ABSTRACT

MIRIANHOSSEINABADI, SEDIGHEHSADAT. A Framework for Real-Time Performance Measurement and Verification and Commissioning Using Building Automation Systems in Existing Buildings. (Under the direction of Dr. Soolyeon Cho.)

Building practitioners are persistently trying to develop more energy efficient buildings while maintaining and improving human comfort to achieve the Architecture 2030, 2025 Commercial Buildings Initiative, and Net-Zero Energy Buildings (NZEBs) initiative goals. In this regard, properly operating and maintaining the high-performance level of the buildings are the crucial factors to keep existing buildings in shape and save energy continuously. Building Automation Systems (BASs) as the key information sources for building Commissioning (Cx) and Performance Measurement and Verification (PM&V) have gained popularity among building managers. However, the BAS installed in these buildings either cannot estimate performance reduction relative to the design intent, or inform the building manager about how much energy has been saved by implementing the Energy Efficiency Measures (EEMs) in the building after the commissioning process. Therefore, building managers and owners hire Cx engineers and spend a lot of time and money to achieve, verify, and document the performance of facilities, systems, and assemblies in the building. This is an expensive process which should be repeated several times during the building life cycle. This problem leads to a widespread demand in using smart meters, devices, and analytics tools, as well as multi-measure whole-building programs among building managers to reduce time, cost, and complexity of Cx and PM&V and to generate deeper savings.

The continuous commissioning is the most recommended commissioning type because its effect persists over time, and it is less costly than the manual periodic commissioning. As one of the most recent and advanced commissioning concepts, the automated continuous Cx process aims to make the on-going Cx activity automated. This is a challenging concept since the human intervention is somehow expected to be able to respond to any problem in a certain degree.

This research presents a cohesive framework to automate the continuous commissioning process to some extent and to measure and verify the performance of buildings in real-time basis in existing commercial buildings. This framework is conceptualized based on the on-going Cx concept and IPMVP option-D approach. Option-D is using a calibrated simulation model to predict facility/building energy consumption.

The proposed methodology in this study aims to integrate an EnergyPlus calibrated model presenting the projected building energy consumption and the BAS providing the whole building's performance metrics data; this would offer real-time building performance monitoring and fault detection and diagnostics. The real-time Cx and PM&V framework is intended to recommend corrective actions in order to maintain the high performance level of the building and to provide potential energy savings and improvement in building performance after implementing those actions for the selected time intervals in the real time.

Calibrating the EnergyPlus model functions as a key procedure in this framework to achieve ideal building performance. A two-step calibration approach, calibration to historical data, and calibration to real time data, is adopted as the main calibration method for accurately projecting the whole building performance in real time.

The Real-Time Cx and PM&V framework is tested by implementing the framework into an office building (the present case study) located in Research Triangle Park, NC for July 2nd to 6th, 2016 and September 1st to 6th, 2016. The experiment results show that the real-time Cx and PM&V framework significantly improves the energy performance of the building by informing the building manager with detected faults, possible causes, recommended corrective actions, and potential energy savings in real time.

A Framework for Real-Time Performance Measurement and Verification and Commissioning Using Building Automation Systems in Existing Buildings

by

Sedighehsadat Mirianhosseinabadi

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APPROVED BY:

Dr. Soolyeon Cho Committee Chair	Dr. Wayne Place
Dr. Ning Lu	Dr. Stephen Terry

Dr. Suwon Song

DEDICATION

To my parents Nasrin Abasalta and Mohsen Mirian, and my sister Zahra Mirian for their continued support and love.

BIOGRAPHY

Nasim Mirian received her master’s degree in sustainable architecture and her Bachelor of Science in physics from University of Tehran. While studying in the PhD program at the College of Design at North Carolina State University, she worked as a research assistant at the Building Energy Technology Laboratory (BETLab). She is particularly interested in building energy modeling and performance evaluation for the design and development of sustainable buildings. Her research focuses on the development of the framework for real-time performance measurement and verification and commissioning using building automation system in existing commercial buildings.

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CHAPTER 1 INTRODUCTION

High performance buildings are currently a cutting-edge topic in the field of sustainability and energy conservation. In this regard, building practitioners are persistently attempting to expand more energy efficient buildings while maintaining and/or improving the human comfort to achieve the Architecture 2030, 2025 Commercial Buildings Initiative, and the Net-Zero Commercial Building Initiative goals.

The Energy Policy Act of 2005 (EPACT) and the Energy Independence and Security Act of 2007 (EISA) try to reduce the building-related energy consumption and dependence on foreign energy sources. EPACT defines a high performance building as, *"a building that integrates and optimizes all major high-performance building attributes, including energy efficiency, durability, life-cycle performance, and occupant productivity"* (Malmedal, Kroposki, & Sen, 2007).

Among the new and innovative technologies for high performance buildings are the Building Automation Systems (BAS) and the Building Energy Management Systems (BEMS) which have gained popularity among building owners/managers. This is mostly because the BAS, the BEMS, and the Energy Management and Control Systems (EMCS) are main information sources for the building Commissioning (Cx) and Performance Measurement and Verification (PM&V) in achieving energy savings. However, the BAS installed in buildings can neither estimate performance reduction relative to the design intent nor inform the building manager about how much energy could be saved by implementing corrective actions or Energy

Efficiency Measures (EEMs) in buildings after the Cx process. Therefore, it is not sufficient to just rely on the BAS in the building to achieve energy efficiency goals.

1.1 Significance

Buildings are the main consumer of primary energy in the world. In the case of United States, buildings consume more than 40% of total energy and more than 70% of the total electricity use. Fossil fuels (petroleum, natural gas, and coal) are still the main sources (about 85%) of energy in the U.S, with other remaining sources such as nuclear (about 7-8%) and renewable energy (7-8%). These fossil fuel energy sources will be eventually exhausted in about 50 years (for petroleum and natural gas) and in about 250 years (for coal) based on the existing reports (EIA, 2013). It is, therefore, important to design, construct, operate, and manage buildings to consume much less energy through energy efficiency technologies. On the other hand, improving/or maintaining the performance of existing building stock is extremely more crucial than newly constructed buildings. In regard to the Intergovernmental Panel on Climate Change (IPCC), *"over the whole building stock, the largest portion of carbon savings by 2030 is in retrofitting existing buildings and replacing energy using equipment"* and energy savings for 50-75% can be achieved in commercial buildings who make smart use of energy efficiency measures (IPCC, 2007).

Building energy systems often represent more energy consumption than it is expected compared to the building design intent (about 20%). According to the Bailey et al. (2011), HVAC systems, mainly air distribution systems, and common control systems are the main sources of flaw in the building. Although identifying the specific and main sources and fundamental origins of energy waste in certain buildings can be challenging, but it is possible to achieve more than 20% of energy savings by conducting existing building commissioning (Mills, 2010). Therefore, most of the buildings go through the commissioning process during their life to maintain a high building performance level. After and during the Cx process, some building owners or managers invest in implementing the suggested corrective actions or Energy Efficiency Measures (EEM) in the building and the savings on energy cost and expenses along with its continuance are their main concerns.

This research aims to develop a new commissioning and performance measurement and verification (PM&V) framework, which can maintain or improve the energy performance level of buildings in real-time basis. A systematic approach for the development of the framework and its application is essential for the success of the research, since it is not easy to identify a problem nor its source in the building, nor to recommend a set of actions. As the new commissioning and PM&V framework is developed, it is expected to reduce the cost associated with the building commissioning process and to save energy moving forward.

1.2 Description of Problem Area

The Cx and PM&V process requires hiring Cx engineers and takes a long time and hard work to achieve, verify, and document the performance of facilities, systems, and assemblies in the building. A critical obstacle is the absence of data/information on adequate features and details because of shortage of measurement systems or issues in obtaining such data. Most of the small and medium size existing commercial building have not been equipped with required sensors and BAS/BEMS to detach abnormal changes in load conditions or irregular operations (Bailey et al., 2011). It is also an expensive process which should be repeated several times during the building life cycle. To perform the commissioning process successfully for energy savings, a standardized framework, both cost- and time-effective, is required for the performance M&V of buildings. This also should integrate the data from existing BAS and/or BEMS as main part of the key evaluation parameters.

BAS, BEMS, and EMCS are key information sources for building commissioning (Cx) and Performance Measurement and Verification (PM&V) process. A systematic BEMS has the potential to save energy by estimated range of 5% to 30% (Pérez-Lombard, Ortiz, & Pout, 2008). However, these systems are not enough for a high performance building. They cannot estimate performance reduction relative to the design intent and are not able to inform the building manager about how much energy has been saved by implementing the EEMs in the building after the commissioning process (Bailey et al., 2011). On the other hand, building managers tend to save the cost, time, and complications of PM&V by using data through smart meters, devices, and analytics tools to generate deeper savings.

Therefore, to stop or minimize the reduction of the building performance level and operating efficiency over the building life cycle, it is highly efficient to apply an active program (automated continuous Cx tool) that identifies and responds to the changes and coordinates with the BAS, BEMS, or EMCS (Hensen & Lamberts, 2012).

1.3 Conceptual Framework

Figure 1-1 shows the relationship between the technologies and processes that support maintaining and improving the performance of buildings. BAS and BEMS are the main sources of information from buildings. This information is used for both commissioning (Cx) and performance M&V. Through the commissioning process, the details obtained from BAS and BEMS are fine-tuned to achieve the optimal performance. PM&V is the process to confirm the difference or performance improvement after Cx actions and certain measures (or EEMs) have been implemented. To achieve energy savings, these processes and technologies will be integrated, as shown in the left side of the diagram, to develop a real-time framework for PM&V and Cx, as shown in the right side of the diagram. The Cx process and PM&V methods are integrated to present a cohesive framework to automate the continuous commissioning process to some extent and to measure and verify the performance of buildings in real-time basis in existing commercial buildings.

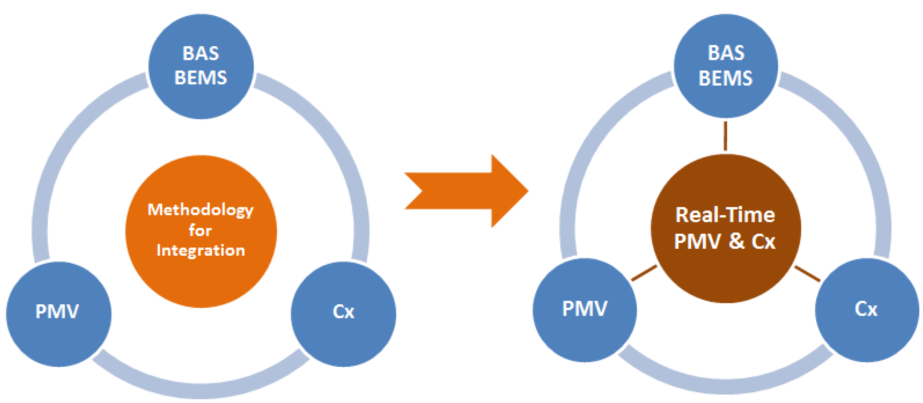


Figure 1-1: Conceptual Framework

This framework implements the building simulation and machine learning techniques (model calibration) to calculate and predict the building energy consumption and savings after implementing EEMs. A calibrated EnergyPlus model which is built based on the building description, geometry and materials, internal heat gains, schedules, and characteristics of building's HVAC system locates between the BAS and building manager and generates an active system. This active system enables the building energy manager to compare alternative corrective actions using whole building metrics after detecting the faults, and finally to validate enhanced performance when corrective actions and required Energy Efficiency Measures (EEMs) have been implemented.

The research success criteria is to demonstrate that the building performance improves (by presenting the energy savings in the case-study building), ideally to its design intent, by executing the corrective actions (adding the EEMs) to the building.

1.4 Research Goal

The ultimate goal of this research project is to achieve energy savings in existing commercial buildings through smart building management system by responding to the following questions.

- What are the typical faults and problems in commercial buildings during the commissioning process?

- What are the important parameters (performance metrics) in BAS and/or BEMS information which can be used to facilitate the process of fault detection and Cx in buildings for building managers?
- How the Cx and PM&V processes can be integrated in a cohesive energy management framework using the data from BAS data?

The scope of this research is to develop a framework that makes it possible to measure and verify the performance of buildings in real-time basis, which in turn enables the commissioning process continuous. The present framework is a real and ideal structure which aims to functions as a guide for the creation of a tool or program in order to develop given structures. The framework consists of key performance metrics and data points from BAS, BEMS, and EMCS that mainly affect the building energy performance and focus on energy related issues for maximum energy savings in buildings.

To answer the research questions properly, the research has been divided into three phases. Specifically, the research phases and objectives are:

- **First Phase:** This phase concentrates on developing a framework for integrating the Cx and PM&V. The main focus in this process is to develop a framework that functions effectively on the commercial buildings. The objectives of the first phase research are as follows:

    – To provide literature review on building commissioning and performance M&V: review existing manuals, standards, and technical documents.

- To identify and analyse available technologies on BAS and BEMS.
- To identify common problems and faults in commercial buildings through the Cx process.
- To develop appropriate framework for the integration of PM&V and Cx.

- **Second Phase:** This phase aims to select a case study building for testing the framework and to develop an analysis model for the IPMVP option-D in order to be integrated with the framework. The objectives of the second phase research are as follows:

  - To select a case-study building. The case-study building could be from the NC State campus buildings or other sources in the Raleigh metropolitan area. In the third phase, the building is used to implement and test the framework developed in the phase-I process.
  - To develop an algorithms for the PM&V options D (IPMVP). The Cx and PM&V process in the framework are systematically organized for the real applications based on this algorithm.
  - To develop case-study building EnergyPlus simulation model (Geometry, loads, and system model).
  - To create the case-study building EnergyPlus calibrated simulation model. In this task we need to develop methods to transfer real-time/trending data from

the BAS and BEMS to the case-study building EnergyPlus simulation model for the calibration purpose (selected inputs).

- **Third Phase:** This phase involves implementing the framework for real- time Cx and PM&V in the case study building. The objectives of the third phase research are as follows:

  - To confirm the framework performance metrics (meters installation for case-study building).
  - To develop key corrective actions and EEMs or ECMs for M&V Options D in the case-study building.
  - To test the framework in the case-study building and document issues such as problems, difficulties, barriers, or new ideas for further development of the framework.

1.5 Definition of Key Terms

1.5.1 Building Automation System

In general, a Building Automation System (BAS) is a focused and intertwined network of hardware and software that screens and supervises the environment in various types of commercial facilities. BAS manages building systems such as chillers, boilers, Air Handling Units (AHUs), Roof-top Units (RTUs), Fan Coil Units (FCUs), Heat Pump Units (HPUs) and Variable Air Volume (VAV) boxes which help to maintain comfort and safety of building occupants. Advanced BAS also includes power monitoring, security Closed-Circuit TV (CCTV), card and keypad access, fire alarm system, escalators, plumbing, and water monitoring. Building Energy Control System (BEMS) is a particular subsection of building automation that link system components and devices to control and connect all the functions and processes in a building (Merz, Hansemann, & Hübner, 2009).

1.5.2 Building Commissioning (Cx)

According to ASHRAE guideline for the commissioning process, Cx is a precise documentation process whose purpose is to ensure that building systems are designed properly, installed suitably, and functionally tested and that they are able to be maintained and operated for performance that is in line with design intent. Cx assures the efficiency of building systems, the proper training of building operators and the goal fulfilments of the owner's expectations (ASHRAE, 2005).

1.5.3 Performance Measurement and Verification (PM&V)

Measurement and Verification (M&V) are the terms specified to the process for measuring savings provided by an Energy Conservation Measures (ECMs) or Energy Efficiency Measures (EEMs). M&V demonstrates how much energy the ECMs have avoided using, rather than the total cost saved. In general, the Performance M&V of buildings is for verifying results of energy efficiency, indoor environmental quality, water efficacy, and projects operating renewable energy. Having compared the energy use pre-and postinstallation of ECMs, energy savings are diagnosed, making appropriate adjustments for changes in conditions.

1.6 Dissertation Overview

Chapter two provides a literature review on BAS technologies, protocols, and data points. That chapter also provides an overview on the previous studies conducted in the field of automated continuous Cx and Real-time PM&V. Chapter three is dedicated to the discussions on research methodologies, including the procedures for developing the framework for real-time Cx and PM&V in existing commercial buildings. Chapter four includes the case study building model development and calibration process. Analyzing performance assessments as well as research findings from implementing the framework into a case study building are discussed in chapter five. Conclusions are drawn out in chapter six follows with overall research findings and future research opportunities.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Considering several technologies and applications that have been integrated in this research, this section is divided into four main domains associated with the proposed research. Figure 2-1 shows the literature review diagram.

Figure 2-1: Literature Review Diagram

2.2 BAS Market and Technologies

BAS, BEMS, and EMCS have become an industry norm for developing and maintaining high-performance buildings since building owners/managers can achieve energy savings and energy efficiency goals for their buildings by utilizing these control tools. On the other hand, BAS, BEMS, and EMCS are the main sources of information related to the building that is used for the Cx and PM&V purpose. In this regard, ASHRAE Guideline 13 - Specifying Building Automation System- aims to provide a BAS designer with a complete package of background information, recommendations for good practice, project considerations, and detailed discussion of options with respect to the design of a BAS system (ASHRAE, 2015).

Therefore, it is necessary to review the features of widely used BASs such as the ones manufactured by Johnson Controls, Honeywell, Siemens Building Technologies, Carrier Corporation, and so forth. A rigorous survey is performed to identify and evaluate each brand's products and data points available on the system. Figure 2-2 summarizes ten BAS companies and their products. The BAS generally is applied in large commercial buildings utilizing products from Johnson Control (Metasys) or Siemens (Apogee). They also have wide range of application in small and medium commercial buildings (Synco from Siemens), hotels (Cassia from Schneider), and residential buildings (Nexia from Trane).

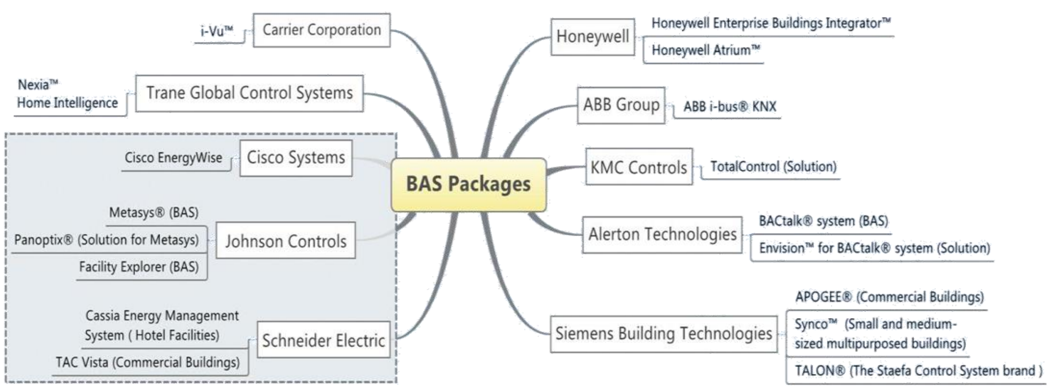


Figure 2-2: BAS Companies and Their Product

Existing BAS/BEMS and EMCS are able to acquire, store, and trend the data earned from building systems equipped by suitable and proper sensors. Using these features, a building manager can detect any system degradation in the long run and also identify situations which systems lack proper functioning (e.g. the HVAC system stays "on" when the building is vacant). Although BASs are the source of building data points, but it is hard for building managers to analyze and estimate the performance reduction relative to the design intent unless a third-party analytic software application exists to optimize the building's performance. Specifically, operational anomalies, such as simultaneous heating and cooling or improperly operated economizer cycles, require a precise and direct measurement to be detected (which is not always feasible). Moreover, BASs are not able to inform the building manager that how much energy have been saved by implementing the EEMs in the building after the commissioning process. These difficulties leads to the future BEMS with an open and secured system which has this ability to identify the user's preferences and particular data that is more important to that user (Hensen & Lamberts, 2012).

2.2.1 BAS/BEMS/EMCS Data Points

The BAS/BEMS/EMCS have the capability to allow the building manager and Operation and Maintenance (O&M) staff to check the status of building operation, to measure energy consumption, and to monitor the overall performance, all of which are critical to the success of optimal building operations and energy efficiency. However, building managers and/or building owners are most often overwhelmed by the amount of the data points and the data sets available in BAS, which makes it difficult for them to efficiently analyze and interpret the performance of buildings. Among those data points some of them are more or less critical to building managers in terms of the analysis of building performances.

To have an overall view on the data points which have been offered by BAS, several BAS interfaces such as Metasys of Johnson Control, SiteNet of SRS, and BMS of Schneider Electric have been explored. These data points are categorized in two main groups:

(1) Schedules and status information in zone, system, and plant level. In the zone level most of the data points are related to the room's condition and occupant thermal comforts. These data points are mostly related to lighting control, occupancy sensors, building CO_2 sensors, equipment control (plug loads), and thermostat control (temperature and relative humidity). In the system level, most of the data points are related to the AHU temperature and humidity control, fans CFM (VFD) and static pressure control, dampers and diffuser controls, and outside air and economizer control. In the plant level, most of the data points are related to the chilled water temperature control in chiller, hot water temperature control in boiler, condenser temperature control, and pumps GPM/motor (VFD) control.

(2) Meters, which include electric meters, natural gas meter, and/or BTU meters. These meters mostly record the whole building performance (energy consumption) for specific time periods.

Figure 2-3 summarizes the BAS/BEMS/EMCS data points in detail.

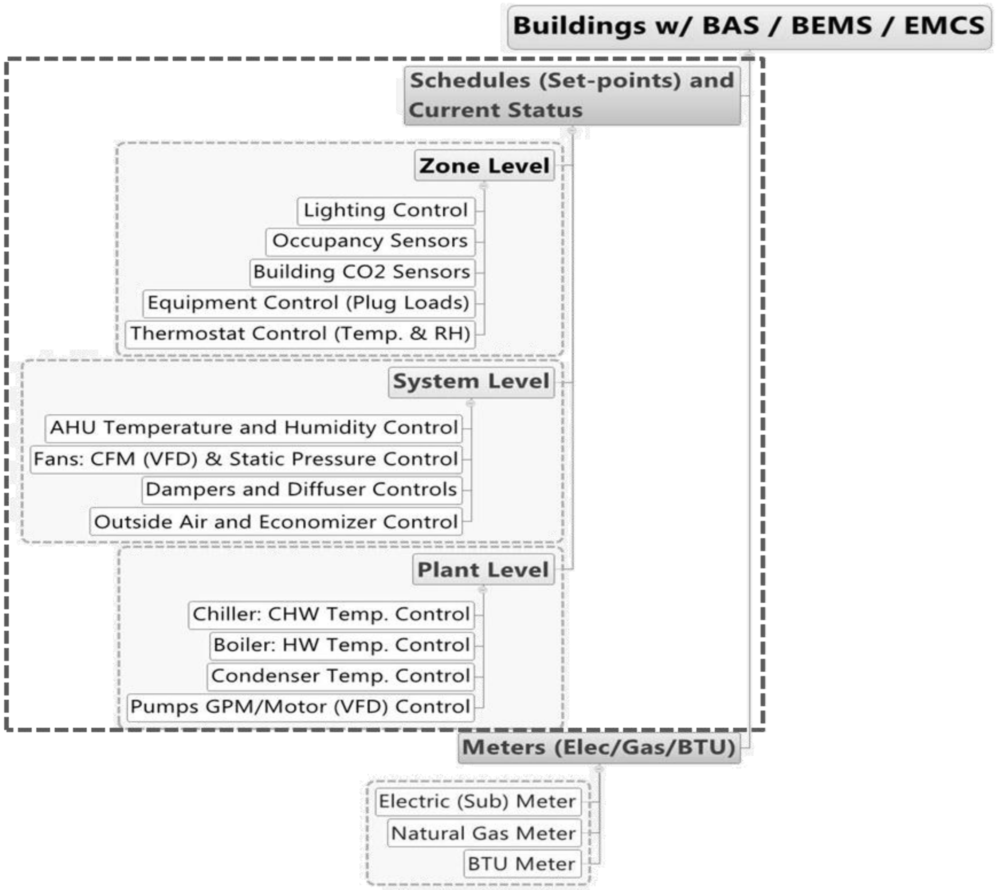


Figure 2-3: BAS/BEMS/EMCS Data Points

2.2.2 BAS Protocols

A BAS communications protocol is a set of rules that govern how two or more computers share information over a digital communications system. Among various BAS communication protocols, BACnet, Modbus, and LonWorks are the most popular protocols for building automation and control networks. Figure 2-4 shows the different BAS protocols.

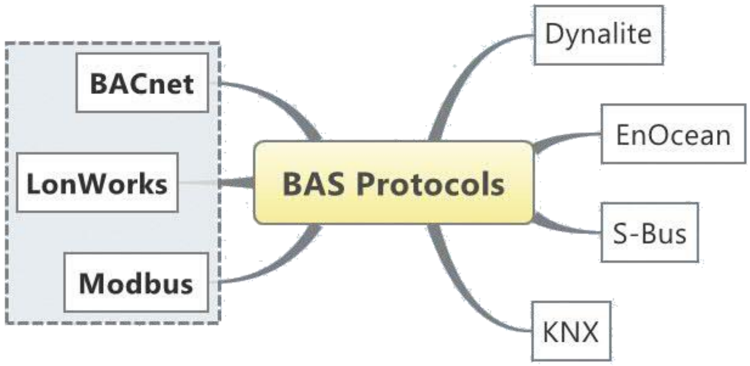


Figure 2-4: BAS Protocols: BACnet/Modbus/LonWorks

BACnet® as the industry's leading communications protocol has been designed specifically to fulfill the communication goals of building automation and control systems for applications such as heating, ventilating, and air-conditioning control, lighting control, access control, and fire detection systems(ANSI/ASHRAE-Standard-135, 2012). Since 1987, after the first meeting of Standard Project Committee (SPC 135 p) in ASHRAE annual meeting place, the BACnet protocol has been under vigorous development. In 1995, BACnet was officially born with the "ANSI/ASHRAE Standard 135." After that BACnet achieved ISO 16484-5 in 2003 and ANSI/ASHRAE Standard 135.1 "Method of Test for Conformance to BACnet" was published. From 2003 to 2013, BACnet was under constant development and has been developed for errata and addenda.

In the scope of building automation and control networks, BACnet plays an important role as a data communication protocol. It allows the incorporation of control products made by different manufacturers into a single, consistent system. The only open, consensus-developed standard in the building controls industry is ANSI/ASHRAE Standard 135-2012, BACnet – A

Data Communication Protocol for Building Automation and Control Networks which provides the opportunity of the affiliation and cooperation of building equipment and systems produced by various companies. In some advanced building commissioning types, BACnet protocol facilitate the data arrangement and transfer from different building components into a particular commissioning and performance monitoring tool.

2.3 Building Commissioning (Cx) technologies

The creation of the Commissioning Guideline Committee generated by the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) was considered as the official initiation of work on the building commissioning process. The committee devised a process that ensures building managers receiving a completely running and active building. According to the ASHRAE commissioning guideline, Cx has a multi-phase and multi-participant method which ensures that "*the various interacting systems in a building are properly installed and operated as the design intent*" (Turkaslan-Bulbul, 2006). Through a wide range of research in the scope of building commissioning, several different terms have been created to describe the time and process of commissioning. These commissioning terms which were generated based on some modifications on top of the original commissioning process can be identified as existing and new building commissioning, re-commissioning, retro-commissioning, continuous commissioning, ongoing commissioning, and persistence commissioning. Figure 2-5 lists the different commissioning terms. Basically the terms "new building commissioning" and "existing building commissioning" are the main two commissioning terms dividing the Cx process between new and existing buildings. Different types of commissioning can be identified as:

Figure 2-5: Commissioning Terms

Retro-commissioning is known as the process of screening, troubleshooting, and adapting electrical, mechanical and control systems in the existing buildings that were never commissioned to optimize energy performance.

Re-commissioning is considered as another form of commissioning that creates when an already-commissioned building experience another commissioning process. The factors that determine the initiation and decision of re-commissioning could be ownership or use change of the building, the existence of an operational problem or etc.

Ongoing/Constant/Continuous Commissioning is a continuous process to resolve operating problems, track and maintain benefits from Retro-Cx. This process also keeps the building documentation up to date (EPA, 2010). In ongoing commissioning process, the performance tracking, on-going training, and periodic Re-Cx are the key components. During the performance tracking process, the commissioning engineers apply special software or tools to monitor the performance of buildings, specific systems, and/or certain equipment. Such tools usually have functions of measuring and monitoring a variety of building systems data points such as electricity use, electric demand, temperatures, and equipment/system efficiencies. Some of the tools are even capable of sending automatic alerts when performance is out of expected range. After detecting the problems, action is required by the building manager to diagnose the problem and identify the solutions.

Figure 2-6 shows a typical timeline of various Cx processes and compares when each Cx process is involved during which phase of the building design through the life of a building (Visier et al., 2005). It shows that retro-commissioning is missing the initial commissioning while re-commissioning and ongoing commissioning are having the initial commissioning during the design and construction phases as well as occupied and operation phase.

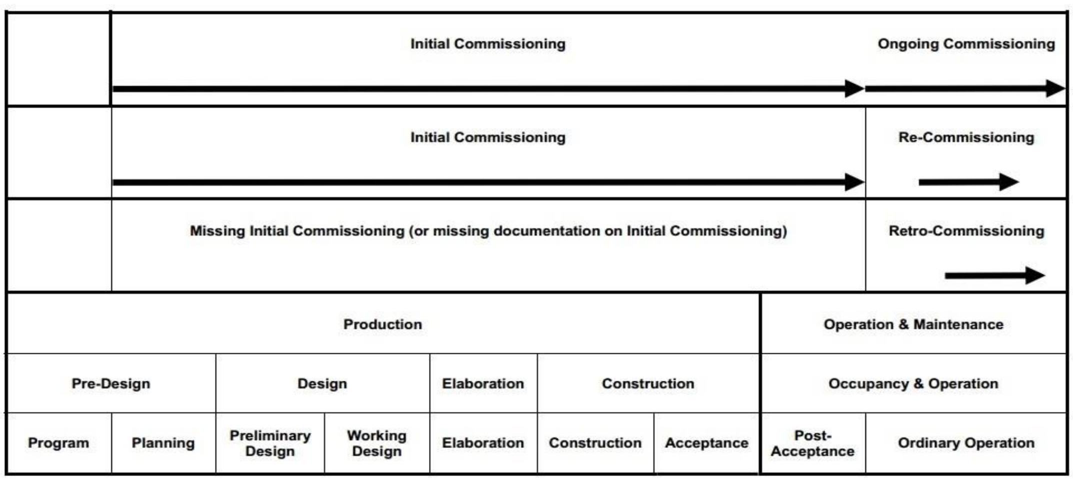


Figure 2-6: Comparison between Different Commissioning Processes

Embedded Commissioning is defined as an overarching building performance evaluation method by Akin in his book "Embedded Commissioning of Building Systems" .The book describes this new term as a building delivery process which is fixed and embedded and continuously certifies and validates design intent throughout the building cycle. The embedded commissioning process is defined "as a co-function of building lifecycle" (O. Akin et al., 2004). During different phases of a building life-cycle, the embedded commissioning accompanies each of these phases and their interactions with timely building system evaluation. The Building Information Model (BIM) is a "*significant database and plays an important role in an embedded commissioning process*" (Ö. Akin, 2011).

BEMS-Assisted commissioning is one of the recent technologies which utilizes BEMS to automate some parts of commissioning. In this approach, utilizing the Information Technology (IT) and web-based energy information and control system have expanded to help commissioning engineers collect simple and efficient information from the high amount of existing data in order to improve the performance of the buildings (Capehart & Capehart, 2007). Figure 2-7 shows the architecture of IT integrating the building automation systems and control technologies. BACnet communication protocol plays an important role in this Cx type.

2.4 Automated Continuous Commissioning

As one of the most recent and advanced commissioning concepts, the automated continuous Cx process aims to make the on-going Cx activity automated. This is a challenging concept since the human intervention is somehow expected to be able to respond to any problems in a certain degree. These efforts are because Cx and retro-Cx fixes do not persist over time. The manual periodic commissioning is also costly. However, if developed, the automated continuous commissioning and diagnostic technologies can be persistent, cost-effective, and continuous. Currently, there are several researches conducted in the scope of automated and continuous commissioning to develop tools and methodologies to consider the intricate and complex issues of building energy performance management and to assist reducing the loss and waste of energy in the buildings by applying various approaches

A commissioning process is divided into four subdivisions. 1) Performance criteria definition, 2) measured data collection, 3) ideal performance and measurement comparison, and 4) problem diagnostic. Automating the commissioning process requires the automation of these four subdivisions. “An automated continuous Cx tool is called successfully automated when almost all four parts perfectly operate in harmony to each other” (Turkaslan-Bulbul, 2006).

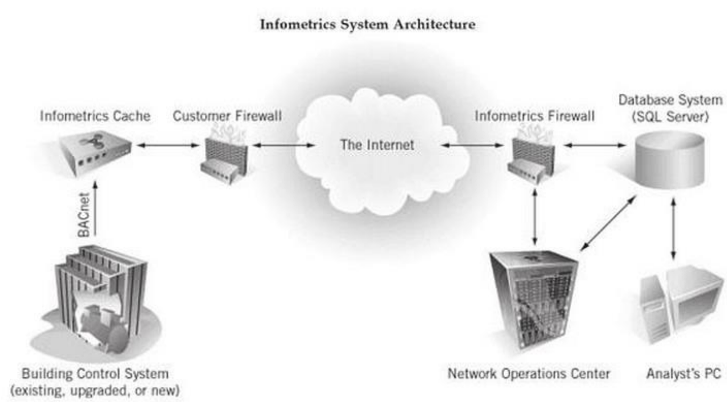


Figure 2-7: Information System Architecture in Web-Based/Online Systems

In 1999, Performance and Continuous Re-Commissioning Analysis Tool (PACRAT) is developed by Facility Dynamics Engineering for continuous analysis and automated diagnostics of specific HVAC systems, whole building energy, and zone distribution. This tool collects measured data from EMCS and compares with the baseline data which is created by PACRAT according to multidimensional parameters (i.e. typical use of equipment, on a particular type of day, at a particular outside condition). Data visualization part lets the user to better understand the building systems, their characteristics and needs (Lee, n/a).

In December 1996, Pacific Northwest National Laboratory (PNNL), Honeywell Technology Center and University of Colorado developed Whole-Building Diagnostician (WBD) which is a modular diagnostic tool and focuses on detecting and diagnosing common problems in HVAC systems and equipment. This tool uses a diagnostic module along with a database to store measured data for analyzing. The operator interacts with the WBD by starting an analysis or viewing the results of diagnoses. A diagnostician module can be scheduled to run at regular intervals or initiated manually.

ENFORMA (Portable Diagnostic Solutions) is commercialized by Architectural Energy Corporation in 1996. This tool uses a portable data logging equipment, and a software module named HVAC and Lighting Analyzer. The data logger records time series data virtually from any sensor or transducer at a minimal cost and independent from any EMCS, however it does not support a diagnostic module. The user should detect problems from the outputs of the software.

In 2001, the CANMET Energy Technology Center developed the Diagnostic Agent for Building Operators (DABO) to guarantee optimum operation of building systems. DABO consists of four interconnecting modules: “the building energy agent, the fault detection and diagnostic agent, the commissioning agent, and the condition-based maintenance agent.” “DABO’s fault detection and diagnostic module initially and mainly utilizes to variable-air-volume (VAV) boxes and air handling units” (Choinière, 2001). Later in 2003, they added a BEMS-assisted commissioning tool to the diagnostic agent on top of the DABO which serves as the interface between the building operator and the BEMS. It supervises building control data, storing it in a structured database. The database role is to perform the advanced analysis of the monitored data, execute extra automated tests of the components and systems (VAV and AHU), recognize faults and diagnosing them, and assess possible enhancements in energy efficiency. “The tools are able to create and develop reports adapted to various partners in the commissioning process” (Corsi & Choiniere, 2003).

In 2007, Curtin proposed an Automated Building Commissioning Analysis Tool (ABCAT), which uses a calibrated mathematical model to foresee the consumption of energy for specific weather conditions. ABCAT is a Microsoft Excel based tool that uses three different sensors to earn its required data, whole building electricity, heating, and cooling. “The estimated and foreseen energy consumption is compared to the measured consumption and defects and faults are detected according to statistically palpable deviations between the two data sets (Curtin, 2007). The user is able “to identify the dates of the periods analyzed, adjust thresholds for different alarms, describe and list the utility costs, set up folder and file locations for automated importation and saving of files, view statistical results for the calibrated baseline model, and inspect a summary of the consumption in the periods analyzed" (Bynum, Claridge, & Curtin, 2012). All the above tools and applications follow a similar structure:

- Collect necessary information
- Process and graphically visualize collected information
- Detect problems
- Diagnose possible causes

The first and second items are easily achievable through BEMS/EMCS, but the third and fourth items are quite challenging in terms of automating the process and they still cannot cover all HVAC equipment. Moreover, the above tools are unconnected software products that cannot be found in a building control system. Data files are required to be treated off-line, or an interface to the building control system needs to be developed to enable on-line analysis (Turkaslan-Bulbul, 2006). These tools also use a "Black Box" model as a baseline model which is a simplified model based on the first principle analysis. It has fewer input and is easier to calibrate.

2.4.1 Simulation-Based Commissioning Tools

Applying simulation to evaluate the actual performance of buildings has been addressed by several researchers in their performance assessment or continuous commissioning tools. Building simulation programs provide a model in which all the elements interrelate and the internal structure of the process is modeled and accessible ("White Box" model). Simulation-based Cx and on-line Fault Detection and Diagnosis (FDD) tools carries the concept of real-time simulation to enhance the building performance in real-time basis. Due to variety of simulation programs, the real-time concept can change from method to method.

In 2002, Clarke et al. presented a simulation-assisted control system to incorporate simulation utilizing ESP-r within real-time EMCS operation to improve control capabilities. However, because of the practical problems, LabVIEW was used in the test instead of an actual EMCS. Also, the ESP-r system needs several changes to deal with the real-time simulation. In ESP-r, the real-time approach requires the data transfer into the simulation program databases to maintain the correct model state until the current time (Clarke et al., 2002).

In 2003, Wang and Yoshida proposed a methodology of how to apply simulation to continuously commission a Variable Air Volume (VAV) air conditioning system. This prototype of persistent and ongoing commissioning tool can be stand-alone or be embedded in a BEMS to continuously monitor the running of a building's HVAC systems and detect faults during operation phase. This approach uses the available models in HVACSIM+ and SIMBAD and evaluates their input and output to figure out if the model matches with the requirements of the new continuous commissioning tool or a new simulation model need to be developed in regard to the design condition. A preset threshold identifies that the differences between the building measured data and simulated data are considered a fault in the system (Wang & Yoshida, 2003).

A prototype hardware-in-the-loop simulation environment was developed in 2004, for controls testing and training using SPARK (Simulation Problem Analysis and Research Kernel). SPARK is an object-oriented, equation-based, simulation program and suitable for the simulation of the dynamics of HVAC systems. When applying simulation in order to test the real control system, the simulation slows down to be able to run in real time. The simulation connects to a control system field panel through a hardware interface consisting of digital-to-analog (D/A) and analog-to-digital (A/D) cards that plug in to the PC running the simulation. However, this mechanism is not scalable because of the limitation in capability of exchanging data via the analog digital converter (Xu, Haves, & Deringer, 2004).

In 2012, Costa et al. proposed a methodology to facilitate the decision making process of energy managers in determining the best building operation plan. "This approach uses the building calibrated simulation model to test the impact of changes in control settings of energy systems before implementing that in the building" (Costa, Keane, Raftery, & O'Donnell, 2012). Later on 2013, they recommended a new integrated toolkit based on the proposed methodology. This toolkit limits the building performance criteria into building function, thermal loads, energy consumption, system performance, and legislation.

This toolkit uses the Building Information Model (BIM), a three dimensional graphical building geometry and its database, to define and gather the information related to building performance and specific building geometry objects. The BIM also helps the researcher to create the Building Energy Model (BEM) and calibrate it using building measured data. In the next step, building manager defines new key factors such as temperature set points or lighting level set points for any different operation plan and runs the simulation again. The comparison between previous results of the calibrated model and results of the calibrated model with different key factors enables the manager to evaluate the thermal comfort and energy consumption of the building related to that key factor (Costa, Keane, Torrens, & Corry, 2013).

Pang et al., proposed a structure in order to link the actual performance of a building to the simulated performance which illustrates the design intent in real-time. In this study, real-time concept implies a building model whose simulation time is synchronized with real-time as represented by the computer clock. The framework structure consists of tools as follows:

- Energy Management and Control System (EMCS)
- Building Controls Virtual Test Bed (BCVTB): This was used as the platform to get applicable inputs from the EMCS and transfer them into EnergyPlus or database through a BACnet interface. BCVTB allows synchronizing simulation time and real time.
- EnergyPlus: was used to create the building's energy performance model

EnergyPlus calibrated model (which was calibrated based on the historical data) receives several weather parameters from EMCS in each time step and runs the simulation in real time. This process presents an advanced calibration procedure for the previously calibrated model. In the next step the measured data stored in a database (from EMCS) and the results from the advance calibrated model were compared for a specified time period to identify any possible anomaly in building (Pang, Wetter, Bhattacharya, & Haves, 2012).

The research team also selected a case study building to verify the methodology. However, as they have mentioned in the paper, they need an appropriate and more user friendly interface and a more completed FDD methodology for future works.

O’Neill et al. used the explained framework and developed a model-based, whole building energy diagnostics and performance monitoring system to constantly get performance measurements of HVAC, lighting and plug equipment usage and compared these measurements in real time to a reference EnergyPlus model that represents the design intent. This approach takes advantage of Statistical Process Control to analyze deviations and detect outliers and changes in the model pattern (O'Neill et al., 2011). Figure 21 shows a screenshot of the interactive user interface. The screen is divided into three sections:

- Loading data (shown in red box), time range
- Energy usage (shown in green box), BEMS data, simulation data
- Anomalies (shown in blue box). The GUI (MATLab Interface) allows the user to view additional visualizations of the data to help in understanding the cause of an anomaly and these can be accessed by buttons marked “Diagnose” and “Explore” (Bailey et al., 2011)

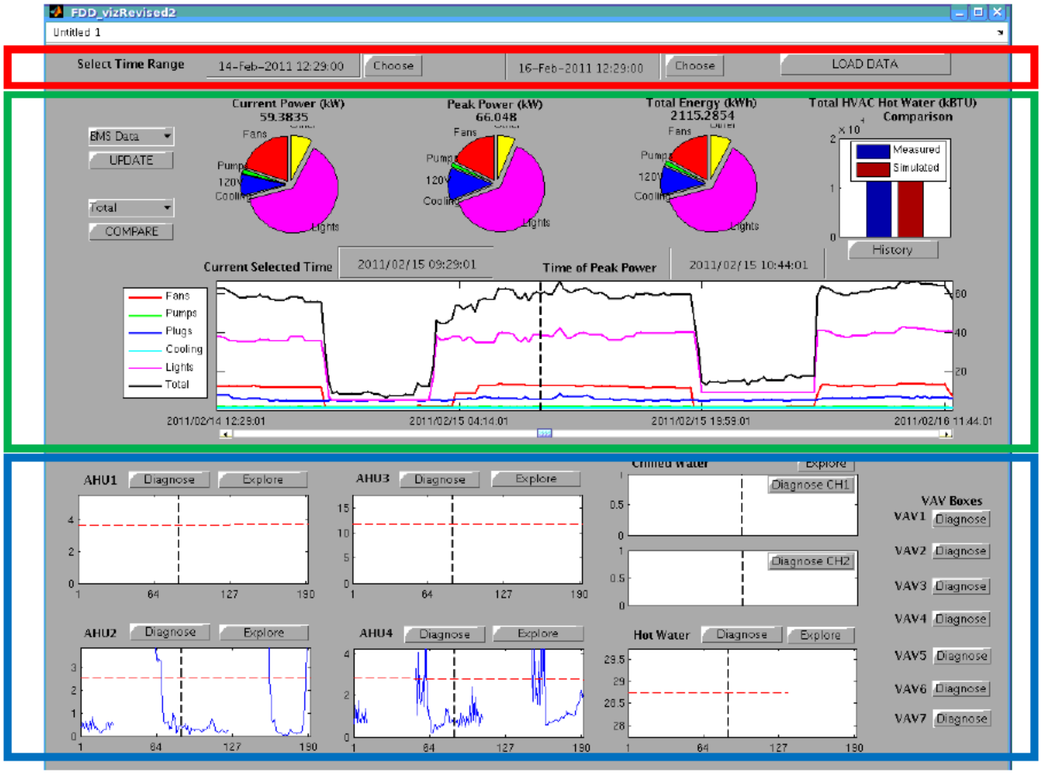


Figure 2-8: FDD User Interface (Bailey et al., 2011)

Although the possibility of linking and implanting an energy simulation model into the BEMS or EMCS had been suggested in previous researches, but in most of the cases, it was beyond the capabilities of the detailed simulation programs and an accessible application of this idea has not yet been reported. Currently with the growth of BACnet compatible devices (HVAC components) and BASs and BCVTB which has this ability to connect to the BACnet compatible devices, the potential difficulties have been significantly reduced.

2.4.2 Building Controls Virtual Test Bed (BCVTB)

BCVTB first is developed by Have et al. at 2007 as a platform to link energy simulation tools such as EnergyPlus with control systems (Haves & Xu, 2007). Later in 2008, the BCVTB was redesigned and upgraded by Wetter at the Lawrence Berkeley National Laboratory (M Wetter & Haves, 2008). BCVTB is based on the Ptolemy II software from UC Berkeley; which is an open source software framework, supporting experimentation with actor-oriented design and a graphical model building environment. BCVTB is a highly capable platform, able to manage multiple building performance analysis tools and technologies, including BAS, programs in thermal simulation and mathematical analysis, and tools for daylighting analysis and fault detection.

