METHODOLOGY AND VISUALIZATION TOOLS FOR MANAGING ENERGY GOALS IN COMMERCIAL OFFICE DESIGNS

by

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ABSTRACT

WILLIAM NATHANIEL LAWLESS. Methodology and Visualization Tools for Managing Energy Goals in Commercial Office Designs. (Under the direction of DR. ROBERT COX)

Managing buildings energy usage is crucial for reducing emissions worldwide along with creating a more energy sustainable future. Building energy goals determined in the initial Phase of the design process is necessary for the development of energy efficient commercial office designs. These energy goals can be used to quantify the tradeoffs associated with different envelope constructions as well as the mechanical system's control strategies and operation. With more complex systems and strategies being available for building design, many new energies saving technology packages are implemented in the building standard as well as other resources dedicated for building energy savings. To understand how these recommendations are implemented, the ASHRAE 90.1 standard is discussed regarding its requirements for key building design choices throughout the envelope and HVAC sections. How these new technology packages are implemented in to the building as well as their resulting energy impact are analyzed by utilizing building models. Each change in the ASHRAE 90.1 standard from versions 90.1-2007 through 2013 are applied to the AHSRAE reference building models to determine each change's energy impact. Once the changes are quantified in terms of energy use, the evolution of key building design choices are understood. Along with the knowledge gained from the standard, historical data is analyzed to determine how real buildings operate in comparison to the building models. The energy impacts due to these operational differences are studied. With the insight from the different building design choices and the operational differences, a realistic energy goal is developed for new commercial office space constructed in the North Carolina Piedmont. Over one million combinations from the key design choices and operational differences are simulated using building models to create a large building database. To be able quickly analyze the energy tradeoffs shown by the database simulations, The Building Design Visualization Tool was developed. Using the Building Design Visualization Tool, users can quickly understand energy tradeoffs when implementing different design choices. When used during the initial phase of the building design process, The Building Design Visualization Tool is able to establish energy goals as well as help make key design and operational choices so that the energy goal can be met once the building is constructed and occupied.

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AEDG	Advanced Energy Design Guide
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
COF	Coefficient of Performance
DCV	Demand Control Ventilation
DX	Direct Expansion
ECB	Energy Cost Budget Method
EUI	Energy Use Intensity
HVAC	Heating, Ventilation, and Air Conditioning
IDP	Integrated Design Process
LEED	Leadership in Energy and Environmental Design
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic System
RTU	Rooftop Unit
VAV	Variable Air Volume
WWR	Window-to-Wall Ratio

I. Introduction

Figure 1 shows that building operations and construction jointly account for approximately 48% of primary energy consumption in the United States (Architecture 2030, 2018). Numerous studies conducted over the years have shown that a combination of better design practices and improved operations can easily reduce this number (AEDG, 2011; Senseable City Laboratory, MIT, 2011). Growing concerns over greenhouse gas emissions initially spurred interest in addressing these issues, and recent developments have demonstrated that more efficient "green" buildings can significantly benefit commercial real-estate partners. Studies show that more efficient buildings can lower operating costs, provide a more productive work environment, and command higher rents (Alker, 2014; AEDG, 2011). Some of the greatest challenges to achieving and maintaining energy reduction are the development of effective goals in the early stages of the design and the understanding of how certain decisions in both design and operations impact those goals. This thesis proposes tools and strategies for helping building owners to address these challenges.

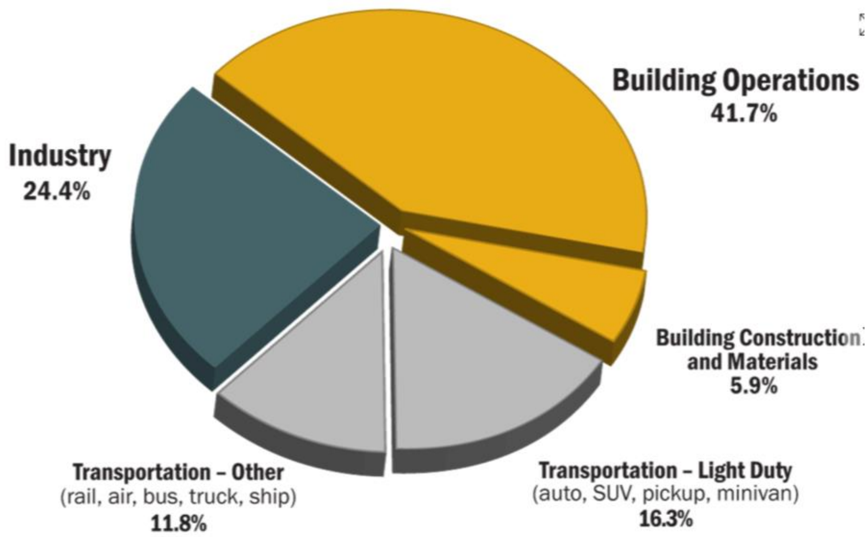

Figure 1. Energy Consumption Breakdown of U.S. Infrastructure - Architecture 2030, 2018

A. The Importance of Setting and Managing Energy Goals Throughout the Design Process

Given the potential significance of reducing building energy consumption, several different groups have provided pathways for achieving better performance. All states now have energy codes that nominally provide standard expectations for energy performance. The American Society of Heating, Refrigerating and Air-Conditioning Engineers, or ASHRAE, sets this standard known as ASHRAE 90.1. ASHRAE uses climate-based energy design requirements which allows for building designs to consider and be optimized based on the weather climate they are in (ASHRAE 90.1 User's Manuel, 2013). Continuing from the energy standard, green building certifications designated by groups such as the Leadership in Energy and Environmental Design, or LEED. These building certifications from LEED, which is administered through the USGBC, are given to buildings that implement more efficient and green technologies into their design (LEED, 2018). Groups such as Architecture 2030 also provide additional guidance in order to reduce emissions and reach the net zero building energy usage (Architecture 2030, 2018). Even though there these groups are providing good design guides and strategies, these recommendations only provide design criteria, do not have operational mandates.

There are numerous examples of buildings that do not achieve the expected energy savings targets. In order to fully understand the problem at hand, the following figure from a study of certified LEED buildings located in the U.S. is given (Turner,2008).

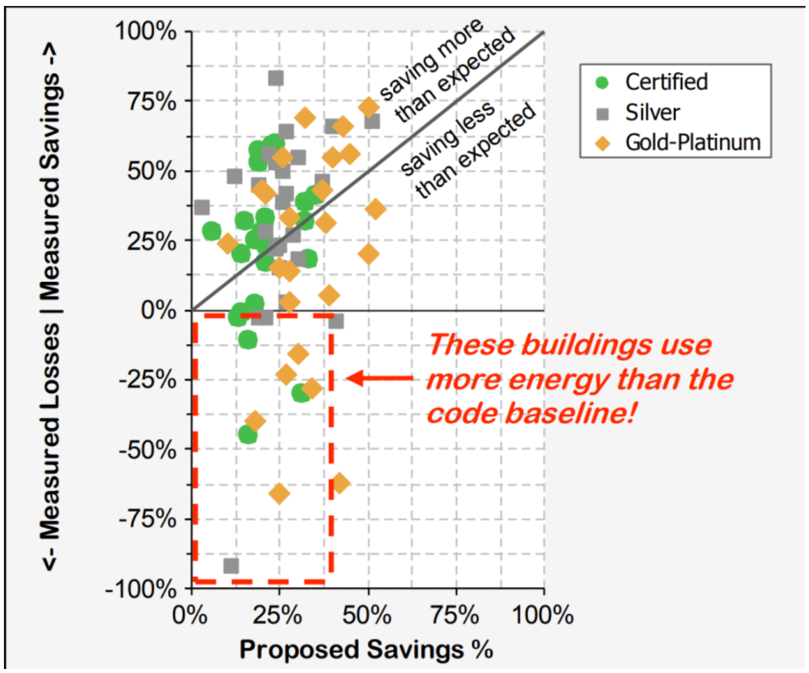

Figure 2. LEED Building Energy Expectations – New Buildings Institute, 2008

Figure 2 shows the distribution of buildings across the measured savings/losses axis against the proposed savings axis. As can be seen, the buildings are widely spread in terms of expected energy usage and actual energy usage. From the initial energy usage estimate, the buildings seen in the chart have about an 50% chance of actually meeting their target energy usage once occupied. This shows that even with more technologically advanced buildings, such as LEED certified buildings, the predicted energy usage and energy goals prove to be fairly inaccurate once the building is constructed and occupied.

To further this point, table 1 shows energy usage data collected for 4,600 banking centers located in the U.S. The bottom two rows show two individual LEED certified buildings while the first row shows the average of all buildings.

Table 1. Banking Center Normalized Energy Usage Over Time (kWh/ft^2)

Banking Centers	2010	2011	2012	2013	2014	2015
All Banking Centers	27	26	25	26	26	24
Retail NC (LEED)	33	24	26	28	26	27
Retail CL (LEED)	20	22	21	24	26	23

After studying the table, the difference in energy usage between the average of all banking centers versus the two LEED banking centers is seen to be very similar regardless of the bottom two row's certification. Even with the advanced technology implemented into the LEED buildings, the resulting energy usage is so close to the average that the certification does not seem to make a difference. When new technology is brought into the buildings design but poorly implemented or operated, once the building is complete may result in the final energy usage of the space being different than what is expected.

Building energy goals, further defined in Appendix definition A1, are often set for buildings that want to be more energy efficient. A commercial office building in Miami, Florida shows the downside of what happens when the energy goals are not met once the building is occupied. The building analyzed was intended to be a net zero building with PV sized based on the set initial energy predictions of the site during the design process. Figure 3 shows the energy predictions of the office space below. On the left, the initial building is estimated to operate at 89,000 kWh using the recommendations directly from the ASHRAE baseline building. The middle chart shows that with advanced energy saving technology implemented into the zones, the estimated energy usage was reduced to 52,000 kWh. From this estimation the PV was sized, and the building and PV was constructed. The graph on the far right shows the resulting energy usage of the building once occupied. Due to the implemented technology not preforming as expected, the building operated at a final energy usage of 73,000 kWh, not considering the PV.

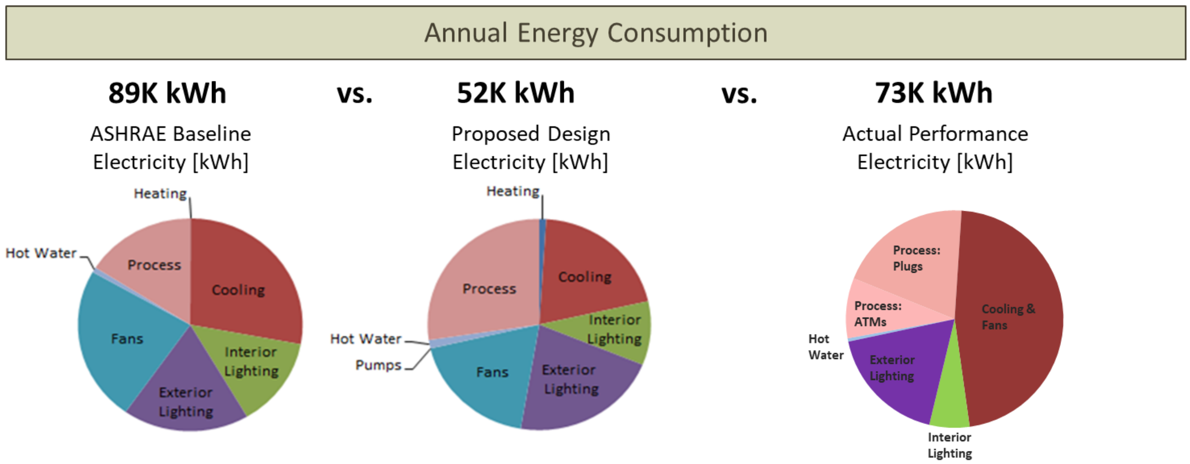

Figure 3. Estimated Versus Actual Annual Energy Consumption for Commercial Office Space

Because the energy goal in this example was not accurate in representing the technologies being implemented into the space, the building used more energy than anticipated. The resulting PV was not correctly sized for the building actual energy usage and the building was not able to be considered a net zero site. From this example, the importance of considering all aspects of the building design and operations when determining energy usage goals is seen to be critical to the performance of the final product.

The problem analyzed in this thesis is the fact that building designs frequently miss expected energy targets once constructed and occupied. This issue is the result of many potential factors. In the design process, the uniqueness of individual buildings are not completely considered. Because designers typically follow a set path in the building design process, many of the building parameters of the building are assumed or get overlooked entirely. This primarily happens due to the design teams lacking the proper incentives or resources to spend the additional time in the early design phase to examine these parameters.

Because of the way the current design process works, the final operation of the building is often not considered, which may have a large effect on the building's resulting energy usage. The biggest reason of why buildings often miss their expected energy targets is because the typical design process does not effectively manage energy goals throughout the entirety of the design process until the building is occupied.

B. Purpose and Strategy to Set and Meet Reasonable Energy Goals

The purpose of this thesis is to propose a solution to building energy goals not being met. To do this, a methodology is created that allows building owners in the North Carolina Piedmont to develop a specific climate-appropriate energy target with specific technology recommendations, easily visualize the trade-off between different technology decisions and potential building designs, and to understand the criticality of effective building operations. In order to be able to form this methodology, the following approach is taken. The first step involves understanding industry-accepted design strategies used by designers currently. To be able to make appropriate recommendations, the appropriate technologies for the Piedmont based on existing codes and standards are investigated. The impact of these technologies are then observed by utilizing reference buildings created by the Department of Energy based on typical suburban commercial office space. Once the appropriate technologies are understood, key areas where building operations are critical to maintaining the set design goal are identified. With the complete understanding of these parameters impact on the resulting energy goal of the building, region specific design recommendations are developed along with a building visualization tool to easily visualize these energy tradeoffs.

The remaining chapters of this thesis describe the full details of the proposed approach. Chapter two provides insight for the incorporation of building energy goals into the design process as well as discuss key portions of the ASHRAE 90.1 standard that defines the methodology of the building design. Chapter three goes on to describe details how building models can be used to determine a buildings energy usage before it is constructed. With this, the 90.1 reference models are analyzed to show key energy differences in the most recent iterations of the standard. Difference in building operations between buildings reflected in the building models are highlighted. A baseline energy goal is then determined for the Piedmont area. Chapter four details The Building Design Visualization Tool, which is the tool developed to gain a higher understanding of the building design and operational tradeoffs in terms of energy usage. This chapter breaks the tool down into what design combinations are available, how each parameter was modeled, and analyzing base cases in terms of energy impact for each parameter. And finally, chapter 5 concludes the benefits of the integrating The Building Design Visualization Tool into the initial phase of the design process.

II. The Design Process and ASHRAE 90.1

To reach the objective of determining and achieving an energy goal for a commercial office building, the design process and building standards must first be broken down to understand how the building energy usage is originally determined. The building design process is analyzed to see how building energy goals are incorporated throughout the entire project. The ASHRAE 90.1 building is then discussed to see how it restricts building design choices as well as influence some of the technologies that are implemented into modern office buildings. Once exploring the factors that these current methods contribute for setting energy goals or determining building design parameters, flaws or holes in the current processes can be highlighted.

A. The Design Process

A building is as only as good as its design, while the design is limited by its process. This chapter analyzes information taken from the Integrated Design Process chapter in the AEDG as well as looking at the design process typically followed while using ASHRAE 90.1. In order to have an efficient design and a concrete energy goal, the building design process must be robust enough in order to factor in many parameters early in the projects lifespan. Unfortunately, the typical design process used by design teams do not incorporate an in-depth analysis of crucial building parameters. Instead designers tend to follow a set path while designing the building. The primary reason designers do this is to eliminate additional costs and resources that would normally be required to consider the crucial building parameters on a case by case basis. The downside is that using a set path in order to shortcut the design process eliminates many opportunities to develop highly efficient buildings. Because advanced energy saving technologies must be considered individually, for every unique building scenario, many savings opportunities are often overlooked or not properly implemented into the building design.

Another issue with the typical building design process is that it does not utilize building energy goals to meet once the building is occupied or to weigh design choices against. A big reason of why this happens is that usually the proper incentives are not in place for the design team to care about developing energy efficient buildings rather than cost efficient buildings. This can be a major issue, since building operations make up such a large part of the modern energy infrastructure.

Purely following a set path without properly considering key design choices or not implementing building energy goals prove to be major flaws in the way typical building design processes are carried out. These issues directly lead to buildings and building systems not functioning to full expectations and the energy target being missed once the building is constructed and occupied. Part of this issue can be resolved with proper commissioning of the project. Normal building practices do not involve commissioning practices and audits. These commissioning practices are implemented so that the design team is partially responsible for the final energy usage of the building project.

To rectify these issues, more advanced design processes must be used. Resources like the Advanced Energy Design Guide, or AEDG, offers more detailed design processes like that represented by the flowchart below. In order to reduce building energy consumption, the building energy goal needs to be defined in the initial phase of the design process so that it can be used as a metric to be carried out all the way until the building is occupied. In the case of the design process shown below, the building energy goals are defined the Concept

Design Phase and is upheld until the final phase of the project. In depth studies of the building design are considered for each building project, such as the Glazing Study seen under the Schematic Design Phase. Studies such as this ensure that advanced designs and technologies brought into the space are correctly implemented and function to expectation. To provide the proper incentive for the design team to meet the set energy goal and ensure that the building designed operates as expected, the advanced design process adds a Commissioning Phase to help hold designers accountable for the final product. These additional steps taken in the design process better ensure that the energy target for the building is met once the project is completed.

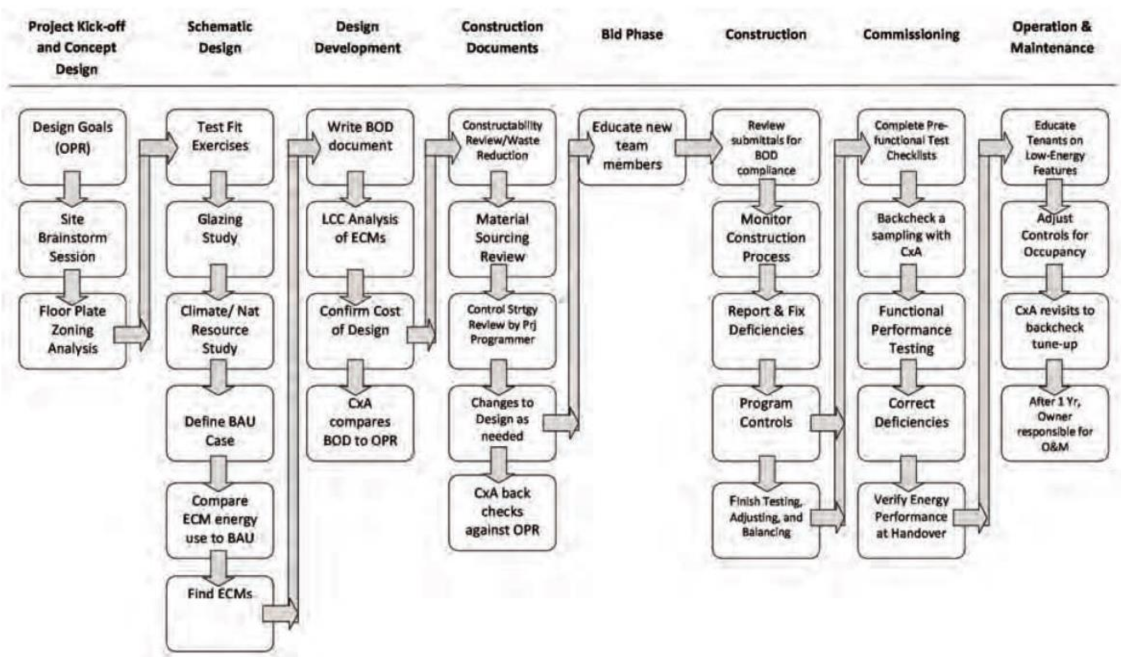

Figure 4. Advanced Design Process – AEDG, 2011

B. The ASHRAE 90.1 Standard

The American Society of Heating, Refrigerating and Air-Conditioning Engineers, or ASHRAE, releases the 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings. This section analyzes the flow in which ASHRAE 90.1 gives recommendations which was studied from the ASHRAE 90.1 User's Manual. In the building energy standard, ASHRAE gives recommendations and design strategies for the construction of new buildings and additions to existing buildings. 90.1 applies to just about every building outside residential buildings three stories tall and smaller, with a few other exceptions. The standard sets goals and makes recommendations for almost every aspect that is considered in building design. When discussing the recommendations, the standard reviews how to appropriately implement the energy saving measures for proper construction and operation, as well as taking an approach of how to know which recommendations to implement in the building design and listing requirements for ones do not necessarily apply. ASHRAE 90.1 also signifies when design documentation should be created and submitted to in order to appropriately prove compliance of the buildings design and construction.

To effectively give recommendations, the building standards are separated into groups and categories. ASHRAE 90.1 separates buildings as a whole by building type, climate zone, square footage and floors, as well as in what ways the space is conditioned. The map of the climate zones in the U.S. can be seen in Appendix A1. For the example of commercial office space in the North Carolina Piedmont, the climate zone is 3A. When giving recommendations, the building is broken up into chapters. For example, the Building Envelope Chapter and the HVAC Systems Chapter separates the parameters dealing with the building envelope and mechanical systems so that each standard can be discussed in detail. To gain a better sense of the standard's influence on the buildings design and energy usage, the Building Envelope and HVAC Systems sections must be analyzed in terms of how the designers are bound to the standards. This analysis will give better insight of how design decisions get made.

1. 90.1 Paths to Compliance

To easily be compliant to all ASHRAE 90.1 standards, each chapter dealing with a different parts of the building is broken down into sections. Figure 5 below shows the flow charts as the standard goes through each section of the Building Envelope and HVAC systems chapters. Following these flow charts throughout the design process ensures that each aspect of the building complies with the standard.

