

ABSTRACT

Title: **TRADE-OFF BASED DESIGN AND
IMPLEMENTATION OF ENERGY
EFFICIENCY RETROFITS IN
RESIDENTIAL HOMES**

David Daily, Master of Science, 2013

Thesis directed by: Professor John Baras
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Energy efficient buildings are becoming more necessary to meet government standards, reduce operating costs, and curb emissions. However, designing efficient buildings is significantly complicated as designers must account for hundreds of design parameters across multiple domains. Simulation-based, design space exploration allows for designers to model a building's performance for multiple designs. These simulations can be computationally expensive and time consuming. This thesis explores trade-off analysis in building design space exploration through the use of multi-objective optimization software that seeks to quickly produce optimal designs. Three different techniques are developed producing optimal design configurations for each technique.

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TRADE-OFF BASED DESIGN AND IMPLEMENTATION OF
ENERGY EFFICIENCY RETROFITS IN RESIDENTIAL HOMES

by

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University of Maryland, College Park in partial fulfillment
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Chapter 1

Overview

1.1 Introduction

According to the U.S. Energy Information Administration (EIA), residential and commercial buildings account for nearly 40% of total U.S. energy consumption [1]. Regulations and minimum energy codes, such as the International Energy Conservation Code, help curb energy usage in new construction by setting minimum levels of certain energy saving capabilities like insulation and infiltration. However, significantly more energy savings can be achieved from existing buildings rather than through new construction. When a retrofit is done on an existing house in order to improve energy efficiency, it is called an Energy Conservation Measure (ECM). Examples include adding the interior insulation of an exterior wall or replacing Heating, Ventilation, and Air Conditioning (HVAC) units. ECM's are estimated to be able to reduce more than 30% of a building's current energy load [18]. However, the exact savings vary depending on the building. A recent project by Newport Partners, as part of the Building America Partnership for Improved Residential Construction research team, achieved 50% energy improvement on a multi-family residential facility through the use of insulation upgrade and HVAC upgrade ECMs. [18].

Energy auditing is a business that is rising in prominence from the increased

demand for energy conservation. Energy auditors inspect homes and recommend a series of ECMs that the homeowner can install to save energy. ECMs are commonly justified by their payback period, which is the time it takes for savings from the utility bill to equal the cost of the initial ECM. Property owners expect a certain degree of confidence in the amount of energy savings and operational costs of the proposed ECM. Energy auditors use a variety of tools to estimate the energy usage of a home. Whole-Building Energy Modeling (WBEM), such as EnergyPlus [22], allow for simulation of a building in a real world environment, taking into account a variety of physical iterations within a building and its surroundings. While WBEM can give reasonable estimates of the performance and expected life cycle cost (LCC) of an ECM, the processes of analyzing the possible ECMs can be time-consuming and challenging.

1.2 Problem Statement

Buildings are an inherently complex system that have multiple interactions across multiple domains. Modeling buildings is incredibly challenging due to many interconnected components in a building that form a complicated and dynamic network of interactions. Each of these components can have different mathematical functions that are evaluated at different scales, which makes evaluating the system, as a whole, incredibly challenging [8].

To overcome these challenges, significant advancements will have to be made in how complex systems are modeled so they can be constructed and analyzed

more quickly and accurately while still preserving all the complexities inherent in a building model [13]. The Department of Energy is aggressively pursuing and funding research in simulation of complex systems, and advancements have been made in the past 10 - 15 years. However, many of the advancements are still only available in a very specialized and academic setting, and have yet to be presented to the public in an efficient and understandable format for industry-wide impact [6]. The current standard programs for energy modeling are EnergyPlus and DOE2. Many programs extend the functionality of these tools. Some of the more recent advancements include OpenStudio, Simergy and MLE+ [10, 17, 20]. OpenStudio and Simergy ease the geometry and building model creation aspects of EnergyPlus. MLE+ allows for co-simulation between EnergyPlus and MATLAB for HVAC controls.

There are 3 main contributions from this thesis. First, BeOpt is used for bi-objective optimization of retrofit design options and attempts to create a workflow model that extends the current level of detail available for analysis with EnergyPlus. Second, multi-objective optimization is formulated for use with an optimization program, Consol Optcad to demonstrate a more encompassing model of trade-off analysis that can be achieved in building design space exploration (DSE). This process illustrates functionality that is currently lacking in WBEM. Third, JEPlus+EA is used to to perform multi-objective optimization along with trade-off analysis to show the best available option for detailed energy model DSE optimization. This work is done in collaboration with the National Institute of Standards and Technology (NIST) and utilizes the building models of their previous work with the Net-Zero Energy Residential Test Facility (NZERTF).

1.3 Objective and Assumptions

The objective of this thesis is to investigate currently supported programs that optimize the design space exploration of ECMs in residential homes. A workflow is developed for BEopt [21] and EnergyPlus with the intent of reducing model complexity for the DSE and optimization trade-off. Process results are examined for validity, then expanded to include an expanded set of optimization objectives. A more robust version of multi-objective optimization is performed to showcase concepts for the next-generation of building DSE tools. The current best implementation of a building DSE optimization tool, jEPlus+EA, is used and discussed in an example use case.

The use case for this scenario is that of a homeowner who currently has a home that meets Maryland minimum energy code compliance (2012 IECC [4]). The homeowner wishes to perform ECMs to achieve Net-Zero or Net-Positive status. Net-Zero describes a facility that creates *as much* energy as it uses in one year. Net-Positive describes a facility that creates *more* energy than it uses in one year. BEopt performs an optimization of LCC and energy savings. This thesis seeks to increase the detail at which results can be analyzed and change the analysis from bi-objective optimization to multi-objective optimization. jEPlus supports multi-objective optimization. Details of BEopt's and jEPlus's operation are discussed in Section 3.1 and 3.3 respectively.

The building is the NZERTF and uses the work in [16] for the 2012 IECC base model. The model is set in Gaithersburg, MD and uses actual meteorological year

weather data from March 2012 to February 2013, along with energy tariff data from the local utility, PEPCO.

Chapter 2

Background

2.1 Net-Zero

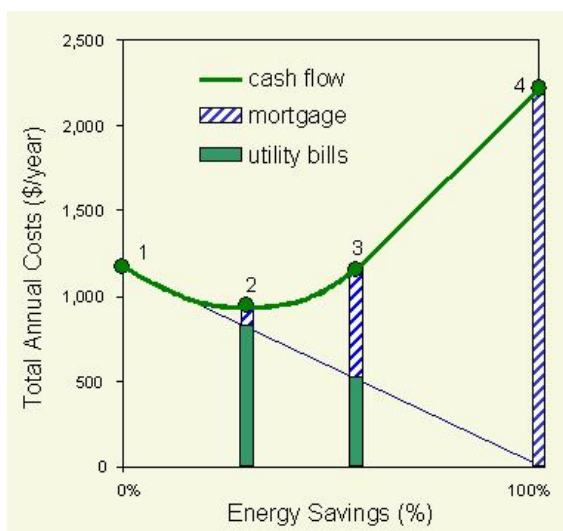


Figure 2.1: BEopt Path to NZE [21]

NIST has been working on defining what is a Net-Zero Energy (NZE) building and constructing a framework for the advancement of building to NZE. Results show that the path to NZE is a multi-step process utilizing a mix of active and passive changes [7, 9, 19]. Moreover, the order of these changes are important. The first energy reductions should be made with ECMs that change the building properties and behaviors. Once ECMs have minimized the building's energy usage, the remainder is matched through renewable energies such as photovoltaics (PV). By following this order, a smaller PV array is necessary to achieve NZE. This is desirable since

upfront costs for PV can be prohibitively expensive. Figure 2.1 illustrates the LCC considerations one needs to consider when attempting to achieve NZE as proposed by BEopt. Detailed analysis of this figure is important since it justifies the necessity of achieving optimal energy saving through the use of ECMs *before* PV is installed. Lessons learned from this analysis yield designs with higher energy efficiency for lower cost. It shows the costs associated with reducing a reference building (point 1) to NZE (point 4) as a function of Energy Savings. While many configurations of building parameters will lead to different LCC vs Energy Savings, only the optimal configurations will lie on the cash flow line. More inefficient configurations will be above the cash flow line indicating that they achieve the same amount of energy savings for more annual cost. In order to illustrate the two main costs (upfront and operational), the Annual Utility Bill (operational) is plotted in black. As the operational costs approach zero, more of the Total Annual Cost becomes upfront cost. Eventually, at NZE, all costs are upfront costs. Point 2 is the optimal point for minimum annual costs. Point 3 is the maximum Cost-Effective Energy Savings possible without PV.

ECMs can be done in both new construction and retrofit situations. All ECMs increase energy savings thus decreasing annual utility costs. Between points 1 and 2, ECMs are highly effective. The money saved in annual utility costs outweighs the money spent for upfront costs for the ECM. These ECMs are highly justifiable since they are easily explained from an economic standpoint.

Between points 2 and 3, ECMs are less effective, yet still worthwhile. An ECM will cost more in upfront costs than the amount saved in utilities. This is effective

until point 3, at which, any ECM will have a increase in annual cost that is greater than the price of electricity for the amount of energy saved. In essence, past point 3, it is more effective to generate the electricity on site rather than try to achieve the Energy Savings through ECMs. Between points 3 and 4 is achieved with PV. Since PV produces energy, it saves energy by reducing the amount of energy required from the grid. The amount of energy created is proportional to the size of the array, so between points 3 and 4 is linear with the slope being the dollars per kWh of PV.

The rise in popularity of PVs, and decrease in price, has made PVs a quick and simple option to reducing home energy bills. However, this is not the optimal use of PV. PV should only be used after all other ECMs have been performed. Otherwise, the cost of achieving NZE is unreasonable and inflated.

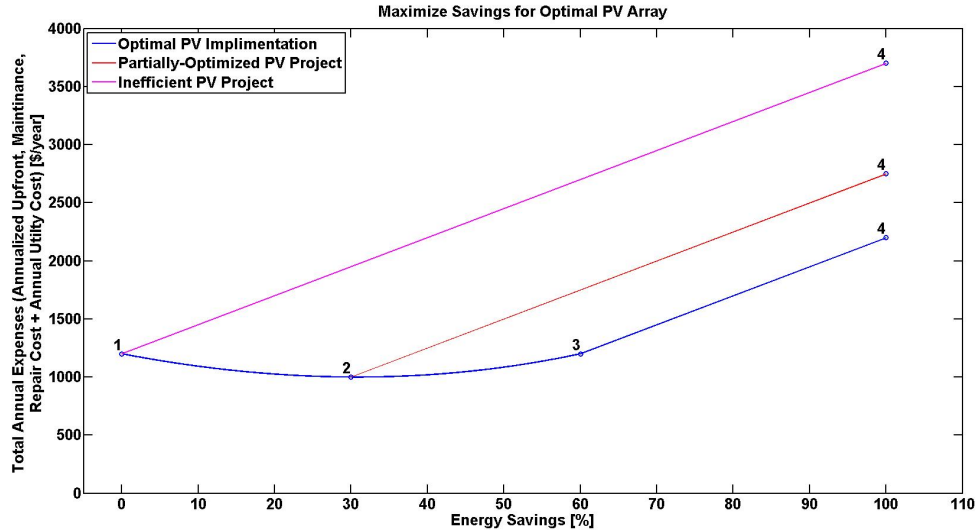


Figure 2.2: Illustrates the overall increase of total cost caused by installing a PV system before energy savings through ECMs are maximized by plotting PV installed at different points on the path to NZE

Figure 2.2 demonstrates the negative aspects of installing PV too early in the

energy conservation process. Annual costs can be exorbitant if PV is relied upon solely for energy savings. Not maximizing energy savings through ECMs first will also result in a higher annual cost for NZE.

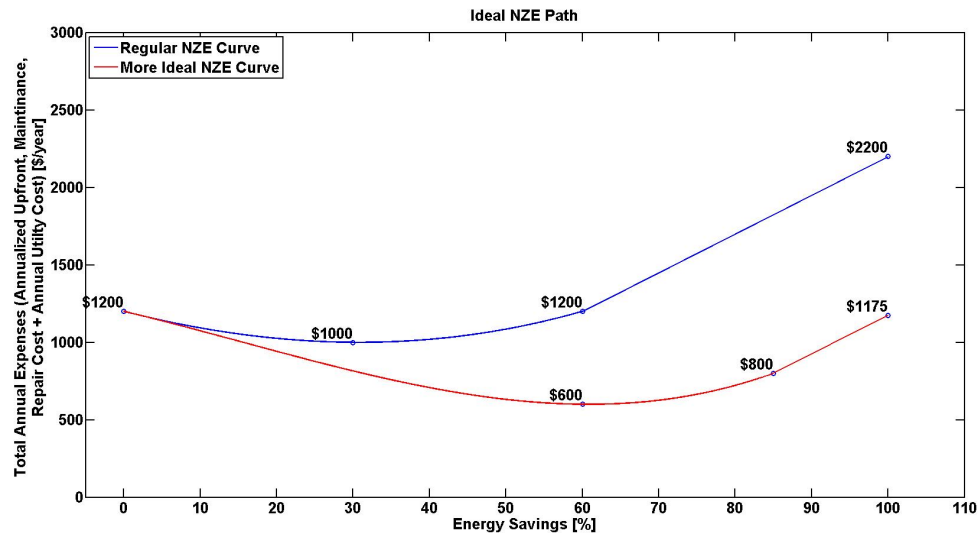


Figure 2.3: Example demonstrating the impact of optimized DSE of ECM. If the proper ECMs are chosen to maximize cost per energy saved, then smaller PV arrays are necessary and at an overall higher annualized cost

In any situation, it is important to evaluate the potential savings of the current configuration. The most effective way of evaluating this is with the use of energy modeling software such as EnergyPlus. However, if optimization is not included in the DSE and coupled with the energy modeling software, then the design may not be ideal. Figure 2.3 shows the path of configurations that has not been optimized. While savings are achieved through the use of ECMs, better combinations of ECMs exist that could save more. As previously stated, a necessary advancement in the design and analysis of energy efficient buildings are tools that perform a DSE and provide optimal designs with a high degree of certainty. BEopt is one program that

provides this functionality. It's drawbacks, discussed more in Section 3.1, are that it lacks detailed results and multi-objective optimization. However, it is very useful as a first attempt at trade-off for energy efficient building design.

For this thesis, the energy model developed by NIST of the NZERTF is used as the basis of design. NIST developed the NZERTF to determine the feasibility of building and operating an average American home to NZE. Details of the construction are found in [15, 16]. Along with defining building parameters, the report confirms some of the properties and challenges of NZE buildings covered in this chapter. Details of components within the model that are studied in this work are presented in section 4.1. The programs used in this thesis to model the NZERTF are discussed in Chapter 3 and the models are discussed in Chapter 4.

Chapter 3

Modeling Tools

3.1 BEopt

BEopt is a building design optimization tool designed to help users find the most cost efficient building design in terms of energy savings. BEopt strengths are its ability to quickly calculate the cost and energy savings of a given building design and easily visualize results for the user.