BCVTB provides this chance for different simulation programs to be more beneficial by connecting and talking to other programs. The modular design of BCVTB provides this ability through a middleware as shown in figure 2-9. With its modular framework, BCVTB is able to assist in simulating virtual experiments before full scale testing, either in laboratory or building setting, to determine the range of boundary conditions and type of experiments required (Nouidui, 2013).

Moreover, the BACnet interface in BCVTB allows coupling BACnet compliant BASs to Ptolemy II and other simulation programs. This approach allows for real-time data to travel from the sensors in the building (or BAS data) into the simulated environment to be analyzed against best-case design scenarios. The technology allows for modeling across the whole building life cycle, ensuring that design intent is accomplished, as well as maintained over time. This tool pave the way to more researches and proposals in advanced building control field (Michael Wetter, 2008).

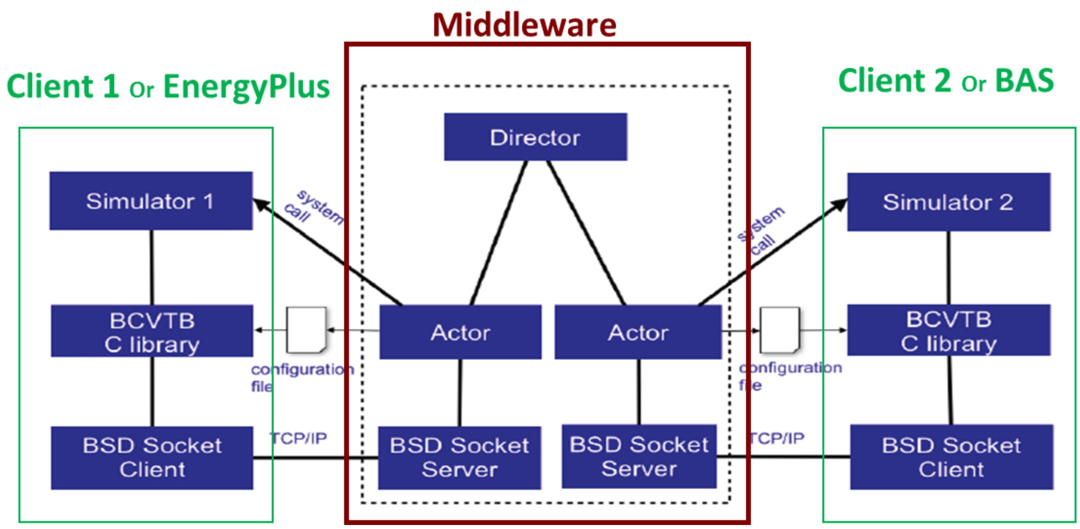


Figure 2-9: Architecture of the BCVTB with the Middleware that Connects Different Clients

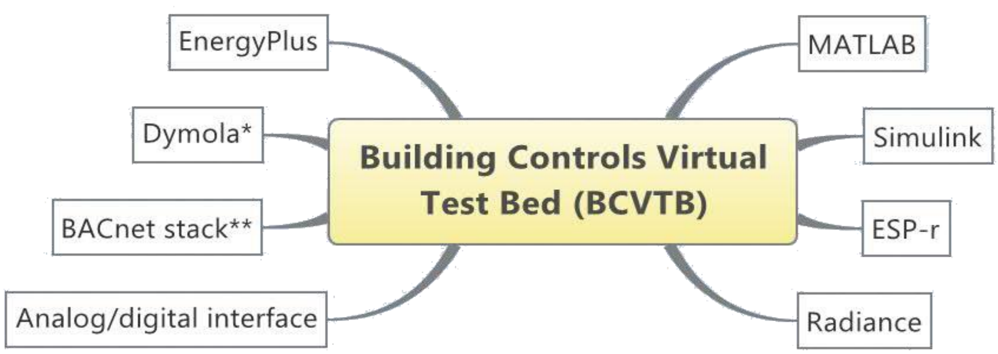


Figure 2-10: Programs that are currently linked to the BCVTB

There are several programs and software that are currently linked to the BCVTB as shown in figure 2-10, such as EnergyPlus, MATLAB, Simulink, Dymola, BACnet stack (an open-source implementation that allows exchanging data with BACnet compatible building automation systems), ESP-r, Radiance and Analog/digital interface.

The co-simulation feature in EnergyPlus which is called as ExternalInterface, was originally developed for BCVTB; however the communication protocol is open and can be used by any program to perform co-simulation with EnergyPlus. Moreover, BCVTB is always up-to-date with the co-simulation feature in EnergyPlus (Nghiem, 2010). Figure 2-11 shows the architecture of the BCVTB with the EnergyPlus as the main client and other clients.

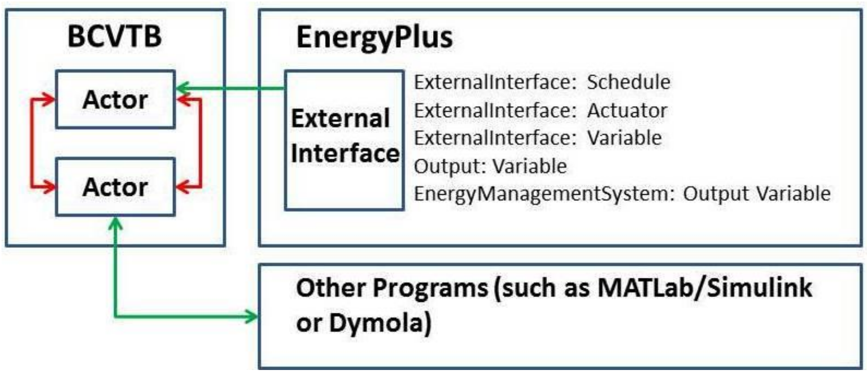


Figure 2-11: Architecture of the BCVTB with the EnergyPlus as one of the client and other clients such as MATLab or BAS

Like all of the other tools and programs, BCVTB also has some advantages, disadvantages and challenges which should be considered by the researcher who wants to build a methodology with the help of BCVTB. It is always hard to start learning a new environment rules such as BCVTB and the user needs to have experiences working with Java, Extensible Markup Language (XML) and simulation software. On the other hand, using different

BCVTB, EnergyPlus, and BACnet versions may cause sever errors in the process which is not easy to solve.

Most of the old or outdated existing buildings have BASs such as Metasys from Johnson Controls which are not open source and have their own dedicated communication protocol which are not BACnet compatible. In such cases, another tools such as a BACnet gateway is necessary and it is challenging to use the real time data from the BAS.

2.5 Typical Faults Identified in Existing Building Cx

According to California Commissioning Guide for existing buildings, *"The majority of the buildings commissioning types carry similar purposes, in order to build a building that fulfills the owner and residents' needs, operates are to provide an efficiently safe and comfortable work environment run and maintained by high-quality trained staff or service contractors"*(Haasl & Heinemeier, 2006). To achieve this goal, Fault Detection and Diagnosis (FDD) phase in commissioning process always was in the center of attention. In general, Fault detection is to identify that overall building action is not unacceptable from the normal behavior. Fault diagnosis is localization of the source of defective operation (Djuric & Novakovic, 2009). However, recognizing the main sources of energy waste in buildings can be challenging mainly because energy flows are normally undetectable (O'Neill et al., 2011).

FDD is the main part of the automated continuous commissioning tools. The FDD foundation's job is to compare of the expected and deviated performance to detect the fault based on statistical methods.

In an integrated whole-building FDD approach, the functional interactions between subsystems which result in sub-optimal building energy performance are captured and manual human intervention and labor-intensive analysis is much more less than conventional approaches. This leads to a much more scalable FDD approach since working with that system does not need a group of experts (Bailey et al., 2011).

To develop a reliable FDD system, it is necessary to gain knowledge about typical or important faults in the buildings. For this purpose, the commissioning reports of several existing commercial buildings and North Carolina State University (NCSU) school halls (Leazar hall and Varsity research building) were reviewed and analyzed to identify the buildings' typical faults.

Although new faults always appear due to growing complexity of the buildings but after reviewing the common problems in commercial buildings, they have been organized in five main categories: BAS/BEMS/EMCS problems, lighting control, HVAC system control, plant equipment, and physical problems. Each group has its own related subcategories. These subcategories are building problems and faults which have more likely occurred during the building life, and they have been identified during the commissioning process in buildings most often. Figure 2-12 briefly shows the five main categories and their subcategories in detail.

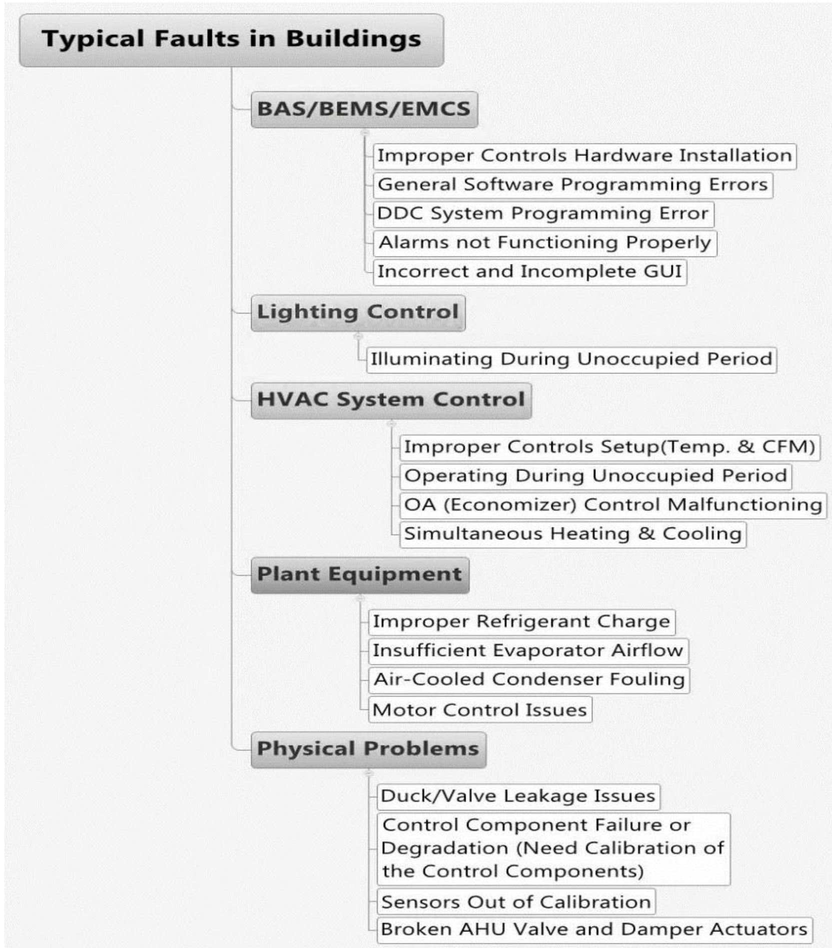


Figure 2-12: Typical faults in existing commercial buildings

There are two groups, BAS/BEMS/EMCS problems and physical problems which are different than other groups. The physical problems are not related to the data points extracted from the BAS/BEMS/EMCS and they need a direct human intervention to be fixed. Also, the BAS/BEMS/EMCS systems have their own issues such as improper installations and the program itself malfunctioning.

The typical faults in existing commercial buildings may be completed and finalized by adding some special faults related to each special case study building and then be used in the FDD process in the real-time Cx and PM&V framework.

2.6 Performance Measurement and Verification (PM&V)

After and during the commissioning process, some building owners or managers implement the corrective actions and/or invest in implementing the suggested EEMs in the building. They naturally want to know how much energy and cost they have saved after FDD and adding EEMs to their building and how long their savings maintain. In order to determine the rate of energy saved, the exact and precise measurements and replicable measurements known as Measurement and Verification (M&V) protocol are required (IPMVP 2001).

IPMVP defines common terminology and the key steps in implementing a robust M&V process. It includes guidance on current best practice techniques available for determining energy savings and verifying the results of energy efficiency, renewable energy, and water efficiency projects in commercial and industrial facilities. Currently, three volumes are available (Figure 2-13).

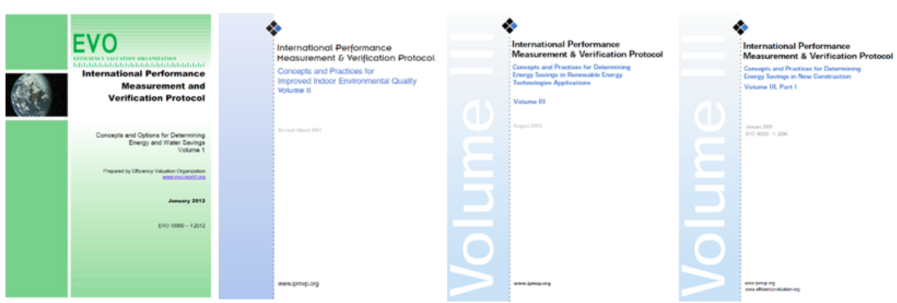


Figure 2-13: IPMVP Guidelines

IPMVP addresses four options to determine savings (A, B, C and D). The choice among the options encompasses many considerations such as project budget, number of independent variables to be monitored, frequency of measurement and reporting, length of the baseline and reporting periods, and sample size, if all equipment is not measured (IPMVP, 2001). The selection of an IPMVP option is the decision of the designer of the M&V program for each project. These options are summarized below:

Option (A) Retrofit Isolation: Key Parameter Measurement: Savings are defined by field measurement of the key performance parameter(s) which define the energy use of the EEM's affected system(s) and/or the success of the project. Typical applications may include a lighting retrofit, where the power drawn can be monitored and hours of operation can be estimated. In this example lighting hour's operation is an important parameter which is not selected for the field measurement. Therefore it can be estimated based on historical data, manufacturer's specifications, or engineering judgment (IPMVP, 2001).

Option (B) Retrofit Isolation: All Parameter Measurement: Savings are calculated by field measurement of all key performance parameters which define the energy use of the EEMs affected system. Typical applications may include a lighting retrofit where both power drawn and hours of operation are monitored and recorded.

Option (C) Whole Facility: This option considers the energy use at whole facility or sub-facility level to calculate energy savings. This approach uses modeling technologies such as regression modeling and inverse modeling for the baseline development based on different independent variables. The option-C process requires several steps such as pre-retrofit data process, post-retrofit data analysis, and data quality control procedure. Typical examples may include measurement of a facility where several ECMs have been implemented, or where the ECM is expected to affect all equipment in a facility (IPMVP, 2001).

Option (D) Calibrated Simulation: Computer simulation software is used to predict facility energy use for one or both of the energy use terms. Simulation model must be "calibrated" to predict an energy use and demand pattern that reasonably matches actual utility consumption and demand data from the real building (EVO, 2010). Typical applications may include measurement of a facility where several ECMs are implemented, but no historical energy data is available (IPMVP, 2001). The presented framework integrates the Cx and IPMVP option-D processes.

2.6.1 Automated Performance Measurement and Verification (PM&V)

Nowadays, traditional PM&V approaches can become too complicated or expensive. Building managers tend to cut down the time, cost, and complexity of PM&V. Moreover, access to data via smart meters, devices, and analytics tools has been increased and building managers are more satisfied in multi-measure whole-building programs that can generate savings more in depth (Granderson, Price, Jump, Addy, & Sohn, 2015). In this regard, a wide variety of Energy Management and Information Systems (EMIS) has been developed and is available to use. EMIS are software tools that automatically store, evaluate, and demonstrate energy use or building systems data. One of the greatest disadvantages about these tools is that it is difficult to validate the EMIS performance. This is because of a general lack of transparency in the embedded analytical capabilities (Kramer, Russell, Crowe, & Effinger, 2013). The Northwest Energy Efficiency Alliance (NEEA) contracted with Portland Energy Conservation, Inc. (PECI) to help provide clarity on the range of EMIS available and their respective feature sets. The final inventory is populated with fourteen EMIS, which are shown in Figure 2- 14 below.

Most of the tools in the inventory back up an IPMVP Option-C approach to M&V; two tools support Option-D calibrated simulation – Retroficiency's AEA and EnergyRM's DeltaMeter.

DeltaMeter uses a thermodynamic simulation to model equipment characteristics and AEA uses whole-building simulation, similar to that of eQuest or EnergyPlus but with a simplified set of inputs. Both DeltaMeter and AEA calibrate the model to actual energy consumption, and determine savings by comparing calibrated post- with pre-implementation simulations (Kramer et al., 2013).

Another EMIS tool named Automated Measurement and Verification (M&V) 2.0 module, recently developed by LBNL. This tool also uses IPMVP Option-C to atomically generate baselines (building energy consumption profile) using historic interval meter data (machine learning techniques) and weather data feeds. User enters the date of EEM implementation and savings atomically will be calculated (Granderson et al., 2015).

Vendor	EMIS	Data Input Frequency	M&V	Opportunity Identifi-cation	Project Tracking
Cascade Energy	Sensei	< Hourly	Option C[i]		Advanced
Elster EnergyICT	EIServer Platform	< Hourly	Option C		Advanced
Energent	Energent	< Hourly	Option C		Advanced
EnergyCAP	EnergyCAP Enterprise	Monthly	Option C		Basic
EnergyRM	DeltaMeter	Monthly	Option D[ii]		
EnerNOC	Efficiency Smart Insight	< Hourly	Option C	Yes	Basic
eSight Energy	eSight Energy	< Hourly	Option C		Basic
FirstFuel	Rapid Building Assessment	< Hourly	Option C	Yes	Basic
Johnson Controls	Energy Performance Monitor	< Hourly	Option C		Basic
MACH Energy	MACH Asset Manager	< Hourly	Option C		Basic
Noesis	Noesis	Monthly	Option C		Advanced
NorthWrite	Energy Worksite	< Hourly	Option C		Advanced
Pulse	Energy Manager	< Hourly	Option C		Basic
Retroficiency	Virtual Energy Assessment (VEA) Automated Energy Audit (AEA)	< Hourly	Option D	Yes	

Notes: i. International Performance Measurement and Verification Protocol (IPMVP), Option C: Actual vs. normalized/adjusted baseline. ii. IPMVP Option D: Calibrated simulation

Figure 2-14: EMIS Inventory by NEEA

In an earlier study about interesting case studies on M&V by European association of Energy Services Companies (ESCO), a summary of the technical standards and ongoing standardization work at the European levels was presented. Figure 2-15 presents interesting findings on the M&V options used by the companies that implement M&V protocols. The analysis results show that 71% of the companies have utilized the Option-C (whole facility) for the measurement of the savings achieved, while 58% and 63% of them have implemented Option-A (retrofit isolation option with the measurement of key parameter) or Option-B (all parameters) respectively. For the same sample of companies, the Option-D (simulation option) is not considered a popular technique as only 10% of the aforementioned organizations have implemented it (Donkelaar, Magyar, Vougiouklakis, Forni, & Venturini, 2013).

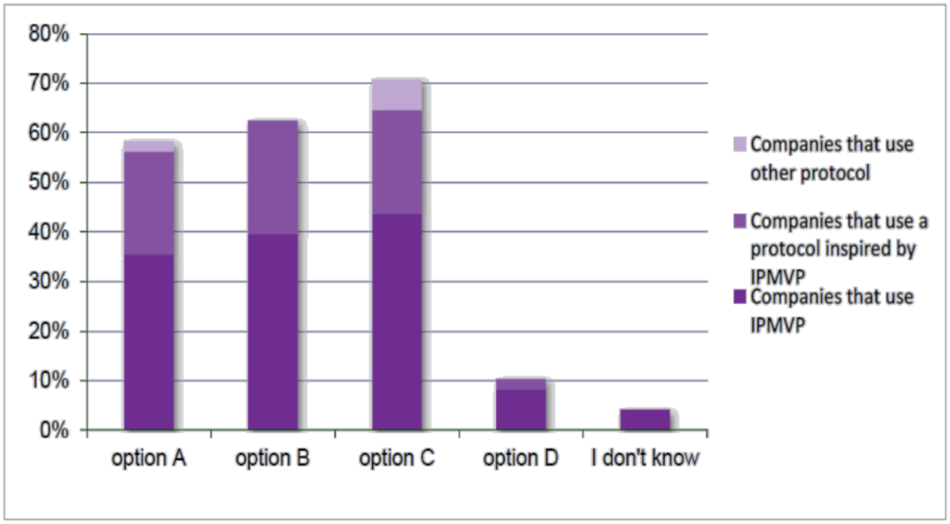


Figure 2-15: Popularity of Each M&V Protocol (Donkelaar et al., 2013)

Among the IPMVP options, option-D is the plausible choice that makes the commissioning and PM&V process easily automated and real-time. This is because option-D encompasses the application of computer simulation software to foresee facility energy use for one or both of the energy use terms in the energy savings equation. Simulations also can be applied to foresee the influence of changes and alterations in the building use by modeling those changes within the simulation, which can facilitate non-routine adjustments to baseline models against which energy savings are estimated. As a result of these opportunities afforded by simulations, the methodologies using option-D have the potential to support different programmatic approaches than do the other tools using option-C (Kramer et al., 2013).

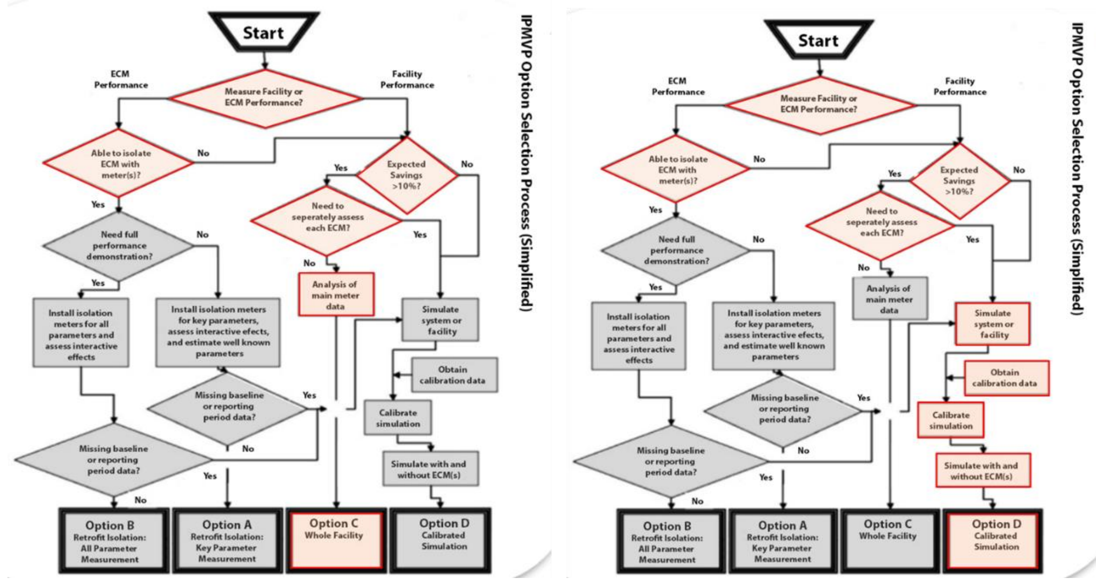
The simulation model in option-D must be "calibrated" so that it predicts an energy use and demand pattern that reasonably matches actual utility consumption and demand data from either the pre-retrofit (baseline) or a post-retrofit year. Exact and precise computer modeling and calibration to measured data are the main issues and challenges associated with option-D. To control the costs of this method while maintaining reasonable accuracy, the simulation analysis requires to be steered and conducted by trained personnel who are familiar with and expert at the particular software and calibration techniques. According to IPMVP, it is better to use option-D when an experienced energy simulation professional is available and adequately funded for gathering suitable input data and calibrating the simulation model. Also we have to make sure that the facility and the EEMs can be modeled by well documented simulation software, and reasonable calibration can be earned against actual metered energy and demand data.

2.6.2 PM&V Option-D Algorithm

PM&V option-D is one of the main fundamentals in this study. After reviewing different sources for M&V Protocol and process, such as International Performance Measurement & Verification Protocol (volume 1 & 3), M&V Guidelines: Measurement and Verification for Federal Energy Projects Version 3.0, and ASHRAE Guideline 14 for measurement of energy and demand savings, a detailed process of PM&V option-D is demonstrated below. This option is thoroughly reviewed to develop a general algorithm of the IPMVP Option-D which can be used in any specific case-study building.

Based on Figure 2-16, option-D is selected among other IPMVP options if:

- It is not possible to isolate the corrective actions or EEM with meters in the building (In case, it is not needed to separately assess each EEM, option-C can be used by analysis of main meter data-Figure 2-16 (a)).
- The expected savings in the building is more than 10%.
- Need to separately assess each EEM in the building. So it is required to simulate the system or facility.
- Need to obtain the calibration data and calibrate the simulation.
- Need to compare the simulation results with and without EEM.
- Pre-retrofit energy data do not exist or are unavailable.
- Post-retrofit energy use data are unavailable or covered by factors whose influence will be difficult to quantify.
- The expected energy savings are not large enough to be separated from the facility's utility meter using Option-C.
- The goal is to determine the savings associated with individual corrective actions or EEMs but Options-A or B isolation and measurements are too complex and costly.



(a) (b)

Figure 2-16: (a) IPMVP Option-C Selection Process (b) IPMVP Option-D Selection Process

According to IPMVP Vol. 1, Option-D is useful where the estimated range for M&V cost for option-D is 3-10% of measured energy savings which can be changed or increased based on the complexity of systems models. Accurate computer modeling and calibration to measured data are the main challenges associated with Option-D. Therefore, the accuracy of the savings thoroughly depends on how well is the simulation model's actual performance and calibrated it is to actual performance (EVO, 2010).

Figure 2-17 demonstrates the procedure of IPMVP option-D in five phases. At the pre-retrofit phase, after installing the required sub-meters in the building, monthly/hourly electricity/gas consumption along with utility bills will be recorded. In this phase, the Building Energy Model (BEM) also will be developed based on as-built drawings and building general information and HVAC characteristics. The second phase includes BEM calibration process which is one of the most important parts and should be implemented precisely. During the calibration process, the simulation results are matched with the measured data by tuning the model input data. This parameters can be found out by conducting a sensitivity analysis. The traditional input-output sensitivity analysis clarifies which parameter input affects uncertainty in the output the most. The BEM output will present the expected/projected building energy consumption for any requested time period.

After corrective actions/EEM identification through commissioning or building audit process, in the fourth phase the whole-building simulation model will be updated by adding the EEMs to the model. The BEM output will present the post-retrofit building energy consumption. In the final phase the energy savings will be calculated by subtracting the post-retrofit energy consumption from the expected/predicted building energy consumption for the specified time period.

As we mentioned above, in the BEM calibration process, the energy modeler modifies and adapts the design case energy model based on measured data to generate an updated energy model that can accurately reflect the actual building's operation performance. However, there are still challenges remaining in this area for more reliable and simpler calibration processes. Next section includes the literature review on the different calibration methods used in previous studies and introduces a relevant method to calibrate an EnergyPlus whole building energy model.

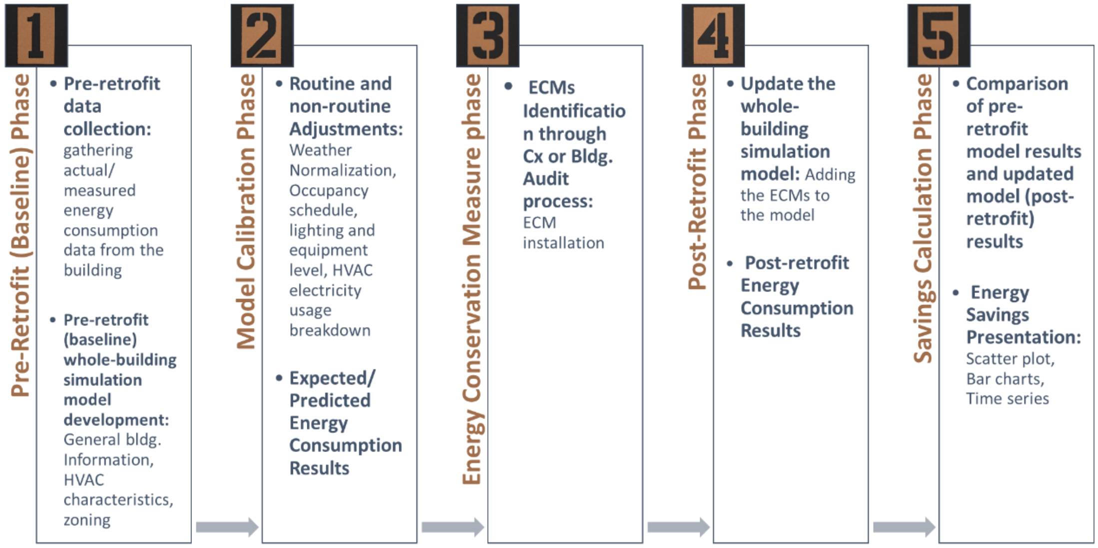


Figure 2-17: Analysis Model for IPMVP Option-D

2.7 BEM Calibration Methods

2.7.1 Performance Gap in BEM

Generally, BEM calibration is to adjust and adapt the design case BEM model based on measured data to produce an updated BEM model that can accurately represent the actual building operation performance. An accurate model calibration can be used for different purposes during the building life cycle (Lam et al., 2014). To achieve a precise calibrated BEM, the reasons that cause performance gap between the "predicted energy performance of design intent" and actual measured performance have to be recognized. De Wilde (2014) reviewed literature on the 'performance gap' concept and developed a framework to investigate its magnitude. There are three main types of gaps which depend on the methods applied for modeling of building energy consumption profile:

- between first-principle predictions (using a physical model) and measurements
- between machine learning (techniques such as regression analysis and artificial neural networks) and measurements
- between predictions and display certificates in legislation (such as ASHRAE 90.1)

The main sources of performance gaps are related to the design stage, construction stage, and operational stage (De Wilde, 2014). Therefore, it is necessary to identify the causes for performance gaps, after developing the baseline model and before starting to calibrate the building model by comparing the simulation results and building measurements.

Today, the legislation is also concerned with the energy performance of buildings, the ASHRAE Standard 90.1. The International Performance Measurement and Verification Protocol (IPMVP) provides frameworks for the calibration process to enforce a minimum standard of efficiency. ASHRAE Guideline 14-2002 informs building modelers to use monthly and hourly data, as well as spot and short-term measurements to calibrate BEM models. Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Squared Error (CVRMSE) are used as evaluation indices. "*The computer model shall have an NMBE of 5% and a CVRMSE of 15% relative to monthly calibration data. If hourly calibration data are used, these requirements shall be 10% and 30%, respectively*" (ASHRAE, 2002).

According to IPMVP, Volume III, model inputs such as weather parameters, occupant, lighting, and equipment schedules, and system parameters such as HVAC components performance curves or system control have to be calibrated based on the “best measured information available” (EVO, 2010).

A study by Coakley (2014) presents a detailed review of current approaches to model development and calibration, highlighting the importance of uncertainty in the calibration process. Having presented the big picture of calibration process in terms of time and methods, the main complexities of a calibrated simulation can be broken down into seven main areas:

- Standards: guidelines are over-simplified and they do not account for issues such as input uncertainty/inaccuracy or the model fit to zone-level environmental data.
- Expense: major expense can be for building auditing, metering and model development.
- Simplification: building simulation requires thousands of inputs for model definition but not all of them are available. Therefore modeler needs to simplify the inputs.
- Input: It is not feasible to have measured data for all the required input to the BEM.
- Uncertainty: since building models are being simplified, the uncertainty in the output should always be considered.
- Identification: the calibration process requires numerous iterations of manual user intervention based on user knowledge. However, there is no standard approach for the process.
- Automation: any degree of automation would greatly aid the calibration process but it is difficult to reach that point.

By having all those issues in mind, the best approach to calibrating a model is to identify the influential parameters and manually tune those parameters to obtain the final solution (Coakley et al., 2014). However, the purpose of calibration process should not be just adjusting any input parameters to match the simulation results with measured data but to create a model, which represents the real building as close as possible (Im & Bhandari, 2014).

2.7.2 Common Calibration Methods

Agami Reddy (2006) classified the common calibration methods as shown in Table 2-1. The manual iterative calibration is the most popular approach than other methods among building modelers. This approach is based on trial and error iterations.

In a study conducted by Lam et al. (2014), a method has been proposed comprising procedures to calibrate an EnergyPlus whole building energy model. Figure 2-18 briefly illustrates the main parts of this process. The calibration process includes weather parameters, occupant, lighting, equipment schedule, and HVAC parameters calibration. The highlighted subject in this study was to develop an occupant behavior data mining procedure which is tested in an office building. Workday occupancy schedules are generated by mining the office appliance energy consumption data. Support vector regression, linear regression, and locally weighted learning are tested as candidate algorithms to build occupancy schedule models. Hourly and monthly power, energy, and temperature data are collected and used for lighting, equipment and HVAC systems energy performance calibration. The result shows a 1.27% mean bias error for the total annual energy use intensity.

Table 2-1: Common Calibration Methods

Method	Highlights
Manual Iterative calibration	Based on user experience, adjustment of inputs on a trial-error basis
Graphical and statistical methods	Based on specific graphical and comparative displays of the results to orient the calibration process
Automated calibration	Based on special tests and analytical procedures

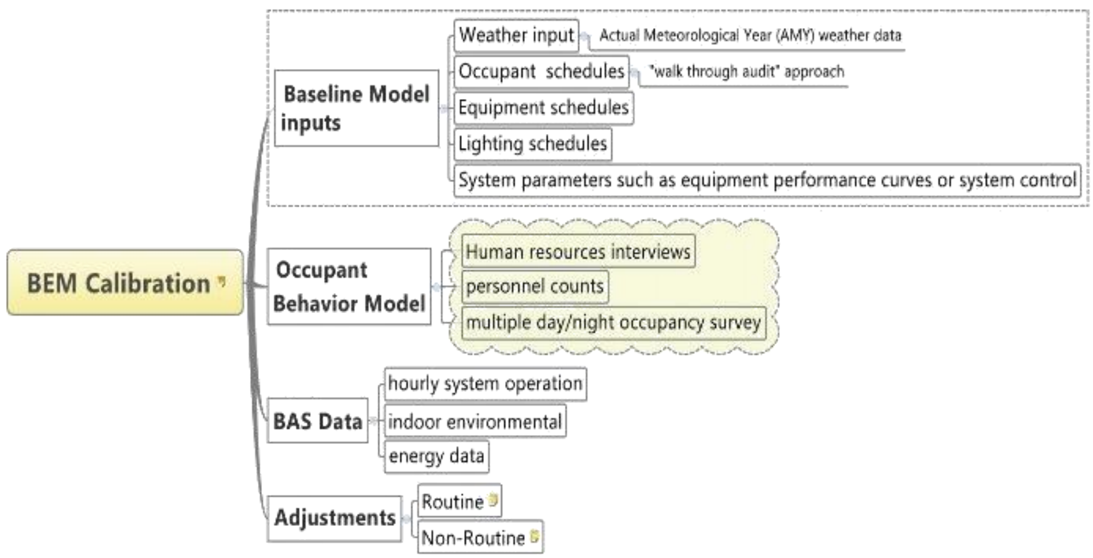


Figure 2-18: Building Energy Model Calibration Process

2.7.3 Examples of Calibrated Simulation

The baseline model in the previous study is created based on ASHRAE 90.1 Appendix G. The proposed design case model is created based on design drawings and specifications, with the same input assumptions as the baseline model for fair comparison purpose. As shown in Figure 2-18: Model input, the first step of the calibration is to replace the TMY3 weather file with real weather information in accordance with the actual data collection period. The second step is to replace the design case occupancy schedules with the "real (or learned)" occupancy schedules generated from the data mining study. The third step is to calibrate the interior lighting, interior equipment, exterior lighting, and exterior equipment power densities and schedules with monthly and hourly energy consumption data with an "inversed calibration method". The fourth and final step is to calibrate HVAC system parameters and controls. It is important that the HVAC system should be calibrated after other input parameters and systems are calibrated because most of these inputs will influence the HVAC system performance (such as internal loads and "disturbances"). The calibration acceptance criterion for each calibration step are MBE<5% and CVRMSE<15% for monthly data calibration, and MBE<10% and CVRMSE<30% for hourly data calibration, respectively (Lam et al., 2014) (ASHRAE, 2002).

According to Yan et al. (2015), the occupancy patterns and behavior are the main and major factors to uncertainty of building performance. This study emphasizes developing occupant models upon observational data. Those occupancy models are developed in order to equip designers with the tools to better predict the energy performance of buildings. The study suggests the use of Building Controls Virtual Test Bed (BCVTB) to link user implementation of occupant behavior models either in MATLAB, Simulink, Modelica, Ptolemy or a user-custom program with EnergyPlus during run-time, so they can exchange data as the simulation progresses.

In the study conducted by Mustafaraj et al. (2014), a case study building with an underfloor heating system and natural ventilation was selected for the building simulation calibration process. The 3D model was developed using as-built drawings. In the next phase, the calibration methodology, which consists of two levels, was applied in order to ensure accuracy and reduce the likelihood of errors. Moreover, a historical weather data file related to year 2011 has been created using an on-site local weather station.

In the first level of the calibration process, the as-built data (plans, schemes and nameplate data of main HVAC components) was used for the parameters screening purpose. Second level involves a rigorous use of Building Energy Management Systems (BEMS) records, monitoring data, and also the information derived from the analysis of the answers to the surveys and interviews (Mustafaraj et al., 2014).

After the calibration process, the values of MBE and CV (RMSE) on hourly based analysis for heat pump electricity consumption varied within the following ranges:

- (MBE) hourly from 5.6% to 7.5%
- CV (RMSE) hourly from 7.3% to 25.1%.

Finally, an Energy Efficiency Measure (EEM) was added to the model to estimate the amount of energy savings related to that EEM (Mustafaraj et al., 2014).

2.7.4 Advanced Calibration Process

Some researches focus on methods to facilitate the calibration process. One of the methods is to automate some parts of calibration process which is quite challenging and problematic. Some toolkits are also available which are limited to special applications and cannot be easily integrated with other tools. The research conducted by Tauber et al. (2014) describes algorithms to perform such an automated calibration process. This framework contains various layers which permits simple component exchangeability and expandability for implementation of different simulation and optimization tools. This framework encompasses a layer-based structure of measurements obtained from physical sensors, calibration service, optimization plugging, and cost function application.

The Monitoring System Toolkit (MOST) provides connector interfaces to collect data from various building systems. It is a vendor and technology independent set of tools to simplify measuring, processing, and visualizing different building data streams (energy use, occupancy, comfort, etc.) (Tauber et al., 2014).

The calibration framework is schematically separated in:

- Pre-processing: contains jobs such as the creation of a weather file for the calibration period
- Calibration: includes the driver for the optimization program
- Post-processing: contains any tasks that should be done after a calibration, e.g. deployment of the calibrated model

According to this research, automated simulation model calibration based on a runtime monitoring represents a promising opportunity for performance enhancement in applications pertaining to building automation, diagnostics, facility management, and model-based system control (Tauber et al., 2014).

In spite of all the efforts in the fields of building model calibration, there are still some challenges associated with the calibration process. The calibration process should be considered as a dynamic process, not a static one. Therefore, the matching process of measured data with simulation results has to be continuous over the course of a year. However, still it is not easy to identify the exact solution to the calibration problem. In most of the cases, sensitivity analysis helps a lot in the calibration field (Mustafaraj et al., 2014). Another important issue in the calibration process is related to the simulation tools such as EnergyPlus. Some limitations in the tool such as limited access to a certain variables or not supporting adequate control interface make it difficult to implement special controls on the calibrated model.

2.8 Literature Review Summary

Digging into previous studies indicates that some of them only focus on the building commissioning and fault detection and diagnosis part, and some of them are concentrated on the measurement and verification part after adding EEMs to the building. Most of the tools mentioned above use a mathematical calibrated model (using machine learning techniques) and a few of them use a calibrated simulation model (using energy simulation modeling tools such as EnergyPlus) as a baseline model to predict energy consumption and compare it to the measured consumption to detect the faults based on statistically significant deviations between the two data sets. In this process, the BCVTB plays an important role in the recent studies.

According to above literature review, a precise model calibration also plays a crucial role in building energy simulation. Therefore, in order to reduce the performance gap between measured data and simulation model, it is totally worth implementing the calibration process into the general practice and trying to enhance and automate the calibration process in future studies.

This research steps a level further and proposes a framework to integrate building commissioning and PM&V methods and BAS data into a customized packaged tool based on the need of the building owner. This cohesive framework aims to automate the continuous commissioning process to some extent and to measure and verify the performance of buildings in real-time basis in existing commercial buildings. The proposed methodology which is discussed more in detain in chapter three integrates an EnergyPlus calibrated model presenting the projected building energy consumption and a BAS providing the whole building performance metrics data to offer a real-time building performance monitoring and fault detection and diagnosis approach. The real-time Cx and PM&V framework is intended to recommend corrective actions in order to maintain the high performance level of the building and to provide potential energy savings and improvement in building performance after implementing those actions for the selected time intervals in the real time.

CHAPTER 3 METHODOLOGY

3.1 Framework Structure

Despite aforementioned research and studies that focused on commissioning and FDD or PM&V independently, the idea/methodology of the proposed framework in this study is conceptualized based on the integration of automated continuous commissioning concept and IPMVP option-D approach. The framework is targeted to have a customized context focusing on the building's energy efficiency and potential savings. This framework is designed to be flexible and can be improved or manipulated based on the owners' needs. As it is demonstrated in Figure 3-1, this new advanced framework takes advantage of the building data (BAS database, BEMS information, installed meters data, and utility bills) and an advanced calibrated EnergyPlus model to detect the faults and recommend some corrective actions to fix the problem with the minimal human interventions. This framework uses some key performance metrics and data points (among thousands of data points in BAS) which highly affect the building energy performance to achieve higher energy savings.

The key parameters are mainly from BAS, which includes control schedules, operation status, control parameters, energy data trends, and various building energy performance data. Additionally, more detailed energy data can be gathered such as for heating/cooling, lights, equipment, fans, and motors by installing extra sensors and meters if not available. In the framework, these gathered data points are used to perform the intended process.

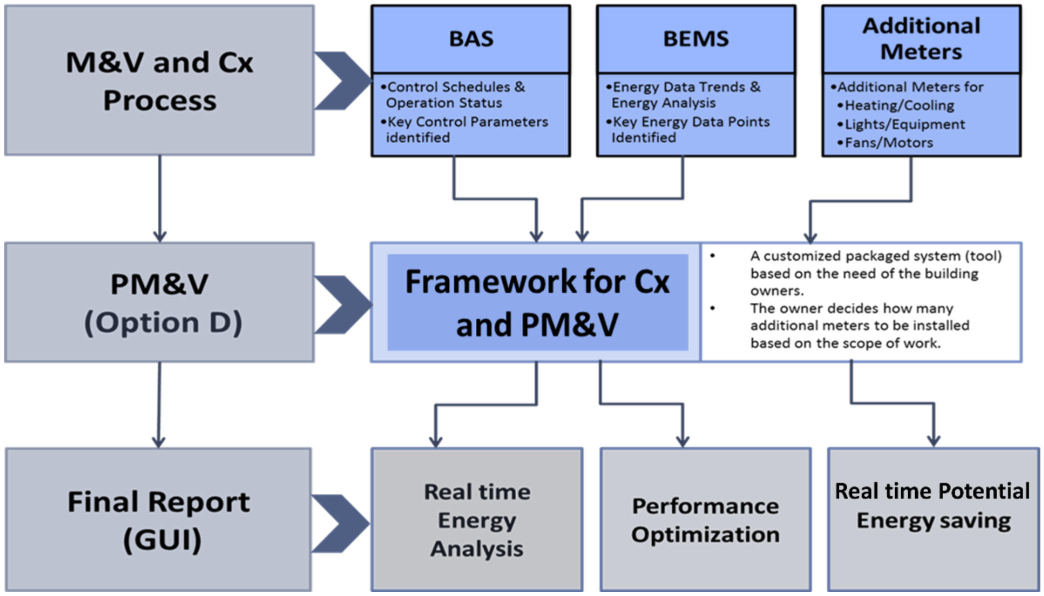


Figure 3-1: Framework Concept

Based on the requirement of the owner, the level of performance analysis is determined. Both the analysis process and the analysis results are available and displayed on a report, or a Graphic User Interface (GUI) for the users to clearly understand the performance status. The energy optimization process is guided by the framework, and, as a result, the corrective actions and potential energy savings will be provided to the user.

This conceptual framework is intended to serve as a support or guide for the development of Real-Time Mini-Building Energy Management System that efficiently expands this framework into a useful and applicable tool/plan.

This framework is intended to significantly improve the efficiency of both Cx and PM&V processes for continuous energy savings in real time through the life of small and medium size existing commercial buildings with minimal costs.

3.2 Framework Development

This framework integrates continuous commissioning and IPMVP Option-D for the performance measurement and verification processes and aims to automate the process to some extent. Figure 3-2 shows the arrangement and sequence of these approaches to provide a cohesive framework. Each section is explained in detail as follows.

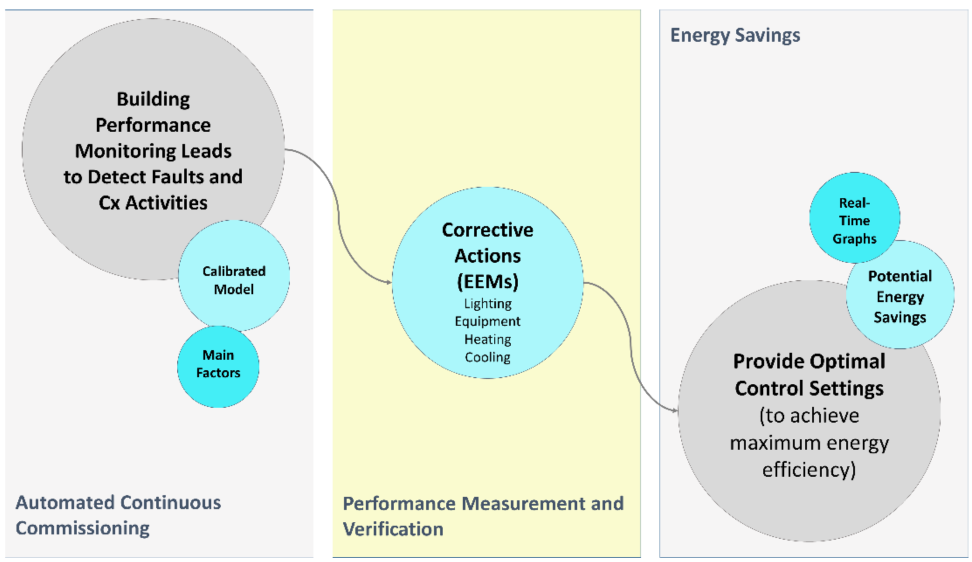


Figure 3-2: Framework Arrangements

3.2.1 Real-Time Automated Continuous Commissioning

This Phase has a similar approach to previous studies which used a calibrated simulation model to calculate and predict/project the intended building energy consumption (design intent). The whole-building EnergyPlus model is built based on the building's envelope description, geometry and materials, roof type, window type, shading geometry, internal heat gains, schedules, and characteristics of building's HVAC system. EnergyPlus model takes those inputs (using default values as indicates by existing templates based on ASHRAE 90.1-2004-primary model) and then computes the energy flows, zonal temperatures, airflows, heating and cooling loads, and comfort levels or whatever performance metric that is required by the building manager at sub-hourly intervals for periods of days to years. Nonetheless, there exist huge discrepancies between the EnergyPlus model results and what utility bills or sub-meters (historical data) indicate as the actual building performance.