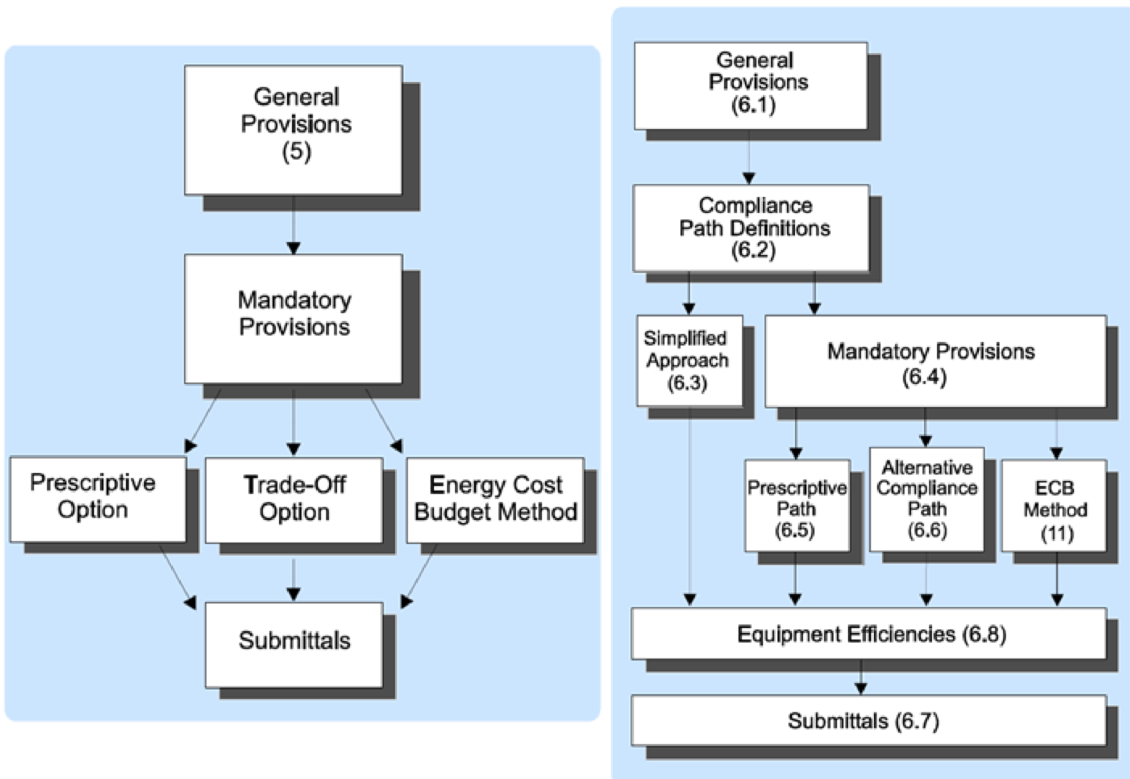

Figure 5. Building Envelope and HVAC Systems Compliance Paths – ASHRAE 90.1 User's Manual, 2013

As can be seen, the two flow charts are very similar in the way they flow through each section of the standard. For the case of the Envelope and HVAC Systems sections, the requirements start to be given with the Mandatory Provisions section. In this section, ASHRAE 90.1 provides general codes that are relevant to almost every building's envelope or mechanical system. A snapshot of these requirements given in the Envelope section can be seen in Appendix A4 for climate zone 3. All the following sections after the Mandatory Provisions must meet every requirement given in the Mandatory Provisions section.

Once the Mandatory Provisions are given, the standard starts to get more building specific, with more variables to consider and more exemptions to be had. To make the standard as easy as possible to follow with all the potentially altering building criteria, while at the same time allowing the building designer to more freedom, the designer is given three different paths to compliance after the Mandatory Provisions section. The three paths the designer can follow are the Prescriptive Option, the Trade-Off Option, or the Energy Cost Budget Method for the Envelope chapter. The three paths for the HVAC Systems chapter is the Prescriptive Path, the Alternative Compliance Path, or the Energy Cost Budget Method. Note the Simplified Approach is limited only to small, single floor buildings and does not apply to typical commercial office space. The Alternative Compliance Path deals only with computer room alternatives to meeting the HVAC Systems section.

The Prescriptive Option provides a fixed, straight forward path for the designer to follow. This path chooses appropriate envelope construction and materials for different parameters of the building's envelope. The key difference between the Mandatory Provisions section and the Prescriptive Option is that the Prescriptive Option goes into much greater detail when defining which standards apply to the building due to certain predefined building conditions or constructions instead of giving high level, generic requirements.

By following the Prescriptive Path, the designer cannot deviate from the standard. This can be a major issue in building design, for example, if the building owner wants an all glass building. A building such as this would reach a WWR much greater than the allowed WWR of 40% in the Prescriptive Path. Instead of not being compliant to ASHRAE 90.1, the building designer can use either the Trade-Off Option or the Energy Cost Budget Method in order to meet the building owners design requirements and the standard at the same time. These alternate paths, however, cannot bypass any component that must comply with the Mandatory Provisions section of the standard.

The Trade-Off Option allows for one envelope component that may not meet the standard can be made up for in terms of energy by another envelope component. This greatly helps with design flexibility in meeting aesthetic requirements from the building owner as well as standards given from ASHRAE 90.1. The Trade-Off Option does add complexity in comparison to the Prescriptive Option because it is necessary to measure the surface area and calculate the wall areas by orientation. 90.1 gives a documented way of doing this in the standard's Appendix C along with tables to create a baseline of performance of the building envelope. The downside of the Trade-Off Option is that the energy trade-offs are limited to components of the envelope, meaning trade-off components dealing with the HVAC system cannot be used to make up for an envelope component that does not meet the standard. This is where the designer can use the Energy Cost Budget Method to make more complex design choices with the Envelope and HVAC systems at the same time and still meet ASHRAE 90.1.

The Energy Cost Budget Method takes advantage of Appendix G of ASHRAE 90.1. Appendix G of the 90.1 standard is the building performance rating method, which purpose is to determine a value for energy saving trade-offs dealing with different systems or constructions of the building. This is done through specified simulation software given by Appendix G. Proving compliance when using the Energy Cost Budget method is primarily done through building modeling. Figure 6 below shows a flowchart of the ECB method.

First the designer would first run a completely 90.1 compliant building in the modeling program. The simulated model will provide the designer with the compliant building's EUI which would act as the baseline building. Once obtaining these metrics, the same building model with the system tradeoffs implemented is then simulated. For the ECB decision to be compliant, the newly obtained EUI must be equal to or less than that of the original baseline model. This gives the building designer much more freedom than that of the Prescriptive Option or the Trade-Off Option, however, adds a much higher level of complexity having to model the baseline building and the alternative trade-off components.

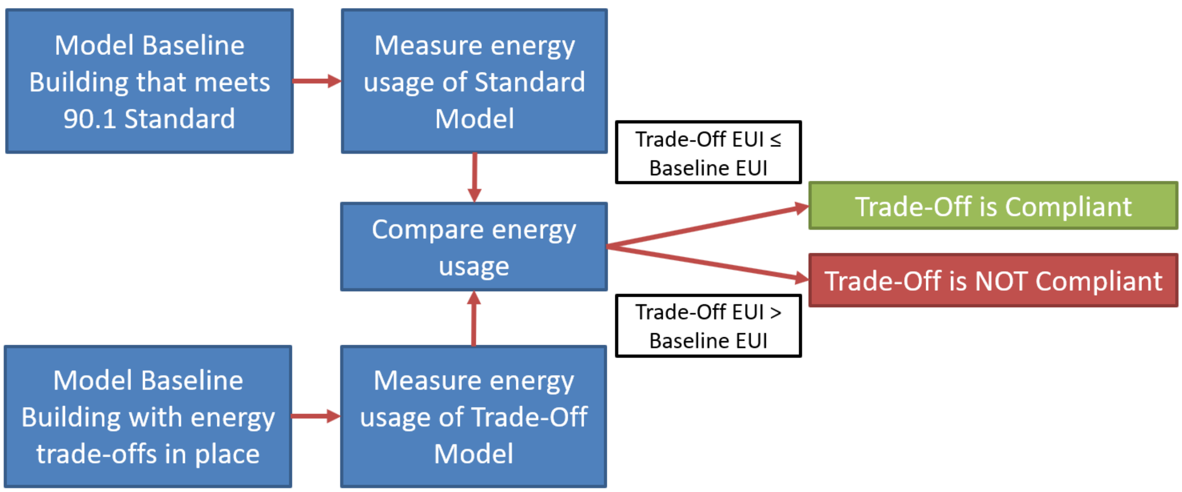

Figure 6. Energy Cost Budget Method

2. 90.1 Standard Editions and Usage

Every three years ASHRAE releases a new version of the 90.1 standard, with the current edition being 90.1-2016. Each state is left to its own discretion on what edition of the standard it wants to use, if a statewide code is used at all. As can be seen in the State Energy Code Adoption Map in Appendix A2, for the case of North Carolina along with the majority of the states in America, the required ASHRAE standard is between 90.1-2007 and 90.1-2010 (Office of the State Fire Marshal, 2013). Because of this ruling, all commercial buildings in North Carolina must meet the entirety of 90.1-2007 as well as aspects from 90.1-2010. In detail, this combination of standards requires designers to use Appendix G of the 90.1-2010 standard. With the use of Appendix G, new buildings must obtain an additional 20% in increased energy efficiency on top of that from 90.1-2007. Not only the 20% additional efficiency ruling was added, but a few key design parameters from 90.1-2010 must be implemented in order to be compliant in North Carolina. These required design parameters are as follows.

- 90.1-2010 thermal envelope tables replaced those of 90.1-2007.
- Standard glazed vertical fenestration is limited to 30% of above grade walls.

For North Carolina, this statewide building energy standard was put into effect March 1, 2012 with estimated savings of nearly $490 million annually by 2030 (U.S. Department of Energy, 2017).

The version of the 90.1 standard used by each state directly impacts the energy goals of the buildings being constructed. Since all building have to be built to code, the code requirements sets the baseline usage that all buildings must meet at a minimum. Because of this, the differences between the different iterations of 90.1 must be further explored to be able to establish reasonable recommendations for the Piedmont area and set building energy goals.

III. Building Modeling

To evaluate the different versions of the standard as well as different technology packages frequently implemented into the building, a benchmark building is needed so that the relationships between these parameters can be studied. The ASHRAE 90.1 Reference building models are utilized to understand these common energy trade-offs in the design process.

Building models can be extremely useful to the design process in terms of analyzing energy tradeoffs for the building as well as help set energy goals. The general concept behind building models are discussed, reviewing their basic inputs, outputs, and overall benefit. Then the differences between the most applicable reference models are analyzed in order to point out major differences in energy usage between the versions as well as understand the impact of the changes of the standard. From historical data collected from commercial office space in the Piedmont, realistic building operations are applied to the building models. From this, the energy differences caused by different building operations can be better understood. With the understanding gained from the technology tradeoffs from the different technologies from the standard as well as the operation of the building, a reasonable energy goal is developed for an office building being constructed in the piedmont.

A. What is a Building Model?

Building models are crucial to developing a more accurate energy goal since the user can tweak every parameter of the building model to reflect a real building and then see the resulting energy usage of the model. The big question is how does the building model able to handle such a complex system such as a building with so many parameters combinations. Figure 7 shows the basic building model that's purpose is to handle the envelope, heating and cooling loads, and the output of HVAC system in terms of the space temperature.

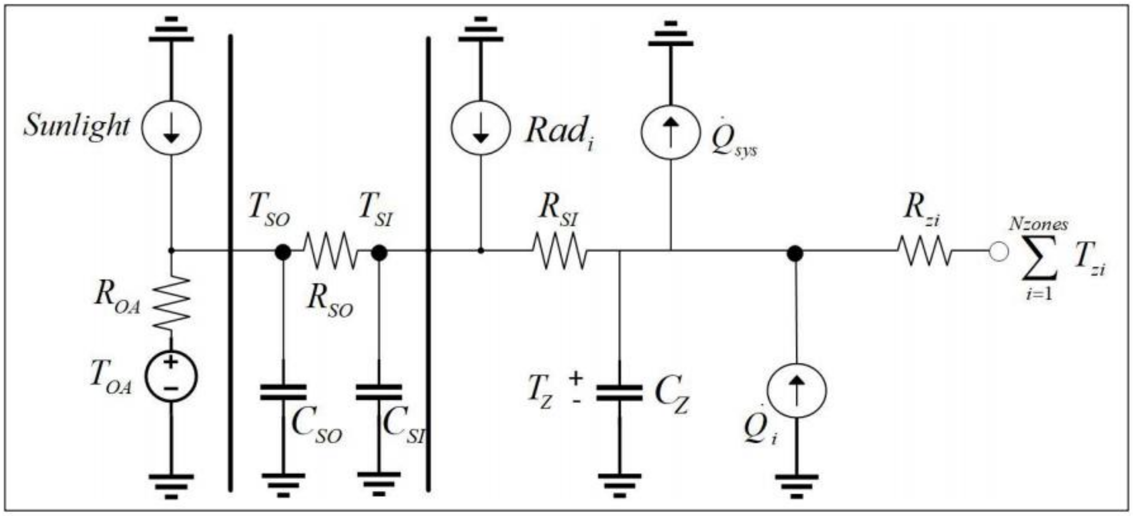

Figure 7. Building Model Network

Because models such as this are the same from building to building, building models simplifies the model for the user so that each parameter of the network is manipulated rather than the user having to building the entire network from scratch. For example, when the number of occupants in the building is changed, the current source Q_i is being adjusted. This directly effects how much heat load is being put into the space. This parameter is often used with a schedule so that the value of the current source changes throughout the each day, representing the coming and going of occupants in the space. When the exterior wall insulation values are being adjusted the resistance R_{SO} is being manipulated. The resistance creates a temperature drop across itself, representing the effect of insulation in a building. This is how building models are able to handle the immense amount of changes in the building and still maintain a certain level of simplicity.

Once simulated the building model returns many key metrics that is useful for system level analysis. As discussed, at the highest level, the building models return the EUI separated into end use metrics. When diving into the model more, the HVAC system loads and operation can be obtained for the amount of time that the model was simulated. This allows the user to look at the relationships between different HVAC control strategies while validating their usefulness on the system. Similarly, the lighting and equipment loads and operation can be separated for review (EnergyPlus, 2018).

Creating building models has many benefits to the design team. Building models allow for the EUI of a building to be predicted prior to the building being built. This allows for designers to be able to optimize the building design on a case by case basis before the building is even constructed. With this the ECB method can be better utilized, which leads to more energy efficient buildings.

B. Reference Models

The engineering team at Pacific Northwest National Laboratory, or PNNL, developed the ASHRAE 90.1 reference models by the order of the U.S. Department of Energy (U.S. Department of Energy, 2013). The reference models were created to measure energy saving impacts of ASHRAE 90.1 and to weigh other systems against to help the overall improvement of building design. As of the time of this report, PNNL has developed reference models for many different types of buildings from hospitals, big-box retail buildings, and even schools for the 90.1-2004, 90.1-2007, 90.1-2010, and 90.1-2013 standards (PNNL, 2016). These models are developed for EnergyPlus, which is an open source building energy simulation program that building designers can use to model entire buildings to the detail of parameters such as internal heating and cooling loads, HVAC and control systems, lighting, internal equipment process loads, and operational schedules. EnergyPlus also has the capability to import different weather and climate files, which allows the reference buildings to be simulated in any climate zone throughout the United States (EnergyPlus, 2018). Using this capability, PNNL developed a reference model for each type of building for the most recent iterations of 90.1 for every climate zone. For the purpose of the research highlighted in this paper, the medium sized commercial office building reference model located in Charlotte, North Carolina was considered.

The ASHRAE 90.1 reference models give insight to how simple changes in the envelope, the mechanical system, and building operation effect the buildings overall energy usage. Because the ASHRAE 90.1 standard is under continuous development and is released every three years, the changes in the standard greatly impacts the reference building's EUI. These improvements in 90.1 over the years must be understood in the way they effect the reference models EUI and how they are implemented into real buildings over time. Because States enforce buildings to meet versions of the ASHRAE 90.1 standard, the reference models are frequently treated as baseline buildings. The purpose of a baseline building is to give a comparable EUI goal that designers should meet or surpass when developing building designs.

For a thorough analysis, the most relevant ASHRAE 90.1 standards for commercial office space in North Carolina were considered so that the key design parameter differences could be highlighted and understood. The editions selected are 90.1-2007, 90.1-2010, and 90.1-2013. These editions were chosen because new commercial office buildings are required by code to meet 90.1-2007 and include aspects of 90.1-2010 to meet the additional efficiency requirements. For building owners who want to achieve even lower energy usage than that provided by 90.1-2007 or 90.1-2010, recommended design parameters are commonly taken from 90.1-2013 and included into the building design.

Throughout each of the medium commercial office reference models provided by PNNL, there are constant parameters that hold true for every iteration considered. These constant parameters include details such as number of zones, number of floors, building square footage, along with general envelope parameters and high level mechanical system definitions. Below is figure 8 showing the medium commercial office building.

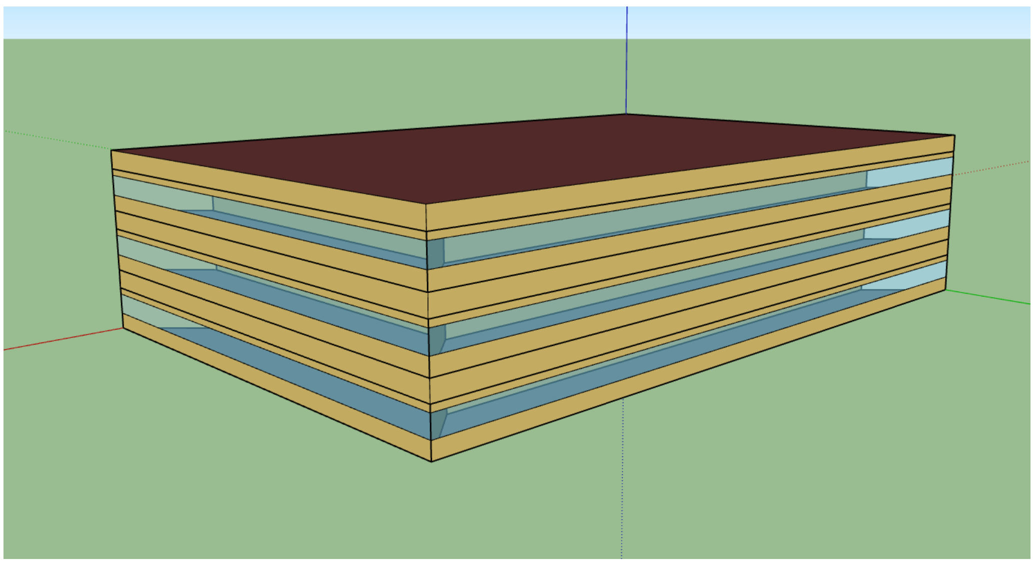

Figure 8. Medium Commercial Office Building Reference Model

Below is the list of constant parameters that hold true across every considered version of 90.1 that are deemed crucial of consideration.

- Location: Charlotte, North Carolina, in climate zone 3
- Floor area: 53,633 ft^2
- North facing typical box building construction (163’ 9” x 109’ 2”)
- 3 stories
- 3 core zones, 12 perimeter zones 15 ft deep
- 32% WWR
- 3 DX VAV Systems (one per floor, serving 5 zones each)
- Peak occupancy: 269 people
- Hours of Operation: Weekdays: 8 a.m. – 5 p.m., Saturdays: 8 a.m. – 12 p.m., None Sundays

The next portion of this chapter analyzes the medium commercial office building reference models and their changes over the ASHRAE 90.1-2007, 90.1-2010, and 90.1-2013 standards. To measure the impact of the changes in the reference models, each change seen in the 2010 and 2013 models are implemented individually in the 2007 base model, which is then ran in EnergyPlus. These changes in the standard and the resulting reference model are measured in terms of End Use and the total change in EUI. The change in EUI is determined by subtracting the EUI of the change implemented in the 2007 base model with the original EUI of the 2007 base model. This process is represented in the equation below.

$$\Delta EUI_{Base} = EUI_{Change} - EUI_{Base} \qquad (1)$$

Using this process, the changes made throughout the iterative versions of ASHRAE 90.1 post 2007 can be weighed and analyzed in terms of EUI. This understanding is key because each of these reference buildings represents an optimized version of the 90.1 standard.

1. ASHRAE 90.1-2007 Reference Model

The 90.1-2007 reference model shows the minimum end use energy consumption requirements for new buildings and expansions being built in North Carolina. For the 2007 reference model, the major parameters to consider are the heating and cooling setpoints and setbacks, outdoor air ventilation control, and the building's interior equipment and plug loads. Note that for the 90.1-2007 base model, no daylighting control, outdoor air ventilation control, or economizer are used.

The heating and cooling setpoints and setbacks for the 90.1-2007 reference model can be seen in the table below. These are the heating and cooling setpoints that determine the temperature of each zone inside the reference building for times when the space is occupied with people and times outside the building set hours of operation where the space is typically unoccupied.

Table 2. 90.1-2007 Reference Model Heating and Cooling Setpoints

Setpoint:	Zone Temperature:
Occupied Cooling	75° F
Unoccupied Cooling	75° F
Occupied Heating	70° F
Unoccupied Heating	60° F

As can be seen, the 90.1-2007 utilized an unoccupied heating setback, going from 70° F to 60° F outside normal hours of occupation. In this case, the occupied heating setpoint is active from 5:00 a.m. till 10:00 p.m. during the workweek. The unoccupied heating temperature setback is active from 10:00 p.m. till 5:00 a.m. during the workweek. Notice that there is no unoccupied cooling setback requirement as of 90.1-2007 for climate zone 3 as the cooling setpoint remains at 75° F during all hours. For the complete setpoint schedule used in EnergyPlus, see table B1 in the appendix.