During the course of design, there are many choices that have to be made, the desired energy demand of the building, meeting local, state, and federal regulations, and the overall cost of the building. These decision points lead to a cascading effect of more design questions such as material choice, construction method, orientation, and design. The scope and answers to these questions vary widely depending on the type of construction. A retrofit project will have different constraints compared to a new construction project. BEopt has the ability to simulate new construction and retrofit projects, and quickly supply optimal designs that take into account the design decisions above. BEopt does not actually perform the simulation, but rather, creates custom input files for EnergyPlus and controls the scheduling of simulations to run.

A weakness of BEopt is that it is not a highly detailed model. Its component

selection is limited and its configuration ability for building geometry and orientation is limited. While BEopt uses EnergyPlus (or DOE2) as a simulation engine, it does not utilize the full modeling capabilities of these engines. It sacrifices accuracy for speed; however, its ability to perform multiple simulations quickly through an intuitive GUI, select optimal building parameter configurations, and visualize results easily, makes BEopt a powerful tool.

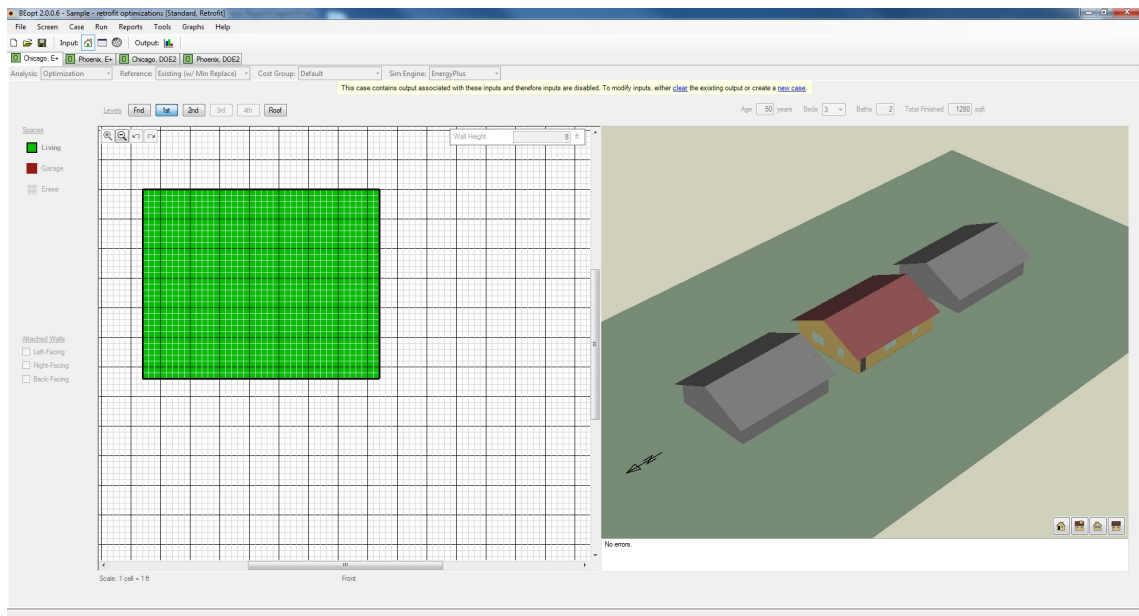


Figure 3.1: Example of BEopt’s geometry creation page [21]

An important mode in BEopt is the “Optimization” mode. For the ease of retrofits, this allows for the user to define a base case that is the current configuration of an existing home. The user can then select a series of available retrofit options to simulate to find the best combinations of ECMs. Options are pulled from the National Residential Efficiency Measure Database (NREMD), a component cost database of common energy efficiency upgrades for commercial and residential buildings. NREMD is operated and maintained by the Department of Energy. This

connection with the nationally recognized and maintained database gives BEopt high-quality data input.

While the component and cost data are reliable, the implementation in the model is not always. While the geometry of the walls can be unique, the wall properties are universally applied. Different wall areas can not be selected to have different properties. This is an instance of the simplified model weakness. Once the range of parametric values are selected, BEopt runs a series of simulations.

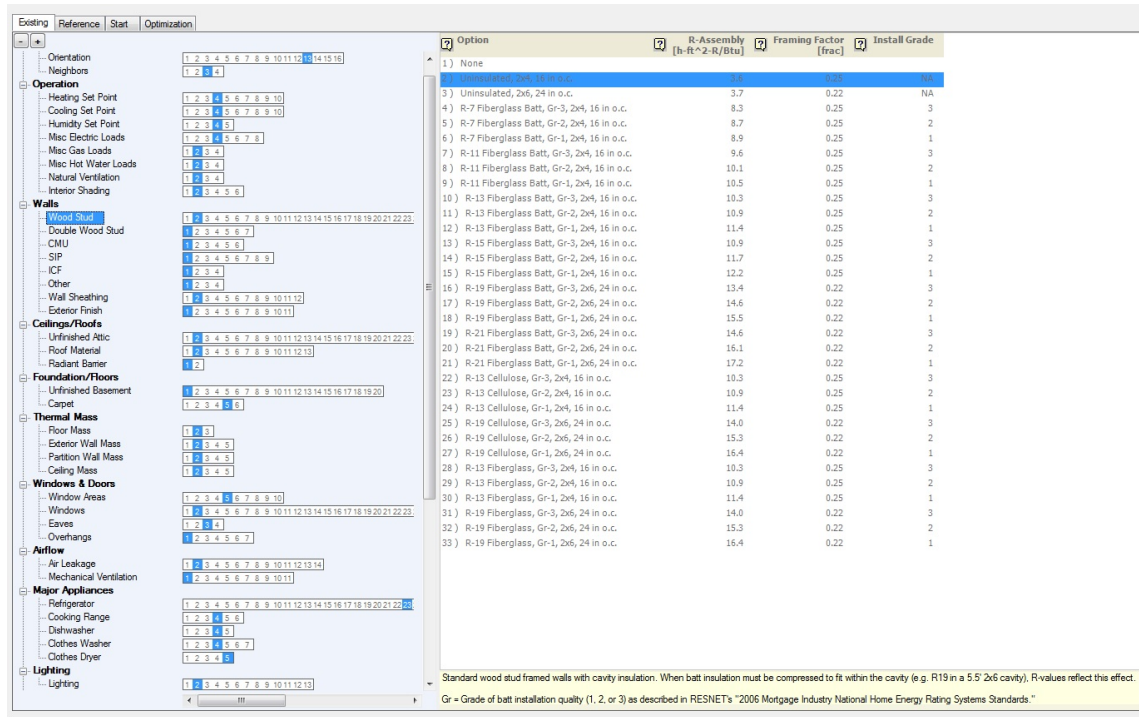


Figure 3.2: Example of BEopt’s component selection page for optimization [21]

One of BEopt’s strengths is its ability to optimize the simulation process. The problem with trying to use simulation for finding the best combination of parameters is the large number of computationally-costly simulations that must be run. As discussed, buildings contain tens or hundreds of these variables depending on the desired level of detail. BEopt has a sequential search algorithm which simulates a

few of the combinations by varying a single component and measures the annual cost and energy savings for the simulations. It then chooses the simulation with the best combination of annualized cost and energy savings and moves to that design configuration. From there, it chooses the next component and repeats the process. This helps reduce the state space size and tests only the most influential components, thus avoiding the configurations that are inferior, reducing the overall simulation time. Figure 3.3 (a) shows the simulation progression as the program finds optimal design configurations to NZE. Figure 3.3 (b)-(d) are special cases that BEopt occasionally checks to make sure more optimal configurations were not missed.

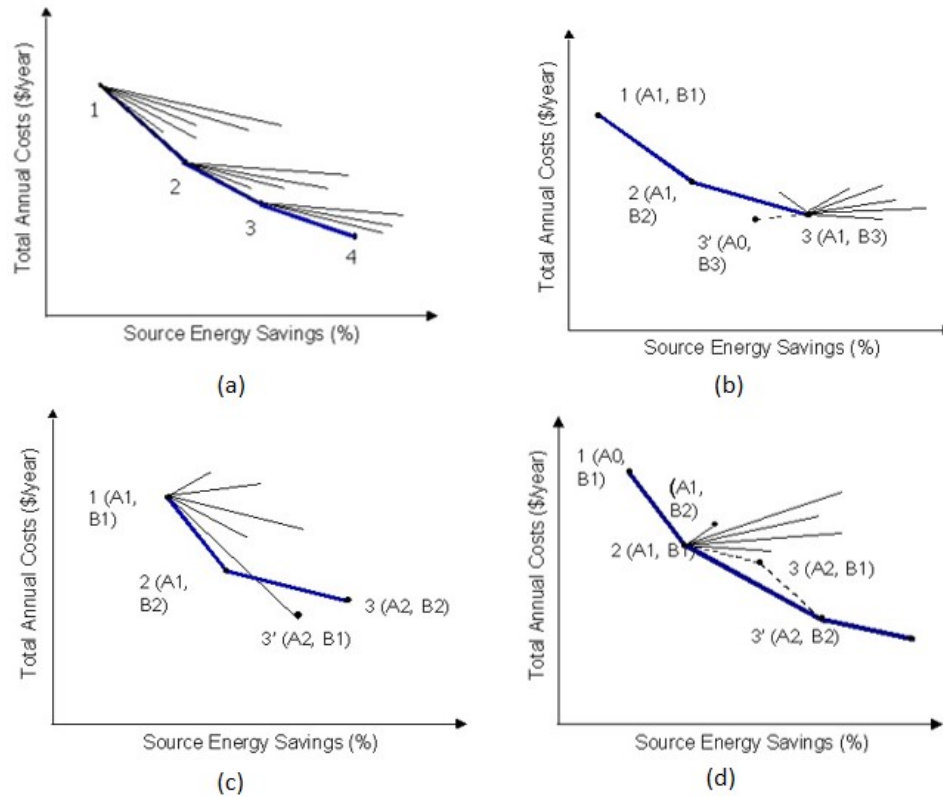


Figure 3.3: (a) A graph of the progression of simulations from a BEopt optimization run. Special Cases: (b) BEopt checks to see if a previously disregarded component yields a more optimal solution when combined with newer component option. (c) larger step sizes are checked for optima compared to the normally traversed path. (d) synergistic interactions between components have a net positive effect on building performance. [21]

Finally, BEopt provides easy results visualization. A user can interact with the data by clicking on the optimal points to view their configuration and cost vs energy data. More detailed reports can be generated upon request.

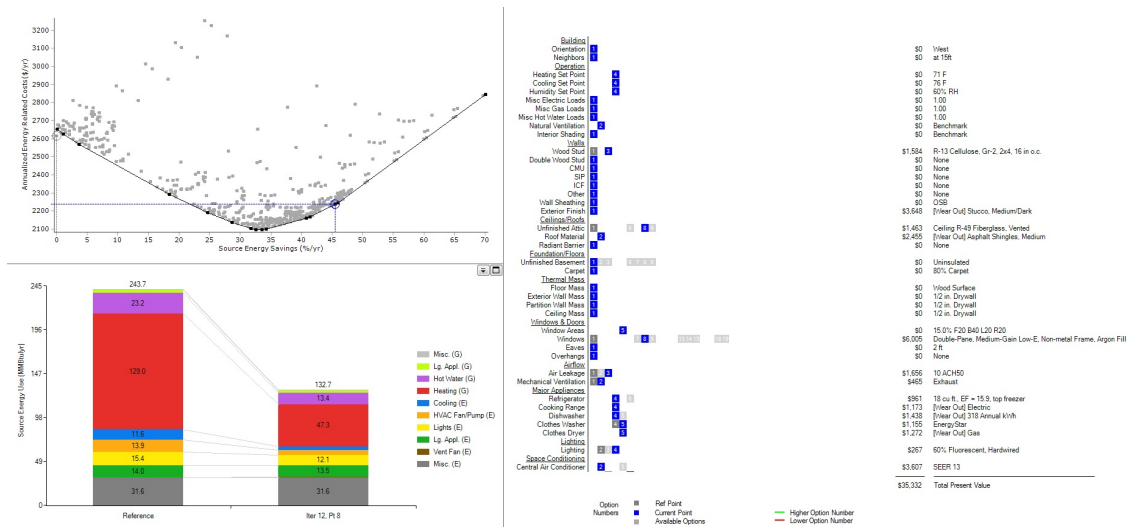


Figure 3.4: Results visualization and interaction in BEopt. The top left graph is the plot of Energy Savings versus Annualized Cost. Grey points are simulations performed while the black points are the optimal design configurations. The bottom left plot compares the reference energy profile to to the energy profile of the selected design from the top left graph. Meanwhile, the right side shows the design configuration of the selected point. [21]

In Figure 3.4, The top left is the interactive display of all tested configurations, with each dot representing a single configuration. Optimal designs are highlighted along the curve. The bottom left shows the current design energy profile compared to the selected optimized-design energy profile. The right shows the details of the selected optimization design.

3.2 EnergyPlus

EnergyPlus is a whole building simulation program developed by the Department of Energy. EnergyPlus can model heating, cooling, ventilation, and airflow of zones and HVAC plants, along with other energy flows for lighting, photovoltaics, water and more. EnergyPlus is highly adaptable and customizable allowing the

designer to develop a model that reflects the real configuration of the building, as much as possible. Detailed schedules of component operation and human occupancy can be included.

For Windows OS, EnergyPlus has a few features that make it particularly useful for detailed model development and analysis. The IDFEditor acts as a GUI for quickly finding and adjusting building properties. Since the EnergyPlus input file is a text file, this GUI makes it easier to navigate the model.

A parametric preprocessor allows for multiple simulations to be run over a list of values for unique variables programmed into the model by the user. The parametric preprocessor generates multiple input files for each configuration, then automates the simulations until all files have been run. This significantly reduces the labor required since a long list of parametric values can be simulated at once.

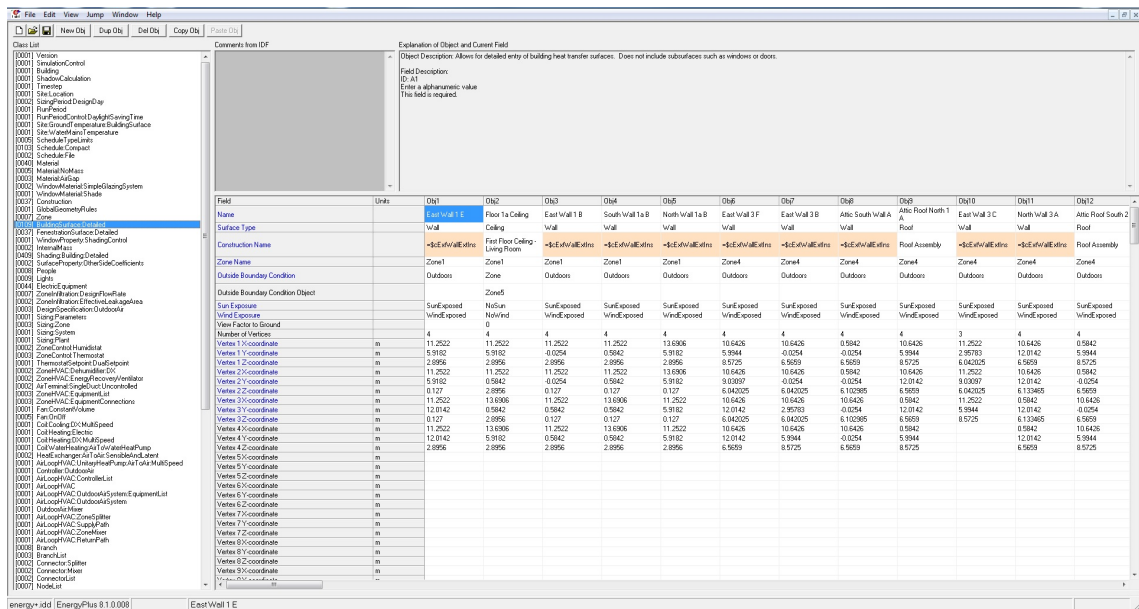


Figure 3.5: Snapshot of the IDFEditor for EnergyPlus. This particular shot is the editor for geometries where coordinate points of the corners are input to create the geometry of the walls

While the IDFEditor is good for changing values of system, it is not very good at building the geometries of the building since it has no visual geometry editor. Programs such as SketchUp + OpenStudio and Simergy have developed even more advanced GUIs for EnergyPlus that address this geometry problem. They also add extra functionality for creating models and visualizing results, however, these details are beyond the scope of this project.

