ENERGY EFFICIENCY ANALYSIS AND OPTIMIZATION FOR THE GLENNAN BUILDING AT CASE WESTERN RESERVE UNIVERSITY

by

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Energy Efficiency Analysis and Optimization for the Glennan Building at Case Western Reserve University

Abstract
by
AYMAN SAMY ELSHAMY

0.1 Abstract

Different energy conservation measures were applied to the Glennan Building located on the Case Western Reserve University Campus in Cleveland, Ohio to assess their potential impact. Building geometry was first developed using the DesignBuilder program, while the EnergyPlus program was used to define the different parameters and systems in the building and to run the energy simulation. A customized weather file for the year 2013 was created using actual weather data on a six-minute interval basis. The energy simulation was run and the model was calibrated to the required accuracy. Using the calibrated model as a baseline, different energy conservation measures were applied to the building model and the corresponding energy savings were evaluated. It was found that ECM set# 3 (changing the cooling/heating set point temperature, the HVAC
system schedules and the plug loads schedules) requires minimal investment but offers significant energy savings. Other ECMs are less attractive due to their long payback period.
1 Introduction

Energy consumption rates have been increasing rapidly worldwide due to the growth of the population and their direct power consumption, manufacturing power needs, climate changes, and other factors. However, the limited availability and cost of natural resources have raised the need for more efficient and lower power-consuming buildings. A more energy-efficient building can be achieved at the design stage but also during operation through smart decision-making about building controls, equipment and materials. Of course each building has specific requirements, and energy efficiency improvements are oftentimes specific to a building’s shape, size, age, orientation, operational capabilities and more. Different software packages are available for the purpose of building energy modeling, and while cumbersome to run, this software can accurately investigate and ultimately help prioritize energy conservation measures that may be implemented for energy savings. The software packages require a computational representation of the building, inputs about the building components’ materials, information about occupancy and equipment power usage schedules, and other related factors. The software simulates the inputs
and predicts the power consumption of the building allowing a comparison between different design modules; creating a choice for the best. Different energy conservation measures may be investigated to assess impact and ascertain the associated payback period.

The objective of this thesis is to identify the key factors that may play an important role in improving the energy efficiency of buildings, and more specifically may lead to energy savings in the Glennan Building on the CWRU campus. By creating a building model and running associated energy simulations, key insight can be gained and scenarios applied to improve the energy efficiency or energy conservation in a building. Although there is a difference between energy efficiency and energy conservation, both actually lead to operational cost-savings and lower CO2 emissions. For example when you turn the TV off when you are not watching it that is energy conservation, but if you buy an Energy Star rated TV, one that consumes less energy while giving you the same size and picture quality, that is energy efficiency. By viewing the new simulation results in a measurable way, the decision maker can prioritize according to, for example, payback periods. This will ultimately lead to reduced energy consumption and a step toward addressing our global environmental challenge.
1.1 Energy and Climate Change

The importance of energy conservation has been increasing over the past several decades, not only due to rising energy costs but also because of global warming and climate change. Of great concern is the rise in global concentration of carbon dioxide (CO2) in the atmosphere, which reached 400 parts per million (ppm) for the first time in 2014, compared to pre-industrial (1750-1850 timeframe) concentrations of about 280 ppm. Today’s 400 ppm is already higher than the 350 ppm that most scientists and climate experts have agreed is the limit for a safe Earth. In order to significantly reduce energy consumption, an interest in designing and operating more energy efficient buildings has developed. An analysis published by Lawrence Livermore National Laboratory and based on the Department Of Energy (DOE) and U.S. Energy Information Administration (EIA) data, suggests that the U.S. wastes a considerable amount of energy each year [1]. For the year 2013, the analysis shows that 59 quadrillion British thermal units (quads) was rejected, with an overall efficiency rate close to 39.4%, as shown in Figure 1.1. Of course some of this wasted energy is a requirement of the system due to thermodynamic limits, but there remains great opportunity for improvement. Ideally, improving energy efficiency would meet the current and future needs of our world, without compromising on process, quality, or comfort. To aid in this cause in January 2006, Architecture 2030 (a non-profit organization) issued The 2030 Challenge, a global initiative requiring that all new
Figure 1.1. The 2013 energy flow chart released by Lawrence Livermore National Laboratory details the sources of energy production, how Americans are using energy, and how much waste exists [1].
buildings be “carbon neutral” by 2030 [2]. Further in May 2007, the American Institute of Architects (AIA), the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), Architecture 2030, the Illuminating Engineering Society of North America (IESNA), and the U.S. Green Building Council (USGBC), supported by representatives of the U.S. Department of Energy, finalized an agreement of understanding, and agreed to define the starting baseline as the national average energy consumption of existing U.S. commercial buildings according to the Commercial Building Energy Consumption Survey (CBECS) 2003 [2], and specified the targeted energy reduction progress to reach the carbon neutral buildings target by 2030.

The commercial and residential building sector accounts for approximately 39% of total energy consumption and 38% of the CO2 emissions in the United States per year, more than the industrial or transportation sectors [3], as shown in Figure 1.2. With energy conservation in mind, in 2013 President Obama announced “A new goal for America: Let’s cut in half the energy wasted by our homes and businesses over the next 20 years” [4].
Buildings account for about 39 percent of total U.S. energy consumption [5].

1.2 Energy Modeling History

The use of an energy modeling tool to assess the expected building energy consumption and potential efficiency opportunities during the design phase is invaluable. A building energy model requires inputs that describe the building location and orientation, building layout, materials used in the construction, occupancy and operational schedules, internal heat gains, and weather conditions. Utilizing these input data, the software can perform load calculations, which allows for selection of the proper heating, ventilating, and air conditioning
system. Inputting the selected HVAC system equipment along with its specifications and data along with other key selections, the total estimated power consumption can be an output for the energy modeling software. The versatility of the software enables engineers to consider a number of HVAC system designs, all of which may satisfy the cooling, heating, and ventilation needs, but may lead to different power consumption. Energy modeling software can also be used to consider different scenarios for an existing building. Using a similar approach as for new buildings and applying different energy conservation measures or scenarios, one can investigate options that will lead to a noticeable conservation of energy in consideration for costs.

According to the Building Energy Modeling Book (BEMBook) [6] – a web based project by IBPSA-USA in collaboration with the Rocky Mountain Institute and the support of ASHRAE, the history of Building Energy Modeling (BEM) can be traced back to 1925 when Nessi and Nisolle used Response Factor Methods (RFM) to perform hand calculations of transient heat flow [7]. Nessi and Nisolle determined a multilayered slab’s heat flux response to a unit step temperature change numerically [8]. Decades later, Mitalas and Stephenson published several papers in the early 1960s examining heat transfer through walls using RFM [9]. They derived a set of heat balance equations to describe the dynamic thermal characteristics of a room, assuming the heat transfer through building elements is one dimensional and a uniform air temperature throughout the room.
In 1960, Carrier also published a first-of-its-kind System Design Manual for HVAC system design. At the time, HVAC companies were using only manual procedures to calculate dynamic heat flow in buildings to aid in system design [11]. Then in the late 1960s, Bradley Peavy at the National Bureau of Standards (NBS) made use of the advanced computers available to him to develop techniques to map heat conduction in underground fallout shelters and published his research in 1968 [12]. He determined the conduction error of the probes that are used in ground temperature measurements with a mathematical analysis for steady periodic, two-dimensional heat flow in a two body composite [12]. In the late 1960s, Tamami Kusuda started developing a computer program that was a major step towards whole-building energy modeling when he developed the National Bureau of Standards Load Determination (NBSLD) [13], which allowed the prediction of temperatures and heating and cooling loads under dynamic conditions. This model was validated by Frank Powell and Douglas Burch by measurements performed on buildings with different energy profiles and under different conditions [13]. In a separate effort but around the same time, Automated Procedures for Engineering Consultants, Inc. developed the APEC Heating and Cooling Peak Load Calculation program [9], that enabled calculating hourly peak and annual heating-cooling HVAC system loads. The 1970s was marked with a rise of interest in BEM by different government organizations. In 1971, the U.S. Post Office recruited the General American Transportation Corporation to develop an energy use analysis program for post office buildings
Later on, the National Aeronautics and Space Administration (NASA) developed its own BEM based on the ‘Post Office Program’ [14]. In 1974, the U.S. Army Construction Engineering Research Laboratory (CERL) created the Buildings Loads Analysis and System Thermodynamics (BLAST) program [15]. Later in 1978, the California Energy Commission adopted the California Energy Research and Development Administration (CAL-ERDA) as the state’s official BEM program. Energy Research and Development Administration (ERDA) became DOE, and CAL-ERDA became DOE-1 [16]. Most of the government-developed BEM programs were revised and updated in the 1980s. As personal computers grew cheaper and became more accessible to the public and small companies, the need for an interactive BEM with a visual interface arose. The Department of Energy (DOE), Lawrence Berkley National Labs (LBNL), and the Electric Power Research Institute (EPRI) joined forces to develop an updated version for DOE-2 with a visual interface to be known as DOE-2.2 [16]. eQuest v1.0, an interface for the DOE 2.2 platform developed by James J. Hirsch & Associates, was released in June 1999 [16]. By the mid-1990s, the Department of Energy developed its own new and improved program called EnergyPlus. EnergyPlus (E+) became a program designed to combine the advantages of BLAST and DOE-2.1E [16]. Newer versions of EnergyPlus were released with more features, EnergyPlus 8.1.0 was released at the end of 2013, while EnergyPlus 8.2.0 was released in October 2014 [17]. The energy modeling history is summarized in Figure 1.3.
Introduction

Figure 1.3 History of building energy modeling [18]
1.3 EnergyPlus

EnergyPlus is arguably the most sophisticated building load simulation and energy analysis program available today. It is the official building simulation program of the United States Department of Energy, and with its wide capabilities and sub-hourly time steps it has become one of the most popular energy modeling software programs for engineers and researchers, and has been rated by experts as the most powerful software for energy analysis and energy efficiency measures [19] [20] with greater capabilities than BLAST and DOE-2.1E programs (which EnergyPlus was based upon) [21].

