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Assessing the Impact of Occupant Behavior on Pre- and Post-Retrofit Energy Usage in Multi-Family Housing

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ASSESSING THE IMPACT OF OCCUPANT
BEHAVIOR ON PRE- AND POST-RETROFIT ENERGY USAGE IN
MULTI-FAMILY HOUSING

by

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The final copy of this thesis has been examined by the signatories, and we
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Assessing the Impact of Occupant Behavior on Pre- and Post-Retrofit Energy Usage inMulti-Family Housing

Thesis directed by Professor Moncef Krarti

ABSTRACT

This investigation creates a tool to aid in the assessment of the impacts that behavior modifications and retrofits have on whole building energy usage. The impact of behavior was quantified using a detailed sensitivity analysis. The tool was created to analyze pre- and post-retrofit/behavior modification data to determine the degree of savings incurred. BEAT can perform two types of analyses: forward and inverse. The inverse model utilizes utility data and HVAC system characteristics to determine representative building parameters. The forward model utilizes building envelope characteristics to predict energy usage and compare to an ASHRAE 90.1 baseline. BEAT was tested using two case studies and was proven to an accuracy of less than 4% when compared to a calibrated eQuest model.

The main focus of the sensitivity analysis was the effects of behavior alone. The study includes the impacts of high energy consuming behavior and low energy consuming behavior, and the effects of these behaviors when coupled with building energy retrofits. Both heating- and cooling-dominated climates were tested. For heating-dominated climates, results show a potential energy use savings of 10% when 100% of occupants adopted low-energy usage behaviors, and a savings of 40% when these behaviors were combined with a whole-building retrofit. On whole building EUI, the number of air changes per hour, the setpoint, and the setback had the most significant savings. The lighting schedule and equipment schedule had a significant impact on electrical energy use, which was met by the opposite and equivalent impact on heating energy usage. In the cooling-dominated climate, behavior had a much higher impact, accounting for 27% of the total 37% energy savings. Equpment schedule and setpoint had the highest impact. Location studies showed that the higher the heating degree days, the less sensitive the building was. Percent participation and apartment orientation also played a part finding that Southern exposed apartments are more sensitive to changes than North facing apartments.

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CHAPTER 1 : INTRODUCTION

This investigation studies the impacts that behavior modifications and retrofits have on whole building energy usage. There is an important relationship between building energy usage, properties of the building envelope, and behavior of occupants. Many different parameters of the envelope have an effect on building heating and energy usage such as envelope thermal properties, orientation, location, and percentage of windows. The usage patterns of lights, plug loads, and appliances, as well as the actual occupancy schedule are just a few of the parameters that describe how occupant behavior affects energy. In single-family homes, these behaviors can much more easily be identified, and their impact on energy usage can be directly quantified. However, in multi-family complexes, the degree of impact an occupants behavior has is more difficult to quantify.

ASHRAE Guideline 14-2002 outlines procedures for reliably measuring the energy and demand savings due to building energy management projects using measured pre- and post-retrofit data. A primary identified method involves formulating a regression model of pre-retrofit energy usage as a function of weather. This regression model is then used to predict how much energy the building would have consumed in the post-retrofit observation period had the retrofits not been implemented. The energy savings are then calculated as the difference between the prediction of baseline energy use during the post-retrofit period and measured energy use. This comparison allows the models to be applied to the same weather year (Kissock, Haberl, & Claridge, 2002). A similar approach will be used in this investigation to develop a tool to assess pre and post retrofit, and pre and post behavior modification energy usage.

A simulation/optimization environment was developed that uses inverse linear regression and forward modeling methods to calculate representative building parameters. This tool will be used to determine the effectiveness of behavior modification programs and retrofits, as described in Section 1.2: Motivation. To isolate the potential impact of various behaviors, and the sensitivity of whole building energy usage to shifts in these behaviors, a detailed sensitivity study was performed. This study includes the impacts of high energy consuming behavior and low energy consuming behavior, relative to the established baseline, and the effects of these behaviors when coupled with building energy retrofits.

1.1 Literature Review

In order to achieve the deliverable outlined in the scope of work, a detailed literature review must be performed to determine what techniques have been developed to perform inverse modeling on data sets with multiple parameters, as well as any previous research on the impact of occupant behavior on building energy usage.