For a given simulation, EnergyPlus requires an input file and a weather file. After auto sizing various component values and “warming up” the model by simulating a few days to generate realistic initial values, the program simulates for the specified run period. EnergyPlus can simulate a single day to multiple years in timesteps of 1 minute to 60 minutes. The smaller the timestep, the more accurate the result, but more computationally expensive. Highly detailed models have realistic constructions, but these models take drastically longer to simulate.

EnergyPlus has a vast array of reporting capabilities. Each component has a set of available outputs often consisting of electricity used, heat transferred, heat lost, parasitic losses, temperature, setpoints, and more. These reports are at the component level and can report the values at timestep, hourly, weekly, monthly, or annual intervals. The Input/Output Documentation [23] gives a detailed list of every reporting possibility for each component. EnergyPlus includes other reporting means such as meters, where multiple component outputs are combined into one output variable, and reports a concise tabular format of common metrics such as utility bill reports or ASHRAE compliance reports.

An interesting development is that EnergyPlus might soon be rewritten in

Modelica [11]. This will make it significantly easier to extend the optimization functionality of simulation and design. Model has a buildings library of common building component equations that are used to describe room, heat transfer, air flow, and other common models. This, coupled with simulation optimizer like GenOpt [26], can bring the optimization necessary for trade-off based DSE.

3.3 jEPlus

jEPlus is a java-based parametric programming tool that uses EnergyPlus as its simulation engine. jEPlus simplifies the parametric analysis part of EnergyPlus by creating a GUI for the parametric components. Keys are written into the energy model similarly to the native EnergyPlus parametric preprocessor, but jEPlus has a much simpler interface and the ability to handle much larger studies [29]. Subsection 4.5.1.1 shows how it is necessary to copy and paste generated code into the input files and then run them. jEPlus manages the code generation and simulation managing through the entire process.

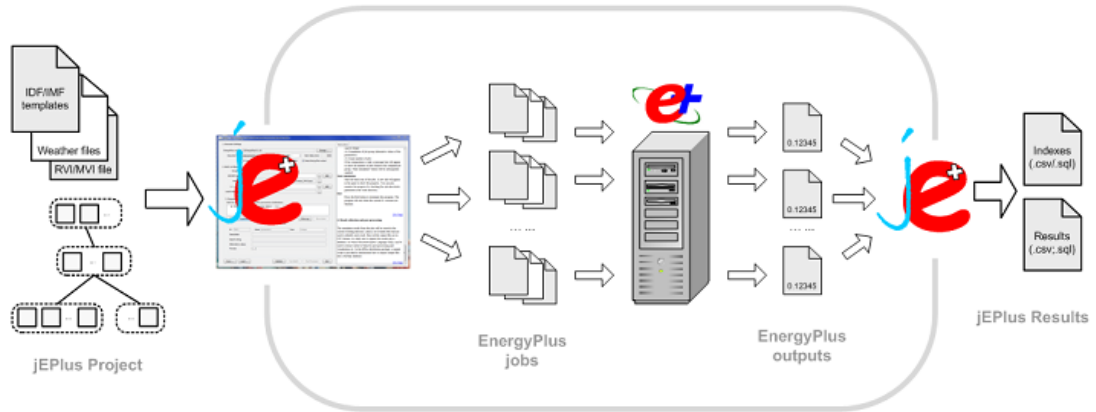


Figure 3.6: Workflow Diagram illustrating how jEPlus handles parametric processing with EnergyPlus. The user first defines the parameter options in the jEPlus GUI. Then jEPlus uses this information to create multiple EnergyPlus input files and simulate all the file. It automatically handles the simulation process and gathers the results into a concise format for the user in the jEPlus interface. [29]

They have also created a client called JESS (jEPlus Simulation Server) which is a free service that gives designers access to a cluster designed specifically to run EnergyPlus [28]. Input files are sent to the server and the high performance computers quickly run multiple simulations. Depending on the complexity of the model, JESS can complete approximately 20,000 simulations in one day [12]. These tools greatly increase the productivity of energy modeling parametric analysis.

Chapter 4

Part 1: BEopt and EnergyPlus Method

4.1 2012 IECC to NZERTF

The use case for this project is of a homeowner who wishes to implement ECMs to reduce their annual utility bill while still maintaining a comfortable environment in their existing home. The existing home is built to Maryland minimum energy code (2012 IECC) and is built in Gaithersburg, MD. The building model is based off the NZERTF and work done in [16] where the NZERTF building parameters were adjusted to satisfy 2012 IECC minimums. Table 4.1 shows the changes.

[16] quantifies the response of the model to the NZERTF set of parameters versus the 2012 IECC set, with results as each ECM is implemented. However, this does not capture the entire set of design configurations that exist between the two sets of parameters. This setup does not give a homeowner much information on what configuration would best meet their needs, nor is it optimized. Since the components synergistically affect each other to varying degrees depending on their value, it is important to observe the different combination's results. This process is a DSE. As mentioned before, the problem with doing a DSE with buildings is that it is cumbersome to try to reduce the complexity of all physical interactions of components into a succinct, mathematical model-based DSE. Therefore, simulation-based

System	Design Variable	Unit	2012 IECC Model	NZERTF
Exterior Wall	Interior Insulation	R Value	21	20
Exterior Wall	Exterior Insulation	R Value	0	24
Basement	Interior Insulation	R Value	0	12
Roof	Exterior Insulation	R Value	4	30
Window	Windows	U Factor/SHGC	.35/.35	.2/.25
Air Leakage	Infiltration Rate	ACH	3	.61
Lighting	High-Efficiency Lighting	% High Efficiency Lamps	75%	100%
Heating/Cooling	Heat Pump	SEER/HSPF	13/7.7	15.8/9.05
Ventilation	Mechanical Ventilator	Type	Min. Outdoor Air	HRV
DHW	Water Heater Tank	Type	Electric	Heat Pump
DHW	Solar Thermal	# of Collectors	0	2
Solar PV	Array Capacity	kW	0	10.2

Table 4.1: Table of Design Variable changes from the 2012 IECC to NZERTF energy models [16]

DSE is necessary which can be computationally expensive and time consuming.

Solving for every combination of Table 4.1 yields 4096 different simulations. As discussed in Section 3.2, the Windows build of EnergyPlus allows for parallel simulations up to to the number of threads on the machine. Even on a fast computer (Intel i7 2.2 GHz Quad Core with Hyper-Threading) running 8 simulations in parallel, a single simulation takes approximately 12 minutes to complete. Simulation time is dependent on multiple parameters including the detail of the model and especially the timestep. This model is reduced to four timesteps per hour, which is considered a coarse measurement, and it still takes 12 minutes on this setup. One machine would take over four days to complete the DSE.

Table 4.1’s parameters are only of minimum efficiency and extremely high efficiency measure. This is not representative of the range of options that are available on the market, of which, others might suit the homeowner’s needs more. A more

Design Variable	Parameter Values				
Exterior Wall Interior Insulation	19	21			
Exterior Wall Exterior Insulation	0	6	12	18	24
Basement Wall Interior Insulation	0	6	12		
Roof Exterior Insulation	6	12	18	24	30
Windows	.35/.35	.26/.65	.17/.25		
Infiltration Rate	3	2	1	.5	
High-Efficiency Lighting	75%	85%	95%	100%	
Heat Pump	13/7.7	14/8	15/8.5	16/9	
Mechanical Ventilator	Min. Outdoor Air	HRV	ERV		
Water Heater Tank	Electric	Heat Pump			
Solar Thermal	0	1	2		
Array Capacity	0	2.5	5.5	7.6	10.2

Table 4.2: Design Space for all NZERTF design variables given current technologies

informative DSE would have intermediate parameters; however, this would greatly increase the number of simulations required. Table 4.2 shows the original design space created that would give an accurate portrayal of realistic combinations given current technology. Such a DSE would require 2,592,000 simulations. Even on a cluster computer designed specifically for running EnergyPlus would take 129 days to complete [12]. This is an unfeasible method for DSE and is at the heart of the issue. Programs must be able to reduce the simulation load yet still provide accurate and meaningful results for the homeowner.

For simplicity, the design space is reduced by removing some of the variables and limiting the maximum number of parameter options to 3 in order to save time. Some variables are harder than others to parameterize. Those that are especially cumbersome are removed, so long as their expected impact on the overall system

is relatively negligible. This includes Lighting, Mechanical Ventilation, and Water Heater Tank. Figure 4.3 shows the final DSE configuration.

Design Variable	Parameter Values		
Exterior Wall Interior Insulation	19	21	
Exterior Wall Exterior Insulation	0	12	24
Basement Wall Interior Insulation	0	6	12
Roof Exterior Insulation	4	12	30
Windows	.35/.35	.3/.3	.2/.25
Infiltration Rate	3	2	.6
High-Efficiency Lighting	100%		
Heat Pump	15/9.05		
Mechanical Ventilator	HRV		
Water Heater Tank	Heat Pump		
Solar Thermal	0	1	2
Array Capacity	0	5.5	10.2

Table 4.3: Final Design Space configuration

Section 4.2 describes the process for performing and analyzing a Detailed DSE where all configurations are considered as well as the proposed reduced form utilizing BEopt. Finally, I attempt to verify that the proposed method yields results that are similar to the detailed method. I also take the optimal design configurations from BEopt, and test their optimality with the objective of user comfort.

4.2 Detailed DSE Workflow

In order to quickly, and accurately perform this DSE, a heavy amount of automation and code generation is written in MATLAB. The first step is to create

a file with the system-level and component-level values of the design space.

4.2.1 System-Level versus EnergyPlus Component-Level

Section 3.2 describes the parametric preprocessor function of EnergyPlus. System-level values are descriptions of the component on the level that is more abstract and of common industry terminology. The tables in Section 4.1 are system-level descriptions. In order to reflect this in EnergyPlus, system level components need to be translated to values that the parametric preprocessor can parse. Continuing with the example, exterior wall insulation values are modeled by setting the conductivity of the insulation material. EnergyPlus does not contain dependencies between system-level and component-level values so this mapping between system and component level values is not automatically understood by EnergyPlus and must be calculated by the programmer.

Not all component-level parameterizations can be mapped to a single EnergyPlus component value. The technology used sometimes require complete model changes. Exterior Insulation, for example, is normally increased by adding multiple layers of insulation on top of each other. In EnergyPlus, the most accurate way to do this is to create multiple “Construction” components; a container of material layers listed in order from exterior to interior. Each “Construction” component has a unique name and a unique layering of material with multiple layers of the insulation material depending on the desired R-Value. Then, in order to make use of the parametric preprocessor, the name of the “Construction” component is passed to

the “Building Geometry” components that represent the walls. Figure 3.5 in Section 3.2 shows the highlighted key that is placed in the geometry object’s construction name field. This key is replaced by the name of the “Construction” component where each name has a different number of exterior layers.

This process is different for every system. Creating a model that is parametric preprocessor compatible can require in-depth knowledge of the subject area, the inner workings of EnergyPlus, and creativity. Such a process makes it difficult for designers with limited detailed knowledge of the subject areas to produce accurate results.

4.2.2 Workflow

Once the State Space file has been created, a MATLAB script reads and generates all possible combinations of the variables. The EnergyPlus parametric preprocessor works by reading in a row of values and inserting the values into the model for each simulation. For the entire design space, it would be unreasonable to enter in each simulation combination individually. That is why the script generates the EnergyPlus code necessary to run the multiple simulations. This code is copied into the EnergyPlus text input file and simulated. The parametric preprocessor takes effect and all simulations are automatically run. On 11 computers, 13,133 simulations takes approximately 1.8 days.

EnergyPlus outputs two variables into a .csv file: “Facility Net Purchased Electric Energy” and “Facility Thermal Comfort ASHRAE 55 Simple Model Sum-

mer or Winter Clothes Not Comfortable Time.” The first output is a vector of the total amount of energy at every timestep. If the value is positive then energy is purchased from the utility; if negative, then it is sold as excess PV generation. The second variable is a binary vector at each timestep where 0 means comfortable conditions and 1 means uncomfortable conditions in the building. The comfort metric is defined in ASHRAE Standard 55. For this output variable, the model is simplified to a look-up table since the actual standard has many factors [2].

Another MATLAB script loops through all of the simulation’s output files and post-processes them into a set of single metrics for the trade-off analysis. The metrics are: annual utility cost, upfront cost, annualized cost, and user discomfort.

4.2.2.1 Annual Utility Cost

Determining the annual utility cost requires the amount of energy used at each timestep (Facility Net Purchased Electric Energy) and the price of energy at the timestep. The energy price is gathered from the PEPCO Time-Of-Use Residential Tariff Schedule [24]. In order to produce compatible results with BEopt, the 2008 Time-Of-Use Residential Tariff Schedule for the District of Columbia is used. This tariff schedule is in the BEopt database.

The annual utility cost is defined as

$$Cost_{Utility} = \begin{cases} \sum_{i=1}^n (E_i \cdot c_{n,i}) & E_t > 0 \\ E_t \cdot c_p & E_t \leq 0 \end{cases} \quad (4.1)$$

where

$$E_t = \sum_{i=1}^n E[i] \quad (4.2)$$

$$c_{n,i} = (c_{g,i} + c_{td,i}) + c_{f,i} \quad (4.3)$$

and $n = 35040$ because it is a year-long simulation with 4 timesteps per hour. E_i is the energy used at timestep i . Equation 4.3 represents the tariff and includes cost of generation (c_g), cost of transmission and distribution (c_{td}) and a fixed monthly cost. Each cost is broken up by timestep. However, when the overall energy use for the year is negative, indicating the customer created more energy than they used, then c_p is a fixed rate calculated by taking the average price of generation at all timesteps where the energy consumption was negative. This yields a return rate for energy at approximately 2/3 the value of consumption.

4.2.2.2 Upfront Costs

Upfront Costs are initial costs associated with performing the retrofit. This includes the cost of labor and materials for installation along with overhead and profit. Values for specific retrofits are gathered from the NREMD. Most design variable's upfront costs are in the NREMD; however, those that are not are taken from the BEopt library in order to have more comparable results. It is expected that the retrofit upfront costs should be similar between the two programs, however, because of the difference in model detail, we expect the energy savings and operational costs to differ slightly.