In EnergyPlus, one must input the data that represents the building and its operational conditions. A geometry model needs to be created for the building that is to be simulated, its orientation and location (longitude, latitude, and elevation) defined, and its corresponding weather file to be chosen. Weather files consist of average weather data for a specific location created from data recorded over a long duration. Special weather information can also be defined. Appropriate construction materials must be inputted to the software, allowing the calculation of the heat transfer rates throughout the simulation. Internal gains are used to estimate the loads inside the building allowing engineers to choose the right HVAC system. The internal gains such as from people, equipment, and lighting should be properly described by a schedule of occupancy/operation. The
HVAC system schedule must also be defined, and an individual equipment schedule set. Infiltration tools are available to estimate the unintended air movement through the zone. While each room can be simulated as a zone (thermal zone), rooms served by the same HVAC equipment can be combined as one zone if they share similar conditions, i.e. occupancy and operation schedules as well as similar set point temperatures. This will even reduce simulation time and data input requirements.

There are many graphical interfaces that can be used with EnergyPlus, as EnergyPlus by itself does not provide a user-friendly graphical interface. For example, Sketchup, with its OpenStudio plugin, is one such graphical interfaces, DesignBuilder is another. These graphical interfaces are used to create the geometry of the building and include some added features and capabilities. Although one can launch EnergyPlus simulations and view results with the graphical interface included with EnergyPlus, exporting EnergyPlus “IDF” files and working in the EnergyPlus IDF editor enables enhanced features, capabilities, and study of a wider range of HVAC systems, allowing for more advanced simulation capabilities.
1.4 Literature review

The results of the energy simulation process vary from one building to another depending on the variables that describe each building model. The effectiveness of each key parameter in improving the energy efficiency of the building also varies from building to building. For example, installing shading devices for a building will be more effective in a hot and sunny location than in a cold one or for south-facing windows rather than those north-facing. Energy modeling is important to understand the effect of shading and the net balance of heat gain (or blocking) due to radiation from incoming sunlight and heat gain/loss due to conduction through the windows. Here we discuss several key studies that have been conducted to investigate the use of building energy modeling on understanding energy consumption in buildings. These studies provided insight to the present work by helping to understand how EnergyPlus can be used for building energy modeling as it is intended in this study, as well as the simulation capabilities that make is a robust simulation tool.

K. Lee and T. Cheng [22] used EnergyPlus to study hourly and daily optimization of chilled water and cooled water set point temperatures in a traditional office building in Taipei, Taiwan. They observed that a dynamic set point temperature for chilled and cooled water can reduce the total energy consumption. They found, for example, that although the energy consumption by the pumps and
cooling tower may increase when decreasing the cooling tower set point temperature and increasing the set point temperature of the chiller, the total energy consumption of the system will decrease. The study was done for four summer days and four winter days. This study revealed important information to the building science community because it considered a new way of thinking about the varying optimum chilled water set point temperatures instead of finding a single optimum one. It also highlighted the importance of the energy modeling in verifying the optimal operating conditions of buildings’ systems, and that EnergyPlus is a good energy simulation tool.

In another study, T. Miyazaki, A. Akisawa, and T. Kashiwagi [23] investigated the application of see-through solar cells to windows in office buildings, and the effect of varying the solar cell transmittance and Window to Wall Ratio (WWR) on the electricity consumption. By using a double glazed window with semi-transparent solar cells, the window will provide electricity production even though additional internal heat gain may arise through the window to the building. In this study EnergyPlus was used to calculate the heating and cooling loads. The study found an optimum photovoltaic window (transmittance & WWR) that can significantly reduce the electricity consumption. This study demonstrated that these technologies should be considered for buildings as the energy simulation verified results showed possible energy savings of 55% in the electricity consumption by using solar cell transmittance of 40% and WWR of 50%,
compared to the electricity consumption when using single glazed window with WWR of 30%. The cost of this application remains important to understand the feasibility of such application.

A.L.S. Chan et al. [24] studied the effect of a double skin façade on the energy consumption for an air-conditioned office building using EnergyPlus. A double skin façade is a set of multiple glass skins with an air gap in between; this air can be tight or ventilated either naturally or mechanically. The investigators started by validating a computer simulation model of a double skin façade air-conditioned room and compared with actual measurements. The results showed that the computer simulation model can reliably predict the energy performance for a double skin façade. They used EnergyPlus to simulate the different possible construction approaches for the double skin façade and compared the saved energy. They concluded that for their case study building in Hong Kong, a 26% savings in the cooling energy can be achieved by using a double skin façade with double reflective glazing on the outer pane and single clear glazing on the inner pane. This saving is relative to the use of a conventional single skin façade with single absorptive glazing. However, the study concluded also that due to the long payback period, local government support is needed to achieve widespread application in buildings.

heat transfer through the layers of the surface construction, to simulate the application of phase change materials (PCM) to a building while maintaining all other aspects of a detailed energy simulation. PCMs can enhance the building’s energy performance by shifting the loads and reducing the peak loads. Construction solutions with PCMs act as latent heat thermal energy storage systems. He concluded that the finite difference solution algorithm is the most flexible in simulating the PCM because of the extreme variability of the layers of the building surface construction. The paper highlighted when it is favorable to use the finite difference algorithm over the Conduction Transfer Functions which is the traditional way of simulating the heat transfer in EnergyPlus. In a separate study, P. Velasco et al. [26] verified and validated the PCM model in EnergyPlus. Using an approach consisting of analytical verification, comparative testing and empirical validation, they identified two bugs and fixed them in the PCM model, and announced that version 8 of EnergyPlus will include the validated PCM model to confidently investigate the application of PCM and its effect on the energy efficiency. The study also showed the predicted improvement in energy efficiency when using PCM at different locations in the building. Their model demonstrated a reduction in the peak cooling load in the peak month of July: 4.3% for their Phoenix, Arizona model.

R. Lollini et al. [27] studied the energy efficiency of a dynamic glazing system and used EnergyPlus to generalize the experimental results conducted on a dynamic
glazing system prototype. They used a triple-glazing system constructed from three glazing layers with air gap between each two layers, arranged from outdoor to indoor as 1-outside glazing, 2- outer air gap of 22 mm, 3-middle glazing, 4- ventilated inner air gap of 11 mm, 5-inside glazing, with a built-in shading venetian blind component in the outer gap whereby the inner gap utilized mechanical ventilation. In order to investigate the effect of the different glazing system construction on the energy efficiency and comfort, they considered four glazing constructions; three triple glazing systems and one double glazing. They applied a low emission coating layer on a different glass side for each of the four systems. The best thermal comfort and energy efficient condition was achieved when mechanical ventilation was applied to the inner air gap with a fan that was activated at a temperature difference of 2 C° between the inner air gap and indoor air temperature, combined with a low emission coating layer is applied on the outer side of the middle glazing. The cost of this application and the payback period remains important to uncover its feasibility for different building applications.

David J. Sailor et al. [28] used the EnergyPlus program to analyze the effects of roof surface design on a building’s energy consumption. They ran simulations for different green roofs and on black and white membrane roofs, for two buildings types in four cities--New York, Houston, Phoenix, and Portland. They discovered that for buildings that are heating dominated, increasing soil depth on green roofs
increased heating savings; while for cooling-dominated buildings, increasing the leaf area index (projected leaf area per unit area of soil surface) was more important for cooling energy savings. In another study by Georgios Kokogiannakis et al. [29], EnergyPlus was used to study the effect of different green roof models on energy efficiency of buildings across major Chinese climate zones in Beijing, Shanghai, Guangzhou, Xian, Harbin and Sanya. Different green roof models were simulated by EnergyPlus with different construction types such as glazing, walls, etc. Their results offered a quick database for selecting the green roof type in Chinese climate. From this study, and comparing the different models’ results, it was found that the effect of green roofs on improving the energy efficiency is not significant if heavy roof insulation is applied.

The effectiveness of applying single and multiple energy retrofit measures on overall energy consumption was studied by S. Chidiac et al. [30]. They adopted EnergyPlus to examine the effectiveness of applying different energy retrofit measures on three building types in three cities--Ottawa, Edmonton, and Vancouver. They compared the linear addition of multiple Energy Retrofit Measures (ERMs) with the simulation results combined using EnergyPlus. They found that the majority of simulation results are less beneficial than the sum of single ERMs, as the effectiveness of multiple ERMs depends upon their interactive effects. They even found that in fewer cases combining ERMs can be more beneficial than using individual ERMs. This study has confirmed the
importance of examining the different possible ECM scenarios on the buildings, and that if different measure sets are available to choose from, these sets should be energy modeled to choose the best effective combination.

Through these studies and many others, EnergyPlus has proved to be a powerful energy simulation tool that can accurately predict buildings' energy efficiency. This is why the tool was preferred over other energy simulation programs for this work. These studies also demonstrated that the program includes many innovative simulation capabilities, making it a robust simulation tool for investigating energy efficiency.
2 Case Study – The Glennan Building

This chapter introduces the Glennan building that is to be modeled, shown in Figure 2.1. An overview is provided for the building layout, location, orientation, and nearby buildings or trees that shade part of the modeled building. The description also includes the building type, occupancy, lighting type, and equipment. It also includes a description of the Heating, Ventilating and Air Conditioning (HVAC) system.

Figure 2.1 The Glennan Building
2.1 Building Description

The building that was modeled in this work is the Glennan Building on the Case Western Reserve University campus in Cleveland, OH. It is named for T. Keith Glennan, who was the fourth president of the Case Institute of Technology. The Glennan Building was built in 1968 and opened officially in January 1969. The building is located on the main campus and is accessible from Adelbert road as well as Martin Luther King, Jr. Avenue, as shown in Figure 2.2. It houses the Mechanical and Aerospace department as well as the Electrical Engineering and

![Figure 2.2 Location of the Glennan Building][1]
Computer Science department. Glennan is an eight-story building, in addition to the penthouse where the old cooling tower was located. The building entrance from Martin Luther King, Jr. Avenue is on the first floor, while the entrance from the field side (Adelbert road) is on the third floor due to the difference in street levels. The north side of the building is mostly toilets, mechanical rooms, stairs, elevators, and a few laboratories. The south, east, and west sides are mainly offices with some laboratories and classrooms. The core of the building is mainly laboratories with a few classrooms. The Glennan Building has no underground parking and is connected to the White Metallurgy Building via an atrium (shown in Figure 2.3); they are connected with an interior access on the first, second, fifth, and sixth floors. The third and fourth floors are still connected, but with no
access between them. On the floors where they are accessible, a door separates the two buildings making each of them a separate, conditioned building. The north and south adjacent buildings, along with few trees on the east side of the building, shade parts of Glennan. Most of the windows are located on the south and east side; there are no windows on the west side (shown in Figure 2.4), and a few windows are located on the north side (only two windows between the third and the eighth floors, and one window on the second floor). Floors have some

Figure 2.4 West side of the building has no windows
differences in area due to the lack of the atrium on the seventh and eighth floors and the smaller first floor footprint area, as shown in Figure 2.5.

\[\text{Figure 2.5} \quad \text{First floor has less footprint area}\]

### 2.2 Building Occupancy

As a typical university educational building, the building consists mainly of offices, classrooms, and laboratories. Offices are usually occupied by one person with possible varying guests throughout the day; some offices are occupied by graduate students where more than one desk can be found in a single room. Classrooms usually have less than the maximum capacity during lectures, and
have a schedule for occupancy that differs from one classroom to another and along the different semesters of the year. Laboratories are usually occupied by few students; however, the third floor labs can have high occupancy.

