GRADUATE SCHOOL
EAST TENNESSEE STATE UNIVERSITY

East Tennessee State University
Digital Commons @ East Tennessee State University

Electronic Theses and Dissertations | Student Works

8-2018

Selecting the Most Effective Energy Modeling Tool Based on a Project Requirement

Sodiq Akande
East Tennessee State University

Follow this and additional works at: https://dc.etsu.edu/etd

Part of the Construction Engineering and Management Commons, Energy Systems Commons, and the Heat Transfer, Combustion Commons

Recommended Citation

Akande, Sodiq, "Selecting the Most Effective Energy Modeling Tool Based on a Project Requirement" (2018). *Electronic Theses and Dissertations.* Paper 3472. https://dc.etsu.edu/etd/3472

This Thesis - unrestricted is brought to you for free and open access by the Student Works at Digital Commons @ East Tennessee State University. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of Digital Commons @ East Tennessee State University. For more information, please contact digilib@etsu.edu.

Selecting the Most Effective Energy Modeling Tool Based on a Project Requirement

---

A thesis

presented to

the faculty of the Department of Technology

East Tennessee State University

In partial fulfillment

of the requirements for the degree

Master of Science in Technology, with a concentration in Engineering Technology

---

by

Sodiq Akande

August 2018

Dr. Mohammad Moin Uddin, Chair

Dr. Keith V. Johnson

Tom Horan, P.E.

Keywords: Model, Building energy modeling (BEM), BEM tools

ABSTRACT

Selecting the Most Effective Energy Modeling Tool Based on a Project Requirement

by

Sodiq Akande

Building energy usage can be derived and controlled by performing building energy modeling. BEM can be performed using numerous software tools such as DesignBuilder, OpenStudio, EnergyPlus etc. These modeling tools can be sorted into three different modeling categories: Black-box, Gray-box and White-box. It is important for a modeler to be able to quickly select the proper tool from the proper category to meet the need of the project. To validate the method of categorizing tools, the three models generated using tools from each category and the modeling outputs required were compared. Each model was designed to estimate the amount of heat transfer through building envelope elements. All the modeling tools were able to generate the required output, therefore, the method for selecting the most effective tool will be based on the output requirements and the time it takes to build the model, time it takes to generate the output and interpret the output.

TABLE OF CONTENTS

Page

ABSTRACT 2
LIST OF TABLES 5
LIST OF FIGURES 6
Chapter
1. INTRODUCTION 7
Background of the Study 7
Building Energy Modeling (BEM) 10
Building Energy Modeling Tools 12
Categorization of Energy Modeling 14
Effect of Energy Modeling Relating to Heat Transfer Through Building Envelope 15
Objectives of the Study 17
Scope of the Study 18
Significance of the Study 18
2. LITERATURE REVIEW 20
Overview 20
Categories of Energy Modeling 20
Building Energy Simulation Tools 22
Literature Review on Building Energy Modeling Tools 26
Building Envelope Elements 30
Walls 30
Fenestration (Doors and Windows) 32
Roofs 33
3. METHODOLOGY 35
Overview 35
Procedure of Modeling Associated with this Study 35
Building Description 35
Materials and Construction 36
Black-box Model 37
Gray-Box Model 48
White-Box Model 51

4. STUDY RESULTS 54
Overview 54
Presentation of The Output Data From Each Modeling Category 54
Comparison of the Steps Involved and Amount of Time Spent In Building Each Model. 57
Modifying and Running the Model 62
Process For Selecting the Right Modeling Tool Developed According to the Observation made from this Study 64
5. CONCLUSION AND RECOMMENDATIONS 70
Conclusion 70
Recommendations 71
REFERENCES……..72
VITA……..75

LIST OF TABLES

Table Page

1. Building Energy Modeling Software Tools and Capabilities 25
2. Placing Modeling Tools in their Respective Modeling Category 25
3. Portion of the Raw TMY Weather Data 39
4. Portion of the Modified TMY3 Weather Data 41
5. Portion of the Bin Calculation 45
6. Portion of Thermal Loads Computation 47
7. Black-Box Tool Modeling Output Generated 55
8. Gray-Box Tool Modeling Output Generated 55
9. White-Box Tool Modeling Output Generated 56
10. Comparison between the Results Of The Three Modeling Tools using Black-Box as the Baseline 56
11. Processes Involved in Model Development used in this Study 58
12. The Rate of Output Generation in each Modeling Category 63
13. General Comparative Analysis between the three Modeling Categories 65
14. Pairing Different Modeling Outputs to its respective Model Category and Software Tools 67

LIST OF FIGURES

Figure Page

1. Basic vs Detailed building modeling examples 9
2. A Sample Wall Section 31
3. A Sample Door Section 33
4. A Sample Roof Section 34
5. Wilson Wallis Hall, ETSU 36
6. Building a Customized Wall in Revit 49
7. Energy Model of Wilson Wallis Generated in Revit 50
8. Rendering of Wilson Wallis Hall Using SketchUp 52
9. Building Construction Set in OpenStudio 53
10. Timeline and Duration of Activities Involved in Using the Black-Box Tool for Modeling 60
11. Timeline and Duration of Activities Involved Using a Gray-Box Tool for modeling 61
12. Timeline and Duration of Activities Involved in Using a White-Box Tool for Modeling 62
13. A Guide to Identify the Proper Modeling Category Based on a Project Requirement 69

CHAPTER 1

INTRODUCTION

Background of the Study

Over the past 50 years, numerous building simulation tools have been developed to estimate the energy use of buildings, analyze the building energy performance and the thermal comfort of the resident. Today, there are multitudes of simulation tools available that possess different capabilities such as: level of input parameters (some tools can handle different simple input parameters, while other tools are designed to process very detail parameters) , level of sophistication in calculation (some tools are designed to perform quick and simple calculation, while other tools are designed to perform complex whole-building calculation), level of detail in result (basic output, detail which includes table and graphical outputs) , and the purpose of the software (some 3D modeling software are geared towards performing design improvements and estimating ROI on design such as Autodesk Revit, while OpenStudio another simulation tool was designed to perform a whole-building simulation). With the multitude features that exist among these tools, modelers find it difficult to properly select the tool that will generate the required project output with minimal time and effort.

Given the significant variability in the tools available and the diversity of domain being modeled, it is very critical to understand the proficiencies of the tools, the complexity of the simulation engine, and the requirement of the projects to properly select a tool for a project. For instance, if a modeling project requires the 3D rendering of the building to generate the simulation output, the modeler will have to select a tool that support 3D geometry rendering or can exchange data with a front-end 3D geometry software tool. Other factors that aids the

selection of the right modeling tools are: team-oriented modeling- need of s the modeling process involves a muilti-disciplinary team and parametric or explicit modeling. Choosing the right modeling tool improves the quality of the output and make modeling much easier and faster.

Therefore, the purpose of this study involves determining the most efficient tool to use for a modeling project and develop a process for modelers to determine the best tool use based on the project's output requirement , team composition and the time involved to develop the model.

This chapter states the importance of selecting the most effective building energy modeling (BEM) tools for a modeling project. This chapter covers topics on modeling, BEM modeling tools, categorization of BEM modeling, and effects of BEM relating to building envelope elements. The objective and scope of the research work, concluding with a summary of the significance of the study to modelers, are also included in this chapter.

Model

A model is a representation of a structure of a physical system and/or its properties. A model allows for non-destructive testing of the behavior of a system and provides better understanding of the system. A model can be made in various forms such as mathematical, statistical, and conceptual formats. Modeling a system or device permits modelers to view aspects of systems before they are built, to predict responses of systems to various inputs, and to perform sensitivity analysis on how changes in the variables of an object or system affect its dynamic behavior. Such analyses can help designers and analysts to make necessary modification to the model with comparatively minimal effort and to identify the risks and

benefits involved in future system modifications. Examples of model application are: aircraft model, ship models, car models, building models and so on. This study will focus on building energy models.

Modeling processes range from basic to detail. The decision on how much effort needs to be expended in constructing a model is a function of the detail required in the analysis or output generated by the tool. Therefore, an effective model is representative of the level of detail the modeler is looking for or requires to answer the questions that initially warranted the development of the model. The amount of time required to design, build and analyze changes to the model, whether it is physical, graphical or mathematical, is a function of the level of sophistication or complexity of the desired results, the system's properties, and/or the required output. Figure 1 below presents an example of variety in model development.

(a). A small office building

(b). A large library building

Figure 1. Basic vs Detailed Building Modeling Examples. Image 1a source: Natural Affordable Small Houses.., n.d. Image 1b, Sherrod Library, ETSU

The two photos in Figure 1 illustrate how a model can vary in complexity. It shows two buildings that differ in their properties, complexity and functionality. The building on the left is a small office building with 150 square feet while the one on the right is a four-story university library of 50,000 square feet. To develop architectural and engineering models of these buildings requires a significant difference in time due to their varying complexity, occupancy, envelope properties and operating systems. Modeling the small building will take significantly less time because of the reduced input parameters, operating system sophistication, environmental requirements, codes and standards, occupancies, and schedules. This difference in model development time exists even if the output requirements for both models are the same (i.e. estimating the annual energy consumed in both buildings). If one has to develop two models of the university library building, one to evaluate the exterior profile, materials, and colors and another to determine its annual energy consumption, the amount of time to develop each model and generate the desired output would also be significantly different. In this example, both the necessary inputs and the desired outputs are different. Therefore, the methods used to model a system vary based on the inputs required and the outputs desired.

Building Energy Modeling (BEM)

BEM is a process that involves the use of software to predict the energy use of a building. BEM is used to perform load design building energy analysis. Uses for BEM include:

- estimating the amount of cooling and heating energy needed for a space/building and choosing the proper size of HVAC systems.
- projecting the monthly energy consumption and utility bills.

- comparing energy improvements achieved through a retrofit in an existing building.
- determining the economic feasibility of making building modifications.

Engineers or modelers can use BEM to evaluate building construction (new and existing), equipment selections, lighting, window, insulation, and other materials and systems that influence the buildings operation. Modeling a new building design helps builders make decisions regarding footprint, height, orientation, materials, and equipment selections that will reduce energy consumption and demand. BEM can define how individual building elements contribute to the annual building energy consumption. Similarly, energy modeling can be utilized to evaluate the operation of existing buildings and guide system upgrades to improve their energy performance. BEM process can investigate building elements to determine their impact on annual energy costs or to design day system sizing requirements.

"The emergence of the energy modeling process began in 1925 with the Response Factor Methods (RFM's) process that was used to calculate heat flow" (BEMBook, 2012). Using RFM method, a model is divided into mathematically perpendicular sections and with each section connecting to a mathematical model of a heat exchanger pipe as a way of modeling energy transfer between these sections. "Each response factor is calculated using a finite element program that solves 2D conduction problems" (Tittelein, Wurtz, & Achard, 2009).

Technological advancements in computer hardware and software have led to the development of numerous modeling tools that can simulate building performance. These tools continue to advance in sophistication and in the accuracy of their output projections and reports. Currently BEM is performed using computer programs written specifically for energy modeling. These tools vary in complexity based on the intended use of the output information. Some are

geared to the engineering disciplines, some to architects, and others to professional teams made up of multiple disciplines who use the tool to evaluate the results of macro-level changes in the design scope.

Building Energy Modeling Tools

Energy modeling tools are very useful for engineers and designers to simulate the response of HVAC designs of proposed buildings and to determine the most cost-effective modifications to existing buildings to estimate and / or reduce the energy. These software-based modeling tools are designed to perform some, or all of the functions listed below:

1. Sizing HVAC systems and equipment.
2. Analyze building energy usage (whole building simulation).
3. Estimate the consumption of building energy usage in an existing building or a proposed building.
4. Evaluate energy improvement possibilities when choosing equipment to retrofit existing building components (determining the economic feasibility of making a change).

The following are some of the energy modeling tools currently available for use by design and operation professionals:

- DesignBuilder
- EnergyPlus
- eQUEST
- Trace 700
- HOT200
- Spreadsheets

- FineHVAC
- FineGreen
- TRNSYS
- Autodesk GBS
- IDA ICE
- ESP-r
- BEAVR
- Others (USDOE, 2016)

One tool does not work equally well for all projects. Modelers need to be able to select the proper tool for a project from this list which continually grows as more vendors enter the field with tools that work with their products.

With so many tools available, how does a modeler choose the right tool for a project? The most effective tool should be capable of producing the required output in the shortest amount of time. If the improper tool is selected, the output may not answer the questions required by the scope of the project. Also, the modeling process will take longer than necessary, costing the modeler more time and expenses for an output that could be produced quickly if another tool was selected. With all the numerous tools available for modeling, designers may find it difficult to select the tool that can effectively generate the output needed for each of the many different projects they are working on at any given time. All the modeling tools listed above have varying capabilities and limitations.

With the increasing availability of new, more sophisticated tools, modelers require assistance in choosing the most effective tool for each project. This study will present a method

to assist modelers with the critical step of selecting the right tool for modeling. This study classifies some BEM tools into three modeling categories based on their available output data, input requirements, time required to generate outputs, and ease in executing parametric runs to determine the impact of making changes in the modeling systems. Once a tool is categorized, a decision tree will be employed to choose a category that is most efficient for generating the required output for a given project scope. The modeler will then select a software tool from that category to generate the required model knowing the tool will efficiently generate the output required by the project team.