4.2.2.3 Annualized Costs

Annualized costs is a metric BEopt uses to compare the different configurations. It divides the upfront cost by the lifetime of the system and adds that to the Annual Utility Cost. This easily captures the LCC of the retrofit.

4.2.2.4 User Discomfort

The user discomfort metric is the total number of hours in a year that the zones of the home are considered uncomfortable based off ASHRAE Standard 55. User discomfort is calculated simply by summing the output variable “Facility Thermal Comfort ASHRAE 55 Simple Model Summer or Winter Clothes Not Comfortable Time.” The metric is user *discomfort* rather than comfort so the objective function is a minimization.

This metric is not something that is calculated by BEopt, nevertheless, this is an important metric since one of the goals of a building is to provide a comfortable environment for the occupants. If changes made to the system decrease its effectiveness at this goal yet decrease overall energy, then the retrofit is not necessarily an optimal configuration for the entire system.

The final step in the workflow is the trade-off of the metrics. MATLAB reads in the database of configurations along with their calculated metric values and plots them in objective space, then identifies the non-dominated solutions and returns their configurations [3]. Examples of this will be shown in the next chapter.

4.3 BEopt Model

BEopt is a design tool that allows for streamlined geometry creation and parameter design by simplifying some of the model detail and flexibility. This results in some creative workarounds to achieve a model relationship between the EnergyPlus model and the BEopt model that fits within BEopt's constraints.

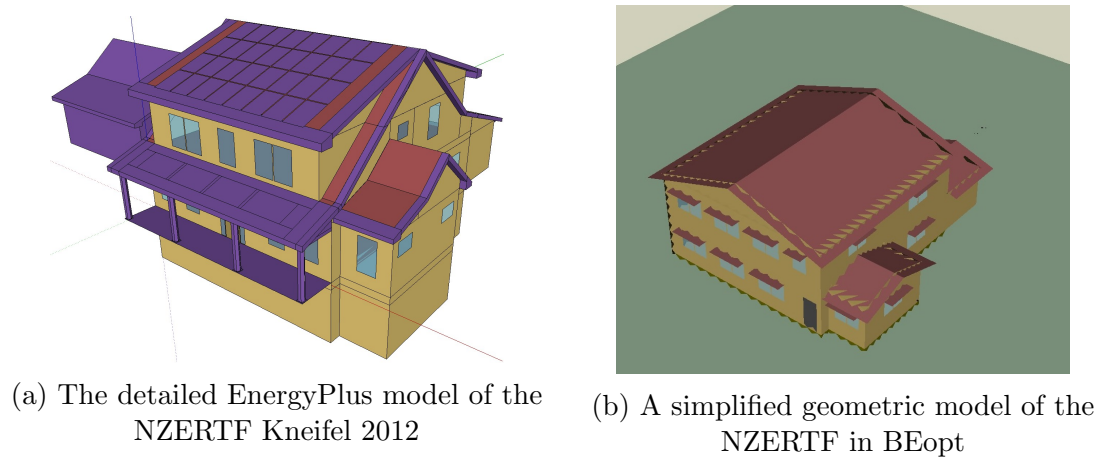


Figure 4.1: A comparison of Building Models between EnergyPlus and BEopt

Another difference is the construction of the building materials. EnergyPlus allows for a unique material sequence to be assigned to every surface. This means that in the basement, one wall can be fully insulated with interior and exterior insulation while another wall could have just interior insulation, as if it was a walk out basement with half of the basement under grade. However, in BEopt, all basement walls are the same construction.

BEopt also has a dependency feature which can be both useful and detrimental to the modeling process. BEopt has a list of building parameter values and types and is aware of the limits that each type of construction involves. For instance,

if a designer wanted to add more cellulose insulation they could do that relatively easily, and BEopt has a pricing scheme specifically for this situation. If the designer wanted to replace the insulation material to spray foam, this is a significantly more cumbersome retrofit since it is not merely adding more of the existing material. The relationship between these two configurations is captured in the retrofit cost, since it should be higher. Finally, BEopt also *prohibits* certain retrofits depending on the base configuration. If the designer wishes to add more exterior roof insulation, they would not be able to do this since BEopt considers this too drastic a retrofit. In practice, the entire roof would have to be removed to add more insulation. This retrofit becomes a new construction situation. BEopt is aware of these dependencies and relationships between components and retrofits. This is a powerful design feature, however, it is not always applicable especially with some ECMs that can be extremely drastic. In order to model some of the ECMs of the NZERTF, the BEopt model has some new construction parameters rather than all retrofits.

4.4 BEopt DSE Workflow

BEopt has the optimization feature which significantly reduces the amount of simulations run. It also runs simulations much more quickly partially due to its simplified model. However it is important for NZE homes that all interactions be considered, given that even parasitic internal heat gains can have drastic effects on heating and cooling to tight-envelope buildings. The proposed workflow utilizes BEopt's optimization mode to choose only the optimal configurations to simulate

in the detailed model where simulations are computationally expensive.

For this model, architectural drawings and the EnergyPlus model itself were used to generate the necessary information for the BEopt model. Once the geometry is created, the existing configuration programmed, and the parametric options selected, then the optimization mode can be selected and run. Once the simulations are complete, the optimal designs are identified. The values are then taken by the designer and translated into an EnergyPlus model. Results can be analyzed similar to section 4.2.2. Detailed simulations should be run and detailed reports generated for the optimal designs so the designer can validate the system response for the customer.

4.5 Results

4.5.1 Annualized Cost versus Energy Savings

Annualized Cost versus Energy Savings is the default trade-off option for BEopt. BEopt is limited in its options for trade-off, all of which revolve around this cost versus energy setup. The Y-axis can be changed to Modified Internal Rate of Return and other cost based metrics, while the X-axis can be changed to Source, Site Energy Savings, or Consumption. Savings are calculated based on the percent decrease in energy usage between the evaluated model and the existing conditions model. This should yield something similar to the characteristic curve shown in Figure 2.1.

4.5.1.1 Detailed DSE

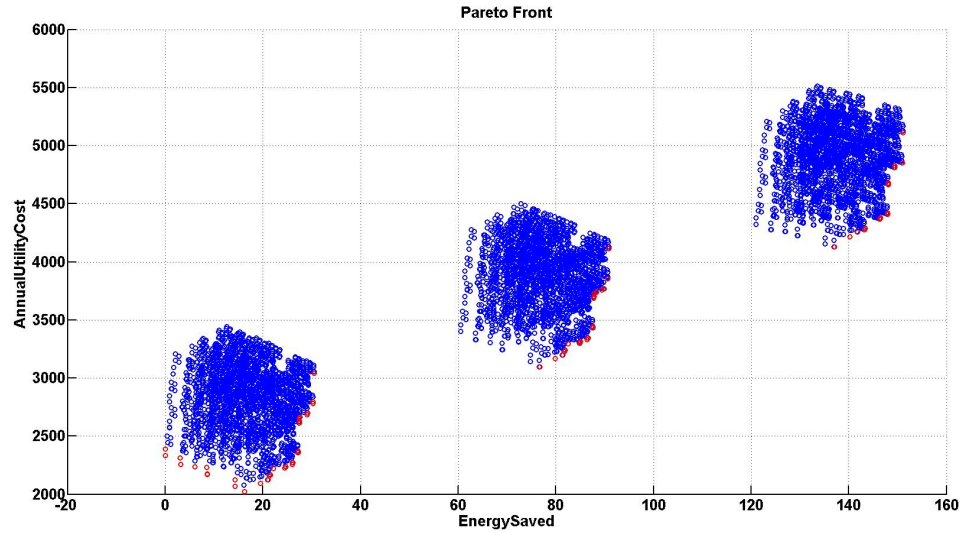


Figure 4.2: EnergyPlus results from Trade-off analysis

Figure 4.2 shows the objective space for the Detailed DSE. The points in red are the optimal points. A representative portion of the configurations are listed in Table 4.4. Three distinct clusters appear. The clusters are grouped by the PV array size with all other parameter combinations. Those combinations with no PV array are closer towards zero energy saved. Note that the large 10.2 kW array meets the entire house load and generates extra energy to be sold back to the grid since it has +120% energy savings. The optimal curve formed by these simulations is similar to the characteristic curve expected. Point B would be around (20, 2000), point C would be around (32, 3200), and point D would be around (150, 5200).

Design Variable	Optimal Points									
	1-3	4-6	7-8	9-11	12-14	15-17	18-19	20-21	22-23	24-25
Exterior Wall Interior Insulation	19	19	19	19	19	19	19	19	19	19
Exterior Wall Exterior Insulation	0	0	0	0	0	0	0	0	0	0
Basement Wall Interior Insulation	0	6	12	0-12	0	6	12	0	6	0-6
Roof Exterior Insulation	4	4	4	4	4	4	4	4	4	4
Windows	0	0	0	0	0	0	0	0	0	0
Infiltration Rate	3-0.6	3-0.6	3-0.6	0.6	3-0.6	3-0.6	3-2	2-0.6	2-0.6	0.6
Array Capacity	0	0	0	5	0	0	0	5	5	10
Solar Thermal	0	0	0	0	0	0	0	0	0	0
Energy Management	0	0	0	0	1	1	1	1	1	1

Table 4.4: Optimal Points from EnergyPlus simulation

4.5.1.2 BEopt

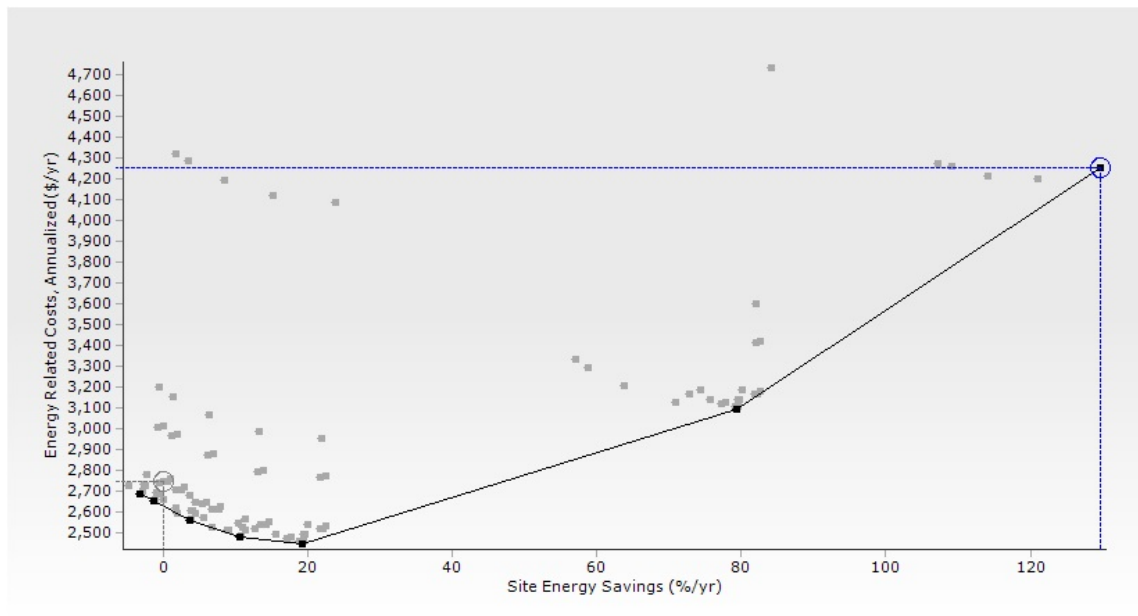


Figure 4.3: BEopt Results from Trade-off analysis

Figure 4.3 shows the objective space results from BEopt. The dark black points are the optimal points along the path to net zero. The optimal configurations are listed in Table 4.5. The BEopt results give a pretty fair representation to all the different stages of net zero design. Again, there are three distinct clusters that

Design Variable	Optimal 1	Optimal 2	Optimal 3	Optimal 4	Optimal 5	Optimal 6	Optimal 7
Exterior Wall Interior Insulation	19	19	19	21	19	21	21
Exterior Wall Exterior Insulation	0	24	24	24	24	24	24
Basement Wall Interior Insulation	0	0	12	12	12	12	12
Roof Exterior Insulation	4	4	30	30	30	30	30
Windows	.35/.35	.35/.35	.35/.35	.35/.35	.35/.35	.35/.35	.35/.35
Infiltration Rate	3	0.6	0.6	0.6	0.6	0.6	0.6
Array Capacity	0	0	0	0	0	5	10
Solar Thermal	0	0	0	0	0	0	0
Energy Management	1	1	1	1	1	1	1

Table 4.5: Optimal Points from BEopt simulation

represent the different PV array values. For the designs that have a PV array, there is only one optimal point for each PV array value.

4.5.1.3 Comparison of Methods

To generate Figure 4.2, 13,133 simulations were run taking approximately 1.8 days with 11 computers running 60 simulations in parallel. Meanwhile, BEopt ran only approximately 108 simulations on one computer taking approximately 45 minutes. BEopt provides a much more reasonable time frame for analysis. The sequential search algorithms significantly improves the efficiency of the DSE. Simulations using parametric mode were performed to analyze without a search optimizer, but results were inconclusive.

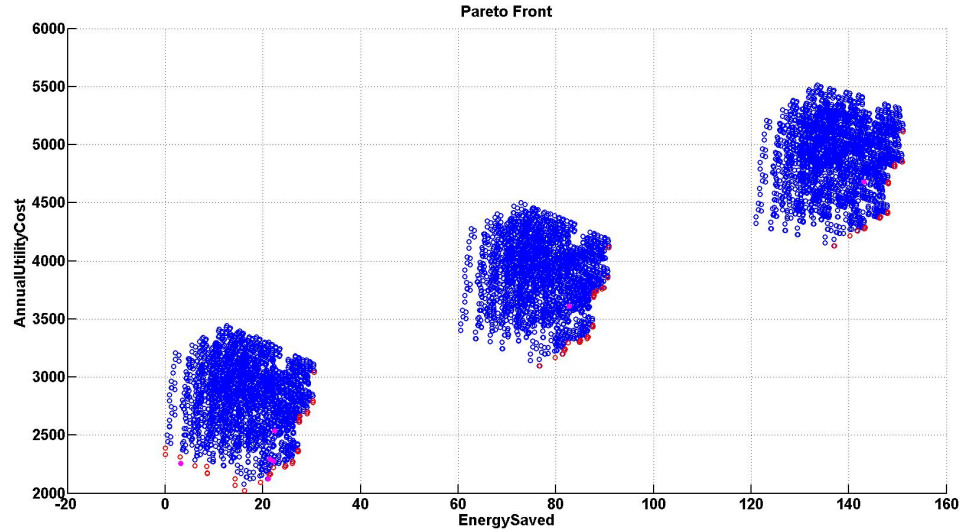


Figure 4.4: Overlapping results

Figure 4.4 has the optimal points from BEopt plotted over the EnergyPlus output in magenta. Upon first glance, the results seem to indicate that the workflow is validated; that the BEopt solutions indicate the combinations that are close to optimal. EnergyPlus, having more detailed models along with a wider variety of configurations, ultimately leads to the most optimal points. Upon inspection, this is not the case.