2.3 Building HVAC System

The Glennan building used to have two chillers (one small electric motor driven compressor chiller and another bigger steam absorption unit chiller); both chillers are not in service now, and the chilled water is being supplied from a central chilled water plant. A chilled water pump located in the penthouse is responsible for pumping the chilled water to the different air handling units (AHU). Each of the eight floors has its own AHU that has two coils; a heating coil as well as a cooling coil. All air handling units are double ducted such that both the cold air duct and the hot air duct are connected to the same AHU. The air handling units blow a mix of return and outside air to the conditioned areas and take outdoor air (OA) by means of intake plenums fixed on wall openings on the north side of the building as shown in Figure 2.6. Variable speed drives are connected to the units in order to control air flow rate. The AHUs blow the air through air ducts that are fitted with terminal VAV (variable air volume) units. A single VAV may serve more than a single room. Exhaust fans serving the laboratories’ hoods are located on the roof (there are seven fans), in addition to the toilets’ exhaust fan, and a fan on the roof that serves the mechanical room, but is usually switched off.
2.4 Building Lighting and Equipment

Most of the installed light bulbs in the building are fluorescent T8 4ft 32W, 2ft 20W, and 8ft 59W. A few 42W four-pin bulbs are used mainly at the vestibules near elevator #1. The building is serviced by two elevators, 2000 lb and 6000 lb each with a 25 hp motor located at the penthouse. Laboratories are laid out across the building, and each lab has its own specific equipment and tools. Most
of the laboratories do not have a fixed schedule for the operation of these tools and equipment; some have not been used for years, and some equipment is used for a few days throughout the year or when needed. Equipment scattered throughout the building also has large variations in their power requirements. Some of the biggest power-consuming labs are in Swagelok (the Surface Analysis of Materials lab) on the first floor, the Think[box] Invention Center on the second floor (which has a wide variety of tools and equipment), and the Biomechanics labs on the 6th floor. The term *equipment* in EnergyPlus also includes all socket loads; such as computers, refrigerators, microwaves, coffee machines, printers, scanners, screens, projectors, air dryers, etc. All of these tools and equipment are considered to be power-consuming devices as well as heat-generating devices. When doing energy simulation, these devices have to be allocated in a service zone, along with their schedule of operation and percentage of loading, if applicable.
3 Modeling and Simulation

This chapter describes the phases or steps that were taken in order to develop a model and run the energy simulation for that model. The model is a virtual building created with computer software. This model should dynamically represent the actual building and any systems that consume power along with their corresponding manner of operation. The model should also reflect the surrounding environment of the building; such as the exact geographical location of the building and the corresponding weather. The Glennan Building, which is the case study here, is a relatively old building, and there were no Computer-Aided Design (CAD) drawings for the building or for the installed systems in the building. Even more, the available required input data for EnergyPlus was limited, and as a result some data needed to be estimated. Comparing the simulation results with the actual measurements obtained from the building electricity and energy meters gives an indication of how close these estimates may have been to actuality.

The geometry of the building can be created using one of the graphical interface software programs, as the energy simulation program (EnergyPlus) does not have a user-friendly graphical interface by itself. The energy simulation is run
after all the data input has been completed for the created virtual model. A weather file describing the different weather parameters at the location of the building must be utilized to capture accurate energy consumption of the building.

### 3.1 Modeling with Sketchup

The first model of the Glennan Building - shown in Figure 3.1 and Figure 3.2- was created using Sketchup. Sketchup (formerly: Google Sketchup) is a 3D modeling software, developed to match the design needs of different industries, such as Engineering (architectural, interior design, civil and mechanical), and other entertainment industries [32]. Sketchup is known to be easy to learn 3D

![Figure 3.1 First model for the Glennan building using SketchUp](image-url)
modeling software. While drawing the building model, the program was found flexible to draw and easy to learn, which makes it a good tool to create a model for the building.

The Legacy OpenStudio plug-in for SketchUp facilitates creating and editing the building geometry model in EnergyPlus input files [33], in addition to adding the energy simulation potentiality of EnergyPlus to the Sketchup module [33]. However, and for advanced simulations, the input file will usually require some editing in EnergyPlus as some input objects are still not available in the Legacy

![Figure 3.2 Section plane using SketchUp](image)
OpenStudio Plug-in [33]. Other than not being a fully-featured interface with EnergyPlus, another disadvantage is that an energy model description for the building should be identified before starting to model.

### 3.2 Modeling with DesignBuilder

A second model was created using a different graphical user interface called DesignBuilder, which gives the flexibility of defining and modifying the thermal zones even after the building geometry is completed, which is not feasible using SketchUp. DesignBuilder is easy-to-use software that requires minimal expertise and only a basic understanding of building engineering [34]. It is integrated with EnergyPlus and has extensive material libraries which are helpful when selecting the used materials. The units system can be chosen to be either SI or IP.

When starting a new project, the location and analysis type is chosen. For this work, Cleveland, OH and EnergyPlus were selected, respectively. The highest level in the model hierarchy is the Site, and therefore a site name is first chosen. The second level in the hierarchy is the Building; a new building is added under the previously-named site, and a building name can be assigned to it. Multiple buildings can be assigned under the same site, each with its own name. The third level in the hierarchy is the Block. The block usually represents one floor, and is commonly named with that floor name or number. The zoning phase
separates the different thermal zones. Considering that this building model is being created for the purpose of energy simulation, different rooms can be joined to form one thermal zone if they share the same thermostat, have similar thermal loads, or use the same HVAC system.

Zoning, or creating thermal zones, is an important task. While using a fewer number of zones is recommended for faster simulation, assigning a more discrete number of zones can improve the accuracy of the simulation results. Even more, a single large open area can also be divided into several thermal zones. For example, two zones representing the core and perimeter may be used to better capture how heat is transferred throughout, allowing for more accurate simulation results. For this work, each room in the Glennan Building is considered a zone, totaling 263 thermal zones. Significant data input and simulation time is required to achieve this representation, but more accurate results were expected. Discrete zoning also allows the assigning of different operational schedules or the application of different energy conservation measures (ECMs) to each zone. Each of the walls in each zone is called surface. Surface is the next level in the model hierarchy. Exterior windows were assigned where applicable, and the DesignBuilder software recognizes windows as sub-surfaces and are called openings. The hierarchy of the Glennan building is partially shown in Figure 3.3.
The DesignBuilder program gives the ability to choose the materials used in the construction of the building through its material libraries, and the chosen materials are assigned to the specified parts of the building. These steps were repeated for all floors to complete the entire building model.
The effect of nearby buildings was also included to simulate their shading of the Glennan Building. Located on the north and south sides of Glennan, these are referred to as *Component Blocks*. A component block allows the modeling of shading without including thermal zones. Nearby trees were also modeled as shading-component blocks; each tree consists of a trunk-component block as well as a branches-component block. Different transmittance schedules for the branches (during the different seasons of the year) and trunk are set. The as-modeled shading buildings and trees are shown in Figure 3.4.

Once the building model created by DesignBuilder is created, it is then exported to the EnergyPlus input data file, and energy modeling and simulation continues using EnergyPlus.
3.3 Modeling & Simulation using EnergyPlus

Following the DesignBuilder import, additional data input required by EnergyPlus can be accomplished either through the *IDF editor* or the *Text editor*—as shown in Figure 3.5 and Figure 3.6. The text editor requires greater experience and familiarity with EnergyPlus. The IDF editor was largely used for this study since it was found to be more convenient.

![EP-Launch](image)

*Figure 3.5 Text editor & IDF editor*
The weather file is a file that describes the different weather parameters throughout the year. Different weather files for different locations around the world can be found in the EnergyPlus library and are downloaded with the program. The Department Of Energy’s Office of Energy Efficiency & Renewable Energy website has more than 2,100 locations available in the EnergyPlus weather format [35]. More than 1,000 of these locations are in the USA. These weather files represent the Typical Meteorological Year (TMY), which corresponds to the average weather across several years for a particular location. For this study, in addition to using the nearest location TMY weather file
(Cleveland-Burke-Lakefront), a custom weather file for the year of 2013 was created to enable an accurate comparison with the actual building energy consumption during the same specified year. The 2013 weather data was collected from the National Oceanic and Atmospheric Administration (NOAA) website [36]. The data is based on six minutes of interval readings (total of 87,600 annually). The EnergyPlus software package provides a weather converter executable that, with the use of the two previously mentioned files (readings file and definition file), can generate an EnergyPlus Weather file (EPW) that can be used by EnergyPlus to perform the simulation.

In EnergyPlus, each data that is to be input is a Field. Different fields are arranged under a common Object. Different objects are arranged under a common Group. The different groups form the information included in the Input Data File. It is important here to note that not all the Groups, Objects, or Fields data will have entries since some are not applicable for the specific building. For example, the fields about solar collectors should be left blank if solar panels are not present.

The first group is the Simulation Parameters. The first object in this group is the Version which describes the version of the software; version 8.1.0.008 was first used and was then updated to 8.1.0.009. The second object is the Simulation Control, the chosen fields are Do Sizing Calculation, Do System Calculation, Run Simulation for Sizing Periods, and Run Simulation for Weather File Run Periods.
The next object (with its fields) describes the building. It was named: Glennan Building, with a 320 degrees orientation with the north axis (as shown in Figure 3.7), city located, with values of 0.08 watts and 0.4C as the Loads Convergence Tolerance Value and the Temperature Convergence Tolerance Value, respectively. When either one of the tolerances is achieved, the convergence is considered done. This tolerance represents the relation between the heat balance and the HVAC system. Using loose tolerances will minimize the run time; however the results will not be accurate.