In ASHRAE 90.1-2007, if the cooling system meets a certain energy efficiency requirement in climate zones 1, 2, and 3, no economizer is required. The standard also states that if no economizer is included in the system, that demand control ventilation is not required as well. To determine the outdoor airflow into the zones, building designers are required to follow section 6 of ASHRAE 62.1 which is the standard for Ventilation for Acceptable Indoor Air Quality (ASHRAE 90.1-2007, 2007). In table 6-1 of ASHRAE 62.1, the default value for the required amount of outdoor air flowing into any occupied zone is given as 17 cfm/person (ASHRAE 62.1-2007, 2007). This default value is used in the 90.1-2007 reference model. Because no economizing or demand control ventilation was used, the outdoor air damper is fixed open and is unchanging. This implementation in EnergyPlus can be seen in table B1.

The operational schedules for the interior equipment, elevator and elevator lights and fans, interior and exterior lighting can be seen in table B1. The interior equipment operates at a design capacity of 0.75 W/ft^2 which is given in the 90.1-2007 standard for office space. This design capacity is then multiplied by the fractional Equipment Schedule given in table B1. The elevators operate on a set schedule, while the elevator's lights and fans remain on constantly. The interior lighting is fairly basic in 2007 with no occupancy based control, dimming, or daylighting control required. The interior lights come on in the morning when occupants come in the morning and hold a constant value until the occupants leave for the day. The exterior lights are all grouped together and can be active throughout the day as seen in the Exterior Lighting schedule, however, they are triggered on and off automatically by a photocell.

Exact parameters of key systems of the 2007 reference model used in EnergyPlus can be seen in table B4. This table includes equipment efficiencies, design levels, notes schedules, system inclusions, and other factors.

When running the 90.1-2007 base model located in Charlotte, North Carolina in EnergyPlus, the End Use parameters of the building are simulated and given in kBtu for Electricity and Natural Gas. From these metrics, the base buildings EUI can be calculated. The following is the resulting End Use metrics and EUI for the 90.1-2007 base model.

Table 3. 90.1-2007 Reference Model End Use Parameters and EUI

End Use Parameters	Electricity [kBtu]	Natural Gas [kBtu]	EUI [kBtu/ft^2]
Heating	135,600	75,285	3.93
Cooling	467,953	0	8.73
Interior Lighting	524,274	0	9.78
Exterior Lighting	214,418	0	4.00
Interior Equipment	774,167	0	14.43
Exterior Equipment	32,013	0	0.60
Fans	87,965	0	1.64
Pumps	139	0	0.00
Heat Rejection	0	0	0.00
Humidification	0	0	0.00
Heat Recovery	0	0	0.00
Water Systems	0	68,212	1.27
Refrigeration	0	0	0.00
Generators	0	0	0.00
Total End Uses	**2,236,528**	**143,497**	**44.38**

The resulting EUI for the 90.1-2007 base model is determined to be 44.38 kBtu/ft^2 with the major energy users being the heating, cooling, interior lighting, and interior equipment. To see these relationships between the End Use parameters, figure 9 displays the previously collected data and plots it in terms of kBtu of electrical energy and natural gas.

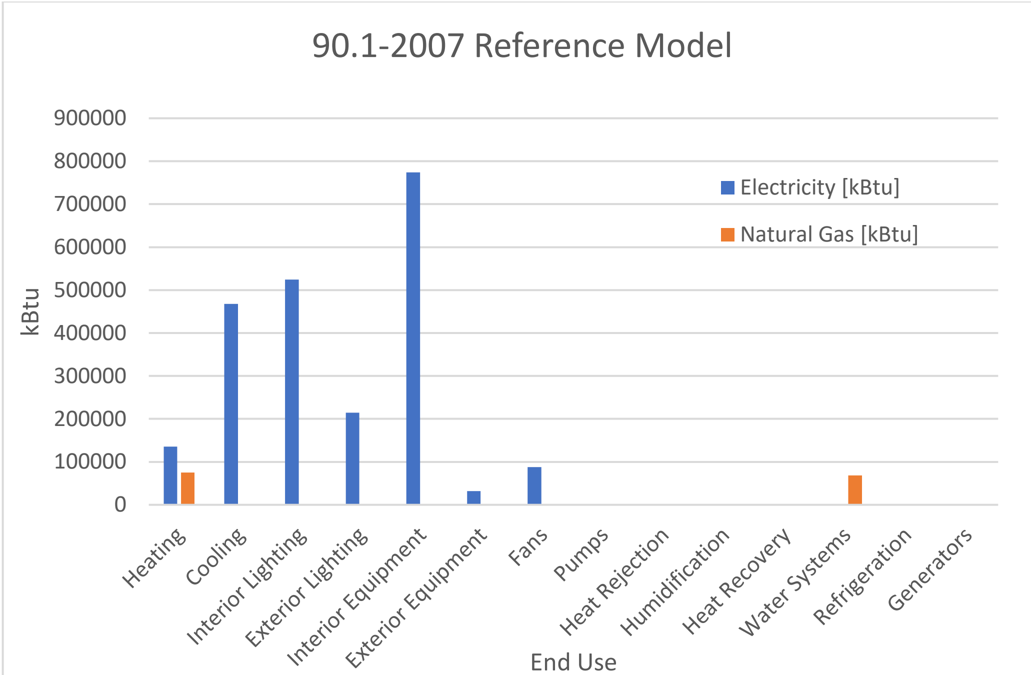

Figure 9. 90.1-2007 Reference Model End Use kBtu

2. ASHRAE 90.1-2010 Reference Model

There was significant improvement in ASHRAE 90.1 between the 2007 and 2010 release. Since 90.1-2010 is an expansion on 90.1-2007, 2010 requires many of the same standards from the previous editions of 90.1 with a few key differences. The major differences that are implemented in the 90.1-2010 base model is the addition of daylighting control, outdoor air demand control ventilation, or DVC, and economizing. Other key differences seen in 90.1-2010 is the change in operation of the building's exterior lights, implementation of interior lighting control, envelope changes, interior equipment operational control strategies, comfort requirements, as well as the natural progression of increased energy efficiency over time. Note that the heating and cooling setpoints and setbacks are the same as those in 90.1-2007 given in table 2. All changes made to the reference model to achieve the 90.1-2010 model in EnergyPlus are in table B4, with additional schedule changes in table B2.

ASHRAE 90.1-2010 is the first time the base model uses daylighting control. Section 9.4.1.1 of 90.1-2010 first requires implementation of daylighting control into the building. In every perimeter zone in the medium commercial office building, a non-aggressive daylighting strategy is used to light a portion of the space when possible. When implementing daylighting control into a perimeter zone, many different factors must be considered such as the WWR, parameters of the fenestration for instance the glazing and transmission characteristics, and even the interior surface reflectance (Liang Wong, 2017). In this case, the daylighting control only supposed to affect the first 5 feet from the exterior walls of each perimeter zone. This is considered as non-aggressive daylighting control because the implementation of daylighting seen in this case has the capability to light up a much larger portion of the room. With the addition of daylighting control, the interior lighting energy usage was degreased significantly, which resulted in a change of -1.76 EUI from the base 2007 model.

Outdoor air demand control ventilation is first used in 90.1-2010. In Section 6.4.3.9, Ventilation Controls for High Occupancy Areas in 90.1-2010, the standard requires DCV for spaces that have a certain amount of occupancy, as well as zones that are above an outdoor air capacity threshold, use an air-side economizer, or have automatic modulation control of the outdoor airflow. As mentioned previously, DCV modulates the outdoor airflow depending on the number of occupants present in the zone. With DCV, the outside airflow into the space can be matched to the exact minimum requirement of outdoor airflow according to ASHRAE 62.1. This change also impacted a portion of the envelope infiltration due to the outdoor air damper being at its minimum position when unused. As a result, the backdraft due to the outdoor air damper was reduced, thus reducing the envelope infiltration rate. To better meet comfort requirements with ASHRAE 62.1, the design outdoor air flow rate was increased slightly with the inclusion of DCV. These exact changes made to the reference model in order to implement DCV can be seen in table B4 in the appendix under the DCV section. This addition of DCV made the difference of -2.05 EUI when implemented in the 2007 base model.

Another major addition brought in with ASHRAE 90.1-2010 is the use of economizing. In section 6.5.1 of 90.1-2010, economizing is now required for climate zone 3. As previously discussed, the purpose of the economizer is to allow for additional outdoor air to flow into the space when beneficial. This way the cooling system does not have to use as much energy to condition the air when the outdoor air is cooler than the return air. Since the cooling system being used in the base model is three DX VAV units, an air side economizer is implemented in the 2010 reference model. For Charlotte, North Carolina in climate zone 3, the recommended economizer control method is differential enthalpy. This control method compares the return air enthalpy with the enthalpy of the outdoor air. When the outdoor air enthalpy is less than that of the return air, the outdoor air damper opens, otherwise the damper sets the outdoor airflow to a minimum. This implementation allows for outdoor air to cool the space when possible instead of always relying on the cooling coils in the DX unit. Because of the change in operation of the outdoor air damper from that in the 2007 reference model, the operational schedule of the damper changed to only open from 7 a.m. till 10 p.m. seen in table B2. The addition of the economizer to the 2010 model brought a reduction of -2.16 EUI when implemented to the 2007 base model.

Exterior lighting had a big impact on the reference model with the changes in the 90.1-2010 standard. Section 9.4.5 of ASHRAE 90.1-2010 first allowed exterior lighting to be broken up into what is known as exterior lighting zones. There are four different zones total, all with different lighting power allowances. These different zones allow for separate lighting requirements for differing regions such as high-activity walk ways and parking lots. With the addition of the exterior lighting zones, the exterior lights in the 90.1-2007 model were separated into two zones. The zone with the higher lighting power allowance is the exterior lights responsible for illuminating the entrance and perimeter walkways of the office building. The exterior zone with the smaller lighting power allowance is for less populated regions of the exterior such as walkways in the parking lot. In the Energy plus model, the exterior lighting was separated into two different groups as seen in table B2. Along with this, the design level for exterior laughing decreased due to improvements in lighting efficiency. The new exterior design levels can be seen in table B4. With these exterior lighting changes, the total energy usage due to exterior lighting decreased greatly since now portions of the building's exterior lighting can use less watts per square foot along with the lights being more efficient themselves, which resulted in a reduction of -2.15 EUI once implemented in the 2007 base model.

The next change in the 2010 base model deals with the interior lighting control. Section 9.4.1.1 of ASHRAE 90.1-2010 first requires forms of occupancy based sensors to control the interior lights, typically using motion detection along with automatic dimming and shutoff sequences. In EnergyPlus, this was modeled by a reduction in the interior lighting schedule, which can be seen in table B2. When implemented in the 2007 base model, the 2010 interior lighting control provided a reduction of -0.90 EUI.

The interior equipment in EnergyPlus refers to any equipment in the interior of the building, such as the plug loads and elevators. With Section 8.4.2 of 90.1-2010, controlled plug loads are required so that certain equipment are automatically be shutoff outside hours of operation. In a real building, controlled plug loads are implemented by installing specially marked outlets that are automatically shutoff outside of the buildings typical hours of operation or are occupancy based. Because of this, designated pieces of equipment are plugged into these outlets and are forced to shut off during unoccupied times to save energy. Along with controlled plug load implementation, the increased efficiency in the interior equipment led to energy savings as well. Both the efficiency change in the interior equipment and the plug load controls are implemented in EnergyPlus by reducing the Equipment Schedule seen in table B2. This lead to a -0.92 EUI reduction of the building’s Interior load when implemented in the 2007 base model.

With Section 10.4.3 of 90.1-2010, the elevators lights and fan must be shutoff outside of the elevator’s hours of operation. In the case of the reference building, the elevators lights and fan are seen only on when the elevator is in use. This change is implemented in EnergyPlus by modifying the Elevator Lights and Fan schedule seen in table B2, which lead in a reduction of -0.17 EUI when implemented in the 2007 base model.

There were a couple of envelope changes with 90.1-2010. In accordance with table 5.5-3 of the 90.1-2010 standard, the model’s built-up roofing thermal and solar absorbance rating requirements were decreased to a lower value as seen in table B4. The rating requirements change for built-up roofing created a reduction of -0.11 EUI when implemented in the 2007 base model. Although a slight reduction in the infiltration rate was seen due to the addition of DCV, there was also a reduction of infiltration due to the envelope as well. The change in envelope based infiltration is documented in table B4 and led to a reduction of -0.28 EUI in the 90.1-2007 base model.

To meet comfort standards highlighted in ASHRAE 61.2, the VAV minimum airflow rate was slightly increased in the 2010 reference model with the implementation DCV. Because DCV limits the amount of outdoor air coming into the space to potentially 0 cfm when unoccupied, the minimum airflow must be increased to maintain comfort in the space when this occurs. To model this in EnergyPlus, the minimum airflow fraction was increased as documented in table B4. Although this change allowed the reference building to be compliant with the airflow standard in ASHRAE 61.2, fan uses more energy for a larger minimum airflow, thus resulting an increase of 0.06 EUI when implemented into the 2007 base model.

Most of the other energy saving factors are due to the increased energy efficiency of the building's equipment. These changes include the standard for interior and exterior lighting wattage per square foot, the internal equipment loads including the buildings elevator system, the cooling coil's gross rated cooling coefficient of performance or COP, the buildings electric transformer's efficiency rating, variable volume fans motor efficiency, and the water heater's parasitic consumption fuel rate reduction. The table below captures each of the equipment efficiency changes along with their resulting change in EUI when implemented into the 2007 base model. Note that the efficiency changes for the building's internal equipment loads, elevator system design level, and exterior lighting were discussed earlier.

Table 4. 90.1-2010 Efficiency Changes

Equipment:	ΔEUI_{2007}
Interior Lights Capacity (W/ft^2)	-1.06
Elevator Lights and Fan Design Level (W)	-0.07
Water Heater On/Off Cycle Parasitic Fuel Consumption (W)	-0.03
Cooling Coil COP (W/W)	-0.43
Variable Volume Fan Efficiency	-0.05
Electric Transformer Nameplate Efficiency	-0.25

With all the pervious requirement changes implemented in the 90.1-2010 reference model, the model was simulated in EnergyPlus to determine the energy breakdown by end use and the office models new EUI. The resulting end use breakdown in terms of electrical and natural gas kBtu can be seen in the table below.

Table 5. 90.1-2010 Reference Model End Use Parameters and EUI

End Use Parameters	Electricity [kBtu]	Natural Gas [kBtu]	EUI [$kBtu/ft^2$]
Heating	153,894	21,664	3.27
Cooling	348,341	0	6.49
Interior Lighting	362,050	0	6.75
Exterior Lighting	99,298	0	1.85
Interior Equipment	718,619	0	13.40
Exterior Equipment	16,502	0	0.31
Fans	77,736	0	1.45
Pumps	139	0	0.00
Heat Rejection	0	0	0.00
Humidification	0	0	0.00
Heat Recovery	0	0	0.00
Water Systems	0	67,185	1.25
Refrigeration	0	0	0.00
Generators	0	0	0.00
Total End Uses	1,776,579	88,849	**34.78**

The EUI seen in the 90.1-2010 model is 34.78 $kBtu/ft^2$. The end use parameters compared to one another in terms of kBtu can be seen in the chart below.

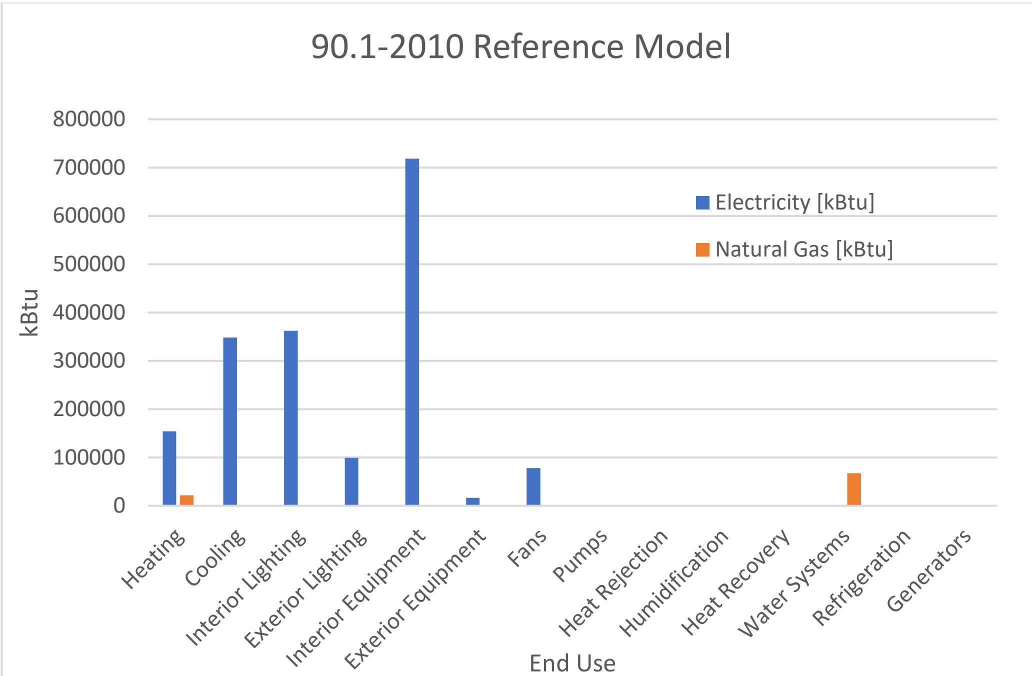

Figure 10. 90.1-2010 Reference Model End Use kBtu

3. ASHRAE 90.1-2013 Reference Model

The final version of the reference office building considered is the ASHRAE 90.1-2013 reference model. The 2013 revision keeps the standards mentioned before in the 2007 and 2010 reference models and adds a few energy saving improvements. The changes in the 2013 reference model deal with the cooling setback, changes in the envelope's insulation U-value, and efficiency improvements.

The primary energy improvement implemented in the 90.1-2013 model is the unoccupied cooling setback. Section 6.4.3.3.2 of the 90.1-2013 standard requires the heating and cooling setback controls during hours when the building is unoccupied. The building's zone level temperature setpoints and setbacks are given in table 5 below. With 90.1-2013, the unoccupied cooling changed from maintaining the 75° F setpoint during unoccupied hours to an 80° F temperature setback. The occupied setpoints are active from 5:00 a.m. till

10:00 p.m. during the workweek, while the temperature setbacks are active from 10:00 p.m. till 5:00 a.m. A more detailed schedule of the setback implementation into EnergyPlus can be seen in table B3. This leads to a sizable cooling energy reduction determined to be -0.86 EUI when implemented in the 2007 base model.

Table 6. 90.1-2013 Reference Model Heating and Cooling Setpoints

Setpoint:	Zone Temperature:
Occupied Cooling	75° F
Unoccupied Cooling	80° F
Occupied Heating	70° F
Unoccupied Heating	60° F

Section 9.4.1.1 of 90.1-2013 expand the requirements for interior lighting control. The occupancy sensors with automatic dimming and shutoff controls first seen in 90.1-2010 are expanded to be required in more zones. This addition of the interior lighting control is implemented into EnergyPlus by changing the Interior Lighting Schedule seen in table B3. The addition of lighting control gives a EUI reduction of -1.29 when implemented in the 2007 base model.

The efficiency improvement of the interior equipment of the building resulted in a reduction of EUI. The reduced plug load is model by the fractional Equipment Schedule in EnergyPlus seen in table B3. The resulting energy difference is -1.06 EUI in the 2007 base model.

The next revision in 90.1-2013 are multiple envelope construction improvements in accordance with table 5.5-3 in the standard. All roofing, exterior wall, and fenestration thermal resistance or insulation requirements increased so that more resistive insulation is used. These envelope improvements lead to a slight reduction in cooling energy. The changes in the envelope insulation in EnergyPlus are documented in table B4. The following table shows the changed envelope components as well as the difference in EUI they provide when implemented into the 2007 base model.

Table 7. 90.1-2013 Envelope Changes

Construction:	ΔEUI_{2007}
Nonres Roof Insulation	-0.19
Nonres Exterior Wall Insulation	-0.09
Exterior Perimeter Windows U-value	-0.05

To further meet comfort standards given in 62.1, the VAV minimum airflow level has been increased due to DCV. Similar to the change made in the 90.1-2010 revision, the minimum airflow fraction was implemented into EnergyPlus using the values given in table B4. The resulting airflow during times of minimum outdoor air coming into the building due to DCV causes more energy to be used to meet the VAV minimum airflow value to meet the comfort requirements. The change results in an increase of 0.11 EUI when implemented into the 2007 base model.

Similar to the previous revisions of 90.1, the gradual energy reduction due to new equipment becoming more efficient is seen in the 2013 model. These efficiency reductions impact the interior lighting wattage per square foot, the internal equipment loads including the buildings elevator lights and fans, and the efficiency rating of the variable volume fans. The exact changes made to create the higher efficiency model can be seen in table B4. The following table show the different parameters that changed based on equipment efficiency and the resulting change in EUI when implemented into the 2007 model. Note that the EUI reduction due to the efficiency increase in the interior equipment for the 90.1-2013 model was analyzed above.

Table 8. 90.1-2013 Efficiency Changes

Equipment:	ΔEUI_{2007}
Interior Lights Capacity (W/ft2)	-1.9
Elevator Lights and Fan Design Level (W)	-0.13
Variable Volume Fan Efficiency	-0.10

With all of the changes mentioned in this section implemented into the base building model for 90.1-2013, the model was simulated in EnergyPlus. From the simulation, the building is separated into end use parameters in terms of kBtu which can be seen in the table below along with the buildings EUI.