The EnergyPlus points that surround the BEopt points are not similar to the configurations of the BEopt points. In fact, all of the optimal points for EnergyPlus seem to be vastly different than the BEopt optimal points. The BEopt optimal points are as expected, with design configurations that have significant retrofits such as high insulation and lower infiltration. These types of designs would have significant energy savings. The EnergyPlus optimal points indicate that the only retrofits that should be done are infiltration and, occasionally, insulation in the exterior wall.

This is counter intuitive and I believe the issue comes from the upfront cost model. Any retrofit in the EnergyPlus model seems to have a penalty that instantly invalidates any combination as a candidate optimal point. Thus, the optimal points are all those that have had very minimal amounts of retrofits performed. This is not realistic. The BEopt model uses a cash flow model that takes into account more than just the material and labor cost of a retrofit. Despite trying to replicate the model from the documentation, I have been unable to replicate the results. Therefore, these results will give us insight into the behavior of the two programs and some high-level relationships, but feasibility of the workflow cannot be established due to an inferior upfront cost model created to analyze the EnergyPlus results.

4.5.2 Energy Savings versus User Discomfort

In an effort to isolate the issue above and show that it lies within the upfront cost models, and not the physical models, I perform a bi-objective optimization where the objectives are solely performance based. Energy Savings is a result of the performance of the house as a whole, and user discomfort should be minimized as the performance of the home increases. Neither metric is a function of the cost model.

Since BEopt does not report user discomfort, the approach for this section is to plot the same optimal design configurations that BEopt produced in Section 4.5.1.2 with the Energy Savings versus User Discomfort data from EnergyPlus. If these design configurations are close to optimal and surrounded by similar design

configurations, then that validates the performance aspects of the models.

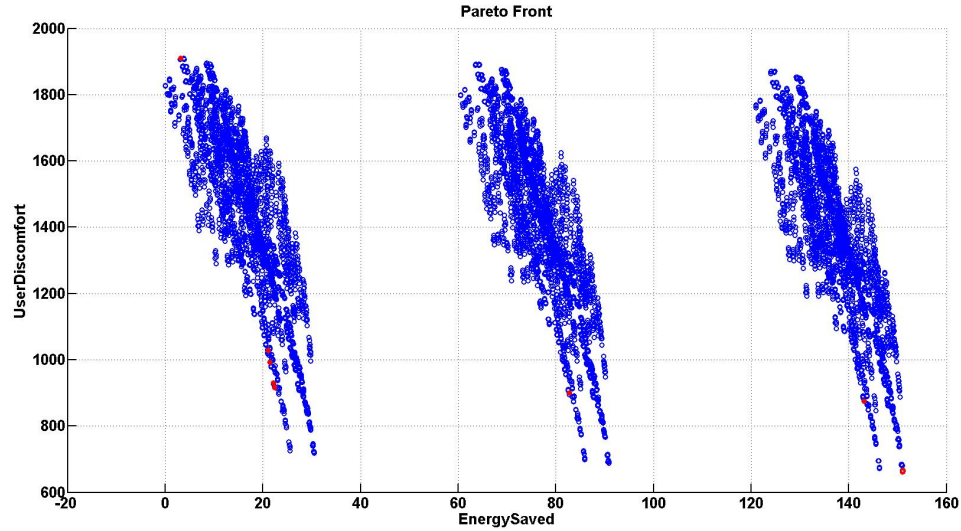


Figure 4.5: Energy Savings versus User Discomfort results

Figure 4.5 is the plot of the results where blue dots indicate a design configuration result, empty red dots indicate the EnergyPlus optimal configurations, and the solid red dots indicate the BEopt optimal configurations plotted with the EnergyPlus data. The results are positive.

First, the EnergyPlus optimal points are at the maximum of Energy Saving and minimum of User Discomfort. These configurations result in significant energy efficiency, so much so that extra energy is produced. They also have more time where the conditioned space is considered comfortable. The configuration for these points are ones where the maximum of the retrofits has been installed across all design parameters. This is as expected.

Furthermore, the BEopt points, which also have many of the maximum retrofits installed, are closer to the minimum, in their respective PV clusters, than many of

the other possible combinations. The local points are similar to the BEopt configurations as well.

These results indicate that the performance of the models are compatible and helps provide a justification for the conclusion that the upfront cost model is the source of the error in Subsection 4.5.1.3. Overall, this method that was applied to the Energy Savings and User Discomfort is similar to the process and results that would be expected for LCC and Energy Savings. This serves as justification for the validity of the performance models, and illustrates the potential for the proposed method.

Chapter 5

Part 2: Multi-Objective Optimization Problem

BEopt achieves great improvements in speed, but is limited to LCC versus Energy Savings. Buildings have significantly more objectives that require attention and trade-off in the design process. A better solution would be one that can handle true multi-objective optimization. Consol Optcad is a multi criteria optimization tool that uses a Feasible Sequential Quadratic Programming (FSQP) algorithm. The program works by defining an optimization problem with design variables, objective functions and constraints. One advantage Consol Optcad has is the ability to define functional constraints. These constraints can be based off free parameters such as time, or some of the design parameters. Consol Optcad runs the simulation with the initial design configuration. It then adjusts the design variables and re-runs the simulation. This process iterates until a design satisfies all of the objectives. The benefit of the FSQP algorithm is that once a design satisfies all objectives, consecutive iterations will also satisfy the objectives. Spropoulos used Consol Optcad to create a model of a microgrid [25]. This model is now adapted for energy efficient buildings. Consol Optcad was unable to run on my system, therefore, results and functionality provided by Consol Optcad are recreated in MATLAB to demonstrate the abilities of the method. The building model is a simplified version of the NZERTF with the same footprint but only one story with windows on the south

facade.

5.1 Design Parameters

Design Parameters	Description	Constraint	Initial	Unit
x_1	Exterior Wall Insulation (R-Value)	$19 \leq x_1 \leq 44$	$x_1 = 19$	$\frac{\text{ft}^2 \cdot \text{°F} \cdot \text{hr}}{\text{Btu}}$
x_2	Roof Insulation (R-Value)	$50 \leq x_2 \leq 75$	$x_2 = 50$	$\frac{\text{ft}^2 \cdot \text{°F} \cdot \text{hr}}{\text{Btu}}$
x_3	Window (U-Value)	$0.2 \leq x_3 \leq 0.35$	$x_3 = 0.35$	$\frac{\text{Btu}}{\text{ft}^2 \cdot \text{°F} \cdot \text{hr}}$
x_4	Window (SHGC)	$0.25 \leq x_4 \leq 0.35$	$x_4 = 0.35$	Unit-less
x_5	Infiltration (ACH)	$0.6 \leq x_5 \leq 3$	$x_5 = 3$	ACH
x_6	HRV/Ventilation (% Energy Recovered)	$0\% \leq x_6 \leq 85\%$	$x_6 = 0\%$	%
x_7	Lighting (% Efficient Lighting)	$75\% \leq x_7 \leq 100\%$	$x_7 = 75\%$	%
x_8	PV (Capacity)	$0 \leq x_8 \leq 10240$	$x_8 = 0$	W

Table 5.1: Design Parameters

5.2 Objective Functions

5.2.1 Initial Cost

The equation governing initial cost is

Minimize

$$IC = \sum (IC_{Wall} + IC_{Roof} + IC_{Win} + IC_{Inf} + IC_{Vent} + IC_{Light} + IC_{PV}), \quad (5.1)$$

where

$$\begin{aligned}
IC_{Wall} &= A_{Wall} (.0666 (x_1 - 19) + 0.7) \\
IC_{Roof} &= A_{Roof} (0.1 (x_2 - 49) + 2.5) \\
IC_{Win} &= A_{Win} (456.2 - 2633 x_3 - 216.6 x_4 + 3863 x_3^2 + 942 x_3 x_4) \\
IC_{Inf} &= \frac{V_{room}}{8} (0.52 x_5^{-0.7462}) \\
IC_{Vent} &= 42(8.571 x_6^2 + 0.8571 x_6) + 1300 \\
IC_{Light} &= 0.2237 (1281 - (-2676 x_7 + 3288)) \\
IC_{PV} &= 2.6 x_8
\end{aligned}$$

5.2.2 Net Energy Use

The equation governing net energy use is

Minimize

$$EU = \sum_{t=0}^{24} \frac{(P_{PV}(t) + P_{Lighting}(t) + \beta_t P_{HVAC}^{op})}{60000}, \quad (5.2)$$

where P_{PV} is the power generated by the PV system, $P_{Lighting}$ is the power used for lighting, β_t is the On/Off factor for the HVAC unit at timestep t , and P_{HVAC}^{op} is the operational power draw of the HVAC unit, and is defined as

$$P_{PV}(t) = \frac{-x_8}{10240} (6970e^{-\left(\frac{t-14.66}{3.014}\right)^2} + 6870e^{-\left(\frac{t-10.55}{2.954}\right)^2}). \quad (5.3)$$

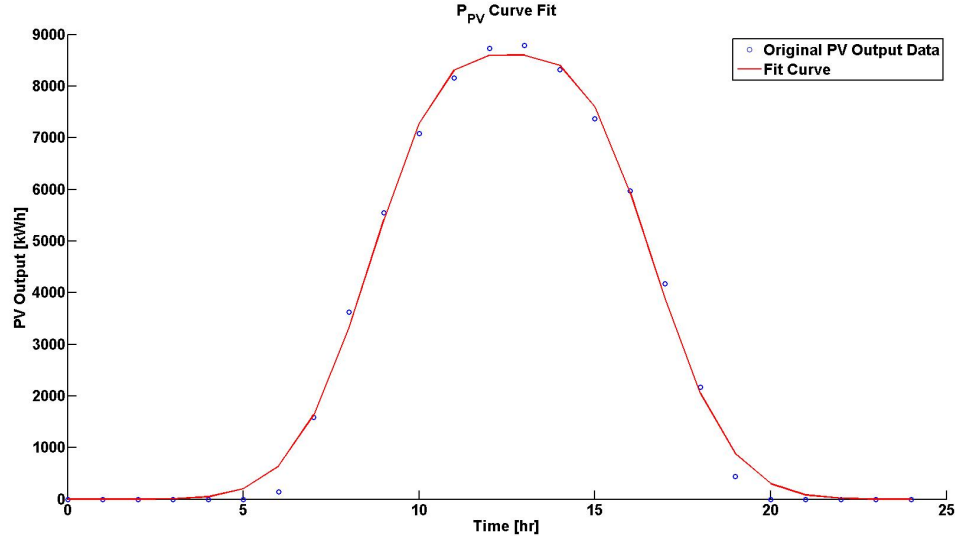


Figure 5.1: P_{PV} Curve Fit

P_{PV} is generated by curve fitting the EnergyPlus PV output data for 7/21/2012.

This is also the same day that all weather data is gathered for this optimization problem.

$$P_{Lighting}(t) = \begin{cases} 0 & \text{for } 0 \leq t < 6 \text{ \& } 8 \leq t < 18 \\ (0.25)(-2676 x_7 + 3288), & \text{for } 6 \leq t < 7 \text{ \& } 22 \leq t \leq 24 \\ (0.5)(-2676 x_7 + 3288), & \text{for } 18 \leq t < 19 \\ (0.75)(-2676 x_7 + 3288), & \text{for } 7 \leq t < 8 \text{ \& } 21 \leq t < 22 \\ (-2676 x_7 + 3288), & \text{for } 19 \leq t < 21 \end{cases} \quad (5.4)$$

For $P_{Lighting}$, $(-2676 x_7 + 3288)$ is the wattage level given the percentage of lights converted to efficient bulbs. It is merely a linear interpolation from the

minimum and maximum points given by the 2012 IECC and NZERTF models. From there a multiplier is included to account for the lighting schedule. The lighting schedule is loosely based on the lighting schedule for the NZERTF, however, much more simplified. Figure 5.2 shows the simplified schedule.

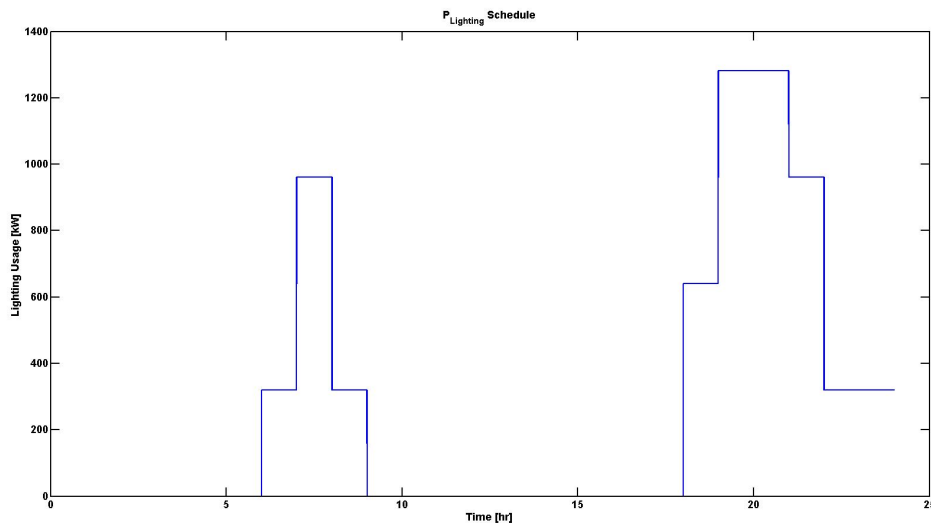


Figure 5.2: $P_{Lighting}$ Schedule

Finally, the HVAC unit is a 2 Ton unit. We assume that it is a single-stage, constant-volume A/C Unit which means it can produce approximately 7 kW of cooling capacity using 1 kW ($P_{HVAC}^{op} = 1000$) of electricity. Modeling the behavior is more challenging. The basic operation is that the HVAC unit will run at max power if the room goes past a temperature threshold (T_{thresh}). Since this use case is for cooling only, this threshold is 2 °F warmer than the setpoint temperature T_{set} . If the temperature in the room, T_{room} , deviates past the threshold, then the HVAC is turned on until the room temperature returns to the setpoint temperature. Once the setpoint temperature is met, then the HVAC unit is turned off until the

room temperature crosses the threshold temperature, at which point the process is repeated. To determine if the HVAC unit is operational, β_t is used to indicate if the HVAC is on (1) or off (0) at every timestep, t .

The operation is described in pseudo-C code in Table 5.2.

```

if  $\beta_{t-1} = 0$  &&  $T_{room,t-1} \geq T_{thresh}$ 
then  $\beta_t = 1$ 
else if  $\beta_{t-1} = 1$  &&  $T_{room,t-1} \leq T_{thresh}$ 
then  $\beta_t = 0$ 
else
 $\beta_t = \beta_{t-1}$ 

```

Table 5.2: Pseudo C code for the formulation of β_t

For this optimization problem, $T_{set} = 72$ and $T_{thresh} = 74$. With this information, we have enough to solve Equation 5.2. The only part missing is solving for T_{room} which will be discussed in Section 5.3.