The Minimum and Maximum Number of Warm-Up Days represents the days that the program simulates before convergence is achieved. If convergence is not satisfied by the maximum number of days, the program will show an error, and an increase in the maximum number of days will be required. The minimum number of days is set to avoid false early conversions. In this case study, 40 and
6 days were used as maximum and minimum, respectively. In fact, the EnergyPlus input/output help file recommends using 6 days as the minimum to avoid a false convergence. The Shadow Calculation object with its fields describes the criteria used to assess the shadowing effect. For this study, a frequency of 20 days was used such that the average sun position over the 20 days is employed to determine the magnitude of the sunlight impinging on the building.

Appropriate methods must be chosen to analyze the heat transfer within the system such as on the outside, through and around the inside of a wall, for example. The two objects Surface Convection Algorithm: Inside and Outside were chosen to be represented by the TARP (for inside) and DOE-2 (for outside) methods as is commonly done in similar simulations. In TARP, the heat transfer coefficient is related to the temperature difference, and is a good choice for flat surfaces, while DOE-2 uses correlations from field measurements. The Heat Balance Algorithm object defines which algorithm is used to analyze the conduction through the different layers of a wall, the Conduction Transfer Function (CTF) algorithm is chosen as a default. All algorithms chosen for convection or conduction are used by the program for all surfaces, but can be modified for each surface as a special case when entering data for zones and surfaces. It is worth remembering that Surface here means the surface level in
the hierarchy and may represent a wall with its thickness, as described earlier in the discussion about DesignBuilder.

The *Time Step* object describes the number of time steps per hour; 10 time steps per hour were chosen for this study, which is the same as the number of readings per hour in the weather file that was developed from the actual 2013 readings. All the previous objects with its related fields are listed under the group *Simulation Parameters*.

Location and climate are described in the following group. The *Site Location* describes the building which is chosen here as the Glennan Building, having a latitude of 41.5015 degrees and a longitude of -81.607 degrees, the time zone is 5 hours and the elevation equals 207m (679 ft.). The *Sizing Period: Design Day* object which comes next, describes the days chosen as a reference for load calculations and sizing of the HVAC equipment. Design days are generally those days that the HVAC system is designed to maintain the indoor conditions. In most applications they are not the most extreme winter and summer days, as extreme-days-data do not reflect the actual or the weather trend during these periods. Designing the HVAC system according to the extreme data would be too costly and is typically not advised. The ASHRAE Fundamentals handbook recommends using 0.4% and 99.6% for summer design day and winter design day values, respectively, which mean only 0.4% and 99.6% of the annual hours will exceed the design days temperatures [37]. For Glennan, the design days that
are included in the weather file were used, which correspond to the ASHRAE guidelines.

The Run Period object specifies the start and end dates of the simulation. An annual simulation for 2013 year starting from January 1st and ending December 31st was defined. The Day Light Saving Time object has been set to start on the 2nd Sunday in March and to end on the 1st Sunday in November. Ground Reflectance was chosen to be 0.2 [38] with a snow modifier of 2 (typical urban site) (Hunn and Calafell 1977) [39]. Different reflectance values from ASHRAE 2009 handbook are shown in Table 3.1 [40].

<table>
<thead>
<tr>
<th>Foreground Surface</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (large angle of incidences)</td>
<td>0.07</td>
</tr>
<tr>
<td>Coniferous forest (winter)</td>
<td>0.07</td>
</tr>
<tr>
<td>Bituminous and gravel roof</td>
<td>0.13</td>
</tr>
<tr>
<td>Dry bare ground</td>
<td>0.2</td>
</tr>
<tr>
<td>Weathered concrete</td>
<td>0.22</td>
</tr>
<tr>
<td>Green grass</td>
<td>0.26</td>
</tr>
<tr>
<td>Dry grassland</td>
<td>0.2 to 0.3</td>
</tr>
<tr>
<td>Desert sand</td>
<td>0.4</td>
</tr>
<tr>
<td>Light building surfaces</td>
<td>0.6</td>
</tr>
<tr>
<td>Snow-covered surfaces:</td>
<td></td>
</tr>
<tr>
<td>Typical city centre</td>
<td>0.2</td>
</tr>
<tr>
<td>Typical urban site</td>
<td>0.4</td>
</tr>
<tr>
<td>Typical rural site</td>
<td>0.5</td>
</tr>
<tr>
<td>Isolated rural site</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Source: Adapted from Thevenard and Haddad (2006).

Table 3.1 Ground reflectance of Foreground surfaces [40], © ASHRAE 2009 handbook (Fundamentals): table:5 P.14.11
A very important descriptive group is the Schedules. In this group, different schedules are created and assigned to different objects that are time dependent. These objects can be occupancy, set point temperature, operation of certain equipment, etc. The Schedule-Type Limits describe the lower and upper limits of each schedule type with a Numeric Type to be chosen as continuous or discrete. For example, the On/Off schedule type has a minimum of zero and a maximum of 1 and its numeric type is discrete, it is not continuous between zero and 1, as zero means off and 1 means on. While a fraction-schedule type has a minimum and maximum of zero and one respectively, but the numeric type is continuous as it can be any number between zero and one. For example, 0.35 is used to represent 35% such as may be the case of classroom 421 occupancy schedule between 16:15 and 17:30 on Tuesdays from January 14th until April 29th, where 35% of the defined classroom maximum capacity attend specific class. Schedule-type limits are editable and new type limits can be created as appropriate. Schedules were created to describe the operation hours and set point temperature of each of the air handling units, daily and annually variable set point temperatures for each zone, zone occupancy, zone people’s activity, zone clothing insulation, zone lighting, zone equipment, and transmittance of the shading trees. Some of these schedules were described simply using a few lines within the simulation software while others required as much as 269 fields (e.g. occupancy) due to frequent variability throughout the day and year.
To arrive at the schedules for Glennan, data was collected through various means. Onsite inspection was used in some cases such that people were surveyed about their own occupancy. Some zones share similar occupancy schedules, like professors’ offices, while others are more random, like the occupancy of the laboratories. Similarly, the operation schedules of the different labs’ equipment varied considerably and in many cases could not be validated. Even the people directly responsible for some of these labs could not provide an exact schedule for the operation of their equipment or tools. Some equipment had not been used recently, but their future use was unknown. In order to arrive at the best possible accuracy for the building occupancy, the actual schedules of all classes held in Glennan Building in 2013 during the different semesters were used, including the number of students and the time of each class. Class occupancy schedules may have a large influence on energy consumption since the number of students entering and leaving the building throughout the day can be high.

*Surface Construction Elements* is another group, with its different objects that describe the materials used in the construction of the building. Different objects describe different element types. For example, *Material* objects describe the limestone, cast concrete, concrete blocks, insulation board, gravel, etc. *Window Glazing*, *Window Gas*, and *Window Blinds* are other objects. Each of the objects has its thermal properties described by EnergyPlus and DesignBuilder, which
both have good material libraries. It is also possible to add new materials to the library and define their thermal properties, such as conductivity, specific heat, density, and roughness. For this work, materials were cited directly in the 1969 drawings of Glennan and used in the simulation. Certain material descriptions were not provided, assumptions were required. Cast concrete, limestone and concrete blocks were selected from the DesignBuilder material library, while the windows’ materials and construction were assumed referring to the manufacturer’s website [41].

An object named Construction arranges the previously defined elements (materials) as layers to form a construction. For example, an installed double glazing window is a construction of three elements: glazing, air, and glazing. Different walls and slabs are other constructions. The Glennan Building roof is an example of a construction object has different elements: gravel, built-up roofing, insulation board, then cast concrete arranged from outside layer to inside layer. Figure 3.8 shows the outer layer of the roof construction. Each of these elements was previously defined (as a materials object) according to the building drawings. Different constructions are also assigned to the different surfaces of the building under the groups: Thermal Zones and Surfaces.
The **Thermal Zones and Surfaces** group describes the different zones in Glennan: 263 zones, 3049 surfaces, 399 fenestration surfaces, shading, and other geometry-related objects. A good DesignBuilder model simplifies the work here and defines the coordinates of each vertex for each surface. Each zone, surface, or fenestration surface should have a unique name. Zones’ names are always used in assigning loads, systems, and their related schedules to the different zones. Each of the 3049 building surfaces is assigned to its zone and assigned a construction name (as previously defined), and assigned a surface type such as a floor, wall, or ceiling, and whether it is sun and/or wind exposed (Figure 3.9). Figure 3.10 and Figure 3.11 shows the shading buildings and window reveals.

Figure 3.8 Roof as a construction object has different layers--cast concrete, insulation board, built-up roofing, and gravel comes as an outer layer
**Figure 3.9** One of the 3049 building surfaces in the Glennan Building

<table>
<thead>
<tr>
<th>Field</th>
<th>Units</th>
<th>Obj41</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>4thFloor:ClassRoom401420_Wall_2_0_0</td>
<td></td>
</tr>
<tr>
<td>Surface Type</td>
<td>Wall</td>
<td></td>
</tr>
<tr>
<td>Construction Name</td>
<td>External Wall 1 Glennan</td>
<td></td>
</tr>
<tr>
<td>Zone Name</td>
<td>4thFloor:ClassRoom401420</td>
<td></td>
</tr>
<tr>
<td>Outside Boundary Condition</td>
<td>Outdoors</td>
<td></td>
</tr>
<tr>
<td>Outside Boundary Condition Object</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sun Exposure</td>
<td>SunExposed</td>
<td></td>
</tr>
<tr>
<td>Wind Exposure</td>
<td>WindExposed</td>
<td></td>
</tr>
<tr>
<td>View Factor to Ground</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Number of Vertices</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Vertex 1 X-coordinate</td>
<td>m</td>
<td>32.003790597</td>
</tr>
<tr>
<td>Vertex 1 Y-coordinate</td>
<td>m</td>
<td>-11.9445701764</td>
</tr>
<tr>
<td>Vertex 1 Z-coordinate</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Vertex 2 X-coordinate</td>
<td>m</td>
<td>-3.7072469764</td>
</tr>
<tr>
<td>Vertex 2 Y-coordinate</td>
<td>m</td>
<td>12.9509520001</td>
</tr>
<tr>
<td>Vertex 2 Z-coordinate</td>
<td>m</td>
<td>32.003790597</td>
</tr>
<tr>
<td>Vertex 3 X-coordinate</td>
<td>m</td>
<td>-3.7072469764</td>
</tr>
<tr>
<td>Vertex 3 Y-coordinate</td>
<td>m</td>
<td>16.8615360001</td>
</tr>
<tr>
<td>Vertex 3 Z-coordinate</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Vertex 4 X-coordinate</td>
<td>m</td>
<td>32.003790597</td>
</tr>
<tr>
<td>Vertex 4 Y-coordinate</td>
<td>m</td>
<td>-11.9445701764</td>
</tr>
<tr>
<td>Vertex 4 Z-coordinate</td>
<td>m</td>
<td>16.0615360001</td>
</tr>
</tbody>
</table>

**Figure 3.10** Shading by other buildings and trees is considered in the model under Shading: Building: Detailed object
The internally generated loads are described in the group *Internal Gains* with its different objects, as not all loads are due to the external weather. In addition to the loads generated internally, this group also considers the power consumption of these load generators, if applicable. The internal gain objects that are applicable to Glennan are: *People, Lights, and Electric Equipment*. As there are 263 zones in Glennan, there are also 263 people objects, 263 light objects, and 263 electric equipment objects. Each one of these objects has a full description for the related load in one of the 263 zones. Each of the 263 people objects describes the people’s internal gain in one of the zones; this includes the number
of people which can be described by different criteria; such as, people/area or area/people or simply the exact number of people in that zone.

