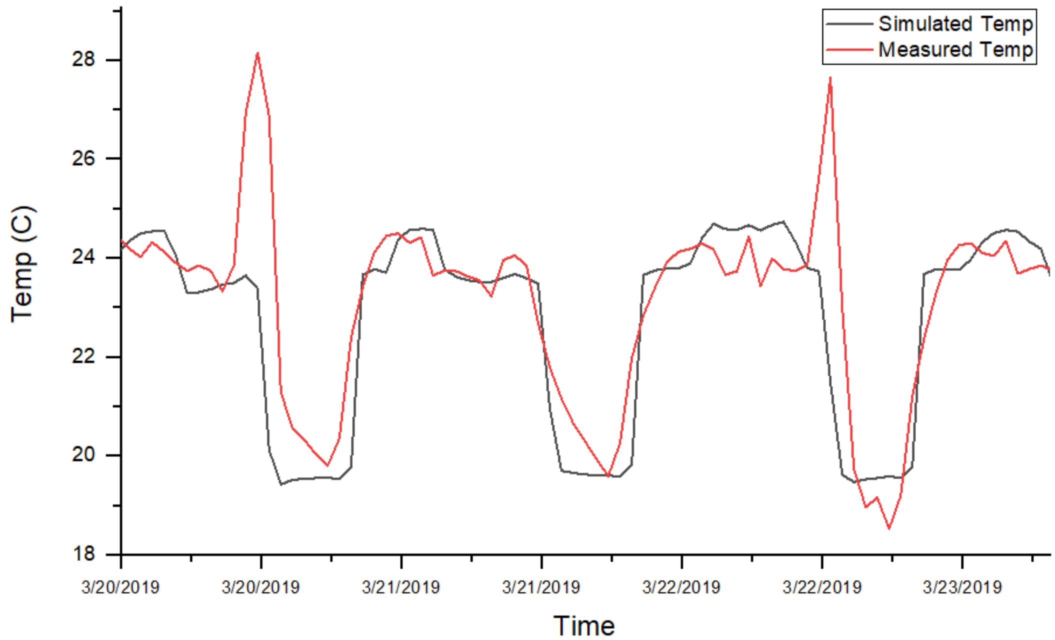


Figure 7-33 Data Discrepancy

The framework is proposed to be used to collect actual data and simulated data, then develop the real-time comparing diagram and report the significant discrepancy. This experiment showed that it assisted in using simulated data as a baseline and identify the potential running error when there was a significant difference between simulated data and measured data. Taking the experiment as an example, the difference of average temperature between simulated result and measured data was 0.113, and the standard deviation between a pair of the simulated and measured points is less than 2 °C. Therefore, if the monitored difference between simulated point and measured point is more than 3°C, the interface can send a warning and show it in the real-time comparing diagram. This function shall assist as an operation fault detecting method.

7.8 Part II: Temperature Profile Comparison

A calibrated energy model predicts future energy consumption with different energy conservation measures (ECM), to improve actual performance. Studies use a calibrated energy model to test various ECMs including assessing different retrofit schemas, such as installing cool roof effects, changing water pumps into variable speed, using daylight sensors to reduce lighting power (Pan, Huang et al. 2007, Bhatia, Mathur et al. 2011), and assisting building control, such as selecting optimal temperature schedules, developing event schedules, etc. (Liu and Claridge 1998, Clarke, Cockroft et al. 2002),(Zhou and Park 2012), (Harmer and Henze 2015)

7.8.1 Schedule Development

Various setting temperature schedules were compared using the calibrated energy model to identify the optimal schedules for energy saving in this case study. The developed temperature schedules were saved in the database module and extracted to the energy simulation module using the GUI. The energy simulation module runs the calibrated model with these schedules to compare the energy consumption and sent the simulated results back to the database. The GUI extracted these results again for comparison and visualization, identified the most efficient schedule. Once a schedule was identified, the calibrated model can run with the selected schedule and actual outdoor temperature to estimate the energy consumption as a reference for the building manager.

The current BAS data report showed that the original running time of the fan was from 6 am to 11 pm every day, the heating point was 73.25 °F (23 °C), and the cooling point was 76.25 °F (24.6 °C). Three energy-saving strategies of setting temperature schedules were applied, the first was to change the fan on/off time into from 7 am to 10 pm, and developed a weekend schedule when the fan works from 7 am to 6 pm. The second was to start the temperature setback as the occupancy rates drop in the afternoon, which was usually from 6 pm. The heating setting point was 76 °F, and the cooling point was 78 °F. The third was to precool or to preheat the indoor air in the morning. From 6 am to 8 am, the heating point was 71 °F and the cooling point was 73 °F. All these schedules are shown in Figure 7-34, and Figure 7-35 shows the GUI gets the cooling setting schedule for Office 410A from the database. The simulated results are presented in Table 7-4 and saved in the database for use.

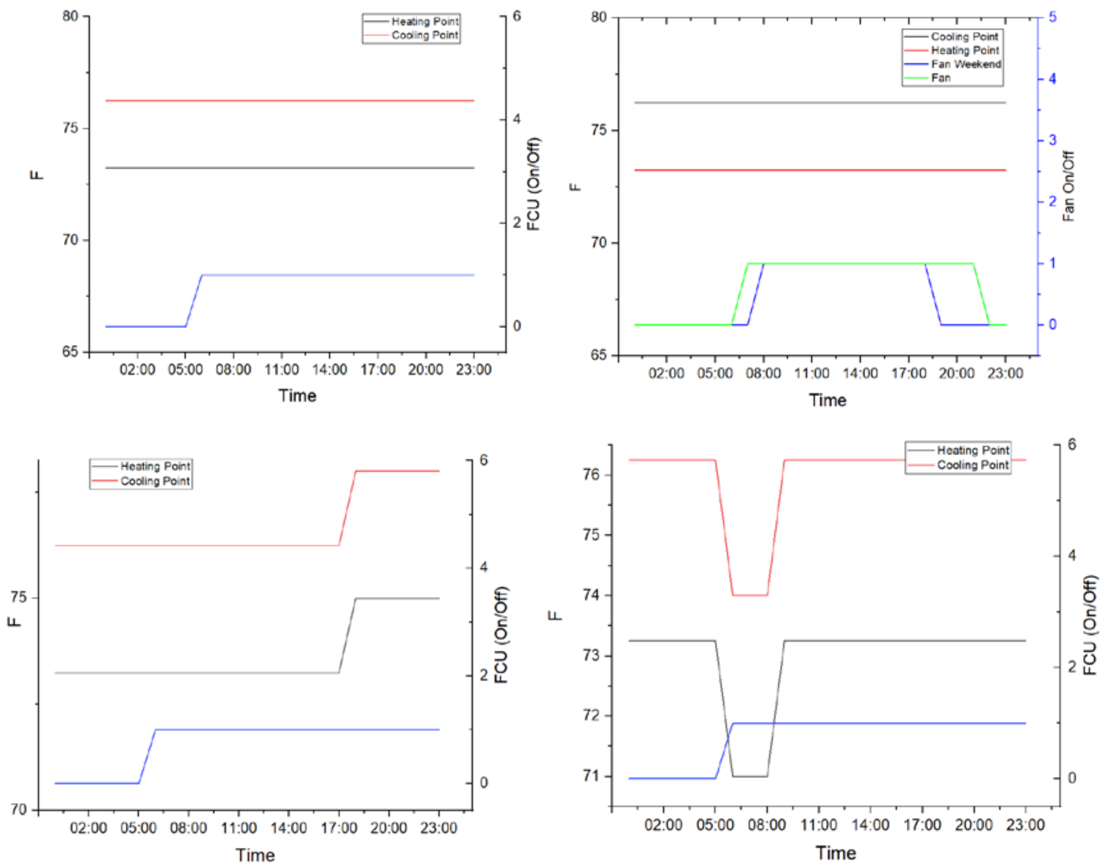


Figure 7-34 Schedule List

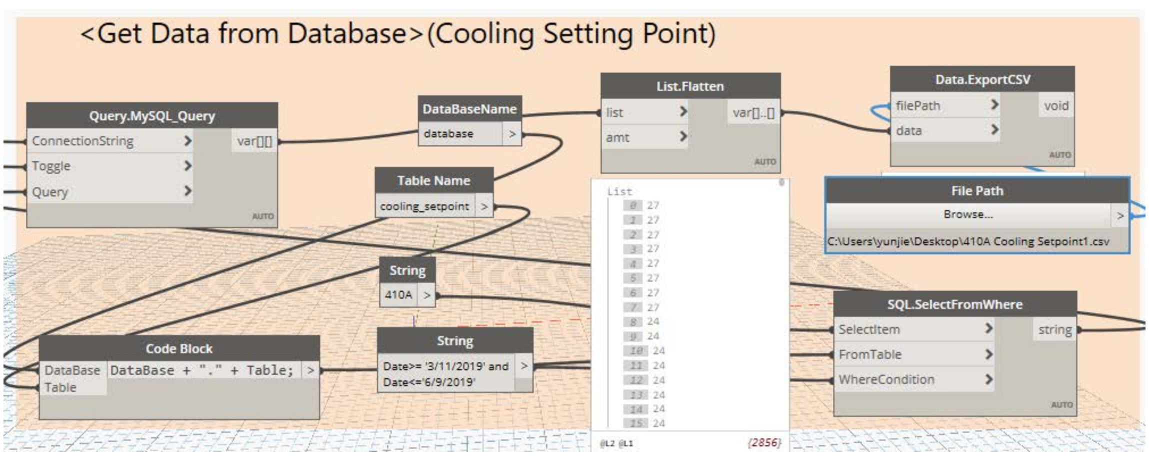


Figure 7-35 Getting Setting Point Schedule from Database

7.8.2 Results Compare and Visualization

Baseline results showed the electricity consumption was 1259.8 kWh, with the indoor temperature distributed from 74 to 76 °F. Changing the fan schedule and adding a weekend schedule does not show much impact on energy saving (0.04%), and the main indoor temperature was still from 74 to 76 °F. Schedule 2 using the setback point which changes the heating/cooling setting point during low occupancy hours saved about 0.07% electricity consumption, and more hours of indoor temperature were between 76 to 78 °F. Schedule 3 using pre-heating/pre-cooling did not show energy-saving, only perform better in unmet heating hours.

Based on these results, the fourth temperature setting schedule was developed, which applied the pre-cooling/heating setting point and setting back point from schedule 2 and 3, and changed the day cooling setting point into 77 °F. It shows a better energy-saving percent (0.22%) when the main indoor temperature hours are between 76 °F and 78 °F.

Table 7-5 Simulated Results

Run	Building area (ft2)	Electricity Consumption (kWh)	Per ft2	Saving %	Unmet hours 410A				Zone Condition 410A			
					Htg	occ	Clg	occ	72-74(F)	74-76(F)	76-78(F)	78-83(F)
Baseline	568	1259.8	2.218		4	0	32	7	168	1501	237	0
Schedule 1	568	1259.33	2.217	0.04%	4	0	30	6	181	1293	362	56
Schedule 2	568	1258.88	2.216	0.07%	4	0	36	7	183	1135	573	14
Schedule 3	568	1259.82	2.218	0.00%	2	0	55	14	260	1369	236	0
Schedule 4	568	1257	2.213	0.22%	2	0	49	13	281	263	959	384

The prototype GUI sent all these simulated results to the database and extracted them with the BIM model for data comparison and visualization. Figure 7-36 shows the example of comparing monthly electricity consumption (kWh) between the baseline model and schedule 4 model from March to June as bar chart in Dynamo.

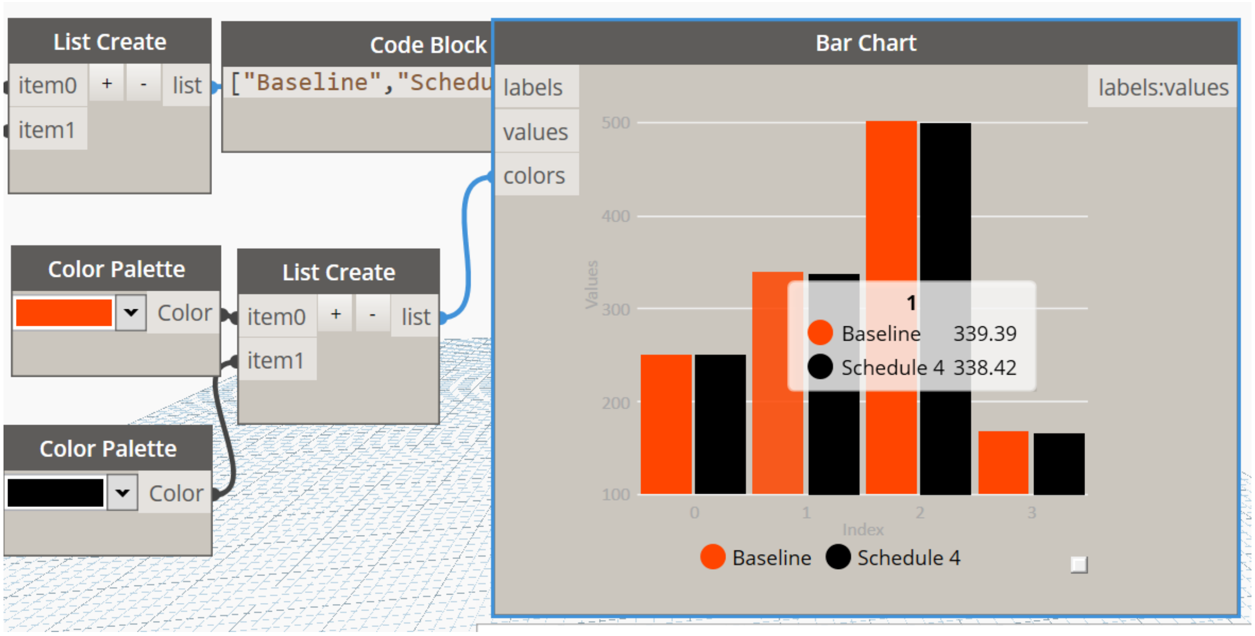


Figure 7-36 Electricity Consumption between Baseline and Schedule 4

8 CONCLUSION AND FUTURE RESEARCH

8.1 Research Findings

The adoption of BIM in the AEC industry has increased steadily and rapidly in recent years. The immense potential of BIM is in its ability to optimize the performance of the life cycle of a building by providing consistent, high-quality, and comprehensive data in a timely manner. This research utilized a BIM-based framework to exchange, analyze, and visualize both simulated and operational data and to assist in building energy management using a systematic approach. The research explored the potential of BIM for increasing productivity, reducing labor costs, and avoiding data error for FM. In addition, the project also inspired comprehensive simulation-assisted building energy management research to be performed.

Specifically, this research aimed to enhance building energy management performance by linking the energy-related operational data and energy simulation data. The most important contribution of this research was that it developed a BIM-based framework as a data management tool to harmonize the BES and BAS. This framework can reduce labor costs and manual error by simplifying energy-related data input and exchange processes. It can also provide a structured, 3D model management approach by reusing the simulated and monitored information from related building projects. Furthermore, the framework created an open, sharable, and automated or semi-automated environment allowing users to define target parameters and to analyze and visualize the simulated and actual values of the parameters for various goals. These various goals include energy model calibration, co-simulation, model-based control, fault detection and diagnostics, and simulation-assisted building energy management. The framework applies not only to energy simulation but to other building performance simulation models, as well. The following subsections conclude the main research findings:

8.1.1 Systematic Literature Review

A systematic literature review was done to assess the existing data exchange capabilities between BIM, BES, and BAS and to identify the commonly exchanged data formats and methods. The review selected 72 original, peer-reviewed studies and the findings were as follows:

First, the data exchange mechanism between BIM and BES was more advanced than the mechanism between BIM/BAS and among BIM/BES/BAS, which were more at the concept level. Considering the potential for integrating operational data and simulation data in order to optimize FM, data exchange mechanism among BIM/BES/BAS is worth being investigated.

Second, although IFC was the most popular choice for BIM application, and it adopted a comprehensive approach to describe building information, the users must extract and define the required information from IFC and add the missing data from external resources to run an energy model.

Third, researchers preferred to use simulation tools with customized functions to make their simulation methods more flexible. This could be explained by the BES application in the building operational phase was more complex than simply comparing design scenarios.

The last finding was that when BAS was involved, the researchers applied platform integration for BIM/BES/BAS and created a database to link BIM and BAS. This showed that a BIM model is not recommended for handling the large amounts of data produced by BAS. Therefore, the database is the storage and management solution for large operational data and BIM serves as a management tool.

This systematic literature review contributed to a general understanding of the existing static and dynamic data exchanging capabilities among BIM, BES and BAS. It also identified the commonly used data format and data exchange methods, which became a starting point for further research.

8.1.2 IFC Data Identification and Proposed Schema

The IDR of the simulation model must be defined in order to implement the BIM/BES/BAS integration for building operation. This study identified the IDR by reviewing a whole-energy model calibration process and listing and classifying all the critical data sets for energy calibration. Then, the study compared IDR against information contained in the IFC 4.2 scheme, defined a subset of IFC data model dealing with energy simulation in the operational phase, and identified the missing concepts. These missing concepts were described as additional properties (e.g. weather data, utility data, schedule and performance curve) with a description method, which extended IFC files supporting dynamic data descriptions for energy simulation.

The IFC data sets with additional data can function as a generic and consistent template for operational information transfer from BIM to BES. Although many studies defined the dataset in IFC for energy simulation, this study was a first attempt at defining the sub-dataset in IFC for energy simulation and calibration. This involved the operational data being used to standardize the calibration process. Furthermore, the IFC data sets not only serve as a template for the energy model calibration process, but they also benefit methods that utilize both operational data and energy simulation output, such as model-based control.

8.1.3 Comprehensive Final Framework

The final framework with a prototype was developed based on the identified datasets. The datasets were described by IFC schema, classified into four modules: 1. BIM module, 2. Operational Data (OD) module, 3. Energy Simulation (ES) module, and 4. Analysis and Visualization (AV) module, and their data exchanging mechanisms were defined. The prototype created a GUI based on the BIM management of the four modules. Toegther, the four modules offered the following functions: 1. The GUI extracted the operational data from OD module, linked them or assigned the value to BIM objects, and prepared the data values as a readable file for the ES module; examples include weather data, schedules, equipment efficiency, etc; 2. The GUI extracted the simulated results from ES module and the operational data from OD module, conducted statistical functions such as NMBE, CV(RMSE), and CV(STD), then visualized the results. These functions were validated by a case study of an office suite in BFH, which used the hourly indoor air temperatures to calibrate the energy model and detected the possible faults during operation.

The prototype and case study demonstrated that the BIM-based framework can be used as a standardized method for information exchange and management within the operational phase. BIM has the potential to provide required static and dynamic inputs for BES, thus reducing the time, effort and expense associated with model adjustment. Beyond data exchanging level, this study proves that BIM supports effective use of large operational data management by enabling a semi-automatic generation, data analysis and visualization process that saving the time taken to sort and arrange the data to make it usable. Many studies enhanced the interoperability of BIM and BES to reduce the time and labor cost of energy model creation while other studies investigated the potential of BIM as a building performance management tool. However, this study is the first attempt to using BIM as an open, generic and reusable data transfer and management platform assisting to integrate an energy model into building energy management. The final developed framework is applicable not only to energy simulation but other building performance simulation as well, thereby making an IFC-compliant dynamic data exchanging process and data management tool capable of conducting operational data and simulated data analysis.

8.1.4 Benefits of Framework

BIM can be of great benefit to integrating various data repositories for the energy management of O&M process. Through the research development, potential BIM-based framework benefits can be concluded as follows:

- This framework automated the data-entering process for energy model creation. By leveraging existing data from the BIM, energy models were generated and calibrated more quickly. This benefits the design phase by saving time and labor for designers and building owners and also supports the operational phase by importing dynamic data in a highly structural and modular way – enhancing efficiency and sustainability.

- The framework defined the key data sets for the energy model calibration process and described them as an IFC sub-dataset template. This template would serve as both a data collection guideline for the energy audits and a generic template for future studies importing the dynamic data into energy model using IFC schema.

- This framework integrated energy simulation into the operational data management process, which benefited various services, such as energy model calibration, energy benchmark development, simulation-assisted control, predictive building automation, co-simulation with other performance models, optimal operational strategies analysis, and more. With the framework, the BAS data was incorporated into the energy model in order to assess operational strategies in an energy and cost-effective manner.

- This framework investigated the potential for the use of BIM as a tool to visualize and manage the performance data of a building. Building objects were linked with the operational data stored in a database across the currently distinct BIM and BAS data environments. This action supports interlinking of these data-rich environments and provides efficient handling of large operational data.

- This framework made it possible to flexibly drive the building model containing the monitored operational data in order to study the dynamic model. Although this BIM-based framework focuses on energy simulation, it can be applied to any other performance model needing analysis of operational and simulation data. In conclusion, operational data was linked with building performance models more effectively with respect to current practices. Thus, added value for the building sector was created, and trends toward sustainability were improved upon.

Much effort was required to fully achieve these benefits on an application level. The author of this dissertation plans to perform future research as denoted in the following section. This research will not only further develop the aforementioned research into the application but will also build valuable connections to other relevant literature and project efforts.

8.2 Future Research

The presented framework was intended to develop a BIM-based platform in order to enhance the data-exchanging process between BAS and BES as an efficient method for building operational energy management. The research focused on data identification and description using IFC schema, prototype development, and a case study for validation. It demonstrated that the integration of BES and BAS can assist building energy management with potential benefits. However, the related research is still limited, so several research paths could potentially improve the framework. The following research areas listed below are areas of potential improvement:

8.2.1 IFC Schema Improvement

Extensive studies have been done surrounding the use of IFC schema supporting energy simulation. Most studies focus on static data, such as geometry, space, and MEP data exchange. A Model View Definition (MVD) for advanced energy simulation has been developed (Pinheiro, O'Donnell et al. 2016). IFC representation was also explored in the building commission and construction domain, such as Construction Operations Building Information Exchange (COBie). This is an MVD for the management and operation of a building. However, the research about IFC supporting energy model simulation, calibration, and energy management is limited. In fact, IFC itself misses several critical requirements for energy model calibration, including the dynamic schedule description, performance curve description, and a more detailed description of an energy model with respect to energy consumption. A specific MVD that defines a reliable and consistent subset of the IFC data model dealing with building energy performance simulation and calibration is expected to clarify the data requirement of energy model calibration and define the schema representation. In turn, this will fully unlock the potential of BIM-based platforms for energy management, which this research has produced results in early stages.

8.2.2 Database Development

A BIM model contains comprehensive building information itself. However, operational data that occurs during the energy model calibration and building operational phase far exceed the original BIM data and are impossible to manage and analyze in a BIM model. The systematic literature review results and the actual implementation steps in this research showed that a database is a possible solution to integrate the BIM and BAS data and to manage the massive amount of dynamic incremental data. BIM functions as a data management tool for handling the operational data saved in the database. Therefore, the database design, which determines the construction of tables and their relationships, is a crucial component in optimizing the overall efficiency of a database application. However, the method of classifying the building information data and identifying their interrelationships in a database are the main challenges for better integration of BIM and a database. In this area, the current related research is limited.

Another trend is the application of a cloud BIM-based platform; even so, solving the issues of different data source compatibility and the designs and classifications of the complex building information in the database remains a challenge. This study suggests starting with designing and optimizing the BIM-based database, focusing on a particular need in AEC, such as energy model calibration.

8.2.3 Energy Modelling and Calibration Methods

This framework provides a chance to utilize the building model along with the monitored operational data in order to study a dynamic model. Therefore, other calibrated methods beyond the traditional calibration method using monthly or hourly utility data can be tested smoothly with the platform. For example, the case study used indoor temperature simulation to enhance the building control. The result showed the R-correlation coefficient was an important indicator in the case study for comparing the simulated indoor temperature and actual indoor temperature, which was not required in the traditional calibration method M&V, option D. With this framework, more experiments and case studies about energy model calibration are expected to test different parameters, increase the accuracy of the calibrated model, and create the calibration criteria.

Another research trend is one where the operating energy data can be used with a simulation model to create a machine learning model that predicts building energy consumption. Due to the enhanced ability to handle the operational data, the BIM-based platform may be used to connect the actual operational data from the database and run the machine learning model. In turn, this may be more accurate than a traditional energy simulation model.

References

Agami Reddy, T. (2006). "Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty, and tools." ASHRAE transactions: 226-240.

Arayici, Y., T. Onyenobi and C. Egbu (2012). "Building information modelling (BIM) for facilities management (FM): The MediaCity case study approach." International Journal of 3D Information Modelling **1**(1): 55-73.

ASHRAE (2014). ASHRAE Guideline 14–2014, Measurement of Energy, Demand, and Water Savings, ASHRAE Atlanta.

ASHRAE (2018). ASHRAE 209-2018. Energy Simulation Aided Design for Buildings Except Low-Rise Residential Buildings.

Augenbroe, G. (2002). "Trends in building simulation." Building and Environment **37**(8): 891-902.

Azhar, S. (2010). "BIM for sustainable design: results of an industry survey." Journal of Building Information Modeling **4**(1): 27-28.

Azhar, S., A. Nadeem, J. Y. Mok and B. H. Leung (2008). Building information modeling (BIM): A new paradigm for visual interactive modeling and simulation for construction projects. Proc., First International Conference on Construction in Developing Countries.

Bank, L. C., M. McCarthy, B. P. Thompson and C. C. Menassa (2010). Integrating BIM with system dynamics as a decision-making framework for sustainable building design and operation. Proceedings of the First International Conference on Sustainable Urbanization (ICSU).

Bazjanac, V. (2004). "Building energy performance simulation as part of interoperable software environments." Building and Environment **39**(8): 879-883.

Bazjanac, V. (2004). Virtual building environments (VBE)-applying information modeling to buildings. eWork and eBusiness in Architecture, Engineering and Construction: Proceedings of the 5th European Conference on Product and Process Modelling in the Building and Construction Industry-ECPPM 2004, 8-10 September 2004, Istanbul, Turkey, Taylor & Francis.

Bazjanac, V. (2008). "IFC BIM-based methodology for semi-automated building energy performance simulation." Lawrence Berkeley National Laboratory.

Bazjanac, V. (2010). Space boundary requirements for modeling of building geometry for energy and other performance simulation. CIB W78: 27th International Conference.

Bazjanac, V. and T. Maile (2004). "IFC HVAC interface to EnergyPlus-A case of expanded interoperability for energy simulation." Lawrence Berkeley National Laboratory.

Bazjanac, V., T. Maile, J. O'Donnell, C. Rose and N. Mrazovic (2011). Data Enviroments and Processing in Sem-Automated Simulation with EnergyPlus. CIB W078-W102: 28th International Conference. CIB, Sophia Antipolis, France.