1.1.1 Whole-Building Analysis

Raffio et al (Raffio, Isambert, Mertz, Schreier, & Kissock, 2007) outline a method to extract the weather-independent energy use, building balance temperature, and total heating/cooling coefficient. These values can be used to identify best practice ECMs to implement in specific cases. For example, buildings with high heating balance temperature are good targets for programmable thermostats. It may be useful to normalize utility data by floor area or number of occupants prior to analysis. The study performed showed that a high gas base load suggests a high water temperature setpoint, low efficiency water heater, or a natural gas stove. A high balance temperature indicates no night setbacks, low solar gain, and low insulation values, and a high heating slop indicates an inefficient furnace, poor insulation, and high infiltration rates (Raffio, Isambert, Mertz, Schreier, & Kissock, 2007).

Guiterman and Krarti (2011) performed energy audits on and implemented energy conservation measures on 30 low-income housing units in Colorado. Measurement and verification (M&V) of the post-retrofit energy savings was performed using three methods: two whole building approach methods and a calibrated simulation approach. The calibrated simulation approach, as outlined by *ASHRAE Guideline 14-2002*, involves the use of a commercially available hourly computer simulation program to create a model of energy used and demand of the building. Guiterman and Krarti used a temperature-based, and a degree day-based whole building approach which involves a regression analysis of pre- and post- retrofit utility data against government-reported weather data. The whole package of ECMs resulted in about 20% heating energy savings in the apartment buildings involved in the study. Three bedroom units, receiving only weatherization and programmable thermostats, saved 17%, while two- and one-bedroom units, receiving weatherization, programmable thermostats, and tankless water heaters, saved 22-27% (Guiterman & Krarti, 2011).

1.1.2 Behavior Analysis

The influence of occupants on the energy usage of a building ranges from presence and activities, affecting internal heat gain, to control actions to improve indoor environmental conditions, such as air temperature, quality, and light. User behavior is one of the most important input parameters influencing the results of building performance simulations (Hoes, Hensen, Loomans, de Vries, & Bourgeois, 2009).

According to many studies, there are measured relationships between demographics of occupants such as age and income level and energy efficiency in the home. It has been shown that seniors, singles, and low-income households were less willing to apply energy-saving measures at home. In a study conducted by Olivia Santin (Santin, 2011), four profiles were built on the basis of answers to questions about potential drivers of energy consumption in relation to income, environment and personal convenience: ‘convenience/ease’ (comfort is important, no interest in saving energy, money or the environment), ‘conscious’ (comfort is important, some environmental- and cost-awareness), ‘costs’ (awareness of energy costs and a concern to save money) and ‘climate/environment’ (concern for the environment). From this study it was found that higher education is associated with less energy consumption, and higher income with more energy consumption. Children and seniors also found to be related to statistically different use of home systems (Santin, 2011). Another study by Ouyang and Hokao found that energy education can reduce household energy consumption by more than 10% (Ouyang & Hokao, 2009).

Research by Clevenger and Haymaker showed that predicted energy consumption can change by more than 150% using all high or all low values for parameters affected by occupant behavior. Their sensitivity study on occupant effects on energy usage in elementary schools found that the parameters of occupant behavior that have the most impact on predicted results are equipment load, ventilation rate, infiltration rate, and occupant schedule. The variation in a single parameter can impact model results by up to 40%. This variation generally results in increased predicted energy usage, instead of decreased (Clevenger & Haymaker, 2006). A study by Sondregger showed that a minimum of 18% of gas consumption used for space heating was attributed to variations in occupant behavior between households. Verhallen and Van Raaj found similar results in the Netherlands, showing that 26% of energy use is associated with occupant behavior.

Many studies found that the management of the setpoint temperature has the most impact on energy usage in residential buildings. Haas et al found that higher heating degree days (HDD) correlated to a decrease in energy demand. They concluded that consumer behavior may be fully described by the chosen level of indoor temperature (Haas, Auer, & Biermayr, 1998).

A significant impact on occupant behavior stems from schedules. This includes occupant presence schedules, lighting fractions, domestic hot water, and miscellaneous equipment fractions. Al-Mumin et al studies the impact of occupant activity patterns in Kuwait. They found that, when using surveyed data versus default schedules, the model predicted a 21% increase in electricity usage (Al-Mumin, Khattab, & Sridhar, 2003). The Building America Research Benchmark Definition from the National Renewable Energy Laboratory (NREL) and the U.S. Department of Energy Commercial Reference Building Models of the National Building Stock have developed reference energy models, including schedules, for a variety of building occupancies, including multi-family (Hendron & Engebrecht, 2009) (U.S. Department of Energy, 2011). EnergyStar's Mutlifamily High Rise certification also provides guidelines, including calculation of daily schedules (Energy Star, 2012). While actual schedules for buildings are always preferred, these reports provide a standardized starting point for analysis.