The number of people in each zone was determined by defining the maximum possible occupancy of this zone set by the occupancy schedule as discussed previously. For example, Glennan 421 (a classroom) has a capacity of 100 but fractions were used to represent the actual occupancy (dates and times) defined by the CWRU schedule of classes. The same approach was used for all the 263 zones and their respective occupancy schedules throughout the year 2013. The activity level, describing how active occupants are, and accordingly, the heat gain per person in Watt/Person, must also be defined. Of course metabolic rates vary, but a constant value of 110 W was used, which is nearly equivalent to 1 met as shown in Table 3.2 from the ASHRAE 2009 handbook [42], and is a good representation for a reading or writing seated person metabolic rate.

Lights and electric equipment were defined under the same group Internal Gains. Similar to the People object, each of the Lights and Electric Equipment has 263 objects representing the lighting and electric equipment in these zones.
<table>
<thead>
<tr>
<th>Activity</th>
<th>Btu/h·ft²</th>
<th>met*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleeping</td>
<td>13</td>
<td>0.7</td>
</tr>
<tr>
<td>Reclining</td>
<td>15</td>
<td>0.8</td>
</tr>
<tr>
<td>Seated, quiet</td>
<td>18</td>
<td>1.0</td>
</tr>
<tr>
<td>Standing, relaxed</td>
<td>22</td>
<td>1.2</td>
</tr>
<tr>
<td>Walking (on level surface)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.9 fps (2 mph)</td>
<td>37</td>
<td>2.0</td>
</tr>
<tr>
<td>4.4 fps (3 mph)</td>
<td>48</td>
<td>2.6</td>
</tr>
<tr>
<td>5.9 fps (4 mph)</td>
<td>70</td>
<td>3.8</td>
</tr>
<tr>
<td>Office Activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reading, seated</td>
<td>18</td>
<td>1.0</td>
</tr>
<tr>
<td>Writing</td>
<td>18</td>
<td>1.0</td>
</tr>
<tr>
<td>Typing</td>
<td>20</td>
<td>1.1</td>
</tr>
<tr>
<td>Filing, seated</td>
<td>22</td>
<td>1.2</td>
</tr>
<tr>
<td>Filing, standing</td>
<td>26</td>
<td>1.4</td>
</tr>
<tr>
<td>Walking about</td>
<td>31</td>
<td>1.7</td>
</tr>
<tr>
<td>Lifting/packing</td>
<td>39</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 3.2 Typical metabolic heat generation for various activities, © ASHRAE 2009 handbook (Fundamentals): table:4 P.9.6 [42]

Lighting level can be assigned to each zone in different ways; in watts, watts per zone area, or watts per person. For this work, the lighting level in watts was defined for each zone using the information provided on the building drawings as well as collected during the site survey. The type of lighting fixture defines the two fields *Return Air Fraction* and *Fraction Radiant*. With the as-installed suspended, surface, or recessed types of lighting in Glennan, the return air fraction is zero. Figure 3.12 shows the different lighting fixtures types. The fraction radiant is 0.42 for the suspended fixture, 0.37 for recessed and 0.72 for
surface mount fixtures, with the fraction visible set to 0.18 for the three types. These are the default values given in EnergyPlus for the respective fixture types.

Figure 3.12 Overhead fluorescent luminaire configurations [43]

Electric equipment and their schedules were also assigned to each of the 263 zones. This includes all plug loads in the zones, such as computers, printers, lab equipment, and tools. Getting the power of the equipment and tools was a challenge since there metering at that level is not done, as was their schedule of operation. Some laboratories’ power ratings were available from personnel responsible for the lab; other labs needed to search online for the average power of similar equipment.
The intended ventilation such as provided by intake and exhaust fans and the unintended infiltration are described by the *Zone Airflow* group. Figure 3.13 shows some exhaust fans on the roof. The *Zone Ventilation* describes the exhaust fans each as a separate object and assigns them to a zone or group of zones. Assignment of fans to a group of zones such as is the case for bathrooms on different floors, a zone list was created as an object under the group *Thermal Zones and Surfaces*, and assigned accordingly. As appropriate, a schedule was assigned to each exhaust fan although some fans were assigned to be thermostatically controlled. The exact design flow rate for each fan was defined in cubic feet per minute (CFM). Exhaust fans mainly serve toilets, labs, the transformer room, and other equipment rooms, while the AHUs supply the different floors with the required outdoor air as a percentage of the supply air.

Figure 3.13  Exhaust fans on the roof, described under *Zone Airflow* group
Infiltration was assumed to be present in zones with external exposure with 0.2 cfm/ft\(^2\) as the assumed rate. The ASHRAE 2009 Fundamentals Handbook [44] points to a study conducted by Tamura and Shaw (1976a) [45], which found that in a study of 8 Canadian office buildings with sealed windows, the air leakage ranged from 0.12 to 0.48 cfm/ft\(^2\). For tight, average, and leaky walls the air leakage is typically 0.1, 0.3, and 0.6 cfm/ft\(^2\), respectively [45]. The Glennan Building was considered to be between tight and average, which is why 0.2 cfm/ft\(^2\) was assumed. In addition, an estimated infiltration through stair and elevator doors of 1400 cfm each floor was also assumed using ASHRAE guidelines. Infiltration through the external access doors varies throughout the day and year. A schedule was created to estimate the first and third floors’ infiltration (since both have external access doors). Figure 3.14 shows open windows as another possible avenue for infiltration although the simulation did not consider this type of infiltration given its rarity.
The *Exterior Equipment* group in this study has only one applicable object which is the exterior lighting. In Glennan, there are three 30W LED fixtures that were included in the simulation.

The *HVAC Templates* group describes the HVAC system and its configurations. In the *Thermostat* objects, the different cooling and heating set points were created and assigned. Each thermostat object can have a constant set point or a defined set point schedule. Typically, each thermostat object has a unique name. The air handling units (AHU) in Glennan are of the dual duct type, each which has two coils: a cooling coil and a heating coil, with two air supply ducts for cold and hot air. The *HVAC Template System: Dual Duct* objects describes each of the AHUs in the building. A unique name and schedule was assigned to each
AHU. The system configuration type was defined; which specifies whether a single or double fan at constant or variable volume is installed. Glennan AHUs are single fan, variable speed. Glennan AHUs range between 940 and 12500 CFM. Other data required for each AHU are: minimum flow fraction (in the case of variable speed), fan delta pressure, motor efficiency, and total efficiency. The object *Main Supply Fan Motor in Air Stream Fraction* sets the conditions of the motor-in-air configuration of the system; a value of 1 indicates that the motor is immersed within the air stream such that all the waste heat from the motor enters into the air stream. The following objects describe the cooling and heating coils of each of the AHUs. For example, the cooling coils in Glennan are defined as chilled water coils. The cooling coil design set point temperatures were taken from the available drawings and ranged between 47F and 53F for the different AHUs. These defined AHUs are assigned to the different zones under the objects of *HVAC Template Zone: Dual Duct*. Each of the air-conditioned zones is assigned a unique name, a dual duct AHU, and a thermostat. The zone cooling and heating design supply air temperatures are 55F and 100F, respectively, according to the building drawing equipment schedule. Baseboard heating types were assigned where applicable such as in the stairs, bathrooms, and vestibules.

The objects *HVAC Template: Plant: Chiller* and *Chilled Water Loop* are the objects that describe the chilled water source. The available options are the different chiller types as well as a *District Cooling* option. Glennan utilizes district
cooling provided by a central plant. The chilled water pump is described under the object named *Chilled Water Loop* which defines the pump schedule, type (variable speed in Glennan), chilled water design set point (5.55 C), pump rated head ($2.0923 \times 10^5$ Pa), and if there is any secondary pump (not applicable for Glennan). The fluid type was chosen as water with a loop design delta temperature of 7.22 C. The pump schedule time was used to represent the availability of the chilled water in Glennan (available from April to October).

There are two additional objects that describe the heating systems: *HVAC Template: Plant Boiler* and *Plant: Hot Water Loop*. Glennan employs a district heating system also provided via steam generated in a central plant. The hot water pump is always available (secondary hot water pump is not applicable for Glennan), and has a rated head of 149454 Pa, and the hot water design set point temperature is 98.88 C.
4 Results and Calibration

4.1 Running the simulation

![Running simulation screen](image_url)
All the previously discussed data forms the Input Data File (IDF) and along with the weather file (EPW) feed into EnergyPlus. The progress of the simulation is initially displayed once the simulation is run (Figure 4.1) along with any errors that may have been flagged. Certain errors will require correction and a new simulation to be run. The total time elapsed for a single simulation depends on the modeled building and their different inputs. For this case study, simulation time was about four hours.

### 4.2 Initial Results

The simulation results are presented in an extensive report document output by the software. To initially assess accuracy, the simulation annual electrical power consumption and the actual power consumption collected from the building electricity meter in 2013 were compared. Chilled water and steam readings were not available since there are no meters at the building level. From 2013 data, the total annual electricity consumption was 1973796.25 kilowatt-hours (kWh). Following some error correction and calibration, the annual electricity consumption from the simulation was 1917023.53 kWh, while the district cooling and heating were 1165525.49 kWh and 2429215.69 kWh, respectively. In comparison, the actual electricity consumption is 2.96% greater than that determined by the simulation (Table 4.1). Figure 4.2 shows simulated and actual daily consumption prior to calibration. While the actual readings do not vary
Results and Calibration

significantly from the simulation results, it is important to assess the accuracy of the simulation and to then make adjustments, or calibrate, accordingly. A formal calibration analysis is adhered to as discussed next.