Categorization of Energy Modeling

In this study, BEM tools are loosely placed into three different categories named here as "boxes". They are Black-box, Gray-box and White-box. The categorization is based on the variables needed, calculations performed, and output details (Amara, 2015). All the tools placed in these three boxes are capable of estimating building energy requirements in terms of its heating and cooling loads and building energy consumption. Each of the tools differs in its intended application, the level of detail of the calculations it can take, the required inputs and possible outputs, and the process time. The tool placed in the Black-box are the least complex modeling tools due to the level of calculations they can perform (e.g. Spreadsheets). They are most suitable for projects that require non-complex output data to answer the modeler's question. Tools placed in the Gray-box are more complex than the Black-box tools. Gray-box tools are suitable for projects where output requires the input from a multidisciplinary team (e.g. Autodesk Revit). Tools placed in the White-box are the most complex in terms of input data requirements and output generated. They are more suitable for projects that require detailed output data based

on many interacting variables (e.g. OpenStudio). Chapter 2 provides detail information about the modeling categories.

Effect of Energy Modeling Relating to Heat Transfer Through Building Envelope

"About 50% of the heating load in residential buildings and 60% in commercial buildings results from energy transferring through exterior walls, foundations and the roof" (USDOE, 2015). This fact highlights the importance of investigating the heat transfer through building envelope elements before a project is constructed or investigating the possibility of reducing energy losses in existing buildings. Appropriate investigation and enhancement of a building envelope's properties results in improving the building's energy performance by reducing heat loss in the building. How much can.., (2013) states that a homeowner can save about 26-52% on utility bills if the windows are replaced with thermal efficient windows.

Energy modeling approaches can be used to investigate the feasibility of improving active and passive strategies to improve a building's energy efficiency. "Active strategies may include improvements made on the building mechanical system (HVAC), lighting, plumbing or domestic hot water systems; while enhancing the building envelope elements, insulation, windows, doors and roofing are passive strategies" (Building Envelope, 2018). It impacts the conditions of the interior air quality based on the exterior weather conditions. The design of building envelope holds an important role in building energy saving. Thermal energy transfers occur through the components of building envelope (walls, windows, doors, skylights and roofs) as the environment temperature changes throughout the day.

Reduction of heat loss through the building envelope significantly improves the energy performance of a building. Several case studies have shown the impacts made on the energy

performance of a building using the passive strategy. Sadineni, Madala, & Boehm (2011) states that,

- 31.4% of energy was saved by implementing the passive energy efficient strategy in a high-rise apartment in Hong- Kong China.
- In a different study in Hong Kong China, the thermal and heat transfer performance of a building envelope in subtropical climatic conditions was studied using DOE-2 building energy simulation tool. An energy effective building envelope design saved as much as 35% and 47% of total and peak cooling demands respectively.
- In Greece, thermal insulation in walls, and roofs reduced energy consumption by 20-40 % (Sadineni et al, 2011).

The amount of thermal energy transferred through the building envelope depends on the characteristics of the element of the building envelope, the differences in temperature (indoor and outdoor), the surface area of the building envelope, and the thermal resistance, R-value of the corresponding building element. The R-value quantifies the insulation properties of a construction material. It is the reciprocal of the overall heat transfer coefficient U-value. As the R-value increases, the U-value decreases and vice versa. The simplest equation used to quantify the amount of heat transfer through a wall section is presented in equation 1 below.

$$\mathbf{Q = UA\Delta T} \quad \textbf{(1)}$$

$Q = \text{Heat transfered per unit}$

$U = \text{Overall heat transfer coefficient}$

$A = \text{Surface area for heat flow}$

$\Delta T = \text{Difference in temperature}$

"The R value is a measure of insulation's ability to resist heat travelling through the building envelop" (STAR, 2018). A material with a high value will have more thermal resistance and better insulating properties thereby reducing heat loss resulting in lower energy bills.

Objectives of the Study

This study investigated three different tools used for building energy modeling. The tools used possess varying capabilities and each fell under a category of modeling discussed in the previous section. With so many tools available, a method must be developed to permit a modeler to quickly choose the tool that generates the necessary output with minimum effort and time. The two objectives of this study are:

1. To determine the most efficient tool to use in modeling a project
2. To develop a process to determine the best BEM tool to use based on the required output data and time needed to develop the model

The selection of the most efficient tool based on the scope of this project is a function of several variables:

- the output data requirements
- the time needed to develop or populate the model
- the time needed to make parametric runs where some characteristic or characteristics of the model are changes and the output is generated to determine the impact
- the time needed to analyze the output data.

Out of the variables listed above, the most important is that the tool should be capable of producing the output data required by the project. If the modeling tool being evaluated does not generate the required output data needed to answer the project questions, it cannot be used. If the

required output is available from more than one modeling tool, the choice of which to use is based on the time it takes to develop the model. There is no value in entering more data into a model than is needed to answer the questions being evaluated.

Scope of the Study

The scope of this study is restricted to using three BEM tools: Microsoft Excel Spreadsheets, Autodesk Revit and OpenStudio that have varying capabilities to estimate the amount of heat transfer through the exterior building envelope elements (exterior wall, roof, windows and doors). The tools selected fell under each category of modeling (Black-box, Gray-box and White-box), and they were selected based on their capabilities to run the analysis and generate the project's required output. Each model built by each modeling tool was able to use the same local weather data of the building location and the actual construction sets. They also had constant heating and cooling set points. Model analysis will examine the steps required in modeling, the tool used, the amount of time required for model development, amount of input variables needed, simulation run time, and the rate at which each model generates output when subjected to the same modification.

Significance of the Study

This study will be beneficial to a variety of professionals in the engineering and energy management fields. The study will explain the processes involved in using different tools that fits in different modeling categories to estimate heat transfer through the building envelope. The study will identify the reasons why the software tools are classified under each modeling category and pair several energy modeling projects with the right software tool. This information will be substantial for professionals in the modeling field to better understand the process,

ability, simplicity, and modeling approach that best suits different projects according to the required outputs. Not only will the study help to choose the proper modeling category and tools, it will also provide a good understanding of the thermal performance of the elements of building envelope.

CHAPTER 2

LITERATURE REVIEW

Overview

This chapter presents some of the most relevant research work on the capabilities and limitations of several building energy modeling tools. The first section of this chapter provides detailed explanation of each category of energy modeling and some of their corresponding modeling tools, along with their respective capabilities. The second section utilizes credible research work to compare the capabilities and limitations of available BEM tools. The final section covers the topic of building envelope elements.

Categories of Energy Modeling

For simplicity, a BEM tool is placed into one of three general boxes. The first category is used to represent a tool with a relatively simple mathematical construction that generates output based on daily, monthly or annual data, referred to as the Black-box. Tools placed in the Black-box can perform basic estimation of energy consumption and compute system loads using relatively few formulas and input tables. It generates a simple output. The tools placed in the second category (Gray-box) can handle detailed energy modeling calculations and iterations. Gray-box building modeling tools are best used to perform building design improvements and are suitable for team-oriented projects. The third category represents tools that are very complex in their design and generated output data (White-box). These tools employ complex methods of calculating the projected energy consumption and the system loads on an hourly or sub-hourly basis.

Black-box: The Black-box modeling category involves the use of mathematical and statistical equations that use sets of input variables such as weather files, occupancy schedules, thermal coefficients, and building surface areas to generate data on building energy performance. Black-box tools permit automatic adjustment of the input parameters. The automatic adjustment of the mathematical model parameters provides the greatest benefit over the models classified under the White-box category (Amara et al, 2015). The Black-box modeling category is mainly data driven, which depends on the correlation between energy consumption and the operational data. Spreadsheet (Microsoft Excel, Numbers for Mac) is the most common tool that fits in the Black-box category. Black-box models are suitable for error detection. However, it may not be suitable for optimization because it appears to be inconsistent with physical reality when applied under hard conditions. (Amara et al, 2015). An example of a Black-box method is the application of a spreadsheet to determine the operating characteristics for a building energy model. A Black-box methodology presents the following benefits:

- Simplicity: User focuses on inputs and outputs, which makes simulation easy.
- Rapidity: Process and preparation time of using the technique is very short compared to the other two techniques.

Gray-box: Models developed from this category fit perfectly in between the Black-box and White-box category. According to Butts (2016), designers use Gray-box tools to quickly design efficient building and gain better understanding of design impact on environment and resources. This was accomplished by easily executing multiple parametric runs easily with greater focus on the projected impact than on the detailed values. “It helps industries to control design models for more than construction documentation and communicate return on investment

on different strategies while reducing design costs" (Butts, 2016). An example of tool used for Gray-box approach is the Autodesk Revit software.

White-box: The White-box modeling category concentrates on the physical and operational knowledge of the building. This category of modeling takes into consideration the building's physical features to predict the energy performance of the whole building and its sub-system behaviors. White-box tools can take in detail input variables such as weather data, building envelope structure, heating and cooling schedules, occupancy rate, and many others to perform building energy simulation. This modeling category utilizes sophisticated computer software tools specifically designed to accommodate the building operational and physical features to create a model of a building. The tool is highly equipped to perform a detailed simulation of the model energy usage. A model placed in the White-box category is usually more elaborate, takes more input parameters and simulates many details of processes involved in the systems compared to models made with a Black-box or Gray-box tools. The model involves extensive calibration, high expertise in using the software tools, and ability to represent the building operations and schedules on the software interface. Mathematical and energy related equations are imbedded in the software tools to perform energy simulation under the White-box modeling category. Examples of the software tools are TRNSYS, Design Builder, EnergyPlus, OpenStudio energy modeling software etc.

Building Energy Simulation Tools

Over the years, there have been numerous energy simulation tools developed to perform building energy analysis. These tools have undergone continuous improvement in terms of performance and efficiency. Building energy simulation is a tool used to estimate the energy performance of an operational building or a model of a non-existent construction. The output

information presented visualizes the reasons and factors behind the energy usage in the building. The output information presented helps to determine the level of interference in the building energy performance to reach an energy improvement target.

An energy simulation tool predicts building energy performance by simulating the thermal, physical and operational features of the building. During the simulation process, the simulation engine considers the outdoor weather condition, mechanical systems, occupancy schedule and the thermal properties of the building's envelope to accurately model how the building responds to changes in these and other variables. Rallapalli (2010), states that building energy simulation tools permits users to

- Predict thermal behavior of building envelope in relation to outdoor weather condition
- Visualize the effect of using natural lighting versus artificial lighting on building energy usage.
- Estimate the size and capacity of the mechanical systems required for ventilation comfort.
- Compare heat transfer results of an insulated building envelope element to a non-insulated element
- Check for compliance with building codes.

Energy simulation is beneficial during the design and construction as well as the building operation and maintenance phases. During the design phase, the design team enjoys the freedom of exploring several design concepts, providing greater possibilities to improve a building's energy performance. Benefits are derived by performing simulations on several design alternatives, which helps to make better decisions related to creating a lower energy use building.

During the design phase, a modeler can evaluate the impacts of building location, orientation and materials.

During the construction phase, building energy simulation ensures that buildings meet their performance and code requirements. For instance, an analysis of the heating and cooling loads data during the construction phase of a project can assist in properly sizing the HVAC systems. Construction phase modeling also helps the design team select the most efficient materials by comparing the energy performance of several building materials using parametric runs. Parametric runs permit modelers to alter the input parameters in existing model for result comparison and optimizations. In the operation and maintenance phase, building energy simulation evaluates the overall building performance and detect building systems that are not functioning effectively.

Tools used for energy simulation are categorized according to their capabilities. Energy modeling tools can perform varying energy analysis such as whole-building simulation, load calculations, HVAC sizing, design optimization, code compliance, lighting simulation and others. Users of these tools should be able to identify each tool and its simulation engine attributes. Table 1 presents a list of energy modeling tools and their associated capabilities, and Table 2 fits some of the software tools in their respective modeling category used in this study.

Table 1

Building Energy Modeling Software Tools and Capabilities

Capabilities	**Software Listing**						
Whole-building Energy Simulation	TRNSYS	DesignBuilder	EnergyPlus	FineGreen	TREAT	ESPr	eQuest
Load Calculations	DesignBuilder	FineHVAC	FineGREEN	HOT2000	TRACE 700	BSIMAC	EnergyPlus
HVAC sizing	EnergyPlus	FineGreen	AcousticCalc	FineHVAC	IDA ICE	HAP	
Energy Conservative Measures	OpenStudio	EnergyElephant	TREAT	Hot2000	Autodesk GBS	Snugg Pro	
Code Compliance	IDA ICE	EnergyPlus	ENERWIN	CYPETHERM SUITE	BEAVER		

Source: Building Energy Software tools, IBPSA-USA

Table 2

Placing Modeling Tools in their respective Modeling Category

Black-Box	**White-Box**	**Gray-Box**
Microsoft Excel Spreadsheet Pen and paper	DesignBuilder OpenStudio EnergyPlus Fine GREEN TRNSYS	Green Building Studio Autodesk Revit eQuest HOT2000 IDA ICE

Literature Review on Building Energy Modeling Tools

BEM tools are used to perform energy simulation to predict the energy performance of a building. These tools can model the energy performance and thermal comfort of the building's life cycle. "They support the understanding of how a given building operates according to certain criteria and enable comparisons of different design alternatives" (Fischer, Bazjanac, & Maile, 2007).

Over the past few years, several BEM tools have been developed and they differ in many ways such as: their thermodynamic models, their graphical user interfaces, their purpose of use and their ability to exchange data with other software applications. Generally, most simulation tools are made up of an engine and a graphical user interface. The engine is comprised of the thermodynamic algorithms which are used to compute energy performance according to the model's input data, while the graphical user interface is used to create the input variables and analyze output data. Furthermore, energy simulation software tools differ in their purpose and mostly do not use complete functionality of the related engine. For instance, a tool that is only developed to be used during the building design phase has a different purpose compared to a tool used in both design, construction and maintenance phases (Fischer et al, 2007).