Becerik-Gerber, B., F. Jazizadeh, N. Li and G. Calis (2011). "Application areas and data requirements for BIM-enabled facilities management." Journal of construction engineering and management **138**(3): 431-442.

Beetz, J., L. van Berlo, R. de Laat and P. van den Helm (2010). BIMserver. org–An open source IFC model server. Proceedings of the CIP W78 conference.

Berard, O. and J. Karlshoej (2012). Information delivery manuals to integrate building product information into design, ITcon.

Bhatia, A., J. Mathur and V. Garg (2011). "Calibrated simulation for estimating energy savings by the use of cool roof in five Indian climatic zones." Journal of Renewable and Sustainable Energy **3**(2): 023108.
Bogenstätter, U. (2000). "Prediction and optimization of life-cycle costs in early design." Building Research & Information **28**(5-6): 376-386.
Bushby, S. T. (1997). "BACnet TM: a standard communication infrastructure for intelligent buildings." Automation in Construction **6**(5): 529-540.
Cemesova, A., C. Hopfe and Y. Rezgui (2012). "PassivBIM–a new approach for low energy simulation using BIM." eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2012: 29.
Cemesova, A., C. Hopfe and Y. Rezgui (2013). "An approach to facilitating data exchange between BIM environments and a low energy design tool." Building Simulation 2013, Chambery, France: 8.
Chen, C., H. Dib and G. Lasker (2011). Benefits of implementing building information modeling for healthcare facility commissioning. Proc., 2011 ASCE International Workshop on Computing in Civil Engineering.
Chen, J., T. Bulbul, J. E. Taylor and G. Olgun A Case Study of Embedding Real-time Infrastructure Sensor Data to BIM. Construction Research Congress 2014@ sConstruction in a Global Network, ASCE.
Chen, J., T. Bulbul, J. E. Taylor and G. Olgun (2014). A Case Study of Embedding Real-time Infrastructure Sensor Data to BIM. Construction Research Congress 2014@ sConstruction in a Global Network, ASCE.
Christensen, L. B., B. Johnson and L. A. Turner (2011). Research methods, design, and analysis, Allyn & Bacon.
Clarke, J. (2007). Energy simulation in building design, Routledge.
Clarke, J., J. Cockroft, S. Conner, J. Hand, N. Kelly, R. Moore, T. O'Brien and P. Strachan (2001). "Control in building energy management systems: the role of simulation."
Clarke, J., J. Cockroft, S. Conner, J. Hand, N. Kelly, R. Moore, T. O'Brien and P. Strachan (2002). "Simulation-assisted control in building energy management systems." Energy and buildings **34**(9): 933-940.
Clarke, J., P. Strachan and C. Pernot (1993). "An approach to the calibration of building energy simulation models." TRANSACTIONS-AMERICAN SOCIETY OF HEATING REFRIGERATING AND AIR CONDITIONING ENGINEERS **99**: 917-917.
Clarke, J. A. (2001). Energy simulation in building design, Routledge.
Cormier, A., S. Robert, P. Roger, L. Stephan and E. Wurtz (2011). Towards a BIM-based service oriented platform: application to building energy performance simulation. Proceedings of the 12th Conference of International Building Performance Simulation Association, Sydney, Australia.
Costa, A., M. Keane, P. Raftery and J. O'Donnell (2009). "Key factors-methodology for enhancement and support of building energy performance." Building Simulation, Glasgow, UK.
Costa, A., M. M. Keane, P. Raftery and J. O'Donnell (2012). "Key factors methodology—A novel support to the decision making process of the building energy manager in defining optimal operation strategies." Energy and Buildings **49**: 158-163.
Crosbie, T., N. Dawood and S. Dawood (2011). "Improving the energy performance of the built environment: The potential of virtual collaborative life cycle tools." Automation in Construction **20**(2): 205-216.

Cumali, Z. (1988). "Global optimization of HVAC system operations in real time." ASHRAE transactions **94**(3112): 1729-1744.

Diamond, R., M. Opitz, T. Hicks, B. Von Neida and S. Herrera (2006). Evaluating the energy performance of the first generation of LEED-certified commercial buildings, Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).

Dong, B., K. Lam, Y. Huang and G. Dobbs (2007). "A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments." Tenth International IBPSA Conference.

Dong, B., Z. O'Neill and Z. Li (2014). "A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics." Automation in Construction **44**: 197-211.

Doukas, H., C. Nychtis and J. Psarras (2009). "Assessing energy-saving measures in buildings through an intelligent decision support model." Building and environment **44**(2): 290-298.

Doukas, H., K. D. Patlitzianas, K. Iatropoulos and J. Psarras (2007). "Intelligent building energy management system using rule sets." Building and Environment **42**(10): 3562-3569.

Eastman, C., P. Teicholz, R. Sacks and K. Liston (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors, John Wiley & Sons.

Elmasri, R. and S. Navathe (2010). Fundamentals of database systems, Addison-Wesley Publishing Company.

Fazio, P., H. He, A. Hammad and M. Horvat (2007). "IFC-based framework for evaluating total performance of building envelopes." Journal of architectural engineering **13**(1): 44-53.

Fellows, R. F. and A. M. Liu (2009). Research methods for construction, John Wiley & Sons.

Glick, S. and A. Guggemos (2009). IPD and BIM: benefits and opportunities for regulatory agencies. Proceedings of the 45th ASC National Conference, Gainesville, Florida, April.

Guglielmetti, R., D. Macumber and N. Long (2011). OpenStudio: an open source integrated analysis platform, National Renewable Energy Lab.(NREL), Golden, CO (United States).

Gupta, A., A. Cemesova, C. J. Hopfe, Y. Rezgui and T. Sweet (2014). "A conceptual framework to support solar PV simulation using an open-BIM data exchange standard." Automation in Construction **37**: 166-181.

Han, J., Y.-K. Jeong and I. Lee (2011). Efficient building energy management system based on ontology, inference rules, and simulation. Proceedings of the 2011 International Conference on Intelligent Building and Management, Singapore.

Harmer, L. C. and G. P. Henze (2015). "Using calibrated energy models for building commissioning and load prediction." Energy and Buildings **92**: 204-215.

Harris, D. (2012). A guide to energy management in buildings, Spon Press London.

Hensen, J. L. and R. Lamberts (2012). Building performance simulation for design and operation, Routledge.

Hetherington, R. (2013). The Integration of Architectural Design and Energy Modelling Software, The Open University.

Hitchcock, R. J. (2002). "Software interoperability for energy simulation." Lawrence Berkeley National Laboratory.

Hitchcock, R. J. and J. Wong (2011). Transforming IFC architectural view BIMs for energy simulation: 2011. Proceedings of building simulation.

Hong, T., S. Chou and T. Bong (2000). "Building simulation: an overview of developments and information sources." Building and environment **35**(4): 347-361.
IPMVP (2001). International Performance Measurement and Verification Protocol: Concepts and options for determining energy and water savings, Volume I, National Renewable Energy Lab., Golden, CO (US).
Jankovic, L. (2013). Designing zero carbon buildings using dynamic simulation methods, Routledge.
Jiang, Y., J. Ming, D. Wu, J. Yen, P. Mitra, J. Messner and R. Leicht (2012). "BIM server requirements to support the energy efficient building lifecycle."
Kastner, W., G. Neugschwandtner, S. Soucek and H. Newmann (2005). "Communication systems for building automation and control." Proceedings of the IEEE **93**(6): 1178-1203.
Keele, S. (2007). Guidelines for performing systematic literature reviews in software engineering. Technical report, Ver. 2.3 EBSE Technical Report. EBSE.
Keller, M., J. O'Donnell, K. Menzel, M. Keane and U. Gokce (2008). "Integrating the specification, acquisition and processing of building performance information." Tsinghua Science and Technology **13**(1): 1-6.
Levermore, G. J. (2000). Building Energy Management Systems: Applications to low-energy HVAC and natural ventilation control, Taylor & Francis.
Lilis, G. N., G. I. Giannakis and D. V. Rovas (2017). "Automatic generation of second-level space boundary topology from IFC geometry inputs." Automation in Construction **76**: 108-124.
Liu, M. and D. Claridge (1998). "Use of calibrated HVAC system models to optimize system operation." Journal of solar energy engineering **120**(2): 131-138.
Liu, R., R. Issa and S. Olbina (2010). Factors influencing the adoption of building information modeling in the AEC Industry. Proceedings International Conference on Computing in Civil and Building Engineering (ICCCBE 2010), June.
Liu, X. and B. Akinci (2009). "Requirements and evaluation of standards for integration of sensor data with building information models." Computing in Civil Engineering: 10.
MacLeamy, P. (2004). "Collaboration, integrated information and the project lifecycle in building design, construction and operation." WP-1202, The Construction Users Roundtable.
Maile, T., M. Fischer and V. Bazjanac (2007). "Building energy performance simulation tools-a life-cycle and interoperable perspective." Center for Integrated Facility Engineering (CIFE) Working Paper **107**: 1-49.
Maile, T., M. Fischer and V. Bazjanac (2010). "A method to compare measured and simulated data to assess building energy performance." Comparing Measured and Simulated Building Energy Performance Data: 18.
Merz, H., T. Hansemann and C. Hübner (2009). Building Automation: Communication Systems with EIB/KNX, LON and BACnet, Springer Science & Business Media.
Miles, M. B. and A. M. Huberman (1994). Qualitative data analysis: An expanded sourcebook, Sage.
Moon, H. J., M. S. Choi, S. K. Kim and S. H. Ryu (2011). Case studies for the evaluation of interoperability between a bim based architectural model and building performance analysis programs. Proceedings of 12th Conference of International Building Performance Simulation Association.
Moss, K. (2006). Energy management in Buildings, Taylor & Francis.
Motawa, I. and K. Carter (2013). "Sustainable BIM-based evaluation of buildings." Procedia-Social and Behavioral Sciences **74**: 419-428.

Naumann, J. D. and A. M. Jenkins (1982). "Prototyping: the new paradigm for systems development." Mis Quarterly: 29-44.
Newsham, G. R., S. Mancini and B. J. Birt (2009). "Do LEED-certified buildings save energy? Yes, but…." Energy and Buildings **41**(8): 897-905.
NIBS (2008). National Building Information Modeling Standard, National Institute of Building Sciences National Institute of Building Sciences

Facilities Information Council Facilities Information Council**:** DF-1.
O'Donnell, J. (2012). "SimModel: A domain data model for whole building energy simulation."
O'Donnell, J. (2013). "SimModel: A domain data model for whole building energy simulation." SimBuild 2011, Sydney, Australia, 11/14/2011-11/16/2011.
Osello, A., G. Cangialosi, D. Dalmasso, A. Di Paolo, M. L. Turco, P. Piumatti and M. Vozzola (2011). Architecture data and energy efficiency simulations: BIM and interoperability standards. proceedings of Building Simulation.
Ozturk, Z., Y. Arayici and S. Coates (2012). "Post occupancy evaluation (POE) in residential buildings utilizing BIM and sensing devices: Salford energy house example."
Pan, Y., Z. Huang and G. Wu (2007). "Calibrated building energy simulation and its application in a high-rise commercial building in Shanghai." Energy and Buildings **39**(6): 651-657.
Pan, Y., Z. Huang, G. Wu and C. Chen (2006). "The application of building energy simulation and calibration in two high-rise commercial buildings in Shanghai." Proceedings of SimBuild: 2-4.
Pérez-Lombard, L., J. Ortiz and C. Pout (2008). "A review on buildings energy consumption information." Energy and Buildings **40**(3): 394-398.
Petticrew, M. and H. Roberts (2008). Systematic reviews in the social sciences: A practical guide, John Wiley & Sons.
Pinheiro, S., J. O'Donnell, R. Wimmer, V. Bazjanac, S. Muhic, T. Maile, J. Frisch and C. Van Treeck (2016). Model view definition for advanced building energy performance simulation. CESBP/BauSIM 2016 Conference, Dresden, Berlin.
Plume, J. and J. Mitchell (2007). "Collaborative design using a shared IFC building model—Learning from experience." Automation in Construction **16**(1): 28-36.
Pratt, M. J. (2001). "Introduction to ISO 10303—the STEP standard for product data exchange." Journal of Computing and Information Science in Engineering **1**(1): 102-103.
Raftery, P., M. Keane and A. Costa (2009). Calibration of a detailed simulation model to energy monitoring system data: a methodology and case study. Eleventh International IBPSA Conference, Citeseer.
Robson, C. (2002). Real world research, Blackwell publishers Oxford.
Robson, C. and K. McCartan (2016). Real world research, Wiley.
Salsbury, T. and R. Diamond (2000). "Performance validation and energy analysis of HVAC systems using simulation." Energy and Buildings **32**(1): 5-17.
Sanguinetti, P., C. Eastman and G. Augenbroe (2009). Courthouse energy evaluation: BIM and simulation model interoperability in concept design. Eleventh International IBPSA Conference.
Schlueter, A. and F. Thesseling (2009). "Building information model based energy/exergy performance assessment in early design stages." Automation in construction **18**(2): 153-163.
Scofield, J. H. (2009). "Do LEED-certified buildings save energy? Not really…." Energy and Buildings **41**(12): 1386-1390.

See, R., P. Haves, P. Sreekanthan, J. O'Donnell, M. Basarkar and K. Settlemyre (2011). Development of a user interface for the EnergyPlus whole building energy simulation program. Proceedings of the 12th International IBPSA Conference, Sydney, Australia.
Stoppel, C. M. and F. Leite (2013). "Evaluating building energy model performance of LEED buildings: Identifying potential sources of error through aggregate analysis." Energy and Buildings **65**: 185-196.
Teicholz, P. (2013). BIM for facility managers, John Wiley & Sons.
Trčka, M. and J. L. Hensen (2010). "Overview of HVAC system simulation." Automation in Construction **19**(2): 93-99.
Tupper, K., E. Franconi, C. Chan, S. Hodgin, A. Buys and M. Jenkins (2011). Building energy modeling: industry-wide issues and potential solutions. Proceedings of the 12th Conference of International Building Performance Simulation Association.
Volk, R., J. Stengel and F. Schultmann (2014). "Building Information Modeling (BIM) for existing buildings—Literature review and future needs." Automation in construction **38**: 109-127.
Webster, L., J. Bradford, D. Sartor, J. Shonder, E. Atkin, S. Dunnivant and B. Slattery (2015). "M&V Guidelines: Measurement and Verification for Performance-Based Contracts-Version 4.0." Federal Energy Management Program, November.
Weise, M., T. Liebich, R. See, V. Bazjanac, T. Laine and B. Welle (2011). "Implementation guide: Space boundaries for energy analysis." General Services Administration (GSA) and Open Geospatial Consortium (OSC).
Wetter, M. (2008). "A modular building controls virtual test bed for the integrations of heterogeneous systems." Lawrence Berkeley National Laboratory.
Yin, R. K. (2013). Case study research: Design and methods, Sage publications.
Yoon, J., E.-J. Lee and D. Claridge (2003). "Calibration procedure for energy performance simulation of a commercial building." Journal of solar energy engineering **125**(3): 251-257.
Zhou, D. and S. H. Park (2012). "Simulation-assisted management and control over building energy efficiency–a case study." Energy Procedia **14**: 592-600.

Appendix A. Systematic Literature Review List

No	Year	Title	Author	Publication Name	Publication Type	Research Area
1	2007	Data-centric simulation interoperability using the DeST simulation platform	Yi, Y. K., Lee, J., Malkawi, A. M., Wang, C., Jiang, Y. and Yan, D.	Building Simulation 2007	Conference	BIM and BES
2	2008	IFC BIM-based methodology for semi-automated building energy performance simulation	Bazjanac, Vladimir	CIB-W78 25th International Conference on Information Technology in Construction	Conference	BIM and BES
3	2009	Implementation of semi-automated energy performance simulation: building geometry	Bazjanac, Vladimir	CIB W (Vol. 78, pp. 595-602).	Conference	BIM and BES
4	2009	A data-warehouse architecture supporting energy management of buildings	Gökçe, HU, Wang, Y, Gökçe, KU and Menzel, K	CIB 26th W78 Managing IT in Construction/Managing Construction for Tomorrow	Conference	BIM and BAS
5	2009	Using building information model data for generating and updating diagnostic models	Provan, G, Ploennigs, J, Boubekeur, M, Mady, A and Ahmed, A	Conf. on Civil Engineering and Computing (August 2009)	Conference	BIM/BES/BAS
6	2009	Courthouse energy evaluation: BIM and simulation model interoperability in concept design	Sanguinetti, Paola, Eastman, Charles and Augenbroe, Godfried	Conference Proceedings	Conference	BIM and BES
7	2010	BIM-based generation of multi-model views	Katranuschkov, Peter, Weise, Matthias, Windisch, Ronny, Fuchs, Sebastian and Scherer, Raimar J	CIB W78	Conference	BIM and BAS
8	2011	SimModel: A domain data model for whole building energy simulation	James O'Donnell1, Richard See2 , Cody Rose1 , Tobias Maile1 , Vladimir Bazjanac1 and Phil Haves1	12th Conference of International Building Performance Simulation Association	Conference	BIM and BES
9	2011	Towards a BIM-based service oriented platform: application to building energy performance simulation	Cormier, Anthony, Robert, Sylvain, Roger, Pierrick, Stephan, Louis and Wurtz, Etienne	Proceedings of Building Simulation 2011	Conference	BIM and BES
10	2011	Energy Simulation System Using BIM (Building Information Modeling)	Kim, Hyunjoo and Anderson, Kyle	Computing in Civil Engineering (2011)	Conference	BIM and BES
11	2011	ThermalOpt: A methodology for automated BIM-based multidisciplinary thermal	Welle, B., Haymaker, J. and Rogers, Z.	Building Simulation	Journal	BIM and BES

		simulation for use in optimization environments				
12	2012	An integrated infrastructure for real-time building energy modeling and fault detection and diagnostics	Dong, Bing, O'Neill, Zheng, Li, ZhengWei, Luo, Dong, Madhusudana, Shashanaka, Ahuja, Sunil and Bailey, Trevor	Proceedings of SimBuild	Conference	BIM/BES/BAS
13	2012	Integrated system architecture for optimised building operations	Goekce, H. Ufuk and Goekce, K. Umut	European Conferences of Product and Process Modelling conference 2012	Conference	BIM/BES/BAS
14	2012	Energy Modeling System Using Building Information Modeling Open Standards	Kim, Hyunjoo and Anderson, Kyle	Journal of Computing in Civil Engineering	Journal	BIM and BES
15	2012	Development of an IFC-based IDF converter for supporting energy performance assessment in the early design phase	Kim, Inhan, Kim, Jieun and Seo, Jongcheol	Journal of Asian Architecture and Building Engineering	Journal	BIM and BES
16	2013	An approach to facilitating data exchange between BIM environments and a low energy design tool	Cemesova, A, Hopfe, CJ and Rezgui, Y	13th Conference of International Building Performance Simulation Association	Conference	BIM and BES
17	2013	Linking building data in the cloud: Integrating cross-domain building data using linked data	Curry, Edward, O'Donnell, James, Corry, Edward, Hasan, Souleiman, Keane, Marcus and O'Riain, Seán	Advanced Engineering Informatics	Journal	BIM and BAS
18	2013	A HIGH LEVEL ARCHITECTURE FRAMEWORK FOR COUPLING BUILDING ENERGY PERFORMANCE MODELS	Menassa, Carol C, Kamat, Vineet R, Lee, SangHyun, Azar, Elie, Feng, Chen and Anderson, Kyle	13th Conference of International Building Performance Simulation Associati	Conference	BIM and BES
19	2013	A BIM-based data model for an integrated building energy information management in the design and operational stages	Moon, Hyeun Jun, Kim, Byung Koo and Choi, Min Seo	The 13th Conference of International Building Performance Simulation Association, Chambery, France. 2013.	Conference	BIM and BAS
20	2013	Advanced building energy management system demonstration for Department of Defense buildings	O'neill, Zheng, Bailey, Trevor, Dong, Bing, Shashanka, Madhusudana and Luo, Dong	Annals of the New York Academy of Sciences	Journal	BIM/BES/BAS
21	2013	Using a BIM flow for the design and operation of Building Energy Management Systems	Pit StenzelJürgen HaufeNoemi Jimenez Redondo	ICT for Sustainable Place, 4th Workshop on eeB Data Models	Conference	BIM/BES/BAS
22	2013	Integrated system platform for energy efficient building operations	Ufuk Gökçe, H and Umut Gökçe, K	Journal of Computing in Civil Engineering	Journal	BIM/BES/BAS
23	2013	Methodology to Develop Ontological Building Information Model for Energy Management System in Building Operational Phase	Wicaksono, Hendro, Dobreva, Preslava, Häfner, Polina and Rogalski, Sven	International Joint Conference on Knowledge Discovery, Knowledge Engineering,	Conference	BIM/BES/BAS

24	2013	Interfacing BIM with building thermal and daylighting modeling	Yan, Wei, Clayton, Mark, Haberl, Jeff, WoonSeong, Jeong, Bun Kim, Jong, Sandeep, Kota, Bermudez, Jose and Dixit, Manish	BS2013	Conference	BIM and BES
25	2014	Model transformation from Sim-Model to Modelica for building energy performance simulation	Cao, Jun, Maile, Tobias, O'Donnell, James, Wimmer, Reinhard and van Treeck, Christoph	*Proceedings of the 5th German-Austrian IBPSA Conference*. 2014.	Conference	BIM and BES
26	2014	A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics	Dong, Bing, O'Neill, Zheng and Li, Zhengwei	Automation in Construction	Journal	BIM/BES/BAS
27	2014	Multi dimensional energy monitoring, analysis and optimization system for energy efficient building operations	Gökçe, H Ufuk and Gökçe, K Umut	Sustainable Cities and Society	Journal	BIM/BES/BAS
28	2014	A conceptual framework to support solar PV simulation using an open-BIM data exchange standard	Gupta, Apeksha, Cemesova, Alexandra, Hopfe, Christina, Rezgui, Yacine and Sweet, Tracy	Automation in Construction	Journal	BIM and BES
29	2014	Translating building information modeling to building energy modeling using model view definition	Jeong, WoonSeong, Kim, Jong Bum, Clayton, Mark J, Haberl, Jeff S and Yan, Wei	The Scientific World Journal	Journal	BIM and BES
30	2014	Building Information Modeling (BIM)-based daylighting simulation and analysis	Kota, Sandeep, Haberl, Jeff S., Clayton, Mark J. and Yan, Wei	Energy and Buildings	Journal	BIM and BES
31	2014	Semi-automatic thermal simulation model generation from IFC data	Lilis, GN, Giannakis, GI, Kontes, GD and Rovas, DV	Proc. of European Conference on Product and Process Modelling,	Conference	BIM and BES
32	2014	Application of a BIM-based data model for the evaluation of real-time building energy performance in the operational stage	Moon, H and Choi, MS	IBPSA Asia Conference	Conference	BIM/BES/BAS
33	2014	An approach to enhancing the connection between BIM models and building energy simulation–HVAC systems in the loop	Robert, Sylvain, Mazza, Davide, Hilaire, Bruno, Sette, Paul and Vinot, Benoît	ECPPM 2014	Conference	BIM and BES
34	2014	Towards the implementation of a 3d heat transfer analysis in dynamic-BIM (dynamic building information modeling) workbench	Srinivasan, R. S., Thakur, S., Parmar, M. and Akhmed, I.	2014 Winter Simulation Conference	Conference	BIM and BES
35	2014	Using a Multi-Model for a BIM-based Design and Operation of Building Energy Management Systems	Stenzel, P, Haufe, J and Jimenez-Redondo, N	10th European Conference on Product and Process Modelling (ECPPM 2014)	Conference	BIM/BES/BAS
36	2014	Data-requirements specification to support BIM-based HVAC-definitions in Modelica	Wimmer, Richard, Maile, Tobias and O'Donnell, James T	*BauSIM 2014, Aachen, Germany, September, 2014*. 2014.	Conference	BIM and BES
37	2015	Sensor handling in building information models. Development of a method and application on a case study	Andriamamonjy, Ando, Klein, Ralf and Saelens, Dirk	14th Conference of International Building Performance Simulation Association, H	Conference	BIM/BES/BAS