<table>
<thead>
<tr>
<th></th>
<th>Electricity [kWh]</th>
<th>District Cooling [kWh]</th>
<th>District Heating [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual reading</td>
<td>1973796.25</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Simulation (prior to calibration)</td>
<td>1917023.53</td>
<td>1165525.49</td>
<td>2429215.69</td>
</tr>
<tr>
<td>Actual / Predicted</td>
<td>1.029615</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 Initial simulation output vs. actual consumption prior to calibration.
Results and Calibration

Figure 4.2 Daily consumption during June prior to calibration.

4.3 Calibration

In energy modeling, calibration is the act of adjusting the different model parameter uncertainties to improve the model to achieve a high level of accuracy. ASHRAE guideline 14-2002 provides recommendations on at what level an acceptable uncertainty is achieved. This is accomplished at a normalized mean bias error (NMBE) of 5% and a coefficient of variation of the root mean square error (CVRMSE) of 15% relative to monthly calibration data [46] such that:
Results and Calibration

\[ NMBE = \frac{\sum(y_i - \hat{y}_i)}{(n - p) \times \bar{y}} \times 100 \]

\[ CVRMSE = 100 \times \left[ \sum (y_i - \hat{y}_i)^2 / (n - p) \right]^{1/2} / \bar{y} \]

where:

- \( y \) = dependent variable of some function of the independent variable(s)
- \( \bar{y} \) = arithmetic mean of the sample of \( n \) observations
- \( \hat{y} \) = regression model’s predicted value of \( y \)
- \( n \) = number of data points or periods in the baseline period
- \( p \) = number of parameters or terms in the baseline model, as developed by a mathematical analysis of the baseline data. The ASHRAE guideline states that \( p = 1 \) when the simulation is compared to actual building meter readings [46].

The initial simulation run led to an \( NMBE \) of 5.44 and \( CVRMSE \) of 7.94. The \( NMBE \) was out of the ASHRAE accepted 5%, requiring attention to be focused on input uncertainties.

To overcome these issues, revisions were made to the data with the highest uncertainty – the scheduled fraction of the used equipment in the different laboratories. These labs are equipped with many tools and equipment that sometimes are rarely used, and for most labs no schedule for equipment was known. Given the relatively large contribution of this equipment to the electricity
usage, the uncertainty of this equipment is of particular concern, and in order to do such adjustments, the fractions that represent the percentage of the used equipment during the different hours in each lab were modified in their corresponding schedules. In addition, lighting was altered to address the fact that some of the classrooms’ and labs’ lighting schedules were not altogether accurate, lighting hours for these zones were extended for about 30 minutes after class hours as it is common to find some students staying after class hours for some time. By re-running the simulation after each calibration and analyzing the results, followed by re-calibration and re-simulation, a final model was reached that meets the ASHRAE-approved accuracy with an NMBE of 0.183 and CVRMSE of 4.79, which are impressive values in consideration for the ASHRAE guidelines.

4.4 Results

The following Table 4.2 shows an annual comparison between the actual and the simulated power consumption following calibration.
The final calibrated model showed compliance with the ASHRAE, NMBE, and CVRMSE accuracy limits, and it demonstrated greater energy consumption than the initial simulated cases. A comparison of the daily electricity consumption during the month of June shows a closer picture of the difference between simulated and actual consumption as demonstrated in Figure 4.3. The higher accuracy is evident in a comparison with Figure 4.2, which is prior to calibration.
Figure 4.3 Calibrated model daily power consumption compared to the actual daily power consumption during the month of June.

Another comparison between actual and simulated monthly electricity consumption during the year 2013 is shown in Figure 4.4. Again, the consumption is similar for both the actual and simulated results with only September demonstrating a large difference. Oftentimes, simulation of the “shoulder” months such as September can exhibit a high uncertainty due to large fluctuations in temperature over the month, and the building’s corresponding
Developing the model for Glennan was an arduous task, requiring months of document referencing (e.g. blueprints), researching materials in the buildings, surveying occupied space (e.g. for equipment and plug load schedules) and then inputting all this information into DesignBuilder and EnergyPlus. To realistically
model and analyze buildings to explore the potential impact of ECMs, a more simplified approach might be required. As a result, a reduced zones model was created for the Glennan Building by merging all the conditioned zones in each floor together. The new model had a total of 49 thermal zones with 1 conditioned zone per floor (9 total) and 40 unconditioned zones (e.g. the transformer room, stairways, etc.) in the building. Based on the experience gained through this study, it is estimated that constructing the reduced zones model would take less than half the time as was required for the full modeling of 263 zones. The duration of the reduced zones simulation was 75 minutes, much less than the four hours spent for the full 263 zones model. This was expected as a result of fewer computational thermal calculations required. The simulation results are shown in Table 4.3.
### Table 4.3  Comparison between the energy consumption of the 263 zone and the 49 zone models

<table>
<thead>
<tr>
<th></th>
<th>Electricity [kWh]</th>
<th>District Cooling [kWh]</th>
<th>District Heating [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual reading from building meters</td>
<td>1973796.25</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>263 zones Simulation (post-calibration)</td>
<td>1970488.75</td>
<td>1171565.09</td>
<td>2436978.6</td>
</tr>
<tr>
<td>49 zones simulation</td>
<td>1845885.05</td>
<td>1088104.56</td>
<td>2266878.94</td>
</tr>
</tbody>
</table>

The simulation results showed some variation between the two models. The electricity consumption for the reduced zones model is 6.3% lower than for the 263 zones model. The district cooling and district heating consumption was also reduced but by 7.1% and 7.0%, respectively. The full zone model results more closely matched the actual electricity readings from the building meters. While using a reduced zones model saves considerable time associated with data input as well as simulation run time, the inaccuracies associated with lumping
differentiated zones together may not be appropriate. Lack of accounting accurately for external exposure is one possible reason why the results differ. The inaccurate distribution of the internal loads (people, lighting and equipment) in the reduced zones model may be another possible reason. In addition, the interchangeability of air and heat transfer between the different rooms is differently accounted for in the two different models. For example with the case of one conditioned zone per floor, if hot air coming from a server room is a heating source for another room, the energy savings for the room during winter and additional cooling requirements in the summer would not be accurately accounted for by the reduced zones model. Alternatively, the reduced zones model could be enhanced by modeling the core of each floor as a separate zone with no exposure to the external weather conditions or solar radiation, while dividing the perimeter into four different zones (north, south, east and west) as the external loads due to solar radiation vary between the four sides. This would nearly double the number of zones in the reduced zones model. For the in-depth study of Glennan, the larger 263 zone model will be used.
5 Analysis

Since the purpose of this study was to analyze the value of potential energy conservation measures (ECMs), it is important to first have a deeper understanding of the nature and breakdown of the energy consumption of the building. As for the site total energy consumption, the district cooling and district heating should also be considered. Among all, district heating is the largest energy consumer as shown in Figure 5.1. The high energy consumption related to the heating of the building is expected due to the cold winters in Cleveland and

![Energy Consumption kWh](image)

**Figure 5.1** Total energy consumption for the building in 2013
the large temperature differential between exterior and interior during this season. Figure 5.2 demonstrates the percentage of power consumption for the different trends. The electricity consumed by interior equipment is the largest fraction at 49.89%, followed by interior lighting at 26.28%, fan consumption at 20.65%, pumps at 2.67%, cooling at 0.49% and exterior lighting at 0.02%. The relatively high energy consumption for interior equipment is largely because the building is comprised of many laboratories. In consideration for the district energy, electricity is 35% of the total energy usage, district heating 44% and district cooling 21%. Given Glennan is located in a heating dominated climate, this balance of load is expected.
The interior equipment accounts for almost 50% of the electricity consumption of the building, which means that any significant savings in energy consumption of equipment can have a major impact.

Figure 5.3 illustrates the breakdown of the power consumption by equipment for each floor. Note that the elevators' electricity consumption is considered within the penthouse consumption. The largest contribution to the equipment energy consumption comes from the Swagelok Center in which many large pieces of equipment for materials analysis are located. The first floor equipment where the Swagelok Center is located, accounts for about 38% of the building's equipment electricity consumption, which is about 19% of total building electricity consumption.
The second major contributor to electricity consumption is the interior lighting. The percentage of the interior lighting distribution by floor is presented in Figure 5.4, and is more uniform in comparison with the equipment electricity distribution over the different floors, this is expected due to the variation of the equipment distribution in the laboratories at these floors.

Glennan, with its 114680.4 ft$^2$ area, exhibits a total energy use intensity (EUI) (total energy use divided by square footage) of 48.7 kWh/ft$^2$ or 166 kBTU/ft$^2$ as
demonstrated by the simulation results. The EUI is a measure typically used to compare building performance given in units of kBTU/ft$^2$. While used for comparison purposes, a good or bad EUI depends on factors such as location (weather), building use (activity), and building age. Typically, an energy efficient hospital in North Dakota will have a very different EUI than an energy efficient elementary school in Florida, for example.

According to the 2003 Commercial Buildings Energy Consumption Survey (CBECS) by the U.S. Energy Information Administration [47], the national average site EUI for a college/university is 120 kBTU/ft$^2$. This is defined for a campus, so in addition to classrooms and offices, the EUI also assumes inclusion of residential areas and other campus buildings. More appropriate might be a comparison with other buildings in a climate similar to Cleveland. The Pittsburgh 2030 district [48] uses a median energy baseline for different building-use types in downtown Pittsburgh (about 130 miles from Cleveland), and for a higher education building, the median site EUI is 165 kBTU/ft$^2$/Year [48].
6 Energy Conservation Measures

Energy simulations may be conducted for various purposes such as to design or retrofit a more energy efficient building. More commonly used during the design phase, energy simulations can be used to maximize the efficiency of the energy consumption expected in the building by investigating how layout, orientation, construction materials, systems installed, etc. influence performance. Here, the objective was to examine the effect of various energy conservation measures (ECMs) and their impact. Using a calibrated model that responds like the actual building, allows one to investigate different potential scenarios.