Conducting BEM can be very useful as long the right tool is used for the right project. Spreadsheet modeling techniques are suitable for non-complex projects involving estimating energy improvements achieved through a retrofit of an existing system such as changing the bulb type in an apartment. Spreadsheet techniques would be easier to use for such projects because they require less input parameters, involve less computations and provide quicker outputs than any other energy modeling tools. This technique requires less computation time and generates

immediate and accurate results. Holladay (2012), in his study finds out that using spreadsheet for energy modeling is more accurate than using energy model tools that require more inputs. An energy model that requires a lot of input variables takes a lot of time to process, which does not necessarily improve the accuracy of the model (Holladay, 2012). Furthermore, spreadsheet techniques could be used for projects that involve evaluating energy improvements made by comparing building features (pre-retrofit vs post-retrofit), evaluating energy conservation measures, and evaluating energy savings, improvement measure costs.

Evans (2000) conducted a study on spreadsheets as a tool for teaching simulation in class, which supports the claim that spreadsheets use mathematical and statistical algorithms to generate immediate output. He stated, “Spreadsheet technique integrates statistical tools and functions which gives modelers the ability to perform on-the-spot analysis of results without transferring data to other software packages” (28). Spreadsheet technique supports dynamic updating of data’s in the case of any design alternative. Simulation input data can be easily altered and generates immediate output using the spreadsheet method of modeling.

To choose the right tool for modeling, it is important to understand the limitation of each tool. Spreadsheet technique is not primarily designed for an energy model that involves a lot of variables and simulates many details of process response involved in the system. Spreadsheet technique is not fit for a project that involves evaluating the total energy consumption of a large public building. White-box or Gray-box energy modeling tools such as EnergyPlus and eQUEST simulation engines are precisely designed for simulating projects that involve whole-building simulation. Seila (2006) conducted a study, which supported this claim by stating that, “Complex algorithms are difficult to implement in spreadsheet”. For instance, complex algorithms usually

involve a lot of computation and calculations which might run over the capacity of what a spreadsheet cell / engine (Black-box) can effectively handle.

The steps involved in the use of spreadsheet modeling technique is somewhat different from other energy simulation techniques. Performing a building model on an Excel spreadsheet does not require the 3D rendering of the building; it involves data collection and interpretation, worksheet organization and setting up equations for computation. For instance, in quantifying heat transfer through building envelope using a spreadsheet method, the input parameters need to be collected including the weather data (change in temperature), the thermal properties of the building envelope, and the surface area of the building envelope. Pecherska & Merkuryev (2005) in their study present the stages involved in using spreadsheet calculations: (a) assignment of spreadsheet areas for data and parameters (b) programming of cell formulas (c) copying cell formulas to provide several trials or a necessary simulation length (d) visualization by using charts.

White or Gray-box models specifically designed to perform BEM possess the strength to handle detailed and complicated energy simulations, unlike the spreadsheet computation method of energy modeling. OpenStudio software implores the EnergyPlus engine for whole-building simulation. This technique has proven to be one of the most substantial and extensively used method of performing energy modeling. Compared to the previously developed simulation engine, EnergyPlus is an improved, powerful and flexible engine for energy simulation. Crawley, Lawrie, Pederson Curtis, & Winkelmann (1999) presented a study highlighting the capabilities of EnergyPlus. EnergyPlus capabilities described in the study include: (a). heat balance load calculations. (b). integrated loads, system and plant calculations in the same step. (c) user-configurable HVAC system description, and (d) simple input and output

data formats to facilitate graphical front-end development. EnergyPlus will be the most suitable technique to use if the capabilities listed above aligns with the project objectives.

Energy simulation could take a lot of processing time due to the level of details involved in the pre-simulation process and the type of engine used. eQuest, which implores the DOE 2 engine, has proven to be faster in terms of run time than the EnergyPlus. Rallapalli (2010), (2010) presented a study on the comparison of EnergyPlus and eQuest, where the author compared run time between both simulation tools. Rallapalli concluded that EnergyPlus runs much slower than eQuest because EnergyPlus performs more thermal calculations than DOE-2. Hong, Buhl, & Haves, (2008) study on EnergyPlus Analysis Capabilities also reinforced the above claim. The study stated that EnergyPlus 1.2.1 took much longer time than DOE 2.1 E to run typical building simulations. For a user that is concerned with speed or process time, eQuest technique will be the preferable modeling method compared to the EnergyPlus method.

Autodesk® Revit computer program is the front-end program for the eQuest engine. Revit's interface allows the modeler to draw the building geometry while associating thermal properties for building elements and performing energy analysis on the same interface. The inbuilt eQuest-modeling engine in Revit allows to execute the energy analysis function. This technique compared to the OpenStudio modeling technique presents a more simplified method of developing building model, assigning thermal properties and operational features to the building. The simulation process using OpenStudio (White-box BEM tool) is a little bit comprehensive and involves more steps and more calculations compared to the Autodesk Revit method (Gray-box). Smith (2016) conducted a study on energy modeling breakdown, which categorized the eQuest engine into the schematic design wizard and the design development wizard. The schematic design wizard is used during the design phase and allows modelers to draw building

geometry and define basic architectural features (construction materials), while the design development wizard allows modeler to define detailed parameters for the simulation (weather data, space types, loads, schedules, HVAC systems, lighting etc.). Therefore, Autodesk Revit can simply be categorized under the Gray-box method because it does not perform a whole building energy simulation. The OpenStudio is an add-in for a computer program called, SketchUp which is used to create building geometry. Once the building model is created, OpenStudio interface is used to define the building operational and physical features by inputting necessary parameters in the model.

Understanding the capabilities and drawbacks of each modeling technique and being able to detect common errors associated with models is very important. Errors can be quickly identified, traced, and corrected on a model developed on a spreadsheet compared to models built using any Gray/ White-box tool. Furthermore, errors in a model can be simply and swiftly traced when a project requires less input variables compared to a project with many variables.

Building Envelope Elements

Walls

According to the ASHRAE 90.1- 2016 standards, Wall is the portion of the building envelope, including opaque area and fenestration that is vertical or tilted at an angle of 60 degrees from horizontal or greater" (ASHRAE,2016). Most of the exterior walls on a building envelope are made up of brick and concrete block. Below is an image showing an example of a typical wall section.

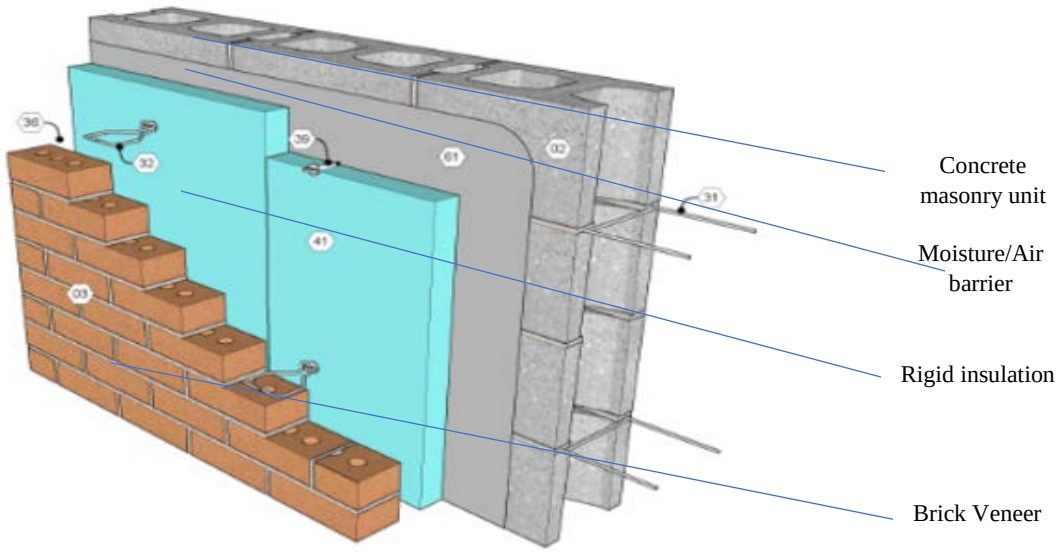

Figure 2. A Sample Wall Section. Image from Mansory Detailing Series, n.d.

The image above shows a section of a brick-faced concrete wall. The wall is comprised of a brick exterior, atmosphere barrier, rigid insulation, air space and concrete masonry block. Each component of the wall has a different level of thermal resistance and conductance. The thermal properties of the wall influence the building energy consumption, as heat is transferred to or from the building through the exterior walls. “About 35% of the heat will escape through the walls and through gaps, in and around windows and doors, and about 10% of heat will disappear through the floor” (Jimbo, 2016). In other words, exterior walls should be designed with highly thermal efficiency materials. Improving the thermal efficiency and insulating properties of an exterior wall will result in reduction of heat loss in the building. The thermal resistance (R-values, resistant values) of a material is its measure of resistance to heat flow; the higher the R value of an exterior wall, the lower the conductive heat loss through the wall. The R-value of the wall can be improved wall insulation. The insulating material has tiny air pods

that slows heat flow from passing through the wall. The thicker the insulation property, the better the wall resistance. It will take a much longer time for heat to travel through a wall that has a double layer of insulation (higher R- value) than a wall with a single layer of insulation (lower R value).

Fenestration (Doors and Windows)

Fenestration refers to the openings in building envelope, especially windows, skylights and doors. Fenestration allows energy transfer in form of solar radiation in to the building. Building fenestration has proven to be one of the weakest thermal unit among the building envelope. ‘An average home loses up to 30% of its heating and cooling energy through air leakage around windows and doors” (How much.., 2018). Fenestration with high insulating capacities possesses the ability for significant energy savings. Upgrading the old units to a more energy efficient unit improve the energy performance of the building and save money on utility bills. The R value of the glass is a measure of the thermal conductivity; as the R value increases, the lower the rate of heat loss (U-value) and the higher the insulating efficiency of the glass material (USDOE, 2016). Figure 3 below represents an image of a typical door section.

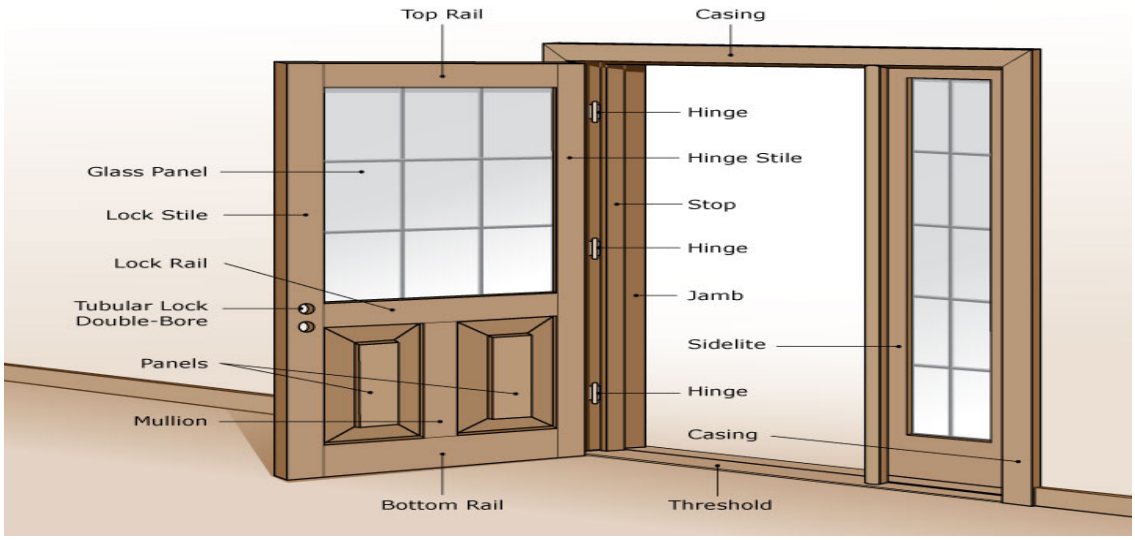

Figure 3. A Sample Door Section. Image from Door Reference Guide, n.d. Source: Top Fire Door Closers Regulations F46 About Remodel Modern Home Interior Design with Fire Door Closers , 2018.

Roofs

A building roof allows passage of heat and moisture transfer in and out of the building. "Up to 25 % of heat loss through an un-insulated roof" (Jimbo, 2016). Heat escapes from the building through any leakage in the attic of the roof. Selecting energy efficient roofing products, sealing the roof leakages and installing proper insulation are the most effective ways to reduce the loss of energy through roof. "The easiest way to prevent heat loss is through insulation of the ceiling in the loft cavity" (Keep the Heat in.., 2017). Installation of loft insulation reduces heat loss and creates a better air and moisture barrier in the attic. Insulation is very simple to install in the roof attics. Insulation levels are specified by the thermal conductivity (R- value); the thermal conductivity is the rate at which the insulation can resist heat transfer. The United States Department of Education (USDOE) suggests an insulation level of R38 for an already existing

attic with about 3-4 inches, and insulation level of R38-R60 for an uninsulated attic (USDOE, 2016). Figure 4 below shows an image of a typical roof section.