1.2 Motivation

The motivation of this thesis is to work with the International Center for Appropriate and Sustainable Technology (iCAST) on their research project through the U.S. Department of Housing and Urban Development (HUD) Energy Innovation Fund (EIF)- Multifamily Energy Pilot Program. This thesis involves the creation of a tool to analyze the pre- and post-retrofit utility data from the multifamily housing units and allow a comparison to ASHRAE 90.1 for benchmarking purposes. It also begins to analyze the potential impacts of occupant behavior, and provides a comparision among energy modeling tools for iCAST to use to analyze their buildings to determine impact of energy conservation measures (ECMs).

The goal of the HUD EIF project is to assess the effect of energy conservation measures (ECMs) and behavioral change programs on energy use patterns. To achieve this, iCAST will involve 800 units in low-income multifamily housing properties in the program. 600 of these units will receive various retrofits, or energy conservation measures (ECMs), to improve the performance of the building envelope and heating, cooling, and ventilation equipment. 400 of the 600 units will be part of a control group. The remaining 200 units will participate in an education program, or behavior change measures (BCMs), prior to receiving ECMs (Track I). 200 of the ECM units will also receive BCMs, after the installation of the ECMs (Track II). Half of Track I units, and half of the Track II units will receive a feedback mechanism to notify the occupants of their energy savings progress. The groups are further broken down into units in which utilities are paid by the residents, and utilities paid by facility owners.

The main objective is to determine if it is possible to establish incentives to behavior modification for occupants in low-income multifamily housing- whether the occupant pays their utilities or not. A behavior modification package will be designed for each experimental group. iCAST will implement the packages along with ECMs, and feedback mechanisms along with with incentives designed to appeal to each group's needs. This project will be successfully completed when what combination of BCMs, incentives, and feedback mechanisms can be used to encourage resident behavior modification to maximize the potential to reduce energy usage.

CHAPTER 2 : BEAT OPTIMIZATION ENVIRONMENT

This section describes the optimization tool, BEAT (Building Energy Analysis Tool) that is used to perform pre- and post-retrofit energy savings calculations. First, the calculation methodology is discussed, as well as the optimization employed by the tool. The software development and parameters are also described.

2.1 BEAT OVERVIEW

BEAT performs two types of models: forward, and inverse. The inverse model uses a regression analysis to estimate representative parameters for the building using measured utility and weather data. There are a few common types of inverse models, this program uses change point linear (CPL) models. The forward model predicts energy usage based on a description of building systems such as construction details, HVAC system type, and operation (Krarti, 2011). BEAT is capable of using the forward model not only to predict energy usage of the building being studied, but also the energy usage the building would use if its constructions prescriptively complied with ASHRAE Standard 90.1 or 90.2 (the "ASRHAE Baseline" building).

The "representative building parameters" include the building load coefficient (BLC), the base-load (BL) and the balance temperature (T_b). The BLC characterizes the total heat transmission of the building, including infiltration losses. T_b is the outdoor temperature at which an equilibrium is reach between the heat gains and heat losses in a building. For a heating model, this is the temperature above which no heating is required.

2.2 USER INPUTS

BEAT requires the user to have, at minimum, basic knowledge of the building HVAC systems, utility data, and average monthly outdoor temperature for the period that the utility data was collected. This information is available on many utility bills, or can be found online. All of this information will allow the inverse modeling method to be performed. To perform the forward modeling method, basic construction types, areas, and insulation values (R-values and U-values) are also required. The forward modeling method cannot be performed independently of the inverse method. Only with the inverse method can the building's balance temperature (T_b)

be calculated. It is unique to every building, is dependent on HVAC operation and type, and is used to calculate building-specific degree days.

The ASHRAE Baseline and Actual Building forward models can be modeled independently of each other. The inverse method is independent of the forward method. Table 2-1 summarizes the inputs:

Table 2-1:User Inputs

Inverse Model	Forward Model	ASHRAE Forward Model
kWh/month	Wall, window, door, roof, floor areas	Wall, window, door, roof, floor areas
Therms/month	Wall, door, roof, floor construction types	Wall, door, roof, floor construction types
Average monthly outdoor temperature	Wall, window, door, roof, floor R- or U-values	ASHRAE climate zone
HVAC system efficiencies		Number of Stories
HVAC system types (i.e. gas or electric, water or air)		

2.3 GRAPHICAL USER INTERFACE

In order to obtain the required information, a graphical user interface was created which allows the user to navigate the calculation process without ever interacting with the base Matlab code. The program, entitled BEAT which stands for "Building Energy Analysis Tool" begins with a cover page, and then prompts the user to navigate both required and optional inputs.