To reduce the performance gap between the EnergyPlus model and building actual performance, the EnergyPlus model should go through a rigorous model calibration process. Throughout the general calibration process the main independent variables have to be identified and modified in the reference model. The main independent variables have to be specifically identified for each case study building regarding to its condition and characteristics. In this practice EnergyPlus model needs full pack of data and input information for a year (8760 hour) to run successfully. The common data and input information to the reference model include weather data (i.e. entire year of 2015), envelope characteristics, Lighting/Equipment Power Density (LPD/EPD), lighting/equipment schedule, occupancy schedule and HVAC operation hours and capacities (based on as-built drawings).

After several iterations between the reference model and current calibrated model, the measured data (building energy consumption) obtained from BAS or extra meters are used to calculate the calibration acceptance criterion which are MBE<5% and CVRMSE<15% for monthly data calibration, and MBE<10% and CVRMSE<30% for hourly data calibration, respectively (ASHRAE, 2005).

As shown in Figure 3-3 the real-time calibration process will take place in real time for a limited number of parameters received from external sources, while the calibrated EnergyPlus model is integrated with BCVTB. Receiving real-time parameters as input into EnergyPlus model through BCVTB enhances the framework ability to run over each specified time-step, as opposed to entire year simulation. Calibrated EnergyPlus model is linked to the BCVTB through External Interface object and receives the real-time data from BAS/BEMS/EMCS and additional sensors installed in the building. The BACnet actor embedded in the BCVTB facilitate this process. As it was mentioned in the Chapter two, BACnet is a data communication protocol for Building Automation and Control Networks. BACnet is an open protocol, which means anyone can contribute to the standard, and anyone may use it. In a BACnet compatible BAS, all of the devices in the system will have an instance number which can be used to identify each device and its specific properties in BCVTB. When talking about real-time, we mean a building model whose simulation time is synchronized with real time as represented by the computer clock (on-line simulation). As shown in Figure 3-4 the building's projected/predicted performance by the real time calibrated model will be further compared with the measurements from the BAS in real time. This comparison detects the faults in the selected performance metrics and building systems or confirms that the building performance is on the desired track.

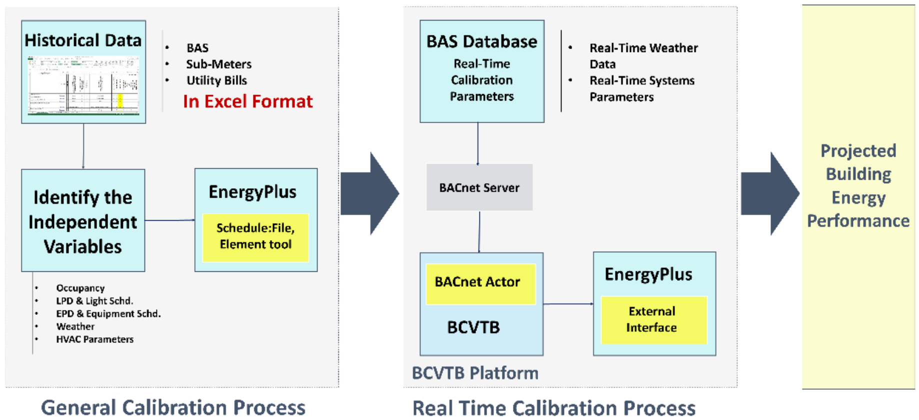


Figure 3-3: EnergyPlus Model Calibration Sequence

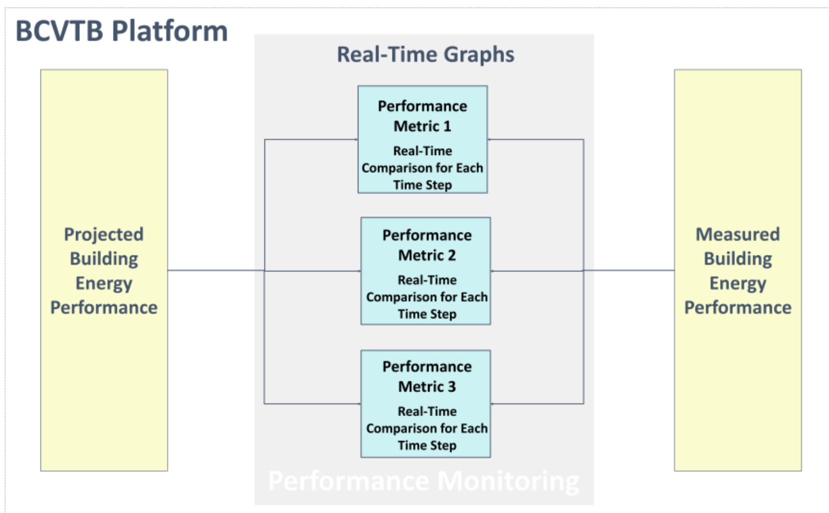


Figure 3-4: Real-Time Automated Continuous Commissioning

3.2.1.1 Framework Performance Metrics

The common problems and faults identified during the commissioning process in many commercial buildings were studied and generally organized in five main categories: BAS/BEMS/EMCS problems, lighting control, HVAC system control, plant equipment, and physical problems. BAS, BEMS, and EMCS data points also were classified based on zone, system, and plant levels. As shown in figure 3-5, these two diagrams are placed side by side to figure out the boundary of the framework key performance metrics which should be considered in developing the framework structure. These performance metrics in the BAS/BEMS/EMCS can help solve the majority of the building faults and problems. However, there are two groups, BAS/BEMS/EMCS problems and physical problems which are different than other groups. The physical problems are not related to the data points extracted from the BAS/BEMS/EMCS. Also, the BAS/BEMS/EMCS systems have their own issues such as improper installations and the program itself malfunctioning.

Basically we aim to figure out which BAS data point can most effectively incorporate in detecting a fault in building during a commissioning process or in calibrating the building simulation model. According to the diagram shown in figure 3-5, lighting, equipment (plug loads), HVAC systems, and air distribution system faults have the highest score in building's faults which can partly be identified and controlled by a BAS data point. However, based on the site visit, consulting with the facility manager, and the budget for the extra sensors needed at any case-study building, some of those parameters can be viewed as significant performance metrics for framework and some of those may be eliminated from the framework. The type and number of performance metrics highly depend on the circumstance and quality of the case-study building and building manager desires.

For example, in the study conducted by the United Technologies Research Center (UTRC) in partnership with the Lawrence Berkeley National Laboratory (LBNL), two buildings were examined by an automated, model-based, whole-building performance monitoring system. In those buildings, the hourly building energy consumption, HVAC (fan, pump, cooling coil), lighting, and water system performance were considered as the main parameters of the automated, model-based, whole-building performance monitoring system to detect and diagnose the faults in the buildings (Bailey et al., 2011).

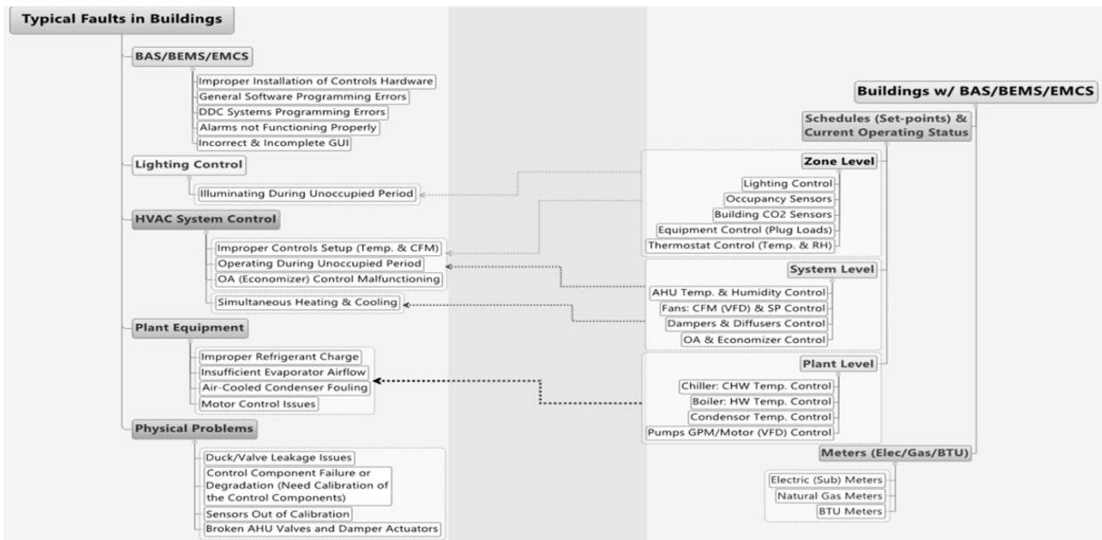


Figure3-5 Framework performance metrics

3.2.2 Performance Measurement and Verification-Corrective Actions

According to the real-time automated continuous commissioning's results (whether there is any abnormal gap between the building's measured performance metrics and real-time calibrated EnergyPlus model results in real time), a list of possible problems and causes and several corrective actions associated with each performance metrics will be recommended to the building manager. The building manager has to decide which option to choose.

After considering and implementing the corrective actions (assumed as EEMs related to the certain performance metric) the real-time Cx and PM&V framework algorithm calculates the final plausible energy savings for the building. The final optimal control settings related to the selected corrective actions (EEM) will be implemented into the real case study building depending on the building manager's decision. Figure 3-6 briefly illustrates this process.

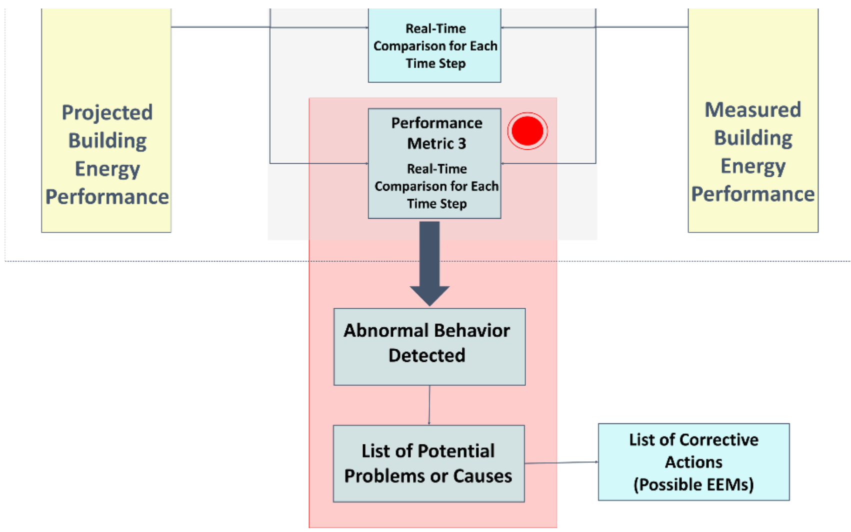


Figure 3-6: PM&V- Corrective Actions and EEMs Development

3.2.3 Performance Measurement and Verification-Energy Savings

If any fault is detected, the list of potential problems, causes and corrective actions (EEMs) are provided to the building manager at the end of each time step. Moreover, the amount of potential energy savings associated with those actions is calculated and provided regarding IPMVP Option-D approach at the end of each time step. Energy savings in this approach are determined by comparing the energy use before (faulty operation) and after implementing of corrective actions (EEMs). Since this process occurs in real time, the adjustments for changes that affect energy use are already considered in the real-time calibrated model.

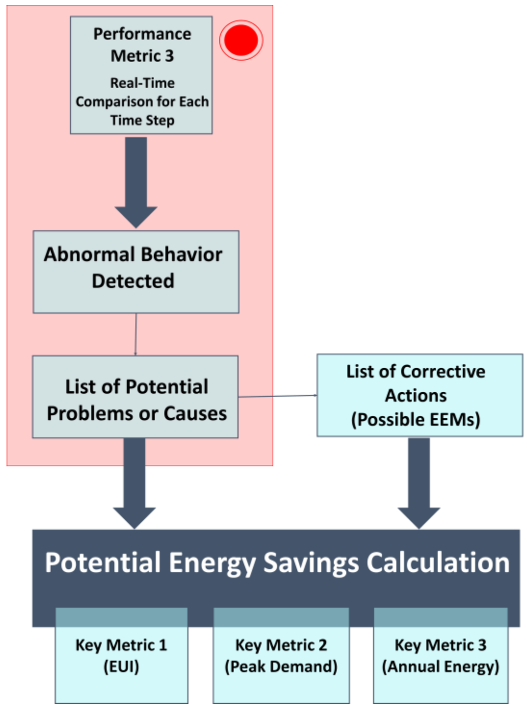


Figure 3-7: Potential Energy Savings Calculation

Savings = (case study building energy consumption – real time calibrated model energy consumption)

The performance monitoring and the energy savings calculation (Figure 3-7) are applied for each performance metric simultaneously in real time.

3.2.3.1 Energy Savings Metrics

Corrective actions (EEMs) are equipment, materials, and practices at a building that result in a reduction in electric energy consumption, measured in kilowatt-hours (kWh), or peak demand, measured in kilowatts (kW), or both.

Energy efficiency savings associated with those corrective actions are often expressed in terms of annual energy, presented as kilo watt hour (kWh)/year. However a key metric can be Energy Use Intensity (EUI). Basically, the EUI expresses a building's energy use as a function of its size. The EUI is expressed as energy per square foot per year. It's calculated by dividing the total energy consumed by the building in one year (measured in kBtu or GJ) by the total floor area of the building (kBtu/ft^2-yr). Since this framework runs in real time for hourly time intervals, the amount of electricity used or energy used for each performance metric is the main key metric.

3.2.4 Advantages and Limitation of the Framework

Compare to previously mentioned Energy Information Systems (EIS) and automated continuous commissioning tools, this framework has integrated the procedure of automated continuous commissioning and Performance Measurement and Verification (IPMVP option-D) in real time to provide new capabilities for building managers as listed below:

- Other existing systems use a "black box" simple model to develop the baseline model. This framework takes advantage of a whole-building real time calibrated energy model in EnergyPlus ("white box" model). The real time calibrated model in this framework is superior to other models in terms of weather, HVAC systems, and plant parameters calibration in real time (offline and real-time input parameters).

- Other existing systems do not present a comparison of whole-building actual performance and projected performance (design intent) or if they do, a specific time interval is used to assess the performance change or deviation. This framework presents the building performance deviation and possible faults and potential energy savings in real time.
- Compare to automated continuous commissioning tool by LBNL (Bailey et al., 2011), this framework tries to follow the research chain and add an extra part to measure and verify the effect of implementing the recommended actions (EEMs) to the case study building and quantify the final potential energy savings.
- This framework presents the performance deviation, changes, and any possible energy savings for each performance metric (building energy end-uses) that has been selected based on the building manager desire and consultation.
- The corrective actions in this framework are categorized and reported based on the previous commissioning reports of the existing commercial building if available and/or the typical faults that were discussed in previous chapter. Other existing systems do not provide corrective action recommendation after detecting the faults and building manager should be an expert personnel who is acquainted with all the systems very well.

- The PM&V section enables building manager to evaluate the effect of recommended corrective actions and quantify the amount of energy savings after adding selected EEMs (among the list of recommended EEMs offered to the building manager) to the EnergyPlus Model before implementing it to the building. If the selected EEM shows a worthy percentage of energy savings (>=10%), it may be considered to be implemented into the building.

  The limitation associated with this framework are listed below:

- The fault diagnosis part is reduced to some corrective actions which needs further exploration and investigation in term of more serious defects in HVAC systems.
- The EnergyPlus calibrated model development along with BCVTB platform need expert people to master these tools.
- EnergyPlus simulation tool has some limitations in term of advanced HVAC modeling which can be prevailed by using precise alternative objects.
- In some old existing buildings with a BAS uses a proprietary protocol, to access to all the devices and their information, a BACnet gateway is needed to be installed on top of the BAS. This process requires time and capital budget to install the BACnet gateway and required sensors if necessary.

3.3 Framework Flow Diagram

Figure 3-8 illustrates the entire process in one comprehensive diagram.

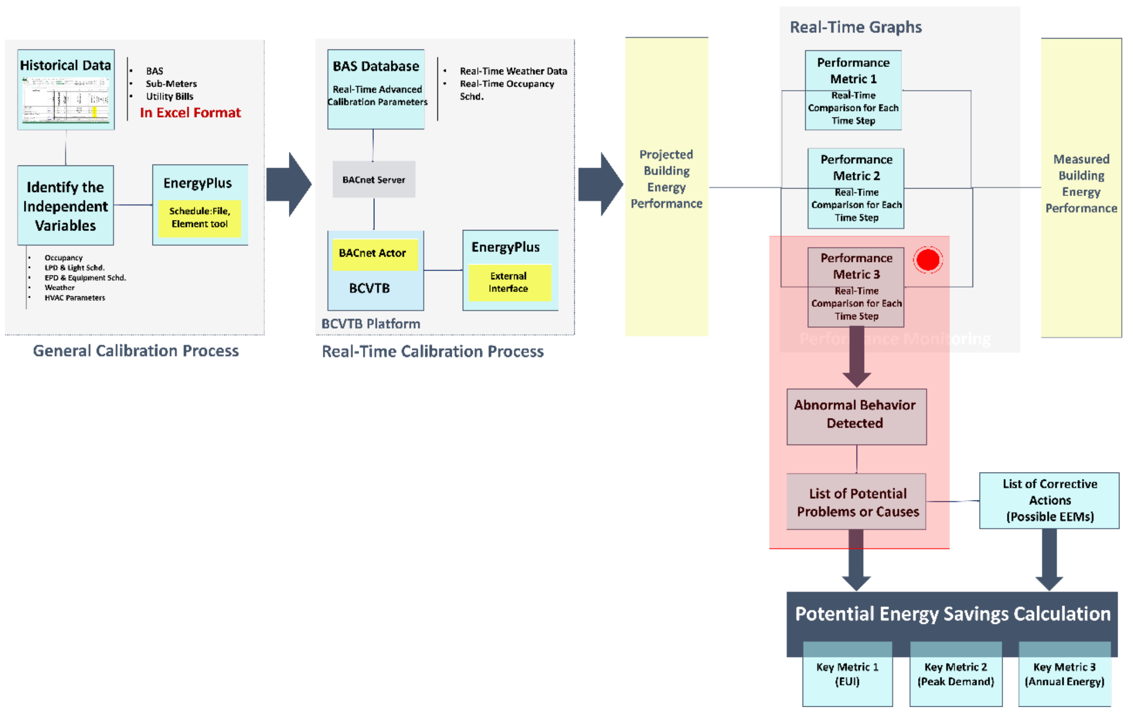


Figure 3-8: Comprehensive Framework Flow Diagram

CHAPTER 4 DEVELOPMENT OF A CALIBRATED SIMULATION MODEL FOR A CASE STUDY BUILDING

The real-time commissioning and performance measurement and verification framework has to be applicable among general building types rather than buildings with unique functions. This feature enhances the applicability and popularity of the framework among building owners in the future. Among different commercial building types, office buildings in different sizes make up the major building stock. According to the Commercial Building Energy Consumption Survey (CBECS), office buildings size range from 1,000 to 5,000 sq-ft for a small size office, 5,000 to 50,000 sq-ft for a medium size office, and over 50,000 sq-ft for a large size office (EIA, 2003). However, the majority of office buildings consist of small and medium size offices that are rarely equipped with BAS and BEMS or any type of automated continuous commissioning tools. Using this framework in such buildings will be more cost effective and appropriate for the building owner than an expensive complete package of BAS. Considering the above mentioned facts, the case-study building would more likely be selected from the small or medium size office building stock.

4.1 Case Study Building Selection Process

The building Operation & Maintenance (O&M) department and energy management department at NCSU deal with facility management. The building O&M department provides the services related to HVAC systems, comfort range temperature inside the buildings, electrical and plumbing problems, elevators, building automation systems, fire sprinkler systems and fire alarms. The energy management department tries to economically manage energy resources purchased and consumed by the university. This unit records and tracks energy and water consumption, in pursuit of additionally beneficial methods in order to utilize the lowest amount of energy while keeping the comfort level for the building residents and enabling university to fulfill its goals and mission.

Using the information and documents from those departments at NCSU, several small and medium size office buildings at NCSU campus such as Kamphoefner Hall, KeyStone Science Center, Partners III, Research IV, and Wildlife building on centennial campus (Figure 4-1) were selected to be reviewed in terms of building types, functions, and available energy consumption data. These buildings are equipped with up-to-date BASs with rich data points in zones, systems, and plant level.

Figure 4-1: NCSU Office Buildings

North Carolina State University buildings use different types of BASs in order to manage the energy costs and achieve energy savings during the buildings life cycle. This variety in BASs is due to building age and construction year. Newer buildings in NCSU utilize the Metasys from Johnson Control and SiteNet from SRS and the older buildings use Schneider Electric as building automation system (Figure 4-2).

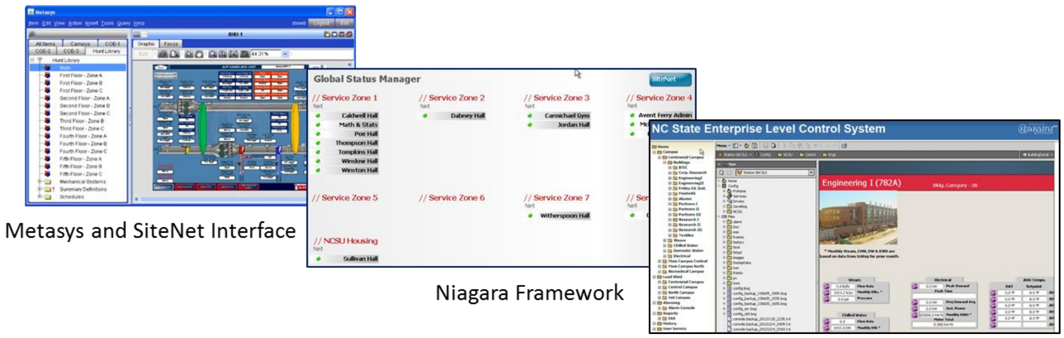


Figure 4-2: NCSU BAS Interface

There is also an Enterprise Level Control System, the Niagara Framework which creates a mutual and common environment that links and shares information amid heterogeneous devices, legacy systems, open system protocols - such as BACnet®, LonWorks® and Modbus™ - the internet and enterprise information systems (Figure 4-3).

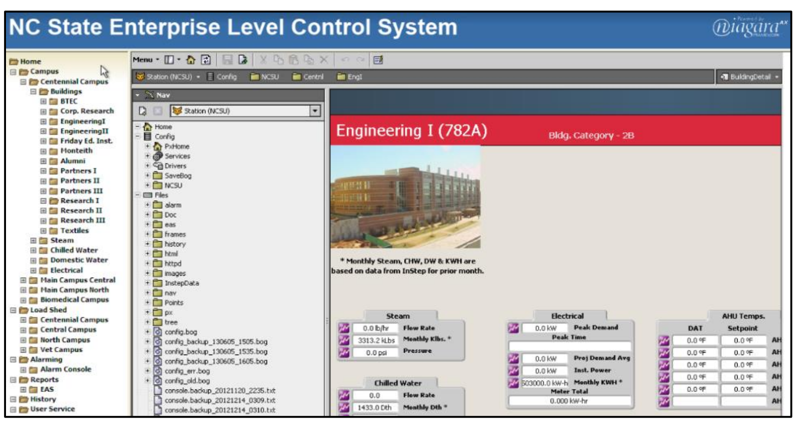


Figure 4-3: Niagara Framework

After interviewing with O&M personnel and reviewing several commissioning reports and BAS data trends for the selected buildings, Research IV has been selected as the final case study building to implement the framework for Cx and PM&V.

Figure 4-4: Research IV Building

Research IV building (Figure 4-4) is a large size office building with various occupancy purposes built in 1996. The building has three occupied floors and a floor space of 80,000 ft^2 divided into spaces for various NCSU and off-campus groups. The main tenants are IES, Advanced Energy, and the Science House. The building is split into four quadrants being served with the same air handling unit via Variable Air Volume (VAV) boxes. Cooling is provided by 75 ton air cooled roof-top units that each serves one quadrant. The unit is not equipped with gas heat, but rather an 80 kW electric strip heater that is not generally used. Most heating in the space is provided by electric strip heaters located in each VAV box. Steam is not available at this building, though there is a gas line just outside on the east side.

The controls are from the original Metasys controllers, one for each floor. Metasys from Johnson Controls in Research IV building uses a proprietary protocol, called N2. This means that not all of the devices in the building are accessible by BACnet to obtain real-time data. Just some of the devices which are installed recently are using BACnet protocol. To access to all the devices and their information, a BACnet gateway need to be installed on top of the BAS. This process requires a long period of time and capital budget to install the BACnet gateway. Figure 4-5 shows the Metasys interface and the each Air Handling Units (AHU) condition.

Figure 4-5: Metasys Interface (4 AHUs)

After reviewing the electrical drawings and walking through the Research IV building and electrical panels with an electrical engineer, we estimated the number of required meters. However, due to some difficulties in meters installation and budget shortage, the building selection process continued with emphasis on the number and type of existing meters already installed in the building and the BACnet compatible BAS.

4.1.1 Final Case-Study Building

The final selected case study building is a medium size government office building located in Research Triangle Park (RTP), NC and consists of the construction of an approximately 46,000 ft^2 (4,273.5 m^2) addition to the B-Wing Atrium built in 2014. The three-story addition project includes administrative offices, conference rooms, commons areas, a tissue archive freezer, archival gel storage, storage, and a data silo.

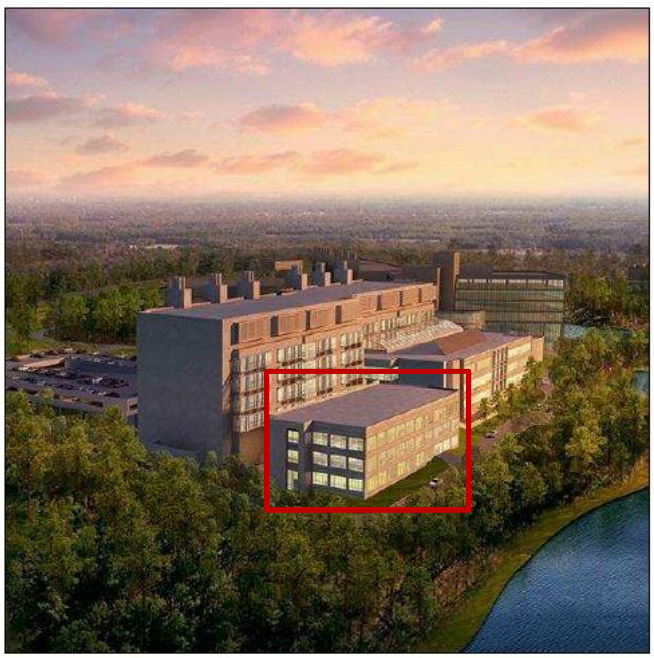


Figure 4-6: Case Study Building

The case study building received the U.S. Green Building Council's LEED® for new construction Gold level certification. This building fulfills the guiding basics and principles for federal leadership in high performance and sustainable buildings due to its existing LEED certification. The case study building features state-of-the-art, energy-efficient building systems, including: temperature controls; variable air volume air and water side economizers that allow for 100 percent outside air ventilation when possible; and under-floor ventilation that uses 6 percent less energy. Extensive daylighting around the perimeter of the building, a skylight in the ceiling, and occupancy sensors throughout the building minimize the use of artificial light. Advanced metering at the facility, including sub-metering for electrical and water use, helps building facility managers identify and fix any power drains and water leaks. Moreover, during the construction process, selected recycled-content materials diverted 95 percent of construction wastes from landfills.

The case study building is constructed of reinforced concrete with double paned windows. The building encompasses enough rooms for varied purposes occupied and served with various types of air handling units. The heating and cooling are provided by AHUs through VAV boxes for each zone. This building also equipped with an Energy Recovery Unit (ERU).

"*During the energy recovery process, the energy contained in normally exhausted building or space air will be used to pre-condition the incoming outdoor ventilation air in HVAC systems*" (Dieckmann, 2008). During the warmer seasons, the system pre-cools and dehumidifies while humidifying and pre-heating in the cooler seasons. The advantage of applying energy recovery is the ability to fulfill the ASHRAE ventilation and energy standards, while improving indoor air quality (maintain a relative humidity of 40% to 50%) and subsiding total HVAC equipment capacity. This technology is not considered as an effective means of minimizing energy cost and heating and cooling loads, but is capable of the scaling down of equipment (Dieckmann, 2008).

The selected case study building is an appropriate building to implement the real-time commissioning and performance measurement and verification framework since this building is equipped with advanced BACnet compatible BAS and required meters to reasonably separate the building energy consumption from the entire campus.

4.1.2 Climate Analysis

The case study building is located at the research triangle park in North Carolina. The environmental features of this area include a humid subtropical climate, with four distinct seasons. Winters are short and generally cool, with a January daily average of 41.0 °F (5.0 °C). On average, there are 69 nights per year that drop to or below freezing, and only 2.7 days that fail to rise above freezing. April is the driest month, with an average of 2.91 inches (73.9 mm) of precipitation. Precipitation is well distributed throughout the year, with a slight maximum between July and September; on average, July is the wettest month, owing to generally frequent, sometimes heavy, showers and thunderstorms. Summers are hot and humid, with a daily average in July of 80.0 °F (26.7 °C). There are 48 days per year with highs at or above 90 °F (32 °C). Autumn and spring are alike overall but has fewer days of rainfall (Figure 4-7 and 4-8).

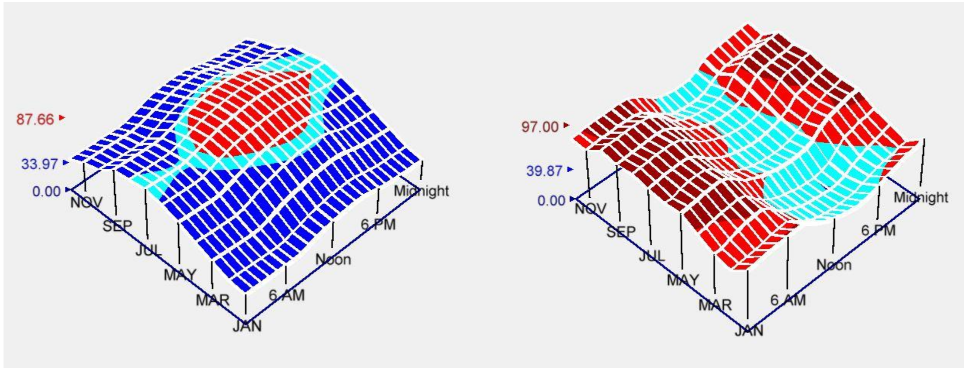


Figure 4-7: Dry-Bulb Temperature and Relative Humidity 3D Chart for Raleigh, Weather Data TMY3

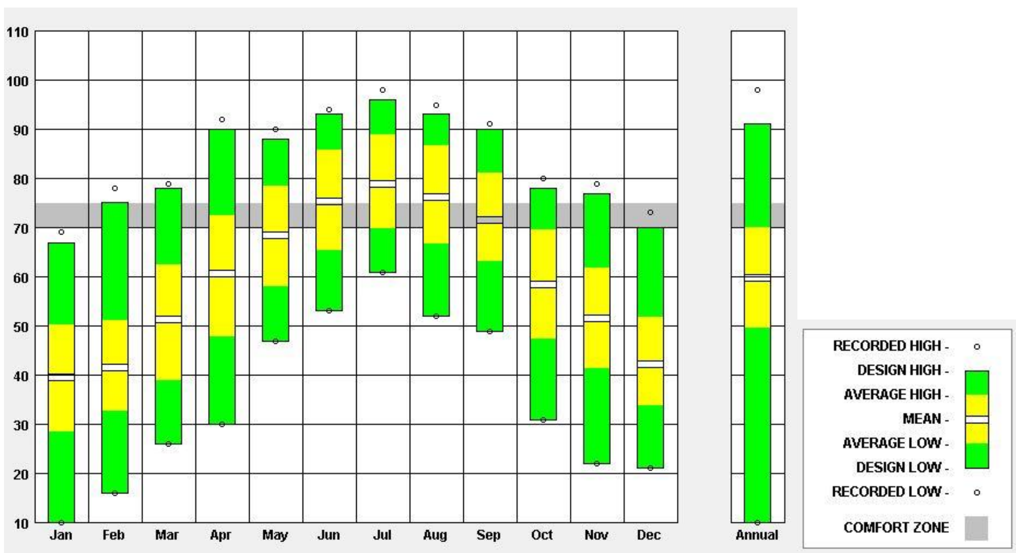


Figure 4-8: Annual Temperature Range for Raleigh, NC

4.2 Case Study Building Primary Model Development

4.2.1 Geometry Development

The case study building is a medium size office building with different kinds of occupancy goals and purposes. The building has three occupied floors and a floor space of 46,000 ft^2 (4,273 m^2). It is constructed of reinforced concrete with double paned windows. The building has rooms of many different purposes being served with three air handling units. The heating and cooling are provided by AHUs through VAV boxes for each zone. This building also equipped with an Energy Recovery Unit (ERU).

The case study building primary model is developed using SketchUp and OpenStudio plugin based on each floor's zoning diagram. Each zone is defined on HVAC design drawings as a separate thermal block and sorted based on its functionality as shown in Table 4-1. Figure 4-9, 4-10, and 4-11 show the floor plan of each floor and zoning arrangement. The detailed zone summary including zone's area, volume, wall area, window area, lighting, people and plug load level are listed in Appendix A.

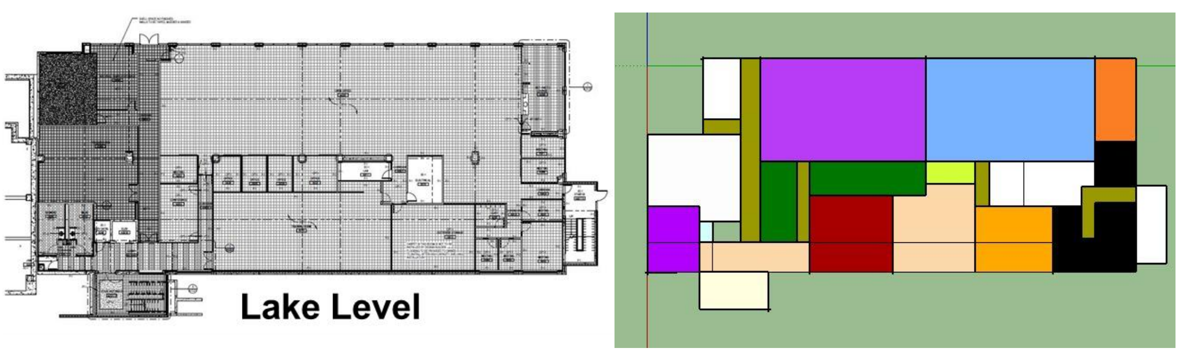


Figure 4-9: Case Study Building Lake Level Plan and Zoning Arrangement

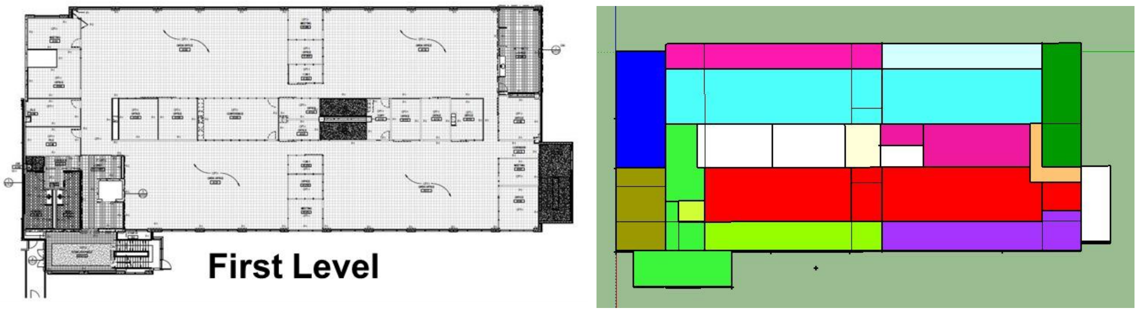


Figure 4-10: Case Study Building First Level Plan and Zoning Arrangement

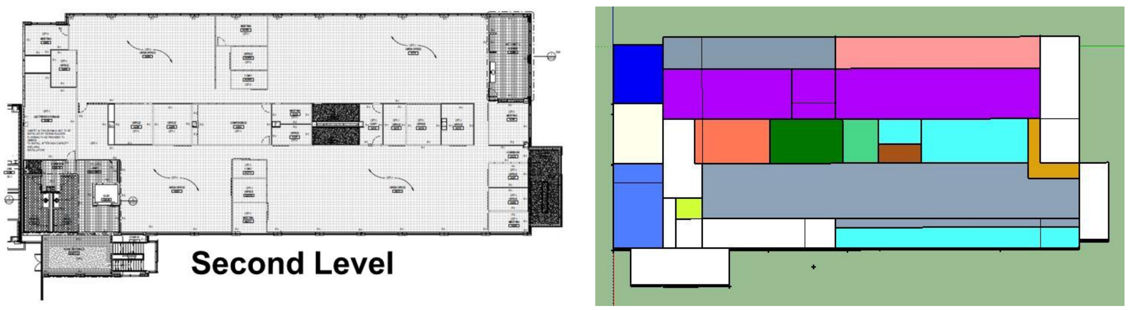


Figure 4-11: Case Study Building Second Level Plan and Zoning Arrangement

The initial user input is set to DOE Reference 2004 template, office type for the 4A climate zone (Figure 4-12). This information will be modified later in accordance with ASHRAE 90.1-2004 chapter 11: Energy Cost Budget Method, to develop the code compliant model.

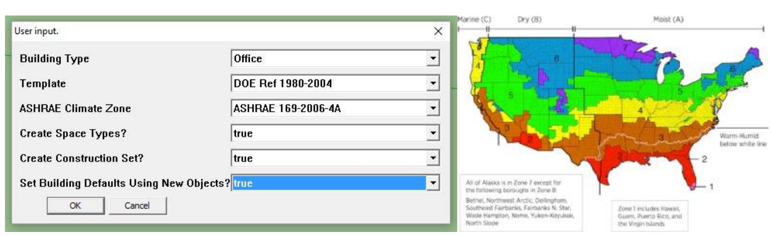


Figure 4-12: User Input and US climate Zones

Table 4-1: Zone List

Zone No	Name
Zone 1	Office – Break Room
Zone 2	Office – Closed Office
Zone 3	Office - Conference
Zone 4	Office – IT Room
Zone 5	Office - Lobby
Zone 6	Office - OpenOffice
Zone 7	Office - Restroom
Zone 8	Office - Stair
Zone 9	Office - Storage
Zone 10	Office - Corridor
Zone 11	Office - Electrical/Mechanical Room

Figure 4-13 represents the west and east facade of the case study building model in SketchUp. In the next step, the geometry model is imported into the EnergyPlus tool as an .idf file to modify the internal heat gains (people, light, and equipment), and add HVAC systems to develop the primary model. Building geometry model is divided to conditioned and unconditioned building area. The unconditioned building area includes stairs, corridor, and storage area. The total simulated building area based on the zoning arrangements and provided floor plan is 45,092 ft^2 (4189 m^2). The total building area includes 42,920 ft^2 (3988 m^2) of conditioned area and 2,172 ft^2 (201 m^2) of unconditioned area as shown in Table 4-2.

Table 4-2: Building Area

Building Area	Area [ft^2]
Total Building Area	45,092
Net Conditioned Building Area	42,920
Unconditioned Building Area	2,172

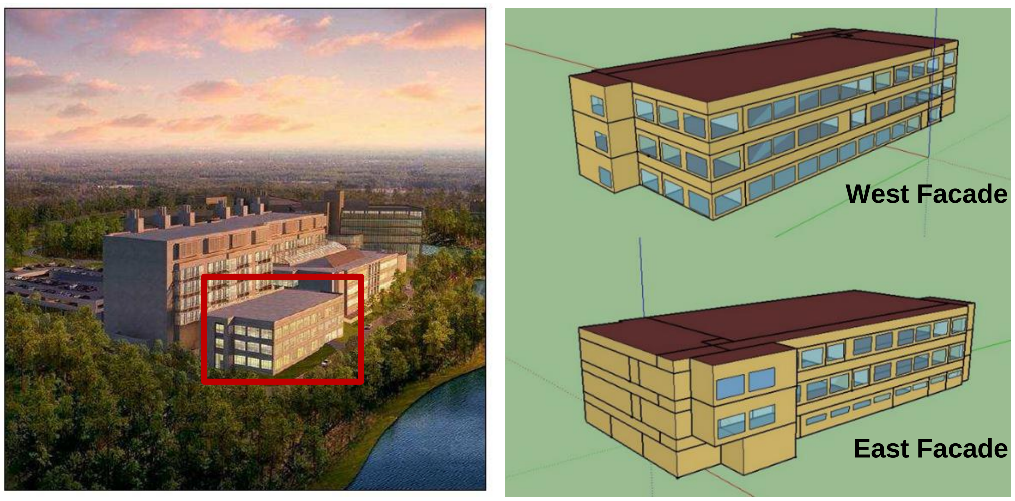


Figure 4-13: West and East Facade of Case Study Building in SketchUp

4.2.2 Primary Model Envelope Characteristics

The office template which is used to develop primary model includes several exterior and interior constructions for wall, roof, floor, ceiling, and window based on ASHREA 90.1-2004. However, all components of the building envelope should be modeled as shown on architectural drawings or as installed for existing building envelope for the purpose of developing the calibrated model and code-compliant model. Therefore, the template constructions are modified based on real building information at the beginning of developing the primary model. Table 4-3, 4-4, and 4-5 list the primary model construction objects with their outside to inside layers. These components are not changed during the calibration process, since they are matched with the as-built architectural drawings. But to develop the code-compliant model, these components are modified to meet the minimum requirement of ASHRAE 90.1-2004 for the opaque components and fenestrations.

Table 4-3: Case Study Building's As-Built Exterior Construction

Climate Zone 4a	Exterior Roof	Exterior Wall Mass	Exterior Shaft Wall-South	Exterior Slab on Grade	Exterior Door
Outside layer	60 mil TPO single ply membrane	4 in (100mm) Lightweight Concrete	¾ in (19mm) gypsum board	Vapor seal - plastic film	Metal surface
Layer 2	4 in (100mm) Lightweight Concrete	Insulation: Mineral fiber: processed from rock - slag - or glass (R-20)	Wall air space resistance	MAT- 4 in (100mm) Heavy weight Concrete	1 in (25mm) Insulation board
Layer 3	Insulation: Mineral fiber: processed from rock - slag - or glass (R-30)	4 in (100mm) Lightweight Concrete	¾ in (19mm) gypsum board	Carpet Pad	-
Layer 4	4 in (100mm) Lightweight Concrete	Wall air space resistance	-	-	-

Table 4-4: Continued

Climate Zone 4a	Exterior Roof	Exterior Wall Mass	Exterior Shaft Wall-South	Exterior Slab on Grade	Exterior Door
Layer 5	-	5/8 in (16mm) Drywall (gypsum board)	-	-	-
U-Factor (Btu/hr.ft^2.F)	0.030	0.040		0.516	0.177

Table 4-5: Case Study Building's As-Built Windows Characteristics

Climate Zone 4a	Exterior windows
U-Factor (Btu/hr.ft^2.F)	0.29
SHGC	0.31
VT	0.6

Table 4-6: Case Study Building's As-Built Interior Construction

CBECS 1980-2004, Climate Zone 4a	Interior Wall	Interior Floor	Interior Ceiling	Interior Door
Outside layer	5/8 in (19mm) gypsum board	Acoustic tile	8 in (200mm) lightweight concrete	1 in (25mm) wood
Layer 2	Wall air space resistance	Ceiling air space resistance	Ceiling air space resistance	-
Layer 3	5/8 in (19mm) gypsum board	8 in (200mm) lightweight concrete	Acoustic tile	-

Window-to-wall ratio (WWR) is the measure of the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area. Table 4-6 shows the case study building window to wall ratio for each facade.

Table 4-7: Case Study Building's Window to wall Ratio

Window-Wall Ratio	**Total**	**North**	**East**	**South**	**West**
Gross Wall Area [ft^2]	25,212.6	4,069.4	8,614.1	4,069.4	8,459.6
Above Ground Wall Area [ft^2]	25,212.6	4,069.4	8,614.1	4,069.4	8,459.6
Window Opening Area [ft^2]	5,875.3	945.7	2,016.5	0	2,913
Gross Window-Wall Ratio [%]	23.3	23.2	23.4	0	34.4

4.2.3 Building Operating Characteristics

The building is assumed to follow typical office occupancy patterns with peak occupancy occurring from 8 AM to 5 PM weekdays with limited occupancy beginning at 7 AM and extending until 6 PM for janitorial functions. For the medium office, Saturday, Sunday and holiday occupancy are modeled at 10-50% of peak. Schedules for lighting and miscellaneous equipment were matched to occupancy schedules with additional limited usage during unoccupied times. HVAC system schedules were matched to the occupancy schedules, and allow for earlier startup times to earn the proper and desired place temperature at the onset of normal occupancy.