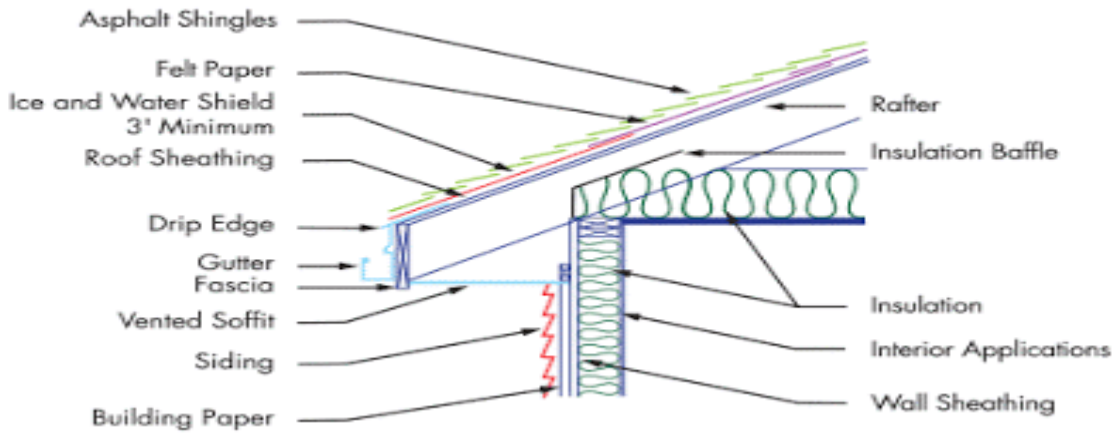

Figure 4. A Sample Roof Section. Image from The Language of a Roof.., 2016.

CHAPTER 3

METHODOLOGY

Overview

This chapter explains the process involved in the development of the three models built in this study. It covers the breakdown of all the steps involved in using three modeling tools from each of the modeling category to build a model that investigates the amount of heat transfer through the building envelope element. The latter part of this chapter compares the time and steps involved using the tools implored in this study for the modeling assignment.

Procedure of Modeling Associated with this Study

The aims and objectives of the study are:

1) to use different modeling techniques to determine the most efficient method of quantifying the heat transfer through a building envelope
2) to develop a method for determining the best tool to use in building modeling based on the necessary output.

With these objectives, the tasks are sub-divided and performed according to what is required by each modeling category.

Building Description

The building used as the basis of these analyses is located on the East Tennessee State University (ETSU) main campus in Johnson City, Tennessee (Figure 3). The location of the building is in Washington County which is classified by ASHRAE 169-2006 as Climate Zone Number 4 Subtype A.

Figure 5. Wilson Wallis Hall, ETSU

The building is classified as an education facility by the building code and it houses the Engineering, Engineering Technology, and Surveying program at ETSU. The building was originally constructed in 1968 with a block and face brick envelope and flat built up roof. The gross building area of this 3-story structure is 59,641square feet. The roof covers the entire third story. The window to wall ratio of the building is 21%, with an additional 1.5% of exterior door area.

Materials and Construction

The exterior walls are comprised of 4-inch brick exterior, a 2-inch air gap and 8-inch concrete masonry units. The inside surfaces are painted. All windows in the building envelope are aluminum framed with thermal breaks, double pane clear gazing and have a low emissivity

coating on the inside pane. The overall U-value of each unit is stated according to the drawing specification to be 0.52 Btu per hour-square foot- degree F by the manufacturer. The roof has been updated since the original installation and consists of three layers. The outside layer is a white polyurethane roof membrane, followed by 2 inches of roof insulation and a steel deck.

Black-box Model

A Black-box modeling tool is typically developed by the modeler using a computer spreadsheet application. The tool developed for this study was created in Microsoft Excel and consists of necessary fundamental heat transfer and geometry equations typically used by the HVAC industry. Heat transfer equations, weather data, and the construction properties of the building envelope elements were entered in the spreadsheet cells. The equations incorporate the variables of temperature, time, heat transfer coefficients and component areas. The execution of the model generated an estimate of the total heating and cooling loads in the building throughout a typical year.

The process of developing the actual model tool using Microsoft Excel is broken down into the following four stages:

1. Data collection and interpretation
2. Formatting weather data
3. Populating weather data into degree bin
4. Organizing input parameters for computation.

1. Data Collection and Interpretation

The building plans and blueprint of the building used in this study were retrieved from the facilities department at ETSU. Studying the building plans helped to determine the building

envelope elements and construction. A drawing section of each envelope element was studied for its constituent materials and thermal properties. The thermal resistance value of each material used to construct the building envelope element was derived from the ASHRAE standard. The overall thermal resistance for each element (wall, window, door and roof) was computed and later converted to an overall heat transfer coefficient (U-value) for computation. The surface area of each building envelope element was manually computed from reading the dimensions of the building plan.

After gathering all the necessary data from the building envelope elements, the next data needed is the weather dataset, which is used to estimate the exterior temperature of the building. The USBristolTN airport weather dataset, which falls in the same climate zone as the building's location was downloaded and used in this study. The weather dataset was formatted as an EnergyPlus weather file (epw) for use in energy modeling tools that incorporate the EnergyPlus engine. The typical meteorological year (TMY3) weather data set associated with the building location was downloaded from the EnergyPlus weather datasets. The TMY3 are hourly data sets of dry-bulb, dew point temperature, relative humidity, pressure, wind speed and solar radiation datasets. The dataset contains over 300,000 points of data formatted into 35 columns and 8,760 rows. Out of all the climate data available in the dataset, only the outside dry-bulb temperature data was used for this Black-box energy model, since the heat transfer is a function of the temperature difference across the envelope elements. The dry-bulb temperature is usually referred to the atmospheric air temperature.

Table 3 shows a portion of the raw TMY data that was used in all the modeling tools used in this study.

Table 3

Portion of the Raw TMY Weather Data

DESIGN CONDITIONS	1	Climate Design Data 2009 ASHRAE Handbook					Heating	1	-11.5	-8.4	-17.4	0.9
TYPICAL/EXTREME PERIODS	6	Summer - Week Nearest Max Temperature For Period					Extreme	20-Jul	26-Jul	Summer - Week Nearest Average		
Temperature For Period	Typical	24-Aug	30-Aug									
GROUND TEMPERATURES	3	0.5				3.97	3.09	4.65	7.09			
HOLIDAYS/DAYLIGHT SAVINGS	No	0	0	0								
COMMENTS 1	Custom/User Format -- WMO#723183; NREL TMY Data Set (2008); Period of Record 1973-2005 (Generally)											
COMMENTS 2	-- Ground temps produced with a standard soil diffusivity of 2.3225760E-03 {m**2/day}											
DATA PERIODS	1	1	Data	Sunday	1/ 1	31-Dec						
1987	1	1	1	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*_*9*9*9*9*9				4.4	-4.4	53	96200
1987	1	1	2	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*_*9*9*9*9*9				3.3	-3.3	62	96200
1987	1	1	3	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*_*9*9*9*9*9				3.9	-4.4	55	96200
1987	1	1	4	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*_*9*9*9*9*9				3.3	-0.6	76	96200
1987	1	1	5	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*_*9*9*9*9*9				3.3	-0.6	76	96100
1987	1	1	6	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*_*9*9*9*9*9				1.1	-0.6	89	96100
1987	1	1	7	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*_*9*9*9*9*9				0.6	0	96	96100
1987	1	1	8	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*9*9*9*9*9				0.6	0	96	96100
1987	1	1	9	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*9*9*9*9*9				0.6	0	96	96000
1987	1	1	10	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*9*9*9*9*9				1.1	0	92	96000
1987	1	1	11	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*9*9*9*9*9				1.7	0	89	96000
1987	1	1	12	0	?9?9?9?9E0?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9?9*9*9*9*9*9				2.2	0.6	89	95900

2. Formatting Weather data

To begin the process of creating the modeling tool using the weather dataset shown in table 3, the csv file was opened in a Microsoft Excel spreadsheet tab as the raw data and reformatted on a subsequent tab in a format that could be used by the tool. The weather dataset contains the data for a typical month based on a 30-year period. The TMY3 datasets represents a year of typical climatic conditions for the building location. It is composed of 12 typical meteorological months that are concatenated to form a single year with a serially complete data record for primary measurement. The data was converted from SI units to IP units and any non-used data was removed from the table. Table 4 shows a portion of the spreadsheet used to scrub the raw data into a format to be used by this modeling tool.

Table 4

Portion of the Modified TMY3 Weather Data

Annual Hour	Typical Year	Month	Day	Hour	Tdb (Degree F)
1	1987	1	1	1	39.92
2	1987	1	1	2	37.94
3	1987	1	1	3	39.02
4	1987	1	1	4	37.94
5	1987	1	1	5	37.94
6	1987	1	1	6	33.98
7	1987	1	1	7	33.08
8	1987	1	1	8	33.08
9	1987	1	1	9	33.08
10	1987	1	1	10	33.98
11	1987	1	1	11	35.06
12	1987	1	1	12	35.96
13	1987	1	1	13	37.04
14	1987	1	1	14	32
15	1987	1	1	15	32
16	1987	1	1	16	32
17	1987	1	1	17	32
18	1987	1	1	18	32
19	1987	1	1	19	33.98

Table 4 presents clearer information when compared to the initial raw dataset downloaded. Formatting steps include getting rid of unnecessary information and unit conversions.

3. Populate weather file into degree bin

To reduce the calculation requirements based on 8,760 hourly temperature records per year, the monthly dry-bulb temperatures were sorted into bins. A bin is a sum of the number of hours the outside air temperature was within a specific range over the course of a typical meteorological year. In this tool, the bin size can range from 1-degree to 20-degrees using a slider tool in the software. For the initial run, the average hourly dry-bulb temperature of the annual weather data (8,760 hours) was sorted into 5-degree bins ranging from the minimum temperature of a TMY to the maximum value recorded, 1.04 and 93.02 degrees respectively. For the weather dataset used in this study, the first 5-degree bin ranged from 1 degree to 6 degrees, the second bin range was from 6 degrees to 11 degrees and the last bin's range is from 91 degrees to 96 degrees. Each succeeding bin's range increased by 5 degrees through the maximum temperature recorded in the TMY of 93.02 degrees. Once the data was sorted, the number of hours and the average bin temperatures were used in the model to calculate heat transfer through the building envelope. Sorting the weather dataset was accomplished using the Microsoft Excel "AND" function written in a way that insured the temperatures in each bin were mutually exclusive, so data could not be double counted. The Excel "COUNT IF" function was used to tally the total hours that the average dry-bulb temperature fell within each of the 5-degree bins, which means that the spreadsheet totaled the number of the dry-bulb temperature for each of the 19 bins. The total hours of occurrence for this dataset was 8,760 hours.

As previously stated, the Black-box tool was designed so the bin size could be easily varied from 1 to 20-degrees to test the sensitivity of the output data to the changes in bin size. This permitted the bin size to be selected in a manner that generated the required output with a minimum of effort after the initial tool was developed. If the tool is set up to run with 1-degree bins, the envelope load will be calculated in 93 delta T steps; 19 steps for 5-degree bins and 5 steps for 20-degree bins. Based on the observations made during this study, using a 5-degree bin showed the least difference in the envelope energy load between the outputs generated using Black, Gray and White tools. The variables, functions and formulas below were used to develop the bin-populating tool that is depicted in table 4.

Spreadsheet variables, functions and formulas:

$$T_a = Min.TMY\ Hourly\ Temp$$

$$T_b = Max.TMY\ Hourly\ Temp$$

$$Min\ Temp(T_{min}) = T_a$$

$$Max\ Temp(T_{max}) = T_{min} + BinSize$$

$$Min\ Temp(T_{2min}) = \text{Min}(\text{ROUND}(T_{max} + 0.01), \$T_b)$$

$$Max\ Temp\ (T_{2max}) = Min(T_{max} + \$\text{D}\$2, \$T_b)$$

$$\frac{T}{F} = \big(AND(\$dbTemp > \$Tmin, \$Tmin, \$dbTemp \leq \$Tmax)\big)$$

$$= COUNTIF(if\ result\ above\ is\ true)$$

From the list above, $\boldsymbol{T_{min}}$ is the minimum dry-bulb temperature recorded in the weather dataset and will be used to establish the initial bin range. $\boldsymbol{T_{max}}$ is the sum of $\boldsymbol{T_{min}}$ plus the desired bin size (1, 5, 10, 25 or 20) for the initial bin range. For the subsequent columns, $\boldsymbol{T_{min}}$ was determined by adding 0.01 to $\boldsymbol{T_{max}}$ of the previous column to ensure that data sets are mutually exclusive and are not double counted. The Outside Air (OA) dry-bulb temperature for each bin was computed by taking the average of $\boldsymbol{T_{min}}$ and $\boldsymbol{T_{max}}$ for each column. The hours of occurrence

were computed by using the “AND” function to determine when a TMY data point was to be included in a particular bin. Lastly, the COUNTIF function was used to sum the number of occurrences throughout the year that the average dry-bulb temperature occurs within the bin’s temperature range.

The underlying reason for using the bin method is to make calculation more manageable with the resources and tools available. Two interior temperature set points were established for the building by ETSU facilities management. The sets points were 72°F during the winter season and 74°F during the summer season. The temperature difference across the envelope was calculated by subtracting the OA temperature from the interior set point. (No solar effects were considered when setting up the mathematical model because it’s difficult for the Black-box tool to accommodate due to the calculation’s complexity). Table 5 show a portion of the spreadsheet that contains the bin calculation.