2.3.1. Required User Inputs

The first page, after the cover page, explains the basic premise of the program and prompts the user to input system efficiencies and units. It also allows the user the option to perform a pre- and post- retrofit comparison. This information is required to perform both the Inverse and Forward calculations.

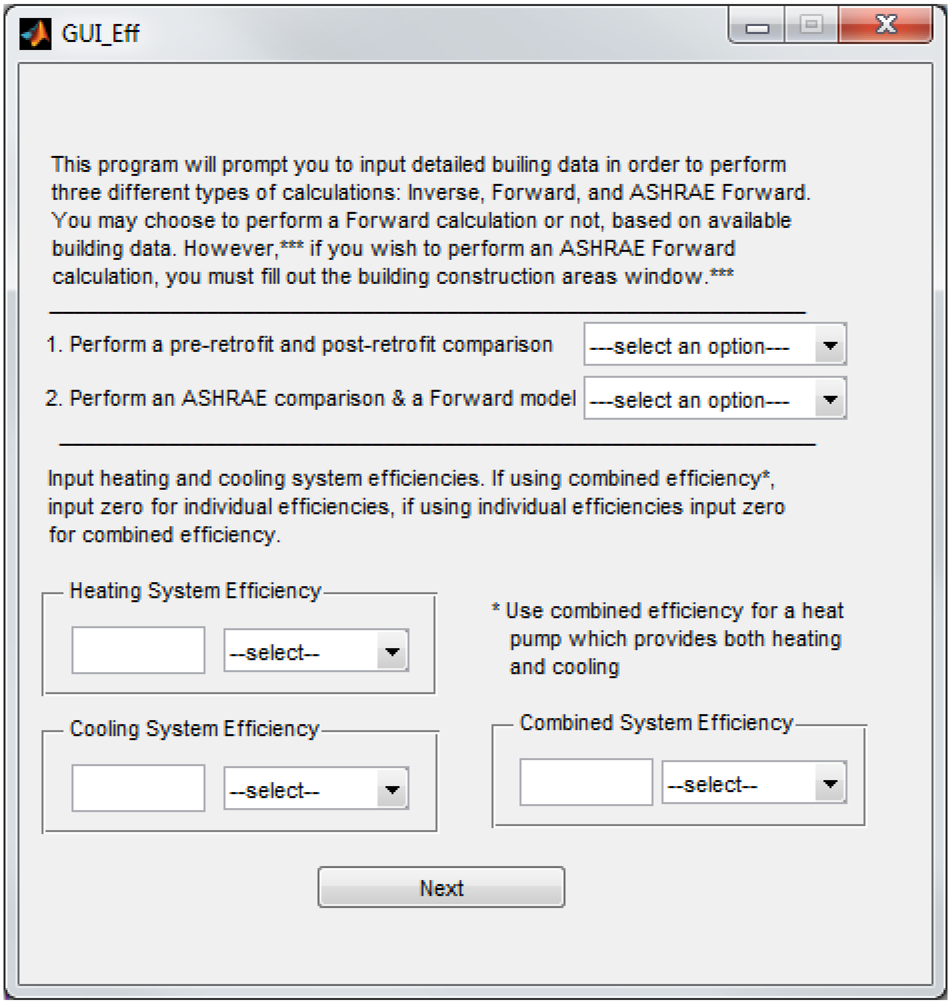

Figure 2.1: First Window of BEAT

The user must select options for all inputs, even if the input is zero. This is to ensure that no important inputs are missed. If the user does not select an option, the following error will appear:

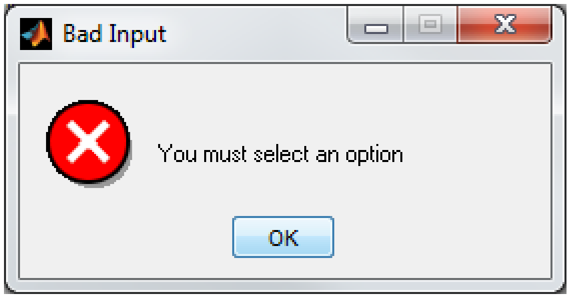

Figure 2.2: Error Window

Next, the user must input the utility data information, as well as basic information about the HVAC system type and operation. If desired, the utility data may be pulled from the utility data template, attached in Appendix B: Utility Data Template.