4.2.4 Primary Model HVAC Systems

The case study building is served by three Air Handling Units (AHUs) to regulate and circulate the air. The AHUs at case study building are three large metal boxes at each floor containing a blower, a cooling coil, filter racks or chambers, sound attenuators, and dampers (Figure4-14). Each AHU in each floor connects to a ductwork ventilation system that distributes the conditioned air through the building and returns it to the AHU. In this building, ductwork ends in several Variable Air Volume (VAV) terminal boxes with or without electric reheat coils for different zone.

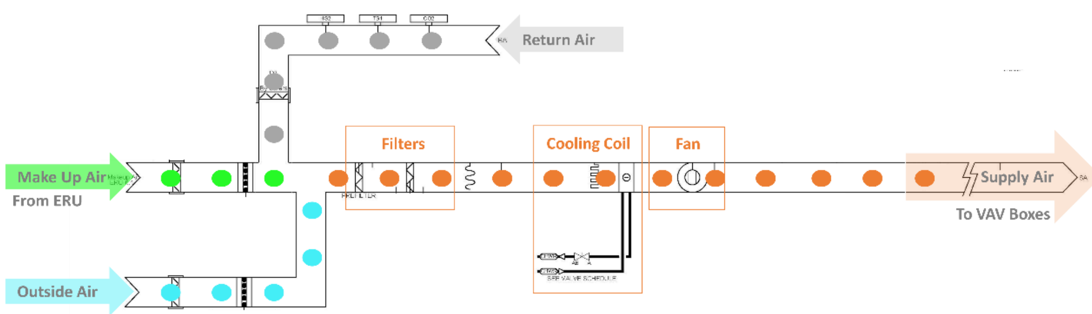


Figure 4-14: Case Study Building AHU Diagram

VAV is a type of HVAC system that change the airflow rate at a constant temperature to meet the increasing and decreasing heat gains or losses within the thermal zone. The simplest VAV system includes one supply duct that, when in cooling mode, distributes supply air at a constant temperature of approximately 55 °F (13 °C) (Figure 4-15).

According to as-built mechanical drawings, there are 35 zones being served by VAV boxes with electric reheat (Figure 4-15) and eight zones being served by VAV boxes without electric reheat (Figure 4-16).

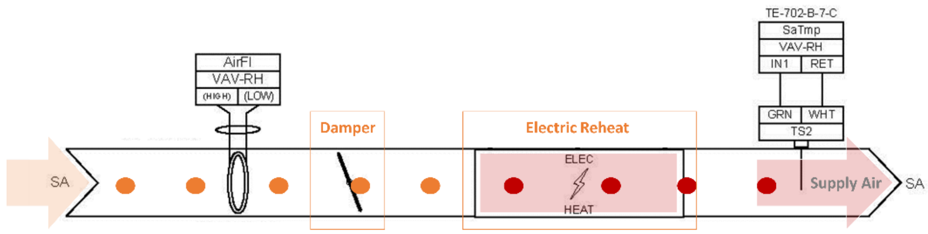


Figure 4-15: Case Study Building VAV with Reheat Diagram

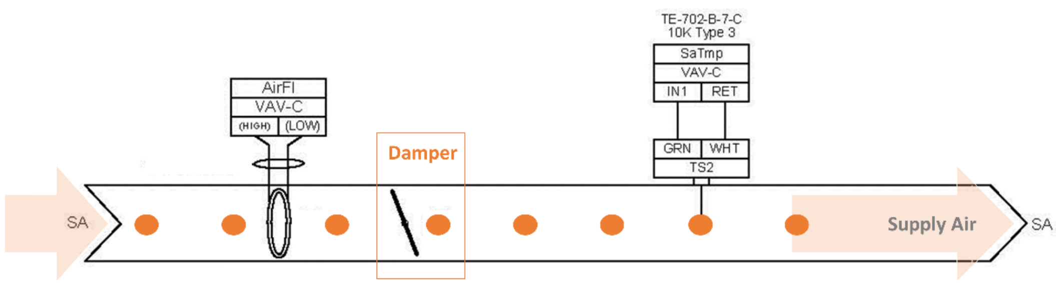


Figure 4-16: Case Study Building VAV with No Reheat Diagram

FreeazerFarm zone which is equiped with several freezers is also served with two fan coil units with cooling coils only. Whenever theVAV box cannot maintain space temperature, the controller shall start the FCU fan and modulate the chilled water valve to maintain space temperature (about 75 F).

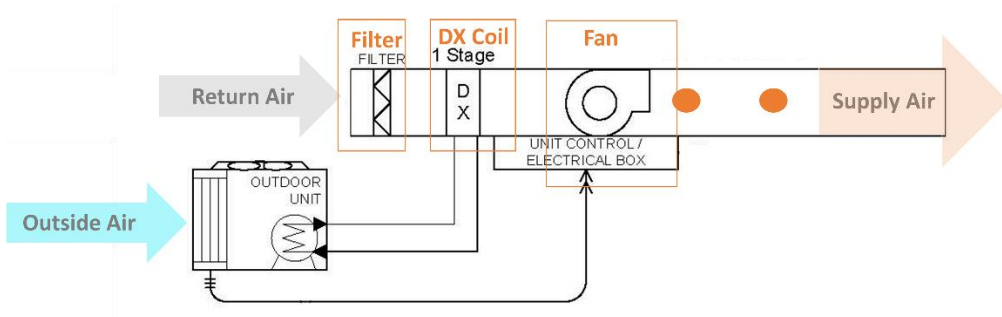


Figure 4-17: Case Study Building Split System Diagram

Four zones (LAN A017, LAN A117, LAN A217, and elevator room) are being served by ductless split systems. A split system contains an indoor section and matching outdoor section which are connected by refrigerant tubing. The indoor section consists of a fan, indoor cooling coil, and filter while the outdoor section includes the compressor and condenser (Figure 4-17).

This building also equipped with an Energy Recovery Unit (ERU) to exchange the energy contained in space air with the incoming outdoor ventilation air to treat (precondition) the make-up air which goes to the AHUs (Figure 4-18).

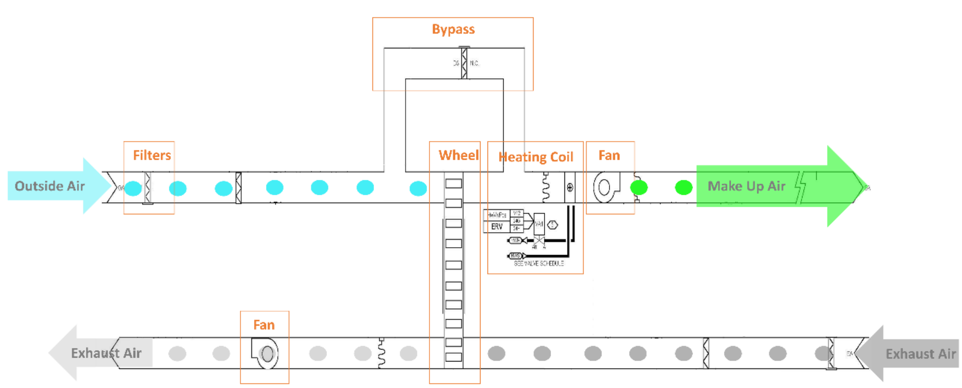


Figure 4-18: Case Study Building Energy Recovery Unit Diagram

EnergyPlus does not support a single ERU serving multiple AHUs. Therefore, a "HeatExchanger:AirToAir:SensibleAndLatent" object needs to be added to the Dedicated Outside Air (DOA) system of each AHU along with a heating coil. According to EnergyPlus input/output reference, the sensible and latent air-to-air heat exchanger typically is used for the exhaust or relief air heat recovery. Heat exchanger performance can be identified to transfer sensible energy, latent energy or both between the supply and exhaust air streams. Performance is defined by specifying sensible and/or latent effectiveness at 75% and 100% of the nominal (rated) supply air flow rate at two operating conditions: heating mode and cooling mode. This heat exchanger object can be used in conjunction with a conventional air-side economizer (DOE, 2015).

The case study building also takes advantage of an economizer to provide free cooling. *"Economizer operates by pulling cooler outside air into building, reducing the load on the mechanical cooling system"* (BSD-Solutions, 2013). For the period of very cold weather (heating mode), the AHU takes in the lowest outdoor airflow and mixes it with returning air. The mixed air is then heated as necessary to sustain the desired supply-air (or space) temperature. ASHRAE Standard 62.1–2004 or building code requirements determine the minimum intake of outdoor air. During "cool" weather (30°F to 55°F [1°C to 13°C], for example), the required space temperature can be maintained without any mechanical cooling or heating by simply adjusting the mix of outdoor air and return air. In this mode, the economizer system adjusts both the outdoor- and return-air dampers, modulating these airflows to match cooling capacity with cooling load—without mechanical cooling. Intake airflow varies between the minimum setting and a maximum value (100% of supply airflow) to maintain the supply-air (or space) temperature at set point. During mild weather (55°F to 75°F [13°C to 24°C], for example), outdoor air can provide some cooling capacity, but not enough to satisfy the load, so mechanical cooling supplements the economizer cooling provided by the wide-open outdoor-air damper. We refer to this mode as integrated economizer because it combines "free" cooling (100% outdoor air) with mechanical cooling to meet the required cooling capacity. The system stays in integrated economizer mode until outdoor conditions reach the high limit shutoff setting (TRANE, 2006).

In EnergyPlus model, a mixed air box has its own controller type called "Controller:OutdoorAir". The outdoor air controller is designed to provide outdoor air for ventilation and also free cooling (through additional outdoor air and/or bypassing an air-to-air heat exchanger) whenever possible. The outdoor air controller encompasses a number of user-selectable limit controls. If any of the selected limits are exceeded, the outdoor airflow rate is set to the minimum. By setting the economizer type to "FixedDryBulb", the economizer will set the outdoor airflow rate at minimum if the outdoor air temperature is higher than a specified dry-bulb temperature limit. The specified dry-bulb temperature limit is set to 65F according to building's control record drawings.

The case study building is equipped with several meters that detach it from the rest of the buildings. These energy performance meters measure the lighting, equipment (plug loads), HVAC, district chilled water, and district hot water of building.

The district chilled water and district hot water measurements enable us to implement the district cooling and heating object in the model instead of modeling the entire plant. In district heating and cooling model, there exist some centralized source of chilled and hot water which allows the user to achieve a simulation without specifying operating parameters or curve fits for chiller or boiler models. This model requires to connect to the loop and the nominal capacity to simulate. This model calculates the output capacity necessary from the inlet temperature to the set point temperature for that loop with the given mass flow rate in Watts (DOE, 2015).

4.2.5 Weather Data for Primary Model

There are three main type of weather data with traditional use cases for each:

(1) "Typical" weather data: representative of some location over an arbitrary period of time, often used for design and performance conditions over the life of a building. Typical Meteorological Year (TMY) files are created by looking at 15 –30 years of hourly data to presents the range of weather phenomena for the location in question, while still giving annual averages that are consistent with the long-term averages for the location in question (Hensen & Lamberts, 2012). The initial TMY file was subsequently replaced by TMY2 and TMY3. TMY2 files use 30 years of data in about 1990, with an enhanced weighted average selection method and served as the default EnergyPlus weather files until late in 2010. TMY3 files use 15 years of data were

introduced in 2005 with a higher emphasis on solar radiation variables and also included precipitation as a variable.

(2) "Actual" weather data: at a specific location for a specific period of time, used for simulation calibration to energy bills

(3) "Future" weather data: used for adaptive control of a building (Bhandari, Shrestha, & New, 2012)

To predict building load and heating and cooling performance over the building life cycle, the TMY3 file for Raleigh-Durham International Airport was used in the code-compliant model and for the real-time calibrated simulation model using AMY weather file is necessary.

4.2.6 Case Study Building Calibrated Model Development

Building Energy Model (BEM) calibration is designed to adjust and adapt the primary BEM model based on measured data to produce an updated BEM model that can accurately mirror the actual building operation performance. Today legislation is also concerned with the energy performance of buildings, The ASHRAE 90.1, and International Performance Measurement and Verification Protocol (IPMVP) develop frameworks for the calibration process to enforce a minimum standard of efficiency. ASHRAE Guideline 14-2002 allows building modelers to use monthly and hourly data, as well as spot and short-term measurements to calibrate BEM models. The guideline uses the Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Squared Error (CVRMSE) indices to represent how well a mathematical model describes the variability in measured data. "*The computer model shall* *have an MBE of 5% and a CVRMSE of 15% relative to monthly calibration data. If hourly calibration data are used, these requirements shall be 10% and 30%, respectively*."(ASHRAE, 2002). NMBE and CV(RMSE) equations are as follows:

- Normalized Mean Bias Error (NMBE)

$$NMBE = \frac{\sum_{i=1}^{n}\left(\mathrm{y}_{\mathrm{simulated,i}} - \mathrm{y}_{\mathrm{measured,i}}\right)}{\bar{\mathrm{y}}_{\mathrm{measured}} \times (\mathrm{n} - \mathrm{p})}$$

Where:

y = monthly (or hourly) energy consumption

ȳ = mean of monthly (or hourly) energy consumption

n =number of data points

p =number of predictor variables

- Coefficient of Variance of Root Mean Square Error (CV(RMSE))

$$CV(RMSE) = \frac{1}{\bar{\mathrm{y}}_{\mathrm{meas}}} \times \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{y}_{\mathrm{sim,i}} - \mathrm{y}_{\mathrm{meas,i}})^2}{(\mathrm{n} - \mathrm{p} - 1)}}$$

Where:

y = monthly (or hourly) energy consumption

ȳ = mean of monthly (or hourly) energy consumption n =number of data points

p =number of predictor variables

The case study building is a new constructed building and started working since 2014. The measured building performance data are available since 2014. The performance meters are trending data for each month till July 2016. After July 2016, meters settings have been changed to our request for hourly and 15 minutes interval data. Therefore, primary model is calibrated using the historical monthly data from 2015.

4.2.7 Weather Calibration

Actual Meteorological Year (AMY) weather data file is an actual hourly data sets over the last year or time period where energy use data are available, but put into the same formats as a TMY file. In the previous studies the challenging issue was to normalize the building simulation model results to the actual weather data. This challenge has been facilitated recently by using the Elements program. Elements is a free, open-source, cross-platform software tool for creating and editing custom weather files for building energy modeling. The goal of this tool is to develop a comprehensive, integrated application suitable for handling all of the common tasks associated with weather files (Big-Ladder-Software, 2015). Elements was developed by Big Ladder Software with the funding and collaboration of Rocky Mountain Institute. Elements uses a smart spreadsheet editor to read/write common weather file formats (DOE-2 .bin, .fmt), and EnergyPlus (.epw)), and browse/edit weather data. Elements also has tools for bulk data transformation: offset, scale, normalize, and copy and paste to/from Excel (Big-Ladder-Software, 2015) .

To use Elements, we need to start from National Oceanic and Atmospheric Administration (NOAA) website and gather the recent year weather data (ex, 2015) and store them in an Excel file. Figure 4-19 shows the Excel spreadsheets of NOAA weather data for 2015. Figure 4-20 also shows how to transfer the data from Excel spreadsheets to the Elements table for making an AMY weather file. After creating the AMY weather file and wrap it into an epw. format, EnergyPlus can use it to simulate the building model and generate the weather calibrated results.

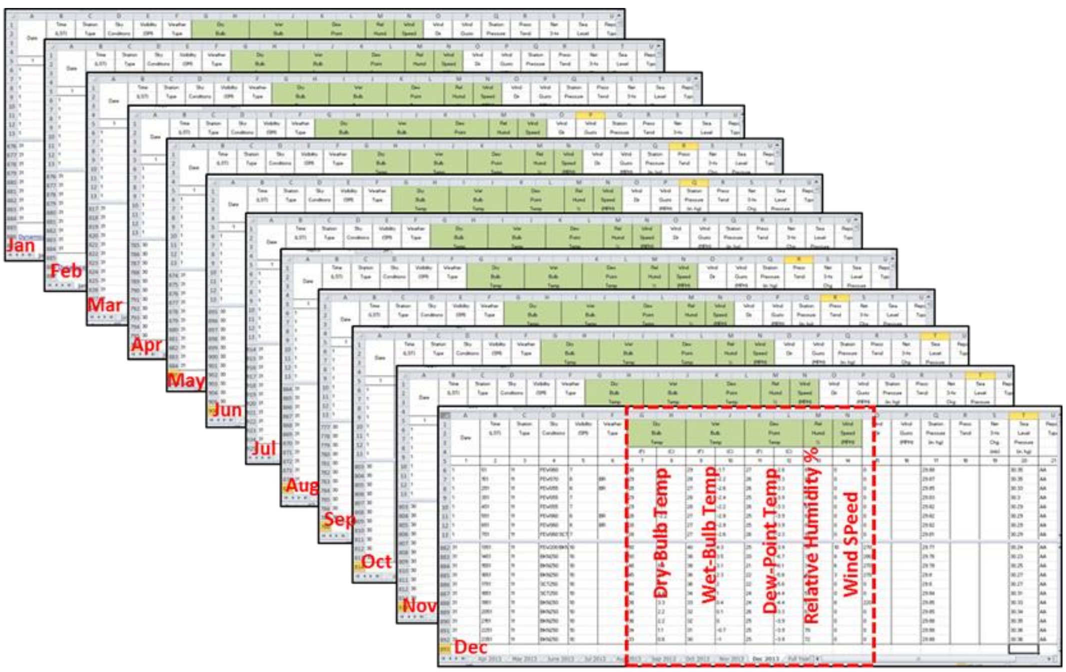


Figure 4-19: NOAA Weather Data for 2015

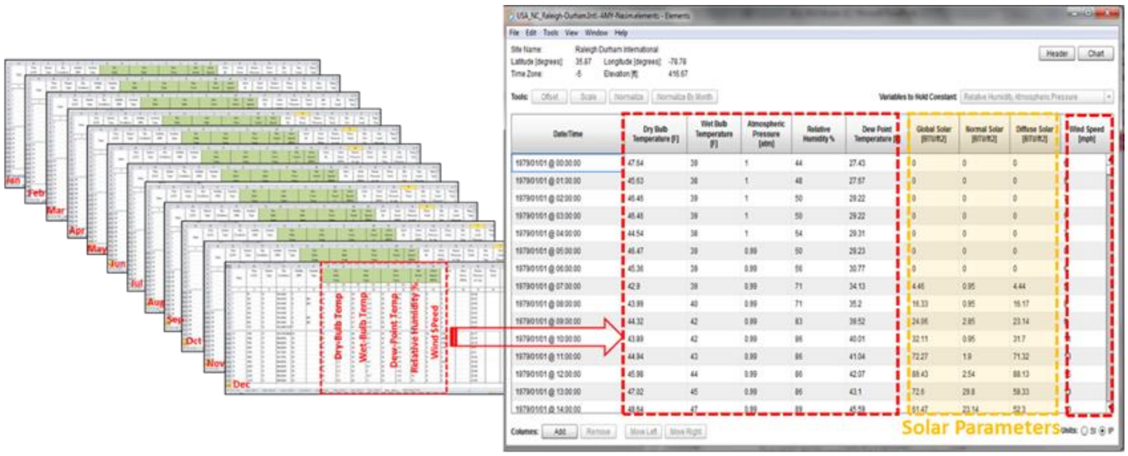


Figure 4-20: Creating AMY Weather File Using Elements

Figure 4-21 shows the comparison between dry bulb temperature in TMY3, and 2015 weather data. Figure 4-22 and 4-23 also compare the TMY3, AMY 2014, and AMY 2015 weather data in terms of dry bulb temperature and relative humidity in 3D graphs. The graphs show less hot days in summer 2014 and rainier days during winter 2014 than TMY weather data and more hot days in summer 2015 and rainier days (humid days) during winter 2015 than TMY weather data.

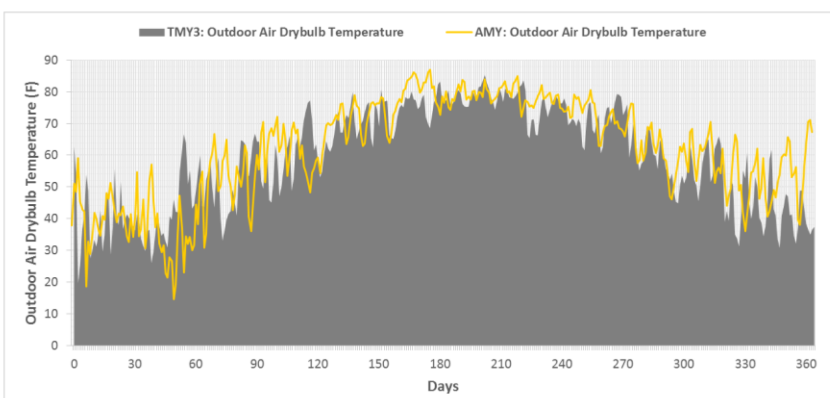
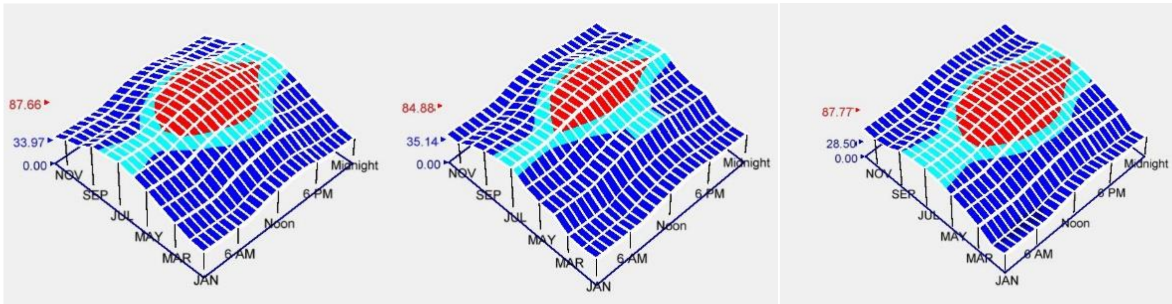
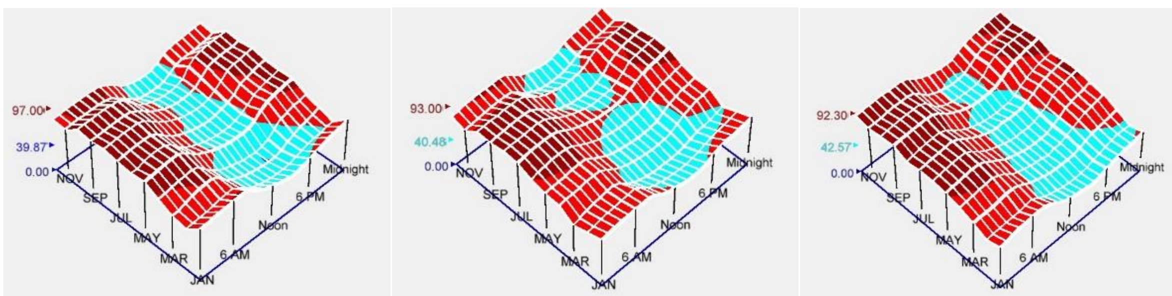


Figure 4-21: AMY-2015 and TMY Weather Data Discrepancies



(a) (b) (c)

Figure 4-22:(a) TMY, (b) 2014 Weather File, (c) 2015 Weather File Dry Bulb Temperature



(a) (b) (c)

Figure 4-23: (a) TMY, (b) 2014 Weather File, (c) 2015 Weather File Relative Humidity

4.2.8 Calibrated Model Internal Loads

Internal loads include heat generated from occupants, lights, and electrical equipment (elevator and plug loads such as computers, printers, small beverage machines, etc.). Modeling the energy impacts of the building internal loads using the EnergyPlus simulation program requires assumptions about the building internal load intensity and operation schedules. For the occupancy loads, the load intensity refers to the peak occupancy for a typical day. For lighting and plug loads, these loads are represented by the peak power density.

4.2.8.1 People

According to EnergyPlus Input Output Reference, the people statement is applied to model the occupant's effect on the space conditions. The occupancy definition in EnergyPlus addresses the initial and basic affects as well as providing information that is applicable to report the thermal comfort of a group of occupants.

There are three methods for calculating the nominal number of occupants (people) in the Zone (DOE, 2015).

1.People: With this choice, the method used will be a straight insertion of the number of occupants (people).

2. People/Area: With this choice, the method used will be a factor per floor area of the zone (No. of occupants/ft^2 or m^2).

3.Area/Person: With this choice, the method used will be a factor of floor area per person.

There is lack of certainty in the internal loads due to people because of the adversity in foretelling the number of occupants in a building at any given time. In the absence of better data, the number of occupants can be estimated on the basis of one occupant per 11 ft^2 (1 m^2) in auditoriums, 27 ft^2 (2.5 m^2) in schools, 32-54 ft^2 (3–5 m^2) in retail stores, and 108-162 ft^2 (10–15 m^2) in offices according to ASHRAE 90.1 2004. In our calibrated model, step 1 and 2, people/area method and in step 3 and 4, area/people method is selected to calculate the occupancy peak in each zone. Table 4-7 shows the peak number of people in each zone in the case study building. The building occupancy profile is listed in a table for each calibration step in order to have a better comparison between each step.

4.2.8.2 Lights

According to EnergyPlus Input Output Reference, the lights statement enables you to identify data on a zone's electric lighting system, including design power level and operation schedule, and how the heat from lights is distributed thermally.

Table 4-8: Occupancy Peak for Each Zone Type in Case Study Building

Zone	People Density (Person/ft^2)	People Density (ft^2/person)
Break Room	0.05	54
Closed office	0.005	130
Open Office	0.005	130
Conference	0.05	130
IT-Room	0.005	130
Lobby	0.01	100
Corridor	0.001	100
Mechanical room	-	150
Stair	-	130
Rest Room	0.01	160
Storage	-	150

A zone may have multiple Lights statements. For example, one statement may describe the general lighting in the zone and another the task lighting. Or you can use multiple Lights statements for a zone that has two or more general lighting systems that differ in design level, schedule, etc. There are three methods for calculating the nominal lighting level in the Zone (DOE, 2015).

(1) Lighting Level: with this choice, the method used will be a straight insertion of the lighting level (Watts) for the Zone.

(2) Watts/Area: with this choice, the method used will be a factor per floor area of the zone. (The Watts per Zone Floor Area field should be filled).

(3) Watts/Person: with this choice, the method used will be a factor of lighting level (watts) per person.

The information gathered from the case study building shows the average Lighting Power Density (LPD) of 0.75 W/ft^2 (8.07 W/m^2) to be used in the calibrated model. Also, the lighting fixture schedule in the electrical drawings is a good source to find out about each room’s lighting types, voltage, and Watt. Another important parameter is the lighting profile (lighting schedule) which is associated with the occupancy sensors at case study building. The lighting schedule identifies the times during the day that each space type uses the peak/specific percentage of lighting power density. This parameter is manipulated in several iteration to achieve the most accurate lighting schedule for different months in a course of 2015 which are listed in a table for each calibration step.

4.2.8.3 Equipment

Miscellaneous electric equipment is a main energy end use sector. In office buildings, plug loads can account for about 25% of total onsite energy consumption (EIA, 2003). The above percentage may go higher as the building becomes more energy efficient. The information gathered from the case study building shows the average Equipment Power Density (EPD) of 1 W/ft^2 (10.76 W/m^2) to be used in the calibrated model. Also, the power plan and panel schedule from the electrical drawings is a good source to find out about each room's plugs. The equipment profile (equipment schedule) identifies the times during the day that each space type uses the peak/specific percentage of equipment power density. This parameter is manipulated in several iteration to achieve the most accurate equipment schedule for different months in a course of 2015. One of the spaces, Freezer Farm, need more precise evaluation in terms of equipment power density and schedule since it has several freezers for special purposes.

4.2.9 Calibration Steps

This study takes advantages of manual iterative calibration method which is based on user experience and adjustment of inputs on a trial-error basis and graphical and statistical calibration method which is based on specific graphical and comparative displays of the results to orient the calibration process. In order to better follow the model calibration's different steps, every step's major parameters changes are shown in a table separately. The results for each step also are illustrated in one graph for every performance metric (Lighting electricity, equipment electricity, mechanical electricity, chilled water and hot water energy consumption) to better visualize the changes.

4.2.9.1 Calibration Process: Step 1

Table 4-9: Step 1 Adjustments

No.	Adjustments
1	AMY weather file is implemented into EnergyPlus model to run the simulation.
2	LPD=0.75 W/ft^2 (8.07 W/m^2), EPD=1 W/ft^2 (10.76 W/m^2). The lighting and equipment schedules are remained the same.
3	ERU heating coils schedules are fixed to be ON during Jan, Feb, March, Oct, Nov, Dec From 6AM-7PM and OFF during May, Jun, Jul, Aug, and Sep.

Table 4-10: Step 1 Lighting/Equipment/Occupancy Schedule

Step 1	Lighting Schedule		Equipment Schedule		Occupancy Schedule	
	Weekdays	Weekends/ Holidays	Weekdays	Weekends/ Holidays	Weekdays	Weekends/ Holidays
1	0.05	0.05	0.2	0.1	0	0
2	0.05	0.05	0.2	0.1	0	0
3	0.05	0.05	0.2	0.1	0	0
4	0.05	0.05	0.2	0.1	0	0
5	0.05	0.05	0.2	0.1	0	0
6	0.1	0.05	0.2	0.1	0	0
7	0.1	0.1	0.2	0.1	0.1	0
8	0.3	0.1	0.2	0.1	0.2	0
9	0.9	0.5	0.5	0.2	0.85	0
10	0.9	0.5	0.5	0.2	0.85	0
11	0.9	0.5	0.5	0.2	0.85	0
12	0.9	0.5	0.5	0.2	0.85	0
13	0.9	0.5	0.4	0.2	0.5	0

Table 4-11: Continued

Step 1	Lighting Schedule		Equipment Schedule		Occupancy Schedule	
	Weekdays	Weekends/ Holidays	Weekdays	Weekends/ Holidays	Weekdays	Weekends/ Holidays
14	0.9	0.5	0.5	0.2	0.85	0
15	0.9	0.05	0.5	0.1	0.85	0
16	0.9	0.05	0.5	0.1	0.85	0
17	0.9	0.05	0.5	0.1	0.85	0
18	0.7	0.05	0.4	0.05	0.7	0
19	0.3	0.05	0.2	0.05	0.05	0
20	0.3	0.05	0.2	0.05	0.05	0
21	0.1	0.05	0.1	0.05	0.05	0
22	0.1	0.05	0.1	0.05	0.05	0
23	0.1	0.05	0.1	0.05	0.05	0
24	0.05	0.05	0.1	0.05	0.05	0
Total	10.5	4	7.2	2.65	8.6	0

4.2.9.2 Calibration Process: Step 2

Table 4-12: Step 2 Adjustments

No.	Adjustments
1	Lighting and equipment schedules are changed for Jan-Feb, March-Nov, and Dec.
2	Hot water temperature is changed from 180 F to 200 F (82.2 C to 93.3 C).
3	Supply air temperature is changed from 65F to 55F (18.3 C to 12.7 C).
4	Heat exchanger nominal supply air flow rate is changed from autosize to 2,500 cfm (ft3/min) (1.18 m^3/s).
5	Coil:Heating:Water maximum water flow rate is changed from 10 gal/min (6.3 $*10^{-4}$ m^3/s) to 3.5 gal/min (2.2 $*10^{-4}$ m^3/s)
6	Economizer is added to the model (type: differential dry bulb, $T_{OA} > T_{RA}$ ➔ Outside Air=min)
7	HW plant loop availability is changed to “always ON”.

Table 4-13: Continued

No.	Adjustments
8	ERU's exhaust fan is added to the model.
9	ERU's rotary wheel electric power is increased based on the as-built drawings.
10	Occupancy schedule level is decreased.

Table 4-14: Step 2 Lighting/Equipment/Occupancy Schedule

Step 2	Lighting Schedule			Equipment Schedule			Occupancy Schedule	
	Jan, Feb, Dec	Mar-Nov		Jan, Feb, Dec	Mar-Nov			
	Weekdays/ weekends/ Holiday	Week days	Weekends/ Holiday	Weekdays/ weekends/ Holiday	Week days	Weekends/ Holiday	Week days	Weekend s/Holiday
1	0.04	0.04	0.04	0.06	0.03	0.06	0	0
2	0.04	0.04	0.04	0.06	0.03	0.06	0	0
3	0.04	0.04	0.04	0.06	0.03	0.06	0	0
4	0.04	0.04	0.04	0.06	0.03	0.06	0	0
5	0.04	0.04	0.04	0.06	0.03	0.06	0	0
6	0.04	0.1	0.04	0.06	0.03	0.06	0	0
7	0.04	0.1	0.04	0.06	0.03	0.06	0.1	0
8	0.04	0.1	0.04	0.06	0.03	0.06	0.2	0
9	0.1	0.2	0.1	0.15	0.15	0.15	0.5	0
10	0.1	0.2	0.1	0.15	0.15	0.15	0.5	0
11	0.1	0.2	0.1	0.15	0.15	0.15	0.5	0
12	0.1	0.2	0.1	0.15	0.15	0.15	0.5	0
13	0.1	0.2	0.1	0.15	0.1	0.15	0.3	0
14	0.1	0.2	0.1	0.15	0.15	0.15	0.5	0
15	0.04	0.2	0.04	0.15	0.15	0.15	0.5	0
16	0.04	0.2	0.04	0.15	0.15	0.15	0.5	0
17	0.04	0.2	0.04	0.15	0.15	0.15	0.5	0
18	0.04	0.2	0.04	0.06	0.1	0.06	0.3	0
19	0.04	0.04	0.04	0.06	0.1	0.06	0.05	0
20	0.04	0.04	0.04	0.06	0.1	0.06	0.05	0
21	0.04	0.04	0.04	0.06	0.06	0.06	0.05	0

Table 4-15: Continued

Step 2	Lighting Schedule			Equipment Schedule			Occupancy Schedule	
	Jan, Feb, Dec	Mar-Nov		Jan, Feb, Dec	Mar-Nov			
	Weekdays/ weekends/ Holiday	Week days	Weekends/ Holiday	Weekdays/ weekends/ Holiday	Week days	Weekends/ Holiday	Week days	Weekend s/Holiday
22	0.04	0.04	0.04	0.06	0.06	0.06	0.05	0
23	0.04	0.04	0.04	0.06	0.06	0.06	0.05	0
24	0.04	0.04	0.04	0.06	0.06	0.06	0.05	0
Total	1.32	2.74	1.32	2.25	2.08	2.25	5.2	0

4.2.9.3 Calibration Process: Step 3

Table 4-16: Step 3 Adjustments

No.	Adjustments
1	Corridor zones are added to the open office area.
2	Split system’s heating coil is set to OFF, since the split systems are cooling only.
3	Cooling set point is changed from 69F (20.5 C) to 72F (22.2 C). The set back is 65F (18.3 C) during winter.
4	Heating set point is changed from 75F (23.8 C) to 72F (22.2 C). The set back is 80F (26.6 C) during summer.
5	LAN room’s set point is changed to 77F (25 C) (no set back).
6	FreezerFarm room’s set point is changed to 72F (22.2 C) (no set back).
7	FreezerFarm EPD is increased to 2.5 W/ft^2 (29.9 W/m^2).
8	Economizer (Fixed dry bulb) parameters is modified based on the as-built drawings.
9	The ERU’s rotary wheel electric use is modified based on the mechanical drawings.
10	Interior window shading is added to the model.

Table 4-17: Step 3 Lighting/Equipment Schedule

Step 3	Lighting Schedule				Equipment Schedule			
	Jan, Feb, Dec		Mar-Nov		Jan, Feb, Dec		Mar-Nov	
	weekends /Holiday	Week days	Week days	Weekends/ Holiday	weekends /Holiday	Week days	Week days	Weekends/ Holiday
1	0.03	0.1	0.05	0.03	0.06	0.08	0.07	0.06
2	0.03	0.1	0.05	0.03	0.06	0.08	0.07	0.06
3	0.03	0.1	0.05	0.03	0.06	0.08	0.07	0.06
4	0.03	0.1	0.05	0.03	0.06	0.08	0.07	0.06
5	0.03	0.1	0.05	0.03	0.06	0.08	0.07	0.06
6	0.03	0.1	0.1	0.03	0.06	0.08	0.07	0.06
7	0.03	0.1	0.46	0.03	0.06	0.08	0.07	0.06
8	0.03	0.1	0.46	0.03	0.06	0.08	0.17	0.06
9	0.03	0.4	0.36	0.03	0.06	0.15	0.17	0.06
10	0.03	0.4	0.36	0.03	0.06	0.15	0.17	0.06
11	0.03	0.4	0.36	0.03	0.06	0.15	0.17	0.06
12	0.03	0.4	0.36	0.03	0.06	0.15	0.17	0.06
13	0.03	0.4	0.36	0.03	0.06	0.15	0.15	0.06
14	0.03	0.4	0.36	0.03	0.06	0.15	0.17	0.06
15	0.03	0.4	0.36	0.03	0.06	0.15	0.17	0.06
16	0.03	0.4	0.36	0.03	0.06	0.15	0.17	0.06
17	0.03	0.4	0.36	0.03	0.06	0.15	0.17	0.06
18	0.03	0.1	0.46	0.03	0.06	0.15	0.15	0.06
19	0.03	0.1	0.46	0.03	0.06	0.03	0.05	0.06
20	0.03	0.1	0.04	0.03	0.06	0.03	0.05	0.06
21	0.03	0.1	0.04	0.03	0.06	0.03	0.05	0.06
22	0.03	0.1	0.04	0.03	0.06	0.03	0.05	0.06
23	0.03	0.1	0.04	0.03	0.06	0.03	0.05	0.06
24	0.03	0.1	0.04	0.03	0.06	0.03	0.05	0.06
Total	0.72	5.1	5.63	0.72	1.44	2.32	2.62	1.44

Table 4-18: Step 3 Occupancy Schedule

Step 3	Occupancy Schedule			
	Jan-Mar, Oct-Dec		Apr-Sep	
	Weekdays	Weekends/ Holiday	Weekdays	Weekends/ Holiday
1	0	0.05	0	0.05
2	0	0.05	0	0.05
3	0	0.05	0	0.05
4	0	0.05	0	0.05
5	0	0.05	0	0.05
6	0	0.05	0	0.05
7	0.9	0.05	0.1	0.05
8	0.9	0.05	0.1	0.05
9	0.9	0.05	0.2	0.05
10	0.9	0.05	0.2	0.05
11	0.9	0.05	0.2	0.05
12	0.9	0.05	0.2	0.05
13	0.9	0.05	0.1	0.05
14	0.9	0.05	0.2	0.05
15	0.9	0.05	0.2	0.05
16	0.9	0.05	0.2	0.05
17	0.9	0.05	0.2	0.05
18	0.9	0.05	0.2	0.05
19	0.9	0.05	0.2	0.05
20	0.9	0.05	0.2	0.05
21	0.9	0.05	0.2	0.05
22	0.9	0.05	0.2	0.05
23	0	0.05	0.05	0.05
24	0	0.05	0.05	0.05
Total	14.4	1.2	3	1.2

4.2.9.4 Calibration Process: Step 4

Table 4-19: Step 4 Adjustments

No.	Adjustments
1	Split systems are changed to "ductless split systems cooling only" with no outdoor air based on mechanical drawings.
2	A unit heater is added to the north stairs zone.
5	LAN room's set point is changed to 75F (23.8 C) (no set back).
6	FreezerFarm room's EPD and schedule are modified based on electrical drawings, EPD = 4 W/ft^2 (43 W/m^2).
7	Fan's efficiency is modified. Fan's static pressure is modified based on the as-built drawings. (AHU, ERU, FCU, Split system fans)
8	The occupancy and infiltration schedules are fixed.
9	Cooling coil schedule is adjusted based on building's operation hours.

Table 4-20: Step 4 Occupancy Schedule

Step 4	Occupancy Schedule						Misc. Occupancy Schedule	
	Jan-Apr, Sep		May-Aug		Oct-Dec		Mar-Nov	
	weekends /Holiday	Week days	Weekend s/Holiday	Week days	weekends /Holiday	Week days	weekends /Holiday	Week days
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0.5	0	0.2	0	0.9	0	0
8	0	0.5	0	0.4	0	0.9	0	0
9	0.1	0.5	0.1	0.7	0.2	0.9	0.1	0.2
10	0.1	0.5	0.1	0.7	0.2	0.9	0.1	0.2
11	0.1	0.5	0.1	0.7	0.2	0.9	0.1	0.2
12	0.1	0.5	0.1	0.7	0.2	0.9	0.1	0.2

Table 4-21: Continued

Step 4	Occupancy Schedule						Misc. Occupancy Schedule	
	Jan-Apr, Sep		May-Aug		Oct-Dec		Mar-Nov	
	weekends /Holiday	Week days	Weekend s/Holiday	Week days	weekends /Holiday	Week days	weekends /Holiday	Week days
13	0.1	0.5	0.1	0.6	0.2	0.8	0.1	0.2
14	0.1	0.5	0.1	0.7	0.2	0.9	0.1	0.2
15	0.1	0.5	0.1	0.7	0.2	0.9	0.1	0.2
16	0.1	0.5	0.1	0.7	0.2	0.9	0.1	0.2
17	0.1	0.5	0.1	0.7	0.2	0.9	0.17	0.2
18	0	0.5	0	0.2	0	0.9	0.15	0
19	0	0.5	0	0.2	0	0.9	0.05	0
20	0	0.5	0	0	0	0.9	0.05	0
21	0	0.5	0	0	0	0.9	0.05	0
22	0	0.5	0	0	0	0.9	0.05	0
23	0	0	0	0	0	0	0.05	0
24	0	0	0	0	0	0	0.05	0
Total	0.9	8	0.9	7.2	1.8	14.3	1.42	1.8

4.2.10 Calibration Steps Graphs

The case study building has several meters installed in order to measure the lighting, equipment, and mechanical electricity, and to monitor the chilled and hot water consumption and energy use. These meters are set to trend monthly data which is started from 2014 to generally assess the building operation by building managers. The historical monthly meters data and utility bills for 2015 are used for the case study building model calibration process. In each calibration step, the EnergyPlus model results are compared with the measured data for 2015 and the NMBE and CV(RMSE) are calculated for each performance metric in order to evaluate the improvement in the calibration process. Figure 4-24 through 4-28 illustrate each calibration step results related to each performance metric (lighting, equipment, whole building electricity, chilled water, and hot water energy use) and the statistics indices (NMBE and CV(RMSE)). The calibration acceptance criteria for each calibration step are MBE< 5% and CVRMSE< 15% for monthly data calibration. The final step (calibrated model) is displayed in red in all of the graphs.

Hot water (200 F (93.3 C)) is only used for ERU heating coil in order to preheat the outdoor air before mixing with return air and entering the VAV boxes. Although the HW energy use pattern in calibrated model step four follows the measured data pattern but still it is very challenging to bring the NMBE and CV(RMSE) into the range.