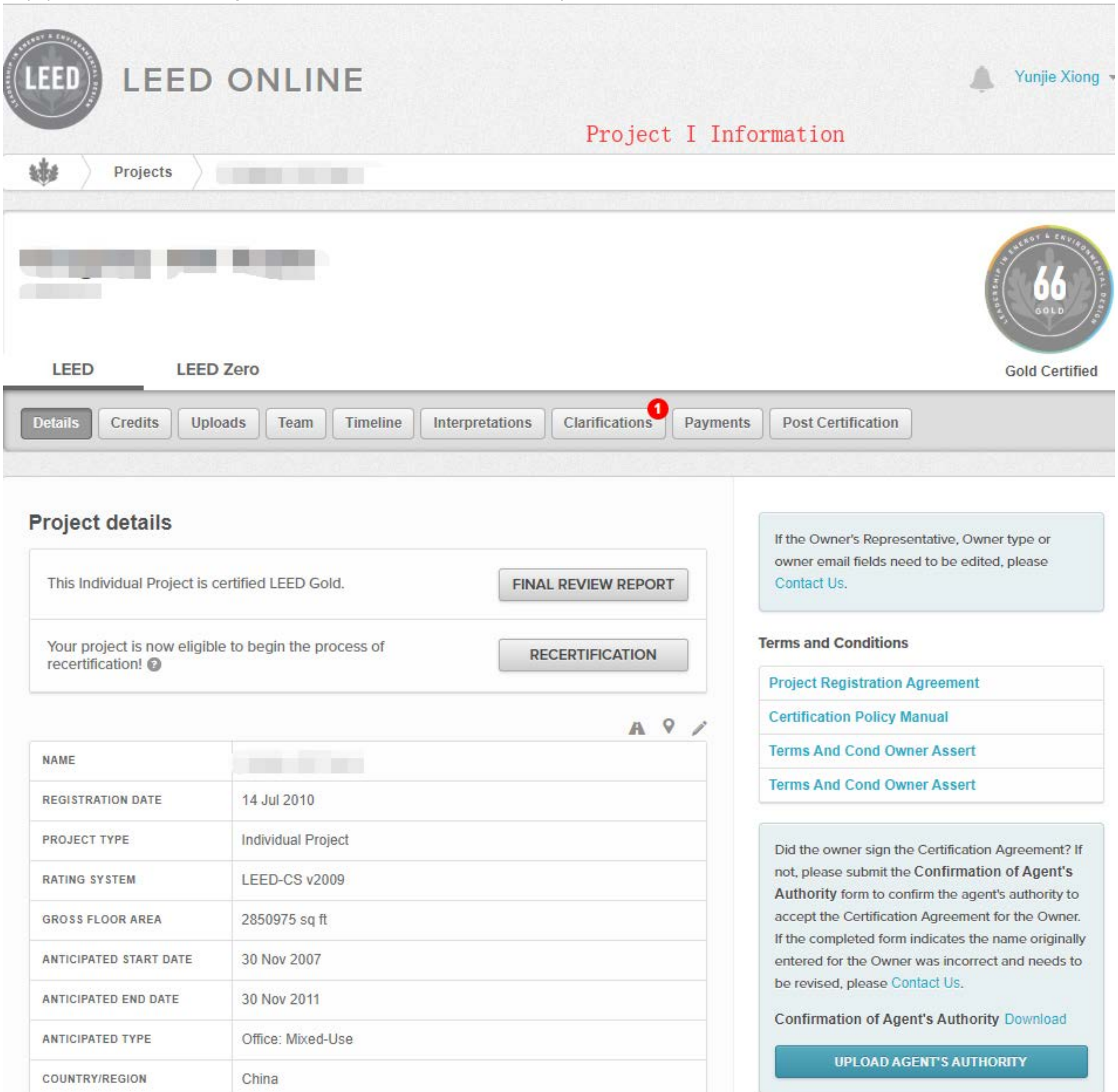
38	2015	A flexible model transformation to link BIM with different Modelica libraries for building energy performance simulation	Cao, Jun, Wimmer, Reinhard, Thorade, Matthis, Maile, Tobias, O'Donnel, James, Rädler, Jörg, Frisch, Jérôme and van Treeck, Christoph	*Proceedings of the 14th IBPSA Conference*.	Conference	BIM and BES
39	2015	PassivBIM: Enhancing interoperability between BIM and low energy design software	Cemesova, Alexandra, Hopfe, Christina J and Mcleod, Robert S	Automation in Construction	Journal	BIM and BES
40	2015	Interoperability from building design to building energy modeling	Garcia, E. G. and Zhu, Z.	Journal of Building Engineering	Journal	BIM and BES
41	2015	A methodology to automatically generate geometry inputs for energy performance simulation from IFC BIM models	Giannakis, GI, Lilis, GN, Garcia, MA, Kontes, GD, Valmaseda, C and Rovas, DV	BS2015	Conference	BIM and BES
42	2015	Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling	Ham, Youngjib and Golparvar-Fard, Mani	Automation in Construction	Journal	BIM/BES/BAS
43	2015	Sustainable Design of Buildings using Semantic BIM and Semantic Web Services	Niknam, Mehrdad and Karshenas, Saeed	International Conference on Sustainable Design, Engineering and Construction	Conference	BIM and BES
44	2015	An open framework for integrated BIM-based building performance simulation using Modelica	Remmen, Peter, Cao, Jun, Ebertshäuser, Sebastian, Frisch, Jérôme, Lauster, Moritz, Maile, Tobias, O'Donnell, James, Pinheiro, Sergio, Rädler, Jörg and Streblow, Rita	14th Building Performance Simulation Conference, Hyderabad, India. 2015	Conference	BIM and BES
45	2015	An algorithm to generate space boundaries for building energy simulation	Rose, Cody M and Bazjanac, Vladimir	Engineering with Computers	Journal	BIM and BES
46	2015	An open toolchain for generating Modelica code from Building Information Models	Thorade, Matthis, Rädler, Jörg, Remmen, Peter, Maile, Tobias, Wimmer, Reinhard, Cao, Jun, Lauster, Moritz, Nytsch-Geusen, Christoph, Müller, Dirk and van Treeck, Christoph	Proceedings of the 11th International Modelica Conference	Conference	BIM and BES
47	2015	Service-oriented architecture for data exchange between a building information model and a building energy model	Zhao, Hu, Nagy, Zoltán, Thomas, Daren and Schlueter, Arno	Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale (	Conference	BIM and BES
48	2015	A framework to integrate object-oriented physical modelling with building information modelling for building thermal simulation	Jeong, WoonSeong, Kim, Jong Bum, Clayton, Mark J, Haberl, Jeff S and Yan, Wei	Journal of Building Performance Simulation	Journal	BIM and BES

49	2016	BIM enabled building energy modelling: development and verification of a GBXML to IDF conversion method	Dimitriou, Vanda, Firth, Steven K, Hassan, Tarek M and Fouchal, Farid	Proceedings of the 3rd IBPSA-England Conference BSO 2016, Great North Museum, Newcastle, 12th-14th September 2016.	Conference	BIM and BES
50	2016	An algorithm to translate building topology in building information modeling into Object-Oriented physical modeling-based building energy modeling	Jeong, WoonSeong and Son, JeongWook	Energies	Journal	BIM and BES
51	2016	BIM IFC information mapping to building energy analysis (BEA) model with manually extended material information	Kim, Hyunjoo, Shen, Zhenhua, Kim, Inhan, Kim, Karam, Stumpf, Annette and Yu, Jungho	Automation in Construction	Journal	BIM and BES
52	2016	Computational geometry in the context of building information modeling	Ladenhauf, Daniel, Battisti, Kurt, Berndt, René, Eggeling, Eva, Fellner, Dieter W, Gratzl-Michlmair, Markus and Ullrich, Torsten	Energy and buildings	Journal	BIM and BES
53	2016	Geometry simplification according to semantic constraints	Ladenhauf, Daniel, Berndt, René, Krispel, Ulrich, Eggeling, Eva, Ullrich, Torsten, Battisti, Kurt and Gratzl-Michlmair, Markus	Computer Science-Research and Development	Journal	BIM and BES
54	2016	A study on data visualization of embedded sensors for building energy monitoring using BIM	Lee, Donghwan, Cha, Gichun and Park, Seunghee	INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 17, No. 6, pp. 807-814	Journal	BIM and BAS
55	2016	A versatile and extensible solution to the integration of BIM and energy simulation	Mazza, D., El Asmi, E., Robert, S., Zreik, K. and Hilaire, B.	Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016),	Conference	BIM and BES
56	2016	A framework for the utilization of Building Management System data in building information models for building design and operation	Oti, AH, Kurul, E, Cheung, F and Tah, JHM	Automation in Construction	Journal	BIM/BES/BAS
57	2016	Model view definition for advanced building energy performance simulation	Pinheiro, S, Donnell, JO, Wimmer, R, Bazjanac, V, Muhic, S, Maile, T, Frisch, J and Van Treeck, C	Proceeding of the CESBP Central European Symbosium on Building Physics and BauSIM 2016	Conference	BIM and BES
58	2016	Leveraging Building Information Models in IFC to Perform Energy Analysis in OpenStudio	Ramaji, Issa J, Messner, John I and Leicht, Robert M	Proceedings of SimBuild	Conference	BIM and BES
59	2016	IFC BIM-Based Facility Management Approach to Optimize Data Collection for Corrective Maintenance	Shalabi, Firas and Turkan, Yelda	Journal of Performance of Constructed Facilities	Journal	BIM and BAS

60	2017	BIMSL: a generic approach to the integration of building information models with real-time sensor data	Alves, Miguel, Carreira, Paulo and Costa, António Aguiar	Automation in Construction	Journal	BIM and BAS
61	2017	Building Information Modeling (BIM) Enabled Facilities Management Using Hadoop Architecture	Arslan, M., Riaz, Z. and Munawar, S.	2017 Proceedings of PICMET '17: Technology Management for Interconnected World	Conference	BIM and BAS
62	2017	Building energy modelling and monitoring by integration of IoT devices and Building Information Models	Bottaccioli, Lorenzo, Aliberti, Alessandro, Ugliotti, Francesca, Patti, Edoardo, Osello, Anna, Macii, Enrico and Acquaviva, Andrea	2017 IEEE 41st Annual (Vol. 1, pp. 914-922). IEEE.	Conference	BIM/BES/BAS
63	2017	Implementation of Cloud BIM-based Platform Towards High-performance Building Services	Chien, S. C., Chuang, T. C., Yu, H. S., Han, Y., Soong, B. H. and Tseng, K. J.	International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16	Conference	BIM and BAS
64	2017	BIM application to building energy performance visualisation andmanagement: Challenges and potential	potentialTristan Gerrisha,b,∗, Kirti Ruikara, Malcolm Cooka, Mark Johnsonb, Mark Phillipb,Christine LowrybaLoughborough	Energy and Buildings	Journal	BIM and BAS
65	2017	Automatic generation of second-level space boundary topology from IFC geometry inputs	Lilis, Georgios N., Giannakis, Georgios I. and Rovas, Dimitrios V.	Automation in Construction	Journal	BIM and BES
66	2017	Integrating 4D thermal information with BIM for building envelope thermal performance analysis and thermal comfort evaluation in naturally ventilated environments	Natephra, Worawan, Motamedi, Ali, Yabuki, Nobuyoshi and Fukuda, Tomohiro	Building and Environment	Journal	BIM/BES/BAS
67	2017	Integration of BIM and utility sensor data for facilities management	Suprabhas, Kamal and Dib, Hazar Nicholas	*Computing in Civil Engineering 2017* (pp. 26-33).	Conference	BIM and BAS
68	2018	An automated IFC-based workflow for building energy performance simulation with Modelica	Andriamamonjy, Ando, Saelens, Dirk and Klein, Ralf	Automation in Construction	Journal	BIM and BES
69	2018	An IFC-based interoperable framework for building linked-data	Hernández, José L, Lerones, Pedro Martín, Álvarez, Sonia, Bonsma, Peter, van Delft, Andrè, Deighton, Richard and Braun, Jan-Derrick	6th Linked Data in Architecture and Construction Workshop	Conference	BIM and BAS
70	2018	Automated Building Energy Modeling and Assessment Tool (ABEMAT)	Kamel, Ehsan and Memari, Ali M	Energy	Journal	BIM and BES
71	2018	MVD based information exchange between BIM and building energy performance simulation	Pinheiro, Sergio, Wimmer, Reinhard, O'Donnell, James, Muhic, Sergej, Bazjanac, Vladimir, Maile, Tobias, Frisch, Jérôme and van Treeck, Christoph	Automation in Construction	Journal	BIM and BES

72	2018	Software Tool for Automation in Building Energy Simulation Using Building Information Modeling (BIM)	Ehsan Kamel1, Ali M. Memari2	4th Residential Building Design & Construction Conference	Conference	BIM and BES

Appendix B Project Information (Snapshots)



LEED ONLINE

Yunjie Xiong

Project I Information

Projects

LEED | LEED Zero

Gold Certified

Details | Credits | Uploads | Team | Timeline | Interpretations | Clarifications | Payments | Post Certification

Project details

This Individual Project is certified LEED Gold. **FINAL REVIEW REPORT**

Your project is now eligible to begin the process of recertification! **RECERTIFICATION**

NAME	
REGISTRATION DATE	14 Jul 2010
PROJECT TYPE	Individual Project
RATING SYSTEM	LEED-CS v2009
GROSS FLOOR AREA	2850975 sq ft
ANTICIPATED START DATE	30 Nov 2007
ANTICIPATED END DATE	30 Nov 2011
ANTICIPATED TYPE	Office: Mixed-Use
COUNTRY/REGION	China

If the Owner's Representative, Owner type or owner email fields need to be edited, please Contact Us.

Terms and Conditions

- Project Registration Agreement
- Certification Policy Manual
- Terms And Cond Owner Assert
- Terms And Cond Owner Assert

Did the owner sign the Certification Agreement? If not, please submit the **Confirmation of Agent's Authority** form to confirm the agent's authority to accept the Certification Agreement for the Owner. If the completed form indicates the name originally entered for the Owner was incorrect and needs to be revised, please Contact Us.

Confirmation of Agent's Authority Download

UPLOAD AGENT'S AUTHORITY

[illegible]-EA Cr 5.1 - Measurement & Verification Plan (Base Building)

Project I M&V Plan Cover

Introduction

The Measurement and Verification (M&V) Plan of [illegible] is developed in accordance with the International Performance Measurement & Verification Protocol (IPMVP) Volume III: Concepts and Options for Determining Energy Savings in New Construction, April, 2003. The project will utilize Option D: Whole Building Calibrated Simulation (Savings Estimation Method 2). Option D allows [illegible] to use the building metering facilities and building energy model to verify the energy use and saving of the project.

This M&V plan aims at evaluating the building performance. The primary item that will be measured and verified is the overall building energy use, which will be compared to the projected energy use and the ASHRAE 90.1-2007 compliant baseline energy use to document and verify savings. Energy use will be metered and sub-metered, together with the building automation and management system operation, which will provide the ability to monitor the building energy use and verify the energy savings associated with various systems and components.

The building management team will be responsible for performing the M&V with including the simulation calibration and ultimately to calculate the projected savings between the actual energy use of the facility and the simulated energy use of the baseline building.

1.0 Objectives and Motivations of Measurement and Verification

The primary objectives and motivations of M&V are as follows:

- Increase energy savings: The approaches and building facilities for the M&V purposes can provide building owner and operators the feedback on the building operations and managements and provide them the ability to verify the energy use calibrated as necessary to reflect actual building energy use with taking into account the actual operation including equipment and/or building operating schedules, temperature setpoints, and actual weather, etc. The calibrated models and the measured results will then be used to determine the difference between the actual energy consumption of the building and the potential energy consumption of the building, and subsequently represent the energy savings estimation.

3.5 Implementation of M&V

The building management team is responsible for the operation and maintenance of the building facilities and equipment including the building management system (BMS). TWith the implementation of M&V, the building management team will perform all the M&V issues including the data tracking and analysis; performance / energy calculation; simulation calibration (the as-built and baseline simulation models are required to have calibration according to the measuring result including weather conditions, occupancy, system operating status / hours and etc.); and the project savings calculation between the actual energy use of the facilities and the simulation energy use of the baseline building.

The M & V period will be recommended for two successive years starting after the building opens for occupancy. The second year will allow the evaluation of operational changes made after occupancy.

4.0 Energy Measuring

Project I M&V plan

4.1 Energy Conservation Measures (ECMs)

Kingkey 100 Tower has incorporated several energy conserving measures which are expected to collectively reduce the energy use of the buildings when compared to the code compliant baseline. The following ECMs are included, but not limited to, in the M&V for identifying and analyzing the operating parameters/performance of the ECMs:

- Thermal Ice Storage System
- Chillers
- Heat recovery system
- Air and water economizer
- Ventilation demand control
- Lighting system and controls

4.2 Metering Provisions and Measuring System

Electrical energy meters, water meters and air conditioning (AC) energy meters are installed for measurement and verification facilities.

Core & Shell Areas

Electrical energy meters will be installed in main switchboard to measure the electrical load in group.
They will measure the electricity consumption in below at the Core and Shell areas:

- Power and lighting for all public areas and public toilets;
- Power consumption for other major plants and equipment, such as chiller plants.

Water meters will be installed in the potable and rainwater plant rooms and provided for measuring the potable and rainwater usage in below at the Core and Shell areas:

Project I M&V plan

Table 4.1. Systems to be Sub-Metered and Monitored

System/Equipment to be Measured /Monitored	Parameters to be Measured/Monitored/Recorded	
Chiller System	1. To have direct measurement and record of the electricity consumption by the system. 2. To calculate the cooling load regarding on the measured parameters and thermal equations. 3. To monitor the system performance through the measured parameters recorded by BMS.	- Electricity consumption - Chilled water temperature (supply & return) - Chilled water flow rate - Condensing water temperature (supply & return) - Condensing water flow rate - System operating time/status
Heat Recovery System	1. To measure, monitor and record the required parameters and calculate the system energy saving together with using thermal equations. 2. To record and monitor the operating status of the dampers.	- Outdoor air temperature and RH - Exhaust air temperature and RH - Damper operating status - System operating time/status
Air Economizer	1. To measure, monitor and record the required parameters and calculate the system energy saving. 2. To record and monitor the operating status of the dampers.	- Outdoor air temperature and RH - Chilled water temperature (supply & return) - Chilled water flow rate - Indoor air temperature and RH - Damper operating status - System operating time/status
Water Economizer	1. To measure, monitor and record the required parameters and calculate the system energy saving.	- Outdoor air temperature and RH - Condensing water temperature (supply & return) - Chilled water temperature (supply & return) - System operating time/status
Ventilation Demand Control	1. To measure, monitor and record the required parameters and calculate the system energy saving. 2. To record and monitor the operating status of the CO_2 sensors.	- Outdoor air temperature and RH - Outdoor air flow rate - Indoor air temperature and RH (supply & return) - Supply air flow rate - Damper operating status - CO_2 sensor operating status - System operating time/status

4.5 *Implementation of M&V*

The building management team is responsible for the operation and maintenance of the building facilities and equipment including the building management system (BMS). With the implementation of M&V, the building management team will perform all the M&V issues including the data tracking and analysis; performance / energy calculation; simulation calibration (the as-built and baseline simulation models are required to have calibration according to the measuring result including weather conditions, occupancy, system operating status / hours and etc.); and the project savings calculation between the actual energy use of the facilities and the simulation energy use of the baseline building.

The M & V period will be recommended for two successive years starting after the building opens for occupancy. The second year will allow the evaluation of operational changes made after occupancy.

5. ***Energy Measuring***

5.1 *Energy Conservation Measures (ECMs)*

Suzhou Kaifa Factory Building has incorporated several energy conserving measures which are expected to collectively reduce the energy use of the buildings when compared to the code compliant baseline. The following ECMs are included, but not limited to, in the M&V for identifying and analyzing the operating parameters/performance of the ECMs:

- Cold Water Storage System
- Chillers
- Air and water economizer
- Lighting system and controls

Project II M&V plan

5.2 *Metering Provisions and Measuring System*

The measurement works in Suzhou Kaifa Factory Building are largely depends on the coordination of sub-metering devices and building management system.

The Power Quality Monitoring (PQM) system installed for monitoring the status(control and protection) of the medium & low voltage switchboard, transformers, generators and the control

The power consumption for some major equipment, such as HVAC system can be calculated by programming with the direct measured values on the own equipment and the BMS system recorded reading. And other necessary parameters shall be measured by BMS system in order to calculate the total energy consumption by MEP system. The BMS shall record the operating hours and invertors frequency (if any) of all AHU, PAU, Fans, Pumps, BIPV, lighting system, and base on the commissioning result, such as the operating performance of the equipment, including power consumption (kW), Current (A), etc. to calculate the energy consumption of the MEP system. The calculated value and also can be used as a reference data to compare with the actual measured readings by the PQM system. The monitoring and energy calculation details relevant to ECMS and other system / equipment are shown as below.

Project II M&V Plan

Table 5.1. Systems to be Sub-Metered and Monitored

System/Equipment to be Measured /Monitored	Parameters to be Measured/Monitored/Recorded	
Chiller System	1. To have direct measurement and record of the electricity consumption by the system. 2. To calculate the cooling load regarding on the measured parameters and thermal equations. 3. To monitor the system performance through the measured parameters recorded by BMS.	- Electricity consumption - Chilled water temperature (supply & return) - Chilled water flow rate - Condensing water temperature (supply & return) - Condensing water flow rate - System operating time/status
Air Economizer	1. To measure, monitor and record the required parameters and calculate the system energy saving. 2. To record and monitor the operating status of the dampers.	- Outdoor air temperature and RH - Chilled water temperature (supply & return) - Chilled water flow rate - Indoor air temperature and RH - Damper operating status - System operating time/status

Water Economizer	1. To measure, monitor and record the required parameters and calculate the system energy saving.	- Outdoor air temperature and RH - Condensing water temperature (supply & return) - Chilled water temperature (supply & return) - System operating time/status
Lighting system	1. To measure, monitor and record the required parameters and calculate the system energy saving. 2. To record and monitor the operating status of the timers/photo sensors/occupancy sensors.	- Sensors operating status - System operating time/status

1.0 Corrective Actions

Project II M&V Plan

Once the measurement and verification tasks have been completed and the data has been analyzed, the building management team may be required to undertake corrective measures to verify any energy saving that have not been realized. Results developed by analyzing the collected monitored data and calculating the verified energy savings will be utilized for continuing improvements and modifications. Potential corrective measures include, but not limited to, the followings:

- Inspecting the completed installation of the systems and equipment, and taking spot measurements of power, temperature, or flow on selected equipment as necessary.
- Analyzing the collected trend data to assess and verify the performance of the systems and equipment.
- Changing equipment operating schedules to more closely follow actual building activities.
- Setting up the required trends including trending time period, and trend duration to analysis the occupancy change, measured parameters change, etc.
- Revising temperature setpoints for correct system operation, without overcooling the air

2.2.1 Chillers

Data required determining chiller performance includes: chiller demand (kW), chilled water flow rate, supply and return temperatures, condenser water flow rate, supply and return temperatures. Data will be collected over the entire range of chiller operation conditions, by monitoring for 4 weeks in summer conditions , 2 weeks in fall/spring conditions. Data will be collected in 15 minute intervals. Chiller kWh will be determined from the average kW over each hour.

2.2.2 Cooling towers

Data required determining cooling towers performance includes: cooling towers demand (kW), cooling water flow rate, supply and return temperatures. Data will be collected over the entire range of cooling towers operation conditions, by monitoring for 4 weeks in summer conditions, 2 weeks in fall/spring conditions. Data will be collected in 15 minute intervals. Cooling towers kWh will be determined from the average kW over each hour.

Project III M&V Plan

2.2.3 Pump performance

Data required determining pump performance includes: pump and chiller demand (kW), water flow rate, water supply and return temperatures. Data will be collected over the entire range of chiller operation conditions, by monitoring for 4 weeks in summer conditions. 2 weeks in fall/spring conditions. Data will be collected in 15 minute intervals. Chillers with heat recovery equipment kWh will be determined from the average kW over each hour.

2.2.4 MAUs with heat recovery equipment from exhaust air

Data required determining MAU performance includes: MAU demand (kW), inlet air rate, outlet air rate, the temperature of inlet air behind and front the equipment, the temperature of outlet air behind and front the equipment. Data will be collected over the entire range of MAU operation conditions, by monitoring for 2 weeks in summer conditions, 2 weeks in transition season conditions. Data will be collected in 15 minute intervals. MAU kWh will be determined from the average kW over each hour.

2.3 Calibration of post-installation building model

The metering structure and mapping to eQuest end use categories are detailed in Table 8 and Table 9 below. For more details in power panels' layout, one could refer to the attached electrical drawings in Appendix C.

Table 8 Electrical metering structure

Meter	Master Panel/ Meter location	Panel/Loads	Description	Load (kW)	Meter Type	Parameter
M1		AL-ADM1	1F Lighting distribution board for	10.7	L20 40/5A	Voltage, current, power factor, power
M2		AL-ADM2	2F Lighting distribution board for	6.5	L20 20/5A	Voltage, current, power factor, power
M3		AS-ADM1	1F Socket distribution board	35	L20 75/5A	Voltage, current, power factor, power
M4		AS-ADM2	2F Socket distribution board	25	L20 50/5A	Voltage, current, power factor, power

Meter	Master Panel/ Meter location	Panel/Loads	Description	Load (kW)	Meter Type	Parameter
M5		AP-ADM1	1F Power distribution board	24.7	L20 50/5A	Voltage, current, power factor, power

Meter	Master Panel/ Meter location	Panel/Loads	Description	Load (kW)	Meter Type	Parameter
M5		AP-ADM1	1F Power distribution board	24.7	L20 50/5A	Voltage, current, power factor, power
M6		AP-ADM2	2F Power distribution board	43.8	L20 100/5A	Voltage, current, power factor, power
M7		AP-DT	Elevator control box	7.5	L20 25/5A	Voltage, current, power factor, power
M8		AP-KIT	Kitchen distribution board	60	L20 200/5A	Voltage, current, power factor, power
M9	AP-UPS	AP-SEC	Security	20	L20 75/5A	Voltage, current, power factor, power
M10		AP-IT	IT	50	L20 150/5A	Voltage, current, power factor, power
M11	AP-ADM1		Access control system	1	L20 15/5A	Voltage, current, power factor, power
M12	AP-HW	AP-HW	Axial exhaust fan	0.18	L20 15/5A	Voltage, current, power factor, power

Project IV M&V Plan

Table 9 End-use category mapping

End-use category	Power panels			
Area lighting	AL-ADM1	AL-ADM2		
Misc. equipment	AS-ADM1	AS-ADM2	AP-DT	AP-KIT
	APE-ADM	AP-ADM1	AP-SEC	AP-IT
Water heating	AP-HW			
Space cooling	AP-ADM1	AP-ADM2		

A comprehensive automation system is installed in the chiller station to monitor the HVAC system on both water and air sides. Its control room is located in the office area of the production building. The monitoring system has trending capabilities which enable the historical operational data to be stored and analyzed.

The amount of variation in a parameter will dictate the frequency of measurement. If a parameter is not expected to change, for example constant speed motor power, the one-time measurement taken during TAB or commissioning might be used. However, this measurement should be reviewed every three months to verify that the parameter is remaining constant. Trending with 15 minutes interval will be set up for time dependent parameters. The operational information will be extracted and input by P&G engineer in the monthly reports transmitted to KENDOW.

Project IV M&V Plan

Because the client did not choose to use BAS for lighting and other miscellaneous equipment, the power meters installed according to Table 8 should be recorded by an engineer every month.

Electric consumption, occupancy levels and O&M activities will be recorded by P&G's engineer as well. Data will be transmitted every month to KENDOW for management and thorough review. The data will be annually input into the as-built building model for calibration.

1.4. Water

As part of LEED certification, this project uses water saving fixtures and practices whenever and wherever feasible. For example, low flow lavatory, showers and toilets have been installed. Water uses of those fixtures are given in Table 10.

Table 10 Equipment's water use

Equipment	Water use
Toilets	0.8/1.6 gpf
Closet	1.45 gpf
Urinal	0.5 gpf
Kitchen sink	1.8 gpm
Water tap	0.9 gpm
Shower	2 gpm

The water metering structure is given in Table 11. A total of 4 water meters needs to be installed.

- ✓ Provide corrective actions when data deviates from expected performance
- ✓ Obtain LEED NC EA credit 5.

3. M&V Scope

The M&V effort covers all energy systems in the LEED scope, which includes air-conditioning, lighting, ventilation etc. Note that according to the M&V objectives, no estimation of long-term energy savings is required. Major end-uses are all directly monitored rather than estimated nor derived. The end use categories covered in M&V are listed in Table 1 below. The number of meters per energy type is indicated in brackets.