5.2.3 Operational Cost

The equation governing operational cost is

Minimize

$$OC = \sum_{t=0}^{24} \frac{C_{tariff}(t)[P_{PV}(t) + P_{Lighting}(t) + \beta_t P_{HVAC}^{op}]}{60000}, \quad (5.5)$$

where

$$C_{tariff}(t) = \begin{cases} 0.0978, & \text{for } 0 \leq t < 8 \\ 0.1124, & \text{for } 8 \leq t < 12 \text{ \& } 20 \leq t \leq 24 \\ 0.1341, & \text{for } 12 \leq t < 20 \end{cases}$$

The schedule for the Tariff is the Time-Of-Use Schedule taken from the PEPCO R-TM Schedule. The schedule values are the sum of all energy related charges, that is the sum of all $\frac{\$}{kWh}$ charges. Figure 5.3 shows the final schedule.

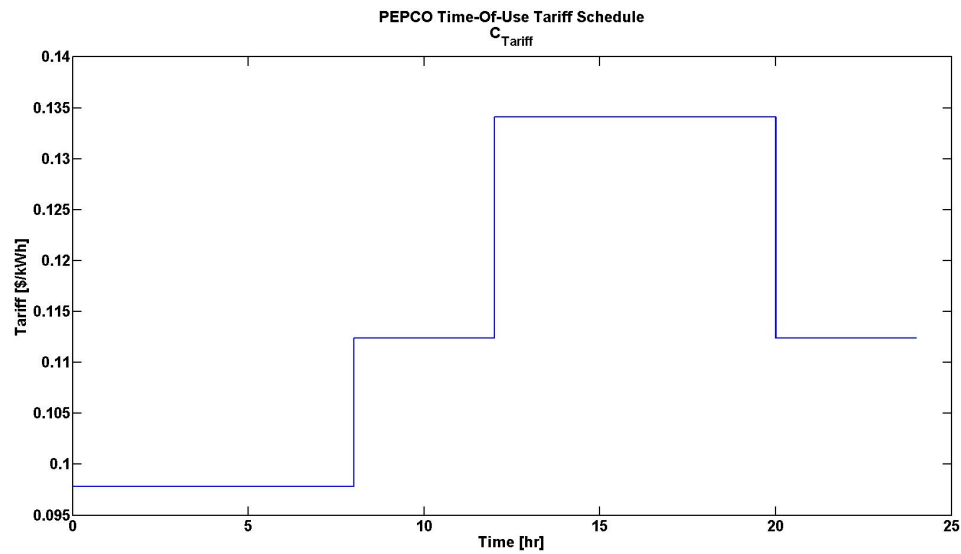


Figure 5.3: C_{Tariff} Schedule

5.2.4 User Comfort

The equation governing user comfort is

Maximize

$$UC = \sum_{t=0}^{24} \gamma_t, \quad (5.6)$$

where

$$\gamma = \begin{cases} 1, & \text{for } T_{room,t} < T_{thresh} \\ 0, & \text{for } T_{room,t} \geq T_{thresh} \end{cases}$$

This objective function counts the amount of time the system stayed within the temperature threshold over the 24 hour simulation. Larger values means more time is spent within a comfortable temperature range, therefore, providing user comfort.

5.2.5 Home Performance

The equation governing home performance is

Minimize

$$HP = \sum_{t=0}^{24} \beta_t. \quad (5.7)$$

This objective function counts the amount of time the HVAC system was turned on over the 24 hour simulation. A smaller value indicated the HVAC system was not utilized often. If User Comfort is optimally maximized and Home Performance is optimally minimized, then the home can be considered of high performance since active means of temperature regulation are not relied upon to maintain comfortable conditions. This can be thought of as a measure of quality passive systems, i.e. the synergy of the passive design parameters (insulation, windows, infiltration).

5.3 Heat Flow

A vital part of this optimization problem is the calculation of the current room temperature, T_{room} . The basis for this calculation is that the net heat transfer in and out of the room will yield a temperature change over a given time. This can be written as

$$T_{room}[t] = \frac{Q_{net,t-1}}{C_p \cdot \rho \cdot V_{room}} + T_{room}[t - 1], \quad (5.8)$$

where $Q_{net,t-1}$ is the net heat transfer in the room from the previous timestep, C_p is the specific heat capacity of air, ρ is the density of air, V_{room} is the volume of the room, and $T_{room,t-1}$ is the temperature of the room from the previous timestep. Since T_{room} is recursive and the initial temperature is 72 °F, T_{room} can be represented as a set

$$T_{room} = \{72, T_{room,1}, T_{room,2}, T_{room,3}, \dots, T_{room,24}\}. \quad (5.9)$$

The static parameters in Equation 5.8 are as follows:

$$\begin{aligned} C_p &= 0.24 \frac{\text{Btu}}{\text{°F} \cdot \text{lb}_m}, \\ \rho &= 0.075 \frac{\text{lb}_m}{\text{ft}^3}, \\ V_{room} &= 12800 \text{ ft}^3. \end{aligned}$$

5.3.1 Q_{net}

Q_{net} is the sum of the heat flow introduced by each component, usually in the form of a simplified conduction or radiation model. The definition for this problem is as follows

$$Q_{net} = Q_{wall} + Q_{roof} + Q_{win} + Q_{winrad} + Q_{infil} + Q_{vent} + Q_{int} + Q_{HVAC}. \quad (5.10)$$

Each of heat transfer equations will require the exterior temperature. This data has been gathered from the same weather data used to create the PV Output data. The data is approximated as a Fourier series

$$\begin{aligned} T_{ext}(t) = & 81.96 - 6.614 \cos(0.2594t) - 7.6 \sin(0.2594t) \\ & + 1.347 \cos(0.5188t) + 1.306 \sin(0.5188t) \\ & - 0.1291 \cos(0.7702t) + 0.3703 \sin(0.7702t). \end{aligned}$$

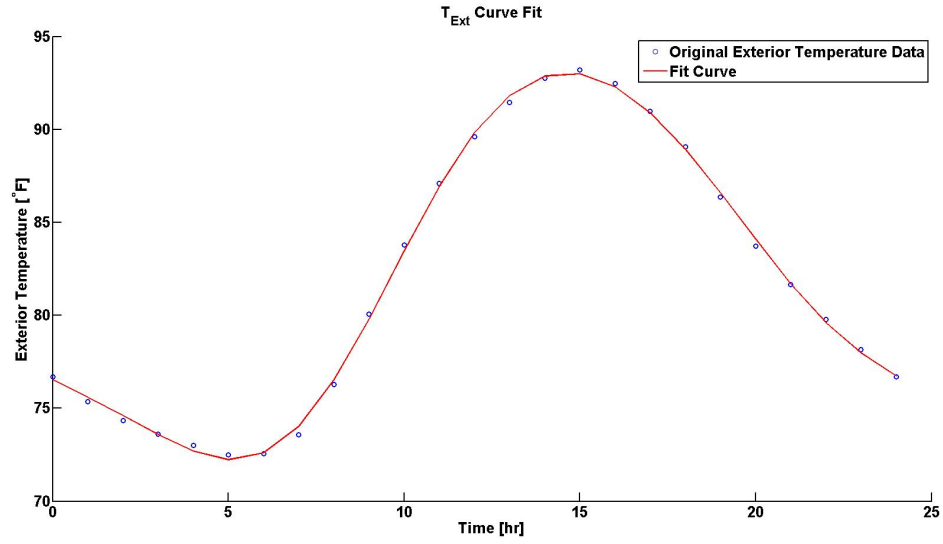


Figure 5.4: T_{ext} Curve Fit

Figure 5.4 shows the curve fit overlaid with the weather file data.

5.3.2 Q_{wall}

Q_{wall} is the heat transfer due conduction through the walls, defined as

$$Q_{wall} = \frac{A_{wall}}{x_1} (T_{ext}(t) - T_{room}[t]), \quad (5.11)$$

where $A_{wall} = 1280\text{ft}^2$

5.3.3 Q_{roof}

Q_{roof} is the heat transfer due conduction through the roofs, written as

$$Q_{roof} = \frac{A_{roof}}{x_2} (T_{ext}(t) - T_{room}[t]), \quad (5.12)$$

where $A_{roof} = 2240\text{ft}^2$

5.3.4 Q_{win}

Q_{win} is the heat transfer due conduction through the window, written as

$$Q_{win} = A_{win} x_3 (T_{ext}(t) - T_{room}[t]), \quad (5.13)$$

where $A_{win} = 137.5\text{ft}^2$

5.3.5 Q_{winrad}

Q_{winrad} is the radiation heat transfer due sunlight entering through the windows

$$Q_{winrad} = \frac{A_{win} E_{DN}(t) x_4 \cos \theta}{3.15}, \quad (5.14)$$

where E_{DN} is the Direct Normal Radiation reaching a vertical surface. This data is also taken from the weather file and is approximated by a piece-wise polynomial function

$$E_{DN}(t) = \begin{cases} -0.1729t^4 + 8.591t^3 - 166.7t^2 + 1497t - 4346, & \text{for } 5.17 < t < 19.93 \\ 0, & \text{otherwise} \end{cases}$$

and

$$\theta = 65.85 \sin 0.2. \quad (5.15)$$

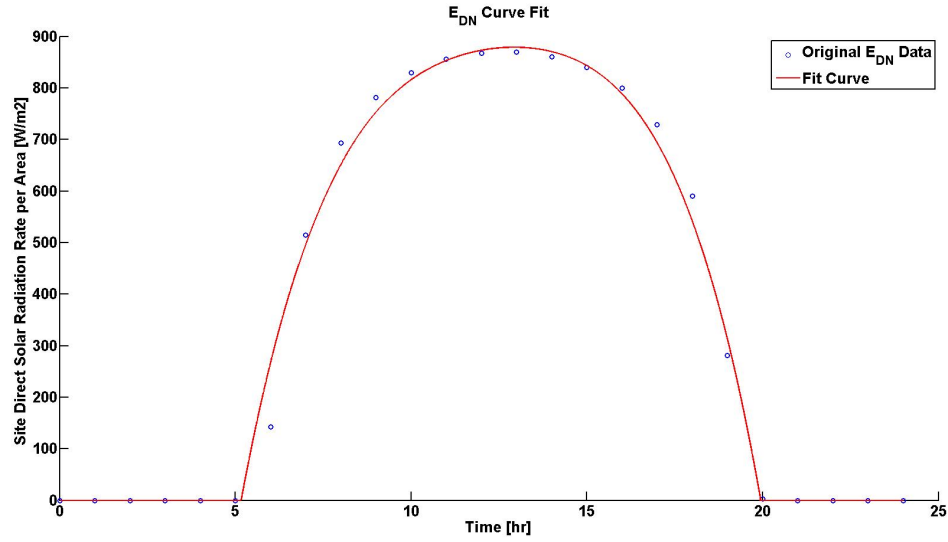


Figure 5.5: E_{DN} Curve Fit

Figure 5.5 shows the curve fit overlaid with the weather file data.

5.3.6 Q_{inf}

Q_{inf} is the heat transfer due to the flow of air from infiltration, defined as

$$Q_{inf} = \rho C_p x_5 (T_{ext}(t) - T_{room}[t]). \quad (5.16)$$

5.3.7 Q_{vent}

Q_{vent} is the heat transfer due to the forced flow of air from the ventilation system. The ventilation is assumed to always be approximately 42 CFM, however,

the presence of an HRV mixes in the conditioned and non-conditioned air before the air is ventilated. This captures energy lost from the conditioned air and re-supplies it back to the room. If no HRV is present ($x_6 = 0$) then all energy is removed from the room. However, if an HRV is present ($x_6 > 0$), then the amount of energy lost is reduced.

$$Q_{vent} = 60 \dot{V}_{vent} \rho C_p (1 - x_6) (T_{ext}(t) - T_{room}[t]), \quad (5.17)$$

where $\dot{V}_{vent} = 42.32$ CFM

5.3.8 Q_{int}

Q_{int} is the heat transfer due to internal loads. The internal loads included are the heat generated by lighting and occupants.

$$Q_{int} = \frac{(P_{People} + P_{Lightng})}{3.412}, \quad (5.18)$$

where $P_{Lightng}$ is shown in Equation 5.4 and

$$P_{People}(t) = \begin{cases} 400, & \text{for } 0 \leq t < 8 \text{ \& } 18 \leq t \leq 24 \\ 0, & \text{for } 8 \leq t < 18 \end{cases}$$

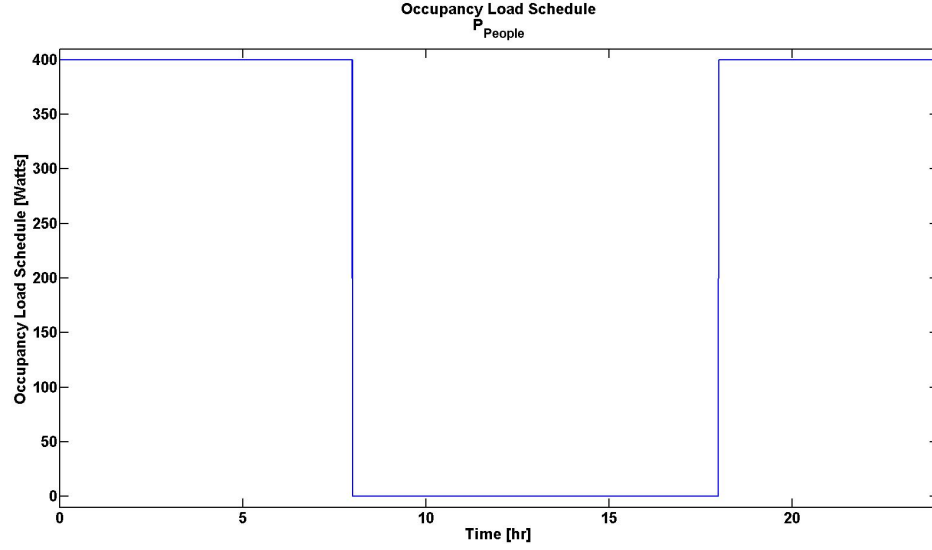


Figure 5.6: P_{People} Schedule

Figure 5.6 shows the occupancy schedule.

5.3.9 Q_{HVAC}

Q_{HVAC} is the heat transfer due to HVAC system.

$$Q_{HVAC} = \frac{3500 : \beta_t}{3.412}, \quad (5.19)$$

where β_t is described in Table 5.2.

5.4 Results

Figure 5.7 shows the time dependent results of the simulation. In the top figure, the green lines are the functional constraints for the setpoint. The purple line shows the temperature inside the room while the red line is the exterior temperature. The periodic behavior of the interior temperature is a result of the HVAC system

activating when the temperature falls outside the setpoint constraints. This is seen in the bottom graph where the blue line is the cooling energy of the HVAC and the red line is the cooling load required. Around hour 17, the cooling load becomes larger than cooling capacity of the HVAC system and begins to drift outside the threshold.