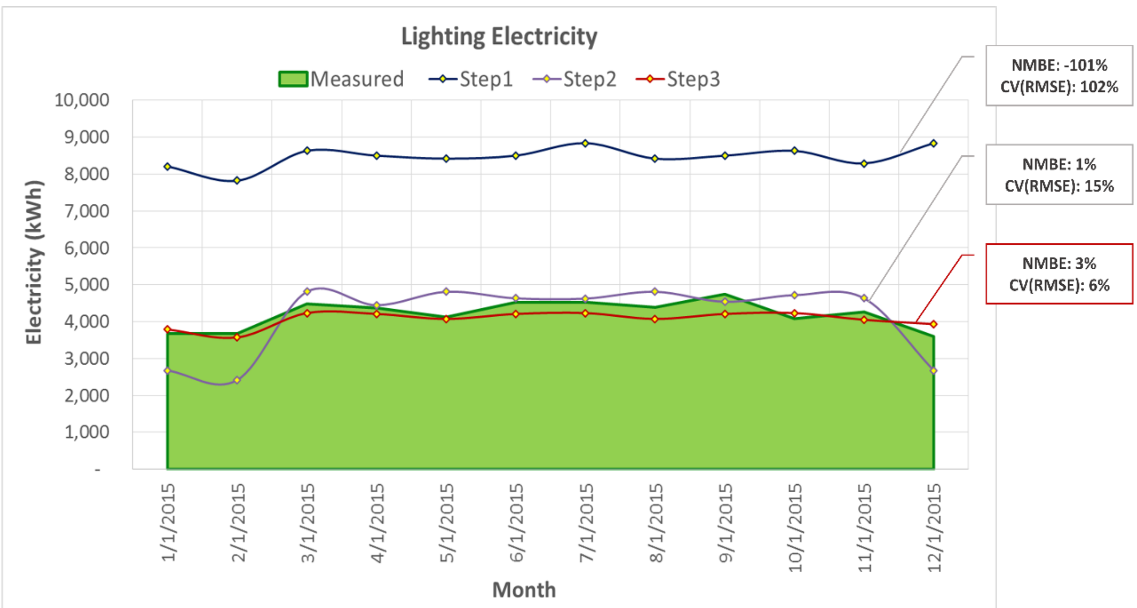


Figure 4-24: Model Calibration Steps: Lighting Electricity

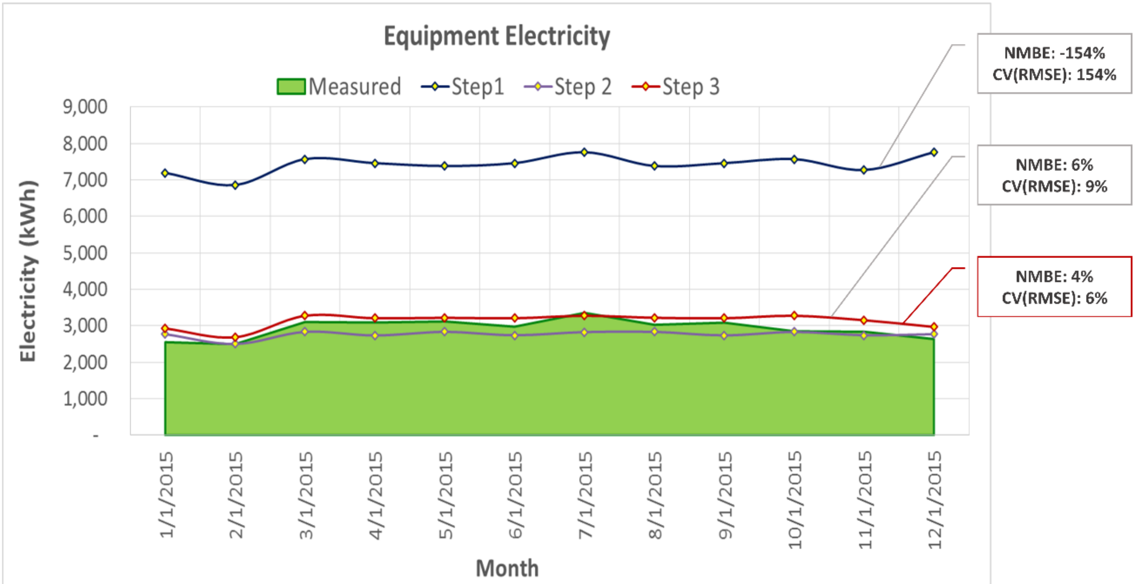


Figure 4-25: Model Calibration Steps: Equipment Electricity

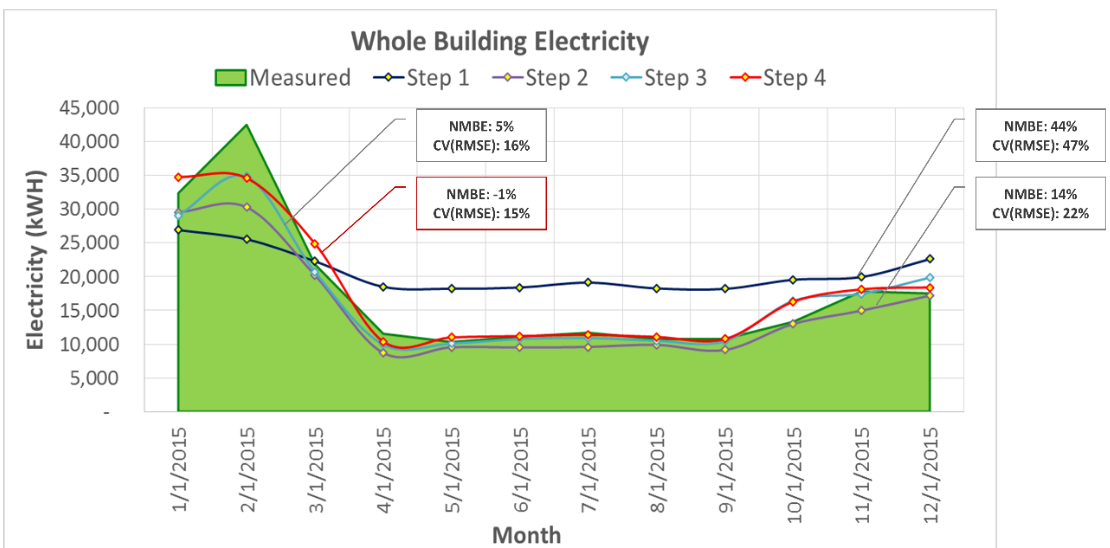


Figure 4-26: Model Calibration Steps: Whole Building Electricity

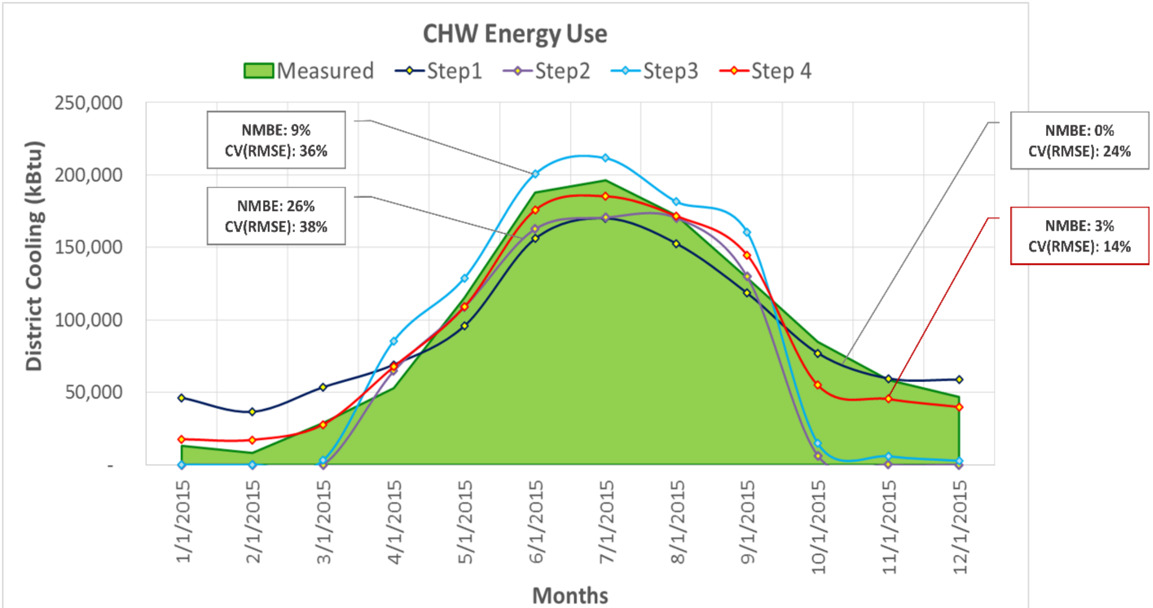


Figure 4-27: Model Calibration Steps: Chilled Water Energy Use

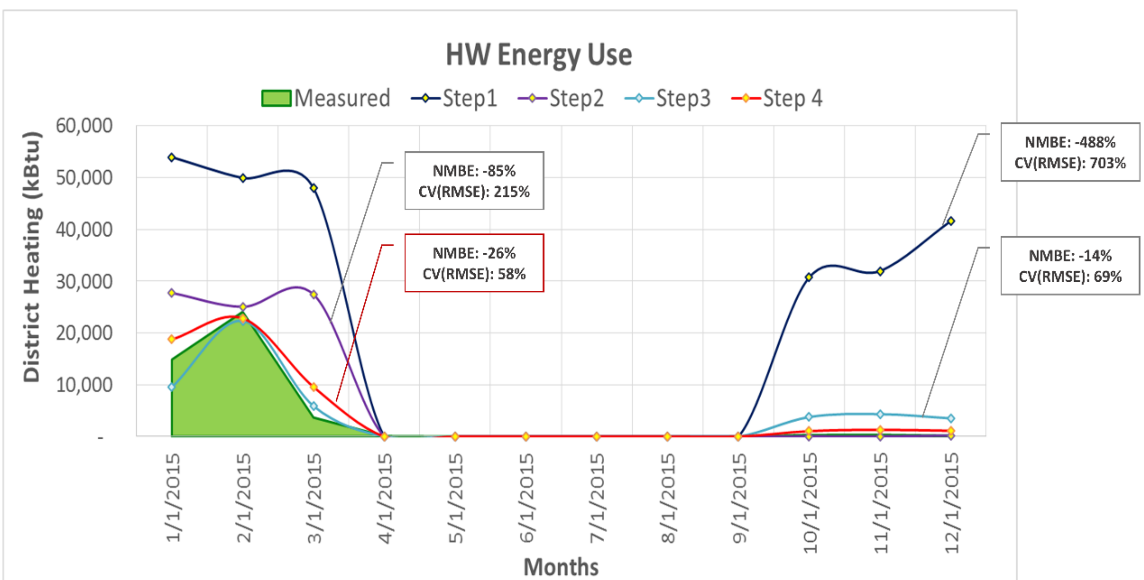


Figure 4-28: Model Calibration Steps: Hot Water Energy Use

4.3 Case Study Building Code-Compliant Model Development

Chapter 11 of ASHRAE 90.1-2004 deals with the Energy Cost Budget (ECB) method which is a critical requirements of LEED-NC. The ECB method is a comparative modeling system in which two models of the same building are created and compared. The first model is the Proposed Building Design (PBD) which is "*a computer demonstration of the actual proposed building design or portion thereof used as the basis for calculating the design energy cost*" (the annual energy cost for the proposed design) (ASHRAE, 2004b). The second model is the Budget Building Design (BBD). According to ASHRAE 90.1-2004, "*the Budget Building Design is a computer representation of a hypothetical design based on the actual proposed building design and is used as the basis for calculating the Energy Cost Budget*". In the other words, this model is presenting the real building characteristics but uses ASHRAE 90.1-2004 minimum requirements to calculate the annual energy cost for the budget building design to determine minimum compliance with the ASHRAE 90.1-2004 (ASHRAE, 2004b).

ASHRAE 90.1-2004 has specific requirements for the comparative models in terms of items that must be similar and identical, such as the occupancy schedule, conditioned areas, temperature set points, building orientation, and minimum outdoor air ventilation rate.

This section explains the process of developing the code-compliant model based on the ECB method. This approach forms a benchmark to better evaluate the performance of the calibrated model, the code-compliant model, and the real building. In this study, the calibrated model developed in the previous section is considered as the proposed building design, since it is consistent with the design documents, including proper accounting of fenestration and opaque envelope types and area; interior lighting power and controls; HVAC system types, sizes, and controls; and service water heating systems and controls. The budget building design (the code-compliant model) is developed by modifying the proposed design as described in Table 11.3.1, Chapter 11, ASHRAE 90.1-2004. It is important to mention that the required schedules have to be identical for the proposed design and budget building design

4.3.1 Code-Compliant Model Envelope Characteristics

According to ASHREA 90.1-2004 Table 11.3.1, the code-compliant model (building budget design) should have the same conditioned floor area and exterior dimensions and orientation as proposed building design, except opaque assemblies and fenestration U-factor, and roof albedo, which should comply with minimum requirements of ASHRAE 90.1-2004. Also, no shading projection are to be modeled. Table 4-17 lists the code-compliant model opaque construction objects with their outside to inside layers and the U-factor for each object. The last two rows in the Table 4-17 list the simulation U-factor and ASHRAE 90.1-2004 minimum U-factor for each opaque component. Comparing these two rows shows that budget building design complies with the ASHRAE 90.1-2004 minimum requirements for the building envelopes. All roof surfaces should also be modeled with the reflectivity of 0.3.

Table 4-18 lists the ASHRAE90.1-2004 exterior windows minimum requirements for code-compliant model versus proposed building design.

Table 4-22: ASHRAE 90.1-2004 Opaque Components Minimum Requirements

Climate Zone 4a-ASHRAE90.1-2004	**Exterior Roof**	**Exterior Wall Mass**	**Exterior Shaft Wall-South**	**Exterior Slab on Grade**	**Exterior Door**	**Interior Floor**
Outside layer	60 mil TPO single ply membrane	4 in (100mm) Heavy weigh Concrete	¾ in (19mm) gypsum board	Vapor seal - plastic film	Metal surface	Acoustic tile
Layer 2	IEAD Roof Insulation (R-15)	1 in (25mm) insulation board (R-5)	Wall air space resistance	MAT- 4 in Heavy weight Concrete	-	1 in (25mm) insulation board (R-5)
Layer 3	4 in (100mm) Heavy weight concrete	4 in (100mm) Heavy weigh Concrete	¾ in (19mm) gypsum board	Carpet Pad	-	200mm lightweight concrete
Layer 4	-	5/8 in (16mm) Drywall (gypsum board)	-	-	-	
Simulation U-Factor (Btu/hr.ft^2.F)	0.059	0.147		0.516	1.177	0.104
Code U-Factor (Btu/hr.ft^2.F)	0.063	0.151		**F-Factor (Btu/hr.ft.F):** 0.703	1.450	0.107

Table 4-23: ASHRAE 90.1-2004 Exterior Windows Minimum Requirements for Code-Compliant Model vs. Proposed Building Design

Climate Zone 4a	Exterior windows (ASHRAE90.1-2004)	Exterior windows (proposed building design)
U-Factor **(Btu/hr.ft^2.F)**	0.57	0.29
SHGC	0.39	0.31
VT	0.6	0.6

4.3.2 Code-Compliant Model Requirements for ECB

Lighting, equipment, and occupancy are also mentioned in ASHRAE 90.1-2004. People and equipment loads should be estimated based on the building type and need to be identical in the proposed building design and budget building design (code-compliant model). However, the lighting and the HVAC systems have to be modified to reflect the code minimum component efficiencies.

4.3.2.1 Lights

The code-compliant lighting system is assumed to be a system that just meets the maximum lighting power density allowed using the space by space method of ASHRAE Standard 90.1- 2004 as shown in Table 4-19. Also the lighting controls should be the minimum required.

Table 4-24: Lighting Power Densities Using the Building Area Method

90.1-2004 Space Type (LPD) Allowance - Partial List		
Building Type	Space Type description	Watts/sqft
Common Space Type	Corridor/Transition	0.5
Common Space Type	Classroom/Lecture/Training	1.4
Common Space Type	Electrical/Mechanical	1.4
Common Space Type	Dining Area	0.9
Common Space Type	Food Preparation	1.2
Common Space Type	Lounge/Recreation	1.2
Common Space Type	Stairs - Inactive	0.4
Common Space Type	Stairway	0.6
Common Space Type	Restrooms	0.9
Common Space Type	Lobby	1.3
Common Space Type	Atrium - first three floors	0.6
Common Space Type	Atrium - each additional floor	0.2
Common Space Type	Office - enclosed	1.1
Common Space Type	Office - open plan	1.1
Common Space Type	Conference Meeting/Multipurpose	1.3
Common Space Type	Inactive storage	0.3
Common Space Type	Active storage	0.8

4.3.2.2 HVAC System

The HVAC zones and thermal blocks need to be identical in the proposed building design and budget building design (code-compliant model). However, the HVAC types and related performance parameters for the code-compliant model need to be determined from the HVAC system map and HVAC system description and notes in ASHRAE 90.1-2004 chapter 11 (Table 11.3.2A Budget System Description), while proposed building design reflects the actual HVAC system type using actual system capacities and efficiencies. Budget building design system description does not include an energy recovery unit for the code-compliant model. Therefore, the ERU components are excluded from the code-compliant model. The proposed building design also uses purchased chilled water with no chiller modeled for the simulation. However, in budget building design (code-compliant model), the chiller plant has to be modeled by selecting the number of chillers and water chiller types from table 11.3.2B and 11.3.2C in ASHRAE 90.1-2004. Each chiller needs to be modeled with separate condenser water and chilled water pumps interlocked to operate with the associated chiller. Table 4-20 lists other required HVAC adjustments based on the energy cost budget method.

Table 4-25: HVAC Adjustments for ECB

Adjustments based on ECB	
VAV w/ reheat minimum volume set point per floor area	0.4 cfm/ft^2
Chilled water supply temperature	44 F (6.66 C)
Chilled water return temperature	56 F (13.33 C)
Pump System	Variable speed
Condenser water pump power	19 W/gpm
Economizer high-limit shutoff	Fixed dry bulb T_{OA}>75F (23 C)

4.3.3 Code-Compliant and Calibrated Model Simulation Result vs. Measured Data

4.3.3.1 Energy Use Intensity (EUI)

The Energy Use Intensity (EUI) is expressed as energy per square foot per year. It is calculated by dividing the total energy consumed by the building in a year (measured in kBtu) by the total/or conditioned floor area of the building.

Table 4-21 lists the case study building's calibrated model, code-compliant model, and real building total energy use (EUI) after running the simulation in EnergyPlus. The code-compliant model inputs are based on the ASHRAE 90.1-2004. Source energy represents the total amount of raw fuel that is required to operate the building. It incorporates all transmission, delivery, and production losses. Site energy, represents the amount of heat and electricity consumed by a building as reflected in the utility bills. Figure 4-29 visualizes the calibrated model, code-compliant model, and real building energy consumption breakdown as they are listed in Table 4-22. The calibrated model and the real building measured data include lighting, equipment, HVAC (fan, heat recovery, reheat coils heating, split systems cooling electricity consumption), and district heating/cooling energy use. But in the code-compliant model, the district heating and cooling energy consumption is zero due to ECB method requirements and HVAC electricity (cooling electricity) is increased due to the chiller modeling.

Table 4-26: Case Study Building Calibrated Model, Code-Compliant Model, and Real Building EUI

Site and Source Energy		**Total Energy** [kBtu]	**Energy Per Total Building Area** [kBtu/ft^2-yr]	**Energy Per Conditioned Building Area** [kBtu/ft^2-yr]
Calibrated Model	Total Site Energy	1,839,378	40.79	42.53
	Total Source Energy	3,616,715	80.21	83.63
Real Building Measured Data				
	Total Site Energy	1,836,575	40.73	42.83
	Total Source Energy	3,507,857	77.79	81.80
Code-Compliant Model				
	Total Site Energy	2,440,546	54.12	56.43
	Total Source Energy	7,729,211	171.41	178.72

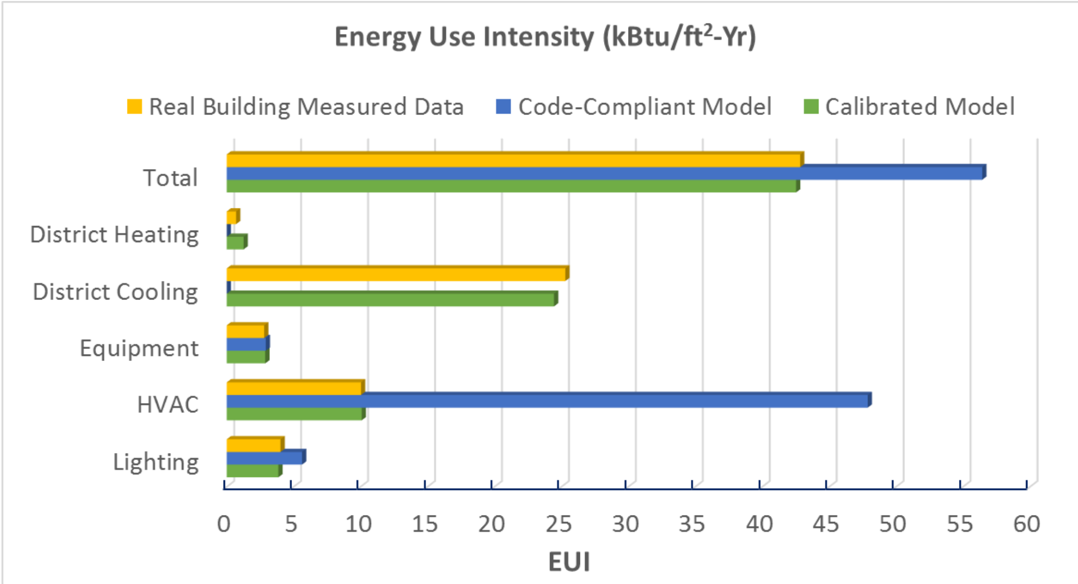


Figure 4-29: EUI Break Down for Calibrated Model, Code-Compliant Model, and Real Building

Table 4-27: Case Study Building Calibrated Model, Code-Compliant Model, and Real Building EUI Break Down

End Use	**Calibrated Model [kBtu/ft^2-yr]**	**Code-Compliant Model [kBtu/ft^2-yr]**	**Real Building Measured Data [kBtu/ft^2-yr]**
Lighting	3.86	5.63	4.02
HVAC	10.08	47.88	10.03
Equipment	2.88	2.92	2.80
District Cooling	24.45	0.00	25.29
District Heating	1.26	0.00	0.70
Total	42.52	56.43	42.82

The case study building energy consumption (according to 2015 utility bills) shows 24 percent less energy use than code-compliant model which is based on ASHRAE 90.1-2004.

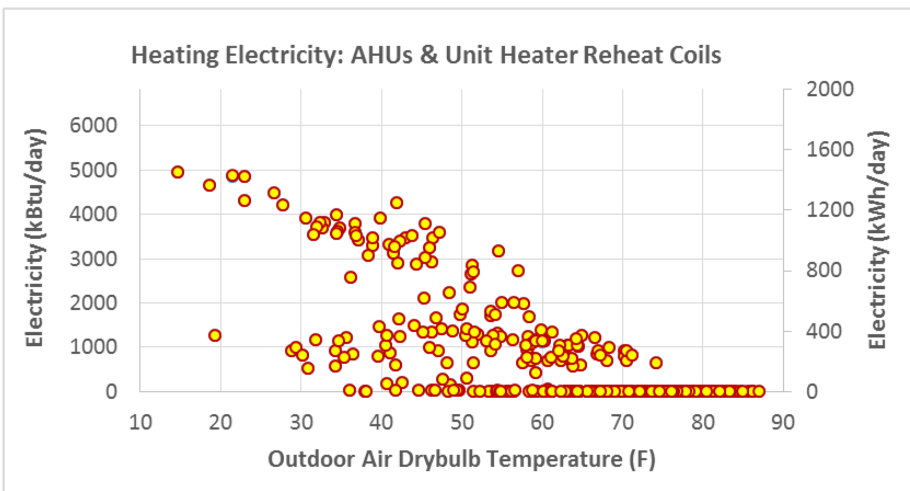
4.3.3.2 Whole Building Energy Use

The Whole Building Electricity (WBE) in the code-compliant model consists of lighting, equipment, HVAC, and plant electricity. In the code-compliant model the plant electricity includes the pumps electricity and chiller electricity, while in the calibrated model, district heating and cooling are used instead of real chiller and boiler. Thus, in the calibrated model, the plant electricity just includes the pump electricity.

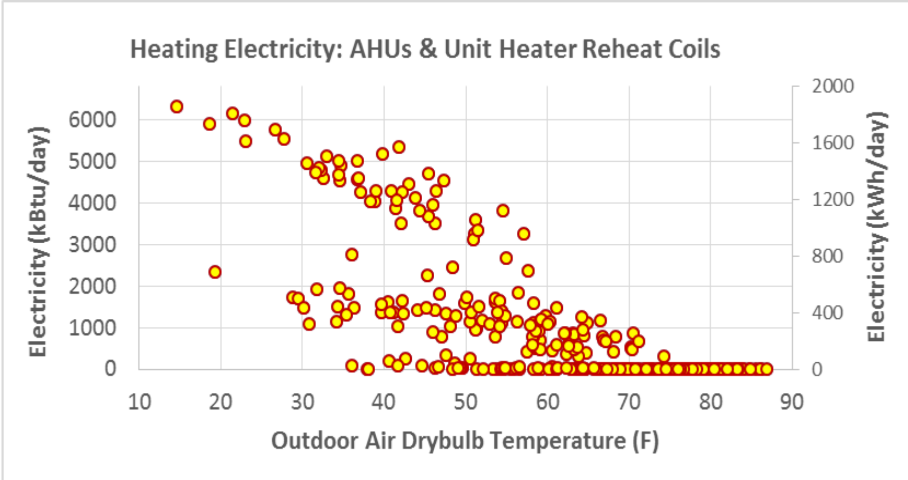
The HVAC electricity includes AHUs, ERUs, split systems, fan coil, and unit heater fan electricity, AHUs reheat coil electricity, ERUs wheels electricity, and split system's cooling electricity.

- WBE = lights electric + equipment electric + HVAC electric + plant electric
- Plant Electric = pump electric + (and chiller, condenser, and cooling tower electric in code-compliant model)
- HVAC Electric: fan Electric + cooling/heating electric (split systems+ AHU reheat unit, unit heater) + heat recovery electric
- Total Energy = WBE + (and district heating + district cooling in calibrated model)

Figure 4-30 show the daily heating electricity in the calibrated and code-compliant models. Heating electricity consists of AHUs reheat coils and north stairs unit heater electricity. The cooling electricity in the code-compliant model (as shown in Figure4-31) and the calibrated model (as shown in Figure4-32) are not the same. In the calibrated model, the cooling electricity specifically is used for the LAN room in each floor which needs cooling whole year because they are located in the center of floor plan and surrounded by open offices and conference rooms. The split systems provide cooling only and does not include any heater. In the code-compliant model, the cooling electricity includes the split systems cooling electricity and chiller electricity which make it significantly higher than the calibrated model.



(a)



(b)

Figure 4-30: Scatter Plot for Heating Electricity (a) Calibrated Model, (b) Code-Compliant Model

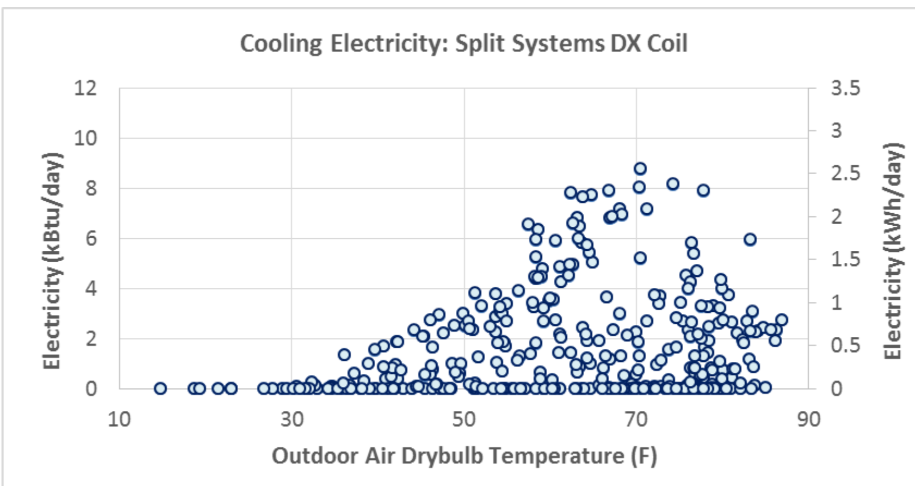


Figure 4-31: Scatter Plot for Cooling Electricity in Calibrated Model

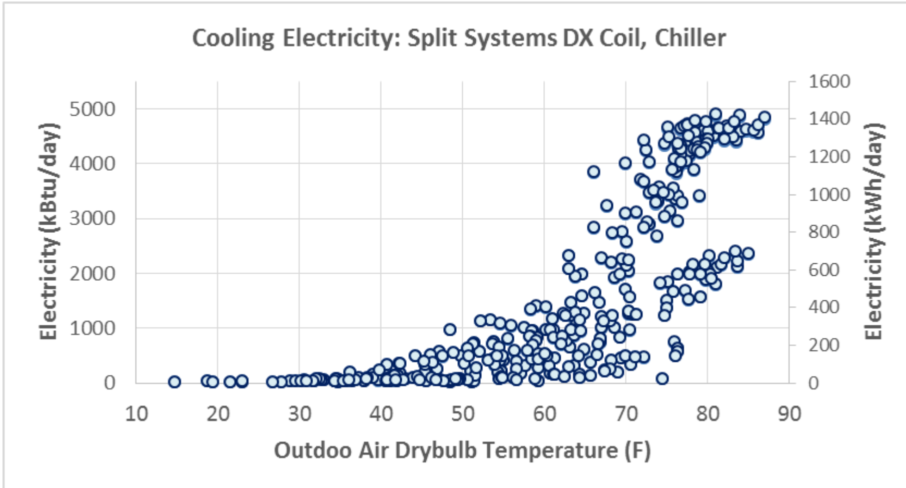
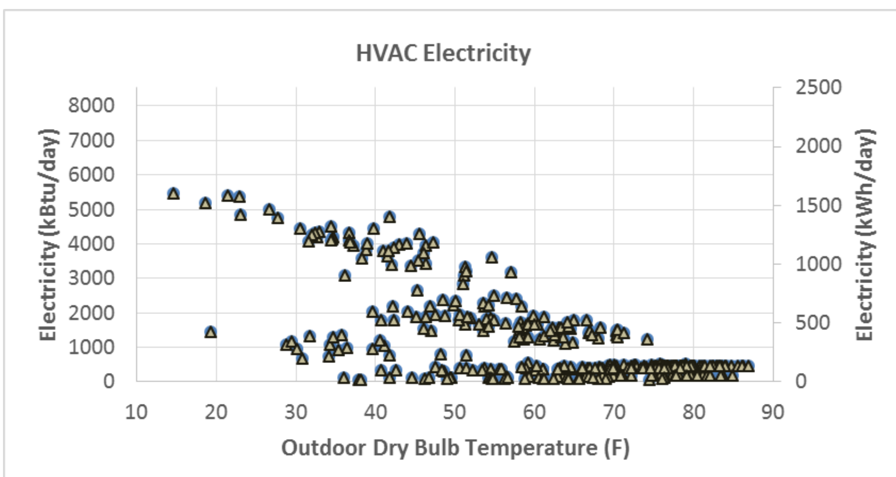
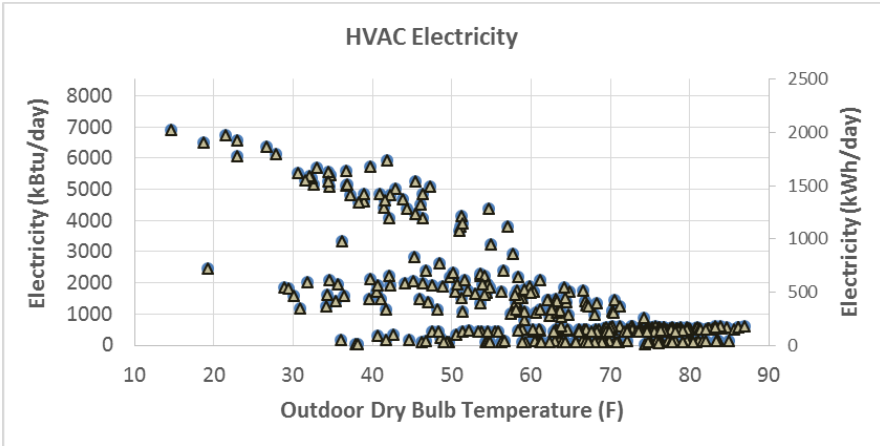


Figure 4-32: Scatter Plot for Cooling Electricity in Code-Compliant Model

Figure 4-33 shows the HVAC electricity in the calibrated and code-compliant models which includes fan, heat recovery, heating, and cooling electricity (only split systems cooling electricity) in the models.



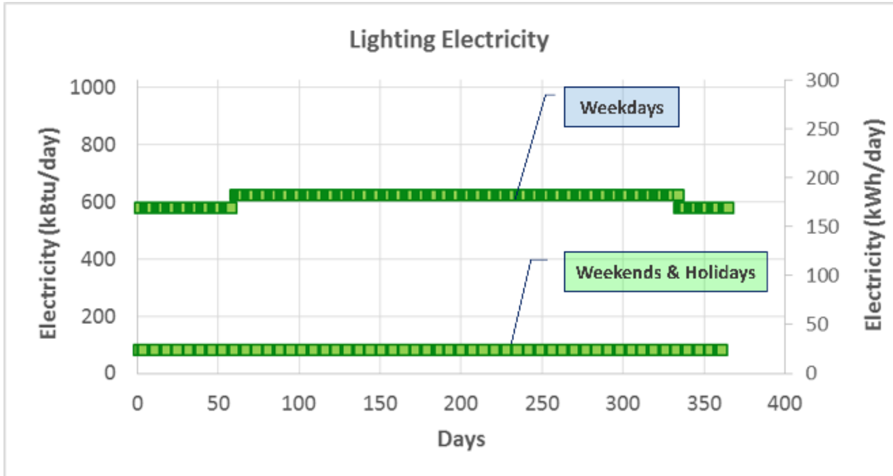
(a)



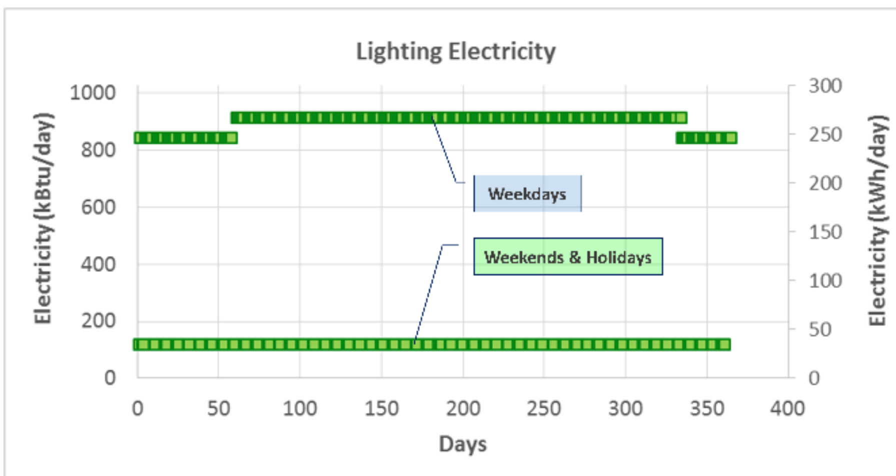
(b)

Figure 4-33: Scatter Plot for HVAC Electricity (a) Calibrated Model, (b) Code-Compliant Model

Figure 4-34 and 4-35 illustrate the lighting and equipment electricity respectively for calibrated and code-compliant model. According to energy cost budget method in ASHRAE 90.1-2004, equipment loads have to be modeled and estimated based on the building type or space type category and shall be assumed to be identical in the calibrated and code-compliant model. But the lighting power in the code-compliant model needs to be set equal to the maximum allowed for the corresponding method (space-by-space method).



(a)



(b)

Figure 4-34: Time-Series Plot for Lighting Electricity (a) Calibrated Model, (b) Code-Compliant Model

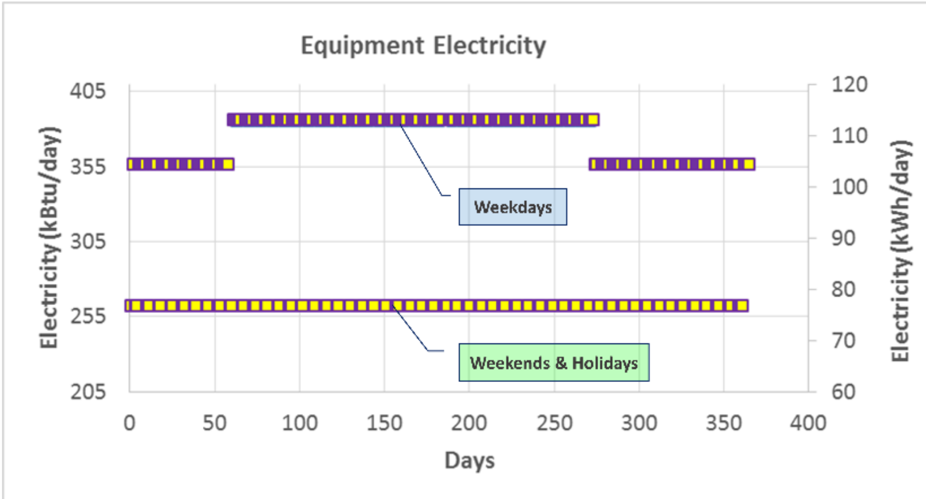
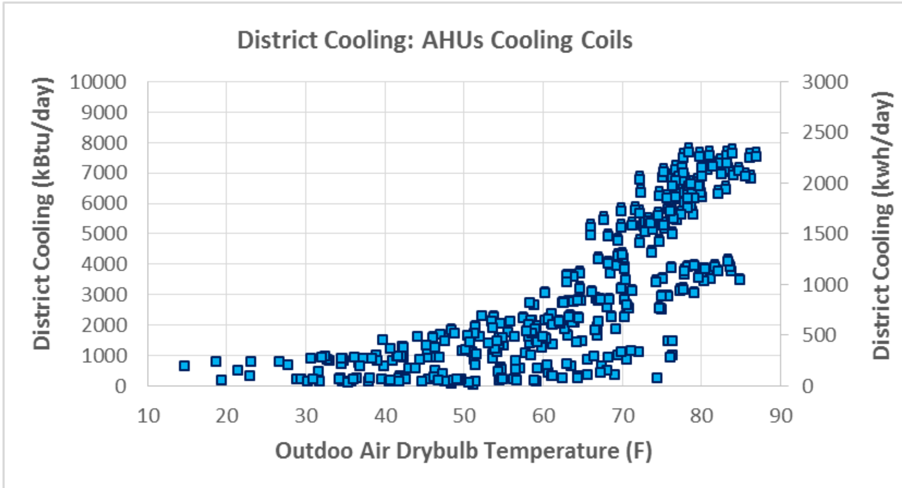
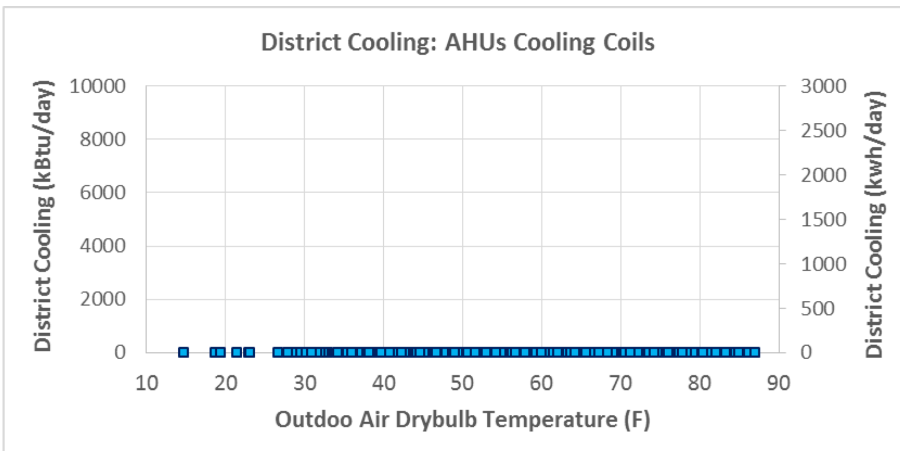


Figure 4-35: Time-Series Plot for Equipment Electricity in the Calibrated, and Code-Compliant Models

Figure 4-36 and 4-37 illustrate the district cooling and heating energy use respectively for the calibrated and code-compliant model based on the occupancy, lighting, equipment and HVAC systems schedules. The code-compliant model has no district cooling and no district heating compared to the calibrated model. This is because the ERU (heating coil) and the district cooling object are eliminated from the code-compliant model.

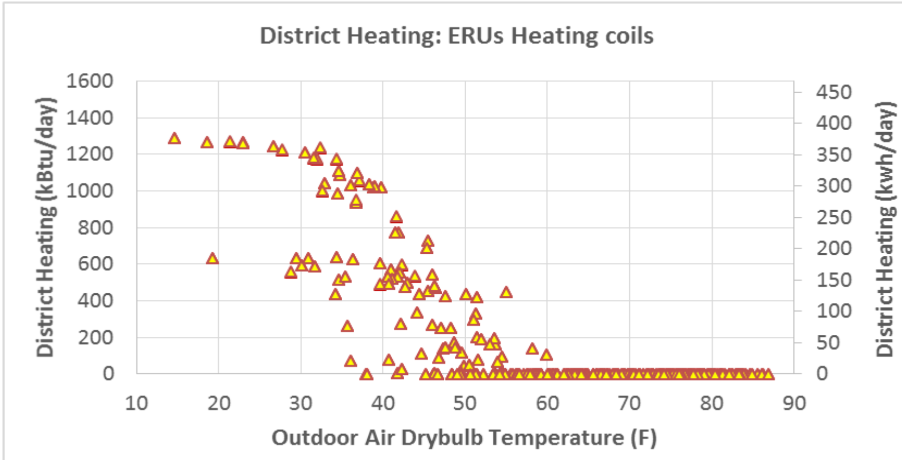


(a)

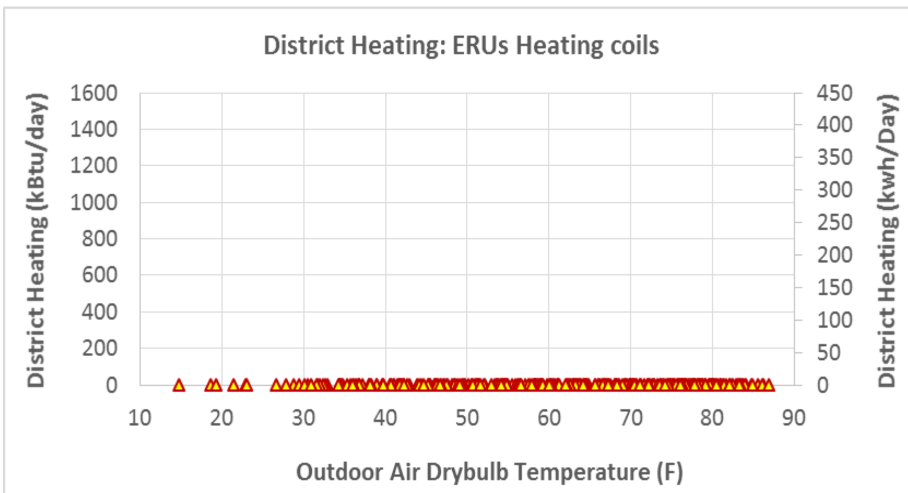


(b)

Figure 4-36: Scatter Plot for District Cooling (a) Calibrated Model, (b) Code-Compliant Model Energy Use



(a)



(b)

Figure 4-37: Scatter Plot for District Heating (a) Calibrated Model, (b) Code-Compliant Model Energy Use

Figure 4-38 shows the amount of electricity used for the chilled and hot water pumps (plant electricity) in the calibrated model. As it is shown in Figure 4-39, the plant electricity in the code-compliant model is much higher than the calibrated model. That is because the plant electricity in the code-compliant model includes the pumps electricity, chiller electricity, and the cooling tower fan electricity.

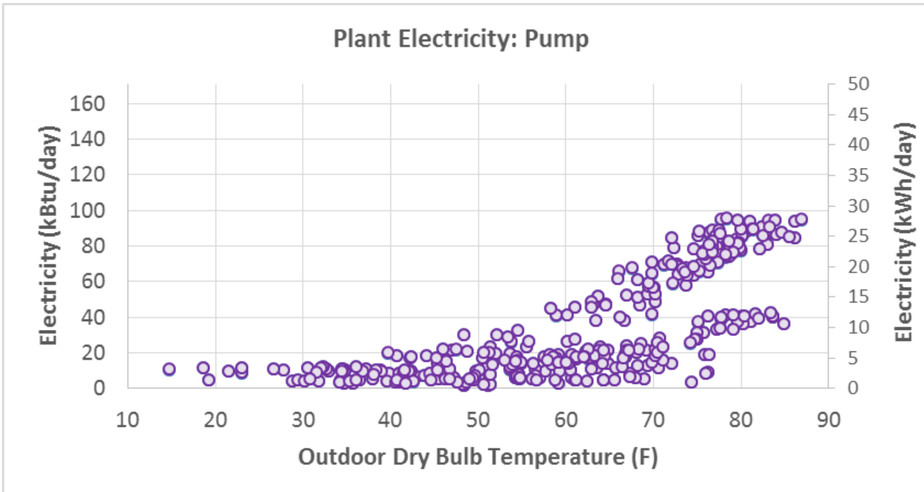


Figure 4-38: Scatter Plot for Plant Electricity in Calibrated Model

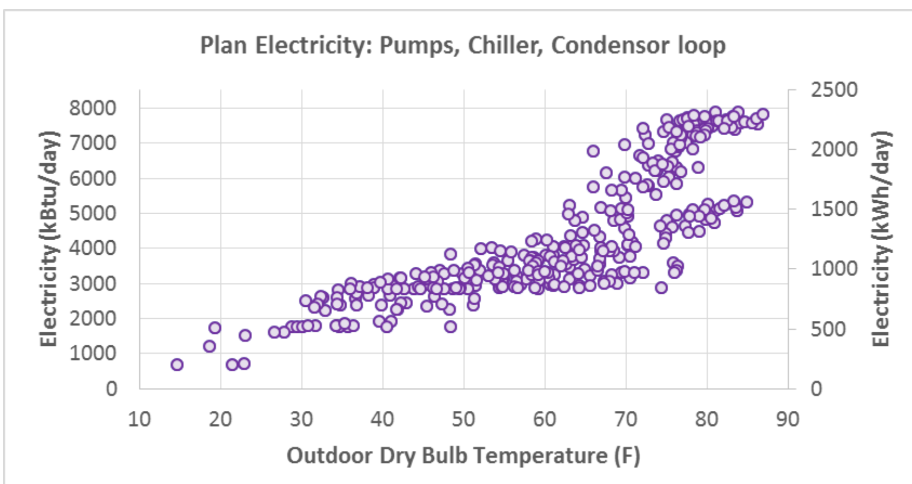


Figure 4-39: Scatter Plot for Plant Electricity in Code-Compliant Model

4.4 Summary

In this chapter, the case study building primary model is developed based on the as-built drawings and mechanical and electrical documents. The calibrated model is also created precisely based on the historical monthly measured data and utility bills from 2015. According to Table 4-22, the calibrated model represents the real case study building characteristics with the difference of less than one percent. Now, the calibrated model is ready to be implemented into the real-time Cx and PM&V framework for the performance analysis and fault detection of the case study building. The detailed process is explained in chapter five.

CHAPTER 5 PLATFORM OF REAL-TIME COMMISSIONING AND PERFORMANCE MEASUREMENT & VERIFICATION

The proposed framework aims to detect the faults (mostly the ones that do not need human intervention to get fixed) by comparing the real building performance with the ideal performance produced from the calibrated building model. Implementing the corrective actions and consequently fixing the detected faults are assumed as EEMs or ECMs added to the building based on the decision of building manager. The corrective actions (or EEMs/ECMs) are a comprehensive set of activities regarding the zones and systems set point checking and controlling or adjusting the building's systems operation schedules. Also in some cases, some of the equipment need an extra visit to check their operation status regarding the detected fault. This framework consists of several sub-systems and auxiliary tools to facilitate co-simulation and integration of models along with fault detection algorithm and corrective actions recommendations. This chapter describes sub-systems in the framework in detail.