Table 1 End use categories covered for M&V process

Energy type	System	Sub System	Meter Type	Remarks
Electricity (64 meters)	HVAC	Chilled water pump	Power meter	Power meters are installed at the main power panel
		Cooling tower water pump		
		Cooling tower		
		Fresh air unit		
		Air handling units		
		Air Coil unit		
		AC units		
		Exhaust fan system		
	Lighting system	Indoor lighting	Power meter, Runtime	Sub-meters are installed at the power panel. Lighting runtime is recorded.
		Outdoor lighting	Power meter, Runtime	
	Production process system	Production lines	Power meter	Power meters are installed at the main power panel
	Process loads	Plug Sockets		
	Auxiliary System	Rolling door		
		Dock Leveller		

Energy type	System	Sub System	Meter Type	Remarks
		Others		
	Utility System	Air compressor		
		Fire pump system		
		Forklift Recharge system		
Water (8 meters)	Air-conditioning	Make-up water for chiller	Water meter	Main water meter has been installed at the main water supply pipe
		Cooling tower		
	Domestic use	Flushing		
		Hand-washing		
	Stormwater collection system	Irrigation		Main water meter installed in the main outlet pipe
	Process	Process lines and laboratory		Water meter installed at the main inlet pipe
Notes	1) The precision of the meter should not be smaller than class 2. 2) The water metered at the chiller level is only for replenished water consumption metering			

4. M&V Option

Project V M&V Plan

IPMVP Option D Calibrated Simulation is determined to be the best M&V option for this project, since the project exercises the integrated holistic design approach and includes a large number of ECMs that are interactive in nature. Option D involves comparing the actual energy use of the building and its systems with the performance predicted by a calibrated building model. Calibration is achieved by adjusting the as-built simulation to reflect actual operating conditions and parameters. To determine energy savings, similar calibration or adjustment is also applied to the baseline model.

Option D serves two purposes:

- ✓ Calibration of the as-built simulation model to actual energy use reveals ECM/design or operational

Appendix C IFC Properties for an Energy Model (All set)

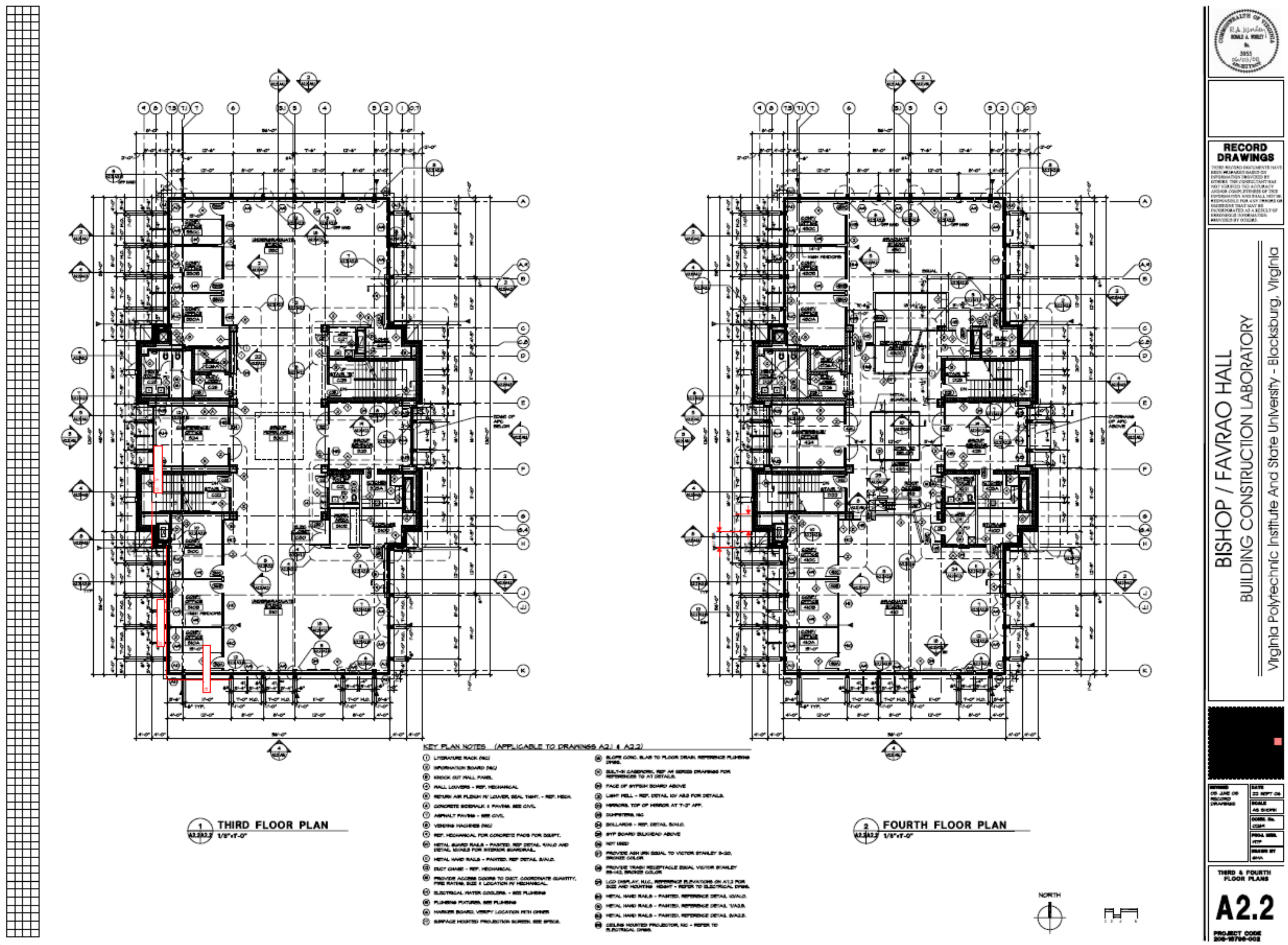
Geometry	Attribute/Property Set	Property	Data Type
IfcSpace	Pset_ThermalLoadDesignCriteria	OccupancyDiversity	P_SINGLEVALUE /IfcPositiveRatioMeasure
	Pset_SpaceThermalDesign	CoolingDryBulb	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		CoolingRelativeHumidity	P_SINGLEVALUE / IfcPositiveRatioMeasure
		HeatingDryBulb	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		HeatingRelativeHumidity	P_SINGLEVALUE / IfcPositiveRatioMeasure
		VentilationAirFlowrate	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
		ExhaustAirFlowrate	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
	Pset_SpaceThermalRequirements	SpaceTemperature	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		SpaceHumidity	P_SINGLEVALUE / IfcRatioMeasure
		SpaceHumiditySummer	P_SINGLEVALUE / IfcRatioMeasure
		SpaceHumidityWinter	P_SINGLEVALUE / IfcRatioMeasure
		NaturalVentilationRate	P_SINGLEVALUE / IfcCountMeasure
		MechanicalVentilationRate	P_SINGLEVALUE / IfcCountMeasure
	Pset_SpaceThermalLoadPHistory	People	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		Lighting	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		EquipmentSensible	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		VentilationIndoorAir	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		VentilationOutdoorAir	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		RecirculatedAir	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		ExhaustAir	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		AirExchangeRate	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		DryBulbTemperature	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		RelativeHumidity	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		InfiltrationSensible	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		TotalSensibleLoad	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		TotalLatentLoad	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
		TotalRadiantLoad	P_REFERENCEVALUE /IfcTimeSeries /IfcPowerMeasure
	Pset_SpaceOccupancyRequirements	OccupancyNumber	P_SINGLEVALUE /IfcCountMeasure
	Pset_SpaceLightingRequirements	Illuminance	P_SINGLEVALUE / IfcIlluminanceMeasure
	Pset_AirSideSystemInformation	TotalAirflow	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
		LightingDiversity	P_SINGLEVALUE / IfcPositiveRatioMeasure *
		InfiltrationDiversitySummer	P_SINGLEVALUE / IfcPositiveRatioMeasure *
		InfiltrationDiversityWinter	P_SINGLEVALUE / IfcPositiveRatioMeasure *
		ApplianceDiversity	P_SINGLEVALUE / IfcPositiveRatioMeasure *
		HeatingTemperatureDelta	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		CoolingTemperatureDelta	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure

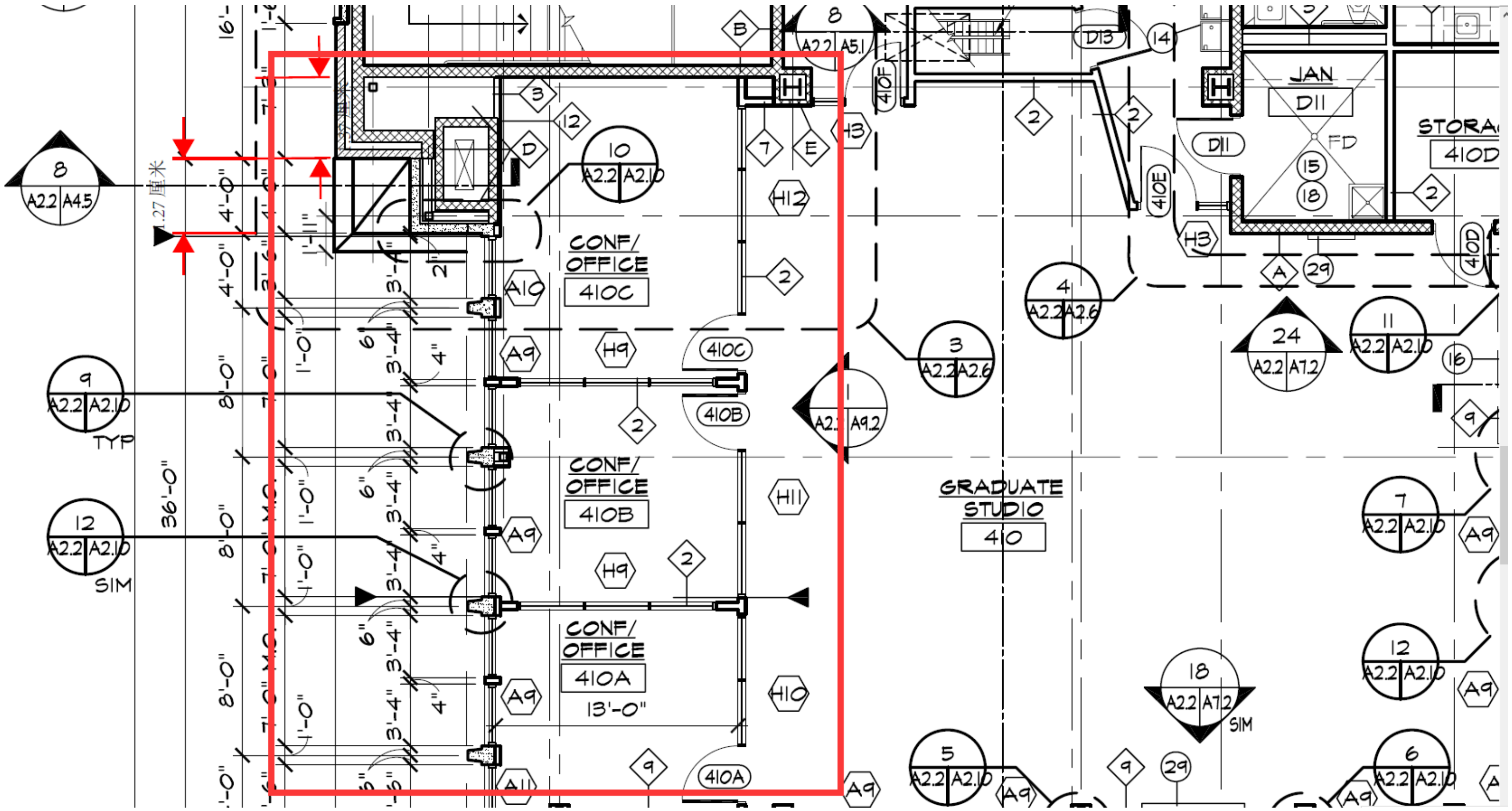
		Ventilation	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
MEP	**Attribute/Property Set**	**Property**	**Data Type**
IfcAirTeminal	Pset_AirTeminalTypeCommon	AirFlowrateRange	P_BOUNDEDVALUE /IfcVolumetricFlowRateMeasure
		TemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasure
	Pset_AirTeminalPHistory	AirFlowRate	P_REFERENCEVALUE / IfcTimeSeries /IfcVolumetricFlowRateMeasure
		SupplyAirTemperatureHeating	P_REFERENCEVALUE / IfcTimeSeries /IfcThermodynamicTemperature Measure
		SupplyAirTemperatureCooling	P_REFERENCEVALUE / IfcTimeSeries /IfcThermodynamicTemperature Measure
		PressureDrop	P_REFERENCEVALUE / IfcTimeSeries /IfcPressureMeasure
		CenterlineAirVelocity	P_TABLEVALUE /IfcLinearVelocityMeasure /IfcLengthMeasure
	Pset_AirTerminalOccurrence	AirflowType	P_ENUMERATEDVALUE / PEnum_AirTerminalAirflowType / PEnum_AirTerminalAirflowType
		AirFlowRate	P_SINGLEVALUE / IfcVolumetricFlowRateMeasure
IfcDamper	Pset_DamperTypeCommon	Reference	P_SINGLEVALUE / IfcIdentifier *
		MaximumAirFlowRate	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
		TemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasure
		MaximumWorkingPressure	P_SINGLEVALUE /IfcPressureMeasure
		TemperatureRating	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		NominalAirFlowRate	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
	Pset_DamperPHistory	AirFlowRate	P_REFERENCEVALUE / IfcTimeSeries /IfcVolumetricFlowRateMeasure
		DamperPosition	P_REFERENCEVALUE / IfcTimeSeries /IfcNormalisedRatioMeasure
IfcValve	Pset_ValveTypeCommon	Reference	P_SINGLEVALUE /IfcIdentifier *
		TestPressure	P_SINGLEVALUE /IfcPressureMeasure
		WorkingPressure	P_SINGLEVALUE /IfcPressureMeasure
		FlowCoefficient	P_SINGLEVALUE /IfcReal
	Pset_ValvePHistory	PercentageOpen	P_REFERENCEVALUE / IfcTimeSeries / IfcPositiveRatioMeasure
		MeasuredFlowRate	P_REFERENCEVALUE / IfcTimeSeries / IfcMassFlowRateMeasure
		MeasuredPressureDrop	P_REFERENCEVALUE / IfcTimeSeries / IfcPressureMeasure
IfcFan	Pset_FanTypeCommon	Reference	P_SINGLEVALUE / IfcIdentifier *
		MotorDriveType	P_ENUMERATEDVALUE / IfcLabel /PEnum_FanMotorConnectionType
		CapacityControlType	P_ENUMERATEDVALUE / IfcLabel /PEnum_FanCapacityControlType
		NominalAirFlowRate	P_SINGLEVALUE /IfcVolumetricFlowRateMeasure
		NominalTotalPressure	P_SINGLEVALUE /IfcPressureMeasure
		NominalStaticPressure	P_SINGLEVALUE /IfcPressureMeasure
		NominalRotationSpeed	P_SINGLEVALUE /IfcRotationalFrequencyMeasure
		NominalPowerRate	P_SINGLEVALUE / IfcPowerMeasure

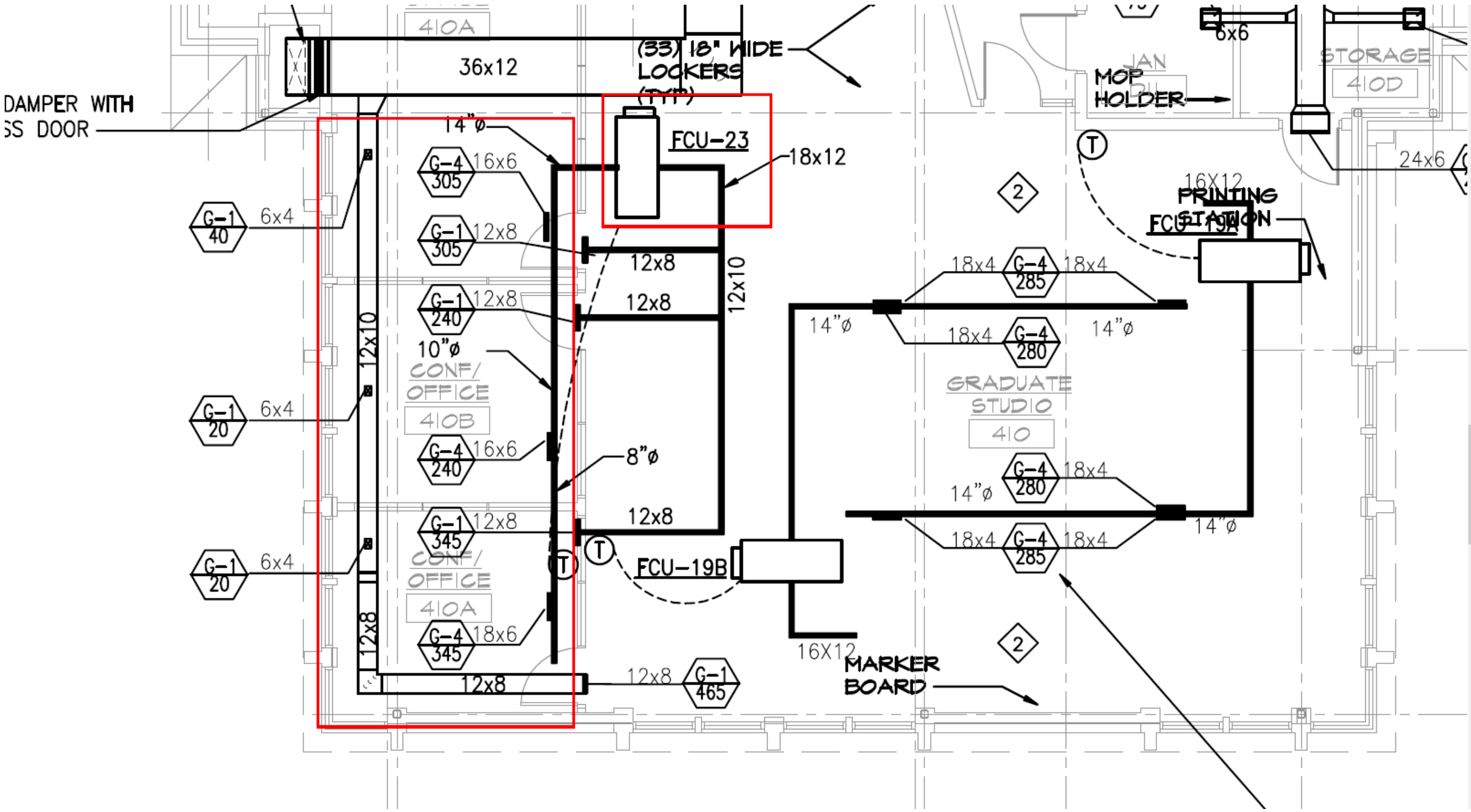
		PressureCurve	P_TABLEVALUE /IfcVolumetricFlowRateMeasure /IfcPressureMeasure
		EfficiencyCurve	P_TABLEVALUE /IfcVolumetricFlowRateMeasure /IfcNormalisedRatioMeasure
	Pset_FanPHistory	FanRotationSpeed	P_REFERENCEVALUE / IfcTimeSeries /IfcRotationalFrequencyMeasure
		OverallEfficiency	P_REFERENCEVALUE / IfcTimeSeries /IfcNormalisedRatioMeasure
		FanPowerRate	P_REFERENCEVALUE / IfcTimeSeries / IfcPowerMeasure
		DischargeVelocity	P_REFERENCEVALUE / IfcTimeSeries / IfcLinearVelocityMeasure
IfcPump	Pset_PumpTypeCommon	Reference	P_SINGLEVALUE / IfcIdentifier *
		FlowRateRange	P_BOUNDEDVALUE /IfcMassFlowRateMeasure
		NetPositiveSuctionHead	P_SINGLEVALUE /IfcPressureMeasure
	Pset_PumpPHistory	MechanicalEfficiency	P_REFERENCEVALUE / IfcTimeSeries / IfcNormalisedRatioMeasure
		OverallEfficiency	P_REFERENCEVALUE / IfcTimeSeries / IfcNormalisedRatioMeasure
		PressureRise	P_REFERENCEVALUE / IfcTimeSeries / IfcPressureMeasure
		RotationSpeed	P_REFERENCEVALUE / IfcTimeSeries / IfcRotationalFrequencyMeasure
		Flowrate	P_REFERENCEVALUE / IfcTimeSeries / IfcVolumetricFlowRateMeasure
		Power	P_REFERENCEVALUE / IfcTimeSeries / IfcPowerMeasure
IfcBoiler	Pset_BoilerTypeCommon	Reference	P_SINGLEVALUE / IfcIdentifier *
		WaterInletTemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasure
		WaterStorageCapacity	P_SINGLEVALUE / IfcVolumeMeasure
		PartialLoadEfficiencyCurves	P_TABLEVALUE /IfcPositiveRatioMeasure /IfcNormalisedRatioMeasure
		OutletTemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasure
		NominalEnergyConsumption	P_SINGLEVALUE / IfcPowerMeasure
		EnergySource	P_ENUMERATEDVALUE / IfcLabel /PEnum_EnergySource
	Pset_BoilerPHistory	EnergySourceConsumption	P_REFERENCEVALUE / IfcTimeSeries /IfcEnergyMeasure
		OperationalEfficiency	P_REFERENCEVALUE / IfcTimeSeries /IfcNormalisedRatioMeasure
		WorkingPressure	P_REFERENCEVALUE / IfcTimeSeries /IfcPressureMeasure
		PartLoadRatio	P_REFERENCEVALUE / IfcTimeSeries /IfcNormalisedRatioMeasure
		Load	P_REFERENCEVALUE / IfcTimeSeries /IfcPowerMeasure
		PrimaryEnergyConsumption	P_REFERENCEVALUE / IfcTimeSeries /IfcPowerMeasure
		AuxiliaryEnergyConsumption	P_REFERENCEVALUE / IfcTimeSeries /IfcPowerMeasure
IfcChiller	Pset_ChillerTypeCommon	Reference	P_SINGLEVALUE / IfcIdentifier *
		NominalCapacity	P_SINGLEVALUE / IfcPowerMeasure
		NominalEfficiency	P_SINGLEVALUE /IfcPositiveRatioMeasure
		NominalCondensingTemperature	P_SINGLEVALUE /IfcThermodynamicTemperatureMeasure
		NominalPowerConsumption	P_SINGLEVALUE / IfcPowerMeasure
		CoefficientOfPerformanceCurve	P_TABLEVALUE /IfcThermodynamicTemperatureMeasure/ IfcReal
		FullLoadRatioCurve	P_TABLEVALUE /IfcPositiveRatioMeasure /IfcNormalisedRatioMeasure
	Pset_ChillerPHistory	Capacity	P_REFERENCEVALUE/ IfcTimeSeries /IfcPowerMeasure

		EnergyEfficiencyRatio	P_REFERENCEVALUE/ IfcTimeSeries / IfcReal
		CoefficientOfPerformance	P_REFERENCEVALUE/ IfcTimeSeries /IfcPositiveRatioMeasure
IfcCondenser	Pset_CondenserTypeCommon	Reference	P_SINGLEVALUE / IfcIdentifier *
	Pset_CondenserPHistory		
IfcCoolingTower	Pset_CoolingTowerTypeCommon	Reference	P_SINGLEVALUE / IfcIdentifier *
	Pset_CoolingTowerPHistory	Capacity	P_REFERENCEVALUE / IfcTimeSeries /IfcPowerMeasure
IfcElectrical Motor	Pset_ElectricalMotorTypeCommon	Reference	P_SINGLEVALUE /IfcIdentifier *
		MaximumPowerOutput	P_SINGLEVALUE /IfcPowerMeasure
		ElectricMotorEfficiency	P_SINGLEVALUE /IfcPositiveRatioMeasure
IfcCoil	Pset_CoilTypeCommon	Reference	P_SINGLEVALUE / IfcIdentifier *
		OperationalTemperatureRange	P_BOUNDEDVALUE /IfcThermodynamicTemperatureMeasure
		AirflowRateRange	P_BOUNDEDVALUE /IfcVolumetricFlowRateMeasure
	Pset_CoilPHistory	AtmosphericPressure	P_REFERENCEVALUE / IfcTimeSeries /IfcPressureMeasure
		AirPressureDropCurve	P_REFERENCEVALUE / IfcTimeSeries