Table 5

Portion of the Bin Calculation

Minimum TMY Hourly Temperature	Maximum TMY Hourly Temperature		Bin Size	Heating to Cooling Change over Temperature	Heating Set Point	Cooling Set Point				
1	94		5	50	72	74				
Temperature Bin		1	2	3	4	5	6	7	8	9
	Min Temp	1	6	11	16	21	26	31	36	41
	Max Temp	6	11	16	21	26	31	36	41	46
	Delta	5	5	5	5	5	5	5	5	5
8760	Bin Hours	12	29	98	128	261	449	544	543	501
	1	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
	2	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
	3	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
	4	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
	5	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE
	6	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
	7	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
	8	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
	9	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE

4. Organize input parameters for computation

This section involves bringing all the input parameters together for computation. Each R-value obtained during the first phase of this process is converted to U-value. The overall total U-value for each envelope element is computed using the equation 2 below.

$$\boldsymbol{U - Value\ total = 1/R\ \ value\ total} \qquad \textbf{(2)}$$

$$\mathrm{U - value\ total = Overall\ Heat\ Transfer\ Coefficient}$$

$$\mathrm{R - value\ total = Overall\ Thermal\ Resistivity\ Value}$$

The surface area of each building element computed during the data collection phase was included among the input parameters used for the computation. The thermal loads computation comprises of the overall heat transfer coefficient, the surface area, temperature difference and the hour of occurrence. Table 6 shows the tab used in the spreadsheet tool used to calculate the heat transfer through the envelope.

Table 6

Portion of Thermal Loads Computation

	Areas ft2		U-Values Btu/hour-ft2-°F			
Opaque Wall	18,185		0.3933			
Fenestration(Window)	3,833		0.3146			
Roof	25,822		0.1033			
Fenestration (Door)	923		0.208125315			
Floor	25,822		0.2			
Mode	Heating		Heating	Heating	Heating	Heating
Inside Temperature Set Point	72		72	72	72	72
Average OA Temperature	3.5		8.5	13.5	18.5	23.5
Temperature Difference	68.5		63.5	58.5	53.5	48.5
Bin Hours	12		29	98	128	261
U*A*delta T						
Opaque Wall		5,879,688.56	13,172,076.02	41,007,608.92	48,983,098.88	90,545,057.99
Window		991,114.58	2,220,361.93	6,912,481.65	8,256,876.73	15,262,802.88
Roof		2,191,968.55	4,910,596.22	15,287,780.68	18,261,071.36	33,755,515.75
Door		157,905.93	353,751.53	1,101,307.38	1,315,498.51	2,431,693.62
Floor		4,245,136.80	9,510,242.60	29,607,505.20	35,365,811.20	65,373,557.40
Heat Load		9,220,677.63	20,656,785.71	64,309,178.63	76,816,545.48	141,995,070.24
Cooling Load		-	-	-	-	-
Unit	BTU					
Annual Heating Load	1,327,631,752.46					
Annual Cooling Load	591,716,234.57 BTU					
Total Loads	1,919,347,987.03 MILLIONSBTU 1,919.35					

Table 6 shows a portion of the thermal load computation tab. All the input parameters used for the heat transfer equation were displayed. The total heat transfer was computed in MILLIONSBTU (MMBTU) to make the value more presentable. The fundamental equation used to calculate the heat transfer through the building envelope in equation 3 below.

Fundamental Equation used to compute the thermal loads in the Black-box modeling category

$$\boldsymbol{Q = UAh\Delta T} \quad \textbf{(3)}$$

$\mathrm{Q} = \text{Heat Transfer}$

$\mathrm{U} = \text{Heat Transfer Coefficient}$

$\mathrm{A} = \text{Surface Area}$

$\mathrm{h} = \text{hour of occurence}$

$\Delta\mathrm{T} = \text{Difference in Temperature}$

$$\mathrm{BTU} = \left(\frac{\mathrm{BTU}}{\mathrm{h} - {}^{\circ}\mathrm{F} - \mathrm{sqft}}\right)(sqft.h.{}^{\circ}\mathrm{F})$$

The tool has the capabilities to modify the interior set points, change between cooling and heating set points, bin size, U-values, and element areas to perform analyses that may improve energy efficiency. Developing and using Black-box modeling tools are appropriate when hourly, daily, or seasonal output is not essential to answer designer's questions. Equipment sizing, simple payback of projects where elements are upgraded, and similar tasks are easily handled by a Black-box modeling tool. If more detailed output is required, the designer needs to select a Gray-box or White-box tool.

Gray-Box Model

Autodesk® Revit software is a standalone product that does not require an external software for sketching the building geometry. Autodesk® Revit allows the modeler to draw the building as well as execute the energy analysis with the use of the integrated eQuest modeling engine. The building Gray-box model was created using Autodesk® Revit software. The process

involved in the Revit software differs in steps from that of the OpenStudio process in that the thermal and physical properties of the building envelope are defined upfront while drawing the building model. The “wall” tool can be used to draw the wall and the “edit type” tool can be used to build up the wall materials and associate thermal properties at the same time. Figure 6 shows the construction of a wall in Revit.

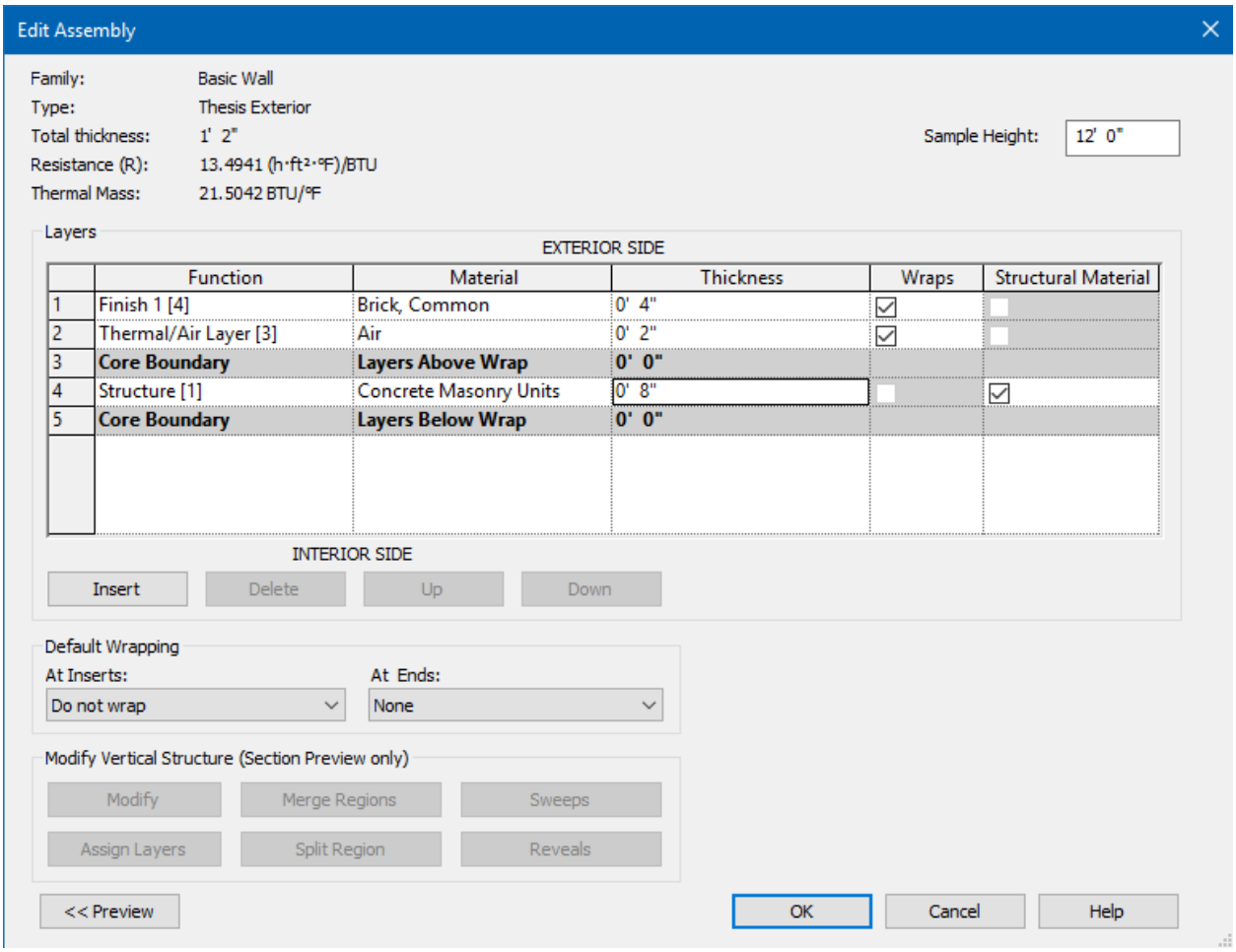

Figure 6. Building a Customized Wall in Revit

Other building elements (window, roof, and doors) were created to complete the building geometry using the same process described above. Figure 5 shows the Revit model. The building envelope element was fine-tuned to have almost similar thermal resistivity values that were generated from the OpenStudio model to minimize differences to only those generated by the

software's execution. Because of the limitation of the Gray-box tool to limit the amount of detail in the input parameters and their customization, the R-values of materials were not easily adjustable to suit the project requirement. This limitation resulted in some differences in the output estimates.

After the building geometry was created, the "space tag" tool was used to assign spaces to each room and the "zone" tool was used to assign thermal zone. Subsequent steps include performing the energy analysis. Energy settings and weather location were set before instructing the engine to create the energy model. The same weather data file used in building the other models was also used for this model to have a basis of comparison. The energy analytical model was generated after creating the engine model. The load simulation was run, which generated a limited level of detailed output of the energy use intensity and the loads transferred through the envelopes. Figure 7 below shows the 3D model of Wilson Wallis made using Revit.

Figure 7. Energy Model of Wilson Wallis Generated in Revit

White-Box Model

The White-box modeling category integrates three different software tools into one modeling tool to estimate the heat transfer through the building envelope (SketchUp, OpenStudio and EnergyPlus). SketchUp is a graphical software used to model the building's geometry. OpenStudio served as a user interface to assign the properties of the envelope into the EnergyPlus engine. EnergyPlus performs the calculations and generates the output.

The building envelope of Wilson Wallis Hall was created using SketchUp with the OpenStudio plug-in (Figure 6). The "line" tool in SketchUp was used to draw the plan of each building level, and "the space diagram" tool was used to extrude the plan up to desired height of the building, thereby creating the building geometry. The window fenestration was added to the drawing by setting a window-to-wall ratio, which was computed by dividing the total window area by the total area of the wall rather than placing each individual window in the wall. The "project loose element" tool was used to properly project the fenestration on the building envelope. The "set attribute" tool was used to name the space type and thermal zone. The "rotate" tool was used to ensure that the building is oriented in the right direction towards the sun. Figure 8 shows the completed rendering of the building used in this study.

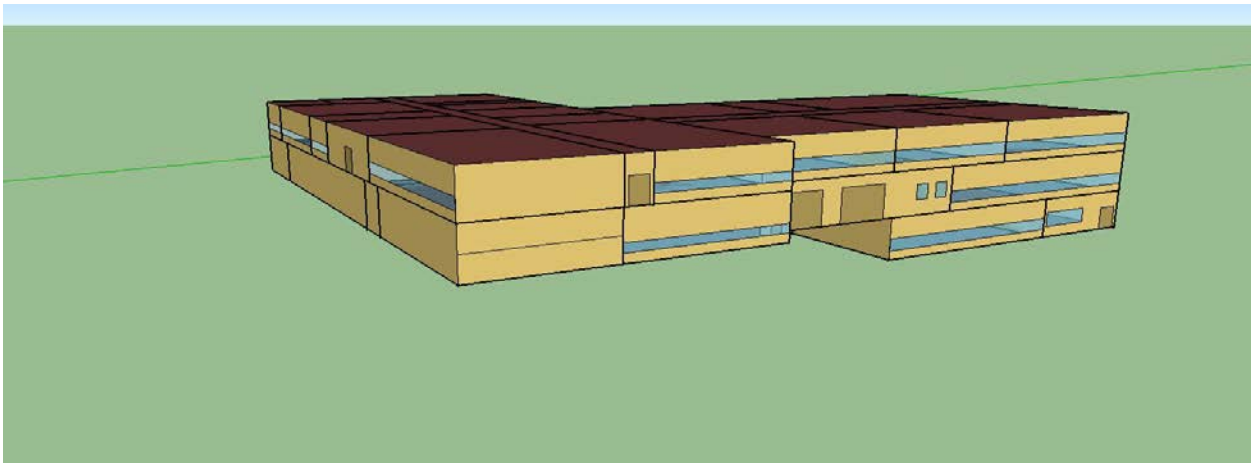

Figure 8. Rendering of Wilson Wallis Hall Using SketchUp

To ensure that the estimated energy transfer through the envelope is reasonable, it is important to accurately input the thermal properties of the building envelope components into the EnergyPlus engine. The correct weather file corresponding to the building's location is also required. These project characteristics were the same as those in the Black-box tool and were input into the Energy Plus modeling engine using the OpenStudio interface.

The building plans were used to develop the 3-D rendering, envelope characteristics, materials and constructions. Some of the materials used in the construction were downloaded from the building component library in the OpenStudio interface to achieve the same R-value used in the Black-box tool. Figure 7 shows a screen shot of the input screen for the components that make up the building envelope. It shows the processes of modeling the exterior wall within the OpenStudio interface to EnergyPlus. The wall's component materials were downloaded from the building component library and assembled to form the wall element. From the image above, the wall comprises of a 4-inch brick on the exterior, a 2-inch air space and an 8-inch concrete masonry unit on its interior. This process is repeated for all other building envelope elements (,

roof, window and door). Figure 9 below shows a sample wall construction in OpenStudio interface.