6.1 ECM# 1 – Cooling/Heating set point temperature

The first ECM examined the effect of modifying the set point temperatures for cooling and heating. Referring to the acceptable range of operative temperature and humidity for occupied spaces in ANSI / ASHRAE Standard 55-2004, the set point temperatures were adjusted to 68 and 76 (for winter heating and summer cooling, respectively), which are still within the thermal comfort zone. Figure 6.1 shows the recommended temperature range for summer and winter (0.5 Clo and
1.0 Clo) which is applicable for typical offices. These temperatures must also fall within the lower and upper recommended humidity limits.

The energy simulation output is shown in Table 6.1. A reduction in the total energy consumption of 6% is achieved at these setpoints, which reflects a potential energy saving if this ECM is applied. District heating and district cooling show the highest reduction in energy consumption compared to electricity, this is expected as the ECM is directly related to the heating and cooling energy consumption.

Figure 6.1 Acceptable range of operative temperature and humidity for spaces that meets the criteria specified in section 5.2.1.1 © ANSI/ASHRAE Standard 55-2004, Figure 5.2.1.1 [49]
### 6.2 ECM# 2 – HVAC system (AHUs and pumps) schedules

The second ECM investigated changing the schedule of each of the AHUs and pumps. All AHUs and pumps were switched off from 10 pm until 2 hours before the scheduled occupied time. This ECM is commonly used in buildings that are not operating on 24/7 basis, and is applicable for the Glennan Building. The expected reduction in energy consumption is shown in Table 6.2. The table shows that a remarkable 11% of the total energy consumption can be saved by applying these modified schedules.

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>District Cooling</th>
<th>District Heating</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (KWh)</td>
<td>1970488</td>
<td>1171565</td>
<td>2436978</td>
<td>5579031</td>
</tr>
<tr>
<td>ECM (KWh)</td>
<td>1941610</td>
<td>957021</td>
<td>2054671</td>
<td>4953302</td>
</tr>
<tr>
<td>% Difference</td>
<td>-1.47%</td>
<td>-18.31%</td>
<td>-15.69%</td>
<td>-11.22%</td>
</tr>
</tbody>
</table>

Table 6.2  Energy saved due to modifying the HVAC schedules
6.3 ECM# 3 – Additional insulation for the external walls

This energy conservation measure focuses on increasing the overall thermal resistance of the external walls in the building. An insulation board is assumed to be applied to the internal side of the external walls, exhibiting a thermal conductivity of 0.25 Btu-in/h-ft²-F. Additionally, insulation is assumed to be injected into the 1” gap between the external wall and the external limestone as indicated is present in the building drawings. This insulation exhibits a thermal conductivity of 0.194 Btu-in/h-ft²-F. Both insulation materials’ were selected from the DesignBuilder materials’ library. The results are shown in Table 6.3, reflecting potential saving in the energy consumption. The total energy consumption is reduced by 3.45% due to this ECM. This comes from a reduction in district heating energy use (7.36%), which is expected given the building location and the cold weather in Cleveland and the corresponding indoor and outdoor temperature difference in winter. Interestingly, there is little impact on the cooling energy consumption.

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>District Cooling</th>
<th>District Heating</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (KWh)</td>
<td>1970488</td>
<td>1171565</td>
<td>2436978</td>
<td>5579031</td>
</tr>
<tr>
<td>ECM (KWh)</td>
<td>1967214</td>
<td>1161962</td>
<td>2257554</td>
<td>5386730</td>
</tr>
<tr>
<td>% Difference</td>
<td>-0.17%</td>
<td>-0.82%</td>
<td>-7.36%</td>
<td>-3.45%</td>
</tr>
</tbody>
</table>

Table 6.3 Energy consumption before and after applying additional insulation to external walls
ECMs

6.4 ECM# 4 – Adding vestibule to building entrance

The access to the building is through exterior doors at the 1\textsuperscript{st} and 3\textsuperscript{rd} floors, but opening and closing these doors increases the infiltration into the building as is included in the model. Applying a vestibule to both doors will decrease this infiltration. Following chapter 16 of the 2009 ASHRAE Handbook [50], and applying the modified infiltration parameter to the building model to simulate two vestibules, the simulated energy consumption was found as given in table Table 6.4. after applying this ECM, district heating is reduced by 3.72\%, district cooling by 1.06\% and electricity by 0.12\%. Again, the largest contribution to the reduced energy usage is heating given the heating-dominated climate in Cleveland.

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>District Cooling</th>
<th>District Heating</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (KWh)</td>
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<td>1171565</td>
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<tr>
<td>ECM (KWh)</td>
<td>1968097</td>
<td>1159118</td>
<td>2346212</td>
<td>5473427</td>
</tr>
<tr>
<td>% Difference</td>
<td>-0.12%</td>
<td>-1.06%</td>
<td>-3.72%</td>
<td>-1.89%</td>
</tr>
</tbody>
</table>

Table 6.4 Percentage difference in energy consumption due to adding vestibule
6.5 ECM# 5 – Plug loads (Equipment) schedules

The plug loads include all the equipment in the building excluding the HVAC system units. Most of the plug loads include laboratory tools and equipment as well as office equipment such as computers, refrigerators, microwaves, printers, scanners, printing machines, etc. Some of the equipment are left on in “stand-by” mode at night and during weekends and holidays, consuming electricity. Some of these loads are small while in other cases such as with the Swagelok Center which consumes up to 50% during these periods, stand-by loads can be large. Assuming that all of these plug loads in “stand-by” mode could be switched off completely when not being used, a significant reduction in energy is expected as shown in Table 6.5. The total energy consumption exhibits a reduction of 9.32%, with the largest impact on electricity, since the equipment accounts for almost 50% of the building electricity as shown in Figure 5.2. For this ECM, heating load has increased while the cooling load has decreased. This is expected since the equipment generates waste heat and minimizing the equipment electricity consumption increases the heating requirement for the building during the winter season but reduces the load during the summer cooling season. Implementation of this ECM would require working with the equipment users to ascertain what equipment might be the best candidates for such a change in operation.
Table 6.5  Difference in energy consumption if equipment switched off during night, weekend, and holidays

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>District Cooling</th>
<th>District Heating</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (KWh)</td>
<td>1970488</td>
<td>1171565</td>
<td>2436978</td>
<td>5579031</td>
</tr>
<tr>
<td>ECM (KWh)</td>
<td>1433110</td>
<td>986230</td>
<td>2639638</td>
<td>5058978</td>
</tr>
<tr>
<td>% Difference</td>
<td>-27.27%</td>
<td>-15.82%</td>
<td>8.32%</td>
<td>-9.32%</td>
</tr>
</tbody>
</table>

6.6  ECM# 6 – LED lighting fixtures

The interior lighting consumes about 26% of the consumed electricity in Glennan, which is about 9.3% of the total energy consumption, as shown in Figure 5.2. Most of the installed lighting fixtures use fluorescent lamps with only three light-emitting diode (LED) lamps in exterior lighting fixtures. Although the fluorescent lamps are considered power savers when compared to incandescent bulbs, there is still room for more savings if LED lamps are used. LED lamps can produce 110 Lumens/W, while the installed fluorescent lamps provide between 83 and 88 Lumens/W. Replacing the fluorescent lamps with LED lamps, and by re-simulating, the power consumption savings are shown in Table 6.6. While the electricity and district cooling reflect a reduction of 6.13% and 3.15% respectively, the district heating has increased by 1.91% due to the reduction in the wasted heat rejected to air, leading to a total energy reduction of almost 2%.
The 6.13% reduction in the electricity consumption is reasonable, given the 26.28% lighting contribution of the electricity, as shown in Figure 5.2.

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>District Cooling</th>
<th>District Heating</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (KWh)</td>
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<td>2436978</td>
<td>5579031</td>
</tr>
<tr>
<td>ECM (KWh)</td>
<td>1849601</td>
<td>1134632</td>
<td>2483622</td>
<td>5467855</td>
</tr>
<tr>
<td>% Difference</td>
<td>-6.13%</td>
<td>-3.15%</td>
<td>1.91%</td>
<td>-1.99%</td>
</tr>
</tbody>
</table>

Table 6.6  Power saving with the use of LED lamps

6.7  ECM# 7 – Heat recovery devices

Heat recovery devices can be installed in the air handling units to recover some of the wasted energy from the air that will be exhausted to the outdoors, and via a heat exchange, minimize the energy required to bring the fresh, outdoor air to the required temperature. Rotary type heat recovery devices with 0.7 sensible heat recovery effectiveness were applied to the different AHUs in the Glennan Building, and the energy simulation was run to explore how these devices impact energy efficiency. A comparison between the energy consumption with and without the use of these heat recovery devices is displayed in Table 6.7. The district heating has reduced by 5.51% due to the recovered heat. However, the electricity exhibits a small increase of 0.08% which can be attributed to the power required for the rotary heat recovery devices. The district cooling reflects an
increase in consumption of 3.39% which can be attributed to the conditions when operating the device when the outdoor air dry bulb temperature is higher than the supply air dry bulb temperature while the outdoor air enthalpy is less than the return air enthalpy, or if outdoor air dry bulb temperature is less than the supply air dry bulb temperature while the outdoor air is higher than the minimum set point [51]. In accounting for these combined effects, a reduction in the total energy consumption of 1.67% is achieved.

<table>
<thead>
<tr>
<th></th>
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<th>District Cooling (KWh)</th>
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<th>Total (KWh)</th>
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<tr>
<td>Actual</td>
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<td>5579031</td>
</tr>
<tr>
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<td>5486108</td>
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<td>% Difference</td>
<td>0.08%</td>
<td>3.39%</td>
<td>-5.51%</td>
<td>-1.67%</td>
</tr>
</tbody>
</table>

Table 6.7  A comparison for the energy consumption with and without using heat recovery devices

6.8 ECMs – Set# 1 (All combined)

Applying all the previous ECMs in combination is expected to lead to significant energy savings although may not result in a simple summation of the individual savings due to coupled effects [30]. Table 6.8 shows the results from the combined ECM simulation, where all the previous ECMs are applied in combination. A reduction in the electricity consumption of 37.41%, district cooling
of 40% and district heating of almost 28% with a corresponding huge reduction in the total energy of 33.82% is achieved. Note that ECM set# 1 exhibits less energy savings than the sum of the individual ECMs savings (35.54%), which can be attributed to interactive effects [30].