Appendix D Case Study Drawing




CONF/
OFFICE
410C
CONF/
OFFICE
410B
CONF/
OFFICE
410A
13'-0"
GRADUATE
STUDIO
410
JAN
D11
STORA
410D
36'-0"
TYP
SIM
FD

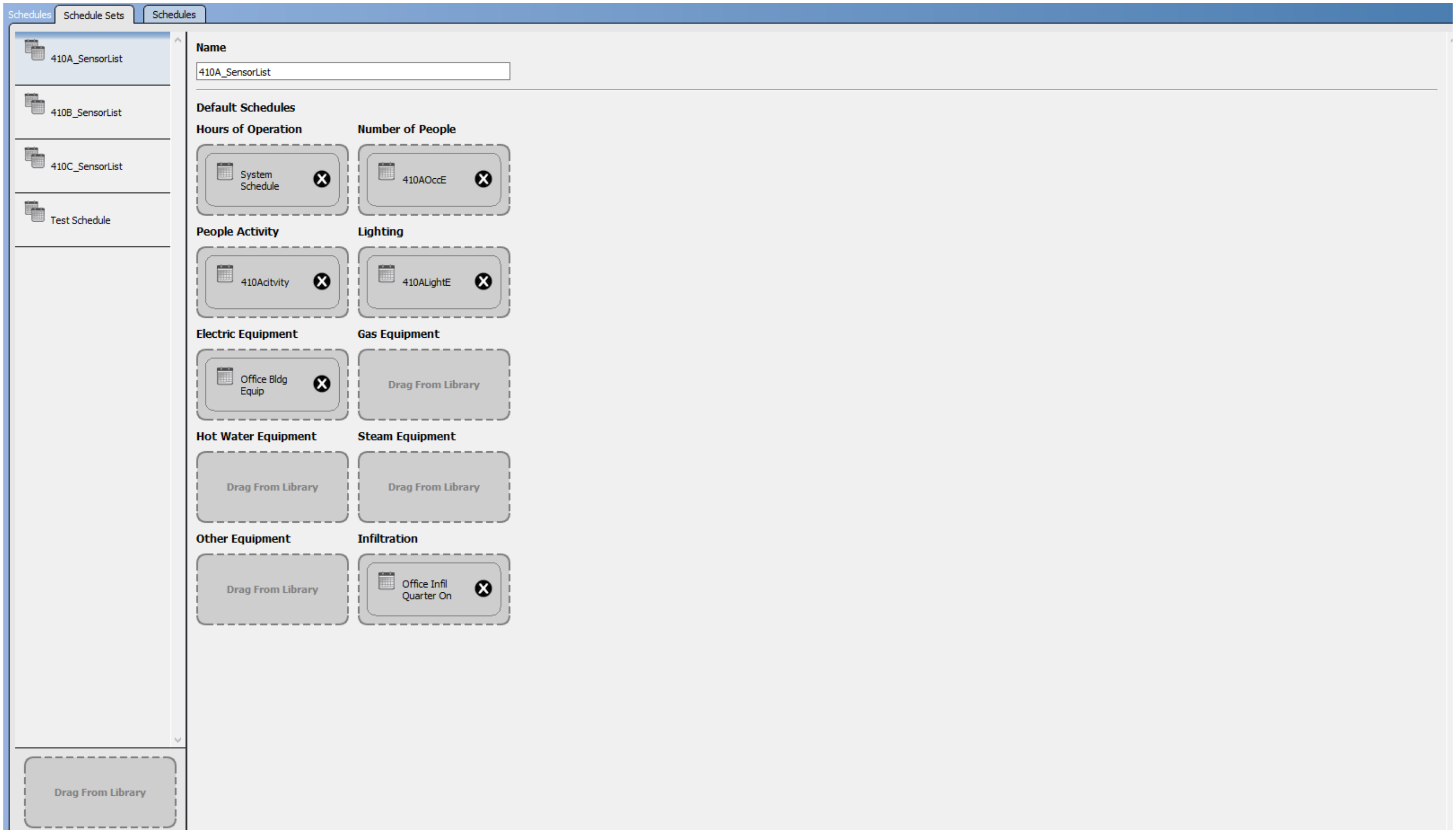


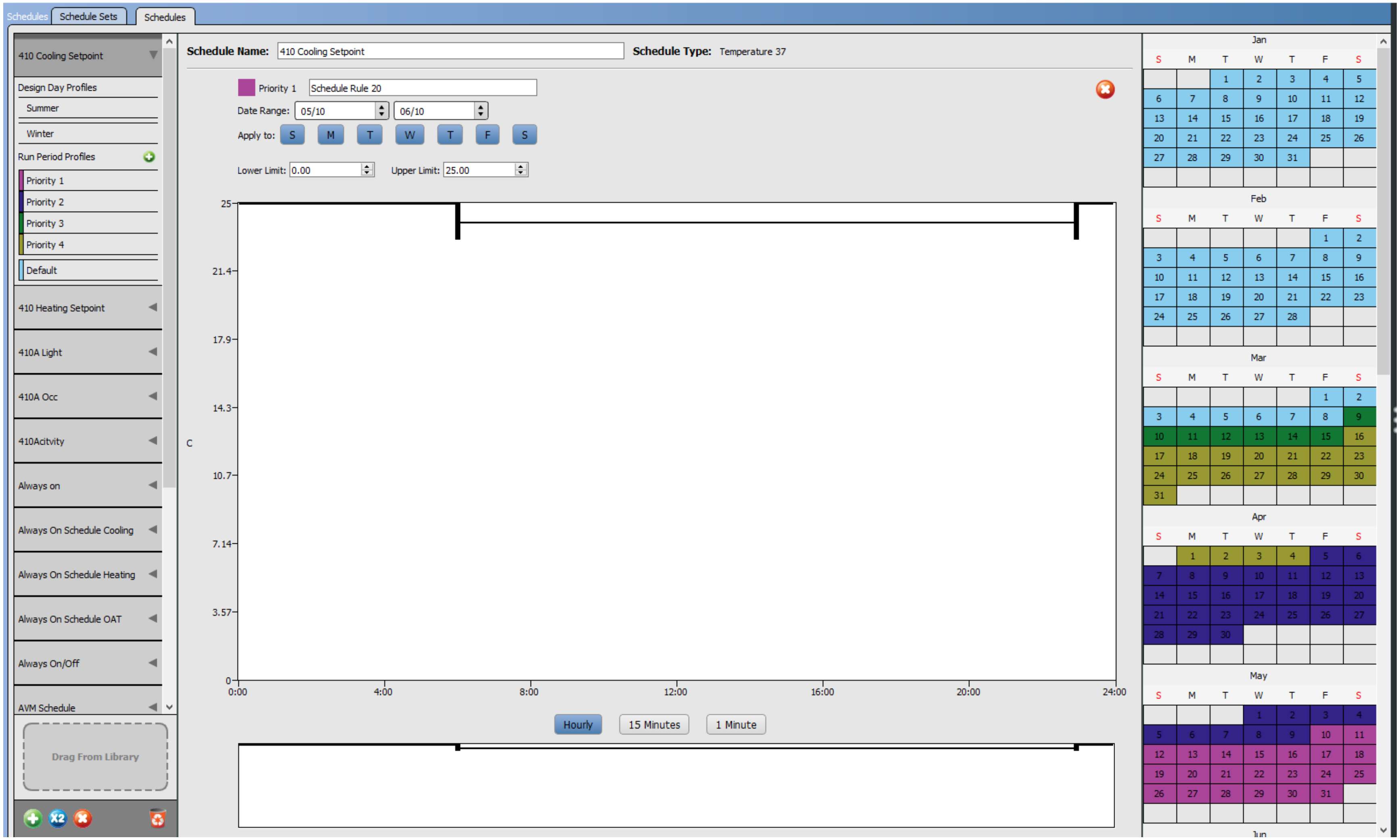
DAMPER WITH
SS DOOR
36x12
410A
(33) 18" WIDE
LOCKERS
(TYP)
FCU-23
18x12
14"ø
16x6
12x8
12x8
12x8
12x10
12x10
10"ø
CONF/
OFFICE
410B
16x6
8"ø
12x8
12x8
FCU-19B
CONF/
OFFICE
410A
18x6
12x8
12x8
12x8
6x4
6x4
6x4
MOP
HOLDER
6x6
STORAGE
410D
24x6
16X12
PRINTING
STATION
FCU-19A
18x4
18x4
14"ø
14"ø
GRADUATE
STUDIO
410
18x4
14"ø
14"ø
16X12
MARKER
BOARD

FAN COIL UNIT SCHEDULE

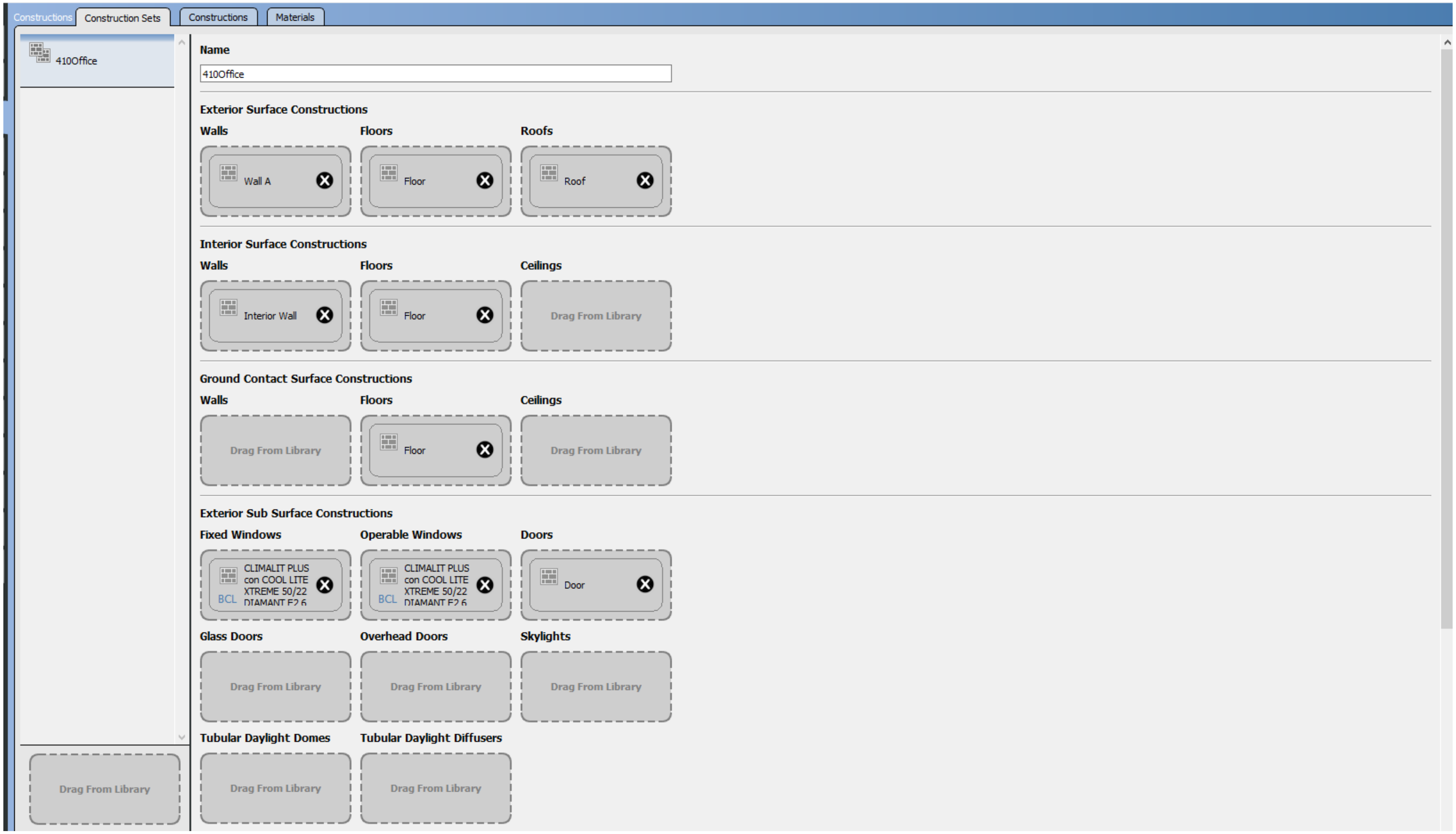
UNIT NUMBER	LOCATION AND AREAS SERVED	FAN DATA CFM	FAN DATA EXT. S.P. IN. W.G.	MOTOR DATA MCA	MOTOR DATA MAX FUSE SIZE	MOTOR DATA V	MOTOR DATA PH	MOTOR DATA Hz	CHILLED WATER COOLING COIL DATA – AIR SIDE DATA EAT °F DB	EAT °F WB	LAT °F DB	LAT °F WB	FACE AREA	WATER SIDE DATA GPM	WATER °F EWT	WATER °F LWT	PD FT WG	ROWS	FPI	COOLING LOAD SENS. BTU/H	COOLING LOAD TOTAL BTU/H	HOT WATER HEATING COIL DATA – AIR SIDE DATA CFM	EAT °F DB	LAT °F DB	WATER SIDE DATA GPM	WATER °F EWT	WATER °F LWT	PD FT WG	ROWS	FPI	HEATING LOAD BTU/H	FILTER DATA PD IN WD INIT.	PD IN WD FINAL	% EFF	TYPE	SELECTION BASED ON MANUFACTURER	MODEL NO.	REMARKS
FCU-1	CLASSROOM 132	1070	0.25	6.35	15	115	1	60	76	63	56.2	54.8	3.2	5.22	45	55	8.22	3	12	21,800	24,730	1070	71	90	2.12	180	160	1.92	1	4	21220	0.08	0.2	30	THROWAWAY	TRANE	FCCB12	
FCU-2	TECH OFFICE 107	80	0.25	0.75	15	115	1	60	76	63	53.6	52.5	1.1	0.49	45	55	0.64	4	12	1,840	2,320	80	71	102	0.5	180	160	0.06	1	4	2540	0.08	0.2	30	THROWAWAY	TRANE	FCBB02	
FCU-3A&B	PRESENTATION CLASSROOM 230	1000	0.28	6.35	15	115	1	60	76	63	56	54.7	3.2	4.99	45	55	7.52	3	12	20,660	23,540	1000	71	91	2.04	180	160	1.79	1	4	20400	0.08	0.2	30	THROWAWAY	TRANE	FCCB10	
FCU-4	LOBBY 220	720	0.25	4.85	15	115	1	60	76	63	57.5	60.9	3.2	2.58	45	55	2.6	2	12	11,820	12,050	720	71	89	1.44	180	160	0.71	1	4	14420	0.08	0.2	30	THROWAWAY	TRANE	FCCB08	
FCU-5	LOUNGE 224 TOILET A128	695	0.31	4.25	15	115	1	60	76	63	60.7	57.5	3.2	2.5	45	55	2.45	3	12	11	11,650	695	71	86	0.5	180	160	0.11	1	4	11030	0.08	0.2	30	THROWAWAY	TRANE	FCCB12	
FCU-6	VESTIBULE 201 WOMEN'S TOILET 204	295	0.27	2	15	115	1	60	76	63	59.8	57.1	1.6	1.14	45	55	1.82	2	12	5,140	5,240	295	71	90	0.61	180	160	0.1	1	4	6140	0.08	0.2	30	THROWAWAY	TRANE	FCCB04	
FCU-7A&B	ASSEMBLY CLASSROOM 210	1100	0.19	6.35	15	115	1	60	76	63	56.3	54.8	3.2	5.33	45	55	8.55	2	12	22,330	25,280	1100	71	90	2.16	180	160	1.98	1	4	21600	0.08	0.2	30	THROWAWAY	TRANE	FCCB12	
FCU-8A&B	UNDERDRADUATE STUDIO 330	1000	0.28	6.35	15	115	1	60	76	63	56	54.7	3.2	4.99	45	55	7.52	3	12	20,660	23,540	1000	71	91	2.04	180	160	1.79	1	4	20400	0.08	0.2	30	THROWAWAY	TRANE	FCCB10	
FCU-9A&B	UNDERGRADUATE STUDIO 310	1000	0.28	6.35	15	115	1	60	76	63	56	54.7	3.2	4.99	45	55	7.52	3	12	20,660	23,540	1000	71	91	2.04	180	160	1.79	1	4	20400	0.08	0.2	30	THROWAWAY	TRANE	FCCB10	
FCU-10	GROUP WORK AREA 301	1080	0.24	6.35	15	115	1	60	76	63	56.2	54.8	3.2	5.25	45	55	58.32	3	12	21,960	24,900	1080	71	90	2.13	180	160	1.94	1	4	21330	0.08	0.2	30	THROWAWAY	TRANE	FCCB12	
FCU-11	CONF/OFFICE 324	375	0.24	2.62	15	115	1	60	76	63	55.7	54.4	3.2	1.92	45	55	6.45	3	12	7,840	9,050	375	71	88	0.5	180	160	0.07	1	4	6470	0.08	0.2	30	THROWAWAY	TRANE	FCCB04	
FCU-12	CONF/OFFICE 330A CONF/OFFICE 330B CONF/OFFICE 330C	730	0.22	4.25	15	115	1	60	76	63	56.3	54.8	3.2	3.46	45	55	5.63	3	12	14,500	16,450	730	71	90	1.39	180	160	0.66	1	4	13910	0.08	0.2	30	THROWAWAY	TRANE	FCCB08	
FCU-13	CONF/OFFICE 310A CONF/OFFICE 310B CONF/OFFICE 310C	730	0.22	4.25	15	115	1	60	76	63	56.3	54.8	3.2	3.46	45	55	5.66	3	12	14,540	16,490	730	71	90	1.39	180	160	0.66	1	4	13930	0.08	0.2	30	THROWAWAY	TRANE	FCCB08	
FCU-14	MEN'S TOILET C28	140	0.42	1.38	15	115	1	60	76	63	59.1	56	0.8	0.63	45	55	2.88	3	12	2,500	2,870	140	71	95	0.5	180	160	0.06	1	4	3550	0.08	0.2	30	THROWAWAY	TRANE	FCCB02	
FCU-15	COMMMUNICATIONS 314	180	0.09	0.75	15	115	1	60	76	63	59	56.1	0.8	0.73	45	55	3.72	3	12	3,170	3,560	180	71	92	0.5	180	160	0.06	1	4	4020	0.08	0.2	30	THROWAWAY	TRANE	FCBB02	
FCU-16	GROUP SEMINAR 323	490	0.31	3.25	15	115	1	60	76	63	58.6	56.1	3.2	2.11	45	55	6.7	3	12	9,000	9,900	490	71	88	0.5	180	160	0.09	1	4	8610	0.08	0.2	30	THROWAWAY	TRANE	FCCB06	
FCU-17	MEN'S TOILET D28	140	0.42	1.38	15	115	1	60	76	63	59.1	56	0.8	0.63	45	55	2.88	3	12	2,500	2,870	140	71	95	0.5	180	160	0.06	1	4	3550	0.08	0.2	30	THROWAWAY	TRANE	FCCB02	
FCU-18A&B	UNDERGRADUATE STUDIO430	860	0.27	4.85	15	115	1	60	76	63	58.2	55.9	3.2	3.77	45	55	6.27	3	12	16,130	17,790	860	71	92	1.88	180	160	1.55	1	4	18780	0.08	0.2	30	THROWAWAY	TRANE	FCCB10	
FCU-19A&B	GRADUATE STUDIO 410	860	0.26	4.85	15	115	1	60	76	63	58.2	55.9	3.2	3.78	45	55	6.3	3	12	16,190	17,850	860	71	92	1.88	180	160	1.56	1	4	18840	0.08	0.2	30	THROWAWAY	TRANE	FCCB10	
FCU-20	LOBBY 420	1100	0.22	6.35	15	115	1	60	76	63	56.2	54.8	3.2	5.28	45	55	8.4	3	12	22,090	25,040	1250	71	90	2.14	180	160	1.95	1	4	21430	0.08	0.2	30	THROWAWAY	TRANE	FCCB12	
FCU-21	CONF/OFFICE 424	370	0.25	2.62	15	115	1	60	76	63	55.7	54.4	3.2	1.91	45	55	6.4	3	12	7,800	9,020	790	71	89	0.69	180	160	0.13	1	4	6920	0.08	0.2	30	THROWAWAY	TRANE	FCCB04	
FCU-22	CONF/OFFICE 415 CONF/OFFICE 416 CONF/OFFICE 417	740	0.21	4.25	15	115	1	60	76	63	56.3	54.9	3.2	3.48	45	55	5.72	3	12	14,650	16,600	1140	71	90	1.4	180	160	0.67	1	4	14010	0.08	0.2	30	THROWAWAY	TRANE	FCCB08	
FCU-23	CONF/OFFICE 404 CONF/OFFICE 405 CONF/OFFICE 406	860	0.26	4.85	15	115	1	60	76	63	58.2	55.9	3.2	3.78	45	55	6.3	3	12	16,180	17,840	1145	71	86	0.5	180	160	0.16	1	4	13650	0.08	0.2	30	THROWAWAY	TRANE	FCCB10	
FCU-24	DEPARMENT ADMIN 4300	185	0.26	1.38	15	115	1	60	76	63	59.3	56.3	1.1	0.79	45	55	4.21	3	12	3,250	3,660	230	71	92	0.5	180	160	0.06	1	4	4120	0.08	0.2	30	THROWAWAY	TRANE	FCCB02	
FCU-25	GROUP SEMINAR 425	655	0.38	4.25	15	115	1	60	76	63	60.6	57.4	3.2	2.39	45	55	2.25	2	12	10,870	11,090	680	71	90	1.35	180	160	0.63	1	4	13560	0.08	0.2	30	THROWAWAY	TRANE	FCCB08	