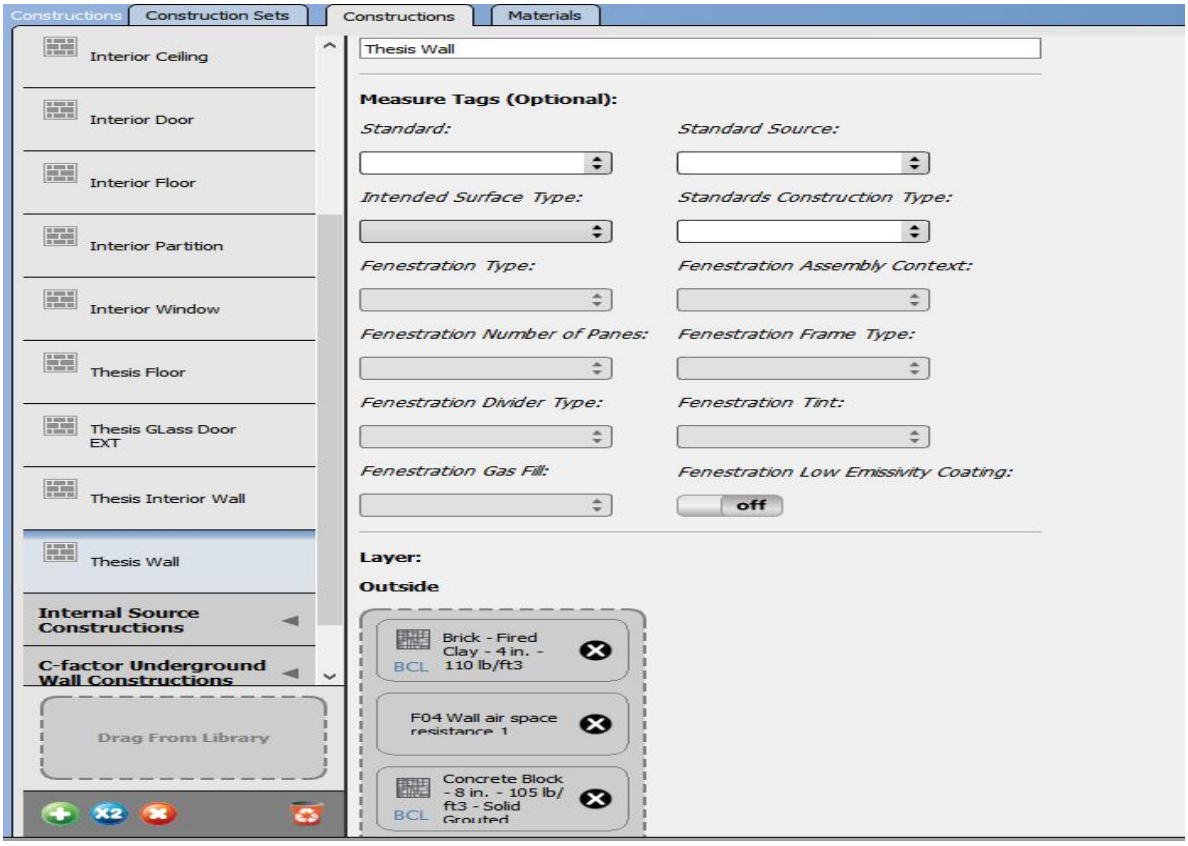

Figure 9. Building Construction Set in OpenStudio

The next step involves setting the interior temperature set points in the OpenStudio interface. This was done under the schedule tab; the cooling set point of 74 degrees F was used during summer periods when the OA temperature was above the heat cool change-over set point of 55 degrees. Similarly, the heating set point was used when the outside air temperature was below the heating set point of 72 degrees. Running the simulation is the final step after carefully building the construction set, linking the right thermal properties to the materials, and setting the indoor temperature. The EnergyPlus modeling engine performed the building simulation in about 3-5 minutes. Detailed results on the building energy usage and the energy transfer through the building envelope were generated.

CHAPTER 4

STUDY RESULTS

Overview

This section covers the output analysis of the study. The first section is aimed at meeting the first objective of the study and contains various tables that compare the output data generated from each modeling tool. There is also a chart that shows the timeline and duration of activities in building the model, and a comparison table showing the amount of time it took each modeling tool to generate output when subjected to the same modification. All the factors stated were used to determine the most effective tool for this project. The latter part of this chapter was channeled to meet the second objective. It consists of a flow chart to help modelers identify the right modelling category to select modeling tools based on a project's requirement. It also includes a table that pairs required modeling output to its respective modeling classes and tools.

Presentation of The Output Data From Each Modeling Category

This section of the output analysis presents the output data generated by each of the modeling tools. Table 7-10 presents the estimated amount of heat transfer through the building envelope elements. The quality of the information provided by each tool will be examined and compared to the result generated by the Black-box tool. The result from the Black-box tool is used as a baseline for comparison because it was the least complex of the formulas used, and calculation methods were transparent.

Table 7

Black-box Tool Modeling Output Generated

Envelope Elements	Bin Size	Heating Loads (MMBTU)	Cooling Loads (MMBTU)
Walls	5 Degree	846.58	377.32
Windows	5 Degree	142.70	63.60
Doors	5 Degree	315.61	140.66
Roof	5 Degree	22.74	10.13
Total Annual Load		1,327.63	591.71
Total Loads (MMBTU)		1,919.35	

MMBTU= 1 million BTU

Table 8

Gray-box Tool Modeling Output Generated

Thermal Zone / Envelope Elements	Walls (MMBTU)	Windows (MMBTU)	Doors (MMBTU)	Roof (MMBTU)
Zone 1	45.19	116.84	0.88	-
Zone 2	101.71	128.73	5.03	-
Zone 3	132.07	161.49	1.88	1229.49
Total Annual Load	278.97	407.07	7.80	1229.49
Total Loads (MMBTU)			1,923.33	

Table 9

White-Box Tool Modeling Output Generated

Thermal Zone / Envelope Elements	Opaque Surface Conduction and Heat Removal (MMBTU)	Window Heat Addition (MMBTU)	Window Heat Addition (MMBTU)
Zone 1	483.93	250.93	61.12
Zone 2	555.63	144.09	34.94
Zone 3	248.94	67.03	11.19
Total Annual Load	1288.50	462.05	107.25
Total Loads (MMBTU)		1,857.80	

Table 10

Comparison Between the Results of the Three Modeling Tools using Black-box as the Baseline

Modeling Tools	Black-Box Tool	Gray-Box Tool	White-Box Tool
Estimated amount of heat transfer through building envelope	1919.35	1923.33	1857.80
Percentage Difference		-0.21%	3.21%

The overall heat transfer through a building envelope is a function of the temperature difference between the inside and outside temperatures, surface area, and the overall heat transfer coefficient of the various materials and assemblies that make up the envelope. Since the output generated were within a few percent of each other, the strategy chosen for developing a selection method was validated. To determine the most suitable modeling tool to use will be based on the characteristics of the output required and the time it takes to execute the steps needed to develop and run the model.

It is important for modelers to understand the requirements, capabilities and the limitations of modeling tools to select the right tool for a project. To achieve the objective of this study, the better modeling tool is the one that achieves the output required and minimizes the time and effort expended on the modeling exercise. Each tool applied in this study is associated with one of the three modeling categories: Black-box, Gray-box or White-box. This was done to develop and evaluate the process necessary for choosing a modeling tool for a project scope. The output generated by each modeling tool came out to be relatively close to each other, thereby validating that all the tools used in this study are capable of generating the output required based on the scope of the study. The table showed that the output generated were within the few percentages of the baseline. Since all the three tools can equally be used to generate the required output, several factors will be considered to select the most effective tool among the three tools used.

Comparison of the Steps Involved and Amount of Time Spent In Building Each Model

The input and amount of time spent on constructing each model differs between the tools evaluated. Each of the modeling tools used in this study are presented with different levels of sophistication. The level of detail in the input requirements, computations and the graphics/tables in the output of each tool differ. To estimate the heat transfer through the building envelope elements, it is important to go through the steps involved in the process and compare different tools or categories of modeling. That way, a professional would be able to select the right tool to effectively generate the required output at a minimal time. Table 11 shows the steps involved in the model development for the three modeling categories utilized in this study.

Table 11

Processes Involved in Model Development used in this Study

Processes involved in modeling	**Black-box tool**	**Gray-box tool**	**White-box tool**
Study blue print to identify the building elements composition	Applies	Applies	Applies
Evaluate building orientation data	Does not Apply	Applies	Applies
Create construction set from materials in the component library	Does not Apply	Applies	Applies
Looked up, converted and validated R-values into U-values	Manual	Within the software	Within the software
Download and format weather data	Manual	Within the software	Within the software
Populate weather file into degree bins	Manual	Does not Apply	Does not Apply
Organize input variables for computation	Manual	Within the software	Within the software
Generate 3D rendering to assign R-values, space type and thermal zone to the building geometry	Does not Apply	Applies	Applies
Run Model Simulation	Applies	Applies	Applies

Does Not Apply – this is not needed in these tools

Manual – Data entered into the tool by the modeler

Within the software – The tool performs the step

While it is useful to be familiar with each process that applies to building the models, it is also beneficial to know the amount of time expended on each task during the process. The time spent on this project for each modeling category can be classified into two, namely:

(1) Time spent learning the modeling tools, their input requirements, equations and output possibilities

(2) Time spent on each task during the modeling development phase.

Significant amounts of time and effort were expended on learning to use the software tools required to build each model used in this study. To create a building energy model, one

should understand and have a basic knowledge of using Microsoft Excel spreadsheet, 3-D CAD software (e.g. AutoCAD, SketchUp, and Revit), energy modeling Software (e.g. OpenStudio, eQuest, EnergyPlus).

Due to my foundational knowledge in using these tools, it took an average of five days for me to properly learn how to set up a model using the Microsoft Excel spreadsheet, fourteen days to learn how to generate a 3-D rendering, set location and associate thermal properties to the elements on Revit and a total of thirty days to learn drawing on SketchUp and assigning thermal properties, weather and building construction sets through the OpenStudio interface. For future projects, the time expended on the software will not be as significant an issue when estimating the duration of the project but will still be required to meet the changing requirements of the projects. Therefore, most of time spent on the basic understanding of the software tools is just a one-time investment which helps modelers to become more comfortable with the modeling tool.

While building each model, the time spent can be subdivided into two phases: time spent on data collection and interpretation and the time spent on creating the model / the model tool. Data collection activities includes the following tasks listed below.

Data collection and Interpretation

a. gathering building plans and specifications
b. understanding the building plan,
c. investigating the building sections,
d. evaluating trend data if available
e. collecting R and U-values,
f. computing surface area for building envelope elements.

Other activities are classified under the Creating The Model tool or Creating The Model phase. Figure 10 presents the timeline and duration of activities involved using the Black-box tool for creating the model tool in this study.

Task Name	Duration	Start	Finish	Predecessor
Data Collection & Interpretation	**5 days**	**Tue 5/1/18**	**Mon 5/7/18**	
Building plans and specifications	2 days	Tue 5/1/18	Wed 5/2/18	
Understanding the building plan	3 days	Thu 5/3/18	Mon 5/7/18	2
Investigating the building sections	1 day	Thu 5/3/18	Thu 5/3/18	2
Collecting R and U values	1 day	Fri 5/4/18	Fri 5/4/18	4
Compute surface area	1 day	Fri 5/4/18	Fri 5/4/18	4
Create model tool	**7 days**	**Thu 5/3/18**	**Fri 5/11/18**	
Import weather file into	1 day	Thu 5/3/18	Thu 5/3/18	2
Format weather fi	1 day	Fri 5/4/18	Fri 5/4/18	8
Populate weather data into degree	1 day	Mon 5/7/18	Mon 5/7/18	9
Tally hour of occurrence of dbTemp	1 day	Tue 5/8/18	Tue 5/8/18	10
Organize input variables for computation	2 days	Wed 5/9/18	Thu 5/10/18	11
Compute thermal loads	1 day	Fri 5/11/18	Fri 5/11/18	12

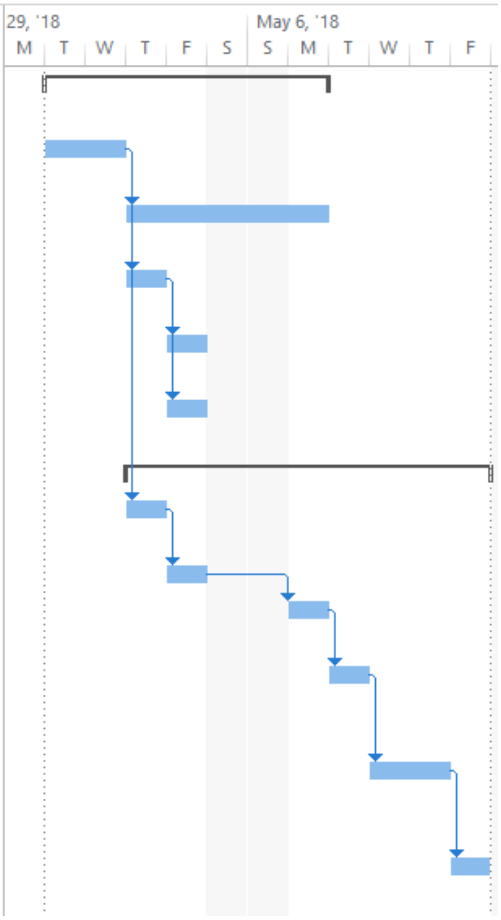

Figure 10. Timeline and Duration of Activities Involved using the Black-box Tool for Modeling

It took a total of nine days (excluding the weekend) to complete all the tasks listed in Figure 10. The Gantt chart on the right shows the relationship between the tasks. Some of the activities started concurrently while others took place consecutively.