Table 9. 90.1-2013 Reference Model End Use Parameters and EUI

End Use Parameters	Electricity [kBtu]	Natural Gas [kBtu]	EUI [kBtu/ft^2]
Heating	152,382	24,445	3.30
Cooling	300,206	0	5.60
Interior Lighting	312,143	0	5.82
Exterior Lighting	99,298	0	1.85
Interior Equipment	711,404	0	13.26
Exterior Equipment	16,178	0	0.30
Fans	68,182	0	1.27
Pumps	139	0	0.00
Heat Rejection	0	0	0.00
Humidification	0	0	0.00
Heat Recovery	0	0	0.00
Water Systems	0	67,161	1.25
Refrigeration	0	0	0.00
Generators	0	0	0.00
Total End Uses	1,659,930	91,606	**32.66**

The EUI seen in the 90.1-2013 base model is 32.66 kBtu/ft^2. The figure below compares the end use parameters by electricity and natural gas in terms of kBtu for the same model.

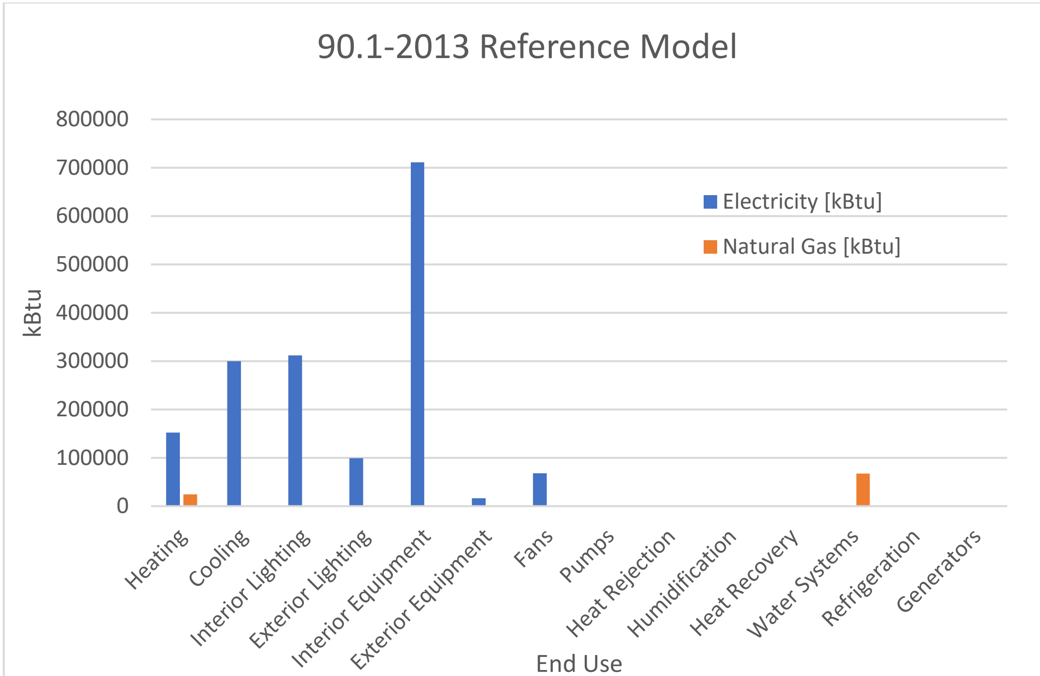

Figure 11. 90.1-2013 Reference Model End Use kBtu

4. Reference Model Comparison

There are many changes throughout the 2007, 2010, and 2013 revisions of 90.1. The impact of these changes can be seen when comparing the end use parameters and EUI difference for each of the base models. Figure 12 below shows each reference models EUI broken up by end use.

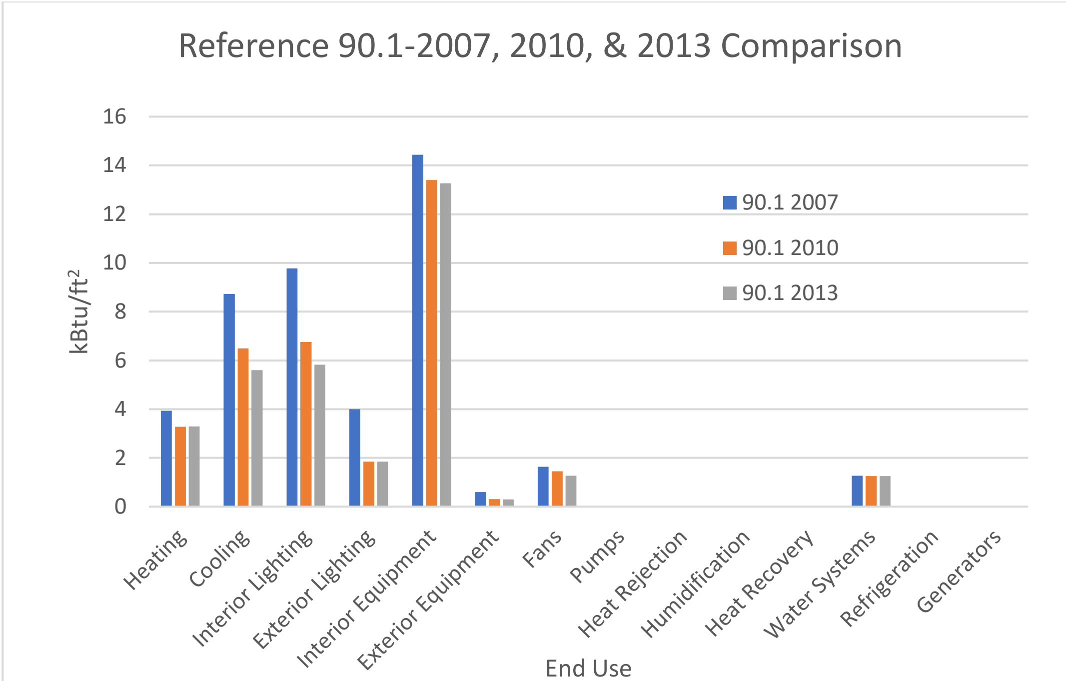

Figure 12. 90.1-2007, 2010, and 2013 Reference Model Comparison

There is a major difference between the 2007 and 2010 standard. The total EUI for the 2007 reference model is 44.38 EUI, while the total EUI for the 2010 base model is 34.78 EUI. The changes implemented with the 90.1-2010 standard gave a reduction of -9.6 EUI. There were major improvements in heating, cooling, interior lighting, exterior lighting, and the interior equipment between the 2007 and 2010 models. With the 2013 reference model having a total of 32.66 EUI, the 90.1-2013 revision gave a slight improvement of -2.12 EUI from the 2010 standards and -11.72 EUI from the 2007 standard. The 90.1-2013 reference model gave major improvements in the building's cooling and interior lighting. To understand the true impact of each change, the table below show each change to the reference models and the resulting impact in terms of the change in EUI when the change is implemented into the 2007 base model. The changes are separated by the 2010 and 2013 changes and are sorted by greatest EUI reduction from the 2013 model.

Table 10. 90.1-2010 and 2013 Reference Model Changes and Resulting Impact

Section:	Change Made:	Δ EUI (2010)	Δ EUI (2013)
Economizer	Outdoor Air Economizer	-2.16	-2.16
Exterior Lighting	Exterior Lighting Power Allowance	-2.15	-2.15
DCV	Outdoor Air Demand Control Ventilation	-2.05	-2.05
Efficiency	Lighting Wattage per Zone Floor Area	-1.06	-1.90
Daylighting	Daylighting Control	-1.76	-1.76
Lighting Control	Lighting Control	-0.90	-1.29
Efficiency & Plug Load Control	Internal Equipment Efficiency and Control	-0.92	-1.06
Temp. Setpoints	Cooling Setback	-	-0.86
Efficiency	Cooling Coil High/Low Speed Gross Rated Cooling COP	-0.43	-0.43
Envelope	Zone Infiltration	-0.28	-0.28
Efficiency	Electric Transformer Efficiency	-0.25	-0.25
Envelope	Nonres Roof Insulation	-	-0.19
Elevator Control	Elevators Lights and Fan Control	-0.17	-0.17
Efficiency	Elevators Lights and Fan Efficiency	-0.07	-0.13
Envelope	Built-Up Roofing Insulation	-0.11	-0.11
Efficiency	Variable Volume Fan Efficiency	-0.05	-0.10
Envelope	Nonres Exterior Wall Insulation	-	-0.09
Envelope	Exterior Perimeter Windows U-value	-	-0.05
Efficiency	Water Heater Parasitic Consumption Fuel Rate	-0.03	-0.03
AirFlow	VAV Minimum Air Flow to meet 62.1	0.06	0.11

The previous table provides general insight to compare the relationships of the 90.1 revisions and their impact when implemented. Using this information, the building designer obtains a higher understanding of what each of these standard revisions really consist of and how effective they are when reducing the buildings EUI. By seeing how buildings have improved, educated guesses can be made in order to identify key systems in these building's design and make future improvements upon them.

C. Operational Differences

When referring to the modeling requirement to prove compliance using the ECB method or the tradeoff method, as long as the building models used contain the same general operational parameters, the real operational parameters of the building once it is occupied are not necessarily considered. Because of this process, the simulated building's EUI is typically different from the actual building once it is constructed and occupied. These types of discrepancies will not necessarily allow for an accurate modeled EUI goal to be made that is achievable by the real building.

This section will discuss the impact of the differences caused by the model's operational assumptions being made between the modeled EUI and the real building's EUI. Once these differences are understood, a more accurate modeling approach can be taken to avoid these differences and achieve model that provides a closely representative EUI of the real building.

The first set of operational differences that typically occur between a building model and a real building are the set schedules and setpoints of the building. Changes in the assumed occupied times of the building as well as the heating and cooling setpoint impact the buildings energy usage. The next set of operational differences are the result of the mechanical system control strategies not preforming as initially expected. The causes and energy impact of these operational differences are explored in the following sections.

1. Setpoints and Schedules Based Operational Differences

When the building is modeled in a simulation software, to achieve a realistic EUI, it is important to consider how the real building is or will be operated. The operational parameters that are most likely to fluctuate the EUI due to not properly communicating or making generic assumptions about is the heating and cooling temperature setpoints, the level of occupancy, and hours of operation of the building. The following case study will give an example of what happens when the real building operations are not correctly considered into the model.

For this case study, different occupancy based schedules, which are changed with the building occupancy levels at any point throughout the day, as well as different heating and cooling setpoints were implemented into the ASHRAE 90.1-2007 reference model. The building's hours of operation were extended from the reference building's 8 a.m. to 5 p.m. schedule to the more realistic 7 a.m. to 6 p.m. schedule. In this case, the building operators made the active decision to keep their building running longer for the custodial staff and employees coming in early and staying late throughout the workweek. The heating and cooling setpoints were changed to reflect those of the commercial office building being studied. Note that AHSRE 90.1 recommends a 5° F deadband to be used between the occupied heating and cooling setpoints. In the building studied, the setpoints were set to have only a 2° F deadband. The following tables show the schedule and setpoint changes implemented in detail.

Table 11. Case Study Heating and Cooling Setpoint Change

Setpoint:	Base 90.1-2007 Zone Temperature:	Case Study Zone Temperature:
Occupied Cooling	75° F	72° F
Unoccupied Cooling	75° F	80° F
Occupied Heating	70° F	70° F
Unoccupied Heating	60° F	60° F

Table 12. Case Study Occupancy Based Schedules Change

	Building Model Schedules:	Base 90.1-2007 Schedules				Case Study Schedules			
		Occupancy Schedule	Equipment Schedule	Lighting Schedule	Elevator Schedule	Occupancy Schedule	Equipment Schedule	Lighting Schedule	Elevator Schedule
Times For Weekdays	12:00 AM	0	0.4	0.05	0	0	0.4	0.05	0
	1:00 AM	0	0.4	0.05	0	0	0.4	0.05	0
	2:00 AM	0	0.4	0.05	0	0	0.4	0.05	0
	3:00 AM	0	0.4	0.05	0	0	0.4	0.05	0
	4:00 AM	0	0.4	0.05	0	0	0.4	0.1	0
	5:00 AM	0	0.4	0.1	0	0.1	0.4	0.1	0
	6:00 AM	0.1	0.4	0.1	0	0.2	0.4	0.3	0.35
	7:00 AM	0.2	0.4	0.3	0.35	0.95	0.9	0.9	0.69
	8:00 AM	0.95	0.9	0.9	0.69	0.95	0.9	0.9	0.43
	9:00 AM	0.95	0.9	0.9	0.43	0.95	0.9	0.9	0.43
	10:00 AM	0.95	0.9	0.9	0.37	0.95	0.9	0.9	0.37
	11:00 AM	0.95	0.9	0.9	0.43	0.95	0.9	0.9	0.43
	12:00 PM	0.5	0.8	0.9	0.58	0.5	0.8	0.9	0.58
	1:00 PM	0.95	0.9	0.9	0.48	0.95	0.9	0.9	0.48
	2:00 PM	0.95	0.9	0.9	0.37	0.95	0.9	0.9	0.37
	3:00 PM	0.95	0.9	0.9	0.37	0.95	0.9	0.9	0.37
	4:00 PM	0.95	0.9	0.9	0.46	0.95	0.9	0.9	0.46
	5:00 PM	0.3	0.5	0.5	0.62	0.95	0.9	0.9	0.46
	6:00 PM	0.1	0.4	0.3	0.12	0.3	0.5	0.5	0.62
	7:00 PM	0.1	0.4	0.3	0.04	0.1	0.4	0.3	0.12
	8:00 PM	0.1	0.4	0.2	0.04	0.1	0.4	0.3	0.04
	9:00 PM	0.1	0.4	0.2	0	0.1	0.4	0.2	0.04
	10:00 PM	0.05	0.4	0.1	0	0.1	0.4	0.2	0
	11:00 PM	0.05	0.4	0.05	0	0.05	0.4	0.1	0

Once the data from the previous tables was implemented into the operational parameter changes case study building model, the model was simulated using EnergyPlus. From the simulation, the resulting EUI by End Use parameters were obtained. The figure below shows the End Use EUI difference between the ASHRAE 90.1-2007 reference model and the operational parameter change case study model.

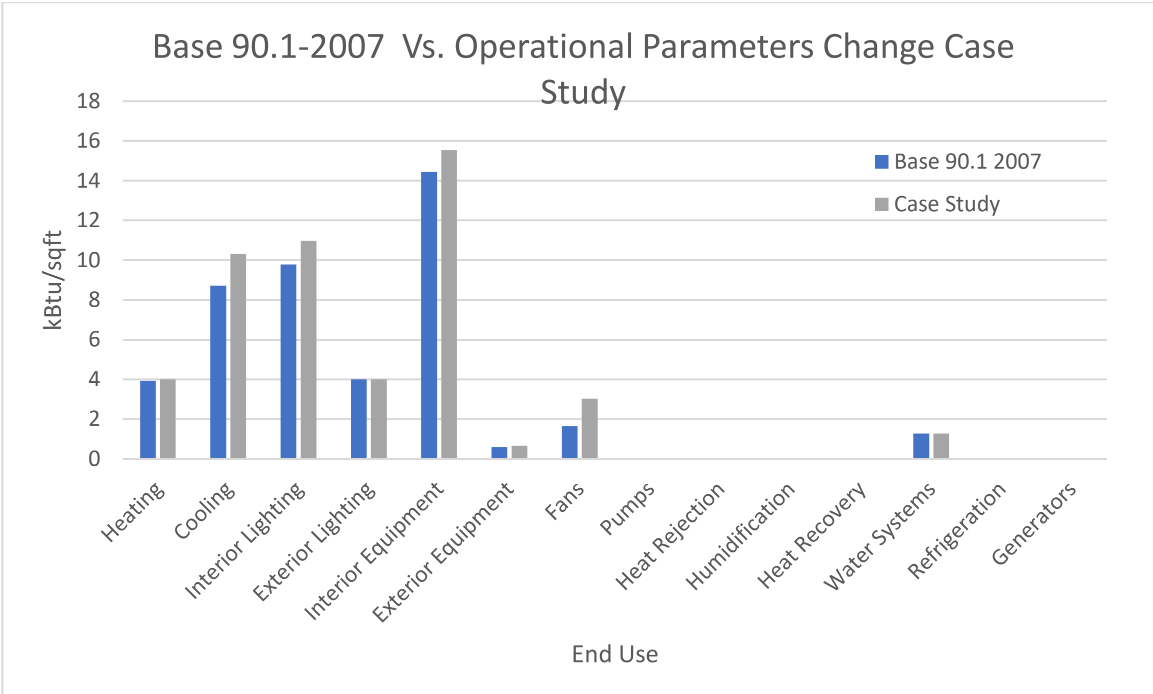

Figure 13. Base 90.1-2007 Vs. Operational Parameters Change Case Study

The resulting EUI of the case study was 49.80 kBtu/ft^2, which is a change of +5.42 EUI from the 90.1-2007 base model. This result proves how big of a difference operational parameters can have on the model.

The best way to handle this issue of obtaining a realistic EUI target due to the real building's operation is to be sure that the model's occupancy, temperature setpoints, and hours of operation match the general trend of the real building. This would mean the building designer would have to know key parameters such as the average amount of occupants in the building, the owner's temperature setpoint policy, and the general hours of operation for Weekdays, Weekends, and Holidays. This level of resolution of the building model should create a good estimate of how the real system will behave, along with a reasonable EUI goal.

2. Operational Differences of Building Control Systems

The second potential cause for operational differences between the building model and the real building lies with real building's equipment, sensors, and controls. It is an obvious statement that the building model assumes that the building operates optimally with all equipment functioning properly, all sensors are calibrated and reading fairly, and the control strategies are implemented correctly. What might not be so clear is how frequently these systems and sensors do not necessarily operate as expected in real HVAC systems. Simple sensor readings and mechanical failures can cause control systems to function substandard, thus making the mechanical system operate outside its designed behavior. To further explore this concept, the historical data of a commercial office building in Charlotte, North Carolina was analyzed. Frequently, the historical trends in the data show how small issues such as these can have a big impact on the building's mechanical system operation. The following is a case study giving an example of this type of issue arising in the commercial office analyzed.

The historical operational data from the office building shows how poor control strategies and zone level interactions can make the static pressure reset not operate as intended. The static pressure reset's purpose is to move the static pressure setpoint based on load conditions in order for the fan to operate more efficiently, resulting in energy savings due to reduced fan usage. The way the static pressure reset frequently fails is when rogue zones in the space are not addressed. These rouge zones are areas where the damper is much more open than the dampers across the rest of the building. These rouge zones can arise for a multitude of reasons, whether the damper is mechanically stuck open, a high heat load in the space that was not accounted for in the building's design, or false or failed senor reading.

The next figures show this concept of the static pressure reset not operating to its fullest capacity due to rogue zones in the building analyzed. In figure 14, the static pressure signal, which tracks the air pressure provided by the supply air fan is shown operating for an entire week.

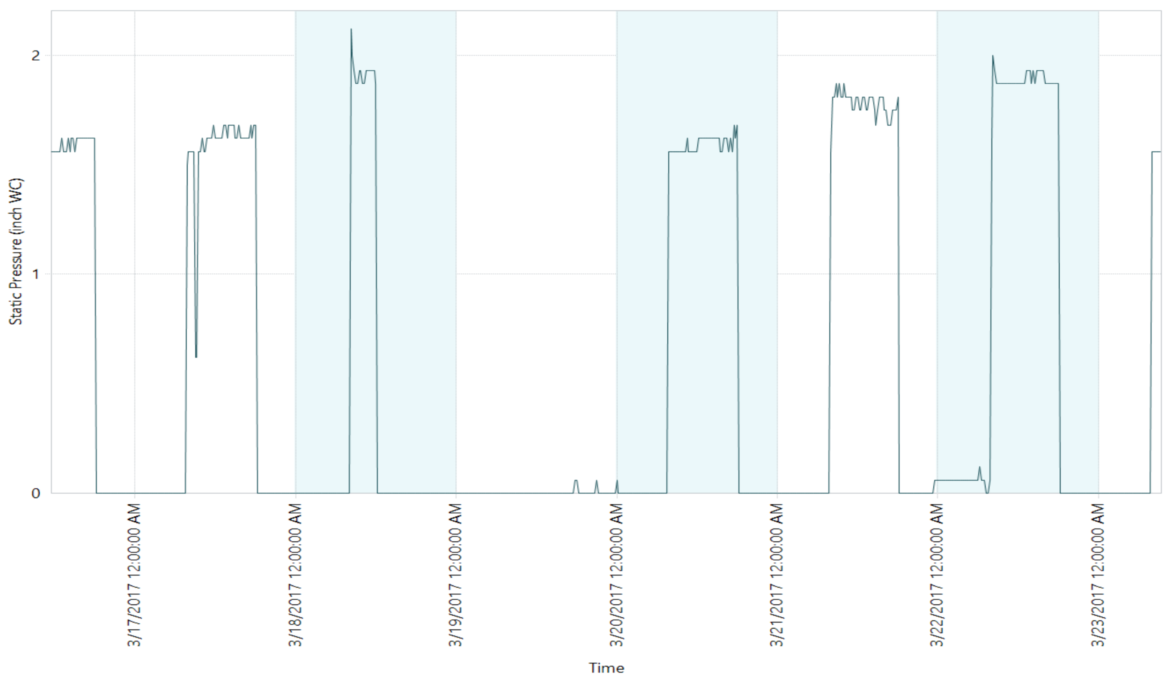

Figure 14. Static Pressure Signal in in. w.c.

Although the static pressure is seen fluctuating up and down by a small margin throughout the week, the air pressure is fairly constant which shows that the reset is not working optimally. To further explore what is causing the pressure to not be reset to its fullest capability, figure 15 shows the terminal unit damper positions that are being serviced by the supply air fan represented in the previous figure.