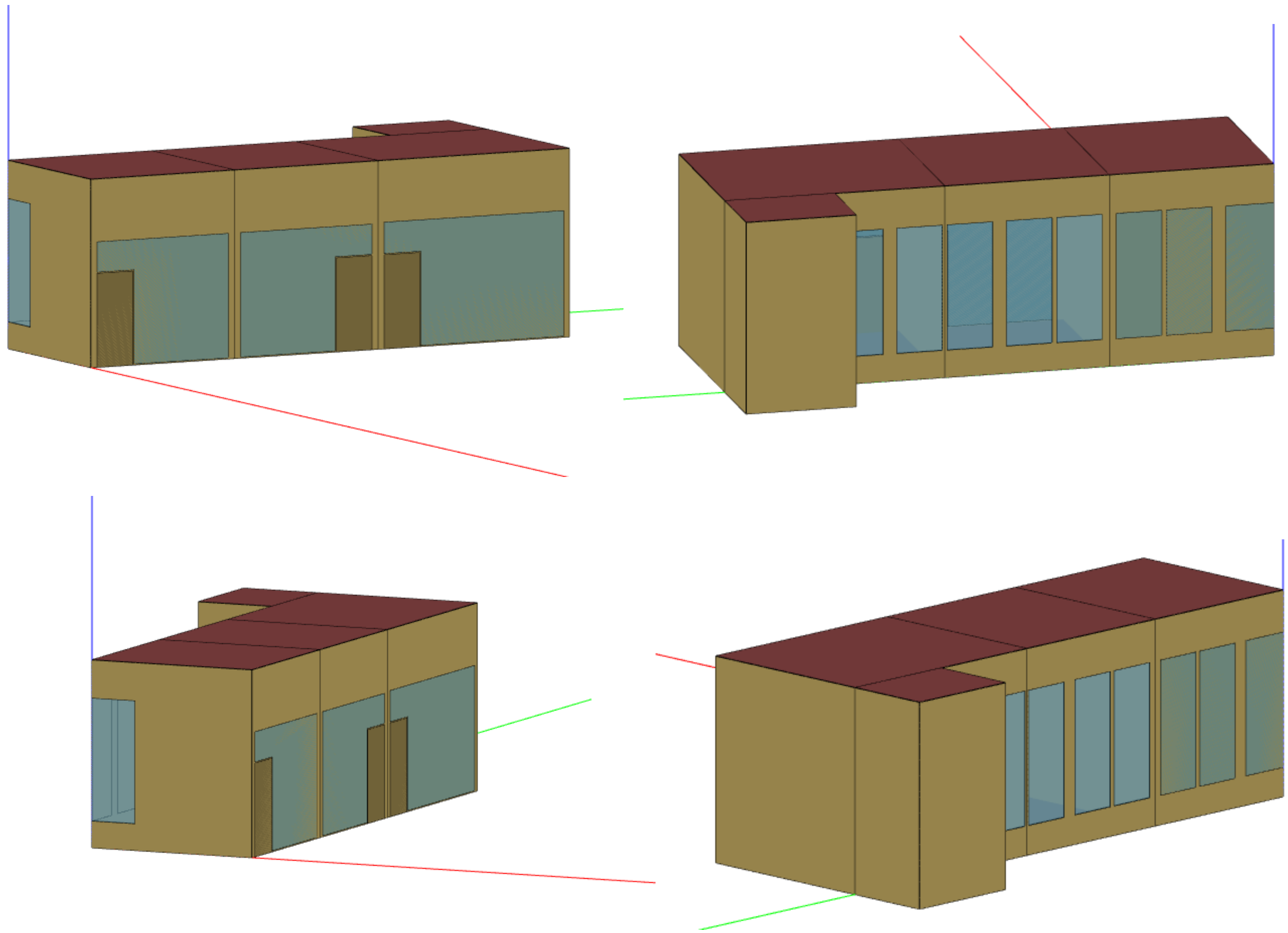
Appendix E Energy Model Setting

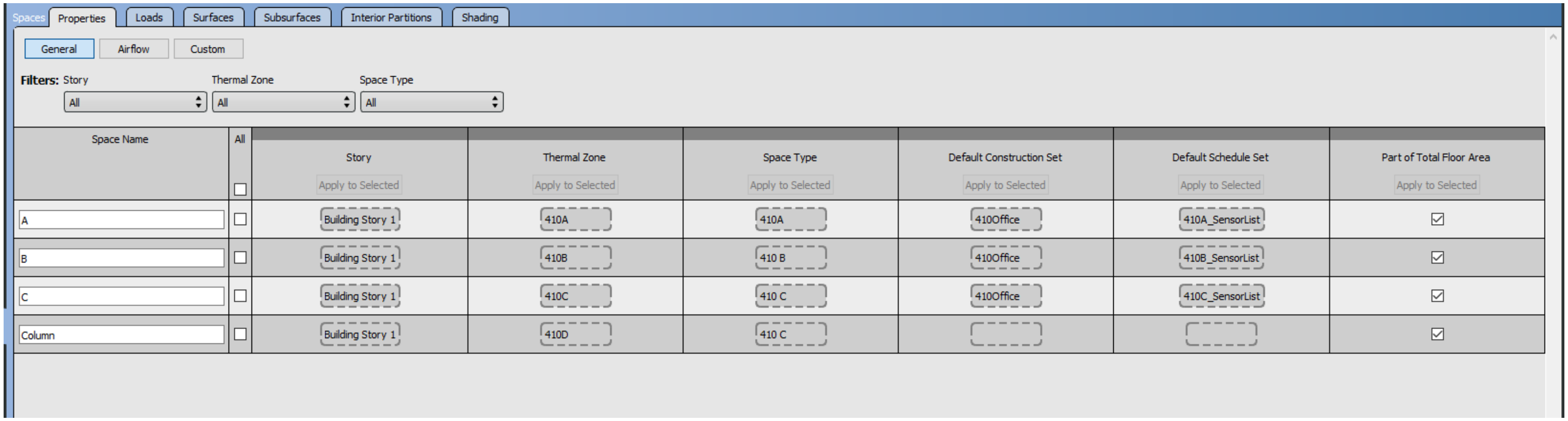


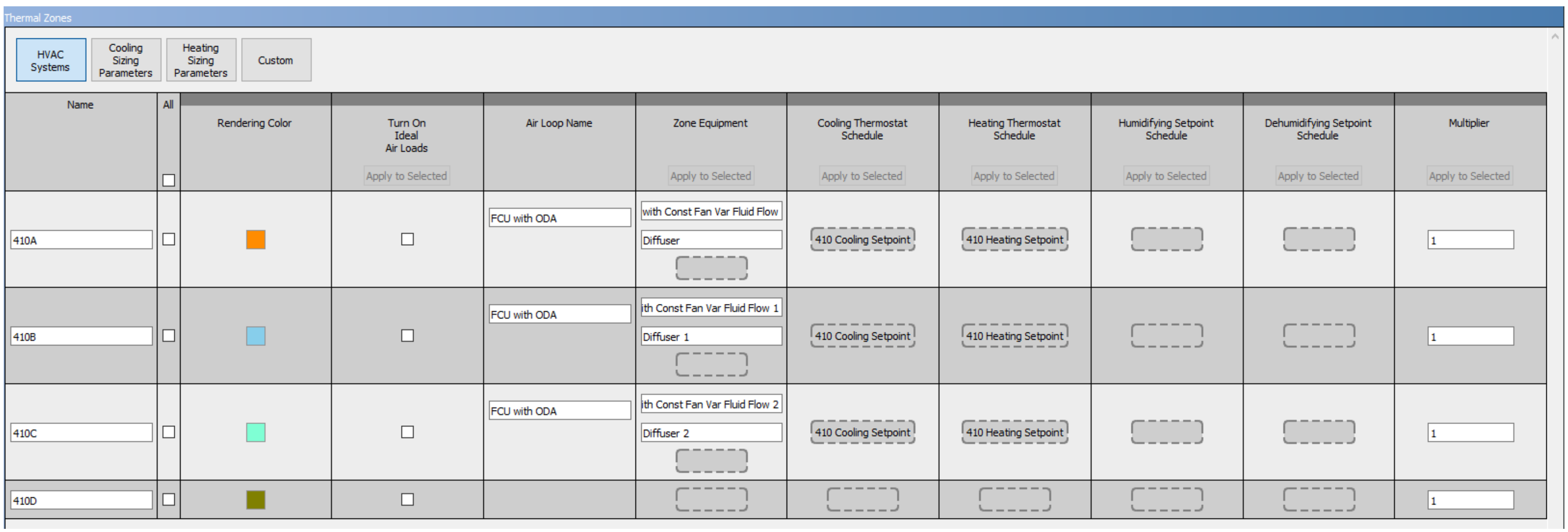


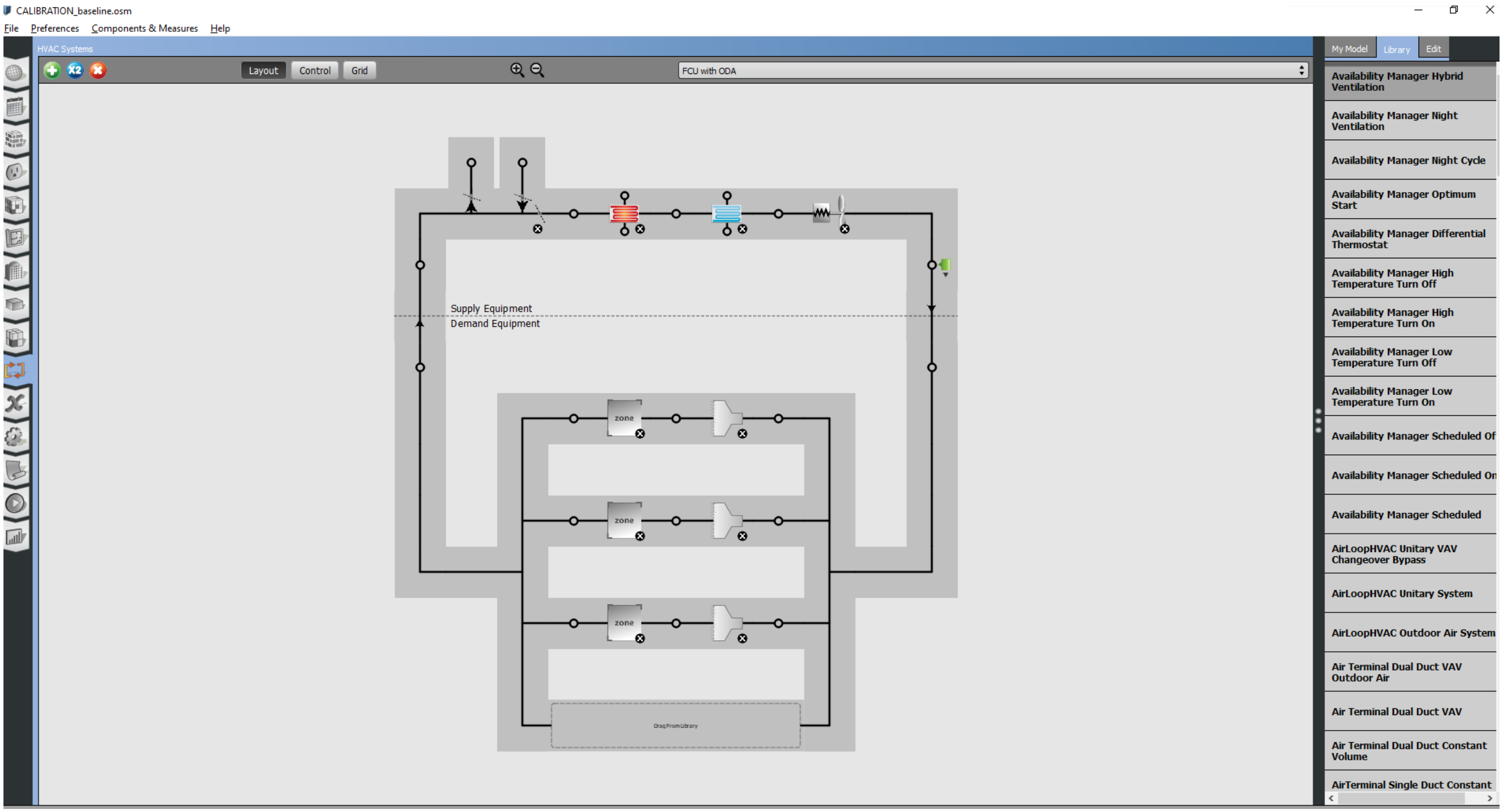
Schedules
Schedule Sets
Schedules
410 Cooling Setpoint
Design Day Profiles
Summer
Winter
Run Period Profiles
Priority 1
Priority 2
Priority 3
Priority 4
Default
410 Heating Setpoint
410A Light
410A Occ
410Acitvity
Always on
Always On Schedule Cooling
Always On Schedule Heating
Always On Schedule OAT
Always On/Off
AVM Schedule
Drag From Library
Schedule Name: 410 Cooling Setpoint
Schedule Type: Temperature 37
Priority 1
Schedule Rule 20
Date Range: 05/10 06/10
Apply to: S M T W T F S
Lower Limit: 0.00
Upper Limit: 25.00
C
Hourly
15 Minutes
1 Minute
Jan
Feb
Mar
Apr
May
Jun


Constructions
Construction Sets
Constructions
Materials
410Office
Name
410Office
Exterior Surface Constructions
Walls
Floors
Roofs
Wall A
Floor
Roof
Interior Surface Constructions
Walls
Floors
Ceilings
Interior Wall
Floor
Drag From Library
Ground Contact Surface Constructions
Walls
Floors
Ceilings
Drag From Library
Floor
Drag From Library
Exterior Sub Surface Constructions
Fixed Windows
Operable Windows
Doors
CLIMALIT PLUS con COOL LITE XTREME 50/22
BCL
CLIMALIT PLUS con COOL LITE XTREME 50/22
BCL
Door
Glass Doors
Overhead Doors
Skylights
Drag From Library
Drag From Library
Drag From Library
Tubular Daylight Domes
Tubular Daylight Diffusers
Drag From Library
Drag From Library
Drag From Library




Spaces
Properties
Loads
Surfaces
Subsurfaces
Interior Partitions
Shading
General
Airflow
Custom
Filters: Story
Thermal Zone
Space Type
All
All
All
Space Name
All
Story
Thermal Zone
Space Type
Default Construction Set
Default Schedule Set
Part of Total Floor Area
Apply to Selected
A
Building Story 1
410A
410A
410Office
410A_SensorList
B
Building Story 1
410B
410 B
410Office
410B_SensorList
C
Building Story 1
410C
410 C
410Office
410C_SensorList
Column
Building Story 1
410D
410 C


Thermal Zones
HVAC Systems
Cooling Sizing Parameters
Heating Sizing Parameters
Custom
Name
All
Rendering Color
Turn On Ideal Air Loads
Air Loop Name
Zone Equipment
Cooling Thermostat Schedule
Heating Thermostat Schedule
Humidifying Setpoint Schedule
Dehumidifying Setpoint Schedule
Multiplier
Apply to Selected
410A
FCU with ODA
with Const Fan Var Fluid Flow
Diffuser
410 Cooling Setpoint
410 Heating Setpoint
1
410B
FCU with ODA
ith Const Fan Var Fluid Flow 1
Diffuser 1
410 Cooling Setpoint
410 Heating Setpoint
1
410C
FCU with ODA
ith Const Fan Var Fluid Flow 2
Diffuser 2
410 Cooling Setpoint
410 Heating Setpoint
1
410D
1


CALIBRATION_baseline.osm
File
Preferences
Components & Measures
Help
HVAC Systems
Layout
Control
Grid
FCU with ODA
My Model
Library
Edit
Availability Manager Hybrid Ventilation
Availability Manager Night Ventilation
Availability Manager Night Cycle
Availability Manager Optimum Start
Availability Manager Differential Thermostat
Availability Manager High Temperature Turn Off
Availability Manager High Temperature Turn On
Availability Manager Low Temperature Turn Off
Availability Manager Low Temperature Turn On
Availability Manager Scheduled Of
Availability Manager Scheduled On
Availability Manager Scheduled
AirLoopHVAC Unitary VAV Changeover Bypass
AirLoopHVAC Unitary System
AirLoopHVAC Outdoor Air System
Air Terminal Dual Duct VAV Outdoor Air
Air Terminal Dual Duct VAV
Air Terminal Dual Duct Constant Volume
AirTerminal Single Duct Constant
Supply Equipment
Demand Equipment
zone
zone
zone

Appendix F Calibration Process

a. Calibration Principle

The calibration method is to adjust simulation parameters iteratively, until certain degrees of accuracy between the monitored and the simulated hourly indoor temperatures are achieved. The model accuracy is controlled through the criteria provided by ASHRAE Guideline 14 (2014), IPMVP (2001), and FEMP (2015).

Table 1 Calibration Criteria

		Calibration Type	
		Hourly	Monthly
ASHRAE 14	NMBE	±10%	±5%
	CV(RMSE)	30%	15%
IPMVP	NMBE	-	±20%
	CV(RMSE)	10%-20%	-
FEMP	NMBE	±10%	±5%
	CV(RMSE)	30%	15%

The energy model runs to export the simulated indoor temperatures for Office 410A while the actual thermostat is installed in Office 410A and the FCU collect the monitored temperature to control the equipment. The simulated hourly indoor temperature and the monitored indoor temperature are compared to conduct the calibration. The steps in the iterative process in calibrating the energy model is in Figure 1.

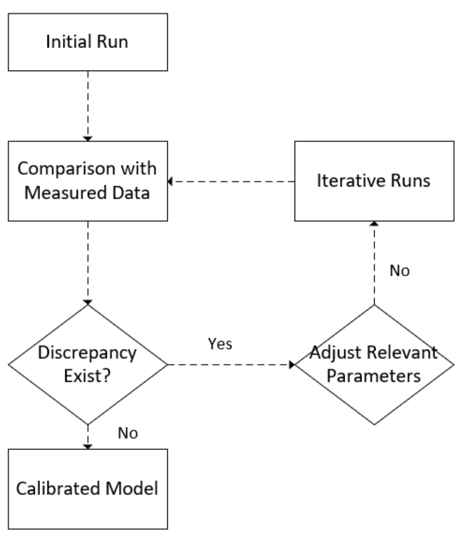


Figure 1 Calibration Steps

b. Actual Data Collection Detailed Data Collected and Cleaning Process

b1. Weather

The actual weather data is from the Climate Data Online (CDO) developed by the National Oceanic and Atmospheric Administration (NOAA). CDO provides free access to NOAA's National Climatic Data Center's archive of global historical weather and climate data with station history information. Dataset as Local Climatological Data is used to collect the necessary weather data. The weather station name is Blacksburg Virginia Tech Airport, VA US and the Network ID is 53881.

The data are collected three times per hour, and some rows with empty values should be deleted manually. The selected weather data are dry bulb temperature, relative humidity, station pressure, wet bulb temperature and wind speed. After clean all empty data, the hourly data value are calculated by averging three measured points per hour.

Original Data

STATION	DATE	REPORT_TYPE	SOURCE	HourlyAltimeterSetting	HourlyDewPointTemperature	HourlyDryBulbTemperature	HourlyPrecipitation	HourlyPresentWeatherType	HourlyPressureChange	HourlyPressureTendency	HourlyRelativeHumidity	HourlySeaLevelPressure	HourlySkyConditions	HourlyStationPressure	HourlyVisibility	HourlyWetBulbTemperature	HourlyWindDirection	HourlyWindGustSpeed	HourlyWindSpeed	REM	REPORT_TYPE	SOURC
72411353881	2019-03-10T21:35:00	FM-15	7	30.15	30	58					34		CLR:00	27.9	10	45	290		7	MET08403	FM-15	
72411353881	2019-03-10T21:55:00	FM-15	7	30.15	32	58					37		CLR:00	27.9	10	46	290	18	10	MET08603	FM-15	
72411353881	2019-03-10T22:15:00	FM-15	7	30.16	32	56					40		CLR:00	27.91	10	45	VRB	17	9	MET08603	FM-15	
72411353881	2019-03-10T22:35:00	FM-15	7	30.17	32	55					41		CLR:00	27.92	10	44	300	18	7	MET08603	FM-15	
72411353881	2019-03-10T22:55:00	FM-15	7	30.18	31	55					41		CLR:00	27.93	10	44	300	17	9	MET08603	FM-15	
72411353881	2019-03-10T23:15:00	FM-15	7	30.18	31	54					42		CLR:00	27.93	10	44	300	18	8	MET08603	FM-15	
72411353881	2019-03-10T23:35:00	FM-15	7	30.18	28	54					37		CLR:00	27.93	10	43	300	16	10	MET08703	FM-15	
72411353881	2019-03-10T23:55:00	FM-15	7	30.18	28	53					38		CLR:00	27.93	10	42	290		7	MET09403	FM-15	
72411353881	2019-03-10T23:59:00	SOD	O																		SOD	O
72411353881	2019-03-11T00:15:00	FM-15	7	30.18	28	53					39		CLR:00	27.93	10	42	290	17	8	MET08703	FM-15	
72411353881	2019-03-11T00:35:00	FM-15	7	30.18	28	52					40		CLR:00	27.93	10	42	VRB	18	9	MET08703	FM-15	
72411353881	2019-03-11T00:55:00	FM-15	7	30.19	28	51					41		CLR:00	27.94	10	41	280	16	5	MET09903	FM-15	
72411353881	2019-03-11T01:15:00	FM-15	7	30.19	29	50					43		CLR:00	27.94	10	41	280		6	MET08403	FM-15	
72411353881	2019-03-11T01:35:00	FM-15	7	30.19	30	49					47		CLR:00	27.94	10	41	290		7	MET08403	FM-15	
72411353881	2019-03-11T01:55:00	FM-15	7	30.2	29	49					46		CLR:00	27.95	10	40	280		7	MET08403	FM-15	
72411353881	2019-03-11T02:15:00	FM-15	7	30.2	30	48					50		CLR:00	27.95	10	40	270		3	MET09503	FM-15	
72411353881	2019-03-11T02:35:00	FM-15	7	30.2	31	48					52		CLR:00	27.95	10	41	260		5	MET08403	FM-15	
72411353881	2019-03-11T02:55:00	FM-15	7	30.2	31	48					52		CLR:00	27.95	10	41	250		5	MET08303	FM-15	

Empty Row

A(Y)	C(Y)	D(Y)	E(Y)	F(Y)	G(Y)	H(Y)	I(Y)
Date	HourlyDryBulbTemperature			HourlyRelativeHumidity	HourlyStationPressure	HourlyWetBulbTemperature	HourlyWindSpeed
	F	C				F	
	reduce every 3 points with Avera			reduce every 3 points with Averag	reduce every 3 points with Average	reduce every 3 points with Avera	reduce every 3 points with Av
		(Col(C)-32)/1.8					
3/11/2019 00:00:00	46.67	8.14815		56.00	27.96	40.00	10.33
3/11/2019 01:00:00	45.33	7.40741		60.00	27.99	39.33	7.67
3/11/2019 02:00:00	45.00	7.22222		61.67	28.01	39.67	8.67
3/11/2019 03:00:00	44.00	6.66667		63.33	28.02	39.00	6.33
3/11/2019 04:00:00	45.33	7.40741		61.67	28.03	40.00	5.67
3/11/2019 05:00:00	48.67	9.25926		47.33	28.03	40.00	7.00
3/11/2019 06:00:00	52.33	11.2963		36.33	28.01	41.00	7.67
3/11/2019 07:00:00	54.00	12.22222		31.67	28.01	41.33	6.67
3/11/2019 08:00:00	53.67	12.03704		29.00	28.00	40.67	6.33
3/11/2019 09:00:00	54.33	12.40741		27.67	27.99	40.67	2.67
3/11/2019 10:00:00	55.33	12.96296		23.67	27.96	40.33	4.00
3/11/2019 11:00:00	56.67	13.7037		20.67	27.95	40.67	5.67
3/11/2019 12:00:00	56.00	13.33333		21.00	27.94	40.33	4.00
3/11/2019 13:00:00	54.00	12.22222		24.67	27.95	39.67	6.67
3/11/2019 14:00:00	51.33	10.74074		26.00	27.96	38.33	7.33
3/11/2019 15:00:00	48.33	9.07407		32.67	27.96	37.33	9.33
3/11/2019 16:00:00	46.33	7.96296		36.00	27.99	36.00	11.67
3/11/2019 17:00:00	44.33	6.85185		39.00	27.99	35.33	9.00
3/11/2019 18:00:00	44.00	6.66667		39.00	27.99	35.00	12.33
3/11/2019 19:00:00	42.33	5.74074		43.00	28.00	34.33	10.00
3/11/2019 20:00:00	40.67	4.81481		42.67	27.99	32.67	9.33
3/11/2019 21:00:00	39.67	4.25926		42.00	28.00	32.00	9.67
3/11/2019 22:00:00	38.67	3.7037		44.33	27.99	31.00	10.67
3/11/2019 23:00:00	38.00	3.33333		47.67	27.99	31.00	11.33
3/12/2019 00:00:00	36.33	2.40741		52.00	27.99	30.33	9.33
3/12/2019 01:00:00	35.33	1.85185		56.00	28.02	30.00	5.33
3/12/2019 02:00:00	34.33	1.2963		61.00	28.02	30.00	6.33
3/12/2019 03:00:00	35.00	1.66667		59.67	28.03	30.33	8.00
3/12/2019 04:00:00	37.00	2.77778		57.00	28.05	31.67	6.33
3/12/2019 05:00:00	39.00	3.88889		46.67	28.07	32.33	7.67
3/12/2019 06:00:00	42.00	5.55556		39.33	28.07	33.33	7.00
3/12/2019 07:00:00	44.67	7.03704		36.00	28.06	34.67	5.33
3/12/2019 08:00:00	47.33	8.51852		32.00	28.05	36.33	5.67
3/12/2019 09:00:00	49.67	9.81481		29.33	28.04	37.33	6.33
3/12/2019 10:00:00	51.33	10.74074		26.33	28.02	38.33	6.00
3/12/2019 11:00:00	51.33	10.74074		23.67	28.02	37.67	7.33
3/12/2019 12:00:00	51.33	10.74074		22.00	28.03	37.33	8.67
3/12/2019 13:00:00	50.33	10.18519		25.67	28.03	37.67	6.67
3/12/2019 14:00:00	45.33	7.40741		32.67	28.03	35.00	6.33
3/12/2019 15:00:00	40.67	4.81481		41.00	28.05	32.67	0.00
3/12/2019 16:00:00	37.67	3.14815		49.67	28.05	31.33	0.00
3/12/2019 17:00:00	34.67	1.48148		57.33	28.06	29.67	0.00
3/12/2019 18:00:00	32.33	0.18519		62.67	28.06	28.00	0.00
3/12/2019 19:00:00	32.00	0		65.00	28.06	28.00	0.00
3/12/2019 20:00:00	31.00	-0.55556		63.00	28.04	27.00	0.00

Cleaned DataSet

b2. BAS Data

The BAS data are collected from the Campus Building Automation System of Virginia Tech. The collected period is from Feb. 21 to July 8. Weekly reports were collected by every weekend, but missing two weeks data, from Mar.6 to Mar 11, and from June 11 to June 17. Therefore, the selected calibrated period is from March 11 to June 10.

Further more, the value of collected point from 6 am to 11:59 pm on every weekend are all missing, the exactly dates are March 17, March 24, March 31, April 7, 14,21,28, May 5,12,19,26, June 2. All these data are replaced manually, and the hourly data value are calculated by averging 12 measured points per hour.

<>Date	Time	Point_1 FC AUX TEMP	Point_2	Point_3 FAN	Point_4	Point_5 ROOM SETTING	Point_6 ROOM TEMP	Point_7 VLV1	Point_8	Point_9 VLV2	Point_10	Point_11	Point_12 OAT	Point_ 13 SAH	Point_14 SAS	Point_15 SAT
3/11/2019	0:00:00	75.5	NIGHT	OFF	HEAT	75.25	74	0	0	0	0	NO	63.26	23.62	67	70.19
3/11/2019	0:05:00	75	NIGHT	OFF	HEAT	75.25	73.75	0	0	0	0	NO	63.2	23.53	67	70.27
3/11/2019	0:10:00	75	NIGHT	OFF	HEAT	75.25	73.75	0	0	0	0	NO	63.13	23.37	67	70.42
3/11/2019	0:15:00	74.5	NIGHT	OFF	HEAT	75.25	73.5	0	0	0	0	NO	63.03	23.26	67	70.62
3/11/2019	0:20:00	74.5	NIGHT	OFF	HEAT	75.25	73.5	0	0	0	0	NO	62.88	23.21	67	70.71
3/11/2019	0:25:00	74.5	NIGHT	OFF	HEAT	75.25	73.5	0	0	0	0	NO	62.74	23.24	67	70.79
3/11/2019	0:30:00	74	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.61	23.13	67	70.96
3/11/2019	0:35:00	74	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.42	22.99	67	71.07
3/11/2019	0:40:00	74	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.35	23.12	67	71.09
3/11/2019	0:45:00	73.5	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.23	23.11	67	71.08
3/11/2019	0:50:00	73.5	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	62.05	23.04	67	71.19
3/11/2019	0:55:00	73.5	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	61.86	22.99	67	71.26
3/11/2019	1:00:00	72.5	NIGHT	OFF	HEAT	75.25	73	0	0	0	0	NO	61.8	22.97	67	71.27
3/11/2019	1:05:00	72.5	NIGHT	OFF	HEAT	75.25	73	0	0	0	0	NO	61.58	22.81	67	71.42
3/11/2019	1:10:00	72.5	NIGHT	OFF	HEAT	75.25	73	0	0	0	0	NO	61.41	22.79	67	71.47
3/11/2019	1:15:00	72	NIGHT	OFF	HEAT	75.25	72.75	0	0	0	0.4	NO	61.27	22.49	67	71.5
3/11/2019	1:20:00	72	NIGHT	OFF	HEAT	75.25	72.75	0	0	0	0.4	NO	61.12	22.39	67	71.57
3/11/2019	1:25:00	72	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.93	22.44	67	71.66
3/11/2019	1:30:00	72	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.78	22.47	67	71.65
3/11/2019	1:35:00	72	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.68	22.81	67	71.57
3/11/2019	1:40:00	71.5	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.53	22.19	67	71.64
3/11/2019	1:45:00	71.5	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0.4	NO	60.39	22.51	67	71.66
3/11/2019	1:50:00	71.5	NIGHT	OFF	HEAT	75.25	72.25	0	0	0	0	NO	60.24	22.79	67	71.58
3/11/2019	1:55:00	71.5	NIGHT	OFF	HEAT	75.25	72.25	0	0	0	0	NO	60.07	22.8	67	71.59
3/11/2019	2:00:00	71.5	NIGHT	OFF	HEAT	75.25	72.25	0	0	0	0	NO	59.92	22.83	67	71.66
3/11/2019	2:05:00	71.5	NIGHT	OFF	HEAT	75.25	72	0	0	0	0	NO	59.85	22.83	67	71.62
3/11/2019	2:10:00	71	NIGHT	OFF	HEAT	75.25	72	0	0	0	0	NO	59.64	22.66	67	71.64
3/11/2019	2:15:00	71	NIGHT	OFF	HEAT	75.25	71.75	0	0	0	0	NO	59.53	22.37	67	71.65
3/11/2019	2:20:00	71	NIGHT	OFF	HEAT	75.25	71.75	0	0	0	0	NO	59.42	22.84	67	71.5
3/11/2019	2:25:00	71	NIGHT	OFF	HEAT	75.25	71.75	0	0	0	0	NO	59.26	22.95	67	71.44
3/11/2019	2:30:00	71	NIGHT	OFF	HEAT	75.25	71.5	0	0	0	0	NO	59.16	23.07	67	71.55
3/11/2019	2:35:00	71	NIGHT	OFF	HEAT	75.25	71.5	0	0	0	0	NO	59.01	22.58	67	71.52
3/11/2019	2:40:00	71	NIGHT	OFF	HEAT	75.25	71.5	0	0	0	0	NO	58.88	22.6	67	71.52
3/11/2019	2:45:00	71	NIGHT	OFF	HEAT	75.25	71.5	0	0	0	0	NO	58.81	22.74	67	71.59

Key	Name:Suffix	Trend Definitions Used
Point_1:	BFRM410A.FC:AUX TEMP	
Point_2:	BFRM410A.FC:DAY.NGT	
Point_3:	BFRM410A.FC:FAN	
Point_4:	BFRM410A.FC:HEAT.COOL	
Point_5:	BFRM410A.FC:RM STPT DIAL	
Point_6:	BFRM410A.FC:ROOM TEMP	
Point_7:	BFRM410A.FC:VLV 1 COMD	
Point_8:	BFRM410A.FC:VLV 1 POS	
Point_9:	BFRM410A.FC:VLV 2 COMD	
Point_10:	BFRM410A.FC:VLV 2 POS	
Point_11:	BFRM410A.FC:WALL SWITCH	
Point_12:	BF01OAT	
Point_13:	BF01SAH	
Point_14:	BF01SAS	
Point_15:	BF01SAT	
Time Interval:	5 Minutes	