5.1 Real-Time Data Acquisition

As mentioned before in chapter three, to transfer real time data from BAS to EnergyPlus and then run the calibrated model in each time-step, we need a platform or middleware to stand between EnergyPlus and BAS and manage the data transfer. In this approach, BCVTB is used to allow real-time data to pass from the BAS sensors into the simulated environment (calibrated EnergyPlus model) and be analyzed against satisfactory design scenarios. BCVTB links BAS with other clients (i.e. EnergyPlus model) and allows users to access each device's information through BACnet actors. BACnet is an open protocol, which means anyone can contribute to the standard, and anyone may use it. The BACnet protocol is a standard way to send and receive messages on the wire containing data that is understood by other BACnet compliant devices. In BACnet, every device looks like an object. BACnet also makes the internal functions of devices, visible to the network. Networks allow computers to exchange data. There are several network types, such as ARCNET, MS/TP (Master-Slave/Token-Passing), PTP (Point to point protocol), LonTalk, ZigBee, and UDP/IP. A user has to identify what kind of BACnet device he uses. For example: BACnet/IP, BACnet MS/TP, or BACnet/Ethernet.

The case study building is supported with the Schneider Electric BAS. The automation server (StruxureWare™ for buildings) is a native BACnet/IP protocol controller with a built-in web server. The automation server also serves as a BACnet protocol router and BACnet/IP Broadcast Management Device (BBMD). It performs BACnet routing functions among attached MS/TP networks. Therefore, the user is able to create a BACnet interface for the automation Server and create the MS/TP network so that BACnet devices can be added for controlling the required data points. Each BACnet device is assigned with an Instance ID that can be introduced to BCVTB for the data transfer.

BACnet actors in BCVTB consist of BACnet Reader and BACnet Writer. BACnet Reader can read from BACnet devices, while BACnet Writer can write to BACnet devices.

Both of these actors use a configuration file (XML format) that specifies the BACnet devices, the object types and the property identifiers with which data are to be exchanged. The XML file would cause the BACnetReader to read the present value of the BACnet Analog Output object type with a specific instance number, which is part of a BACnet device object with particular instance number X (Nouidui, 2013). Figure 5-1 shows the architecture of linking the BACnet reader/writer actor (as client 2) with EnergyPlus simulator actor (as client 1) in the Ptolemy II interface. By clicking on each actor, the user is able to insert the xml configuration file paths for the BACnet reader/writer as shown in Figure 5-2, and the EnergyPlus idf. file and weather data epw. file for the EnergyPlus simulator actor. BCVTB (Ptolemy II) connects to the external interface in EnergyPlus. In the external interface, the input/output signals that are exchanged between Ptolemy II and EnergyPlus are mapped to EnergyPlus objects.

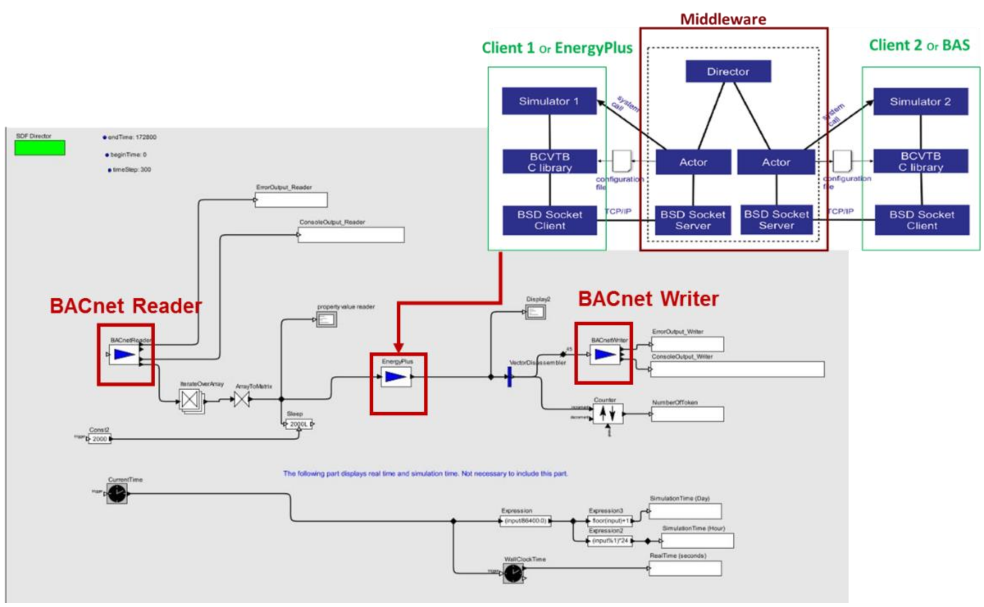


Figure 5-1: Linking BACnet Actor/Writer with EnergyPlus in BCVTB

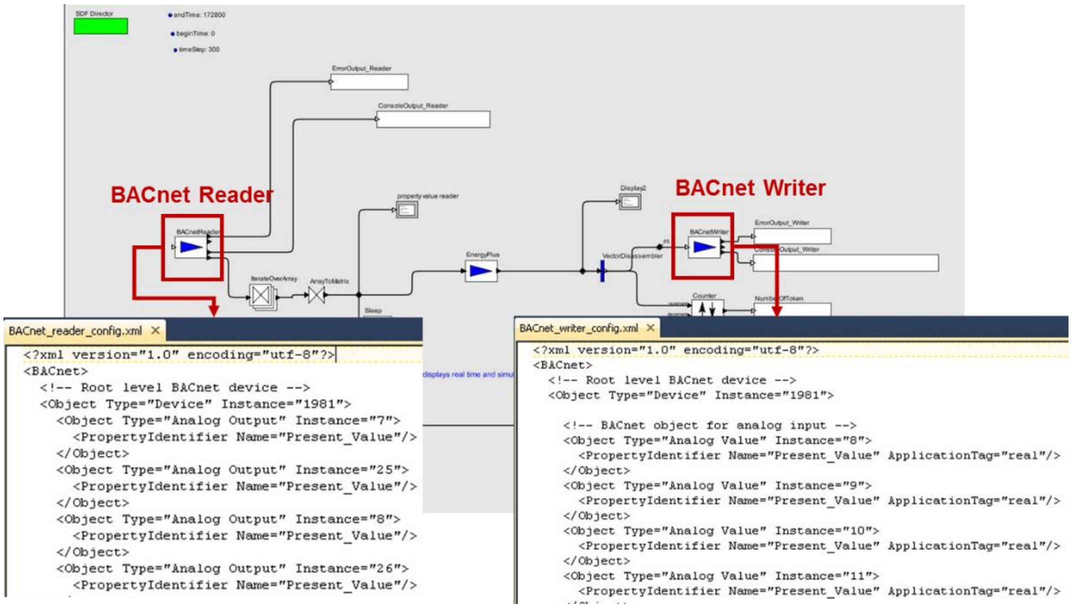


Figure 5-2: Adding Configuration Files for BACnet Reader/Writer

However, since the case study building is a government office building, after several meetings and briefing sessions about the project concept with the security and IT departments, they concern with the network security and the probability of opening up a security hole by installing a gateway on automation server. Based on their security protocol, they are required to perform a risk assessments and several people are required to sign off on that because this project significantly changes the security posture of the case study building's BAS. So, they suggested to move to a plan-B approach to off load the data from that Struxture ware server onto a safer, non-network connected environment.

To overcome this situation and not to jeopardize the main concept of project which is the real time feature of this framework, several options are evaluated and discussed with case study building's security people and experienced consultants. The practical plan-B approach is to imitate the real time situation by using a database software. In this approach, all the required BAS data points are trended in a given specified time intervals and saved into an SQL database format. The BAS database performs as a replacement for the BAS in this framework. The real-time data exchange from database to EnergyPlus through the database actors in BCVTB. The database actors in plan-B approach play the BACnet actor role in the main approach which was impractical in this building due to security issues.

5.1.1 DataBase Actors in BCVTB

Database actors in BCVTB consists of one database manager and four database actors with different SQL queries. According to Ptolemy II manual, database manager initiated a connection to a specific database on the computer in use. It is important to indicate that BCVTB needs the Java Database Connectivity (JDBC) driver to help the user to connect the java based program (BCVTB) to the database and manipulate data through BCVTB. A comprehensive technical guideline is provided in Appendix B.

The DataBaseQuery and SQLStatement actors execute any valid SQL statement with different output types (Figure 5-3). DataBaseQuery output is an array of records, one for each row in the returned result as shown in Figure 5-4 and SQLStatement output is a string description of the results as shown in Figure 5-5.

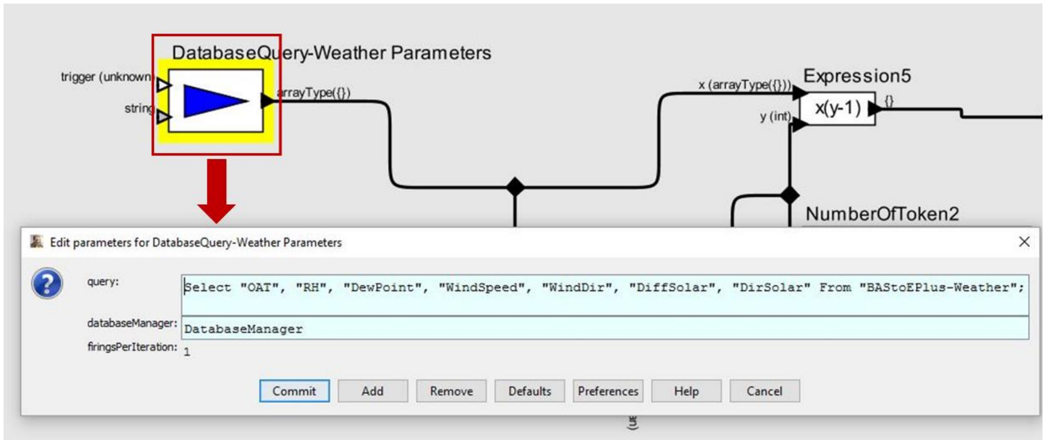


Figure 5-3: Edit Parameters for DataBase Query in BCVTB Interface- SQL Language

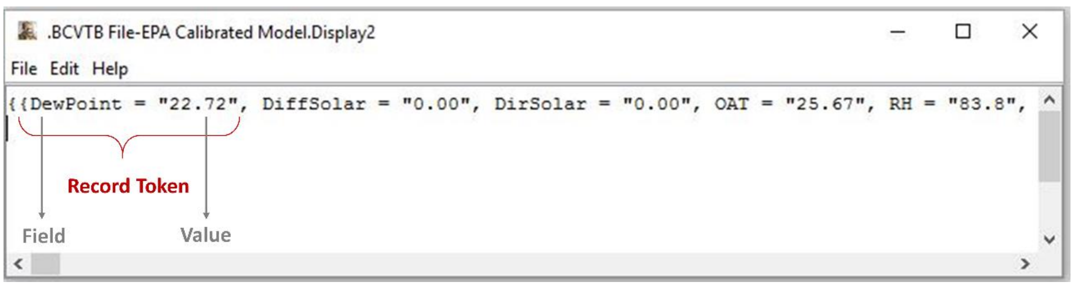


Figure 5-4: Array of Records Data Type Output from DataBAseQuery Actor in BCVTB.

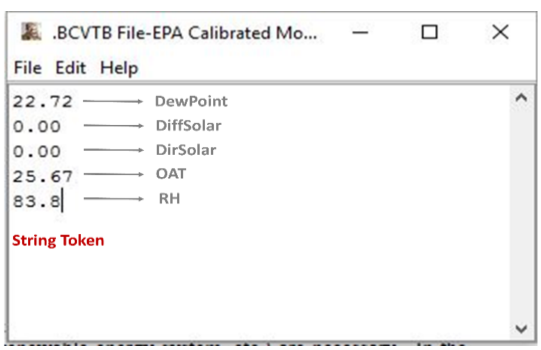


Figure 5-5: String Data Type Output from SQLStatement Actor in BCVTB.

The other two actors, DataBaseSelect and DataBaseInsert, are used for query the database and to insert records to database respectively. These actors operate in conjunction with an external database software to transfer data into BCVTB in each time step.

It is important to select a right database software to be linked with BCVTB. According to a study conducted by Li et al., among free database systems on the market, PostgreSQL has the higher performance in terms of transaction speed and functional support (Li & Augenbroe, 2011). In this study, PostgreSQL is used as the database software and it includes different tables containing required data points from case study building BAS to be transferred to BCVTB and EnergyPlus.

5.1.2 Simulator Actor in BCVTB

Simulator actor in BCVTB calls a simulation program of a dynamic system that is coupled to Ptolemy II. Simulator actor needs to be linked to the EnergyPlus idf file and weather file as shown in Figure 5-6. Ptolemy II connects to the external interface in EnergyPlus. In the external interface, the input/output signals that are exchanged between Ptolemy II and EnergyPlus are mapped to EnergyPlus objects. External Interface objects map to three EnergyPlus input objects called ExternalInterface:Schedule, ExternalInterface:Actuator and ExternalInterface:Variable. The ExternalInterface:Schedule can be used to overwrite schedules. The other two objects can be used in place of Energy Management System (EMS) actuators and EMS variables (Nouidui, 2013). The ExternalInterface:Actuator value is assigned by the external interface and is fixed during the zone time step because this is the synchronization time step.

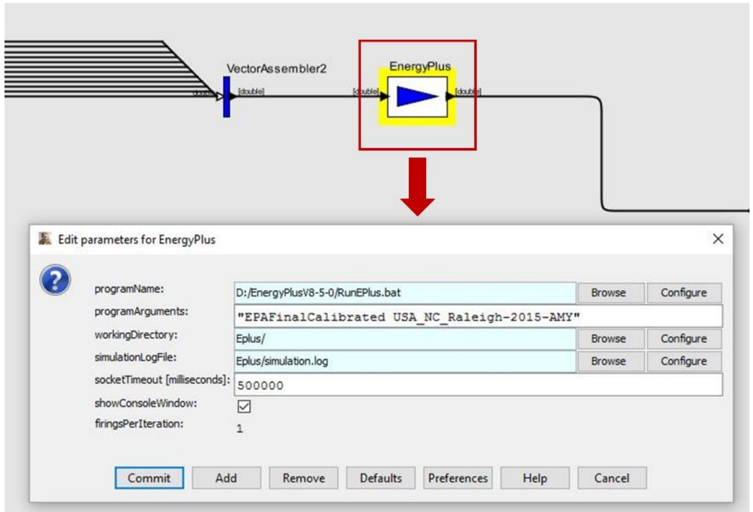


Figure 5-6: EnergyPlus Simulator Actor Parameters.

An xml file called variables.cfg includes all the elements in the signal vector that is exchanged between EnergyPlus and the BCVTB respectively as they are defined as input to and output from EnergyPlus.

5.2 BCVTB Platform

The case study building is equipped with several meters such as lighting electricity, receptacle electricity, mechanical electricity, and chilled water/hot water meters. Also the BAS enables the building manager to easily trend the required data points with preferred time interval. Per our request, the following data points and meters data were trended or their trending settings were changed to 15-minute intervals if they had already trended in the system. This configuration has started since July 2nd, 2016. These data points are used as an input to EnergyPlus calibrated model (independent variables) or for the building performance monitoring and fault detection purpose.

On-site weather station data:

- Outdoor air dry bulb temperature (C or F)
- Outdoor relative humidity (%)
- Outdoor dew point temperature (C or F)
- Wind speed
- Wind direction (degree)
- Global solar radiation (W/m^2 or $Btu/hr.ft^2$)

BAS data points:

- AHUs discharge air temperature (C or F)
- AHUs make up air flow rate (m^3/hr or CFM)
- AHUs outdoor air flow rate (m^3/hr or CFM)
- ERU outdoor air flow rate (m^3/hr or CFM)
- Chilled water flow rate (kg/s or gal/min)
- Chilled water supply temperature (C or F)
- Chilled water return temperature (C or F)

Electricity meters' data:

- Lighting electric (kWh or kBtu)
- Mechanical system (HVAC) electric (kWh or kBtu)

- Equipment electric (kWh or kBtu)

5.2.1 BCVTB Model Development

After developing the EnergyPlus calibrated model and database configuration, the BCVTB model is created to establish a preliminary interface for the framework. The BCVTB model consists of five main domains as mentioned below:

- BCVTB model director
- EnergyPlus calibrated model inputs (independent variables)
  - Weather data
  - Systems data
  - Plant data
- Building performance data (measured vs. simulated)
- Fault detection, possible whys and wherefores, recommended actions, and potential energy savings
- Real time and simulation time

These domains together build the BCVTB model and the framework interface as illustrated in Figure 5-7.

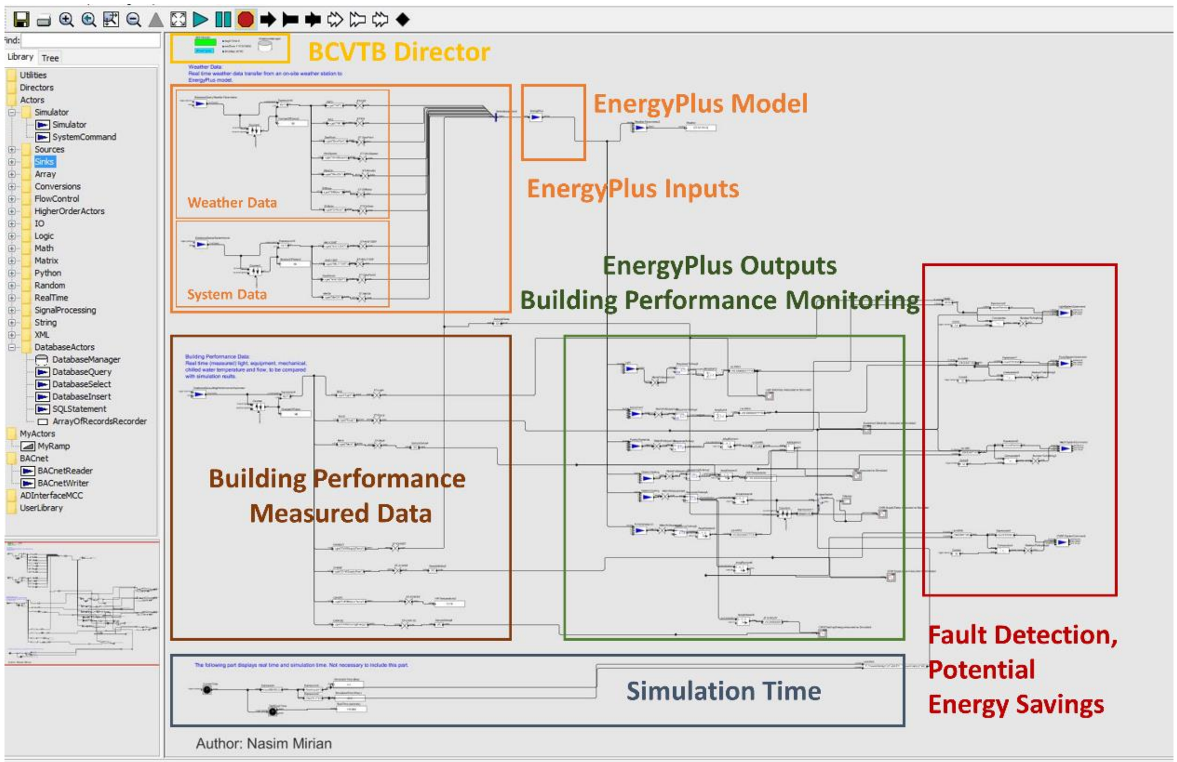


Figure 5-7: BCVTB Model Main Domains

5.2.1.1 BCVTB Model Director

According to Ptolemy ll tutorial, the user needs to specify the model of computation or domain in the design to define the “laws of physics” for the interaction between components. A director specifies the model of computation in the flow chart diagram and can be dragged into the model from the left box in Ptolemy ll interface as it is shown in Figure 5-8 (Ptolemaeus, 2011). For the BCVTB, Synchronous Dataflow director, or SDF director is used since when an actor is executed in SDF, it consumes a fixed amount of data from each input port, and produces a fixed amount of data to each output port (M Wetter, 2013). This director can be dragged into the model from the left pane shown in Figure 5-8.

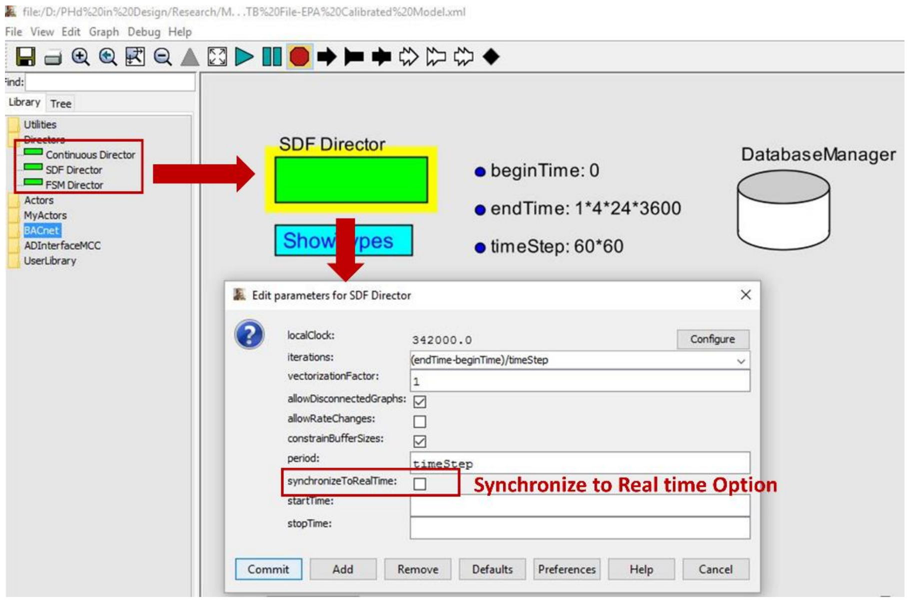


Figure 5-8: BCVTB Model SDF Director

The “synchronize to real time” option enables us to reduce the simulation speed to match with the real time intervals. For example, if the run period in EnergyPlus model is set for five days, July 2nd to 6th, 2016, after the warm up period BCVTB and EnergyPlus data exchange and simulation take four days instead of seven minutes. This feature is useful when the goal is to continuously monitor the building performance and detect the faults in the building (Automated continuous commissioning).

5.2.1.2 EnergyPlus Calibrated Model Inputs

The EnergyPlus calibrated model already includes all the building geometry, HVAC systems, operation hours and AMY weather data for 2015 (since the model has been calibrated based on the 2015 utility bills). However, since this model needs to be implemented into a real time framework during July and September 2016, a more accurate predicted building performance can be achieved if some parameters are inserted into EnergyPlus calibrated model from an external data source in real time for each time step (measured data from BAS and meters). These parameters vary during the time and it is challenging to build their pattern by EnergyPlus schedule objects.

EnergyPlus EDD output file lists the available actuators to do control operations. According to EDD file, seven weather parameters that can be overridden by an on-site weather station data are as follow:

- Environment, Weather Data, Outdoor Dry Bulb, [C or F]
- Environment, Weather Data, Outdoor Dew Point, [C or F]
- Environment, Weather Data, Outdoor Relative Humidity, [%]
- Environment, Weather Data, Diffuse Solar, [W/m^2 or $Btu/hr.ft^2$]
- Environment, Weather Data, Direct Solar, [W/m^2 or $Btu/hr.ft^2$]
- Environment, Weather Data, Wind Speed, [m/s]
- Environment, Weather Data, Wind Direction, [deg]

The case study building is equipped with a small on-site weather station which provides us with the above information. Wind directions are in sixteen compass points which were converted into degree before inserting into EnergyPlus calibrated model. Also, the on-site weather station only measures the global solar radiation, which is a measure of the intensity of the sun's radiation reaching a horizontal surface. This irradiance includes both the direct component from the sun and the reflected (or diffused) component from the rest of the sky.

The solar radiation reading gives a measure of the amount of solar radiation hitting the solar radiation sensor at any given time, expressed in watts per square meter (W/m^2). The global solar radiation was differentiated to direct solar radiation and diffuse solar radiation according to "TYPE 16"model, solar radiation processor, in the TRNSYS program (Perez, Stewart, Seals, & Guertin, 1988).

The systems variables including each AHU supply air temperature and outside air flow (CFM) and the plant variable including chilled water supply temperature were added to the EnergyPlus calibrated model input. The calibrated model's AHU supply air temperature was set to 55F, but by adding the AHU supply air temperature actuator to the calibrated model, the supply air temperature set point will fluctuate from 55F to 60F during summer (July and September).

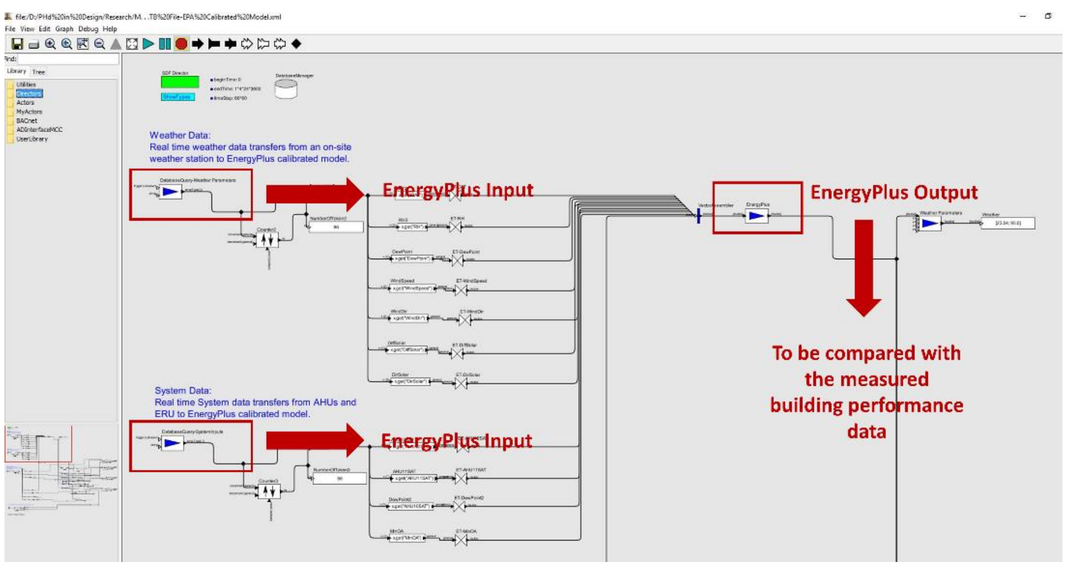
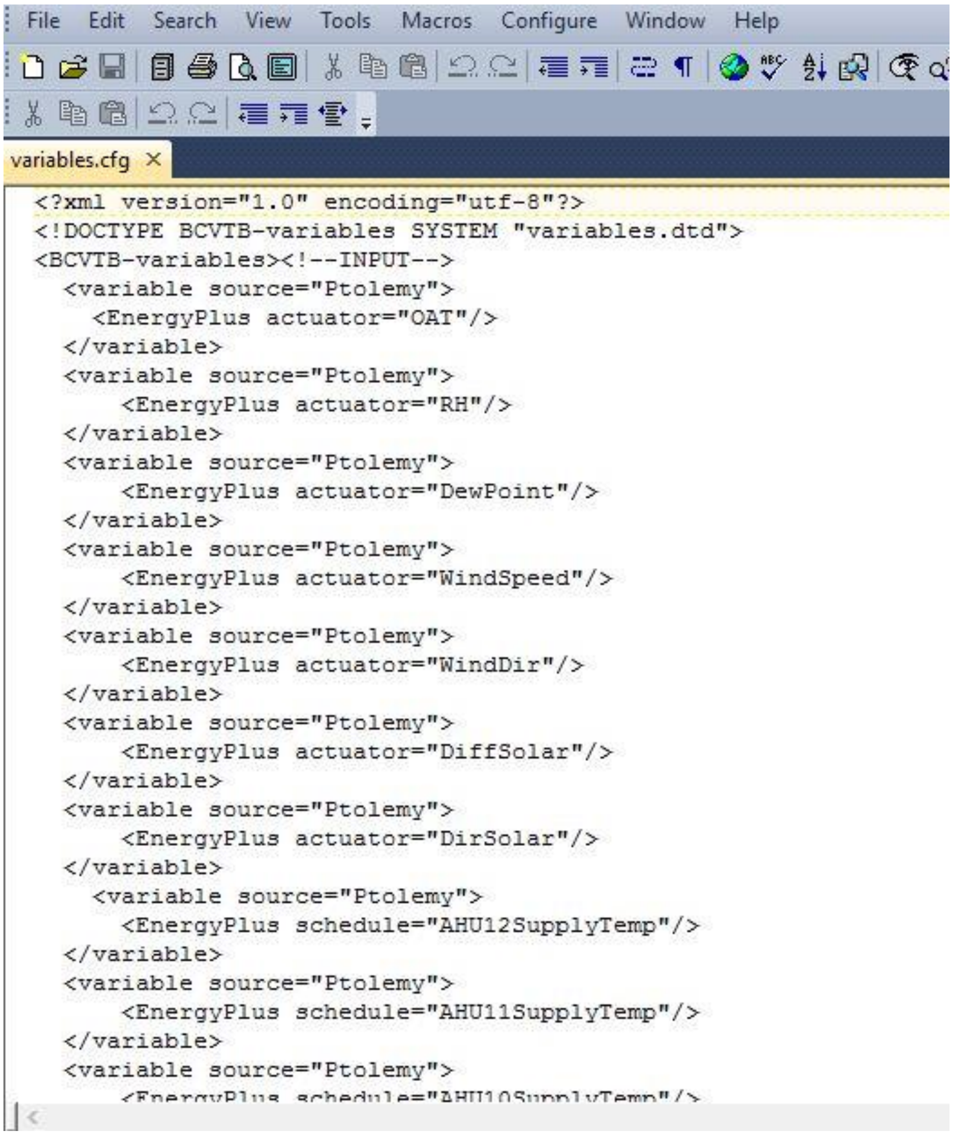


Figure 5-9: EnergyPlus Calibrated Model Input- BCVTB Interface

Figure 5-9 shows the BCVTB interface, transferring data from weather and system database to EnergyPlus calibrated model input. Figure 5-10 illustrates the variable.cfg file (input section) which is necessary for BCVTB to identify input and output variables to/from EnergyPlus.




```
<?xml version="1.0" encoding="utf-8"?>
<!DOCTYPE BCVTB-variables SYSTEM "variables.dtd">
<BCVTB-variables><!--INPUT-->
  <variable source="Ptolemy">
    <EnergyPlus actuator="OAT"/>
  </variable>
  <variable source="Ptolemy">
      <EnergyPlus actuator="RH"/>
  </variable>
  <variable source="Ptolemy">
      <EnergyPlus actuator="DewPoint"/>
  </variable>
  <variable source="Ptolemy">
      <EnergyPlus actuator="WindSpeed"/>
  </variable>
  <variable source="Ptolemy">
      <EnergyPlus actuator="WindDir"/>
  </variable>
  <variable source="Ptolemy">
      <EnergyPlus actuator="DiffSolar"/>
  </variable>
  <variable source="Ptolemy">
      <EnergyPlus actuator="DirSolar"/>
  </variable>
    <variable source="Ptolemy">
      <EnergyPlus schedule="AHU12SupplyTemp"/>
  </variable>
  <variable source="Ptolemy">
      <EnergyPlus schedule="AHU11SupplyTemp"/>
  </variable>
  <variable source="Ptolemy">
      <EnergyPlus schedule="AHU10SupplyTemp"/>
```

Figure 5-10: Variable.cfg File for EnergyPlus Inputs

5.2.1.3 Building Performance Data

Several installed meters at case study building enable us to monitor the sub-systems performance. All the meters data are gathered in a database table labeled as Building Performance Data with five columns: lighting electricity (kWh or kBtu), equipment electricity (kWh or kBtu), HVAC electricity (kWh or kBtu), chilled water supply flow (kg/s or gal/min), and chilled water cooling energy (kWh or kBtu). Through the database actor in BCVTB, these data are called in each time step to be compared with simulation data to monitor the building performance and detect the faults (Figure 5-11).

The case study building is equipped with chilled water supply, return temperature, and flow. Theses parameters can be used to calculate the cooling energy used for the building in summer. The equation is:

Q (kBtu/hr) = m (mass flow rate, gal/min) * C_p (water specific heat)* Delta T (F)

The chilled water cooling energy for the case study building was calculated based on the above information available and compared with the district chilled water energy output from EnergyPlus calibrated model simulation results in each time step.

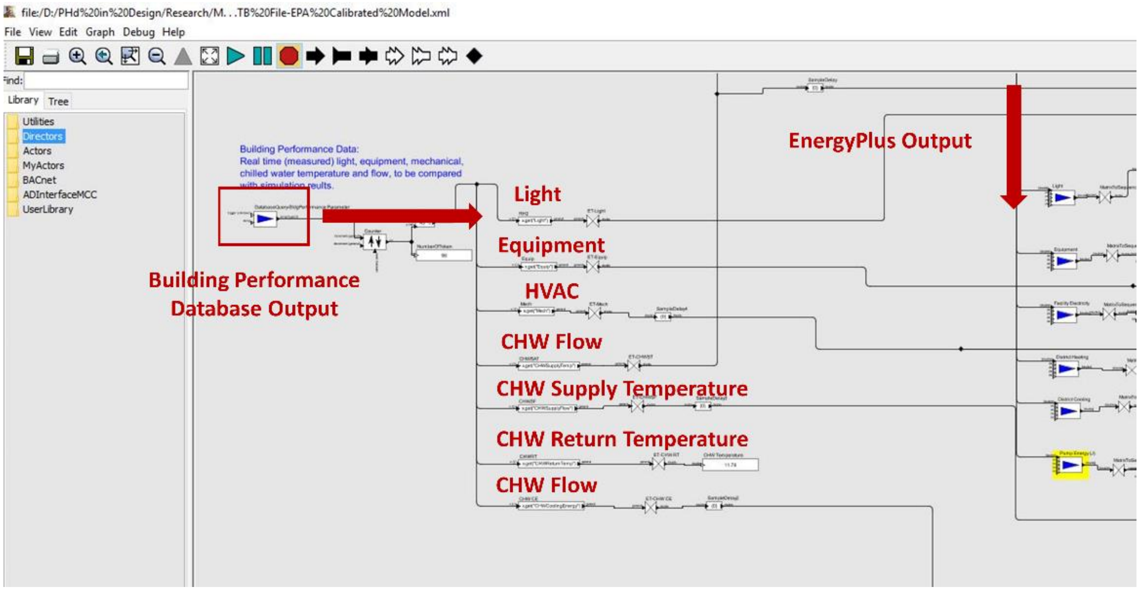
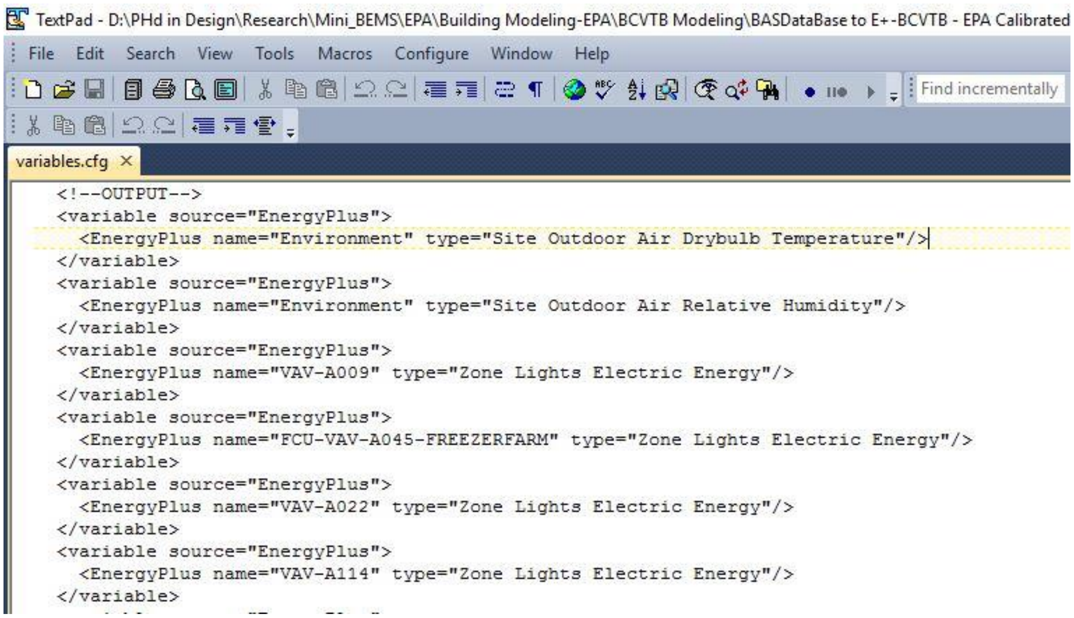


Figure 5-11: Building Performance Data-BCVTB Interface

5.2.1.4 Building Performance Monitoring

The EnergyPlus model outputs have to be specifically identified in the variable.cfg file as EnergyPlus output (variable source=EnergyPlus) as shown in Figure 5-12. The output name and type have to be specified exactly as they are shown in the eplus variable output Excel file. EnergyPlus simulator output type is a matrix for each time step. To be able to monitor each performance metric separately, a sub-matrix containing information related to that specific performance metric needs to be extracted from the EnergyPlus output matrix.

Zone Lights Electric Energy and Zone Electric Equipment Electric Energy are EnergyPlus output variables for lighting and equipment electricity for each zone in each time step. For the case study building with fifty-six zones, all the zones lighting and equipment electricity are added together to be compared against the measured whole building lighting and equipment electricity coming from the Database. Figure 5-13 shows the lighting and equipment electricity simulation data conversion process.



```
TextPad - D:\PHd in Design\Research\Mini_BEMS\EPA\Building Modeling-EPA\BCVTB Modeling\BASDataBase to E+-BCVTB - EPA Calibrated
variables.cfg

<!--OUTPUT-->
<variable source="EnergyPlus">
  <EnergyPlus name="Environment" type="Site Outdoor Air Drybulb Temperature"/>
</variable>
<variable source="EnergyPlus">
  <EnergyPlus name="Environment" type="Site Outdoor Air Relative Humidity"/>
</variable>
<variable source="EnergyPlus">
  <EnergyPlus name="VAV-A009" type="Zone Lights Electric Energy"/>
</variable>
<variable source="EnergyPlus">
  <EnergyPlus name="FCU-VAV-A045-FREEZERFARM" type="Zone Lights Electric Energy"/>
</variable>
<variable source="EnergyPlus">
  <EnergyPlus name="VAV-A022" type="Zone Lights Electric Energy"/>
</variable>
<variable source="EnergyPlus">
  <EnergyPlus name="VAV-A114" type="Zone Lights Electric Energy"/>
</variable>
```

Figure 5-12: Variable.cfg File for EnergyPlus Input

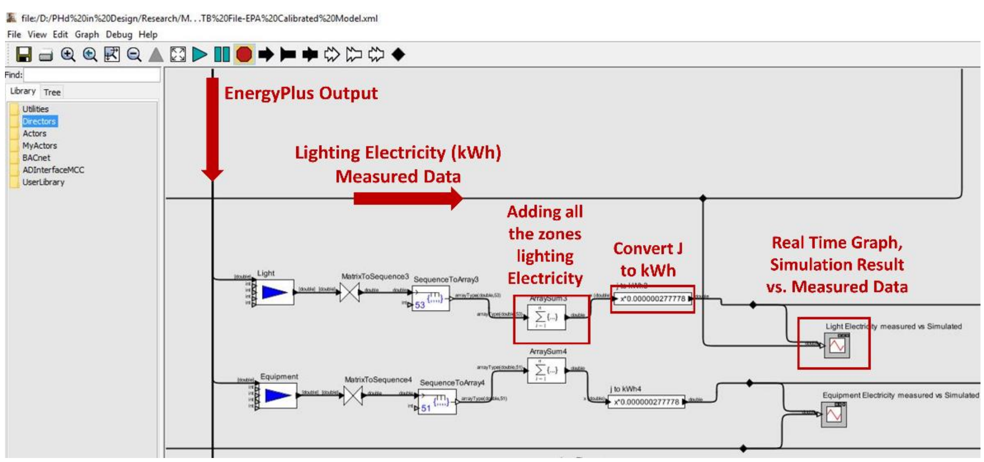


Figure 5-13: Lighting and Equipment Electricity Simulation Data Conversion - BCVTB Interface

Facility Total HVAC Electric Demand Power is EnergyPlus output variable for the mechanical systems electricity inside the building and plant as expanded in detail below:

Facility Total HVAC Electric Demand Power = VAV reheat electricity +AHUs fans electricity + ERU wheel electricity + ERU fan electricity + split system DX coil electricity + split system fans electricity + unit heater fan electricity + fan coils fan electricity + pump electricity.

Since the pump electricity is not considered in the mechanical electricity measured from the case study building, the pump energy was excluded from the Facility Total HVAC Electric Demand Power. Figure 5-14 shows the HVAC Electricity simulation data conversion process.

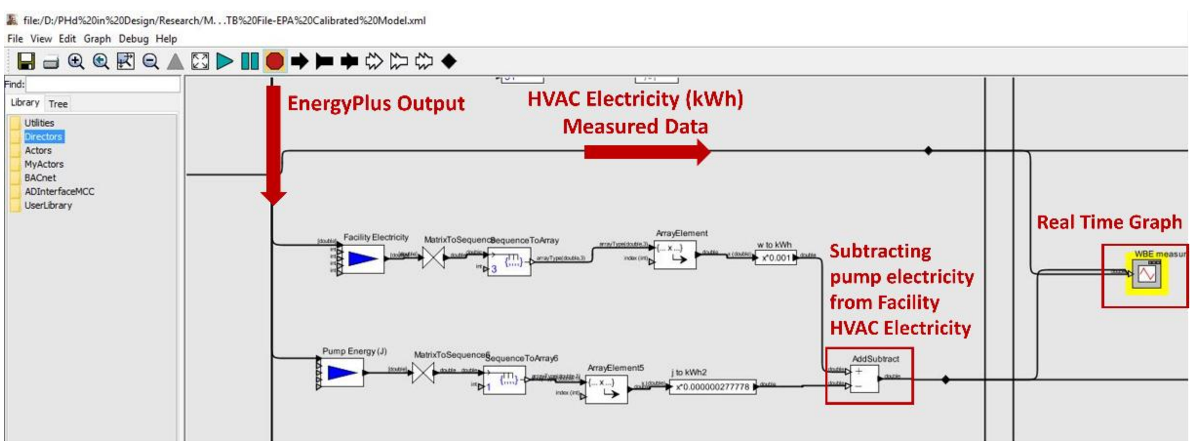


Figure 5-14: HVAC Electricity Simulation Data Conversion – BCVTB Interface

District heating EnergyPlus output variables listed below are provided in the BCVTB model in case the model needs to run for the whole year run period including winter months.

- District Heating Hot Water Energy
- District Heating Inlet Temperature
- District Heating Mass Flow Rate

District cooling EnergyPlus output variable are listed below:

- District Cooling Chilled Water Energy
- District Cooling Inlet Temperature
- District Cooling Mass Flow Rate
- District Cooling Outlet Temperature

District cooling chilled water energy (kWh or kBtu) and mass flow rate (kg/s or gal/min) are the main performance metrics to monitor the plant chilled water consumption and energy use. Figure 5-15 shows the district cooling and heating simulation data conversion process.

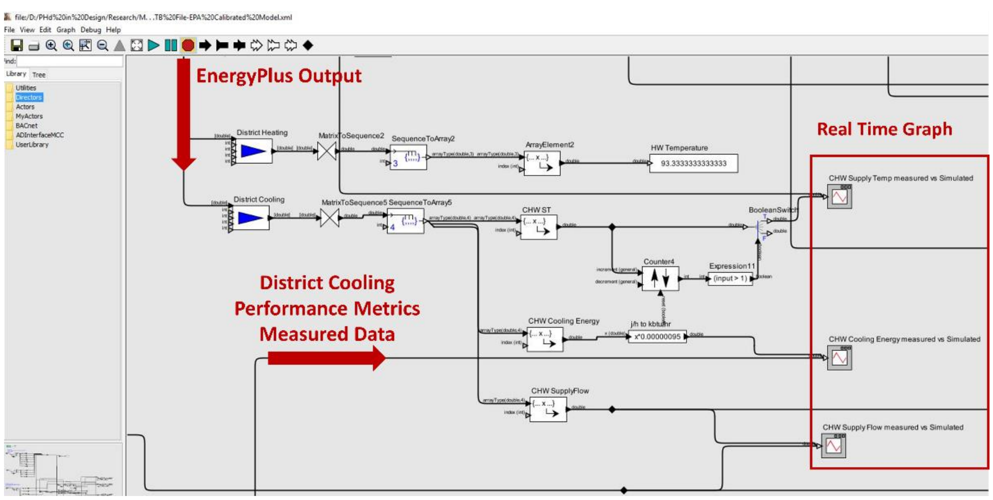


Figure 5-15: District Cooling and Heating Simulation Data Conversion – BCVTB Interface

The measured vs. simulated data graphs are running in real time for each time step (i.e. for every hour) and are actively presenting the building performance while simulation is running.

5.2.1.5 Fault Detection, Recommended Actions, and Potential Energy Savings

The fault detection algorithm in this study takes advantage of the top-down approach (or whole building diagnostics). In this method, the higher-level performance metrics are used to find possible sources for degradation of the lower level systems (Najafi, 2010).

This framework's algorithm for detecting the faults starts with analyzing the difference between measured and simulated data for each performance metric in each time step (every hour). If the difference is greater than the safe range that is defined for each performance metric separately, the out of range behavior sends an alarm to a SystemCommand actor in BCVTB which causes a GUI page to arise and provide the building manager with the list of possible faults detected and corrective actions in each time step.

According to ASHRAE 14-2002, The EnergyPlus model is allowed to have an NMBE of 10% relative to hourly measured data. The safe ranges are calculated based on the NMBE of 10% for each performance metric's peak during occupied hours. The hourly safe range for each performance metric are listed below:

- Lighting Electricity: safe range: 1.5 kWh (5.12 kBtu)
- Equipment Electricity: safe range: 0.6 kWh (2.1 kBtu)
- HVAC Electricity: safe range: 1.2 kWh (4.1 kBtu)

- Chilled water flow: safe range: 1.5 kg/s (23 gal/min) (The safe ranges for the chilled water flow and cooling energy is calculated based on the NMBE of 15% for the peak demand during occupied hours. This is because the chilled and hot water energy calibration is more challenging and difficult to imitate in the EnergyPlus model)

In the next step, the building manager has this option to click and close the page or click on the potential energy savings button to find out about how much energy will be saved by implementing the corrective actions. The potential energy savings for each performance metric is calculated based on the measured data deviation from the simulated data safe range and will be provided to building manager if requested. This process in BCVTB is facilitated by using the SystemCommand actor.