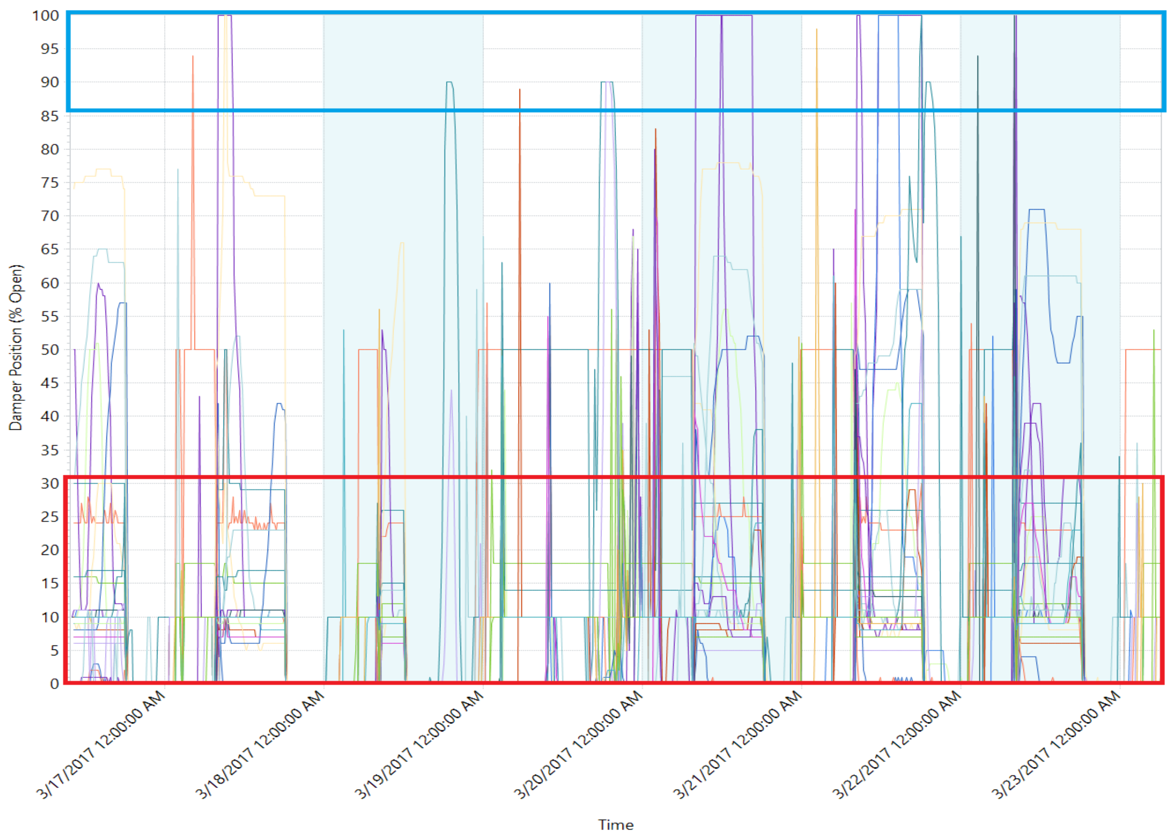

Figure 15. Damper Positions of All Terminal Units Serviced

Figure 15 plots all damper positions in terms of percent open, meaning 100% refers to the damper being fully open while 0% is when the damper is fully closed. Notice in the figure that the majority of the dampers, seen in the red box, are only operating 30% open or less. Ideally, if the static pressure reset was operating to its fullest potential, the majority of the terminal dampers should be operating closer to 70% open or higher. The rogue zones preventing the reset can be seen in the blue box in the figure above. Only two rogue zones operate at 100% open. It is these zones that define the pressure supplied into the space. Because of this interaction, the static pressure reset is not able to occur effectively and therefore results in energy loss, since the reset is not operating to its fullest capability.

As can be seen, simple interactions as these can have a large impact on the control algorithms of the space if not implemented robustly or maintained. If this building was modeled to the standard that most buildings are, these rogue zones would not be depicted because the model would assume the every terminal damper is operating closely to another and therefore not effecting the static pressure reset. This is the kind of simple relationships that cause discrepancies from the model to the real building.

To show this impact of the static pressure reset not operating properly in the building model, this case study was simulated in EnergyPlus. Because the air pressure being supplied to the building was relatively constant throughout each day, the model was approximated to show what would happen if no pressure reset took place in the 90.1-2007 reference building. To create this simulation, the 2007 reference model was edited to no have a static pressure reset implemented and then was ran in EnergyPlus. The following chart in figure 16 compares the End Use parameters of the 2007 base model with and without the static pressure reset implemented.

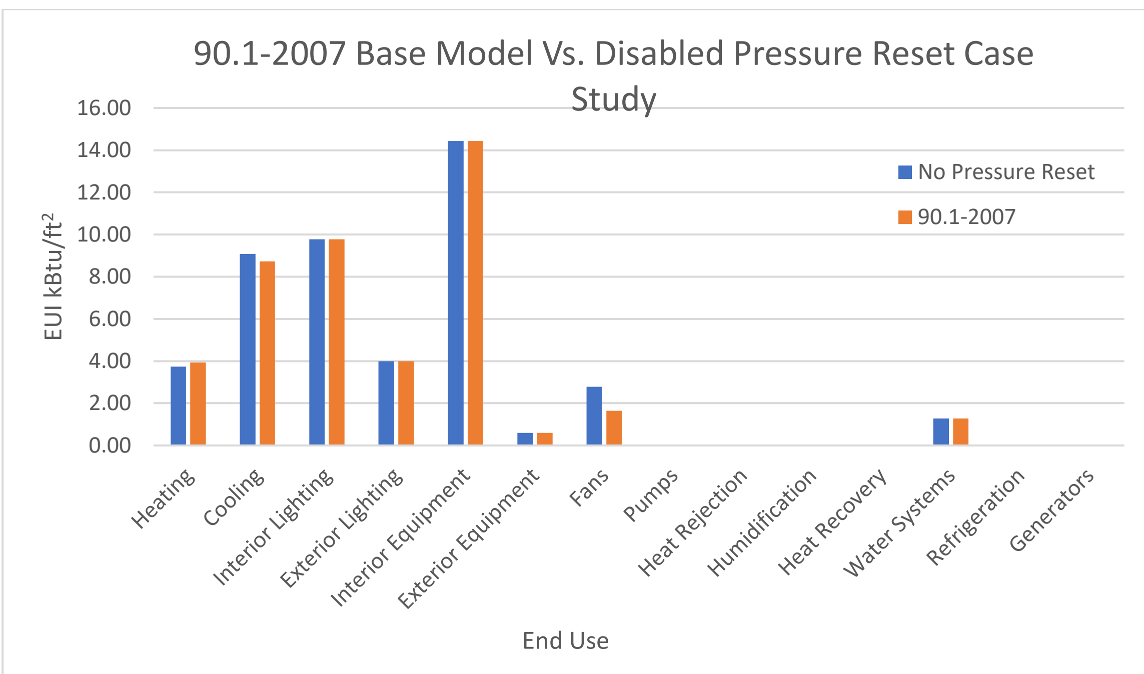

Figure 16. 90.1-2007 Base Model Vs. Disabled Pressure Reset Case Study

Not surprisingly, the removal of the static pressure reset had great impact on the fan's energy usage. Slight changes were also seen in regards to the heating and cooling loads due to more unnecessary airflow coming into the space. The model with the static pressure reset disabled gives a EUI of 45.67, which is 1.30 EUI above the original 90.1-2007 reference model. This impact shows how crucial working control systems are when dealing with the operation of a building.

During the design process, the risk of implementing more complex control systems needs to be understood if they do not work as intended. When realizing how much impact a certain system has on the buildings EUI, priority to key systems known to potentially perform under expectation can be given. This way additional resources are subjugated to ensure that the control systems and sensors are correctly installed, calibrated for the space, and are maintained, resulting in a well-controlled, efficient building.

In order to obtain a reasonable EUI goal, these types of operational differences must be considered. Minor changes in a building's setpoints and schedules or its control system operation can result in a massive difference in EUI. The building model needs to implement accurate parameters according to how each building operates, while tradeoffs in functional system controls need to be understood. This requires the building designer to have an open dialog with the owner as well as future building operators and occupants to better understand the future operation of the building project. This helps ensure the building is designed with the understanding of its future operation, and a proper EUI goal can be established and met.

D. Establishing Reasonable Energy Goals

Utilizing building models is important for establishing initial energy goals for building projects in the early phase of the design process. With the understanding of energy trade-offs due to using aspects of different 90.1 iterations as well as considering operational differences, a reasonable energy goal can be defined. In this chapter, a baseline building will be defined for the North Carolina Piedmont as well as a reasonable energy goal for the region.

Because most modern office buildings constructed today closely represent the 90.1-2013 standard, the 90.1-2013 reference model is used as a starting point in defining a baseline building model. From the 90.1-2013 reference model the following changes are made.

- No Demand Control Ventilation
- Realistic Setpoints: 74° F Occupied Cooling
- Realistic Operation: 8 a.m. to 6 p.m.
- Differential Dry Bulb Economizer

From this list, the first change from the reference model is not implementing Demand Control Ventilation. DCV is not included because of the additional sensors required to implement into the design. To measure the number of occupants, DCV systems often use CO^2 sensors. Even though DCV could be somewhat expensive to implement, the major reason for building owners and operators not wanting to add DCV into the building design is usually due to the additional maintenance the CO^2 sensors require. If the sensors are not properly maintained and calibrated with the required preventive maintenance, the DCV system will operate poorly and possibly even result in more energy usage than it would if it was not implemented at all. Because of this, DCV was taken out for the baseline model.

The next two changes are operational based. The 90.1-2013 model assumes a 75° F occupied cooling setpoint is used in the space. After looking at the operations of real buildings in the area, it is often seen the occupied cooling setpoint is lower than 75° F. Because of this, the occupied cooling setpoint was adjusted to 74° F. The other operational change deals with the occupied times of the building. 90.1 assumes the buildings hours of operation is from 8:00 a.m. to 5:00 p.m. For local buildings, these times are typically extended due to the building owners wanting to keep the building tempered for the maintenance and janitorial staff. Because of this, the hours of operation was extended to be from 8:00 a.m. to 6:00 p.m.

The final change from the 90.1-2013 reference model deals with the economizer. For climate zone 3, ASHRAE recommends a Differential Enthalpy based economizer control. However, when looking a local buildings, the economizers seen uses either Fixed or Differential Dry Bulb. This is change in sensors typically happen due to the reliability difference between dry bulb temperature sensors versus enthalpy sensors. Because of this, the control type used in the Piedmont baseline model assumes Differential Dry Bulb based control for the economizer.

Now that the differences have been identified, the baseline building can be modeled and a realistic energy target can be obtained for the Piedmont area. Once these changes were made to the 90.1-2013 reference model, the model was ran in EnergyPlus. The following graph shows the building model's EUI separated by end use parameters.

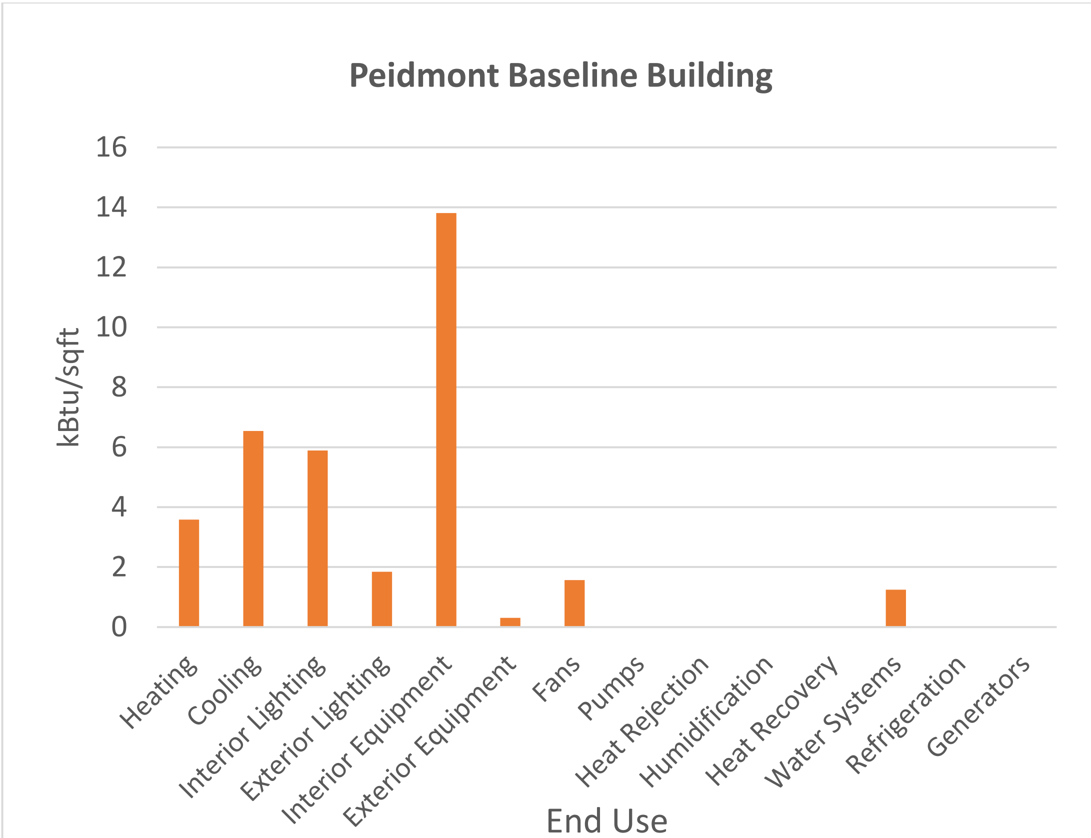

Figure 17. Piedmont Baseline Building Model End Use EUI

The Piedmont Baseline Building was determined to have a total EUI of 34.82 kBtu/ft^2. This EUI is only gains 2.16 kBtu/ft^2 when comparing it to the 90.1-2013 reference model. Knowing that this EUI reflects the modern office space being constructed in the North Carolina Piedmont, the EUI of 34.82 is determined to be a reasonable energy goal for the region.

IV. Building Design Visualization Tool

To build on the concept of creating a EUI goal from the building models, the idea of the Building Design Visualization Tool was developed. The mission of the tool is to allow users to get a better idea of key system tradeoffs, obtain a realistic EUI goal, and be able to point out key systems that may inhibit this goal from being reached. Because of this, the tool can be utilized early into the building design process so that building both building owners and designers can select key building parameters they want implemented as well as determine a EUI goal for their building. Because these key building parameters are not decoupled from one another, each combination of design choices has to be considered individually to obtain realistic energy usage for that particular building. To be effective across a wide range of designs and operations, the tool contains over 1 million unique building parameter combinations that effect the building envelope heat load, mechanical system controls, and its operational schedules and setpoints. Users can easily filter through these combinations by checking boxes representing different envelope construction parameters, HVAC control systems, as well as choosing the general operation of the building. Once every parameter is selected in the tool, the EUI and End Use values are instantly presented to determine, or weigh against, the EUI goal. A reference EUI goal functionality is also implemented into the tool so that users can input a EUI goal and acceptable range. The tool will automatically determine whether or not the goal was reached with the parameters selected.

In order to know what choices the tool needs to have included, the comparable office buildings located in North Carolina as well the ASHRAE reference models were analyzed. This allowed for key envelope, HVAC system, and operational parameters that had the biggest impact in their resulting EUI to be determined and included. The most common deviations designers and building owners make from the 90.1 prescriptive path were considered as well so that these energy tradeoffs could easily be seen in the tool without the need of additional modeling. Researching historical data from real buildings also gave an insight of how buildings are frequently operated. With this, crucial operational trends were added to the tool in order for the model to reflect realistic operations of the building.

Because buildings are so unique, even with the amount of pre-ran simulations, it is unlikely that the exact building model lies in the design tool. However, the system tradeoffs would still carry over from model to model. For example, understanding how large of a EUI impact a certain orientation and building form have on the internal heat loads of the building applies to every building design and model. The tool excels at giving users an in-depth understanding of the impact of the system and parameter design choices. The EUI is shown how it fluctuates as different envelope constructions, HVAC systems and controls, and building operations are implemented and adjusted. Seeing the different levels of fluctuation allows all users to easily understand the impact of these design choices. Priority to constructions, systems, and operations that is seen to have a large impact on the building can be given so that they are implemented correctly in the real building.

The biggest benefit the Building Design Visualization Tool provides is that is lays down the foundation for good building design and creating reasonable EUI goals. The tool brings building design to an extremely simple level so that anyone involved in the IDP can fully understand the impact of the design choices made. This allows the conversation to reach a level that all of the necessary personnel can assist in making the key design choices, and that all can be in agreement and satisfied with the end result.

The building models available in the tool are most comparable to the 90.1-2013 reference model. Although North Carolina currently only requires building to be between the 90.1-2007 and 2010 standards, North Carolina is expected to adopt the 90.1-2013 standard within the next two years since there are only small differences between 90.1-2010 and 2013. To future proof the tool, the models are based from the 90.1-2013 standards like most modern buildings being constructed. The only difference between the models in the design tool and the 90.1-2013 reference model is that the natural gas heating coil is disabled in the rooftop DX units. From the historical data analysis, for real buildings in the Piedmont area, the gas coils are hardly used in the area due to the electric reheat available in each terminal unit along with the cost of electricity being less than natural gas.

The following sections are broken up into the sectionalized design choices seen in the tool. The sections, in order of the design process, is the Envelope Heat Load Minimization, the Mechanical System Operation and Controls, and finally the Mechanical System Selection. Each section discusses what design choices are available in the tool, how each design choice is implemented into the building model, as well as explaining the coupled interactions between the different parameters implemented in the building. Figure 18 shows the flow chart of how the tool is used.

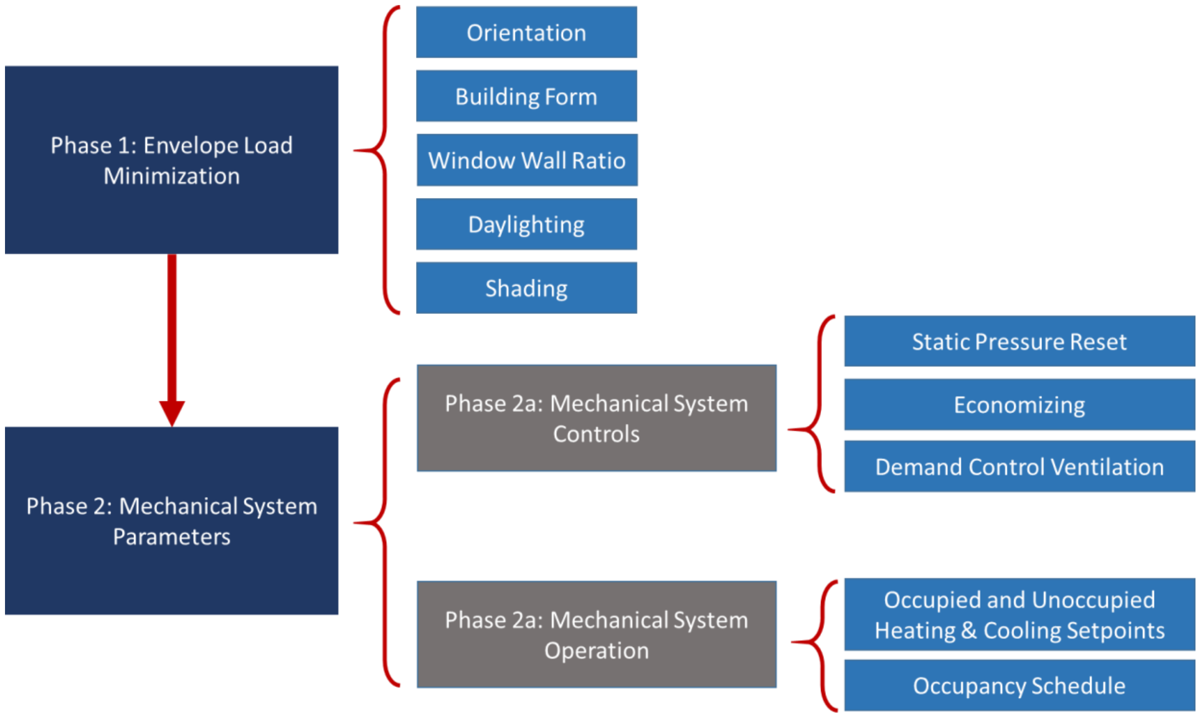

Figure 18. Building Design Visualization Tool Flowchart

In the first phase of the tool is the Envelope Load Minimization section where users adjust parameters relating to the buildings envelope. For reference, every parameter option is listed in table 13 below. The goal of the Envelope Load Minimization is to optimize the heating and cooling load of the envelope so that the mechanical system only has to overcome the minimum amount of load in the buildings zones. Once the envelope heat load is minimized, the user can move on to the second phase which consists of the mechanical system parameters. This phase discusses the key principles behind the controls and operation of the building's mechanical system. In the first section of the second phase of the tool the mechanical systems control strategies are selected and implemented into the design. The second section allows the users to define the mechanical systems operation. Here the user can establish key operational parameters of the building which directly correlate to the functionality of the mechanical system.

Table 13. Building Design Visualization Tool Parameters

Building Parameter:	90.1 Standard	Option 1	Option 2	Option 3	Option 4	Option 5
Building Orientation	0° Orientation	0° Orientation	45° Orientation	90° Orientation	-	-
Building Form	Rectangular Building	Rectangular Building	Square Building	Long Building	-	-
WWR	Standard WWR	Standard WWR	All Glass Building	-	-	-
Daylighting	Daylighting	No Daylighting	Daylighting	Advanced Daylighting	-	-
Shading	No Shading	No Shading	Shading	-	-	-
Occupancy In	8:00 AM	6:00 AM	7:00 AM	8:00 AM	-	-
Occupancy Out	5:00 PM	5:00 PM	6:00 PM	7:00 PM	-	-
Occupied Heating Setpoint	70° F	68° F	69° F	70° F	71° F	72° F
Unoccupied Heating Setpoint	60° F	60° F	65° F	-	-	-
Occupied Cooling Setpoint	75° F	74° F	75° F	76° F	77° F	78° F
Unoccupied Cooling Setpoint	80° F	80° F	85° F	-	-	-
Economizer	Differential Enthalpy	No Economizer	Differential Dry-Bulb	Differential Enthalpy	-	-
DCV	DCV	No DCV	DCV	-	-	-
Static Pressure Reset	Reset	No Reset	Reset	-	-	-

The following sections in this chapter will go into each parameter included in the Building Design Visualization Tool and their impact on the building in terms of energy usage. For easy comparison, the baseline building for the Piedmont established in the previous chapter will be used in order to quantify the tradeoffs between each parameter. Because there are so many available combinations included in the tool, only one-off changes from the baseline model will be discussed, except for the parameters that have been determined to be extremely coupled with one another in terms of energy usage.