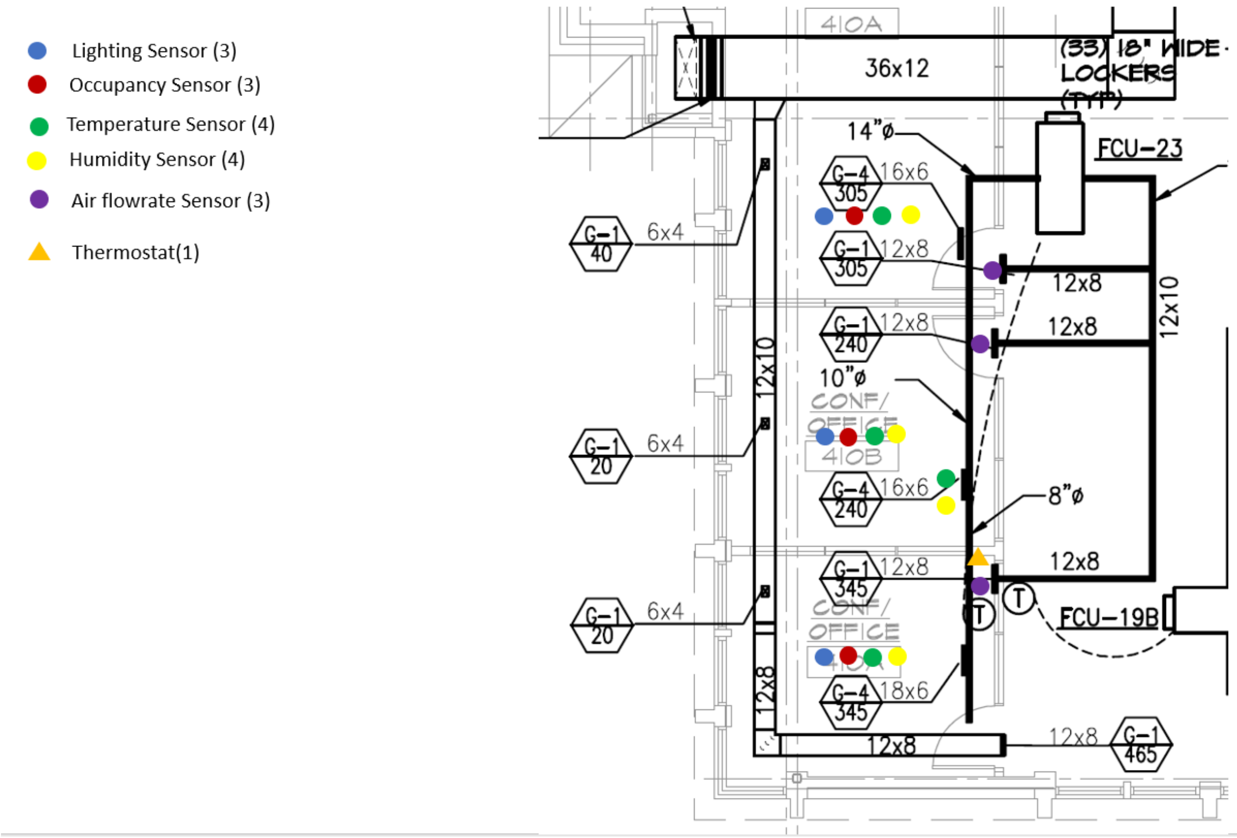
Data Name

<>Date	Time	Point_1 FC AUX TEMP	Point_2	Point_3 FAN	Point_4	Point_5 ROOM SETTING	Point_6 ROOM TEMP	Point_7 VLV1	Point_8	Point_9 VLV2	Point_10	Point_11	Point_12 OAT	Point_13 SAH	Point_14 SAS	Point_15 SAT
3/17/2019	6:45:00	85	DAY	ON	HEAT	75.25	69	0	0	100	100	NO	31.79	16.55	67	67.18
3/17/2019	6:50:00	85	DAY	ON	HEAT	75.25	69.5	0	0	100	100	NO	31.44	16.57	67	67.22
3/17/2019	6:55:00	85.5	DAY	ON	HEAT	75.25	69.75	0	0	100	100	NO	31.4	16.6	67	67.14
3/17/2019	7:00:00	85.5	DAY	ON	HEAT	75.25	70	0	0	100	100	NO	31.24	16.66	67	67
3/17/2019	7:05:00	86	DAY	ON	HEAT	75.25	70.25	0	0	100	100	NO	31.64	16.47	67	67.04
3/17/2019	7:10:00	86	DAY	ON	HEAT	75.25	70.75	0	0	100	100	NO	32.23	16.64	67	66.92
3/17/2019	7:15:00	86	DAY	ON	HEAT	75.25	70.75	0	0	100	100	NO	31.47	16.48	67	67.01
3/17/2019	7:20:00	86.5	DAY	ON	HEAT	75.25	71	0	0	100	100	NO	32.26	16.39	67	67.12
3/17/2019	7:25:00	86.5	DAY	ON	HEAT	75.25	71.5	0	0	100	100	NO	32.74	16.43	67	67.12
3/17/2019	7:30:00	86.5	DAY	ON	HEAT	75.25	71.5	0	0	100	100	NO	32.38	16.65	67	67.0
			Missing Period													
<>Date	Time	Point_1	Point_2	Point_3	Point_4	Point_5	Point_6	Point_7	Point_8	Point_9	Point_10	Point_11	Point_12	Point_1	Point_14	Point_15
3/18/2019	0:00:00	76	NIGHT	OFF	HEAT	75.25	73.75	0	0	0	0	NO	54.25	15.34	67	69.8
3/18/2019	0:05:00	76	NIGHT	OFF	HEAT	75.25	73.5	0	0	0	0	NO	54.22	15.31	67	69.97
3/18/2019	0:10:00	76	NIGHT	OFF	HEAT	75.25	73.5	0	0	0	0	NO	54.15	15.25	67	70.06
3/18/2019	0:15:00	75.5	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	54.07	15.25	67	70.16
3/18/2019	0:20:00	75.5	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	53.97	15.3	67	70.24
3/18/2019	0:25:00	75.5	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	53.88	15.32	67	70.32
3/18/2019	0:30:00	75	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	53.75	15.39	67	70.39
3/18/2019	0:35:00	75	NIGHT	OFF	HEAT	75.25	73.25	0	0	0	0	NO	53.61	15.38	67	70.45
3/18/2019	0:40:00	75	NIGHT	OFF	HEAT	75.25	73	0	0	0	0	NO	53.51	15.42	67	70.51
3/18/2019	0:45:00	74.5	NIGHT	OFF	HEAT	75.25	73	0	0	0	0	NO	53.32	15.41	67	70.56
3/18/2019	0:50:00	74.5	NIGHT	OFF	HEAT	75.25	72.75	0	0	0	0	NO	53.14	15.39	67	70.59
3/18/2019	0:55:00	74.5	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0	NO	52.99	15.39	67	70.67
3/18/2019	1:00:00	74.5	NIGHT	OFF	HEAT	75.25	72.5	0	0	0	0	NO	52.77	15.47	67	70.75

	C(Y)	E(Y)	G(Y)
Long Name		Room Temp	Room Temp
Units		F	C
Comments		reduce every 12 points with A	RT C
F(x)=			(COL(E)-32)/1.8
1	3/11/2019 00:00:00	73.45833	23.03
2	3/11/2019 01:00:00	72.625	22.57
3	3/11/2019 02:00:00	71.6875	22.05
4	3/11/2019 03:00:00	70.875	21.60
5	3/11/2019 04:00:00	70	21.11
6	3/11/2019 05:00:00	69.33333	20.74
7	3/11/2019 06:00:00	68.72917	20.41
8	3/11/2019 07:00:00	69.5625	20.87
9	3/11/2019 08:00:00	72.22917	22.35
10	3/11/2019 09:00:00	73.8125	23.23
11	3/11/2019 10:00:00	75.33333	24.07
12	3/11/2019 11:00:00	76.04167	24.47
13	3/11/2019 12:00:00	75.85417	24.36
14	3/11/2019 13:00:00	74.75	23.75
15	3/11/2019 14:00:00	74.5	23.61
16	3/11/2019 15:00:00	74.875	23.82
17	3/11/2019 16:00:00	75.64583	24.25
18	3/11/2019 17:00:00	76.41667	24.68
19	3/11/2019 18:00:00	76.3125	24.62
20	3/11/2019 19:00:00	76.02083	24.46
21	3/11/2019 20:00:00	75.29167	24.05
22	3/11/2019 21:00:00	74.10417	23.39
23	3/11/2019 22:00:00	73.02083	22.79
24	3/11/2019 23:00:00	72.08333	22.27
[illegible]	[illegible]	[illegible]	[illegible]

Cleaned BAS data for room temperature (410A thermostat sensor) b3. HOBO Data

HOBO data node and data receiver are used with sensors to monitor the indoor environmental condition of 410 Office. HOBOware Pro is used for launching, reading out, and plotting the collected data from data loggers and sensors to monitor the indoor environmental condition of 410 Office. The connected sensors are installed as follows.



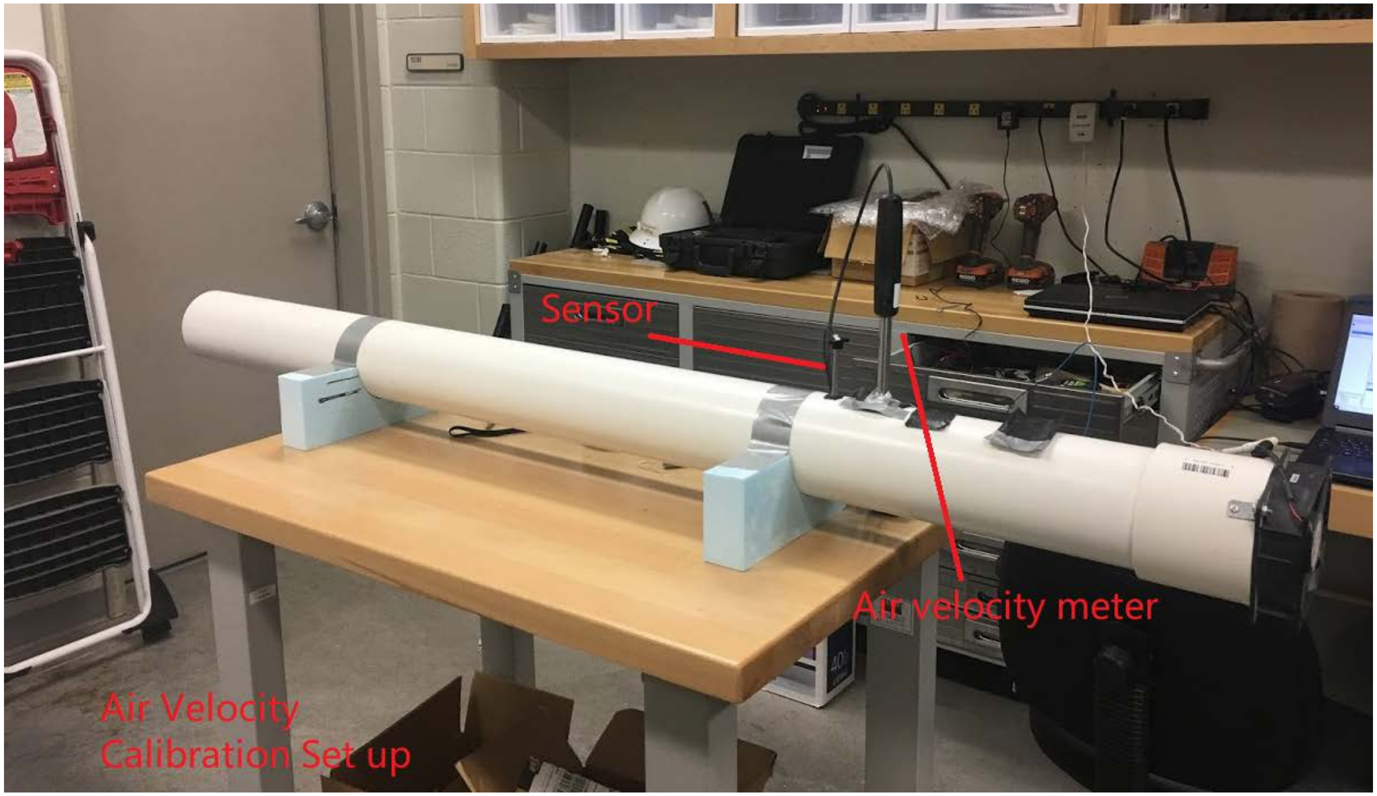
a. Temperature and humidity of every office (410A, 410B,410C) are monitored by temperature and humidity sensors, which installed with the illuminance and occupancy sensors together, above the light with 6.7 feet height, in the middle of office.

b. Indoor illuminance of every office (410A, 410B,410C) are monitored by lighting sensors which installed under the lights. The monitored data are used as lighting schedule in energy model.

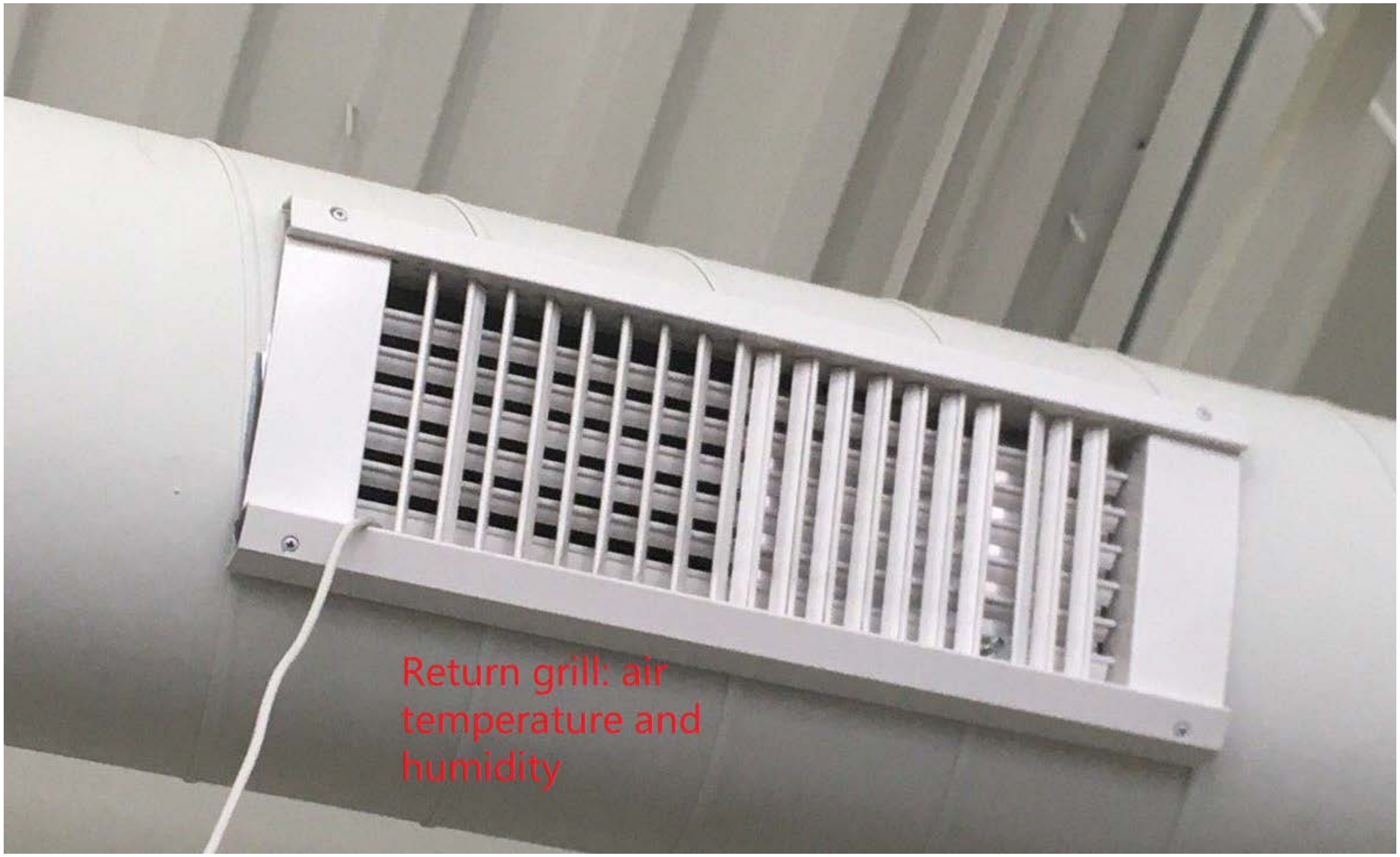
c. Occupancy of every office (410A, 410B,410C) are monitored by occupancy sensors which installed under the lights. The monitored data are used as occupancy schedule in energy model.

d. Airflow velocity of every supply vent per office (410A,410B,410C) are monitored by calibrated velocity sensors which installed at the middle of the vent. The area of vent is 7 inch by 11 inch. The monitored unit is feet per minute(fpm), which was converted into CFM for energy model.

e. All the three airflow rate sensors are calibrated with an air velocity meter (VELOCICALC Air Velocity Meter, mode:9545). The flowrate of a fan installed in a tunnel are measured by the HOBO sensor and the standard air velocity meter simultaneously, and the monitored results of sensor are calibrated based on the results of air velocity meter.



f. Supply air temperature and relative humidity are monitored by a sensor installed on the return grill in 410 B.


Return grill: air
temperature and
humidity

The monitored period is from Jan 2019 to July 2019, data are collected every minute without missing values, and the hourly data value are calculated by averaging 12 measured points per hour. The airflow velocity was converted into CFM, which is about 0.47 m^3/s for all spaces with the whole load.

HOBO Original Data

A	B	C	E	F	G	H	I	K	L	M	N	O	P	Q	R	S	V
Date Time, GMT-04:00	Temp, °C (LGR S/N: 10072541, SEN S/N: 10072541-1, LBL: T-B)	RH, % (LGR S/N: 10072541, SEN S/N: 10072541-2, LBL: RH-B)	lux (LGR S/N: 10072541, SEN S/N: 10072541-4, LBL: L-B)	(LGR S/N: 10072541, SEN S/N: 10072541-3, LBL: O-B)	(LGR S/N: 10072543, SEN S/N: 10072543-1, LBL: T-C)	S/N: 10072543, SEN S/N: 10072543-2, LBL: RH-C)	Occupancy, % (LGR S/N: 10072543, SEN S/N: 10072543-3, LBL: O-C)	Illuminance, lux (LGR S/N: 10072543, SEN S/N: 10072543-4, LBL: L-C)	Temp, °C (LGR S/N: 10105949, SEN S/N: 10105949-1, LBL: T-A)	RH, % (LGR S/N: 10105949, SEN S/N: 10105949-2, LBL: RH-A)	Occupancy, % (LGR S/N: 10105949, SEN S/N: 10105949-3, LBL: O-A)	Illuminance, lux (LGR S/N: 10105949, SEN S/N: 10105949-4, LBL: L-A)	Temp, °C (LGR S/N: 10072542, SEN S/N: 10072542-1, LBL: T-SA-B)	RH, % (LGR S/N: 10072542, SEN S/N: 10072542-2, LBL: RH-SA-B)	Velocity, fpm (LGR S/N: 10072542, SEN S/N: 10072542-4, LBL: V-R-B)	Velocity, fpm (LGR S/N: 10082655, SEN S/N: 10082655-1, LBL: V-R-A)	Velocity, fpm (LGR S/N: 10082656, SEN S/N: 10082656-1, LBL: V-R-C)
3/11/2019 0:00	22.824	25.042	0	0	22.633	25.641	0	0	22.345	26.57	0	0	23.184	24.112	9.31	19.68	9.91
3/11/2019 0:01	22.8	25.075	0	0	22.609	25.707	0	0	22.345	26.57	0	0	23.16	24.315	9.31	19.68	9.91
3/11/2019 0:02	22.8	25.109	0	0	22.609	25.673	0	0	22.321	26.636	0	0	23.136	24.245	9.31	19.68	9.91
3/11/2019 0:03	22.776	25.141	0	0	22.609	25.707	0	0	22.321	26.636	0	0	23.136	24.177	9.31	19.68	9.91
3/11/2019 0:04	22.776	25.175	0	0	22.585	25.74	0	0	22.298	26.635	0	0	23.112	24.38	9.31	19.68	9.91
3/11/2019 0:05	22.753	25.173	0	0	22.585	25.638	0	0	22.298	26.702	0	0	23.112	24.38	9.31	19.68	9.91
3/11/2019 0:06	22.753	25.173	0	0	22.585	25.638	0	0	22.298	26.702	0	0	23.088	24.31	9.31	19.68	9.91
3/11/2019 0:07	22.753	25.173	0	0	22.585	25.706	0	0	22.274	26.701	0	0	23.064	24.445	9.31	19.68	9.91
3/11/2019 0:08	22.729	25.172	0	0	22.585	25.74	0	0	22.274	26.701	0	0	23.064	24.514	9.31	19.68	9.91
3/11/2019 0:09	22.729	25.206	0	0	22.561	25.772	0	0	22.25	26.699	0	0	23.04	24.444	9.31	19.68	9.91
3/11/2019 0:10	22.705	25.238	0	0	22.561	25.772	0	0	22.25	26.699	0	0	23.04	24.512	9.31	19.68	9.91
3/11/2019 0:11	22.705	25.238	0	0	22.561	25.772	0	0	22.226	26.765	0	0	23.016	24.578	9.31	19.68	9.91
3/11/2019 0:12	22.705	25.238	0	0	22.537	25.77	0.99976	0	22.226	26.765	0	0	22.992	24.577	9.31	19.68	9.91
3/11/2019 0:13	22.681	25.236	0	0	22.537	25.77	0	0	22.202	26.763	0	0	22.992	24.645	9.31	19.68	9.91
3/11/2019 0:14	22.681	25.304	0	0	22.537	25.838	0	0	22.202	26.797	0	0	22.968	24.643	9.31	19.68	9.91
3/11/2019 0:15	22.681	25.304	0	0	22.537	25.77	0	0	22.202	26.864	0	0	22.968	24.712	9.31	19.68	9.91
3/11/2019 0:16	22.681	25.304	0	0	22.537	25.838	0	0	22.178	26.829	0	0	22.944	24.71	9.31	19.68	9.91
3/11/2019 0:17	22.657	25.303	0	0	22.513	25.836	0	0	22.178	26.863	0	0	22.944	24.744	9.31	19.68	9.91
3/11/2019 0:18	22.657	25.303	0	0	22.513	25.802	0	0	22.154	26.861	0	0	22.92	24.776	9.31	19.68	9.91
3/11/2019 0:19	22.657	25.303	0	0	22.513	25.836	0	0	22.154	26.895	0	0	22.896	24.775	9.31	19.68	9.91
3/11/2019 0:20	22.633	25.369	0	0	22.513	25.768	0	0	22.13	26.893	0	0	22.896	24.809	9.31	19.68	9.91
3/11/2019 0:21	22.633	25.369	0	0	22.489	25.835	0	0	22.13	26.893	0	0	22.872	24.773	9.31	19.68	9.91
3/11/2019 0:22	22.633	25.369	0	0	22.489	25.835	0	0	22.106	26.959	0	0	22.872	24.841	9.31	19.68	9.91
3/11/2019 0:23	22.609	25.367	0	0	22.489	25.767	0	0	22.106	26.959	0	0	22.848	24.84	9.31	19.68	9.91
3/11/2019 0:24	22.609	25.367	0	0	22.489	25.835	0	0	22.082	26.957	0	0	22.848	24.908	9.31	19.68	9.91
3/11/2019 0:25	22.609	25.401	0	0	22.465	25.833	0.99976	0	22.082	26.957	0	0	22.824	24.906	9.31	19.68	9.91
3/11/2019 0:26	22.585	25.366	0	0	22.465	25.867	0	0	22.058	27.023	0	0	22.824	24.906	9.31	19.68	9.91
3/11/2019 0:27	22.585	25.434	0	0	22.465	25.833	0	0	22.058	27.023	0	0	22.8	24.904	9.31	19.68	9.91
3/11/2019 0:28	22.585	25.434	0	0	22.465	25.901	0	0	22.058	27.023	0	0	22.8	24.972	9.31	19.68	9.91
3/11/2019 0:29	22.561	25.432	0	0	22.441	25.831	0	0	22.034	27.021	0	0	22.776	24.971	9.31	19.68	9.91
3/11/2019 0:30	22.561	25.432	0	0	22.441	25.831	0	0	22.034	27.055	0	0	22.776	24.971	9.31	19.68	9.91
3/11/2019 0:31	22.561	25.432	0	0	22.441	25.899	0	0	22.011	27.019	0	0	22.753	25.037	9.31	19.68	9.91
3/11/2019 0:32	22.537	25.464	0	0	22.441	25.899	0	0	22.011	27.053	0	0	22.753	25.037	9.31	19.68	9.91

Table F-1 Sensor List

Room	SEN S/N						
	Indoor Temperature	Indoor Humidity	illuminance	occupancy	Supply air CFM	Supply air temperature	Supply air humidity
410A	10105949-1	10105949-2	10105949-4	10105949-3	10082655-1		
410B	10072541-1	10072541-2	10072541-4	10072541-3	10072542-4	10072542-1	10072542-2
410C	10072543-1	10072543-2	10072543-4	10072543-3	10082656-1		