Correspondingly, Figure 11 below shows the timeline and duration of activities in developing a model using a Gray-box modeling tool. The second phase of the activities comprises of creating the model on the software, and not creating the model tool which applies

in the Black-box modeling category. Below is the list of all the tasks involved using the Gray-box tool for this study.

Task Name	Duration	Start	Finish	Predecessors
Data Collection & Interpretation	**3 days**	**Tue 5/1/18**	**Thu 5/3/18**	
Understanding the building plan	2 days	Tue 5/1/18	Wed 5/2/18	
Investigating the building sections and thermal properties	1 day	Thu 5/3/18	Thu 5/3/18	2
Create model in software	**9 days**	**Fri 5/4/18**	**Wed 5/16/18**	
Generate 3D rendering of the building geometry in Revit	3 days	Fri 5/4/18	Tue 5/8/18	3
Create construction set from materials in the componenet library	3 days	Wed 5/9/18	Fri 5/11/18	5
Assign thermal properties (R-values, Space type and thermal zones) to building geometry	3 days	Wed 5/9/18	Fri 5/11/18	5
Specify building location	1 day	Mon 5/14/18	Mon 5/14/18	7
Organize input variables for computation	2 days	Tue 5/15/18	Wed 5/16/18	8

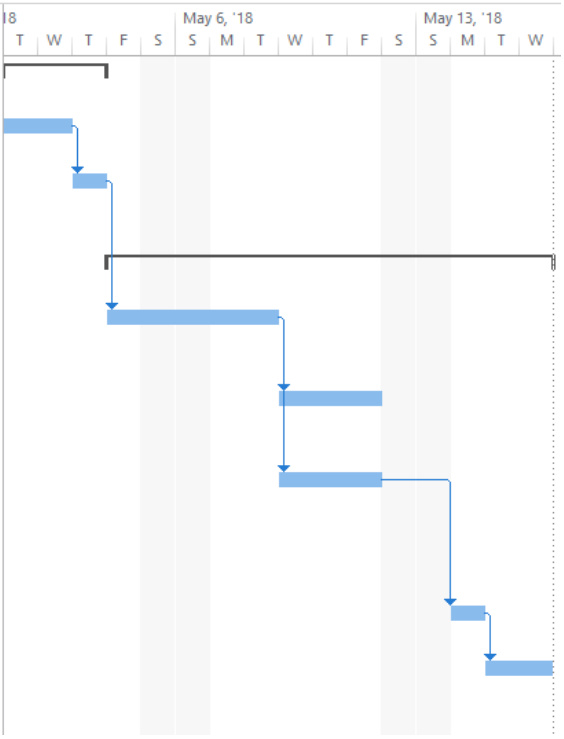

Figure 11. Timeline and Duration of Activities Involved using a Gray-box tool for Modeling

The model was completed in twelve days (excluding the weekend). Some activities were done subsequently, while some were concurrently. Lastly, Figure 12 below presents the timeline of activities, duration and the Gantt chart showing the relationship between the tasks involved in using a White-box tool for modeling in this study.

Task Name	Duration	Start	Finish
Data Collection & Interpretation	**3 days**	**Tue 5/1/18**	**Thu 5/3/18**
Understanding the building plan	2 days	Tue 5/1/18	Wed 5/2/18
Investigating the building sections and thermal properties	1 day	Thu 5/3/18	Thu 5/3/18
Create model in software	**12 days**	**Fri 5/4/18**	**Mon 5/21/18**
Generate 3D rendering of the building geometry in SketchUp	5 days	Fri 5/4/18	Thu 5/10/18
Import weather file	1 day	Fri 5/11/18	Fri 5/11/18
Create construction set from materials in the componenet library	3 days	Fri 5/11/18	Tue 5/15/18
Set schedule for annual interior temperature	1 day	Mon 5/14/18	Mon 5/14/18
Assign thermal properties (R-values, Space type and thermal zones) to building geometry	3 days	Wed 5/16/18	Fri 5/18/18
Run model simulation	1 day	Mon 5/21/18	Mon 5/21/18

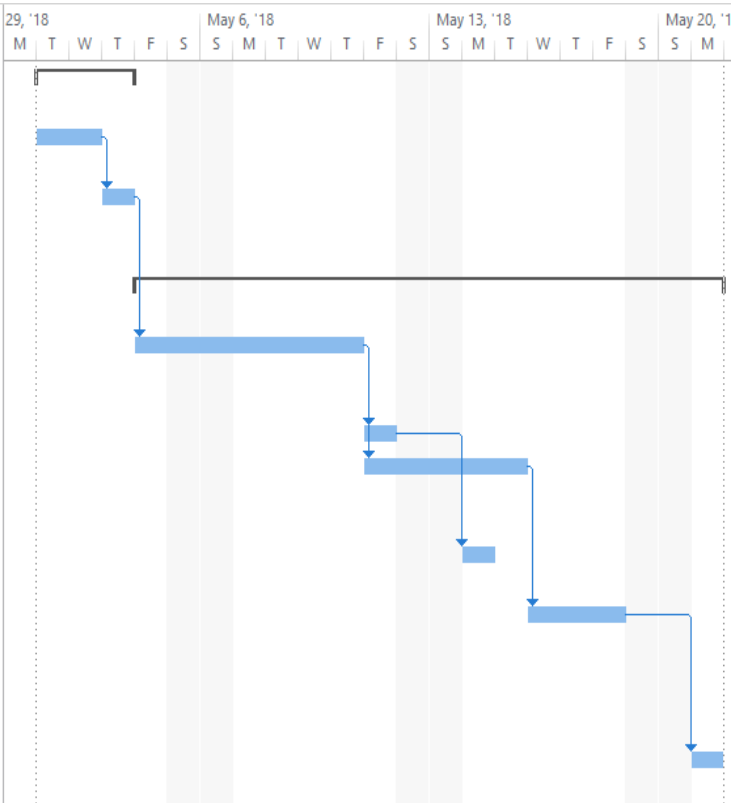

Figure 12. Timeline and Duration of Activities Involved in using a White-box Tool for Modeling

The model was developed in fifteen days (excluding the weekend). Due to the complexity, level of detail and methods required to enter the input parameters of the White-box tool, this model took the most time to develop.

Overall, when comparing the time spent in developing the model using each tool, the Black-box tool came out as the most effective tool. By nature, the Black-box tool is less complex in terms of the calculation involved. The model was developed in 9 days using the Black-box tool, 12 days using the Gray-box tool and 15 days using the White-box tool.

Modifying and Running the Model

Based on the model category, the time it takes to modify and run the model are different. To identify the most efficient modelling tool for this study, the models were subjected to the

same set of modifications, and the rate at which each model tool generates output were observed and compared. The same modification applies to each of the three models, and the time it takes the model to process and generate outputs were resulted and compared.

The most efficient modelling tool is the model that can generate the required output in a very short time compared to other models. Modifications will include changes in thermal resistance and surface area of building element, changes in heating and cooling set points, changes in the building geographical location etc. Table 12 presents the comparison between the speed rates of output generated for each modeling category.

Table 12

The Rate of Output Generation in Each Modeling Category

Model Modifications	Black-Box	Gray-Box	White-Box
Thermal resistance of building elements	Less than a minute	3-5 minutes	7-10 minutes
Cooling and heating set points	Less than a minute	3-5 minutes	3-5 minutes
Size of outside air temperature bins	Less than a minute	NA	NA
Changes in surface area of elements	10-15 minutes	60-90 minutes	60-90 minutes
Changes in building geographical location	NA	10-15 minutes	10-15 minutes

The information presented in Table 12 shows the total time to locate where changes need to be made, time to make the changes needed, and time to generate and interpret the required output. Changing the surface area of elements takes long time in the Gray and White-box category because the 3D rendering of the building must be re-drawn, whereas, in the Black-box category, it's only involves reading the plan to find the new area and changing the number on the

spreadsheet. Outputs were quickly generated on modifications made on the Black-box category compared to the other two modeling categories. The information reported from the table proves that the Black-box modeling category requires the least amount of time for model modification. Since the Black-box model category can generate the required output and needs the least amount of time to model and modify the model, the Black-box tool used in this study is the most efficient tool to use for this study's project requirement.

Process For Selecting the Right Modeling Tool Developed According to the Observation made from this Study

According to the observations made during this study, some recommendations were made based on the abilities and limitations of the tools that fit in each of the three modeling categories. Several measures were used to evaluate and compare the tools in the three modeling categories, such as:

1. data requirements
2. the ability to compute dynamic variables,
3. the sophistication of calculation involved,
4. the simulation computational time,
5. the number of different tools needed to develop the model
6. the level of detail in output generated,
7. time needed for the modeler to interpret output generated.

Table 13 presents comparative data of some of the features associated with the three different modeling tools utilized in this study to represent the different categories. The three models were built for the same purpose. However, the process, complexity and calculation involved in building model varies considerably. For example, the Black-box tool can only

compute static variables, whereas, the White-box possesses the ability to compute changing variables during simulation and can generate more detail output than the Black-box tool

Table 13

General Comparative Analysis Between the Three Modeling Categories

Measures	**Black-box tool**	**Gray-box tool**	**White-box- tool**
Data Requirements to develop the model	Weather file Architectural drawings ASHRAE handbooks Construction data	Weather file Building orientation Set of building drawings Building geometry data Construction data	Weather file Building orientation Set of building drawings Construction data Building geometry data
Need to compute dynamic variable (temperature change during simulation)	No; Only Static Variables	Yes, Engine is capable of handling changing input variables	Yes, Engine is capable of handling changing input variables
Sophistication level in calculation	Required non- complex linear equation	Required complex simultaneous equations embedded in simulation engine	Required complex simultaneous equations embedded in simulation engine
Simulation computational time	Required the least amount of computational time	Required less computational time compared to the White-box	Required the most amount of time for simulation to complete
Software tools required to build the model	Microsoft Excel	Autodesk Revit & eQuest engine	SketchUp, OpenStudio &EnergyPlus engine
Level of detail available in the Output	Basic Table	Tables graphics charts and graphs	Tables, graphics charts and graphs
3D Rendering of the building geometry	Not required to estimate heat transfer	Requires 3D rendering required to input properties and surfaces	Requires 3D rendering required to input properties and surfaces
Time to interpret output generated	Does not require	Requires significant amount of time to interpret outputs	Requires significant amount of time to interpret outputs

All the characteristics listed in table 16 have some impact on choosing the category of the tool that should be used to model a project, but the most important driver is the output requirements of the project. If there are minimal requirements for the output–for example, only sizing information or quick analysis for upgrading a subsystem are needed--a Black-box tool will likely be more efficient to develop and use than a White- or Gray-box tool. Conversely, if hourly data analyses are needed to determine the interactions between systems, a White-box tool is required. Gray-box tools have more detailed output data than a Black-box tool but are used for quickly evaluating design and concept modifications.

The desired outputs of performing building energy modeling differs from one project to another. One project might require estimating the annual energy consumption in the building, whereas, the other might require the use of an energy model to determine the heating and cooling equipment size in a room. Projects are classified into each modeling category based on the required output. The level of output required for a project should be the determining factor for selecting the proper software tool and modeling approach. A software tool that is designed to perform basic energy modeling might not be equally appropriate for performing a detailed building energy modeling. Therefore, it is important for modeling practitioners to consider the reason for performing energy modeling before choosing the tools and techniques that will be used. Another key factor in selecting the right tools and techniques for modeling depends on the amount of input variables required to effectively generate the output needed. If the output needed for a project can be computed by a relatively small amount of input variables, this project can conveniently fit into a Black-box model category. Table 14 presents which category of model some energy modeling projects fits in considering the outputs required.

Table 14

Pairing different Modeling Outputs to its Respective Model Category and Software Tools

Output data Required	Black-Box Tools	Gray-Box Tools	White-Box Tools	Software Tools
Daily energy consumption of a multi-zone building	Not Suitable	Possible depending on the detail required	Best Choice	EnergyPlus eQuest DesignBuilder
Tables, graphs and daylight renderings outputs of result	Not Suitable	Possible depending on the detail required	Best Choice	EnergyPlus eQuest DesignBuilder
Impact of changing building orientation on energy usage	Capable but not the most suitable	Capable but not the most suitable	Best Choice	EnergyPlus eQuest GBS TRANSOL
Building design transformation	Not Suitable	Best Choice	Capable but not the most suitable	EnergyPlus eQuest Revit
Estimating the heating and cooling loads in a single zone building	Best Choice	Capable but not the most suitable	Capable but not the most suitable due to the amount of time	Excel Spreadsheet EnergyPlus eQuest
Estimating heating and cooling loads in a multi-zone building	Not Suitable	Possible depending on the detail required	Best Choice	EnergyPlus eQuest DesignBuilder
Evaluate heat transfer through building envelope	Best Choice	Possible depending on the detail required	Capable but not the most suitable due to the time expended	Excel Spreadsheet EnergyPlus EQuest BSim
Evaluate the impact of the building occupants on building energy performance	Not Suitable	Capable but not the most suitable	Best Choice	EnergyPlus eQuest DesignBuilder TREAT
Evaluating the energy impact on replacing sets of lightbulbs in a single zone building to LED lights.	Best Choice	Capable but not the most suitable due to the amount of time expended	Capable but not the most suitable due to the amount of time expended	Excel Spreadsheet EnergyPlus eQuest Hot2000

The information presented in table 14 will help a modeler to choose the right modeling tool for a project based on the required output. In cases, where a Black-box tool comes out as the best choice over the White-box tool, the reason is mainly because the project can be done effectively, and outputs can be generated faster using a Black-box tool over a White-box tool. A Gray-box tool can apply to most of the projects described in the table, however, they might not

be the most suitable tool to use due to the minimal level of detail presented in the output and the purpose of the tool. Gray-box tools are generally used for evaluation of design considerations.