A. Envelope Load Minimization

The Envelope Load Minimization section of the Building Design Visualization Tool allows the user to select crucial envelope parameters with the intention of minimizing the heating and cooling load in the building in order to reach the lowest possible EUI. The heating and cooling load is the amount of load created by factors such as the insulation used, the orientation of the exterior walls and fenestration, the amount of fenestration used, as well as internal occupant and equipment heat loads in the building. Minimizing this load reduces the amount of HVAC energy that is used to condition the space, and therefore saving energy. The parameters that can be manipulated in the tool in regards to the envelope is given in the following list.

- Building Orientation
- Building Form
- Building Window-to-Wall Ratio
- Daylighting Control
- Shading Devices

The envelope parameters listed above directly impact the heat load that must be overcome by the HVAC system. Next, each envelope design parameter along with each of the choices provided in the tool will be discussed in terms of how they were implemented into the building model along with their impact on the building and other design parameters.

1. Building Orientation

The building's orientation refers to the angle that the north most wall is facing. During the design process, the building's orientation is typically chosen by considering the plot of land and the roads around the building site to give the building curb appeal and so it is easily accessible. Because of this, designers and building owners may not have complete control of the building's orientation outside of choosing the building site itself. To explore the impact that different building orientations have on the EUI, three building orientations are given in the design tool. The orientations are 0° (normal north wall is facing north), 45° (normal north wall is facing northeast), and 90° (normal north wall is facing east). This parameter allows for the building to be rotated so that a general idea can be obtained regarding any orientation, since the results should be very similar for a rectangular building rotated at any orientation with a step size of 45°. The following figure shows a building model being rotated at 0°, 45°, and 90°.

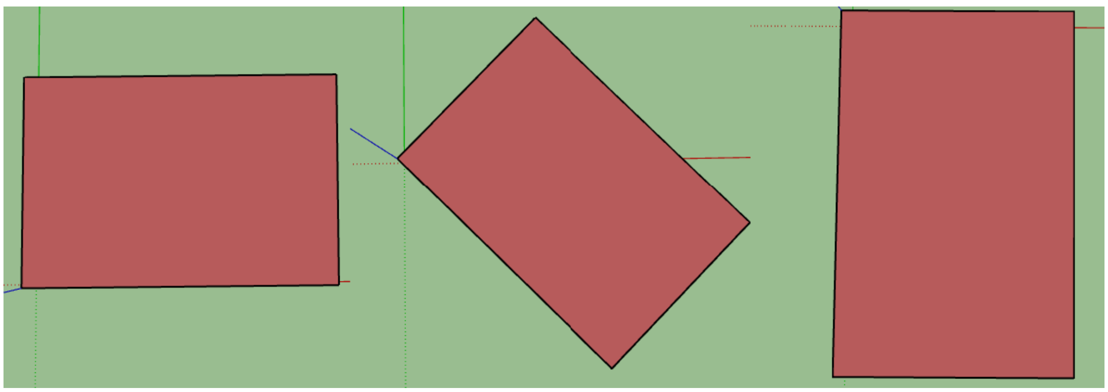

Figure 19. Building Rotated at 0°, 45°, and 90°

Table B5 in the Appendix shows how the orientation of the building model was changed for each option given in the design tool.

Once simulated and implemented in the tool, the building's orientation is seen to be a crucial design factor when considering which building form and WWR is used. To show how these parameters are coupled together in terms of energy usage, the following table includes each building orientation, building form, and WWR option from the tool along with the resulting EUI and Δ EUI when comparing each one to the baseline building. The table is organized from least to greatest Δ EUI.

Table 14. Orientation, Form, and WWR Comparison

Building Orientation:	Building Form:	WWR:	Total EUI:	□ EUI:	Notes:
0□	Rectangular	32%	34.82	0.00	Baseline Building
0□	Square	32%	35.01	0.19	Baseline Building with Square Form
□□□	Square	32%	35.07	0.25	
□□□	Square	32%	35.38	0.56	
□□□	Rectangular	32%	35.44	0.62	Baseline Building at 90□□Orientation
□□□	Rectangular	32%	35.49	0.67	Baseline Building at 45□□Orientation
0□	Long	32%	35.60	0.78	Baseline Building with Wide Form
□□□	Long	32%	37.48	2.66	
□□□	Long	32%	38.29	3.47	
0□	Rectangular	68%	39.90	5.08	Baseline Building with 68% WWR
0□	Square	68%	40.28	5.46	
□□□	Square	68%	40.33	5.51	
□□□	Square	68%	41.02	6.20	
□□□	Rectangular	68%	41.21	6.39	
□□□	Rectangular	68%	41.31	6.49	
0□	Long	68%	41.39	6.57	
□□□	Long	68%	45.30	10.48	
□□□	Long	68%	47.08	12.26	

As seen in the table, orientation has the potential of making a large difference in EUI when poorly considered with very wide building forms. It is a general rule of thumb for architects to minimize the fenestration on the east and west most facing walls for the least amount of solar heat gain due to sunlight. This is the primary reason of why the building forms are seen to behave worse at 45° angles than at 0°, assuming the longest side of the building is the north most facing wall. To keep the interior heat loads down, it is important to consider what orientation the building has so the proper building form and fenestration can be selected to reduce this effect.

2. Building Forms

Office buildings can come in all shapes and sizes, however the most common form for a medium sized office building is a rectangular, box-like building. There are a multitude of cosmetic and site restrictions that go into play when determining a building's form. To understand the EUI impact due to different building forms, the tool offers three generic forms to select from. The forms created represent a rectangular building, a long building, and a square building. Note that all three forms contain the same square footage of 53,633 ft^2, three stories, 15 total zones, 4 ft. plenums, and 9 ft. ceilings for consistency. All three forms can be seen in figures B1 through B3 in the Appendix along with the exact dimensions seen in Table B5.

Like with the Building's orientation, the severity of the impact of the building's form is coupled with the Buildings orientation and WWR. With the multiple forms implemented in the tool, the resulting EUI combinations can be seen previously in Table 14. The table's results shows a balance between square and very rectangular buildings provides a lower EUI overall, seen in the rectangular building form. It is also noted that more square buildings are seen to be more robust when dealing with orientation, since poor EUI due to orientation is greatly impacted by building form.

3. Window-to-Wall Ratio

The next envelope parameter included in the tool is the Window-to-Wall Ratio, or WWR. The WWR can be a major point of deviation from the ASHRAE 90.1 prescriptive path. As previously discussed, it is very desirable for buildings to have a large WWR for comfort, productivity, or daylighting reasons. Sometimes a large WWR is unavoidable to reap other benefits, like when the WWR must be 32% or larger due to the daylighting strategy used. These tradeoffs must be analyzed on a case by case basis to see if the benefits from one factor outweigh another. The two options given in the tool is for a building with a 32% WWR as well as a 68% WWR, which represents an all glass building. Figures B1 through B3 show the 32% WWR implemented into the building models, while Figures B4 through B6 show the 68% WWR.

When simulated and included in the design tool, these different WWR's show the user that the smaller the WWR, the smaller the EUI will be in all cases. The change from a 32% WWR to a 68% WWR typically shows a gain of ~5 EUI depending on the other envelope parameters. A poor form and orientation combination can be very bad when a high WWR is implemented. This is seen with the 90°, Long form, and 68% WWR, which results in an increase of 12.26 EUI difference.

For the ideal case, the WWR would be minimized and placed in prime locations to allow for the desired daylighting control and comfort benefits. This way no unnecessary energy is lost due to underutilized fenestration.

4. Daylighting Control

Adding daylighting control to modern buildings is very common for the energy benefit and the aesthetic it brings. Because daylighting is coupled with the buildings WWR, this is a major point of where owners and designers often deviate from the prescriptive path of 90.1. The primary purpose of daylighting is to bring sunlight into the areas where it is possible so that the energy used due to interior lighting can be reduced. To do this, multiple photocells are used throughout the building which measures the illumination in the space in foot candles. The daylighting controller uses this reading to adjust the interior lighting so that the sunlight with no or some additional electric lighting meets the desired foot candle. Because daylighting design must be considered from zone to zone, there is a wide range of how much of the space wants to utilize daylighting control.

In the tool, three daylighting options are given to select from; no daylighting, daylighting, and advanced daylighting. Table B5 in the appendix shows how the 90.1-2013 reference model was manipulated to create these options. The no daylighting option removes any daylighting control in the model. The daylighting option, most similar to the 90.1-2013 reference model's daylighting strategy, breaks up all of the perimeter zones in to thirds. In this case, two thirds of the perimeter zones are included in the daylighting control. This makes up 10 ft. of the 15 ft. perimeter zone. The advanced daylighting option splits the perimeter zone in to halves and give daylighting controls to the entire zone. The figure below shows these differences in a perimeter zone.

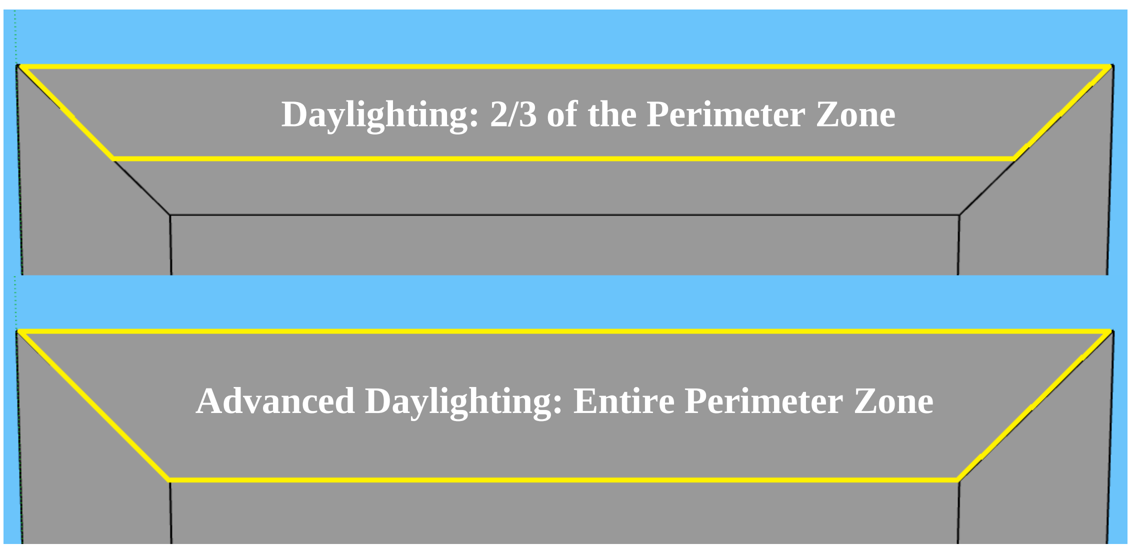

Figure 20. Daylighting and Advanced Daylighting Control in Perimeter Zones

Once implemented in the design tool, the impact of the daylighting techniques can be seen. The addition of the normal daylighting option in the baseline building provides a EUI difference of -1.84 Δ EUI. The advanced daylighting control option gives a change of -2.42

Δ EUI when implemented in the baseline building. Like with the other options, the impact of daylighting will scale slightly depending on the total EUI of the building.

From the tool, it can be seen that adding the most advanced daylighting control strategy that the space will allow can be very beneficial to the building's total EUI. However, the level of daylighting must be considered on a case by case bases due to the cost of the controllers and sensors, as well as the limitations due to the exterior fenestration of the building.

5. Shading Devices

The last parameter in the Envelope Heat Load Minimization Section is the option to include shading devices over the building's exterior fenestration. There are two main reasons for including shading devices into the build's design. For sunnier climate zones or areas of the building, shading devices block excess solar heat gain coming into the space via the exterior fenestration. The other reason to consider shading devices is to diffuse the natural illumination from sunlight coming into the zones to improve daylighting (WBDG, 2016). During the building design process, the shading devices must carefully be designed on a case by case basis to achieve improvements for daylighting strategies and eliminating excess solar heat gain effectively. The figure below shows the building model with the shading devices included.

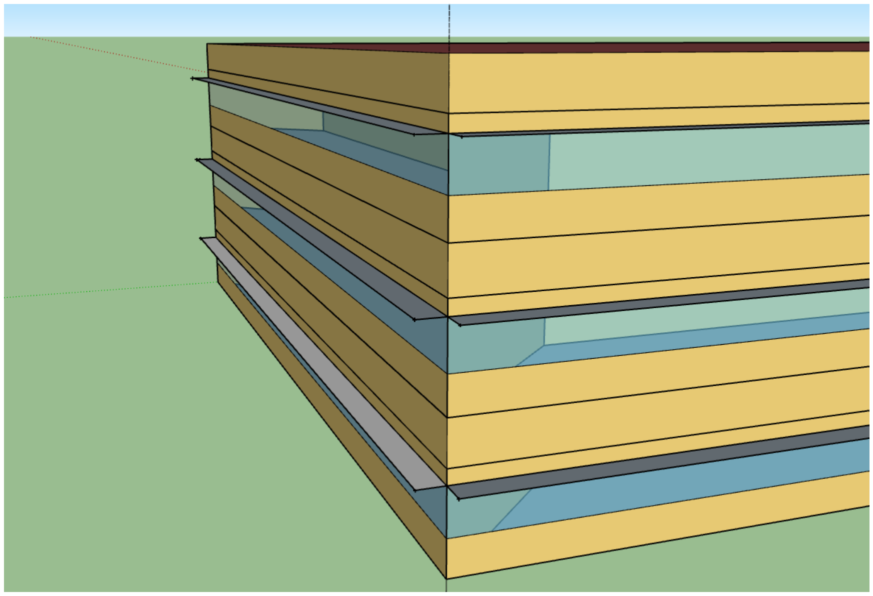

Figure 21. Building Model with Shading Devices

Table B5 in the Appendix shows how the shading devices were implemented into the building model. For every exterior fenestration in the building model, a shading device was added directly at the top of each window. The shading devices extrude from the building 2.5 ft.

Once implemented into the model and simulated, the shading devices show an improvement of -0.86 Δ EUI when included in the baseline model. This savings in EUI will fluctuate slightly when comparing the impact from model to model. Although the impact of the shading devices may be less than what some of the other envelope parameters may provide, there is still a fair amount to be gained with their inclusion.

B. Mechanical System Operation and Controls

This section of the Building Design Visualization Tool covers the operation and controls of the HVAC system. The crucial factors of the system's operation is broken down into setpoints and schedules. These are separated into the building's hours of operation as well as the occupied and unoccupied heating and cooling setpoints. The controls for the HVAC system is split into key groups as well. The controls included in the tool consist of Demand Control Ventilation, or DCV, Economizing, and the Static Pressure Reset.

The remainder of this section will discuss each one of the aforementioned operational parameters and control systems consist of, how they were implemented into the model, and what general impact they have on the building's EUI. Changes made to the building model regarding the options for the mechanical system's operation and controls can be seen in Table B6 in the Appendix.

1. Building Hours of Operation

In order to obtain an accurate EUI measure from the building models, the buildings hours of operation must properly reflect what takes place, or what will take place in the real building. In the building model, the buildings hours of operation directly relate to the building's occupancy schedule. The building's occupancy schedule is a fractional schedule that describes the level of occupancy in the building at any given hour. In the building models, the occupancy schedule directly effects when the HVAC system starts up and shuts down, what level of interior equipment is being utilized, the building's interior lighting schedule, and the elevator schedule. The relationship between the occupancy schedule and the other schedules mentioned can be seen in Table B7 in the Appendix which provides the schedules for the baseline model. To manipulate these schedules in the Building Design Visualization Tool, the user is prompted to input what the building's hours of operation are. The current options are from 6:00 a.m. till 8:00 a.m. for the majority of the occupants coming into the building, and from 5:00 p.m. till 7:00 p.m. for the majority of the occupants leaving the building. Note that the baseline building operates from 8 a.m. till 5 p.m.

Knowing the building's hours of operation, the tool makes a simple approximation to determine the resulting occupancy, equipment, lighting, and elevators schedules based on those seen in the 90.1-2013 reference model. The tool manipulates the schedules by shifting or expanding them up or down hourly to the set hours accordingly. For example, figure 15 below shows the difference between an 8 a.m. till 5 p.m. occupancy schedule and a 6 a.m. till 7 p.m. occupancy schedule.

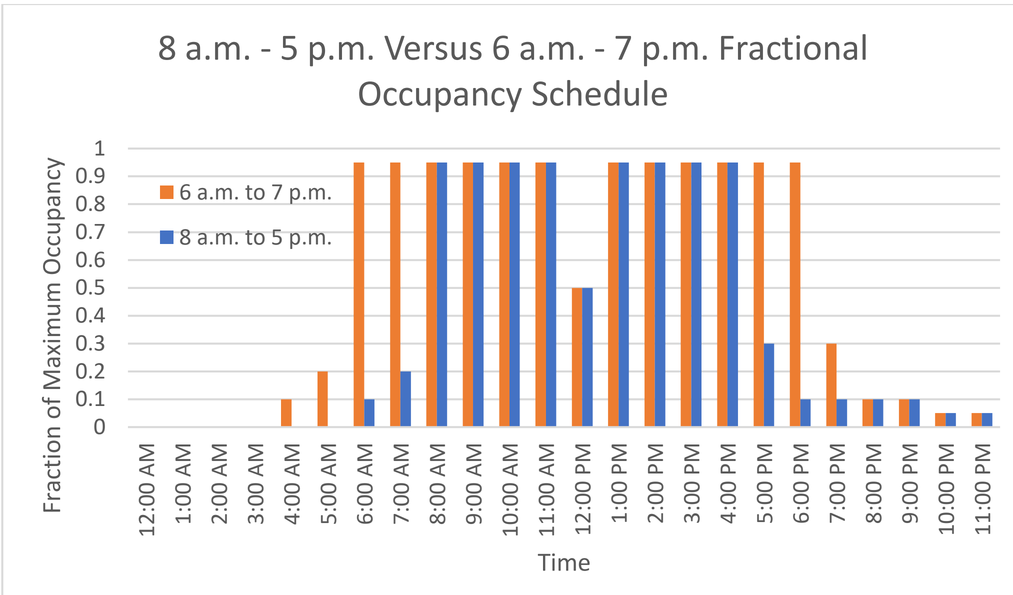

Figure 22. 8 a.m. - 5 p.m. and 6 a.m. - 7 p.m. Fractional Occupancy Schedules

Once simulated added into the visualization tool, each hour of operation was then weighed in the baseline building model. The following table shows the impact in terms of EUI that each schedule had on the baseline building. The table is organized from lowest to highest EUI.

Table 15. The Impact on the Baseline Model with Different Hours of Operation

Occupancy In:	Occupancy Out:	EUI:	□ EUI:
8:00 AM	5:00 PM	33.74	-1.08
7:00 AM	5:00 PM	34.79	-0.03
8:00 AM	6:00 PM	34.82	0.00
6:00 AM	5:00 PM	35.88	1.06
7:00 AM	6:00 PM	35.89	1.07
8:00 AM	7:00 PM	35.91	1.09
6:00 AM	6:00 PM	36.99	2.18
7:00 AM	7:00 PM	36.99	2.18
6:00 AM	7:00 PM	38.11	3.30

As can be seen the occupancy schedule have a fair amount of leverage on the building EUI. The difference of impact from the shortest schedule to the long schedule simulated gives a change in 4.38 EUI. Without proper consideration, the occupancy schedule has the ability to greatly influence the building's resulting EUI during operation.

2. Occupied and Unoccupied Heating and Cooling Setpoints

The next operational parameter considered in the Building Design Visualization Tool is the occupied and unoccupied heating and cooling setpoints. For occupied times, the heating and cooling setpoint range typically anywhere ±2° F from 70° F for the heating setpoint and 75° F cooling setpoint. These setpoints could be selected to use for a real building in order to comply with the recommended 5° F deadband and to save energy, or for comfort reasons. From real building data, occupied cooling setpoints have also been seen down to 72° F to keep occupants comfortable. For the unoccupied setpoints, ASHRAE 90.1 requires buildings to implement a heating and cooling temperature setback when the building is not in use. The most common unoccupied heating setbacks seen from the reference model and local office buildings is 60° F and 65° F. For the cooling setback, it is almost always around either 80° F or 85° F for local buildings.

Table B6 in the Appendix shows the full range of options the tool has for the building models. Table 14 below shows the direct impact of these setpoints when applied to the baseline model in terms of EUI.

Table 16. The Impact on the Baseline Model with Different Setpoints

Occupied Heating Setpoint:	**EUI:**	**□ EUI:**
72° F	36.91	2.09
71° F	35.65	0.83
70° F	34.82	0.00
69° F	34.14	-0.68
68° F	33.52	-1.30
Occupied Cooling Setpoint:	**EUI:**	**□ EUI:**
78° F	31.54	-3.28
77° F	32.22	-2.60
76° F	33.00	-1.82
75° F	33.76	-1.06
74° F	34.82	0.00
Unoccupied Heating Setpoint:	**EUI:**	**□ EUI:**
65° F	35.20	0.39
60° F	34.82	0.00
Unoccupied Cooling Setpoint:	**EUI:**	**□ EUI:**
85° F	35.12	0.30
80° F	34.82	0.00

From the table above, a relationship between the setpoints and the buildings total energy usage can be drawn. For the heating setpoints and the unoccupied cooling setpoint, the lower the temperature, the better the EUI. The opposite is seen with the cooling setpoints, where the higher the temperature, the better the EUI. The occupied setpoints have the biggest impact on the buildings EUI because of the HVAC equipment they control during system operation. The setbacks also play a role in the energy usage as well. The heating setback of

65° F keeps the temperature closer to the occupied heating setpoint so that there is less heating demand in the zones once the HVAC system turns on. However, the 60° F heating setback allows the system not to run as frequently overnight and is ultimately the more efficient heating setback because of this. The cooling setbacks operate the opposite of this. The 80° F setpoint is more efficient than the 85° F setback because it reduces the amount of cooling demand at startup. Because the interior zones warm up naturally throughout most of the year during unoccupied hours, the cooling setbacks are vital to the systems operation.