Design Parameters	Description	Value
x_1	Exterior Wall Insulation (R-Value)	19
x_2	Roof Insulation (R-Value)	50
x_3	Window (U-Value)	0.35
x_4	Window (SHGC)	0.35
x_5	Infiltration (ACH)	3
x_6	HRV/Ventilation (% Energy Recovered)	0%
x_7	Lighting (% Efficient Lighting)	75%
x_8	PV (Capacity)	0

Table 5.3: Parameter values for the first iteration

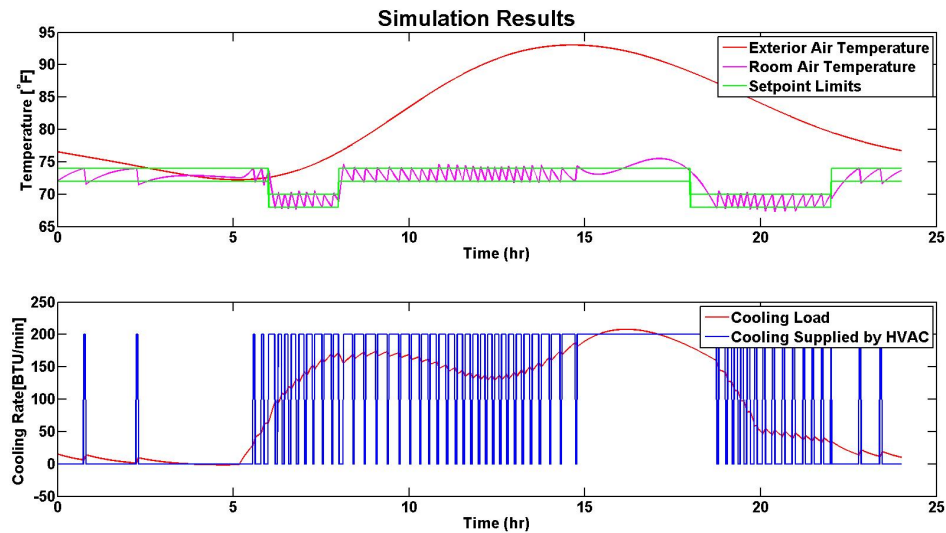


Figure 5.7: Simulation results for the first iteration

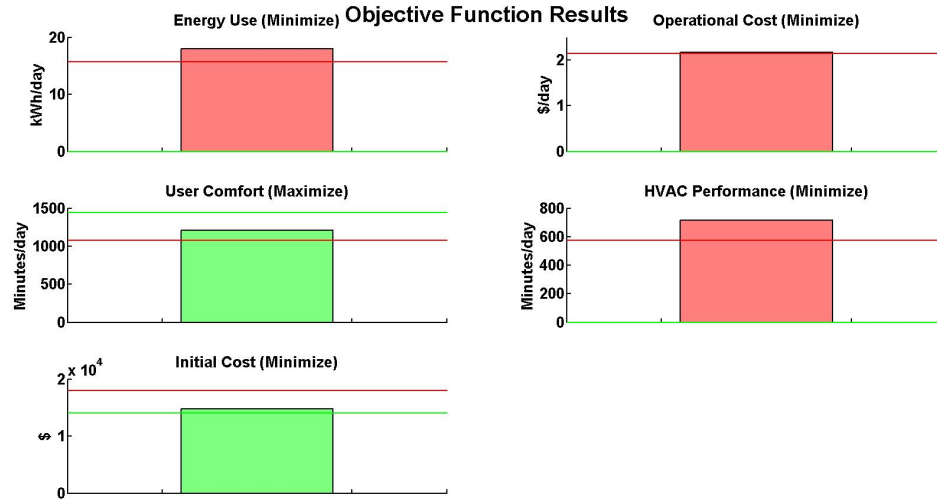


Figure 5.8: Objective function results for the first iteration

Figure 5.8 shows the current values of the objective functions with the current design. Good and bad values are set for each objective. If the problem is a minimization, then the objective is not satisfied if the value is above the bad value. This is shown with a red line while the green line is the good value. If the objective is satisfied, then the color of the graph switches to green, otherwise it is red and the design must be adjusted. At this point, Consol Optcad would choose new values for the design variables based off its FSQP algorithm. However, for this project values were chosen manually based off observation.

Design Parameters	Description	Value
x_1	Exterior Wall Insulation (R-Value)	30
x_2	Roof Insulation (R-Value)	50
x_3	Window (U-Value)	0.35
x_4	Window (SHGC)	0.35
x_5	Infiltration (ACH)	3
x_6	HRV/Ventilation (% Energy Recovered)	0%
x_7	Lighting (% Efficient Lighting)	75%
x_8	PV (Capacity)	0

Table 5.4: Parameter values for the next iteration

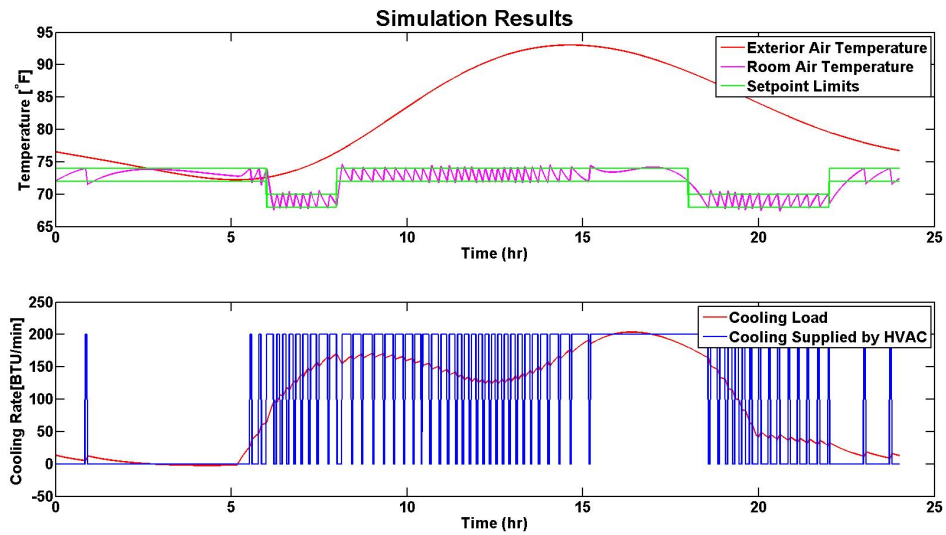


Figure 5.9: Simulation results for the next iteration

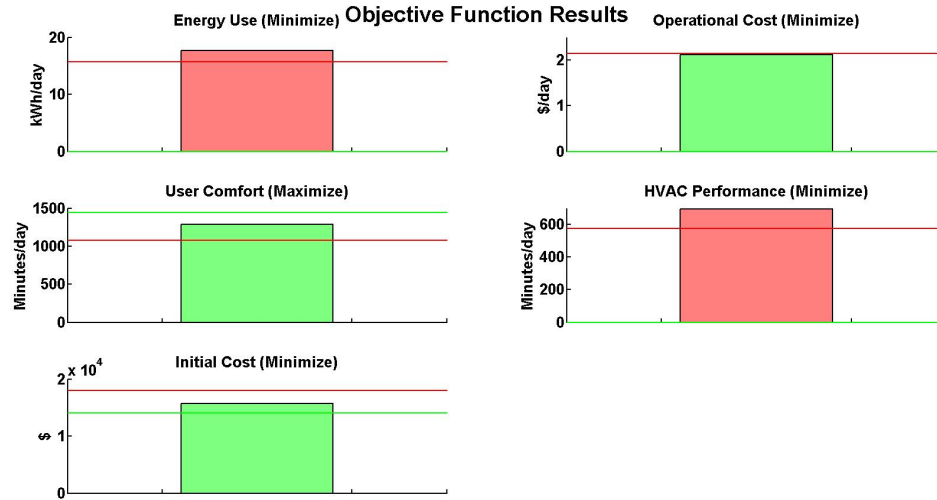


Figure 5.10: Objective function results for the next iteration

In this iteration, the exterior wall insulation has been increased. Figure 5.9 still has the interior temperature drifting outside the setpoint threshold; however, it is not as severe as before. Figure 5.10 confirms that this is a better design configuration than before, since three out of five objectives are satisfied, rather than two. Since all objectives are not satisfied, the iterations continue.

Design Parameters	Description	Value
x_1	Exterior Wall Insulation (R-Value)	30
x_2	Roof Insulation (R-Value)	50
x_3	Window (U-Value)	0.25
x_4	Window (SHGC)	0.25
x_5	Infiltration (ACH)	3
x_6	HRV/Ventilation (% Energy Recovered)	0%
x_7	Lighting (% Efficient Lighting)	75%
x_8	PV (Capacity)	0

Table 5.5: Parameter values for the final iteration

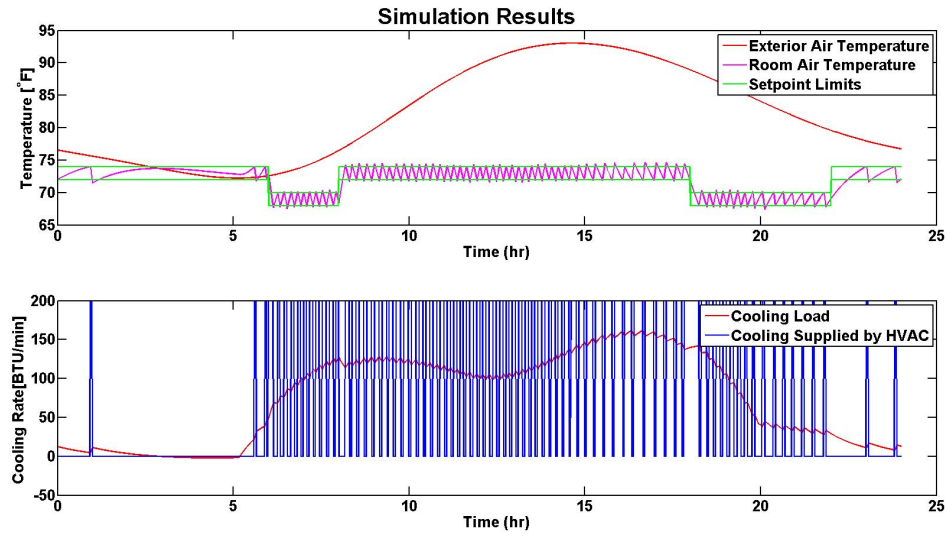


Figure 5.11: Simulation results for the final iteration

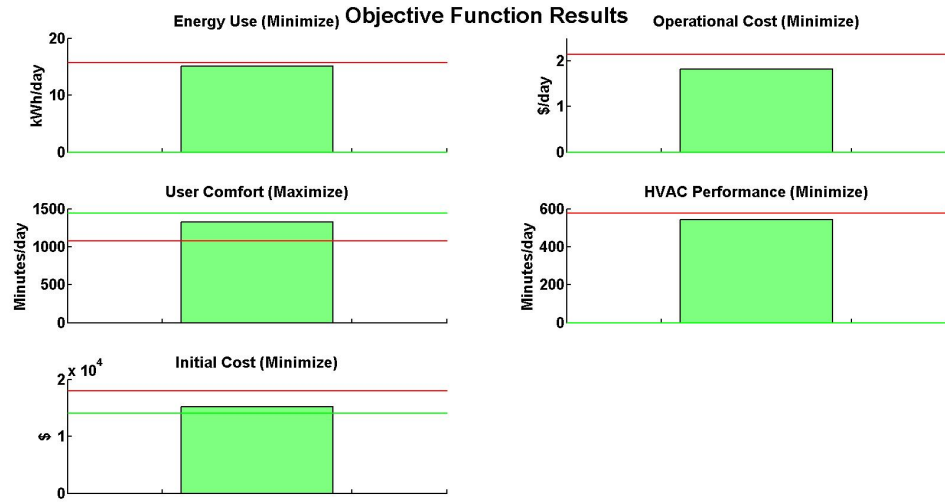


Figure 5.12: Objective function results for the final iteration

After multiple iterations, a configuration is achieved that satisfies all objectives. This process can continue to find other designs that are also satisfactory. Another key feature of Consol Optcad is the real time interaction the user has with the progression of the simulation. The user has the ability to change the values of

the objective function to set new upper and lower limits. This allows the user to influence the final design configuration based as the simulation is running to produce a more applicable result to the designers needs as needs change. The results visualization, fast and powerful solving algorithm, and ability to interact with the solver in real time are aspects of Consol Optcad that set it apart from other simulators.

Chapter 6

Part 3: jEPlus+EA

6.1 jEPlus+EA

While Section 5.4 does provide a way to satisfy multiple objectives, it is using a custom made energy simulator. A much better solution would be one that uses previously established energy simulator such as EnergyPlus. Section 3.3 describes jEPlus and how it is a java shell for EnergyPlus that handles parametric analysis. This means that the energy simulator is inherently EnergyPlus, thus, any results will be the detailed model, rather than BEopt which creates a simplified input for EnergyPlus. This would yield the same issue before where no time is saved since the detailed EnergyPlus model take significantly longer to simulate. However, the creators of jEPlus have created an extension called jEPlus+EA that allows for Evolutionary Algorithms to optimize the progression of simulations run in order to find the optimal solutions. While, BEopt is using a sequential search algorithm to determine which design configurations to simulate, jEPlus+EA is using the Nondominating Sorting Genetic Algorithm 2 Evolutionary Algorithm to make these decisions. This method can greatly reduce the number of simulations necessary to result in the optimal configurations. One example problem has a state space of over one million combinations where the optimal design configuration was found

after only 20,000 simulations [27]. This type of algorithm is considered one of the state-of-the-art solvers for multi-objective optimization problems [5]. In order to demonstrate the current leading tool available, I used jEPlus+EA with the EnergyPlus energy model from Chapter 4 and the optimization objectives from Chapter 5. With jEPlus, values are directly gathered from EnergyPlus results output.

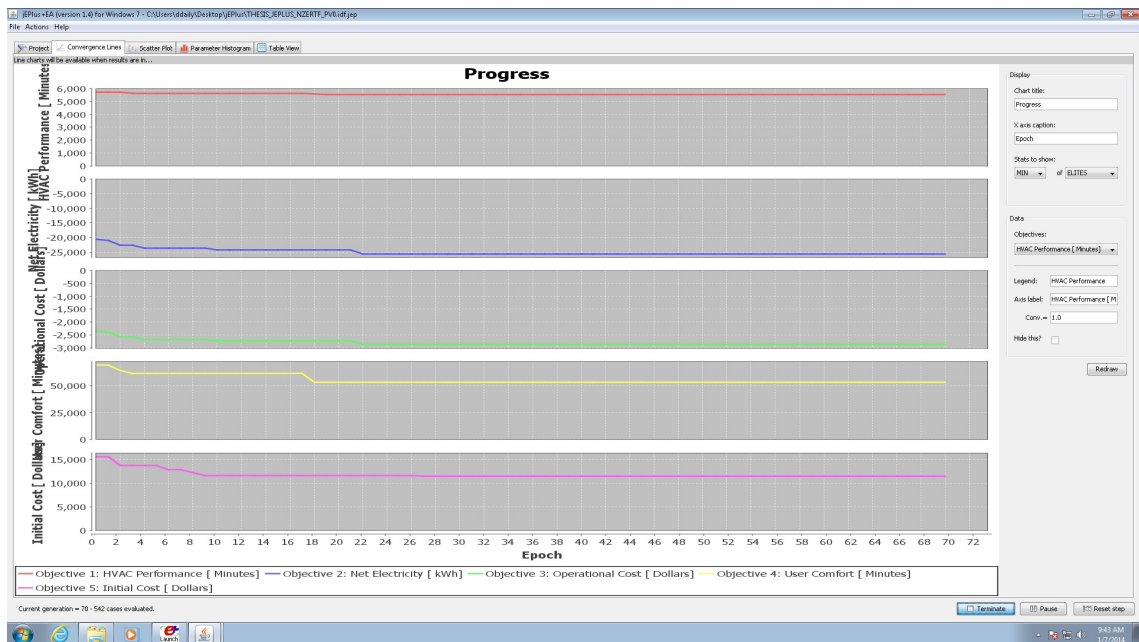


Figure 6.1: Screenshot of jEPlus’s progress view

Figure 6.1 shows each objectives functions value at the optimal design as the algorithm progresses through iterations. At some iteration, or “Epoch,” the values converge at the Pareto points where a decrease in one objective value increases the others. At these points, design configurations are considered to be the best. This can be seen more clearly when the design configurations are plotted in objective space.