The SystemCommand actor in BCVTB enables the user to call a custom program (executable program) from the BCVTB at each time step. In this framework, the SystemCommand actor links the BCVTB model to series of Python codes related to each performance metric as shown in Figure 5-16.

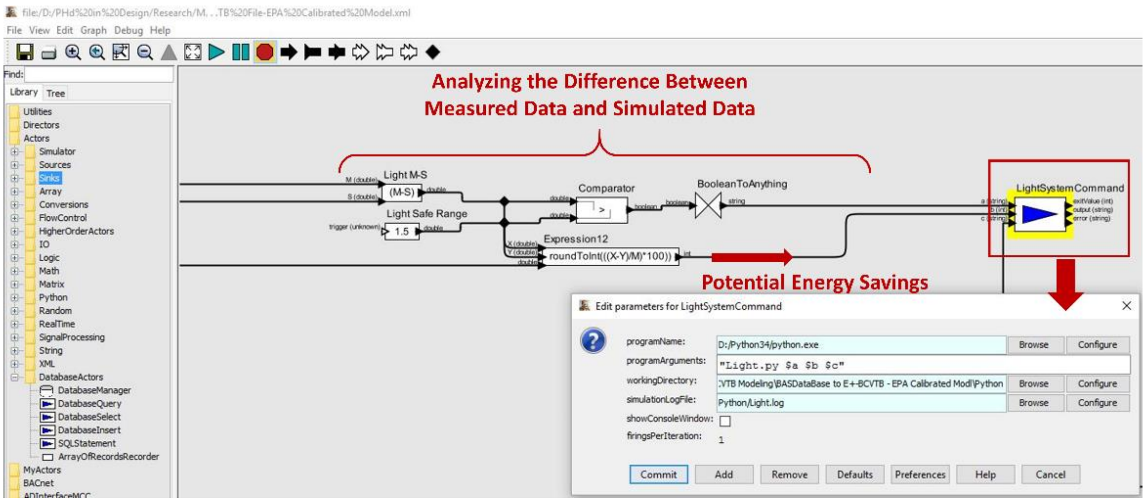


Figure 5-16: SystemCommand Actor for Calling the FDD Python Codes – BCVTB Interface

The Python codes needs three variable (system arguments) from the BCVTB model as listed below:

A: This argument triggers the python code if the difference between measured and simulated data is more than ten percent of the maximum of simulated data.

B: This argument brings the calculated potential energy savings from BCVTB model for each time step into the GUI.

C: This argument brings the date and time into the GUI from BCVTB model.

5.2.1.6 Real time and simulation time

This domain consists of two “TimedSource” actors in BCVTB model: “CurrentTime”, and “WallClockTime” as shown in Figure 5-17. The “CurrentTime” actor outputs the current time in seconds every hours and is used to show the simulation time and hour. The “WallClockTime” actor outputs the elapsed time in second which shows the real time passed in second. If the synchronize-to-real-time option in the SDF director is activated, the simulation time and real time will be the same. In most of the BCVTB models, this domain is just for time display and is not necessary to be included in the model. However, in the real time Cx and PM&V framework, this domain is used to bring the date and time into the python codes for the detected faults.

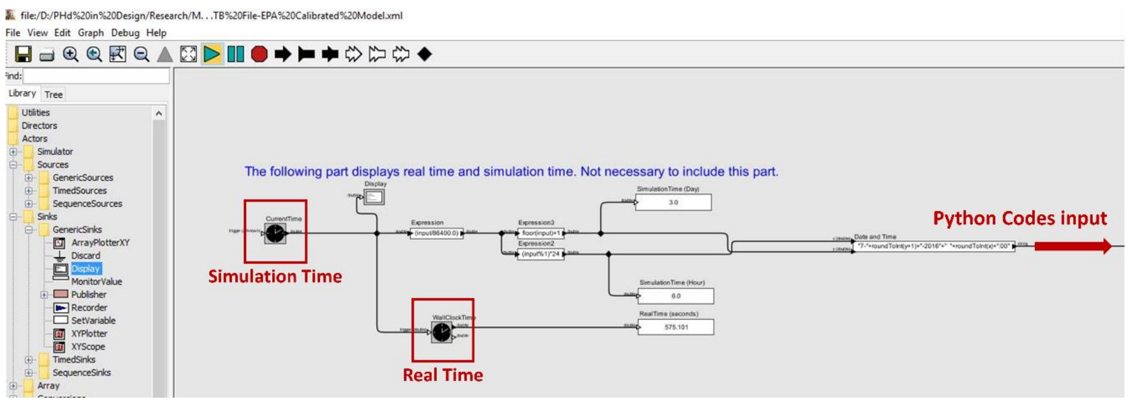


Figure 5-17: Simulation Time and Real Time – BCVTB Interface

5.3 Input Data to Test the Integrated Platform with the Case Study Building

After successfully developing the case study calibrated EnergyPlus model and BCVTB model, it is time to assess the operability and test the effectiveness of the automated real-time Cx and PM&V framework in a real case study building with provided measured data to monitor the building performance and to identify the opportunities for the improvement and potential energy savings while performing this analysis. The integrated platform includes BCVTB, EnergyPlus calibrated simulation model, real-time database, and a graphic user interface. The graphic user interface is the gateway for the user to interact with the tool.

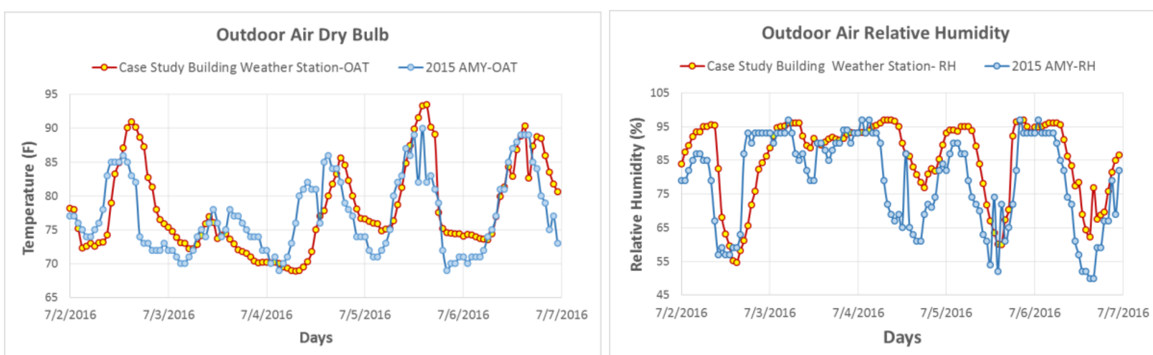
Per our request, the measured data are set to be trended every 15 minutes and the hourly data are produced out of them. Due to the limited capacity of the BAS database, only two weeks of data are selected to be evaluated by the real-time Cx and PM&V framework: July 2nd to 6th, 2016 and September 1st to 6th, 2016.

The lighting, equipment, and HVAC electricity, chilled water flow, and cooling energy are the main performance metrics for the case study building. The chilled water supply and return temperature are also monitored to observe the AHUs cooling coils operation.

As mentioned in previous section, seven weather parameters including outdoor air dry bulb temperature, outdoor air wet bulb temperature, outdoor humidity ratio, wind direction, wind speed, direct, and diffuse solar radiation and two system parameter including AHUs supply air temperature and outdoor air flow rate, and a plant parameter, chilled water supply temperature are selected to be implemented into EnergyPlus calibrated model as real-time inputs. These inputs adjust more accurately the calibrated EnergyPlus model results to be matched with the real time situation and to predict/project the energy use and demand pattern.

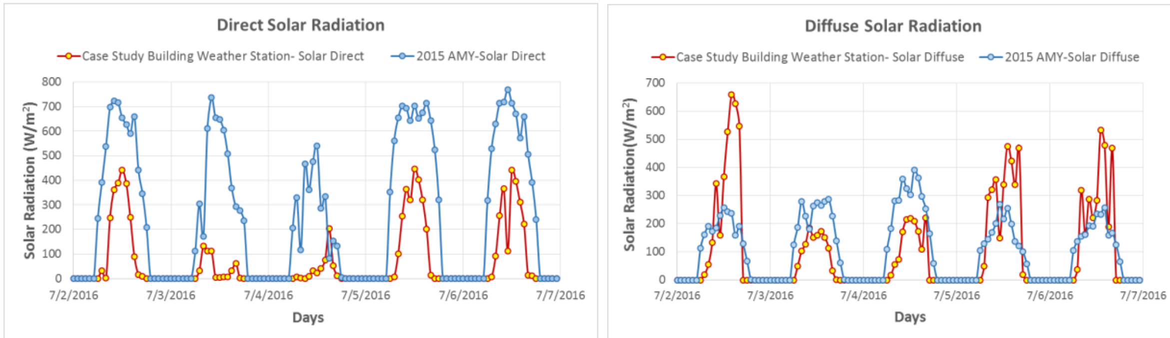
Figure 5-18 shows the comparison between the weather station (2016-real time) and AMY weather (2015) data, outdoor air dry bulb temperature and outdoor air humidity ratio for July 2nd to 6th. According to the case study building weather station data, the first week of July 2016 (July 2nd to 6th) has higher outdoor air temperature and relative humidity than 2015 AMY weather data. So, higher amount of electricity and chilled water consumption are expected by inputting the real time weather data into the EnergyPlus calibrated model.

Figure 5-19 shows the comparison between the weather station (2016-real time) and AMY weather (2015) data, direct and diffuse solar radiation for July 2nd to 6th. The comparison demonstrates the lower direct solar radiation in weather data station than in AMY weather data which is due to cloudier days in July 2nd to 6th, 2016. Figure 5-20 shows the comparison between the weather station (2016-real time) and AMY weather (2015) data, outdoor air dry bulb temperature and outdoor air humidity ratio for September 1st to 6th. According to the case study building weather station data, the first week of September 2016 (September 1st to 6th) has lower outdoor air temperature and higher relative humidity than 2015 AMY weather data due to rainy days.



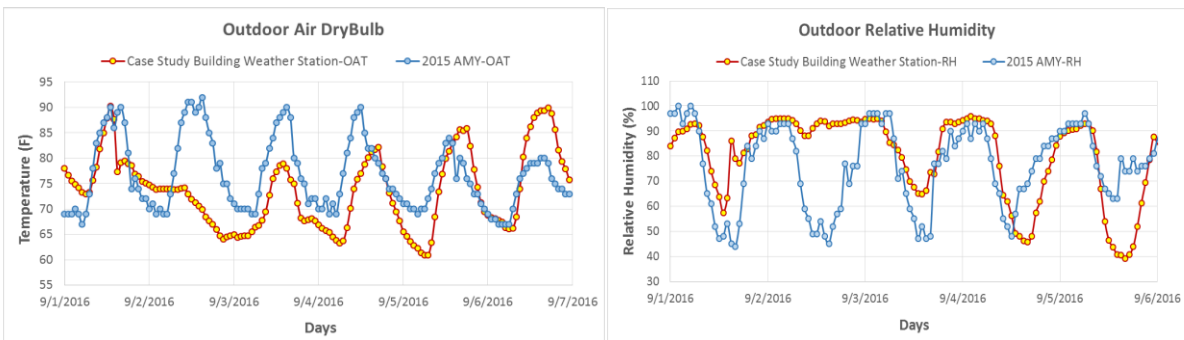
(a) (b)

Figure 5-18: Weather Station Data 2016 vs. 2015 AMY Weather Data for July 2nd to 6th (a) Outdoor Air Dry Bulb (b) Outdoor Air Relative Humidity



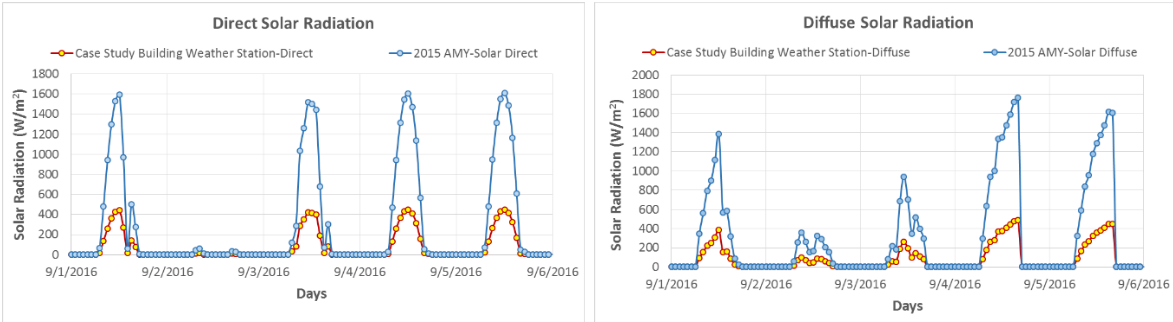
(a) (b)

Figure 5-19: Weather Station Data 2016 vs. 2015 AMY Weather Data for July 2nd to 6th (a) Direct Solar Radiation (b) Diffuse Solar Radiation



(a) (b)

Figure 5-20: Weather Station Data 2016 vs. 2015 AMY Weather Data for September 1st to 6th (a) Outdoor Air Dry Bulb (b) Outdoor Air Relative Humidity

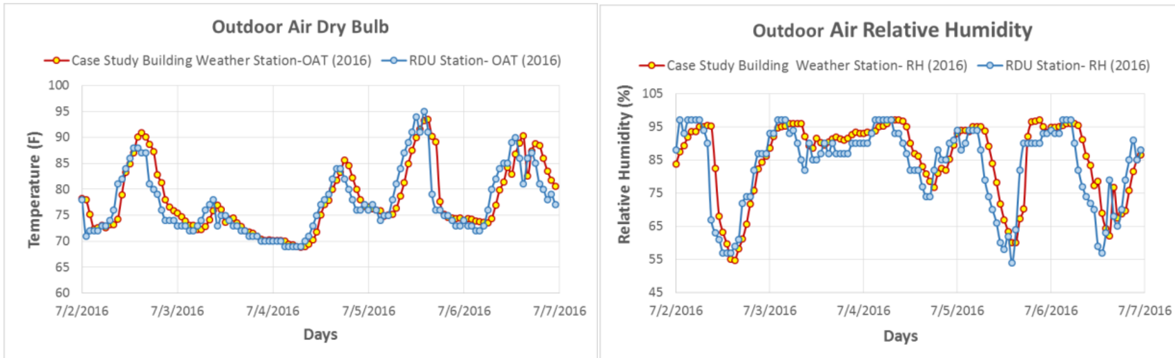


(a) (b)

Figure 5-21: Weather Station Data vs. 2015 AMY Weather Data for September 1st to 6th (a) Direct Solar Radiation (b) Diffuse Solar Radiation

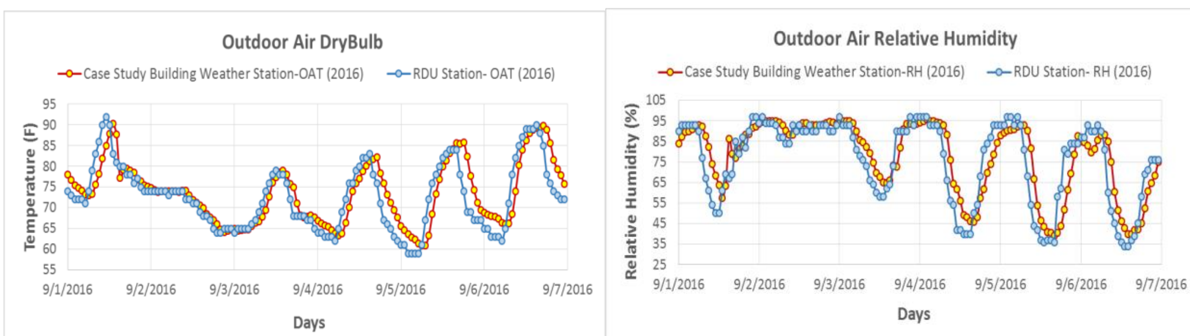
Figure 5-21 depicts the comparison between the weather station (2016-real time) and AMY (2015) weather data, direct and diffuse solar radiation for September 1st to 6th. The comparison demonstrates the lower direct and diffuse solar radiation in weather data station than in AMY weather data which is due to the cloudier and rainier days during September 1st to 6th, 2016.

Another series of comparisons between the RDU weather station and the case study's weather station data for July 2nd to 6th, 2016 and September 1st to 6th, 2016 show that the RDU weather data are quite consistent and similar to the case study weather station data. Thus, in case of some other buildings which are not equipped with a weather station, building manager can rely on the RDU weather station data (Figure 5-22 and 5-23).



(a) (b)

Figure 5-22: Weather Station Data 2016 vs. RDU Weather Data 2016 for July 2nd to 6th (a) Outdoor Air Dry Bulb (b) Outdoor Air Relative Humidity



(a) (b)

Figure 5-23: Weather Station Data 2016 vs. RDU Weather Data 2016 for September 1st to 6th (a) Outdoor Air Dry Bulb (b) Outdoor Air Relative Humidity

Two system input parameters into EnergyPlus calibrated model are AHUs supply air temperature and outdoor air flow rate. These parameters are trended from BAS for every 15 minutes. After checking the AHUs supply air temperature profiles, it turns out that the AHU supply air temperature sensors are always recording and saving data even when the AHUs are off during nights and weekends. So as it is shown in Figure 5-24 for July 2nd to 6th and Figure 5-25 for September 1st to 6th, during nights and weekends AHU supply air temperature sensors are recording temperature in range of 65 F to 77 F (18.3 C to 25 C) which causes error and false results if entering the EnergyPlus calibrated model. To prevent causing this problem, the AHUs supply air temperature during nights and weekends entering the EnergyPlus calibrated model are reset to 55F (12.7 C). This strategy enables us to follow the AHUs supply air temperature fluctuation during weekdays (55F to 60F [12.7 C to 15.5 C]) and adjust the system operation during nights and weekends if zones temperature goes beyond setback temperature (80F [26.6 C]). During these situations which are observed in July 2nd and September 4th during evening hours (Figure 5-24 and 5-25), the corresponding AHU turns ON to maintain the zone setback temperature.

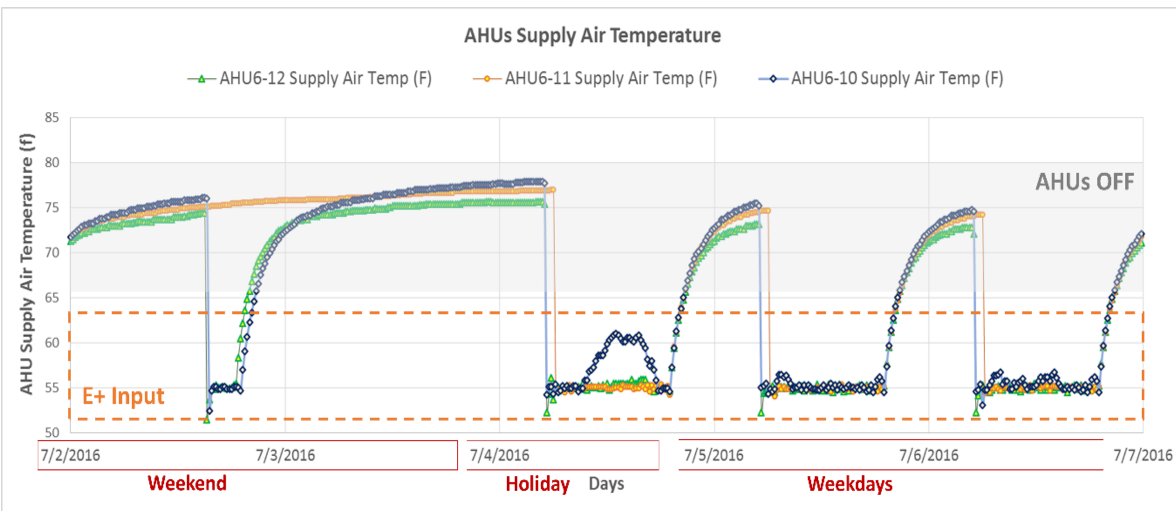


Figure 5-24: AHUs Supply Air Temperature Measured on July 2nd to 6th, 2016

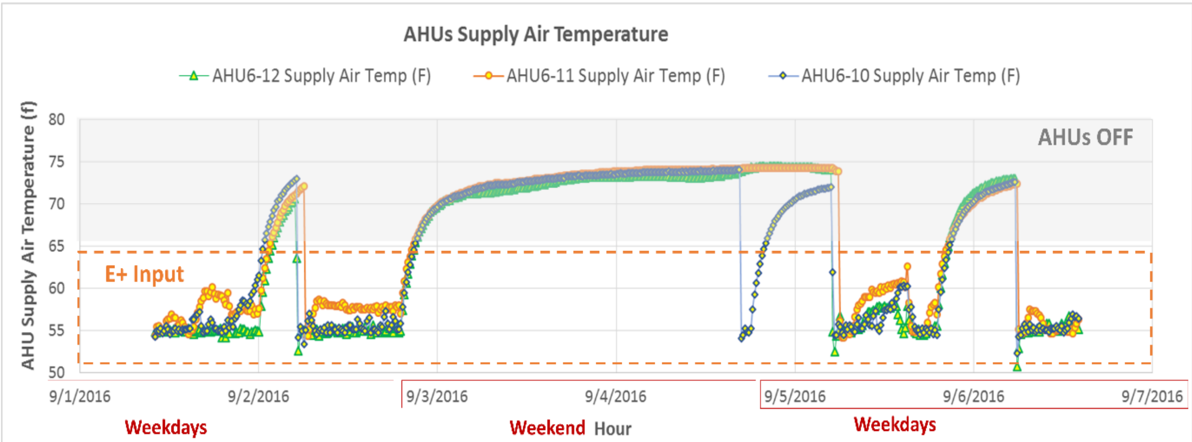


Figure 5-25: AHUs Supply Air Temperature Measured on September 1st to 6th, 2016

The similar problem occurs for outdoor air flow sensor at ERU outdoor air entrance. Although during unoccupied hours, AHUs do not use fresh air to maintain the setback temperature (80 F [26.6 C]) in the zones, but the outdoor air flow profiles for July 2nd to 6th and September 1st to 6th demonstrate that the outdoor air flow sensor is always recording and saving the constant minimum air flow (1,250 CFM for each AHU) even when the AHUs are off during nights and weekends. This might be a sensor reading error or AHUs damper fault, but after consulting with the building manager, this fault is considered as a sensor fault.

To prevent causing false high electricity consumption and chilled water flow during nights and weekends, the outdoor air flow rate entering to EnergyPlus calibrated model is reset to zero during unoccupied hours as shown in Figure 5-26 and 5-27. This strategy enables us to follow the outdoor air flow rate exact amount during weekdays and adjusts the system outdoor air intake during nights and weekends if zones temperature goes beyond setback temperature (80F [26.6 C]).

The only plant parameter is chilled water supply temperature which is implemented into EnergyPlus calibrated model in real time. This parameter sits at the exit of the supply side of the plant loop and is the temperature of water supplied to the inlet of chilled water coils. Figure 5-28 and 5-29 show the chilled water supply and return temperature profile for July 2nd to 6th and September 1st to 6th , 2016 respectively. Whenever there is a load on the plant loop during weekdays, the chilled water return temperature and chilled water flow increase to provide enough cooling energy for the building. The chilled water cooling energy for the case study building is calculated using the temperature difference between chilled water supply and return and the chilled water flow.

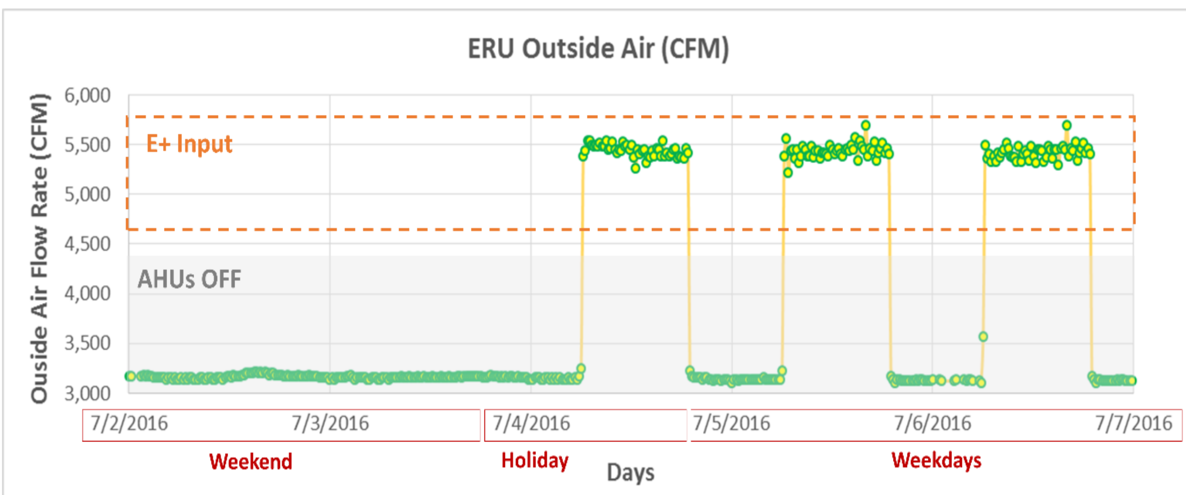


Figure 5-26: AHUs Outside Air Flow Rate Measured on July 2nd to 6th, 2016

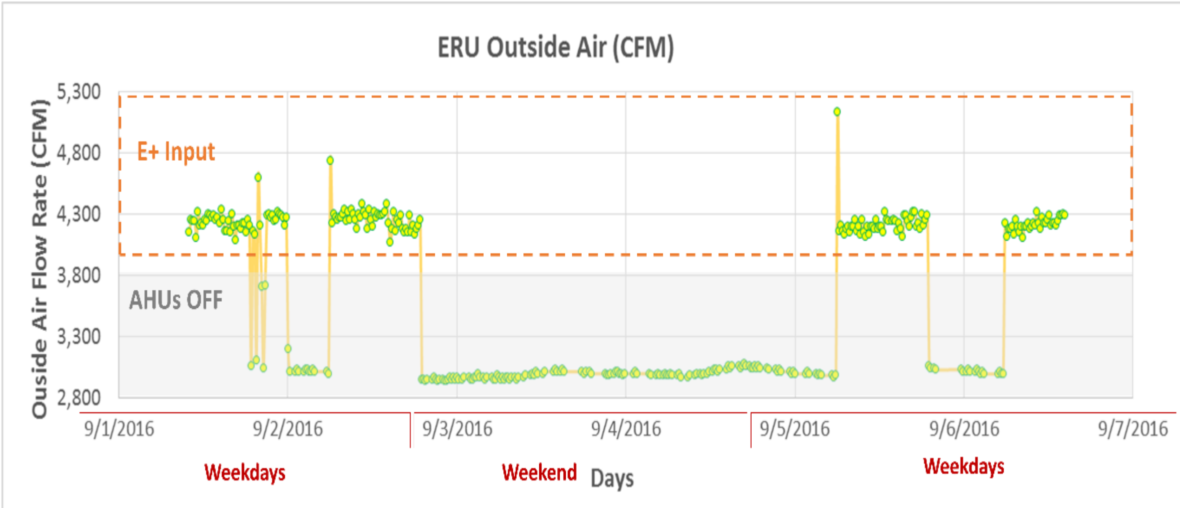


Figure 5-27: AHUs Outside Air Flow Rate Measured on September 1st to 6th, 2016

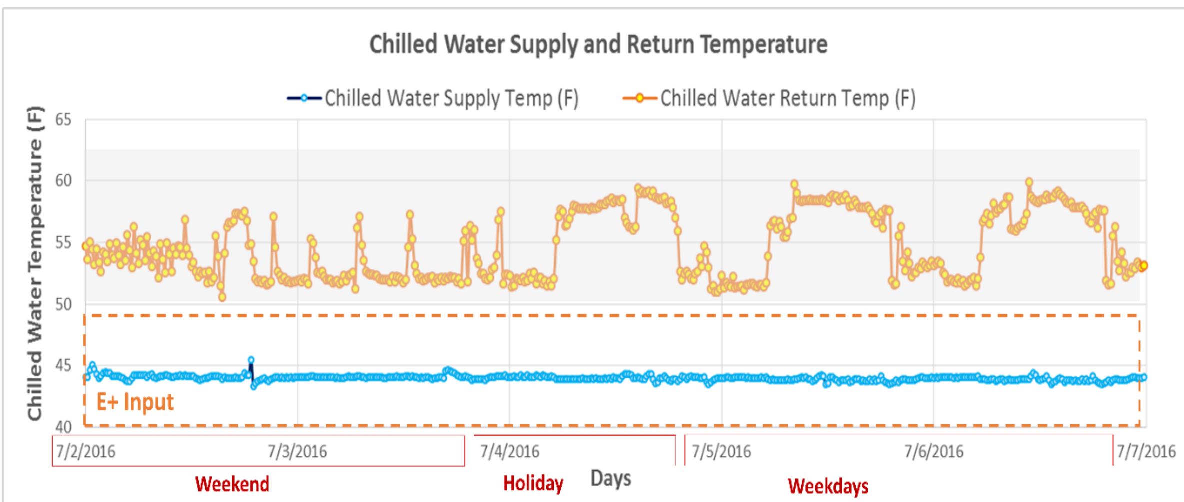


Figure 5-28: Chilled Water Supply and Return Temperature Measured on July 2nd to 6th, 2016

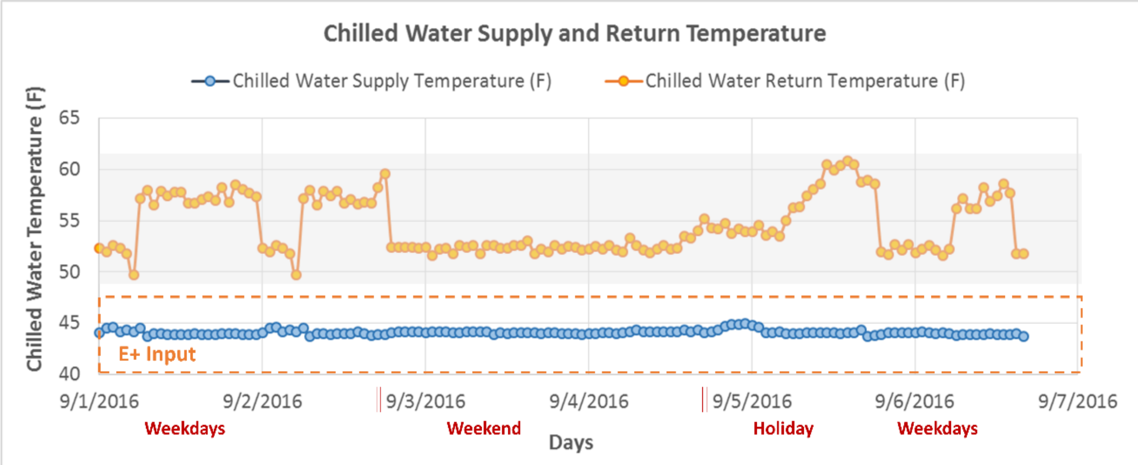


Figure 5-29: Chilled Water Supply and Return Temperature Measured on September 1st to 6th, 2016

5.4 Results and Discussion

After setting the EnergyPlus calibrated model inputs in an organized database and linking them to BCVTB, now it is time to execute the real-time Cx and PM&V framework. In future application, this framework is able to sit on top of a BAS as a plug-in tool. Whenever it is needed, the building manager can set up the time step (i. e. hourly time step) and run the framework for a specific time period or let the framework to run continuously.

In this research the real-time Cx and PM&V framework is executed for two time periods with hourly time step: July 2nd to 6th, 2016 and September 1sr to 6th, 2016.

5.4.1 Test Results of Cx an PM&V Framework: July 2nd to 6th, 2016

At the beginning of each hour started from July 2nd, 12:00 AM, the framework compares each performance metric's measured data from BAS (database) to the EnergyPlus calibrated model results. According to each performance metric's fault detection algorithm, if the difference between the measured data and calibrated simulation model exceeds the safe range, then the framework stops running the simulation and asks for more attention to this situation. Figure 5-30 demonstrates lighting electricity performance monitoring graph with and without safe zone. The blue dots represent the measured data from the case study building and the red dots represent the EnergyPlus calibrated model results (projected lighting performance) for every hour. The safe zone is illustrated in light green dots.

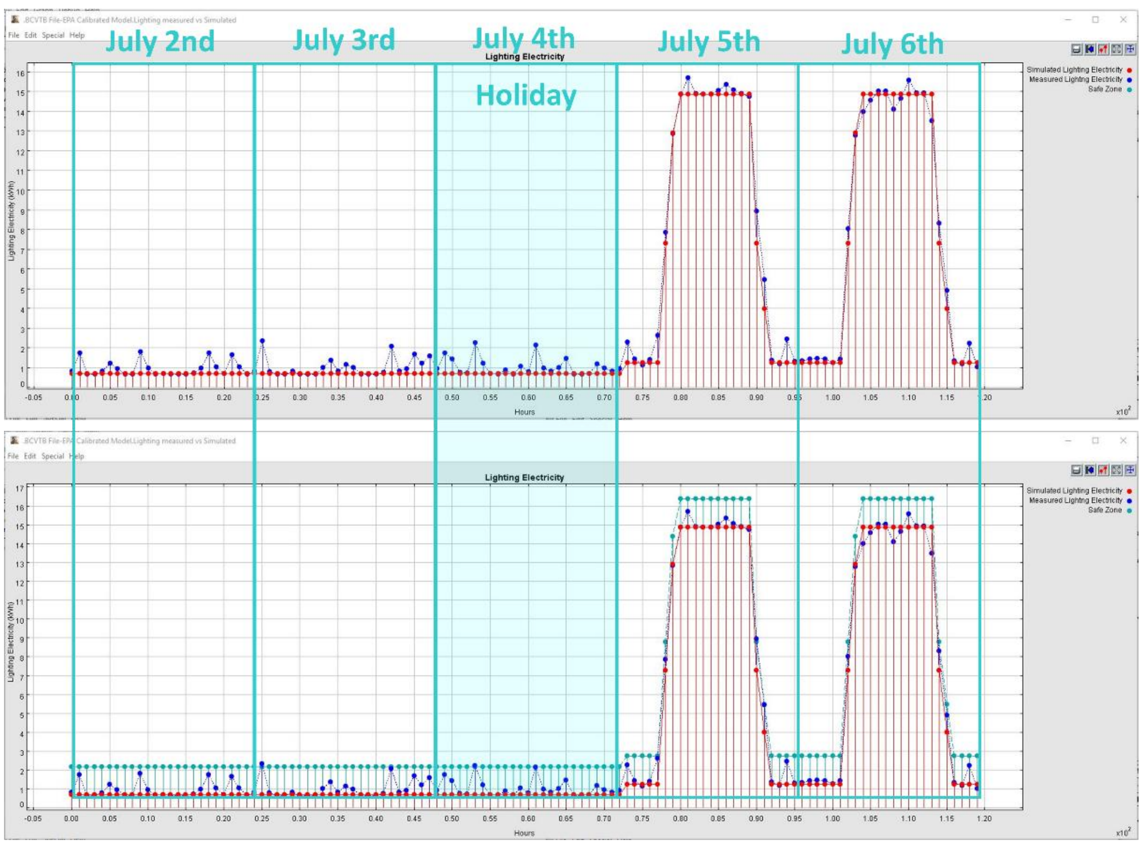


Figure 5-30: Lighting Electricity Performance Monitoring With and Without Safe Zone

As it is shown in Figure 5-31, if hourly real-time measured data cross the simulation result's safe zone, a warning page pops up and provides building manager with error possible causes and a short and effective list of corrective actions related to each performance metric.

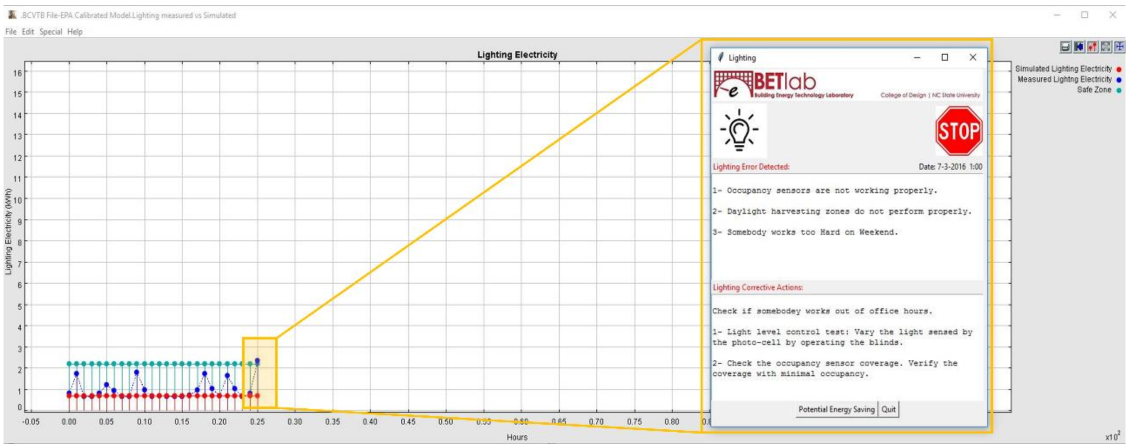


Figure 5-31: Fault Detected, Possible Causes and Corrective Actions

The building manager has to study the possible error causes and the corrective actions and takes actions according to the building condition. As it is shown in Figure 5-32, in addition to the error causes and corrective actions, the potential energy savings are provided to the building manager in case he/she decides to apply the corrective actions. The real-time Cx and PM&V framework delivers the potential energy savings in each time step (hourly) and the average potential energy savings during the run period for each performance metric in case any fault was detected.

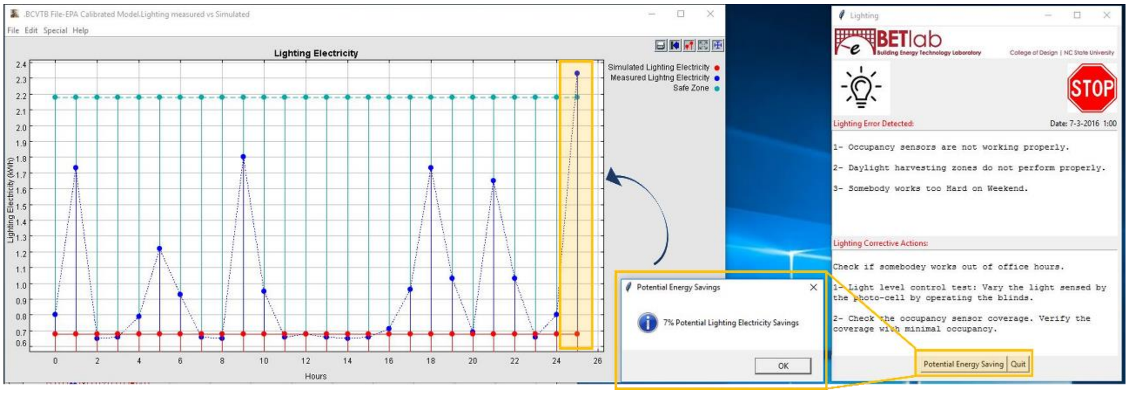


Figure 5-32: Potential Energy Savings if Implementing the Corrective Actions

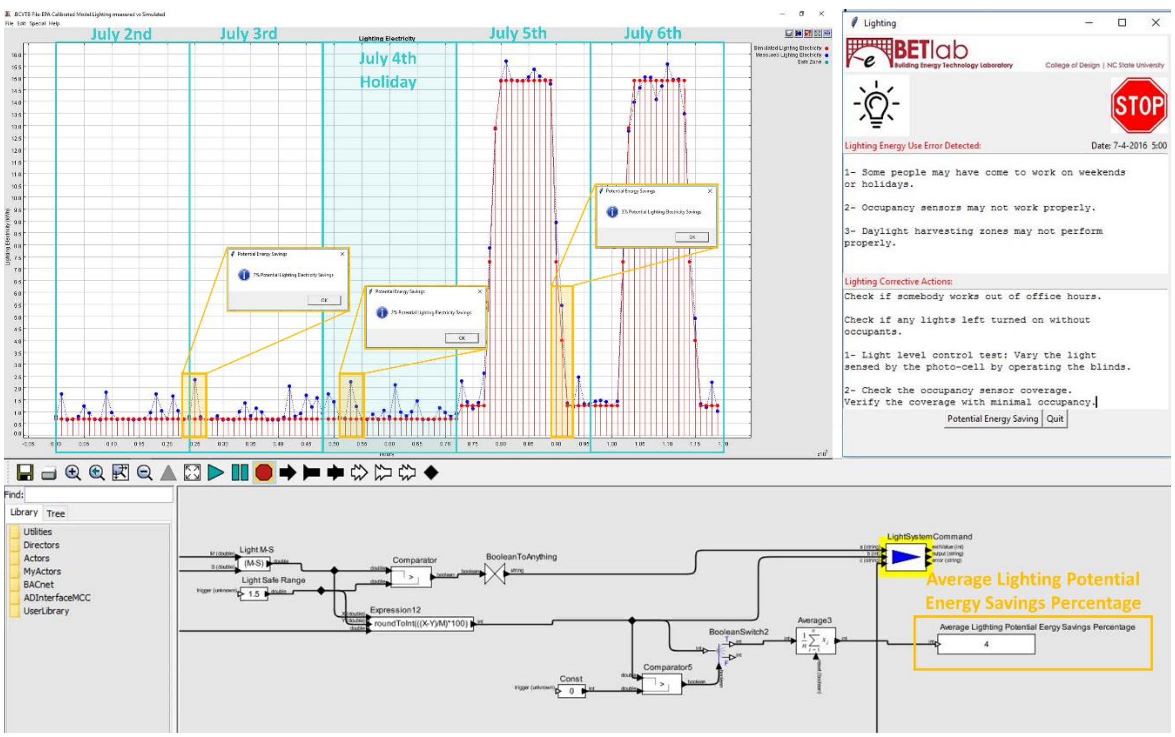


Figure 5-33: July 2nd to 6th Average Lighting Energy Use Fault Detection and Potential Energy Savings

According to the real-time Cx and PM&V framework running for July 2^{nd} to 6^{th} , some abnormal behaviors in lighting energy use pattern were noticed during July 3^{th} and 4^{th} (holiday). Some of them are accounted as a fault by crossing the safe zone as it is shown in Figure 5-33. The possible error causes are listed as follows:

- Some people may have come to work on weekends or holidays.
- Occupancy sensors may not work properly.
- Daylight harvesting zones may not perform properly.

The list of corrective actions is provided for each fault as follows:

- Check if some employees work overtime.
- Check if any lights left on without occupants.
- Light level control test: Vary the light sensed by the photo-cell by operating the blinds.
- Check the occupancy sensor coverage. Verify the coverage with minimal occupancy.

If the given corrective actions are considered and implemented, the average lighting energy use potential energy savings are 4 percent for the duration of July 2^{nd} to 6^{th}, 2016.

The similar performance monitoring is running simultaneously for case study building equipment energy use as it is shown in Figure 5-34. Although, there is some abnormal behavior during July 4^{th} (holiday), however the equipment energy use remained in the safe zone and does not require any further actions.

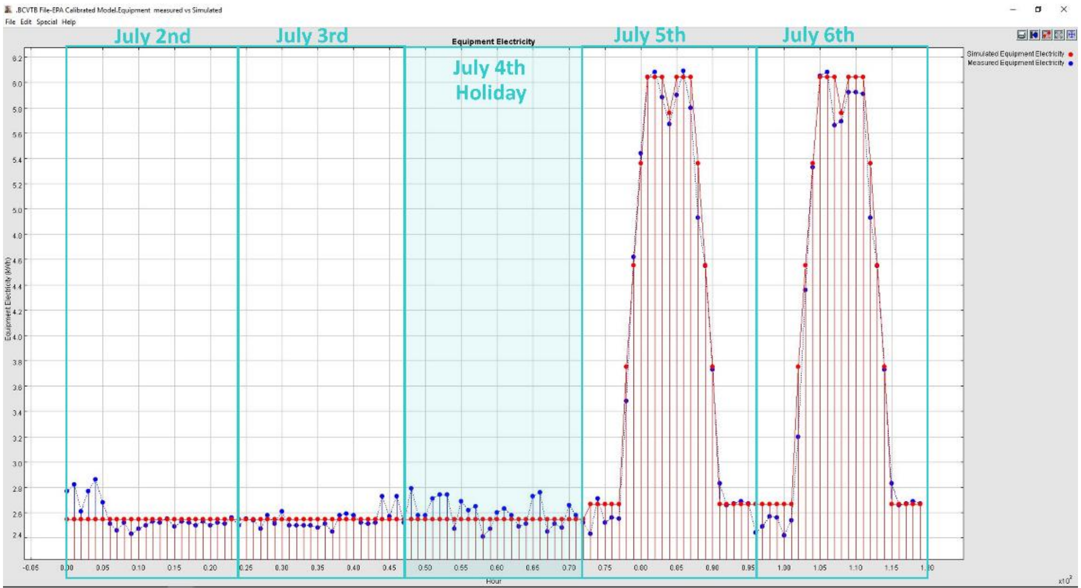


Figure 5-34: July 2nd to 6th Equipment Energy Use Performance Monitoring

A parallel performance monitoring is also running simultaneously for case study building HVAC energy use as it is shown in Figure 5-35. The HVAC energy use includes AHUs supply fans, VAV boxes reheat coils, ERU fans and rotary wheel, split systems fans and DX cooling coil, and fan coil system fan. The split systems are working 24/7 to maintain the set point temperature (75F) in the LAN rooms. So during the weekends and nights the constant minimum HVAC electricity represents the split systems operating. Also the AHUs are Off during unoccupied hours, however they are scheduled to be turned ON in case any zone temperature passes the 80F (setback) by using the AvailabilityManager:NightCycle in EnergyPlus model. These peaks can be seen during weekend (July 2nd and 3rd), when AHUs are turned on to maintain the space setback temperature. Modeling of this process in EnergyPlus has some difficulties and might cause some minor errors which are detected by the real-time Cx and PM&V framework during July 2nd. These small errors can be assumed as the data transfer rate issues in BCVTB, and it is negotiable as they are shown in Figure 5-35.