To see the severity of the impact that different operational setpoints can have on the building's annual energy usage, combinations of key setpoints and setbacks were analyzed. The combined best and worst setpoint and setback cases can be seen in Table 17 below.

Table 17. Best and Worst Setpoint Combinations

Occupied Heating Setpoint:	Occupied Cooling Setpoint:	Unoccupied Heating Setpoint:	Unoccupied Cooling Setpoint:	EUI:	□ EUI:
68° F	78° F	60° F	80° F	30.78	-4.04
72° F	74° F	65° F	85° F	37.67	2.85

3. Demand Control Ventilation

Demand Control Ventilation allows the outdoor airflow to be based on the amount of occupants in each zone. Without DCV, the outdoor airflow into the space must be able to satisfy the maximum amount of occupancy that could be in the space at any given point in time. DCV allows for the outdoor airflow to minimized, thus saving energy required to temper the air that is sent to the occupied zones. Although DCV has the potential to save a fair amount of energy, building owners and operators are sometimes hesitant to include DCV into their buildings HVAC operation due to the additional sensor maintenance it requires. To get an idea of how many occupants are in the zone, DCV requires CO_2 sensors in each zone, which adds more cost to the initial build and more preventive maintenance to ensure the system functions properly.

The tool allows for users to select whether they want DCV or no DCV controls to be included in their building model. Table B6 in the Appendix shows how DCV was implemented into the building model. When DCV gives a EUI reduction of -1.03 EUI when considered in the baseline model without the use of economizer control.

4. Economizing

Economizing allows for outdoor air to be used in lieu of the tempered air when the outdoor air temperature and humidity allows. Because of this, during the time the system is economizing, the cooling coils are not utilized, thus saving energy. The tool allows the user to choose between different economizing control types between no economizing, differential dry bulb, and differential enthalpy. Differential dry bulb will force the outdoor airflow to a minimum when the dry bulb temperature higher than the dry bulb temperature of the return air. Likewise, differential enthalpy will set the outdoor airflow to a minimum when the enthalpy of the outdoor air is greater than that of the return air. No economizing disables any outdoor economizing and sets the outdoor airflow to the constant minimum requirement. Table B5 in the Appendix shows how the economizer and economizing control types were implemented in the tool.

The EUI improvement with the addition of the Economizer control types when considered in the baseline model were measured. The differential dry bulb economizer resulted in a -1.64 EUI reduction in comparison to no economizer, while the differential enthalpy economizer resulted in a -1.64 EUI reduction.

As can be seen from the resulting change in EUI, economizing can be beneficial to saving a fair amount of energy. When choosing the economizer's control type, it is important to consider the climate zone of the build site due to humidity levels.

5. Static Pressure Reset

The purpose of the static pressure reset is to change the static pressure setpoint to match the current load in the building. As discussed before, the static pressure reset is a control system in commercial office buildings that is frequently seen operating poorly when implemented if the proper maintenance is not kept up to date. The reset was included in the tool so its impact on the system could be better understood when it performs well versus preforming poorly. To model the static pressure reset in EnergyPlus, the supply air part-load fan curves were adjusted to reflect the difference in energy usage according to the PNNL study. The exact changes to the building model can be seen in Table B5 in the Appendix.

When analyzed in the baseline model, the static pressure reset makes a difference of 1.18 EUI. This change shows how much is saved with the static pressure reset is maintained and functioning properly so that the fan energy being correctly minimized.

V. Conclusion

Creating energy goals for commercial office building design is the first step of creating an energy efficient building. Establishing an energy goal for the building project gives the design team a point of which to justify different design choices made throughout the building design process. To design an energy efficient building, the ASHRAE 90.1 standard must be understood in terms of the energy impact each recommendation has on the building as a whole. Operational impacts need to be considered as well so that the building's energy goal can be met once constructed and occupied. Using this information, a reasonable EUI goal for the modern commercial office building in the Piedmont was determined.

The Building Design Visualization Tool allow users to get a better idea of key system and operational tradeoffs, obtain a realistic energy goal, and be able to point out key systems that may inhibit this goal from being reached. Incorporating The Building Design Visualization Tool into the Pre-design Phase of the building design process offers multiple benefits to building owners and designers tackling a new project. Because the tool is easy to use, fast to update, and provides simple energy results, anyone with a basic understanding of building systems can benefit from it. This allows for an energy goal to be quickly established once the parameters of the project are better understood.

With the knowledge gained from the tool, the building owner and design team fully understand the energy tradeoffs their design and operational choices have on the building in terms of EUI. Because of this newfound grasp on the building's energy, the correct questions can be asked and the key building parameters and operations can be clearly communicated to the design team, thus resulting in a building design that satisfies all parties. To achieve the energy goal set, the knowledge of the design choice's energy impact can be applied to assigning additional resources to be put towards key parameters so that they perform as expected once the building is occupied.

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Appendix A. Standard Information

Definition A1: Energy Goals

The purpose of these energy goals is to set a design requirement for the annual energy usage for a building once it is occupied. In the U.S., the energy usage goal is measured in the buildings Energy Use Intensity, or EUI, which takes the following per unit form.

$$EUI = \frac{Energy}{Area} \tag{2}$$

The buildings energy goal, when implemented into the design process, is defined in the first phase of the design process. The purpose of the energy goal is to weigh technology tradeoffs against a set metric, as well as determine the overall energy efficiency of the building, which directly corresponds to the effectiveness of the design.

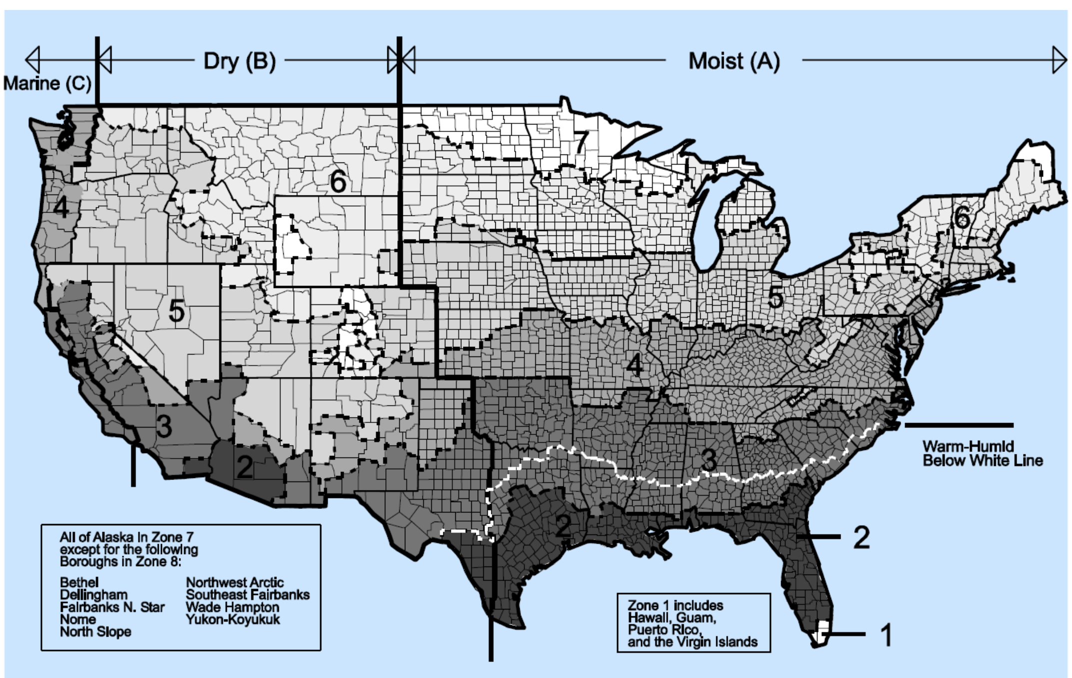

Figure A1. United States Climate Zones – ASHRAE 90.1 User's Manual

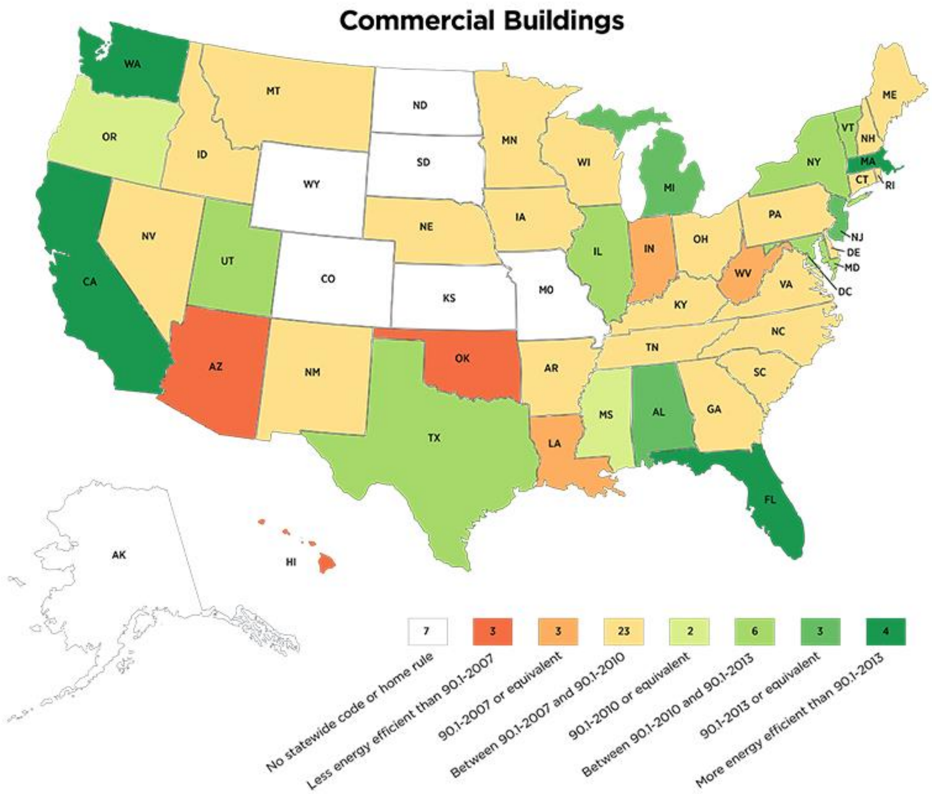

Figure A2. State Energy Code Adoption Map – U.S. Department of Energy

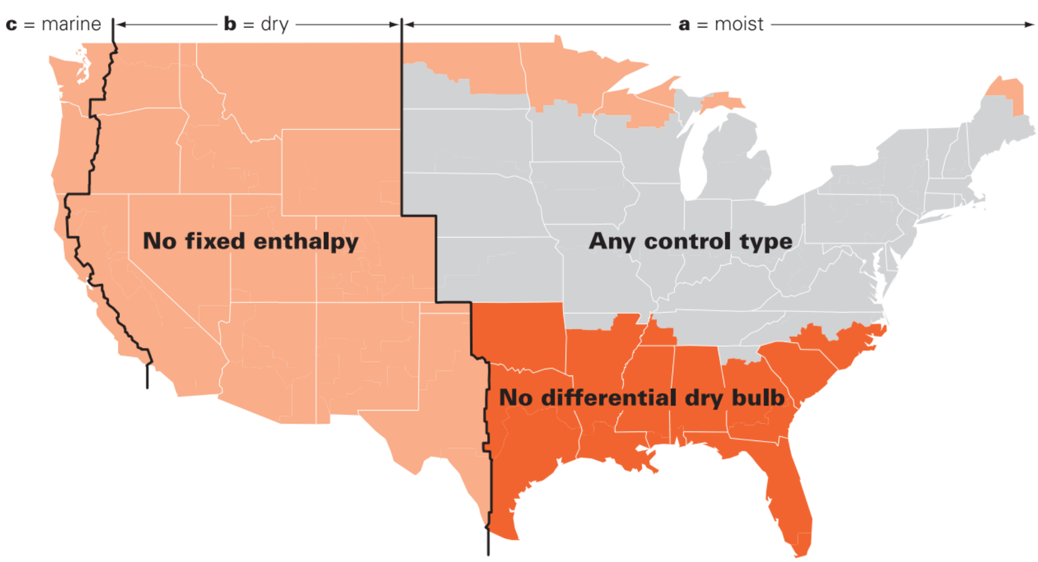

Figure A3. 90.1-2010 Economizer Control Requirements by Climate Zone

Table A4. ASHRAE 90.1-2007 Building Envelope Requirements for Climate Zone 3 – AHSRAE 90.1-2007

Table 5.5-3 Building Envelope Requirements for Climate Zone 3 (A,B,C)*

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.039	R-25 c.i.	U-0.039	R-25 c.i.	U-0.119	R-7.6 c.i.
Metal Building[a]	U-0.041	R-10 + R-19 FC	U-0.041	R-10 + R-19 FC	U-0.096	R-16
Attic and Other	U-0.027	R-38	U-0.027	R-38	U-0.053	R-19
Walls, above Grade						
Mass	U-0.123	R-7.6 c.i.	U-0.104	R-9.5 c.i.	U-0.580	NR
Metal Building	U-0.094	R-0 + R-9.8 c.i.	U-0.072	R-0 + R-13 c.i.	U-0.162	R-13
Steel Framed	U-0.077	R-13 + R-5 c.i.	U-0.064	R-13 + R-7.5 c.i.	U-0.124	R-13
Wood Framed and Other	U-0.089	R-13	U-0.064	R-13 + R-3.8 c.i. or R-20	U-0.089	R-13
Wall, below Grade						
Below Grade Wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.074	R-10 c.i.	U-0.074	R-10 c.i.	U-0.137	R-4.2 c.i.
Steel Joist	U-0.038	R-30	U-0.038	R-30	U-0.052	R-19
Wood Framed and Other	U-0.033	R-30	U-0.033	R-30	U-0.051	R-19
Slab-on-Grade Floors						
Unheated	F-0.730	NR	F-0.540	R-10 for 24 in.	F-0.730	NR

Appendix B. Modeling Information

Table B1. EnergyPlus Schedules for 90.1-2007 Base Model

Times For Weekdays	Reference Model Schedules:	Occupancy Schedule	Equipment Schedule	Lighting Schedule	Exterior Lighting	Elevator Schedule	Elevator Lights and Fan	Heating Setpoint Schedule (°C)	Cooling Setpoint Schedule (°C)	Outdoor Air Schedule
	12:00 AM	0	0.4	0.05	1	0	1	15.6	24	1
	1:00 AM	0	0.4	0.05	1	0	1	15.6	24	1
	2:00 AM	0	0.4	0.05	1	0	1	15.6	24	1
	3:00 AM	0	0.4	0.05	1	0	1	15.6	24	1
	4:00 AM	0	0.4	0.05	1	0	1	15.6	24	1
	5:00 AM	0	0.4	0.1	1	0	1	21	24	1
	6:00 AM	0.1	0.4	0.1	1	0	1	21	24	1
	7:00 AM	0.2	0.4	0.3	1	0.35	1	21	24	1
	8:00 AM	0.95	0.9	0.9	1	0.69	1	21	24	1
	9:00 AM	0.95	0.9	0.9	1	0.43	1	21	24	1
	10:00 AM	0.95	0.9	0.9	1	0.37	1	21	24	1
	11:00 AM	0.95	0.9	0.9	1	0.43	1	21	24	1
	12:00 PM	0.5	0.8	0.9	1	0.58	1	21	24	1
	1:00 PM	0.95	0.9	0.9	1	0.48	1	21	24	1
	2:00 PM	0.95	0.9	0.9	1	0.37	1	21	24	1
	3:00 PM	0.95	0.9	0.9	1	0.37	1	21	24	1
	4:00 PM	0.95	0.9	0.9	1	0.46	1	21	24	1
	5:00 PM	0.3	0.5	0.5	1	0.62	1	21	24	1
	6:00 PM	0.1	0.4	0.3	1	0.12	1	21	24	1
	7:00 PM	0.1	0.4	0.3	1	0.04	1	21	24	1
	8:00 PM	0.1	0.4	0.2	1	0.04	1	21	24	1
	9:00 PM	0.1	0.4	0.2	1	0	1	21	24	1
	10:00 PM	0.05	0.4	0.1	1	0	1	15.6	24	1
	11:00 PM	0.05	0.4	0.05	1	0	1	15.6	24	1

Table B2. EnergyPlus Schedules for 90.1-2010 Base Model

Times For Weekdays

Reference Model Schedules:	Occupancy Schedule	Equipment Schedule	Lighting Schedule	Exterior Lighting Zone A	Exterior Lighting Zone B	Elevator Schedule	Elevator Lights and Fan	Heating Setpoint Schedule (°C)	Cooling Setpoint Schedule (°C)	Outdoor Air Schedule
12:00 AM	0	0.318	0.05	1	0.7	0	0	15.6	24	0
1:00 AM	0	0.318	0.05	1	0.7	0	0	15.6	24	0
2:00 AM	0	0.318	0.05	1	0.7	0	0	15.6	24	0
3:00 AM	0	0.318	0.05	1	0.7	0	0	15.6	24	0
4:00 AM	0	0.318	0.05	1	0.7	0	0	15.6	24	0
5:00 AM	0	0.318	0.1	1	0.7	0	0	21	24	0
6:00 AM	0.1	0.384	0.094	1	0.7	0	0	21	24	0
7:00 AM	0.2	0.384	0.271	1	0.7	0.35	0.35	21	24	1
8:00 AM	0.95	0.864	0.813	1	0.7	0.69	0.69	21	24	1
9:00 AM	0.95	0.864	0.813	1	0.7	0.43	0.43	21	24	1
10:00 AM	0.95	0.864	0.813	1	0.7	0.37	0.37	21	24	1
11:00 AM	0.95	0.864	0.813	1	0.7	0.43	0.43	21	24	1
12:00 PM	0.5	0.768	0.813	1	0.7	0.58	0.58	21	24	1
1:00 PM	0.95	0.864	0.813	1	0.7	0.48	0.48	21	24	1
2:00 PM	0.95	0.864	0.813	1	0.7	0.37	0.37	21	24	1
3:00 PM	0.95	0.864	0.813	1	0.7	0.37	0.37	21	24	1
4:00 PM	0.95	0.864	0.813	1	0.7	0.46	0.46	21	24	1
5:00 PM	0.3	0.48	0.452	1	0.7	0.62	0.62	21	24	1
6:00 PM	0.1	0.384	0.271	1	0.7	0.12	0.12	21	24	1
7:00 PM	0.1	0.384	0.271	1	0.7	0.04	0.04	21	24	1
8:00 PM	0.1	0.384	0.18	1	0.7	0.04	0.04	21	24	1
9:00 PM	0.1	0.384	0.18	1	0.7	0	0.04	21	24	1
10:00 PM	0.05	0.384	0.094	1	0.7	0	0.04	15.6	24	0
11:00 PM	0.05	0.384	0.045	1	0.7	0	0.04	15.6	24	0

Table B3. EnergyPlus Schedules for 90.1-2013 Base Model

Times For Weekdays	Reference Model Schedules:	Occupancy Schedule	Equipment Schedule	Lighting Schedule	Exterior Lighting Zone A	Exterior Lighting Zone B	Elevator Schedule	Elevator Lights and Fan	Heating Setpoint Schedule (°C)	Cooling Setpoint Schedule (°C)	Outdoor Air Schedule
	12:00 AM	0	0.307	0.05	1	0.7	0	0	15.6	26.7	0
	1:00 AM	0	0.307	0.05	1	0.7	0	0	15.6	26.7	0
	2:00 AM	0	0.307	0.05	1	0.7	0	0	15.6	26.7	0
	3:00 AM	0	0.307	0.05	1	0.7	0	0	15.6	26.7	0
	4:00 AM	0	0.307	0.05	1	0.7	0	0	15.6	26.7	0
	5:00 AM	0	0.307	0.1	1	0.7	0	0	21	25.6	0
	6:00 AM	0.1	0.381	0.086	1	0.7	0	0	21	25	0
	7:00 AM	0.2	0.381	0.259	1	0.7	0.35	0.35	21	24	1
	8:00 AM	0.95	0.857	0.776	1	0.7	0.69	0.69	21	24	1
	9:00 AM	0.95	0.857	0.776	1	0.7	0.43	0.43	21	24	1
	10:00 AM	0.95	0.857	0.776	1	0.7	0.37	0.37	21	24	1
	11:00 AM	0.95	0.857	0.776	1	0.7	0.43	0.43	21	24	1
	12:00 PM	0.5	0.762	0.776	1	0.7	0.58	0.58	21	24	1
	1:00 PM	0.95	0.857	0.776	1	0.7	0.48	0.48	21	24	1
	2:00 PM	0.95	0.857	0.776	1	0.7	0.37	0.37	21	24	1
	3:00 PM	0.95	0.857	0.776	1	0.7	0.37	0.37	21	24	1
	4:00 PM	0.95	0.857	0.776	1	0.7	0.46	0.46	21	24	1
	5:00 PM	0.3	0.476	0.431	1	0.7	0.62	0.62	21	24	1
	6:00 PM	0.1	0.381	0.259	1	0.7	0.12	0.12	21	24	1
	7:00 PM	0.1	0.381	0.259	1	0.7	0.04	0.04	21	24	1
	8:00 PM	0.1	0.381	0.172	1	0.7	0.04	0.04	21	24	1
	9:00 PM	0.1	0.381	0.172	1	0.7	0	0.04	21	24	1
	10:00 PM	0.05	0.381	0.086	1	0.7	0	0.04	15.6	26.7	0
	11:00 PM	0.05	0.381	0.043	1	0.7	0	0.04	15.6	26.7	0

Table B4. 90.1 Reference Model Changes for 2007, 2010, and 2013.