Applying these classifications, a modeler will be able to quickly identify the technique and tools that best fit the project in terms of the efficient use of time and other important measures. Black-box and White-box techniques may both be suitable to handle a project that requires evaluating the heating and cooling loads in a space, however, the modeler should implore the most efficient technique considering the amount of the time and effort spent on the processes, the software tools needed and cost and licensing of the tools. To determine the heating and cooling loads in a room, the Black-box modeling approach does not require a 3D rendering of the building, whereas, the White-box approach does require the 3D rendering of the building geometry, which requires an outside 3D rendering tool and a significant amount of time and skills to develop. The Black-box model can utilize Microsoft excel spreadsheet to easily determine the loads, whereas the White-box model would use the combination of SketchUp, OpenStudio and EnergyPlus engine to complete the same assignment

The flowchart and tables presented in this section guide modelers to identify the right modeling category to select the appropriate tools needed for modeling projects based on the projects requirement. Based on the observation and knowledge acquired during this study, several project requirements are classified under their suitable modeling category. Figure 13 below presents a guide for selecting proper modeling category based on a project requirement.

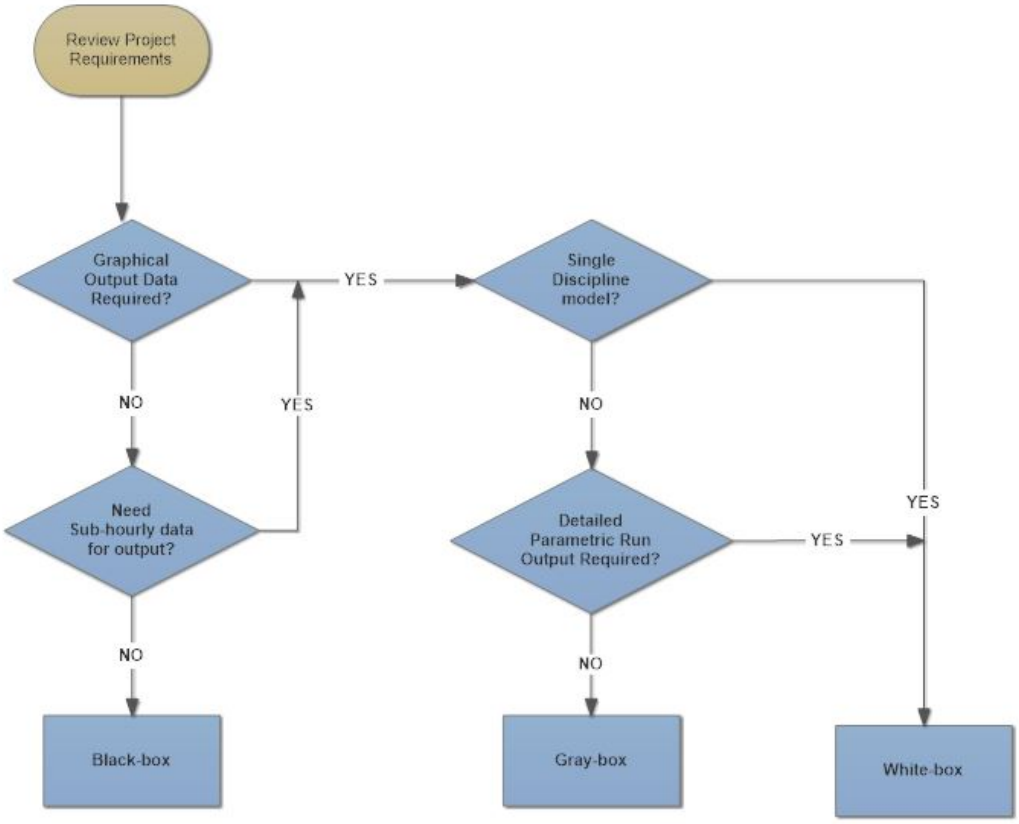

Figure 13. A Guide to Identify the Proper Modeling Category Based on a Project Requirement

The flow chart can be used for any modeling process based on the project requirements. For instance, a project that involves designing a football stadium will demand a multi-discipline team. By looking at the flow chart, a multi-discipline project should select its modeling tool from the Gray-box modeling category. Additionally, White-box tools are most suitable for projects that require detailed parametric runs, and Black-box tools are suitable for projects that do not require graphical output data.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Conclusion

The process of building energy modeling utilizes software tools to perform load design and analysis of buildings and systems. BEM offers a significant benefit for designers in developing new energy-efficient buildings and improving the energy performance of existing buildings. This study listed several common BEM tools and then categorized them into three groups according to their capabilities. These three categories or "boxes" were labeled Black-box, Gray-box, and White-box. With respect to their sophistication and capabilities, Black-box tools are generally categorized on the simpler side of the modeling tool spectrum. White-box tools are typically the most detailed and complex tools and are placed on the complex side of the modeling tool spectrum. The capabilities of Gray-box tools fall between the two extremes.

The scope of this study was designed in a manner that permitted a modeling tool from each of the three categories to be evaluated. Through analysis of using each of the tools to develop the necessary output of the project, I determined that the best approach for selecting the software tool category is a function of the desired output characteristics and the composition of the project team. Therefore, by evaluating the answers to a few project-related questions a modeler can select the most efficient tool for a project. The first question is: Can the tool selected from the Black-box category produce the required output needed by the project team? If the answer is no, a tool must be selected from the Grey-box or White-box categories. The second question is: Does the project team consist of more than one discipline? If the answer is yes, a Gray-box tool is more efficient for the project. If the answer is no, a White- box tool will

generate an output more closely aligned with the discipline of the project team. The most effective tool is the one that generates the necessary output based on the characteristics of the project team.

For this study, all of the tools used were able to generate the required output data but in slightly different formats. Each tool was expected to estimate the heat transfer through the elements of the Wilson Wallis building located on the ETSU campus. Since a Black-box tool could be used to produce the necessary required output based on my project scope, then using a Gray-box or White-box tool would not be necessary. In this study, the Black-box tool can be considered the most efficient tool for the project because of the simplicity of development and use along with the speed involved in using the tool for parametric runs.

A process represented with a flowchart was developed to assist modelers in identifying the recommended category when selecting a modeling tool based on any project's output requirements and team composition.

Recommendations

This study developed a process that can be used by modelers to simplify the selection of an efficient software tool from the ever-growing list of tools available from professional organizations, researcher, universities, software vendors, and manufacturers. An efficient tool is selected based on the category it belongs to and the project requirements. The flow chart can be used to direct a modeler to the right modeling category from which a tool may be selected. It is left up to the modeler to choose the best tool within that category. A proposed future study could focus on developing a method of choosing the most effective tools within each of the modeling

categories presented in this study. Criteria to evaluate may include pricing options, licensing, tools availability, training, and learning curve.

REFERENCES

Amara, F., Agbossou, K., Cardenas, A., Dube, Y., & Kelouwani, S. (2015). Comparison and Simulation of Building of Thermal Models for Effective Energy Management. *Smart Grid and Renewable Energy*, 95-112.

ASHRAE. (2016). ANSI/ASHRAE/IES Standard 90.1-2016. User's Manual. "Energy Standard for Buildings Except Low-Rise Residential Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, Georgia.

BEMBook. (2012, September 13). *International Building Performance Simulation Association.* Retrieved from BEMBook: http://bembook.ibpsa.us/index.php/History_of_Building_Energy_Modeling

Building Envelope. (2018, April 24). Retrieved from Autodesk Knowledge Network: https://knowledge.autodesk.com/support/revit-products/getting-started/caas/simplecontent/content/building-envelope.html

Butts, D. (2016). *Powering BIM-Capitalizing on Revit for Building Energy Modeling*. Retrieved from Autodesk University: http://au.autodesk.com/au-online/classes-on-demand/class-catalog/2016/revit/mep19638#chapter=0

Crawley, D., Lawrie, L., Pederson Curtis, & Winkelmann, F. (1999). Energyplus, A New Generation Building Energy Simulation Program. *Building Simulation, 1*, pp. 81-88.

Door Reference Guide. (n.d.). Retrieved from Owen Henry windows and doors: http://www.owenhenrywindows.com/door-reference-guide/

Evans, J. (2000). Spreadsheets as a Tool for Teaching Simulation. *INFORMS Transactions on Education*, 27-37.

Fischer, M., Bazjanac, V., & Maile, T. (2007, December). *Building Energy Performance Simulation Tools-a Life Cycle and Interoperable Perspective.* Retrieved from Center for Integrated Facility Engineering: https://stacks.stanford.edu/file/druid:ww813hh4225/WP107.pdf

Holladay, M. (2012, March 30). *Energy Model Isn't very Accurate.* Retrieved from GreenBuilding Advisor: http://www.greenbuildingadvisor.com/blogs/dept/musings/energy-modeling-isn-t-very-accurate

Hong, T., Buhl, F., & Haves, P. (2008, July 16). *EnergyPlus Analysis Capabilities for Use in California Building Energy Efficiency Standards developement and Complaince Calculations.* Retrieved from Ernest Orlando Lawrence Berkerley National Laboratory: https://www.osti.gov/servlets/purl/944980

How Much Can Replacement Windows Save on my Energy Costs? (2013, February 20). Retrieved from Southwest Exterior:

https://www.southwestexteriors.com/blog/p.130220000/how-much-can-replacement-windows-save-on-my-energy-costs/

How much energy are you losing through your old windows? (2018, Febuary 15). Retrieved from LAS: https://lashome.com/how-much-energy-are-you-losing-through-your-old-windows/

Jimbo. (2016, January 7). *Where am I losing heat in my home?* Retrieved from the Greenage: https://www.thegreenage.co.uk/where-am-i-losing-heat-home/

Keep the Heat in: How to Reduce Heat Loss in Your Home. (2017, June 20). Retrieved from Warmup: https://www.warmup.com/blog/keeping-the-heat-in-how-to-stop-heat-loss-in-your-home

Mansory Detailing Series. (n.d.). Retrieved from International Mansory Institute: http://imiweb.org/masonry-detailing-series/

Natural Affordable Small Houses That Used Wooden Materials As The Dominated Color Of The Exterior And Interior House Design With Simple Design Inside Natural House Design Inside. (n.d.). Retrieved from Fandung: http://www.fandung.com/affordable-small-houses/natural-affordable-small-houses-that-used-wooden-materials-as-the-dominated-color-of-the-exterior-and-interior-house-design-with-simple-design-inside-natural-house-design-inside/

Pecherska, J., & Merkuryev, Y. (2005). Teaching simulation with spreadsheets. *19th European Conference on Modelling and Simulation.*

Rallapalli, H. S. (2010). *A Comparison of EnergyPlus and eQUEST Whole Building Energy Simulation results for a Medium Sized Office Building.* Tempe: Arizona State University.

Sadineni, S. B., Madala, S., & Boehm, R. F. (2011). Passive building energy savings: A review of building envelope components. *Elsevier Ltd*.

Seila, A. (2006). Spreadsheet Simulation. *Engineering Management Review, IEEE*.

Smith, M. (2016, March 27). *The Energy Modeling Breakdown.* Retrieved from Verdical Group: http://verdicalgroup.com/the-energy-modeling-breakdown/

Star, E. (2018). *Energy efficiency*. Retrieved from energystar: https://www.energystar.gov/

The Language of a Roof: Understanding the most important element of your home! (2016, February 20). Retrieved from A leak Proof Roof!: http://aleakproofroof.blogspot.com/2016/02/the-language-of-roof-understanding-most.html

Tittelein, P., Wurtz, E., & Achard, G. (2009). Use of response factor method to model earth-to-air heat exchanger behaviour. Integration in a whole building simulation into simspark plat form. *Eleventh International IBPSA Conference.* Glasglow, Scotland.

USDOE. (2015, September). *Quadrennial Technology Review: An Assessment Of Energy Technologies And Research Opportunities.* Retrieved from https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter5.pdf

VITA

SODIQ AKANDE

Education:	National Diploma, Federal Polytechnic, Ede, Osun State, Nigeria, 2011
	B.S. Construction Engineering Technology, East Tennessee State University, Johnson City, Tennessee, 2016
	M.S. Engineering Technology, East Tennessee State University, Johnson City, Tennessee, 2018
Professional Experience	Information Technology Specialist, Sherrod Library. East Tennessee State University, Johnson City, Tennessee, 2012-2016.
	Graduate Research Assistant, East Tennessee State University, College of Business and Technology, 2016-2018
Publications:	Sodiq Akande., Mohammad Moin Uddin., Keith Johnson., Oduwa Omigie.(2017) “Sustainability Learning and Energy Conservation: A Capstone Design Project” American Society of Engineering Education.
Honors and Awards:	Department of Engineering, Engineering Technology, and Surveying. East Tennessee State University. The Graduate Program Outstanding Student Award2017-2018.