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>District Cooling</th>
<th>District Heating</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (KWh)</td>
<td>1970488</td>
<td>1171565</td>
<td>2436978</td>
<td>5579031</td>
</tr>
<tr>
<td>ECM (KWh)</td>
<td>1233421</td>
<td>702411</td>
<td>1756160</td>
<td>3691992</td>
</tr>
<tr>
<td>% Difference</td>
<td>-37.41%</td>
<td>-40.05%</td>
<td>-27.94%</td>
<td>-33.82%</td>
</tr>
</tbody>
</table>

Table 6.8  All ECMs combined and the related power consumption

6.9 ECMs – Set# 2 (All combined without heat recovery devices)

The second scenario focused on combining all ECMs except removed the heat recovery devices (#7) since this has the least energy saving compared to other ECMs. The simulated reduction in the energy consumption was found as shown in Table 6.9. The total energy consumption was reduced by 32.51% due to a reduction in electricity consumption of 37.42%, district cooling of 42.2% and district heating by 23.88%. This ECM set still shows a great energy savings
opportunity that is simply and approximately ECM set #1 minus that of the heat recovery device, as expected.

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>District Cooling</th>
<th>District Heating</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (KWh)</td>
<td>1970488</td>
<td>1171565</td>
<td>2436978</td>
<td>5579031</td>
</tr>
<tr>
<td>ECM (KWh)</td>
<td>1233149</td>
<td>677219.55</td>
<td>1854961.15</td>
<td>3765329.7</td>
</tr>
<tr>
<td>% Difference</td>
<td>-37.42%</td>
<td>-42.20%</td>
<td>-23.88%</td>
<td>-32.51%</td>
</tr>
</tbody>
</table>

Table 6.9 Combined ECMs (without heat recovery devices) and the related power consumption

6.10 ECMs – Set# 3 (ECMs with low or no cost)

Since application of ECMs to an actual building has a cost associated with it, it may be important to consider only those that are feasible with relatively low payback periods. Some ECMs have low or no cost and still demonstrate potential energy savings, including ECM# 1, 2 and 5: changing the cooling/heating set point temperature, the HVAC system schedules and the plug loads schedules. The energy simulation demonstrated the savings in energy consumption as shown in Table 6.10. This ECM set seems attractive, with its 26.36% reduction in the total energy consumption, along with its expected low or no cost. Electricity is reduced by 30.91%, district cooling by 38.65% and district heating by 16.78%. The district cooling reduction is greater than the reduction in district heating consumption; this can be attributed largely to the reduced heat rejection of the
ECMs due to re-scheduling their operation. Recall that the respective savings from the individual ECMs 1, 2 and 5 are 6.0%, 11.2% and 9.3%, respectively. The total savings from the set of ECMs is roughly equivalent to the summation of the savings from the individual measures.

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>District Cooling</th>
<th>District Heating</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual (KWh)</td>
<td>1970488</td>
<td>1171565</td>
<td>2436978</td>
<td>5579031</td>
</tr>
<tr>
<td>ECM (KWh)</td>
<td>1361500</td>
<td>718813</td>
<td>2028057</td>
<td>4108370</td>
</tr>
<tr>
<td>% Difference</td>
<td>-30.91%</td>
<td>-38.65%</td>
<td>-16.78%</td>
<td>-26.36%</td>
</tr>
</tbody>
</table>

Table 6.10  Energy consumption expected with the application of low cost ECMs

6.11 ECMs - Comparison

A comparison of the different energy conservation measures and sets is shown in Figure 6.2 in kWh. For the single ECMs, ECM# 2 --HVAC system schedule-- demonstrates the largest reduction in the total energy consumption (11.22%), followed by ECM# 5 --equipment schedules-- (9.32%), ECM# 1 --cooling/heating set point temperatures-- (6%), ECM# 3 --external wall insulation-- (3.45%), ECM# 6 --LED lighting-- (1.99), ECM# 4 --adding a vestibule-- (1.89%) and finally ECM# 7 --heat recovery devices-- (1.67%). Interestingly, the largest energy savings is achievable without any significant capital investment and may be implemented to some extent without much impact on the building occupants. In comparison of
the different ECM sets, ECM set#1 –all ECMs in combination-- exhibits the largest savings (33.82%), followed by ECM set# 2 –all ECMs except heat recovery devices-- (32.51%), and finally ECM set# 3 –low / no cost ECMs-- (26.36%). The implementation of the low cost/no cost ECMs (set #3) is not significantly less than implementing all the ECMs (set #1), emphasizing that there are great opportunities in Glennan to save energy without requiring much investment.
Figure 6.2  Comparison between the different ECMs' energy consumption
6.12 Financial analysis

Since application of all ECMs is unrealistic, it is important to prioritize accordingly. The decision to apply any ECM will typically depend on its payback period, which is a common way to provide such a comparison. The payback period is the period in which the initial cost of an investment is recovered by its profit or savings. The payback period can be simply calculated by dividing the cost of applying each ECM with the corresponding annual operating dollars. The operational savings is calculated using an estimated price of energy. For this work, 8 cents per kWh of electricity, $14 per 1000 lb steam and 24 cents per ton hour of chilled water were considered [52].

A comparison of the estimated cost of applying each ECM and its corresponding payback period is shown in Table 6.11. The insulation and LED lighting prices were taken as average online prices for commercially available products [53], and the insulation prices include material and labor. The heat recovery device cost was estimated [54]. The Air Movement and Control Association International, Inc. (AMCA) [55] as well as Berner International Corp. [56] suggest that a vestibule costs from $20,000 to $60,000; an average value of $30,000 was used for the payback calculation. The vestibule estimated cost is for two vestibules.
<table>
<thead>
<tr>
<th>ECM</th>
<th>Estimated cost</th>
<th>Annual energy saving (KWh)</th>
<th>Expected annual saving</th>
<th>Payback period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECM# 1</td>
<td>$0</td>
<td>334855</td>
<td>$16,831.66</td>
<td>0.0</td>
</tr>
<tr>
<td>(Cooling/heating set point temperature)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM# 2</td>
<td>$0</td>
<td>625729</td>
<td>$32,243.00</td>
<td>0.0</td>
</tr>
<tr>
<td>(HVAC system-AHUs and pumps-schedules)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM# 3</td>
<td>$210,000</td>
<td>192301</td>
<td>$8,094.16</td>
<td>25.9</td>
</tr>
<tr>
<td>(Additional insulation for the external walls)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM# 4</td>
<td>$60,000</td>
<td>105604</td>
<td>$4,671.30</td>
<td>12.8</td>
</tr>
<tr>
<td>(Adding vestibule to building entrance)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM# 5</td>
<td>$0</td>
<td>520053</td>
<td>$47,531.10</td>
<td>0.0</td>
</tr>
<tr>
<td>(Plug loads - equipment-schedules)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM# 6</td>
<td>$145,000</td>
<td>111176</td>
<td>$10,325.50</td>
<td>14.0</td>
</tr>
<tr>
<td>(LED lighting fixtures)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM# 7</td>
<td>$90,000</td>
<td>92923</td>
<td>$2,532.0</td>
<td>35.5</td>
</tr>
<tr>
<td>(Heat recovery devices)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM Set# 1</td>
<td>$505,000</td>
<td>1887039</td>
<td>$118,213.1</td>
<td>4.3</td>
</tr>
<tr>
<td>(All combined)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM Set# 2</td>
<td>$415,000</td>
<td>1813701</td>
<td>$116,001.9</td>
<td>3.6</td>
</tr>
<tr>
<td>(All combined without heat recovery devices)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECM Set# 3</td>
<td>$0</td>
<td>1470661</td>
<td>$95,971.7</td>
<td>0.0</td>
</tr>
<tr>
<td>(ECMs with low or no cost)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.11 Cost vs. saving for each ECM
ECM set# 3 is shown as a first priority given it is expected to save about $117,652 in the first year with almost no cost (i.e. an immediate payback). ECM set# 1 exhibits a payback period of 3.3 years and saves almost $151,000 annually. If only a single ECM can be achieved, ECM# 2 (HVAC system schedules) is estimated to save $50,058 annually with zero up-front costs. Interestingly, ECM #6, the installation of LED lights looks much less attractive with a payback period of over 16 years. However, this is a very common ECM to employ in many of the campus buildings.
7 Conclusion

A building model was developed to study the application of different possible energy conservation measures scenarios and their corresponding energy consumption savings in a measurable way. The DesignBuilder program was used to create the geometry that represents the actual Glennan Building, located on the Case Western Reserve University campus in Cleveland, OH. Using the EnergyPlus software program, the building internal gains (occupancy, lighting, and equipment) were described for each of the 263 zones along with their schedules. The HVAC system of the building was assigned to the various zones. A custom weather file for the year 2013 was created using actual weather data. An energy simulation was performed for the building model using EnergyPlus, and energy consumption was obtained as an output. The building model was calibrated to meet the ASHRAE calibrated model acceptable accuracy guidelines. Different energy conservation measures were applied to the calibrated model, and the following conclusions were obtained:
Heating power consumption is more than double that of cooling. Glennan, therefore, can be considered a heating-dominated building, which is expected given its location and the cold weather in Cleveland.

Electricity consumption is 35% of the total energy consumption in the Glennan Building. Interior equipment contributes to almost 50% of the electricity consumed by the building. 1st floor electricity consumption is higher than any other floor because of the Swagelok Center’s equipment loads, which consumes 17.4% of the electricity.

Distribution of lighting electricity consumption across the different floors is more uniform than the distribution of the equipment electricity consumption. This is due to the variation of the laboratories’ plug loads across the different floors and the similarities in lighting needs across the building.

ECM# 5, turning off equipment in stand-by mode at night and on weekends and holidays, is an attractive opportunity given the large savings in electricity (27.27%) from the reduction in equipment energy consumption. However, equipment users may show resistance to implementation.

Changing the HVAC system set point temperatures (ECM# 1) and switching off the HVAC system during unoccupied periods (ECM# 2) are easy to implement and offer significant savings (6% and 11.22%,
respectively, of total energy consumption). If implementing these ECMs, even partially, can be implemented without sacrificing comfort, they are particularly attractive.

- Significant savings are achievable if all ECMs are applied in combination. This equates to $151,000 annually.

- ECM set# 3 with low or no cost is the most attractive ECM (26.36% saving of total energy consumption), but may be difficult to implement given building occupants may not approve of schedule variations and/or switching off all laboratory equipment at nights and on weekends.

- ECM combinations offer equal or less energy savings than a sum of the individual ECMs savings, depending on the set considered.

- Energy modeling is a good and effective way of applying different scenarios to a virtual building model to evaluate their effectiveness in improving the energy efficiency.
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