Section:	Part:	Input Parameter:	90.1 2007 Input:	90.1 2010 Input:	90.1 2013 Input:
Airflow	Airterminal:SingleDuct: VAV:Reheat	Constant Minimum Air Flow Fraction: Core Mid VAV Box	0.3381	0.3477	0.3573
Airflow	Airterminal:SingleDuct: VAV:Reheat	Constant Minimum Air Flow Fraction: Core Top VAV Box	0.3047	0.3274	0.3445
Airflow	Airterminal:SingleDuct: VAV:Reheat	Constant Minimum Air Flow Fraction: Perimeter Bot VAV Box Zone 3	0.3	0.3145	0.3270
Daylighting Control	Daylighting	Added Daylighting Control	No Daylighting	Added Daylighting Control	Same as 2010
DCV	Zone Inflitration/ Design Flow Rate	Flow Per Exterior Surface Area: Top Floor Plenum	0.0001114 m3/s-m2	6.1925 *10^-5 m3/s-m2	6.1925 *10^-5 m3/s-m2
DCV	SizingSystem	Design Outdoor Air Flow Rate	1.13m3/s	1.19m3/s	Same as 2010
DCV	Controller:OutdoorAir	Minimum Outdoor Air Flow Rate	AUTOSIZE	0 m3/s	Same as 2010
DCV	Controller:OutdoorAir	Lockout Type	Lockout with Compressor	No Lockout	Same as 2010
DCV	Controller:OutdoorAir	Mechanical Ventilation Controller Name	None	Added DCV	Same as 2010
Economizer	Controller:OutdoorAir	Economizer Control Type	No Economizer	Differential Enthalpy	Same as 2010
Economizer	Controller:OutdoorAir	Minimum Outdoor Air Schedule, See Schedule Table	Outdoor Air Damper Always Open	Scheduled Outdoor Air Damper	Same as 2010
Efficiency	Lights	Watts per Zone Floor Area	10.76 W/ft2	9.68 W/ft2	8.82 W/ft2
Efficiency	Electric Equipment/ Elevators_Lights_Fan/ Design Level	Design Level (W)	323.8 W	211.8 W	125 W
Efficiency	Exterior Lights/Schedule, Design Level, and Exterior Lights 'b' addition	Design Level (W)	14385 W	a' = 623.03 W, 'b' = 7476.45 W	Same as 2010
Efficiency	Water Heater:Mixed	Off Cycle Parasitic Fuel Consuption Rate	1383 W	1277 W	Same as 2010
Efficiency	Water Heater:Mixed	On Cycle Parasitic Fuel Consuption Rate	1383 W	1277 W	Same as 2010
Efficiency	Coil:Cooling:Dx:TwoSpeed	High Speed Gross Rated Cooling COP	3.23 W/W	3.39 W/W	Same as 2010
Efficiency	Coil:Cooling:Dx:TwoSpeed	Low Speed Gross Rated Cooling COP	3.23 W/W	3.39 W/W	Same as 2010
Efficiency	Fan:Vairable Volume	Fan Total Efficiency	0.5915	Bot&Top: 0.6045 Mid: 0.6006	0.6006
Efficiency	Fan:Vairable Volume	Pressure Rise (Pa)	1389.42	1389.42	Bot&Top: 1314.72 Mid: 1389.42
Efficiency	Fan:Vairable Volume	Motor Efficiency	0.91	Bot&Top: 0.93 Mid: 0.924	0.924
Efficiency	ElectricLoadCenter: Transformer	Nameplate Efficiency	0.961	0.977	Same as 2010

Efficiency & Plug Control	Schedule:Compact/ BLDG_EQUIP_SCH	Many Changes, See Table	None	Requires Plug Load Control & Efficiency Reduction	Higher Requirements of Plug Load Control & Efficiency Reduction
Elevator Control	Electric Equipment/ Elevators_Lights_Fan/Schedule	Schedule Change, See Table	24/7 Operation	Reduced Operation	Same as 2010
Envelope	NONRES_EXT_WALL	Thermal Resistance	R-1.7128	Same as 2007	R-1.9034
Envelope	NONRES_ROOF	Thermal Resistance	R-3.4722	Same as 2007	R-4.3188
Envelope	All exterior perimeter wall windows	Construction	U-0.62	Same as 2007	U-0.55
Envelope	Material/ F13 Built-Up Roofing	Thermal Absorptance	0.9	0.75	Same as 2010
Envelope	Material/ F13 Built-Up Roofing	Solar Absorptance	0.7	0.45	Same as 2010
Envelope	Zone Inflitration/ Design Flow Rate	Flow Per Exterior Surface Area: Rest (No Change in Door_Inflitration)	0.001024 m3/s-m2	0.00056896 m3/s-m2	Same as 2010
Exterior Lighting	Exterior Lights/ Schedule, Design Level, and Exterior Lights 'b' addition	Schedule Change, See Table	None	Exterior Lighting Power Allowance	Same as 2010
Exterior Lighting	Exterior Lights/ Schedule, Design Level, and Exterior Lights 'b' addition	Exterior Lights 'b' addition	None	Exterior Lighting Power Allowance	Same as 2010
Lighting Control	Schedule:Compact/ BLDG_LIGHT_SCH	Many Changes, See Table	No Occupancy Sensors	Requires Occupancy Sensors	Higher Requirement of Occupancy Sensors
Temp. Setpoints	Thermostat Setpoint/ Dual Setpoint	Heating Setpoint Temperature Schedule, See Schedule Table	70 F to 60 F Unoccupied Setback	Same as 2007	Same as 2007
Temp. Setpoints	Thermostat Setpoint/ Dual Setpoint	Cooling Setpoint Temperature Schedule, See Schedule Table	75 F No Setback	Same as 2007	75 F to 80 F Unoccupied Setback

Table B5. Building Design Visualization Tool Envelope Parameter Changes

Building Parameter:	Object:	90.1 Standard	Option 1	Option 2	Option 3
Building Orientation	**Option**	**90.1 Standard**	**0° Orientation**	**45° Orientation**	**90° Orientation**
Building Orientation	Degrees from North Axis	0	0	45	90
Building Form	**Option**	**90.1 Standard**	**Rectangular Building**	**Square Building**	**Long Building**
Building Form	Building Model Form	Base	Base	Square	60ft Wide
Building Form	Length	163’ 9”	163’ 9”	133’ 8”	127’ 11”
Building Form	Width	109’ 2”	109’ 2”	133’ 8”	60’
WWR	**Option**	**90.1 Standard**	**Standard WWR**	**All Glass Building**	
WWR	Building Model Windows	32%	32%	68%	-
Daylighting	**Option**	**90.1-2013 Standard**	**No Daylighting**	**Daylighting**	**Advanced Daylighting**
Daylighting	Lighting Control Type	Stepped	None	Continuous	Continuous
Daylighting	Minimum Input Power Fraction for Continuous or ContinuousOff Dimming Control	0.3	None	0.1	0.1
Daylighting	Minimum Light Output Fraction for Continuous or ContinuousOff Dimming Control	0.2	None	0.067	0.067
Daylighting	Number of Stepped Control Steps	3	None	0	0
Daylighting	Reference Point 1 Location	5 ft	None	5 ft	3.75 ft
Daylighting	Reference Point 2 Location	10 ft	None	10 ft	11.25 ft
Daylighting	Fraction of Zone Controlled by Reference Point 1	0.3835	None	0.3835	0.5
Daylighting	Fraction of Zone Controlled by Reference Point 2	0.1395	None	0.1395	0.5
Shading	**Option**	**90.1 Standard**	**No Shading**	**Shading**	
Shading	Shading Object	None	None	Shading Overhang	-
Shading	Depth Projecting Out From Wall	None	None	2.5 ft	-

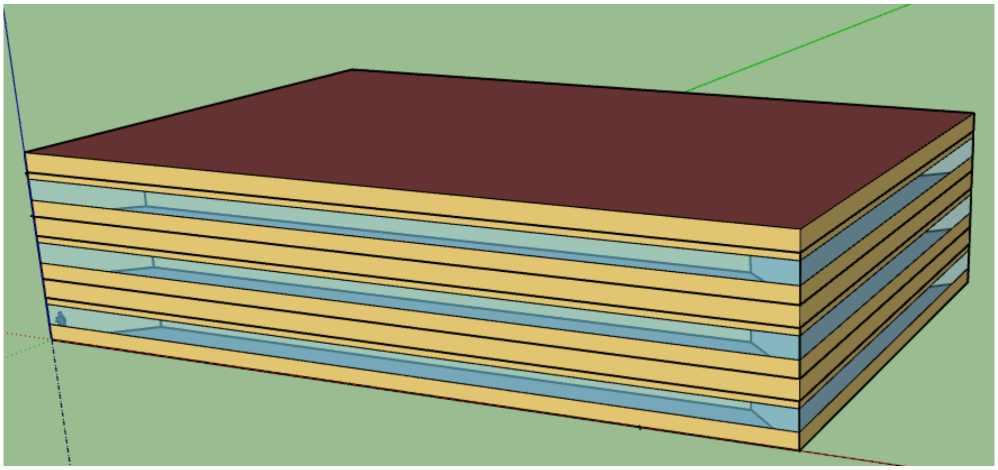
Figure B1. Rectangular Form with 32% WWR

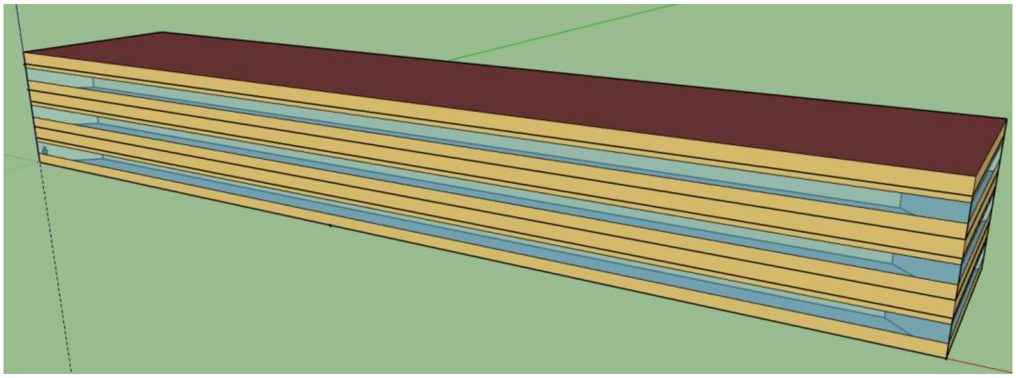
Figure B2. Long Form with 32% WWR

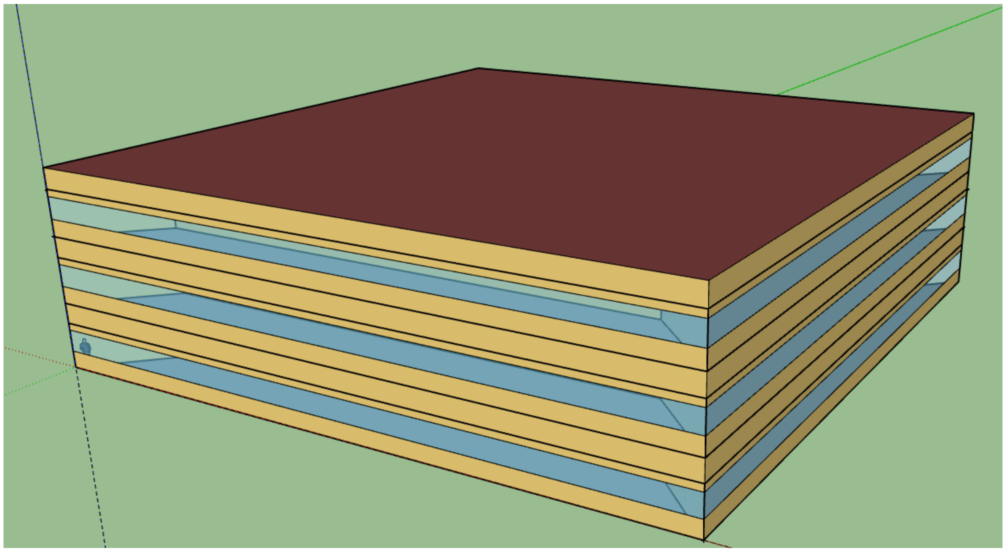
Figure B3. Square Form with 32% WWR

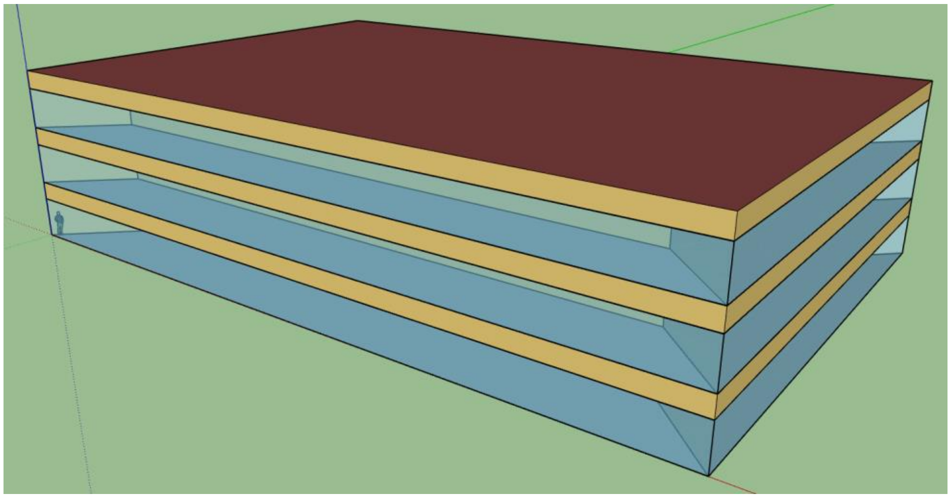

Figure B4. Rectangular Form with 68% WWR

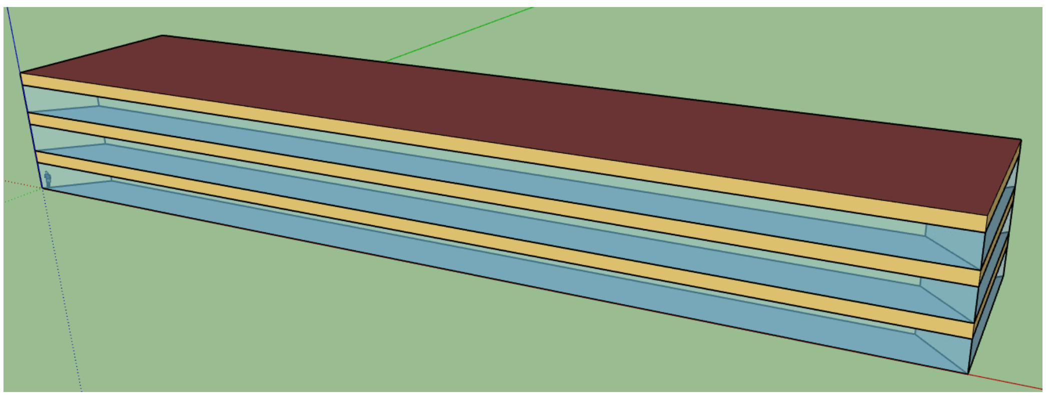

Figure B5. Long Form with 68% WWR

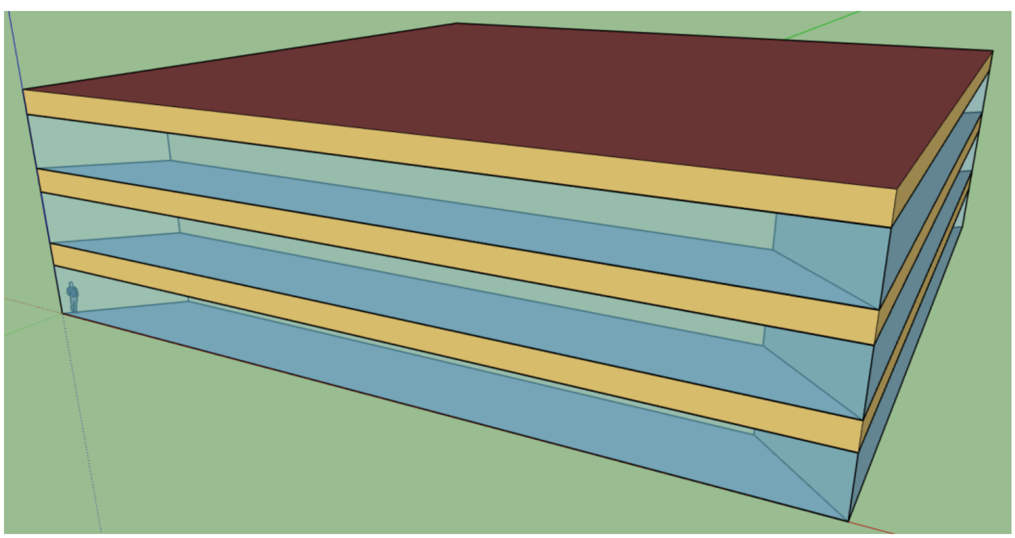

Figure B6. Square Form with 68% WWR

Table B6. Building Design Visualization Tool Operation and Control Parameter Changes

Building Parameter:	Object:	90.1 Standard	Option 1	Option 2	Option 3	Option 4	Option 5
Occupancy In	**Option**	**90.1 Standard**	**6:00 AM**	**7:00 AM**	**8:00 AM**		
Occupancy In	Opening Time	8:00 AM	6:00 AM	7:00 AM	8:00 AM	-	-
Occupancy Out	**Option**	**90.1 Standard**	**5:00 PM**	**6:00 PM**	**7:00 PM**		
Occupancy Out	Closing Time	5:00 PM	5:00 PM	6:00 PM	7:00 PM	-	-
Occupied Heating Setpoint	**Option**	**90.1 Standard**	**68° F**	**69° F**	**70° F**	**71° F**	**72° F**
Occupied Heating Setpoint	Temperature	70° F	68° F	69° F	70° F	71° F	72° F
Unoccupied Heating Setpoint	**Option**	**90.1 Standard**	**60° F**	**65° F**			
Unoccupied Heating Setpoint	Temperature	60° F	60° F	65° F	-	-	-
Occupied Cooling Setpoint	**Option**	**90.1 Standard**	**74° F**	**75° F**	**76° F**	**77° F**	**78° F**
Occupied Cooling Setpoint	Temperature	75° F	74° F	75° F	76° F	77° F	78° F
Unoccupied Cooling Setpoint	**Option**	**90.1 Standard**	**80° F**	**85° F**			
Occupied Cooling Setpoint	Temperature	80° F	80° F	85° F	-	-	-
Economizer	**Option**	**90.1 Standard**	**No Economizer**	**Differential Dry Bulb**	**Differential Enthalpy**		
Economizer	Outdoor Air Flow (With DCV/Without DCV)	1.0	1.0	1.0/0.7	1.0/0.7	-	-
Economizer	Outdoor Air Damper Schedule	Minimum Outdoor Air	24-7	Minimum Outdoor Air	Minimum Outdoor Air	-	-
Economizer	Economizer Control Type	Differential Enthalpy	No Economizer	Differential Dry Bulb	Differential Enthalpy	-	-
DCV	**Option**	**90.1 Standard**	**No DCV**	**DCV**			
DCV	Minimum Outdoor Air Flow Rate	0	AUTOSIZE	0	-	-	-
DCV	Lockout Type	No Lockout	Lockout With Compressor	No Lockout	-	-	-
DCV	Mechanical Ventilation Controller	DCV	None	DCV	-	-	-
Pressure Reset	**Option**	**90.1 Standard**	**No Reset**	**Reset**			
Pressure Reset	Fan Power Coefficient 1	0.0408	0.0704	0.0408	-	-	-
Pressure Reset	Fan Power Coefficient 2	0.0088	0.385	0.0088	-	-	-
Pressure Reset	Fan Power Coefficient 3	-0.0729	-0.4609	-0.0729	-	-	-
Pressure Reset	Fan Power Coefficient 4	0.9437	0.0092	0.9437	-	-	-

Table B7. Baseline building model occupancy based schedule

Times For Weekdays	Baseline Building Model Schedules:	Occupancy Schedule	Equipment Schedule	Lighting Schedule	Elevator Schedule
	12:00 AM	0	0.31	0.05	0
	1:00 AM	0	0.31	0.05	0
	2:00 AM	0	0.31	0.05	0
	3:00 AM	0	0.31	0.05	0
	4:00 AM	0	0.31	0.05	0
	5:00 AM	0	0.31	0.1	0
	6:00 AM	0.1	0.38	0.09	0
	7:00 AM	0.2	0.38	0.26	0.35
	8:00 AM	0.95	0.86	0.78	0.69
	9:00 AM	0.95	0.86	0.78	0.43
	10:00 AM	0.95	0.86	0.78	0.37
	11:00 AM	0.95	0.86	0.78	0.43
	12:00 PM	0.5	0.76	0.78	0.58
	1:00 PM	0.95	0.86	0.78	0.48
	2:00 PM	0.95	0.86	0.78	0.37
	3:00 PM	0.95	0.86	0.78	0.37
	4:00 PM	0.95	0.86	0.78	0.46
	5:00 PM	0.3	0.48	0.43	0.62
	6:00 PM	0.1	0.38	0.26	0.12
	7:00 PM	0.1	0.38	0.26	0.04
	8:00 PM	0.1	0.38	0.26	0.04
	9:00 PM	0.1	0.38	0.17	0
	10:00 PM	0.05	0.38	0.09	0
	11:00 PM	0.05	0.38	0.04	0