Cleaned data example

	A(X)	B(Y)	C(Y)	D(Y)	E(Y)	F(Y)	G(Y)	H(Y)	I(Y)	J(Y)	K(Y)	L(Y)	M(Y)	N(Y)	O(Y)	P(Y)	Q(Y)	R(Y)
Long Name	Date time	410B T	410B RH	410B L	410B O	410C T	410C RH	410C O	410C L	410A T	410A RH	410A O	410A L	SAT	SAR	410B V	410A V	410C V
Units		C				C				C				C		fpm	fpm	fpm
Comments		Temp		Lux	Occ	Temp		Occ	Lux	Temp		Occ	Lux	Supply air Temp	Supply air RH	Velocity	Velocity	Velocity
F(x)=																		
1	3/11/2019 00:00:00	22.571	25.421	0.000	0.000	22.457	25.867	0.033	0.000	22.044	27.023	0.000	0.000	22.796	24.922	9.310	19.680	9.910
2	3/11/2019 01:00:00	22.151	25.908	0.000	0.000	22.174	26.148	0.000	0.000	21.499	27.746	0.000	0.000	22.241	25.718	9.310	19.680	9.910
3	3/11/2019 02:00:00	21.766	26.264	0.000	0.000	21.939	26.351	0.000	0.000	21.035	28.286	0.000	0.000	21.825	26.190	9.310	19.680	9.910
4	3/11/2019 03:00:00	21.406	26.566	0.000	0.000	21.722	26.520	0.000	0.000	20.610	28.742	0.000	0.000	21.461	26.643	9.310	19.827	9.910
5	3/11/2019 04:00:00	21.089	26.814	0.000	0.000	21.532	26.689	0.017	0.000	20.222	29.190	0.000	0.000	21.134	27.064	9.310	20.172	9.910
6	3/11/2019 05:00:00	20.779	27.036	0.000	0.000	21.354	26.861	0.000	0.000	19.845	29.594	0.000	0.000	20.832	27.245	9.310	22.632	10.065
7	3/11/2019 06:00:00	20.492	27.262	0.000	0.000	21.197	27.027	0.000	0.000	19.492	29.993	0.017	0.000	20.558	27.361	9.310	25.912	10.080
8	3/11/2019 07:00:00	22.665	24.879	0.567	0.000	22.181	25.620	0.017	0.055	21.031	28.020	0.017	0.210	27.186	19.718	434.338	831.054	581.513
9	3/11/2019 08:00:00	23.889	23.280	10.611	0.000	23.000	24.445	0.000	2.789	22.595	25.824	0.000	7.193	29.107	17.449	442.135	843.272	589.840
10	3/11/2019 09:00:00	24.391	22.533	42.648	0.000	23.439	23.681	0.000	13.678	23.445	24.561	0.017	62.741	29.401	17.016	444.116	847.289	587.669
11	3/11/2019 10:00:00	24.376	22.020	58.447	0.000	23.556	23.009	0.067	20.050	24.139	23.158	0.000	104.095	28.541	17.408	445.921	848.258	587.504
12	3/11/2019 11:00:00	23.934	21.540	65.832	0.000	23.339	22.175	0.000	28.726	24.232	22.018	0.000	111.209	26.774	18.322	443.140	851.259	582.834
13	3/11/2019 12:00:00	23.060	21.651	97.208	0.000	22.734	21.837	0.000	41.409	23.625	21.751	0.000	103.940	23.959	20.585	440.500	849.538	580.388
14	3/11/2019 13:00:00	22.659	21.280	64.944	0.000	22.330	21.401	0.000	23.227	22.827	21.608	0.000	50.717	23.199	20.696	439.994	849.504	580.703
15	3/11/2019 14:00:00	23.142	20.045	65.851	0.000	22.625	20.460	0.000	24.158	22.997	20.732	0.000	50.888	25.117	18.026	441.995	848.306	583.285
16	3/11/2019 15:00:00	23.697	18.805	89.151	0.000	23.001	19.496	0.000	31.103	23.555	19.537	0.000	66.745	26.201	16.362	442.555	847.503	579.321
17	3/11/2019 16:00:00	24.109	17.938	337.528	0.000	23.273	18.700	0.017	115.997	24.162	18.492	0.000	228.537	25.524	16.536	442.505	848.733	581.114
18	3/11/2019 17:00:00	24.625	17.887	157.138	0.000	23.194	18.936	0.000	47.235	24.779	18.579	0.000	94.962	24.368	17.961	16.497	33.964	19.534
19	3/11/2019 18:00:00	24.083	19.473	182.321	0.000	22.760	20.093	0.000	24.850	24.147	20.384	0.000	71.973	24.073	19.312	9.310	19.680	9.910
20	3/11/2019 19:00:00	23.814	20.349	50.327	0.000	22.513	20.737	0.000	5.646	23.833	21.338	0.000	19.174	23.813	20.168	9.310	19.680	9.910
21	3/11/2019 20:00:00	23.080	21.393	0.000	0.000	22.148	21.365	0.000	0.000	23.004	22.437	0.000	0.000	23.251	20.794	9.310	19.680	9.910
22	3/11/2019 21:00:00	22.519	22.074	0.000	0.000	21.835	21.888	0.000	0.000	22.326	23.161	0.000	0.000	22.644	21.501	9.310	19.680	9.910
23	3/11/2019 22:00:00	22.031	22.596	0.000	0.000	21.554	22.298	0.000	0.000	21.757	23.660	0.000	0.000	22.096	22.128	9.310	19.680	9.910
24	3/11/2019 23:00:00	21.600	22.982	0.000	0.000	21.307	22.650	0.000	0.000	21.244	24.097	0.000	0.000	21.656	22.669	9.310	19.680	9.910
25	3/12/2019 00:00:00	21.200	23.283	0.000	0.000	21.079	22.973	0.000	0.000	20.754	24.547	0.000	0.000	21.278	23.106	9.310	22.369	9.910
26	3/12/2019 01:00:00	20.823	23.559	0.000	0.000	20.857	23.318	0.017	0.000	20.283	24.962	0.000	0.000	20.918	23.560	9.310	34.899	10.000
27	3/12/2019 02:00:00	20.459	23.801	0.000	0.000	20.637	23.677	0.017	0.000	19.823	25.406	0.000	0.000	20.569	23.951	9.310	42.444	12.459
28	3/12/2019 03:00:00	20.095	24.042	0.000	0.000	20.432	23.931	0.000	0.000	19.357	25.852	0.000	0.000	20.223	24.274	9.310	49.840	14.261
29	3/12/2019 04:00:00	19.729	24.275	0.000	0.000	20.236	24.155	0.033	0.000	18.891	26.297	0.000	0.000	19.878	24.463	9.310	53.545	15.311
30	3/12/2019 05:00:00	19.364	24.464	0.000	0.000	20.047	24.390	0.000	0.000	18.431	26.724	0.000	0.000	19.536	24.682	9.310	61.795	19.550
31	3/12/2019 06:00:00	19.042	24.696	0.000	0.000	19.872	24.747	0.000	0.000	18.013	27.261	0.000	0.000	19.246	25.114	9.310	72.782	27.081
32	3/12/2019 07:00:00	20.868	22.602	2.435	0.000	20.615	23.336	0.000	0.732	19.236	25.599	0.000	1.550	25.557	18.329	324.202	637.222	446.094
33	3/12/2019 08:00:00	23.287	19.277	21.982	0.000	22.110	20.648	0.000	7.077	21.864	21.625	0.000	17.993	30.310	12.974	441.730	845.075	592.113
34	3/12/2019 09:00:00	24.039	18.189	42.767	0.000	22.822	19.551	0.000	12.915	23.001	20.038	0.000	52.014	30.810	12.331	444.166	847.979	593.634
35	3/12/2019 10:00:00	24.465	17.322	64.725	0.000	23.142	18.734	0.000	22.442	23.810	18.722	0.000	83.896	30.602	12.115	444.027	846.568	593.478
36	3/12/2019 11:00:00	24.680	16.666	88.956	0.000	23.382	17.967	0.000	36.813	24.339	17.706	0.000	105.667	30.001	12.161	444.456	844.568	591.031
37	3/12/2019 12:00:00	24.453	16.477	104.803	0.000	23.409	17.471	0.000	47.412	24.402	17.229	0.000	117.654	28.286	13.087	443.110	846.699	585.927
38	3/12/2019 13:00:00	23.258	17.296	125.030	0.000	22.771	17.528	0.000	54.099	23.692	17.588	0.000	143.970	24.092	16.342	440.635	846.552	580.703
39	3/12/2019 14:00:00	23.325	17.056	234.473	0.000	22.746	17.358	0.017	99.283	23.767	17.319	0.000	226.361	23.496	16.795	442.100	848.585	580.378
40	3/12/2019 15:00:00	23.777	16.497	342.032	0.000	22.877	17.175	0.000	135.053	24.110	16.874	0.000	271.884	22.048	18.340	443.025	852.096	583.395
41	3/12/2019 16:00:00	22.948	16.836	329.309	0.000	22.148	17.332	0.017	118.237	23.069	17.301	0.000	217.972	20.129	19.989	442.065	849.619	582.124
42	3/12/2019 17:00:00	24.283	16.073	290.637	0.000	22.668	17.190	0.017	79.535	23.996	16.950	0.000	164.712	23.031	17.418	16.542	33.571	19.344
43	3/12/2019 18:00:00	24.776	16.655	419.830	0.000	22.776	17.761	0.000	54.129	24.355	17.695	0.000	172.015	24.156	17.132	9.310	19.680	9.935
44	3/12/2019 19:00:00	24.466	17.536	10.400	0.000	22.546	18.413	0.017	1.587	23.972	18.479	0.000	3.519	24.203	17.162	9.310	19.680	9.910
45	3/12/2019 20:00:00	23.460	18.719	0.000	0.000	22.110	19.123	0.000	0.000	22.857	19.627	0.000	0.000	23.424	18.023	9.310	19.680	9.910
46	3/12/2019 21:00:00	22.733	19.463	0.000	0.000	21.760	19.707	0.000	0.000	22.037	20.421	0.000	0.000	22.710	18.962	9.310	19.795	9.910
47	3/12/2019 22:00:00	22.161	20.059	0.000	0.000	21.456	20.204	0.000	0.000	21.360	21.096	0.000	0.000	22.152	19.693	9.310	26.863	9.910
48	3/12/2019 23:00:00	21.598	20.536	0.000	0.000	21.166	20.645	0.017	0.000	20.753	21.731	0.000	0.000	21.650	20.343	9.310	44.018	11.667

	A(X)	B(Y)	C(Y)	D(Y)	E(Y)	F(Y)	G(Y)	H(Y)	I(Y)	J(Y)
Long Name	Date	410B	410A	410C	410 All	410 All	410 All	410B	410A	410C
Units		fpm	fpm	fpm	fpm	CFM	M3/S	CFM	CFM	CFM
Comments		Velocity	Velocity	Velocity	Velocity	Vent, 0.5347ft2	Velocity	Velocity	Velocity	Velocity
F(x)=					Col(B)+Col(C)+Col(D)	Col(E)*0.5347	Col(F)*0.0004719	Col(B)*0.5347	Col(C)*0.5347	Col(D)*0.5347
1	3/11/2019 00:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
2	3/11/2019 01:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
3	3/11/2019 02:00	9.31	19.8275	9.91	39.0475	20.8787	0.00985	4.97806	10.60176	5.29888
4	3/11/2019 03:00	9.31	20.172	9.91	39.392	21.0629	0.00994	4.97806	10.78597	5.29888
5	3/11/2019 04:00	9.31	22.63217	10.06517	42.00734	22.46132	0.0106	4.97806	12.10142	5.38185
6	3/11/2019 05:00	9.31	25.91183	10.08017	45.302	24.22298	0.01143	4.97806	13.85506	5.38987
7	3/11/2019 06:00	434.33783	831.05367	581.5125	1846.904	987.53957	0.46602	232.24044	444.3644	310.93473
8	3/11/2019 07:00	442.13533	843.27233	589.84017	1875.24783	1002.69501	0.47317	236.40976	450.89771	315.38754
9	3/11/2019 08:00	444.11583	847.28917	587.6685	1879.0735	1004.7406	0.47414	237.46873	453.04552	314.22635
10	3/11/2019 09:00	445.92133	848.25767	587.50367	1881.68267	1006.13572	0.4748	238.43414	453.56338	314.13821
11	3/11/2019 10:00	443.14033	851.25933	582.83417	1877.23383	1003.75693	0.47367	236.94713	455.16836	311.64143
12	3/11/2019 11:00	440.49967	849.5375	580.38783	1870.425	1000.11625	0.47195	235.53517	454.2477	310.33337
13	3/11/2019 12:00	439.994	849.50367	580.7035	1870.20117	999.99657	0.4719	235.26479	454.22961	310.50216
14	3/11/2019 13:00	441.9945	848.306	583.285	1873.5855	1001.80617	0.47275	236.33446	453.58922	311.88249
15	3/11/2019 14:00	442.55467	847.503	579.321	1869.37867	999.55677	0.47169	236.63398	453.15985	309.76294
16	3/11/2019 15:00	442.50483	848.73317	581.11367	1872.35167	1001.14644	0.47244	236.60733	453.81763	310.72148
17	3/11/2019 16:00	16.497	33.96433	19.5345	69.99583	37.42677	0.01766	8.82095	18.16073	10.4451
18	3/11/2019 17:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
19	3/11/2019 18:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
20	3/11/2019 19:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
21	3/11/2019 20:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
22	3/11/2019 21:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
23	3/11/2019 22:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
24	3/11/2019 23:00	9.31	22.36933	9.91	41.58933	22.23781	0.01049	4.97806	11.96088	5.29888
25	3/12/2019 00:00	9.31	34.89917	10	54.20917	28.98564	0.01368	4.97806	18.66059	5.347
26	3/12/2019 01:00	9.31	42.44367	12.459	64.21267	34.33451	0.0162	4.97806	22.69463	6.66183
27	3/12/2019 02:00	9.31	49.83967	14.26067	73.41034	39.25251	0.01852	4.97806	26.64927	7.62518
28	3/12/2019 03:00	9.31	53.5455	15.311	78.1665	41.79563	0.01972	4.97806	28.63078	8.18679
29	3/12/2019 04:00	9.31	61.79517	19.54983	90.655	48.47323	0.02287	4.97806	33.04188	10.45329
30	3/12/2019 05:00	9.31	72.7825	27.08083	109.17333	58.37498	0.02755	4.97806	38.9168	14.48012
31	3/12/2019 06:00	324.20167	637.22167	446.0935	1407.51684	752.59925	0.35515	173.35063	340.72243	238.52619
32	3/12/2019 07:00	441.73	845.075	592.1125	1878.9175	1004.65719	0.4741	236.19303	451.8616	316.60255
33	3/12/2019 08:00	444.166	847.979	593.63367	1885.77867	1008.32585	0.47583	237.49556	453.41437	317.41592
34	3/12/2019 09:00	444.02667	846.56817	593.478	1884.07284	1007.41375	0.4754	237.42106	452.66	317.33269
35	3/12/2019 10:00	444.4555	844.56767	591.031	1880.05417	1005.26496	0.47438	237.65036	451.59033	316.02428
36	3/12/2019 11:00	443.11017	846.699	585.92733	1875.7365	1002.95631	0.4733	236.93101	452.72996	313.29534
37	3/12/2019 12:00	440.6345	846.55183	580.7035	1867.88983	998.76069	0.47132	235.60727	452.65126	310.50216
38	3/12/2019 13:00	442.0995	848.58533	580.37767	1871.0625	1000.45712	0.47212	236.3906	453.73858	310.32794
39	3/12/2019 14:00	443.02517	852.0955	583.39517	1878.51584	1004.44242	0.474	236.88556	455.61546	311.9414
40	3/12/2019 15:00	442.065	849.61883	582.124	1873.80783	1001.92505	0.47281	236.37216	454.29119	311.2617
41	3/12/2019 16:00	16.542	33.57083	19.34417	69.457	37.13866	0.01753	8.84501	17.95032	10.34333
42	3/12/2019 17:00	9.31	19.68	9.935	38.925	20.8132	0.00982	4.97806	10.5229	5.31224
43	3/12/2019 18:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
44	3/12/2019 19:00	9.31	19.68	9.91	38.9	20.79983	0.00982	4.97806	10.5229	5.29888
45	3/12/2019 20:00	9.31	19.79467	9.91	39.01467	20.86114	0.00984	4.97806	10.58421	5.29888

CFM Calculation

c. Energy Model Description

R1, the initial model, was created with basic information that was collected through building audit. The simulated period is March 11th to June 10. The used information are presented in table 2 and applied in R01 as the initial model.

Table F-2 Actual data

Data Type	Measure Data point	Comment
Weather data	dry bulb temperature	Measured hourly data from NOVA, use dry bulb temperature, relative humidity, wet bulb temperature and wind speed in weather file.
	wet bulb temperature	
	relative humidity	
	wind speed	
Lighting schedule	410A illuminance	Measured hourly data by HOBO, the lighting power is 170w per office
	410B illuminance	
	410C illuminance	
Occupancy Schedule	410A Occupancy	Measured hourly data by HOBO, the number of people per office is 1.
	410B Occupancy	
	410C Occupancy	
Supply air temperature	410B supply air temperature	Measured hourly data by HOBO
Supply air relative humidity	410B supply air humidity	Measured hourly data by HOBO
Supply Air flow rate	410A supply air flowrate	Measured hourly data by HOBO, calculated the total flowrate for energy model
	410B supply air flowrate	
	410C supply air flowrate	
Fan on/off schedule	Fan on/off	From BAS DATA

R01 used the above information as schedule, and the thermal properties of building enclosure are extracted from the drawing and the Open Studio Material library. For example, the roof layers are roof Membrane, 3''Rigid Insulation, and ½'' Metal Decking, the conductivity of 3'' rigid insulation is the default value in Open Studio Material library, which may be different from the actual situation.

Figure 2 Material Parameter (Roof)

The FCU serves for three offices (410A, 410B and 410C). The model defines these three offices as 3 thermal zones. Heating coil and cooling coil are simulated separately with a supply fan for all the zones, the setpoint manager is dual set point which controls the high and low temperature of supply air. Every zone has a diffuser. In actual situation, outdoor air is supplied by a MAU. Considering the air flow of outdoor air is low, the energy model integrates the outdoor air into the fan air loop.

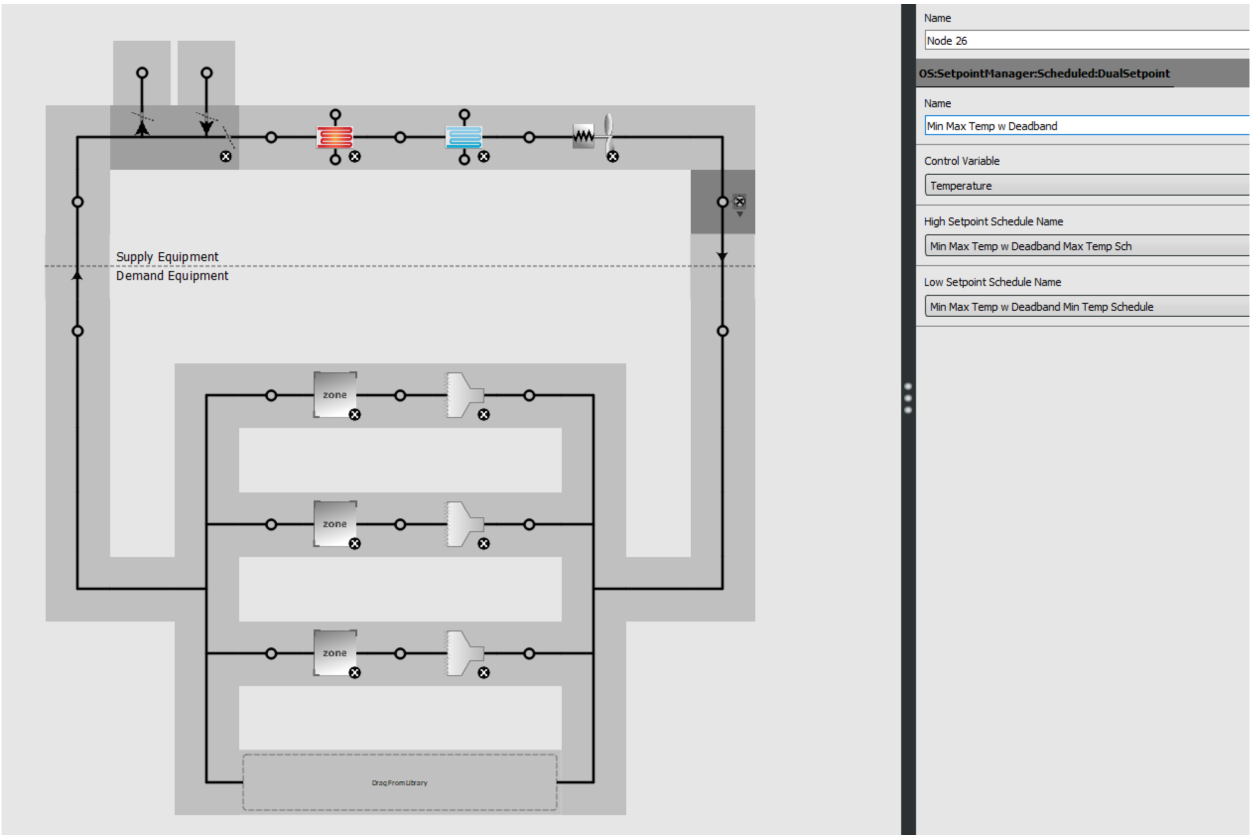


Figure 3 System Setting （Initial Model）

Iterative runs were conducted to calibrate the result, R1 to R10 show a low linear correlation (about 0.5), R11 use VAV diffusers and the linear correlation is only 0.22, so the researcher adjusted the HVAC setting as follows.

Three FCUs are added per zone as zone equipment to circulate the indoor air, in which the maximum outdoor air flowrate is 0. The fan only delivers the outdoor air, so the maximum flow rate for fan is limited as 0.04m^3/s (84 cfm), and the supply air temperature uses the actual supply air temperature schedule from BAS. The simulate results shows a better correlation.

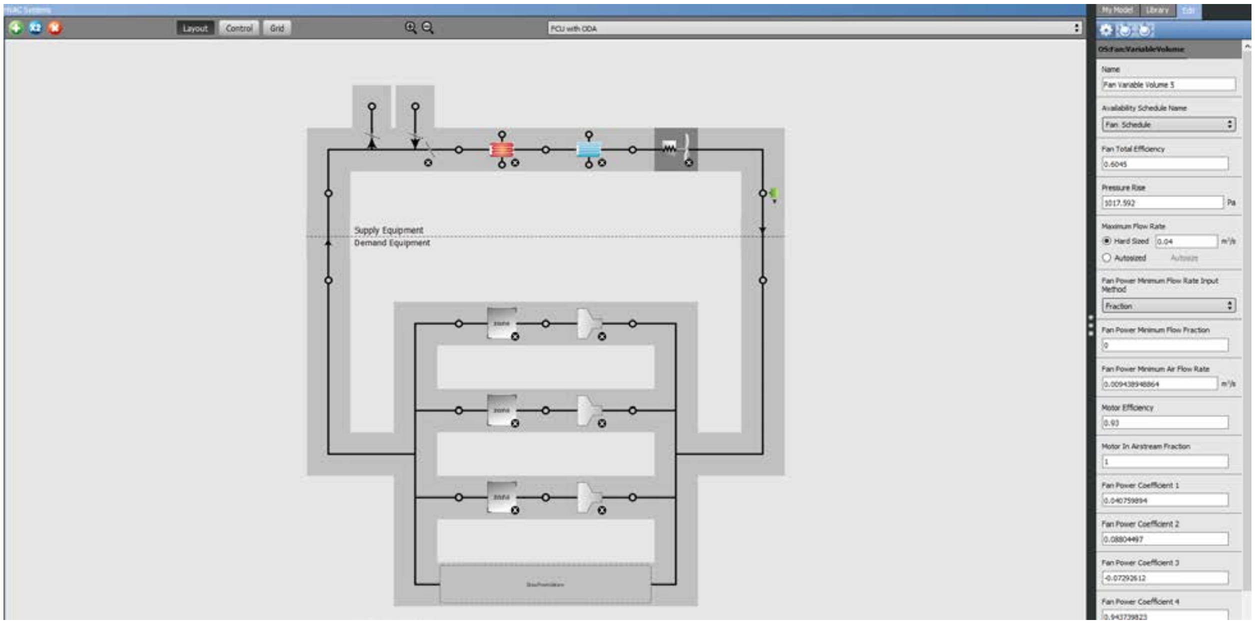


Figure 4 System Setting （Final Model）

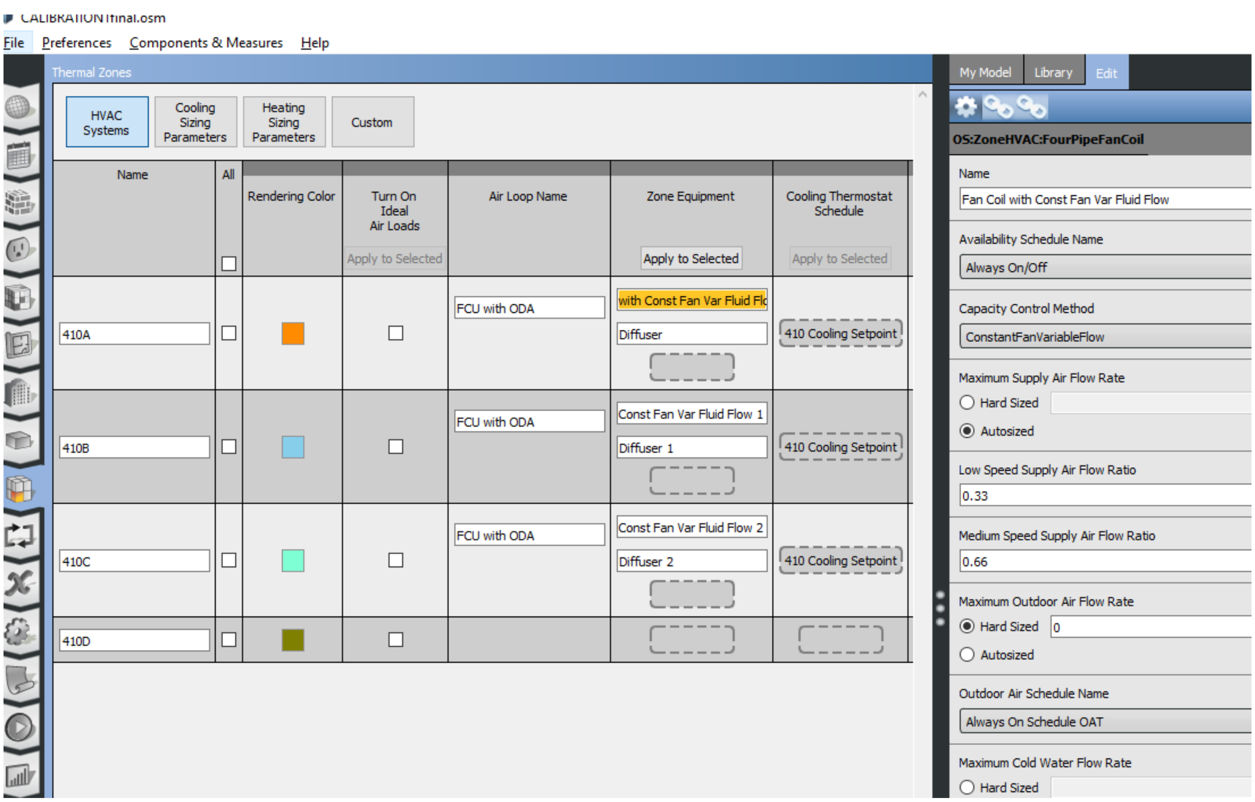


Figure 5 System Setting:FCU （Final Model）

Table F-3 The analysis results of every runs

RUNs	Indoor Temperature Calibration					Description
	CV(RMSE)	CV(STD)	NMBE	Eav	R	

R1	3.54%	5.57%	-0.8%	0.2	0.48	Glass 0.013w/m.k
R2	3.54%	5.57%	-0.7%	-1	0.39	Add a deck temp controller to control supply air temperature, edit thermal setting temperature schedule, glass 1.5W/M2.K
R3	3.54%	5.57%	-0.7%	-0.39	0.55	Remove dual-point temp, only use deck temp controller
R3-R10	3.54%	5.57%	-0.7%	-0.56	0.51	Change thermal setting temperature schedule, change envelope parameter, change System control method, ensure the air flowrate is off during the night.
R11	3.54%	5.57%	-0.7%	-4.3	0.22	Use VAV no reheat terminal for zones
R12-R18	3.54%	5.57%	-0.7%	-0.1	0.78	Drop VAV terminal, use zone FCU equipment for all the three zones, setting the schedule on/off as BAS report, change the fan flowrate into the amount of outdoor air. edit the thermal setting temperature schedule
Final Simulation	3.6%	5.74%	0.48%	0.113	0.78	
HOBO vs FCU	3.21%	5.39%	2.3%	0.543	0.89	