Moreover, according to the real-time Cx and PM&V framework running for July 2nd to 6th, some abnormal behaviors in HVAC energy use pattern were noticed during July 4th (holiday). The possible error causes are listed as follows:

- AHUs schedules may not set for holidays.
- Air Dampers may not operate properly.
- The economizer and outside sensors may not work correctly.
- Heating and cooling coils and AHU filters may be dirty or clogged.
- Outside Airflow Rates may be increased and CO_2 sensors do not work properly.

The list of corrective actions is provided for each fault as follows:

- Adjust the AHUs schedule for holidays.
- Check the AHUs fans and dampers.
- Check the DDC system control sequence to see if the current control system is using an air-side economizer.
- Verify proper operation of heating and cooling valves.
- Make sure that night setback controls have been implemented.
- Slow down systems during unoccupied hours.
- Double check if the duct pressure (inH_2O) settings are too high.

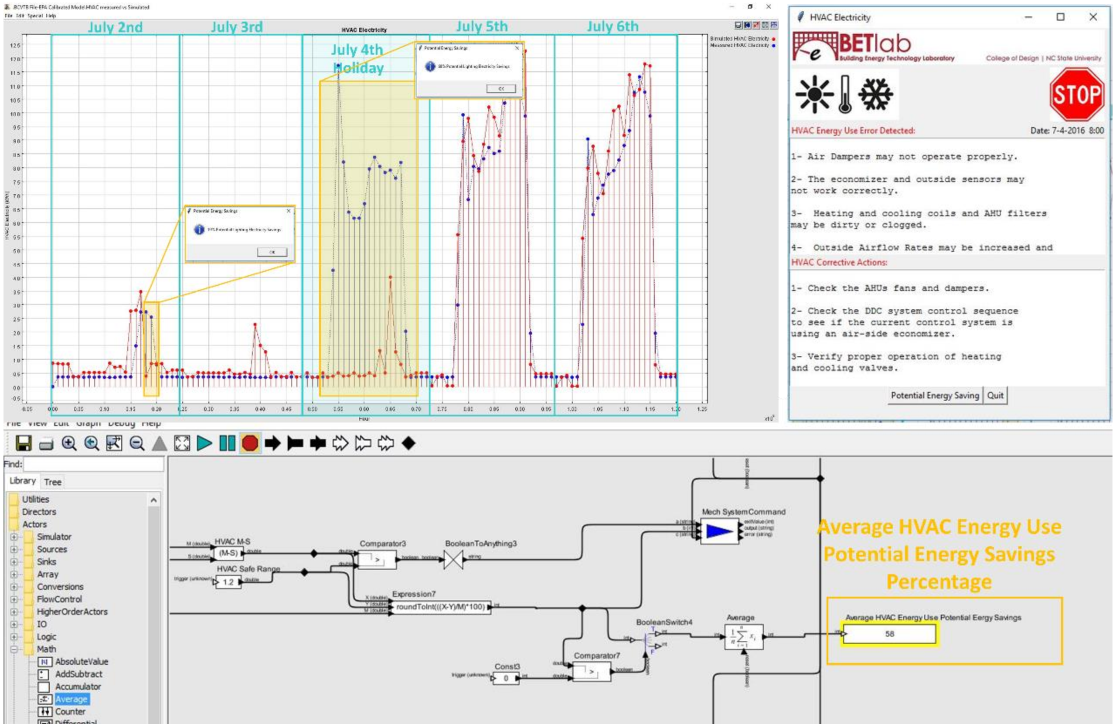


Figure 5-35: July 2nd to 6th, 2016 HVAC Energy Use Fault Detection and Average Potential Energy Savings

If the given corrective actions are considered and implemented, especially checking the case study building AHUs schedule for holidays, the average HVAC energy use potential energy savings are 58 percent for the duration of July 2nd to 6th, 2016.

The final performance metric is chilled water flow along with chilled water cooling energy which are monitored simultaneously for the case study building as it is shown in Figure 5-36.

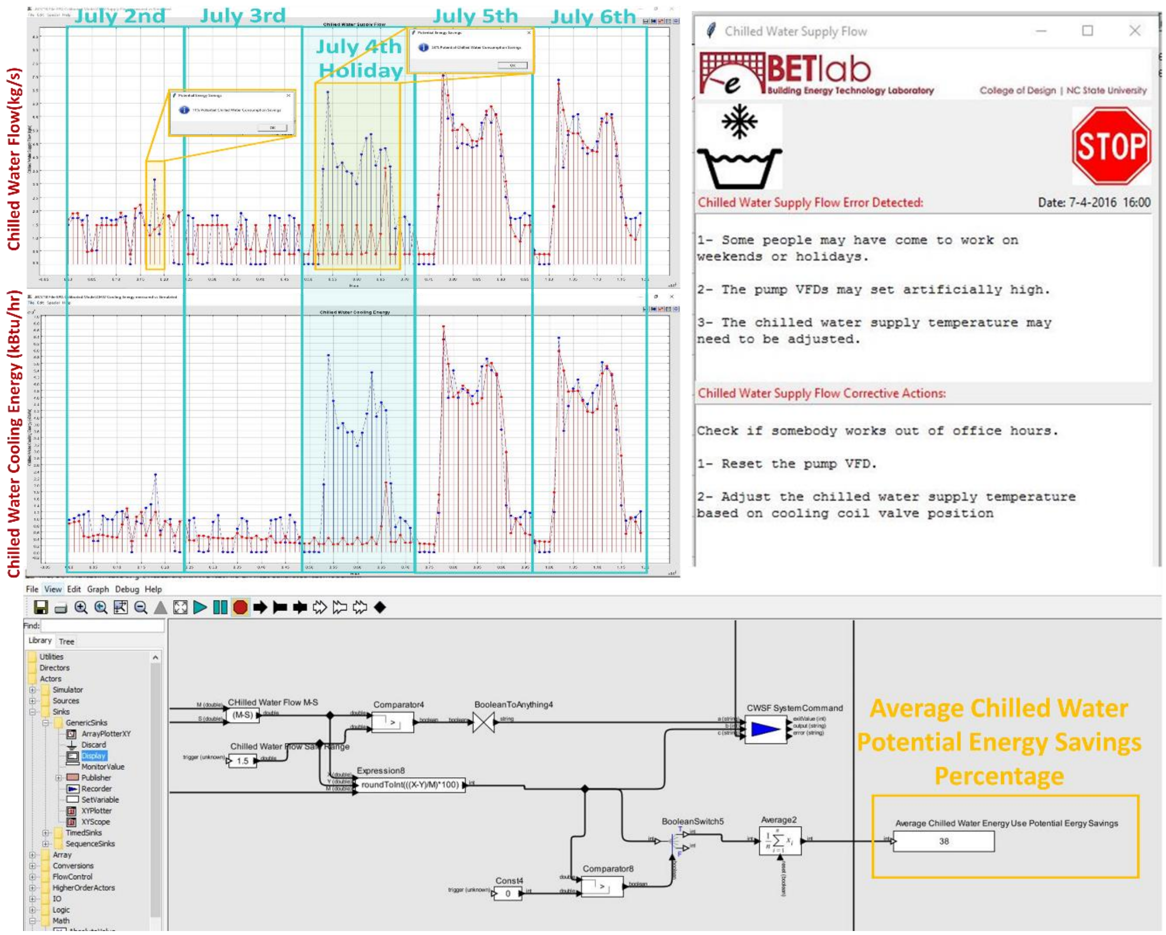


Figure 5-36: July 2nd to 6th, 2016 Chilled Water Flow and Cooling Energy Fault Detection and Average Potential Energy Savings

According to this framework running for July 2nd to 6th, some abnormal behaviors in chilled water flow and cooling energy pattern were noticed during July 4th (holiday). The possible error causes are listed as follows:

- AHUs schedules may not set for holidays.
- Some people may have come to work on weekends or holidays.

- The pump VFDs may set artificially high.
- The chilled water supply temperature may need to be adjusted.

The list of corrective actions is provided for each fault as follows:

- Adjust the AHUs schedule for holidays.
- Check if some employees work overtime.
- Reset the pump VFD.
- Adjust the chilled water supply temperature based on cooling coil valve position.

If the given corrective actions are considered and implemented, especially checking the case study building AHUs and cooling coil schedule for holidays, the average cooling energy potential energy savings are 38 percent for the duration of July 2nd to 6th, 2016. Comparing the lighting, equipment, and HVAC energy use graphs with the chilled water flow and cooling energy graphs verifies that AHUs are ON during holiday without any lighting and equipment load in the building. Adjusting the AHUs schedule for holidays increases the potential energy savings during the course of a year.

5.4.2 Test Results of Cx and PM&V Framework: September 1st to 6th, 2016

At the beginning of each hour started from September 1st, 12:00 AM, the framework compares each performance metric's measured data from BAS (database) to the EnergyPlus calibrated model results. According to the real-time Cx and PM&V framework running for September 1st to 6th, 2016 , some abnormal behaviors in lighting energy use pattern were noticed during Sep 3rd and 4th (weekend) and Sep 5th (holiday). Also some high lighting electricity use was detected during Sep 1st evening hours which indicates occupant behavior before the long weekend. Among those some of them are accounted as a fault by crossing the safe zone as it is shown in Figure 5-37.

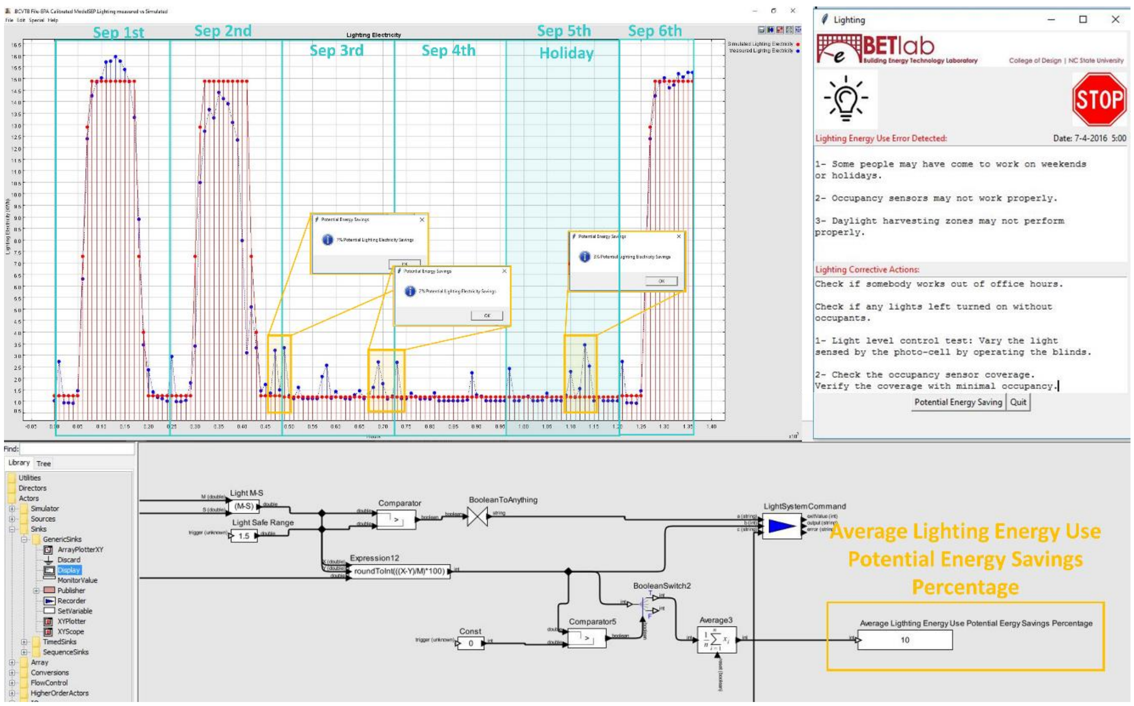


Figure 5-37: September 1st to 6th, 2016Average Lighting Energy Use Fault Detection and Potential Energy Savings

The pattern of abnormal behavior and faults in lighting energy use indicates that there might be some issues and problem with some of the occupancy sensors or daylight harvesting system (dimming lights) that causes the high lighting electricity use during the midnight hours intermittently. According to the real-time Cx and PM&V framework list of corrective action, the following actions might be useful.

- Check if any lights left on without occupants.
- Light level control test: Vary the light sensed by the photo-cell by operating the blinds.
- Check the occupancy sensor coverage. Verify the coverage with minimal occupancy.

If the given corrective actions are considered and implemented, the average lighting energy use potential energy savings are 10 percent for the duration of September 1st to 6th, 2016.

The equipment energy use monitoring is shown in Figure 5-38. In Figure 5-38, some abnormal behavior can be clearly seen during Sep 1st (Thursday), and Sep 4th (Sunday) which crossed the safe zone and are accounted as faults. Also during Sep 2nd, a decrease in equipment electricity level is palpable which is most likely related to the occupant behavior before the long weekend. The possible error causes are listed as follows:

- Some people may have come to work on weekends or holidays.
- Occupancy sensors power strips may not work properly (For noncritical office equipment).
- Vending Machines lights are ON.

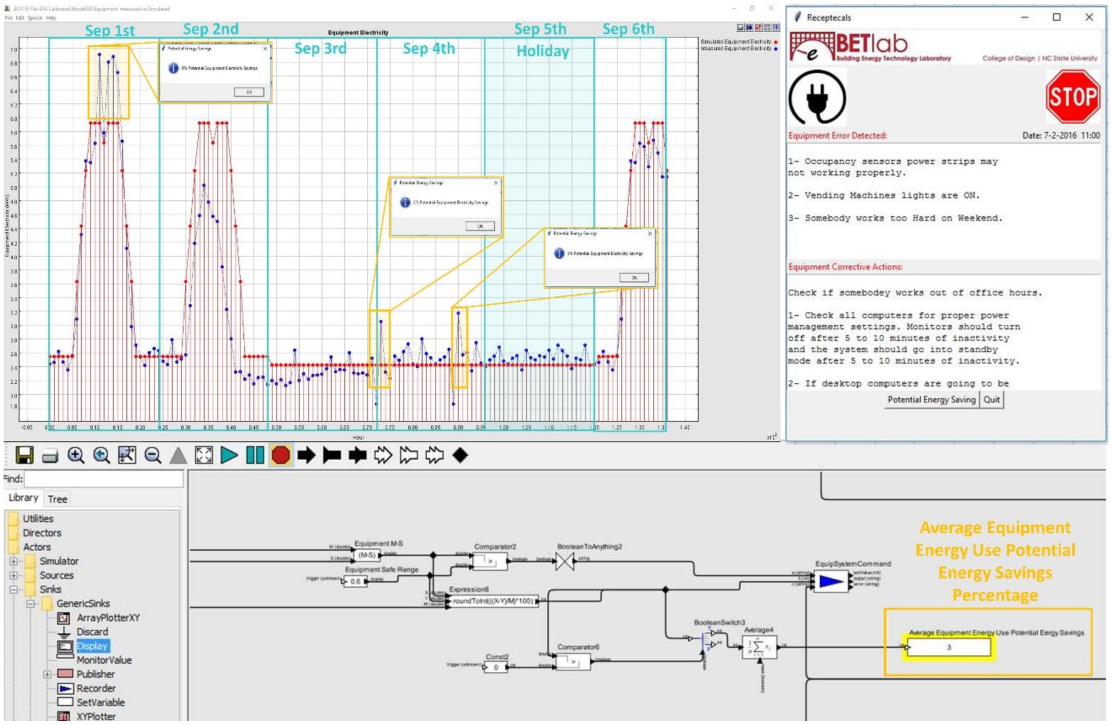


Figure 5-38: September 1st to 6th, 2016 Average Equipment Energy Use Fault Detection and Potential Energy Savings

The list of corrective actions is provided for each fault as follows:

- Check if some employees work overtime.
- Check if any equipment left on without occupants.
- Check all computers for proper power management settings. Monitors should turn off after 5 to 10 minutes of inactivity and the system should go into standby mode after 5 to 10 minutes of inactivity.
- If desktop computers are going to be replaced, replace them with low energy desktops.
- All vending machines should be de-lamped and have misers installed.

- Occupancy sensor power strips should be used for all noncritical office equipment (task lights, printers, faxes, scanners, speakers, radios, fans, etc.)
- Replace office equipment with ENERGY STAR Models.

If considering and implementing the above corrective actions the average equipment energy use potential energy savings are 3 percent for the duration of September 1st to 6th, 2016.

A parallel performance monitoring is also running simultaneously for case study building HVAC energy use as it is shown in Figure 5-39.

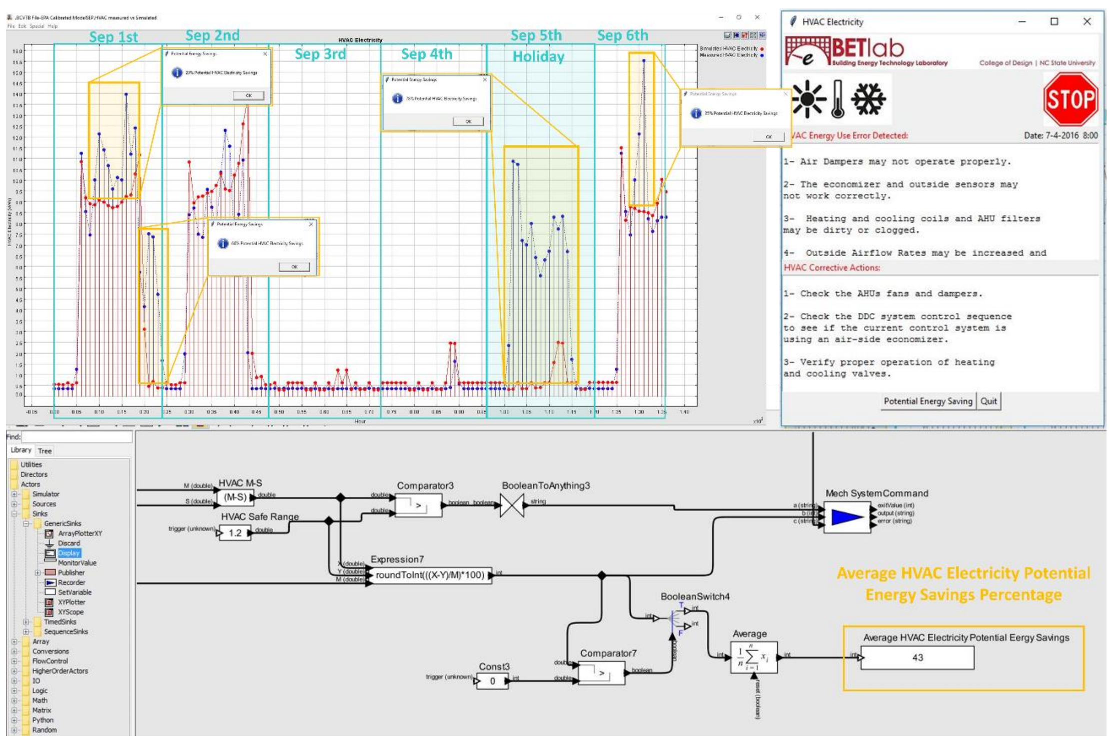


Figure 5-39: September 1st to 6th, 2016 HVAC Energy Use Fault Detection and Average Energy Savings Potential

In Figure 5-39, some abnormal behavior can be clearly seen during Sep 1st (Thursday), and Sep 5th and Sep 6th (Holiday and Tuesday) which crossed the safe zone and are accounted as faults. The high HVAC electricity consumption during evening hours and night of Sep1st are most likely related to the overtime working of occupants and consequently increasing of internal heat gain in the building. This situation continues overnight and it seems that the AHUs are manually turned on and the setback temperature are not applied. Also, the faults detected during Sep 5th (holiday) verify that the AHUs schedules are not set for holidays. The possible error causes are listed as follows:

- Some people may have come to work on weekends or holidays.
- AHUs schedules may not set for holidays.
- Air Dampers may not operate properly.
- The economizer and outside sensors may not work correctly.
- Heating and cooling coils and AHU filters may be dirty or clogged.
- Outside Airflow Rates may be increased and CO_2 sensors do not work properly.

The list of corrective actions is provided for each fault as follows:

- Adjust the AHUs schedule for holidays.
- Check the AHUs fans and dampers.
- Check the DDC system control sequence to see if the current control system is using an air-side economizer.
- Verify proper operation of heating and cooling valves.

- Make sure that night setback controls have been implemented.
- Slow down systems during unoccupied hours.
- Double check if the duct pressure (inH_2O) settings are too high.

If the given corrective actions are considered and implemented, the average HVAC electricity potential energy savings are 43 percent for the duration of September 1st to 6th, 2016.

The final performance metric is chilled water flow along with chilled water cooling energy which are monitored simultaneously for the case study building as it is shown in Figure 5-40. According to the real-time Cx and PM&V framework running for September 1st to 6th, some abnormal behaviors in chilled water flow and cooling energy pattern were noticed during Sep 1st during night hours (Thursday) and Sep 5th (holiday). The possible error causes are listed as follows:

- AHUs schedules may not set for holidays.
- Some people may have come to work on weekends or holidays.
- The pump VFDs may set artificially high.
- The chilled water supply temperature may need to be adjusted.
- The list of corrective actions is provided for each fault as follows:
- Adjust the AHUs schedule for holidays.
- Check if somebody works out of office hours.
- Reset the pump VFD.
- Adjust the chilled water supply temperature based on cooling coil valve position.

If the given corrective actions are considered and implemented, especially checking the case study building AHUs and cooling coil schedule for holidays, the average cooling energy potential energy savings are 41 percent for the duration of September 1st to 4th, 2016.

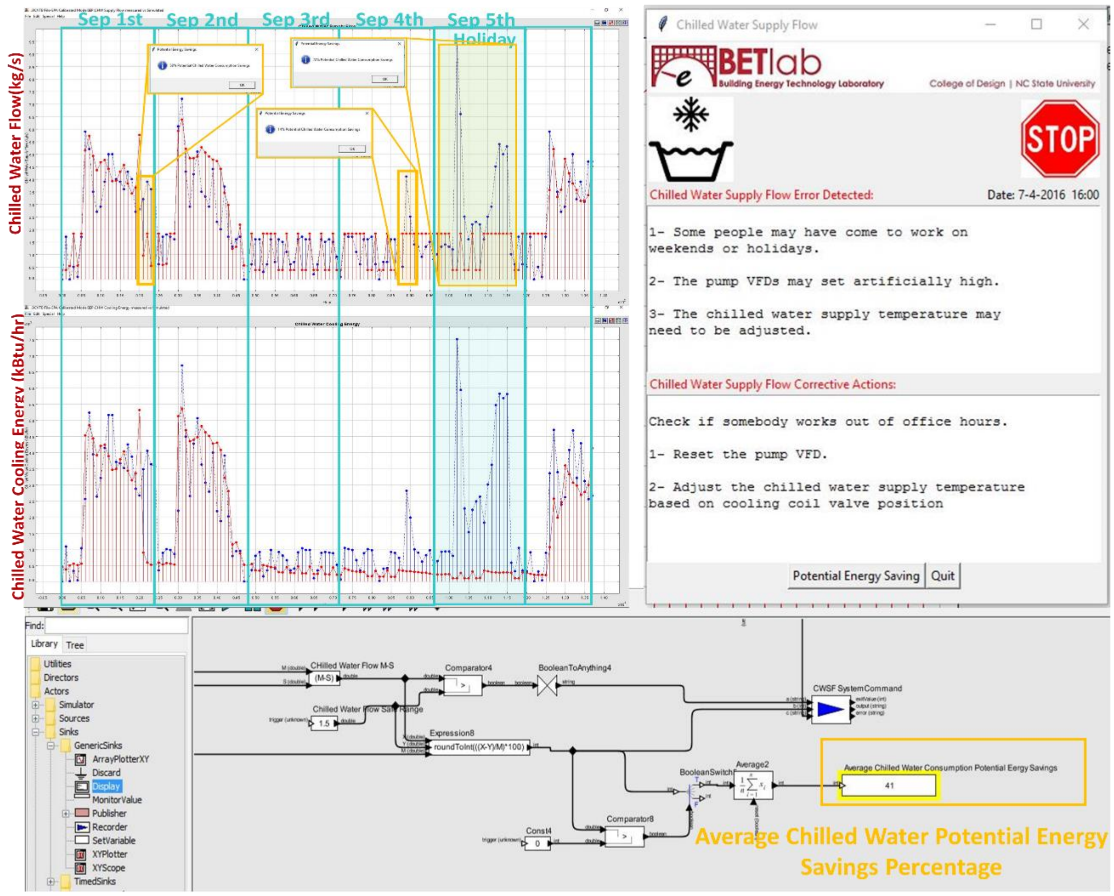


Figure 5-40: September 1st to 6th Chilled Water Flow and Cooling Energy Fault Detection and Average Potential Energy Savings

Figure 5-41 illustrates the chilled water supply temperature from Sep 1st to 6th, 2016. The chilled water from the central plant feeds the AHUs, and FCU coils in the case study building directly. Since EnergyPlus calibrated model uses the district cooling/heating object for modeling the plant loop in this building, the measured chilled water supply temperature is directly be sent to the plant loop supply outlet node to enter the coils. Figure 5-41 verifies that the simulation chilled water supply temperature exactly matches the measured chilled water supply temperature. In case of any unmet load occurrence in the model, the simulation chilled water supply temperature will be variated from the measured data.

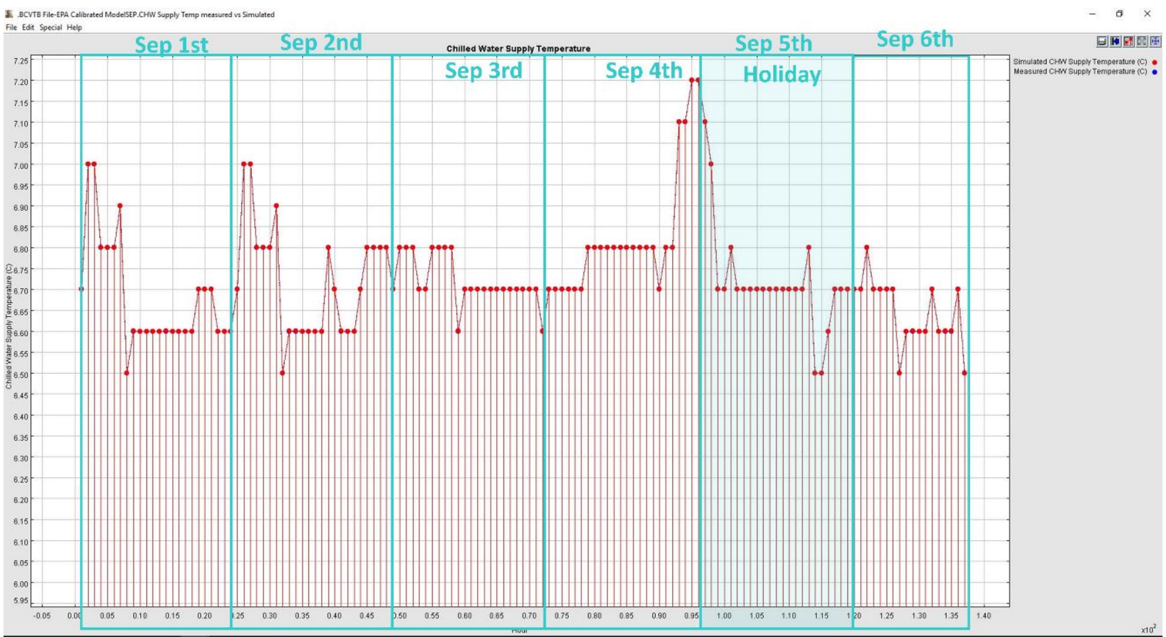


Figure 5-41: September 1st to 6th, 2016 Chilled Water Supply Temperature

CHAPTER 6 CONCLUSION AND FUTURE STUDIES

In order to achieve the Architecture 2030, 2025 Commercial Buildings Initiative, and Net-Zero Energy Building (NZEBs) initiative goals, correctly operating and maintaining the high-performance level of commercial buildings are the crucial factors to keep existing buildings in shape and save energy continuously. Building managers have to be equipped with the advanced tools and be educated encountering the state-of-art analysis software to improve the continuous Cx quality and to increase the energy savings in the buildings by implementing corrective actions and/or EEMs and ECMs.

The continuous commissioning and performance measurement and verification process in the commercial buildings are the main two concepts that use BAS's pool of data points to assess the building performance and monitor its operation during the building life cycle. Those activities significantly contribute into a building's energy savings. As a result there is a clear demand for integrating these concepts into a cohesive structured framework to facilitate the building manager's job and to easily lead them to find the building faults as well as controlling the building profile pattern.

The real-time Cx and PM&V framework proposed in this research is an advanced platform to support the automated continuous commissioning, building performance monitoring, and potential energy savings assessment. This study follows the research chain which started at LBNL in 2010 and expands it to the real-time Cx and PM&V framework with the fault detection and corrective actions recommendations for the building manager. This framework has this ability to sit on top of a BAS and performs as an online helping tool to monitor the whole building energy performance, detect the faults and provide corrective actions along with potential energy savings at every time step.

In addition to the proposed framework, this study presents a comprehensive advanced EnergyPlus model calibration process as the main part of the building performance monitoring and fault detection. The building energy model calibration is always a challenging and difficult procedure. This study benefits from previous studies in the field of BEM calibration and provides a detailed step-by-step model calibration process which occurs in two phases: model calibration with historical measured data as well as utility bills, and real-time model calibration using real-time data obtained from online BAS database. Looking at the building performance monitoring diagrams in chapter five, the accuracy and precision of the real-time EnergyPlus calibrated model becomes evident.

This framework was tested in a government office building located in Research Triangle Park (RTP) Area, NC. Although the case study building is almost a brand new building, built in 2014, received a LEED Platinum, and expected to work efficiently, but this framework revealed a number of abnormal behaviors and faults during July 2nd to 6th, 2016 and September 1st to 6th, 2016. The main fault is associated with the AHUs schedule for holidays which needs to be adjusted. The minor faults are mostly associated with the occupancy behavior during nights and weekends, and lighting defects. The average potential energy savings for each performance metric are listed in Table 6-1.

As it can be clearly seen from the figures in previous section, the EnergyPlus calibrated model, which is now being used for an on-line building energy analysis, projected the whole building energy performance properly and is reliable for this framework. However, the EnergyPlus tool's minor shortcomings itself and the BCVTB data transfer issues challenge the energy modeler for developing an acceptable EnergyPlus calibrated model. In this study, the EnergyPlus modeling difficulties are mostly noticeable in the modeling of ERU, in connecting it to each AHU, and in scheduling the AHUs night cycle to maintain the setback temperature during nights, weekends, and holidays. The BCVTB challenges can be summarized in data transfer issues and the BCVTB interface itself which is not that user friendly and needs an expert user to learn the environment and work with that. Moreover, it seems that the timestep delay in passing data with BCVTB is an intentional part of the design of the co-simulation capability. The lagging makes the computing safer and more robust. Most of the energy modelers are suggesting to shorten the timestep to decrease the impact of the lag in data transfer.

Table 6-1: Average Potential Energy Savings for Each Performance Metric Provide by Real-Time Cx and PM&V Framework

Test Time Period	Lighting Electricity	Equipment Electricity	HVAC Electricity	Chilled Water Flow and Cooling Energy Consumption
July 2nd to 6th ,2016	4 %	-	58 %	38 %
September 1st to 6th , 2016	10 %	3 %	43 %	41 %

This research takes advantage of several real-time EnergyPlus inputs in the second phase of calibration process (seven weather parameters, two system parameters, and one plant parameter) which leads to output a more accurate projected building performance. However, future works may include adding CO_2 and occupancy sensors data to the EnergyPlus calibrated model as a real-time input to predict the people's behavior and consequently the building internal heat gains in real time.

Now that the real-time Cx and PM&V framework is set up and tested in a case study building, there are a lot of opportunities for future studies and experiments. The case study building is capable of being used as a living lab to experiment more options of Real-Time Cx and PM&V framework as follows:

- Occupancy behavior, lighting and equipment energy use profile may be improved in EnergyPlus calibrated model by using the CO2 and occupancy sensors.
- The fault detection and diagnosis algorithm may be improved. A research project may focus on the particular HVAC operational fault and the list of corrective actions can be extended for each specific fault. The BCVTB model may run for the shorter timestep (15-minute or one-minute interval) to detect the fault precisely.
- The corrective action recommendation may be studied more in detail and for each particular performance metric, a specific control algorithm could be developed to be able to write to the system in real time and change the building system operation in real time.

- According to the building codes, the calibrated model should be accurate enough to be reliable for being used in the Cx and PM&V cases, but EnergyPlus calibration process (IPMVP Option D) is so challenging and time consuming. Developing methods to automatically tune and automate the calibration process will facilitate the real time building performance monitoring and save a lot of time and resources in this field.

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APPENDICES

APPENDIX A. CASE STUDY BUILDING ZONE SUMMARY

Table A-1 : Case Study Building Zone Summary

Zone Name	Area [ft^2]	Conditioned (Y/N)	Volume [ft^3]	Gross Wall Area [ft^2]	Window Glass Area [ft^2]	Lighting [Btu/h-ft^2]	People [ft^2 per person]	Plug [Btu/h-ft2]
A0-ELECELEV	38.88	Yes	388.84	0	0	1.7058	64.59	14.329
A0C9-CORRIDOR	1002	No	10018.18	73.17	0	2.5588	129.18	3.4117
CORRIDOR-LVL1	201.7	No	2017.08	0	0	2.5588	129.18	3.4117
CORRIDOR-LVL2	201.7	No	2017.08	0	0	2.5588	129.18	3.4117
EASTSTAIRS	357	No	5177.17	775.34	0	1.7058	129.18	0
ELEV BOX	81.03	No	3524.94	0	0	1.7058	129.18	10.235
FCU-VAV-A045-FREEZERFARM	1027	Yes	10270.38	0	0	2.9237	129.18	10.235
LAN A017	154.2	Yes	1541.91	0	0	2.5588	129.18	4.094
LAN A117	142.3	Yes	1423.07	0	0	2.5588	129.18	4.094
LAN A217	123	Yes	1230.02	0	0	2.5588	129.18	4.094
NORTHSTAIRS	328.5	Yes	14291.16	2246.58	189.67	1.7058	129.18	0
PLENUM-LAKE LVL	14467	No	65114.38	1760.23	0			
PLENUM-LVL1	14472	No	65126.65	1703.15	0			
PLENUM-LVL2	14472	No	65126.65	1703.15	0			
VAV-A006	991.6	Yes	9918.13	510.59	148.51	2.5588	129.18	3.4117
VAV-A009	479.7	Yes	4796.73	464.94	252.02	2.5588	32.29	8.5292
VAV-A010	620.7	Yes	6190.5	0	0	2.5588	129.18	3.4117
VAV-A013	710.4	Yes	7103.81	289.07	0	2.5588	129.18	1.7058
VAV-A015A	964.8	Yes	9648.59	310.07	0	2.5588	129.18	3.4117
VAV-A015B	883	Yes	8830.5	310.07	0	2.5588	129.18	3.4117
VAV-A020A	2392	Yes	23922.63	620.47	336.03	2.5588	129.18	3.4117
VAV-A020B	2439	Yes	24964.14	1265.22	672.07	2.5588	129.18	3.4117
VAV-A022	553.4	Yes	5534.54	0	0	2.5588	129.18	3.4117

Table A-2 : Continued

Zone Name	Area [ft2]	Conditioned (Y/N)	Volume [ft3]	Gross Wall Area [ft2]	Window Glass Area [ft2]	Lighting [Btu/h-ft2]	People [ft2 per person]	Plug [Btu/h-ft2]
VAV-A034	415.5	Yes	4158.39	0	0	2.5588	129.18	3.4117
VAV-A044	324.2	Yes	3242.52	142.4	84.01	2.5588	129.18	1.7058
VAV-A048	482.3	Yes	4823.31	195.23	0	1.7058	129.18	1.7058
VAV-A0LOBBY	458.6	Yes	4581.37	154.98	32.25	2.5588	129.18	1.7058
VAV-A108	738.5	Yes	7385.78	632.48	336.03	2.5588	129.18	3.4117
VAV-A110	614.8	Yes	6148.32	630.06	336.03	2.5588	129.18	3.4117
VAV-A111	934.4	Yes	9344.24	814.96	420.04	2.5588	129.18	3.4117
VAV-A114	841.9	Yes	8419.85	0	0	2.5588	129.18	3.4117
VAV-A122	234.4	Yes	2343.88	0	0	2.5588	129.18	3.4117
VAV-A130A	680.3	Yes	9762.76	851.38	504.05	2.5588	129.18	3.4117
VAV-A130B	3152	Yes	31525.11	0	0	2.5588	129.18	3.4117
VAV-A131A	773.1	Yes	7731.45	592.28	336.03	2.5588	129.18	3.4117
VAV-A131B	2910	Yes	29103.87	0	0	2.5588	129.18	3.4117
VAV-A134	477.1	Yes	4771.48	0	0	2.5588	129.18	3.4117
VAV-A136	496	Yes	4960.4	0	0	2.5588	129.18	3.4117
VAV-A144	879.6	Yes	8796.83	195.23	84.01	2.5588	129.18	3.4117
VAV-A148	1155	Yes	11554.78	276.42	0	1.7058	129.18	1.7058
VAV-A1LOBBY	1152	Yes	13913.3	759.43	189.02	2.5588	129.18	1.7058
VAV-A208	738.5	Yes	7385.78	632.48	336.03	2.5588	129.18	3.4117
VAV-A210	965	Yes	9650.79	804.19	420.04	2.5588	129.18	3.4117
VAV-A211A	734.4	Yes	7344.76	989.09	504.05	2.5588	129.18	3.4117
VAV-A211B	3303	Yes	33034.43	0	0	2.5588	129.18	3.4117
VAV-A214	861.3	Yes	8612.9	0	0	2.5588	129.18	3.4117
VAV-A219	234.4	Yes	2343.88	0	0	2.5588	129.18	3.4117
VAV-A230A	812.7	Yes	8127.42	677.25	420.04	2.5588	129.18	3.4117
VAV-A230B	2820	Yes	28308.23	11.12	0	2.5588	129.18	3.4117
VAV-A231	580	Yes	5800.37	418.15	252.02	2.5588	129.18	3.4117
VAV-A232	496	Yes	4960.4	0	0	2.5588	129.18	3.4117
VAV-A234	477.1	Yes	4835.5	2.13	0	2.5588	129.18	3.4117

Table A-3 : Continued

Zone Name	Area [ft2]	Conditioned (Y/N)	Volume [ft^3]	Gross Wall Area [ft^2]	Window Glass Area [ft^2]	Lighting [Btu/h-ft^2]	People [ft^2 per person]	Plug [Btu/h-ft^2]
VAV-A244	436	Yes	4360.23	195.23	84.01	2.5588	129.18	3.4117
VAV-A245	443.6	Yes	4436.59	0	0	2.5588	129.18	1.7058
VAV-A248	624.4	Yes	6244.68	68.39	0	1.7058	129.18	1.7058
VAV-A2LOBBY	1152	Yes	13913.3	759.43	189.02	2.5588	129.18	1.7058
Total	45091		474736.32	16667.84	6125	2.509	125.08	3.3517
Conditioned Total	43248		451981.87	15819.33	6125	2.5156	124.91	3.3645
Unconditioned Total	1843		22754.45	848.51	0	2.356	129.18	3.0508
Not Part of Total	86822		390735.36	10333.08	0	0		0

APPENDIX B. TECHNICAL GUIDELINE

This guideline leads the user through installation and technical issues of each software or tool that are used in this research.

JRE 1.8.0-92 (JAVA Runtime Environment)

1) Check the java version of your computer by typing code below into the command prompt.

C:\>java –version (It shows the java version on your computer.) if the java version is not up to date, download the latest version.

2) Download the installation file from (http://www.oracle.com/technetwork/java/javase/downloads/jre8-downloads-2133155.html). This package includes JDK 1.8.0-92 (JAVA Development Kit) which is needed to run BCVTB).

3) For Windows 10:

Go to ➔ Control Panel\System and Security\System\Advanced System Settings\Environment Variable\System Variable\click on Path\ Copy jre and JDK paths and paste them here. Now you can compile and run java codes including BCVTB functions.

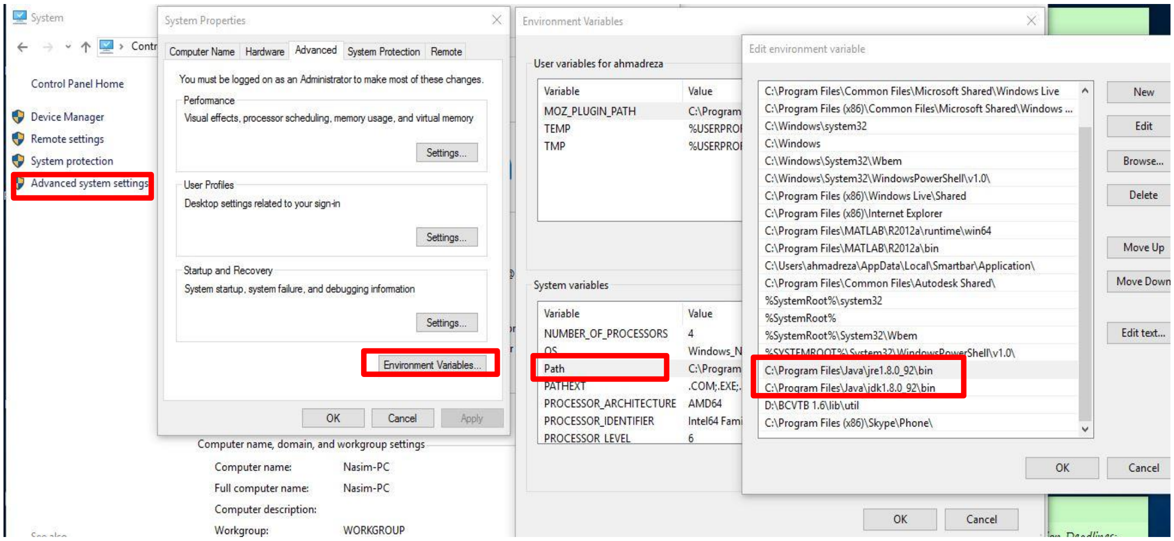

Figure B-01: Java Class Path Settings

EnergyPlus 8.5

Download the installation file from (https://energyplus.net/downloads)

Building Controls Virtual Test Bed (BCVTB) 1.6.0 (win 64bit)

The main required tools are Java, version: 1.8.0-77 or higher (win64bit) and EnergyPlus, version: 8.5 or higher.

1) Download the installation file, bcvtb-install-win64bit-1.6.0.jar, from the download page run the installation program and install the program in a directory called BCVTB.

2) Depending on your installation, you may need to set system environment variables. When the BCVTB starts, it reads environment variables from the file bcvtb/bin/systemVariables-win.properties. This file needs to be modified by the user to set the

path to the different programs that are used by the BCVTB. The file can be edited with any text editor.

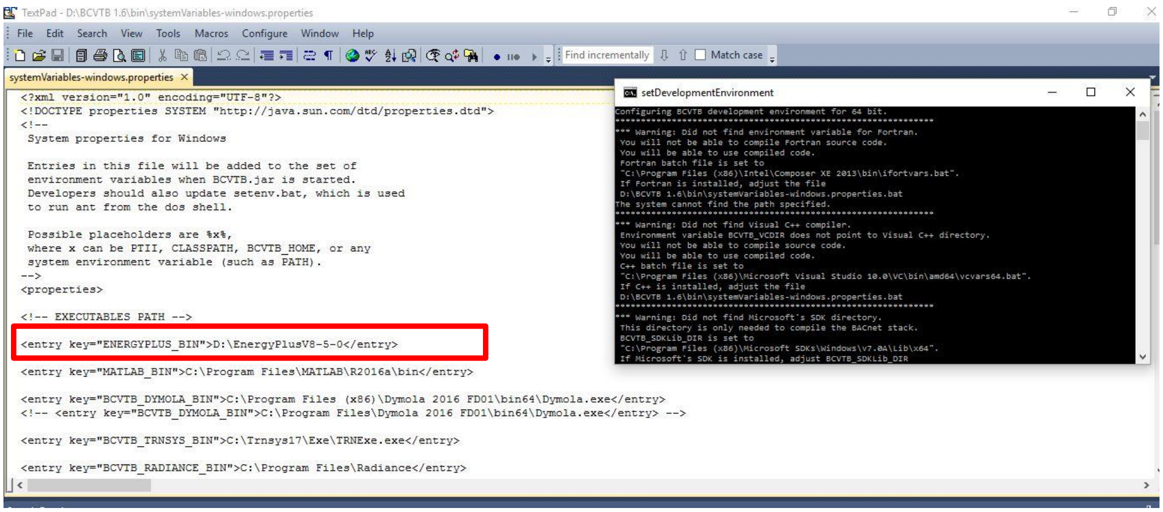

Figure B-2: System Variables File

PostgreSQL 9.5 (DataBase)

1) Download the installation file from (https://www.postgresql.org/). You can find how to install the PostgreSQL on Windows here on YouTube: https://www.youtube.com/watch?v=-f9lke78g2U

2) Restore the X.backup file in PostgreSQL

3) Create a Database as named in BCVTB

4) Right-click on that DataBase, and restore the X.backup file

JDBC (JAVA Database Connectivity)

It is an API that helps you connect your java program (BCVTB) to the database (PostgreSQL) and do the manipulation of data through Java program (BCVTB)

1) For JDK 1.8 please download JDBC42, Postgresql Driver, Version 9.4-1208 at (https://jdbc.postgresql.org/download.html)

2) Then go to ➔ Driver C \ Program File \ Java\ jre 1.8.0-92\lib\ext (copy the JDBC42 file here)