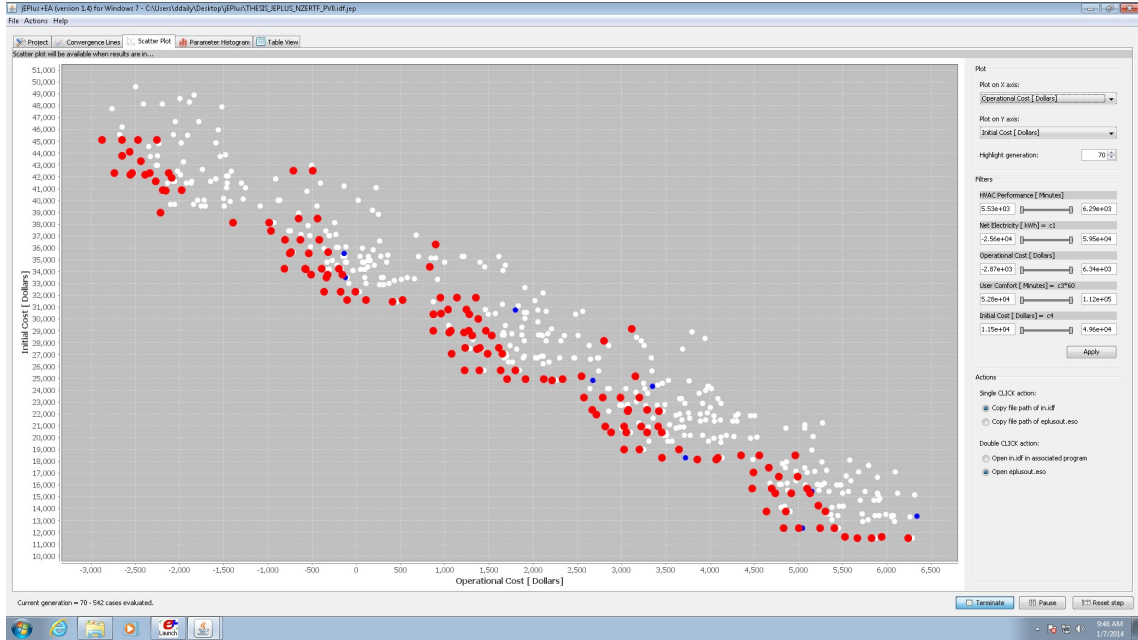


Figure 6.2: Plot of simulation results for Operational Cost vs Initial Cost objectives. The red dots are the Pareto points across all five objective functions.

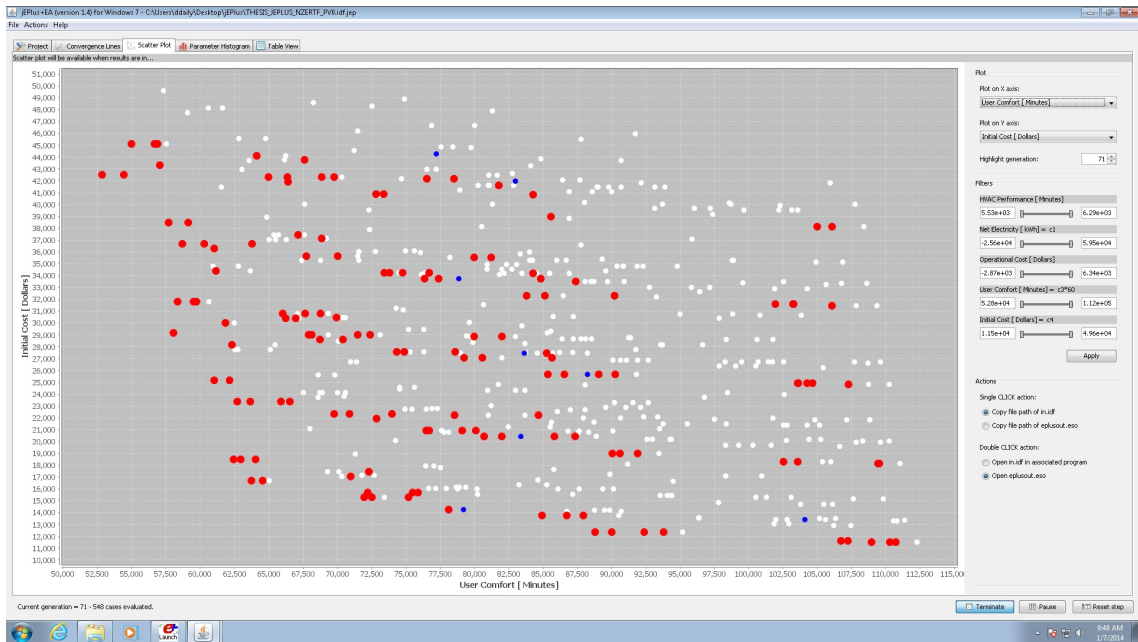


Figure 6.3: Plot of simulation results for User Comfort vs Initial Cost objectives. The red dots are the Pareto points across all five objective functions.

The red dots in Figures 6.2 and 6.3 are the Pareto points across all 5 objectives.

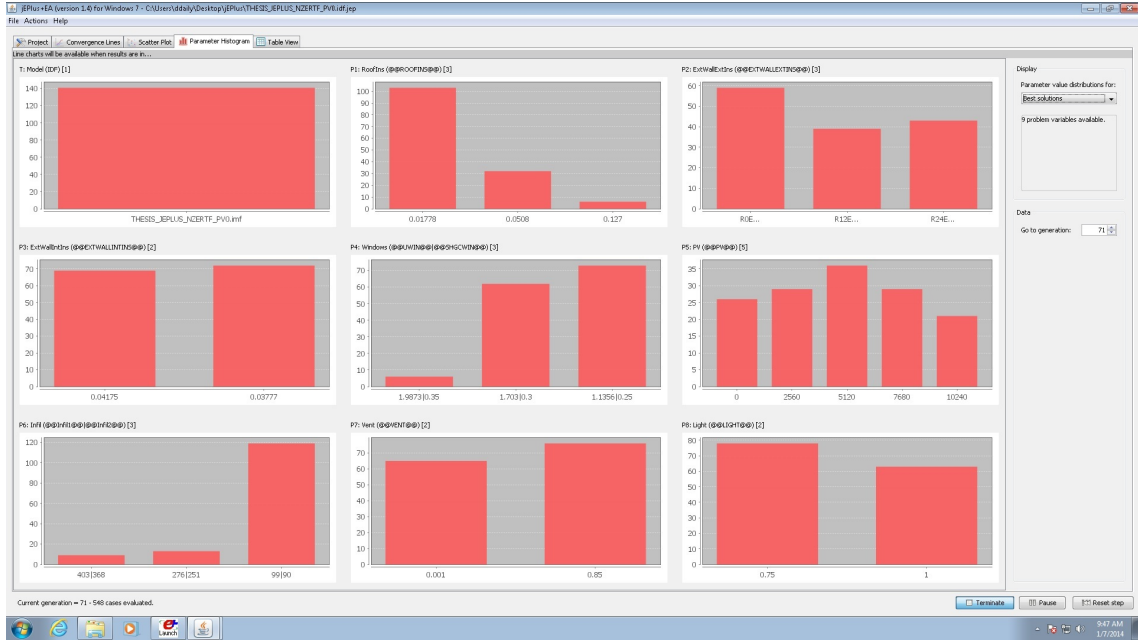


Figure 6.4: Histogram plot of each design variable value for the Pareto points

Figures 6.2 and 6.3 allow a user to interpret the minimums of the objective functions that can be achieved with the given design variables while Figure 6.4 gives more data on the type of design configurations that lead to the best functioning designs. Each design variable has its own histogram plot where the frequency of appearances of a value in a Pareto point is tracked. With this view, it is very easy to spot design trends and highly influential parameters. For example, it is clear that a low infiltration rate retrofit is necessary for an optimal design, while a roof insulation retrofit is not advised since the base value is the most frequent. These is a very useful view to a designer and one of the strength of jEPlus+EA. However, it does not allow me to identify a single option that meets the homeowner’s needs. In order to do this, I apply a weighted sum method to the list of Pareto points from jEPlus+EA in order to narrow the design choices, where the weights add importance

to objectives that reflect the homeowner’s desired goals.

HVAC Performance (w1)	0.025
Net Electricity (w2)	0.90
Operational Cost (w3)	0.025
User Comfort (w4)	0.025
Initial Cost (w5)	0.025

Table 6.1: Use Case 1: Weighted Values

In this case, the homeowner is environmentally conscious and wishes to emphasize the reduction on their energy load. With these weights, the best design configuration is shown in table 6.2 and the final objective values are shown in figure 6.3.

Roof Insulation (R Value)	57.00
Exterior Wall Exterior Insulation (R Value)	24
Exterior Wall Interior Insulation (R Value)	21
Windows (U-Value/SHGC)	0.25 / 0.25
PV (Watts)	10240.00
Infiltration (ACH)	0.61
Ventilation (% Heat Recovered)	0.85
Lighting (% Energy Efficient Bulbs)	1.00

Table 6.2: Use Case 1: Best Design

HVAC Performance (Minutes In Operation)	5648.75
Net Electricity (Annual kWh)	-25577.29
Operational Cost (Annual \$)	-2874.57
User Comfort (Minutes Uncomfortable)	56805.00
Initial Cost (\$)	45122.54

Table 6.3: Use Case 1: Objective Function Values

However, if a homeowner has different priorities, such that they are on a budget and wish to emphasize a lower upfront cost then the optimal design changes.

HVAC Performance (w1)	0.025
Net Electricity (w2)	0.025
Operational Cost (w3)	0.025
User Comfort (w4)	0.025
Initial Cost (w5)	0.90

Table 6.4: Use Case 2: Weighted Values

Roof Insulation (R Value)	50.00
Exterior Wall Exterior Insulation (R Value)	12
Exterior Wall Interior Insulation (R Value)	19
Windows (U-Value/SHGC)	0.25 / 0.25
PV (Watts)	10240.00
Infiltration (ACH)	0.61
Ventilation (% Heat Recovered)	0.85
Lighting (% Energy Efficient Bulbs)	1.00

Table 6.5: Use Case 2: Best Design

HVAC Performance (Minutes In Operation)	5808.25
Net Electricity (Annual kWh)	-24276.32
Operational Cost (Annual \$)	-2738.10
User Comfort (Minutes Uncomfortable)	69780.00
Initial Cost (\$)	42307.57

Table 6.6: Use Case 2: Objective Function Values

Chapter 7

Conclusions

7.1 Findings

The proposed method uses BEopt to find optimal configurations to create configurations in EnergyPlus for a more detailed trade-off analysis. This method reduces the number of necessary simulations for EnergyPlus and allows for faster analysis since detailed simulations are computationally expensive. Work done in this thesis has been inconclusive as to the validity of this method since the upfront cost model created for the EnergyPlus postprocessing is missing factors that are captured in the BEopt upfront cost model. Should this disconnect be fixed, it would be possible to conclusively state the validity of the proposed workflow. Nevertheless, there are similarities between the models. The characteristic path to net zero energy curve is present in both. Further analysis in performance shows that the models are comparable in their energy outputs and the proposed method does apply to the performance. Multi-Objective Optimization is performed in Consol Optcad that demonstrate the ability of multi-objective optimization and trade-off in building DSE. The quick analysis and view of satisfied constraints and objectives along with behavior plot of the system provide critical insight for designers and should be included in future tools. Finally, examples are discussed that show that trade-off in

building DSE yields more effective designs.

A full systems approach to streamlined, detailed energy modeling in buildings is currently a topic that requires a lot research. Whole Building simulators are a relatively new tool and their processes and methods require some optimization. Other functionality needs to be built in to many of these tools such as model dependencies and multi-objective optimization with trade-off analysis. Most simulators are also steady state models while many of the optimization methods require continuous functions that are more common with dynamic models. Kim lists many of these pain points within the energy modeling community and describes an architecture for the required framework for a full systems approach [14]. A strong emphasis is placed on the importance of model interconnections and being able to easily integrate multiple programs together for seamless model development and analysis. These methods can lead to easier optimization in building DSE.

BEopt and jEPlus has been used exhaustively in this work and its weaknesses and strengths have been analyzed. Overall, BEopt is an excellent tool for the building design industry and has some novel approaches to some of the barriers that impede design progress. There is a rapid development in software that is enhancing functionality to the building design process, as well as enhancing the ability to quickly and accurately gather and interpret large amounts of parametric data. jEPlus is currently the best at detailed parametric handling and, when used with Evolutionary Algorithms, is an effective tool at quick, detailed multi-objective optimization. However, it still has some room for improvement as demonstrated by the Consol Optcad and BEopt examples. The ability to select a Pareto design point

on the graph and see the location of the point on the other objective space graphs is a simple yet worthwhile adjustment for the designer. Also, the ability for real time interaction with the simulator could be added to jEPlus. Functionality like this gives the designer an opportunity to alter the path of convergence to global optima more suited to the homeowner's needs. jEPlus allows for EA properties to be changed (like population or max generations) mid optimization, however, this does not change the properties of the system being simulated and does not have the same effect. Such dynamic functionality will enhance the capabilities of the designer. Finally, current multi-objective optimization tools do not integrate complex controllers very well into the energy model. MLE+ [20] is a new tool that allows for MATLAB controllers to be written for EnergyPlus components and co-simulated. Not only does this bring the capabilities of MATLAB for controller design, but it allows for component level optimization inside the simulation with MATLAB Optimization Toolbox. Up until now, we have been optimizing the way the simulations are run rather than the simulation itself. Currently, jEPlus, BEopt, and MLE+ are not compatible, however, it will be necessary to merge these capabilities, especially as more complex systems are developed in and around the home.

All of these programs show a trend towards easing the entire design process through simplification of modeling elements, enhancing simulation completion time, and assisting in the transition from model to deployment. Yet it is not currently enough to rely on one tool to achieve a full and accurate picture of the building being modeled. As has been shown, BEopt significantly improves the design and simulation time, however, it lacks in model detail and customization of components.

For this, EnergyPlus is required in order to better understand the nature of the performance of components, especially when working with NZE buildings. However, a new tool will be necessary that brings capabilities from each of these programs together to perform efficient, multi-objective optimization and trade-off for building DSE.

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