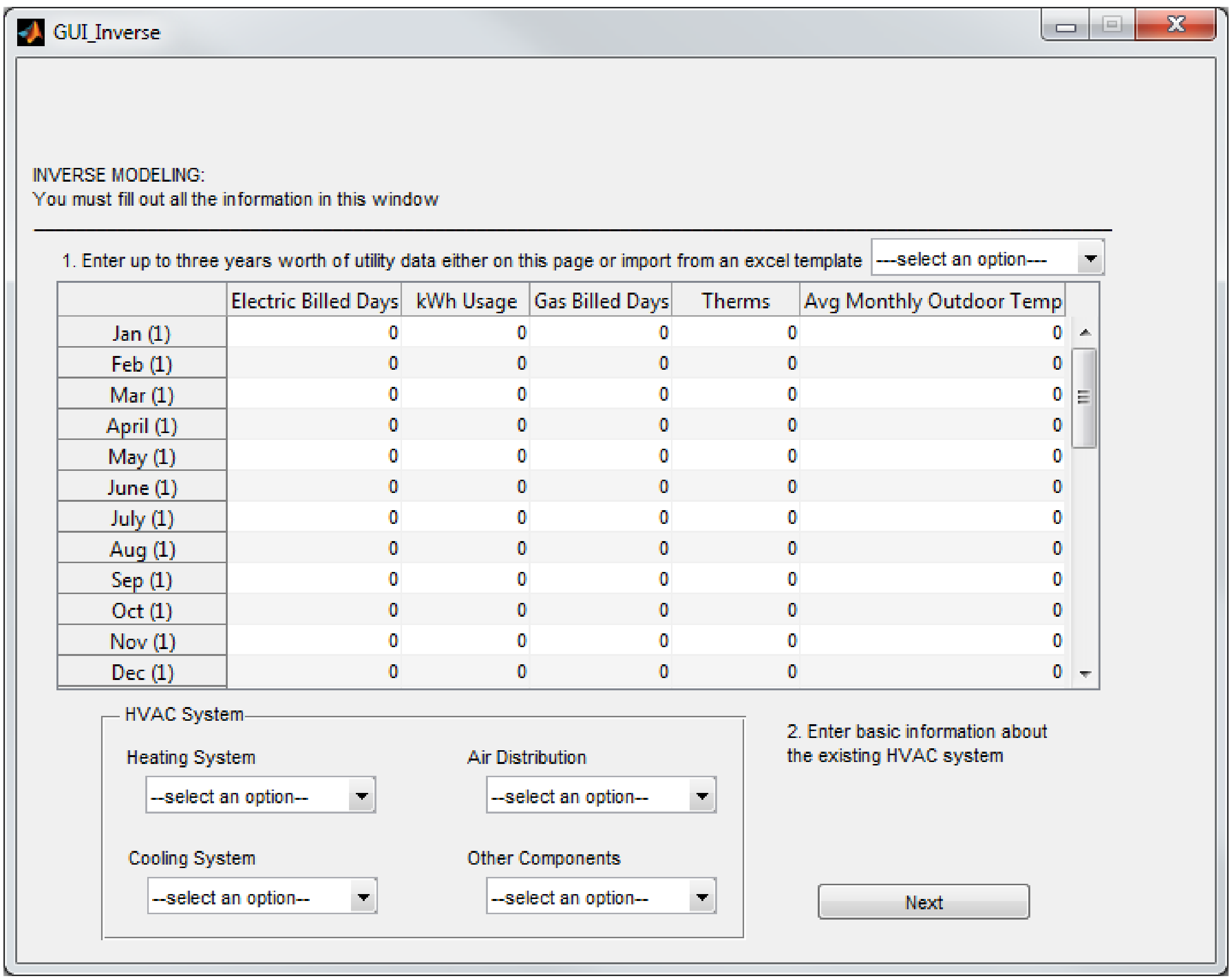

Figure 2.3: Second Window of BEAT

The following options are available for the HVAC system type and controls:

Table 2-2: HVAC System Inputs

Heating System	Cooling System	Air Distribution	Other Components
(1) Gas or oil w/ forced air	(1) Electric w/ forced air	(1) Constant Air Volume	(1) Economizer
(2) Gas or oil w/ baseboard or radiant	(2) Electric w/ baseboard or radiant	(2) Variable Air Volume	(2) Heat recovery ventilator
(3) Electric w/ forced air	(3) none	(3) none	(3) Enthalpy recovery ventilator
(4) Electric w/ baseboard or radiant			(4) none
(5) none			

These parameters are what BEAT uses to determine what the most appropriate type of change-point model to use to model the utility data. Most midrise apartments will have a furnace for heating, a packaged air-conditioning unit, and will use a single-zone constant volume air distribution method. However, many apartments in Colorado have no cooling at all, or have radiant (hot water) baseboards.

In the third page, the ASHRAE climate zone should be selected based on the map on the left, as well as the number of stories in the building being analyzed.

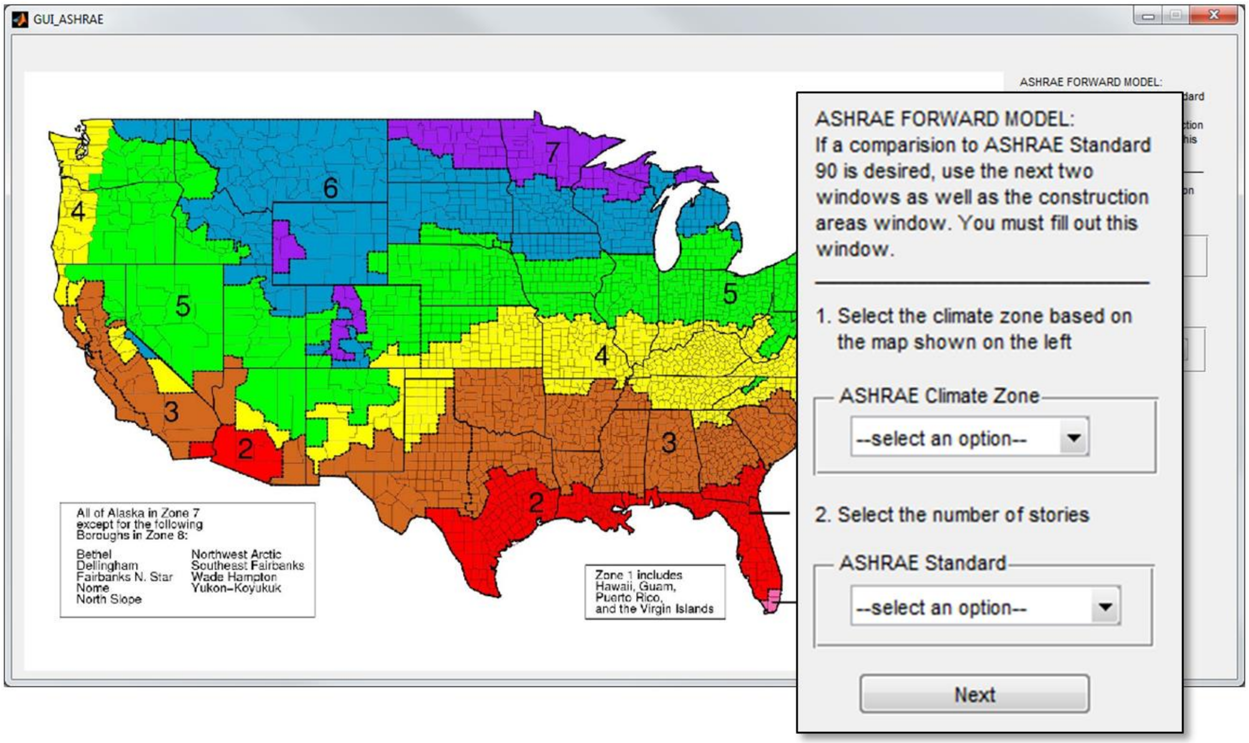

Figure 2.4: Third Window of BEAT

2.3.2 Optional User Inputs

After the required pages, are the optional, Forward modeling inputs. This part of BEAT is not required to complete the calculations, but it will add an extra element of accuracy to the model. Depending on whether the building is above 3 stories, or 3 stories or less, different menu options will appear which correspond to the constructions described in the ASHRAE Standard 90 tables.

First are the construction menus with witch the user should select the closest construction type to the building being analyzed. This menu selects the assembly U values for the ASHRAE BLC calculation. If this calculation is not required, the user must still make a selection.

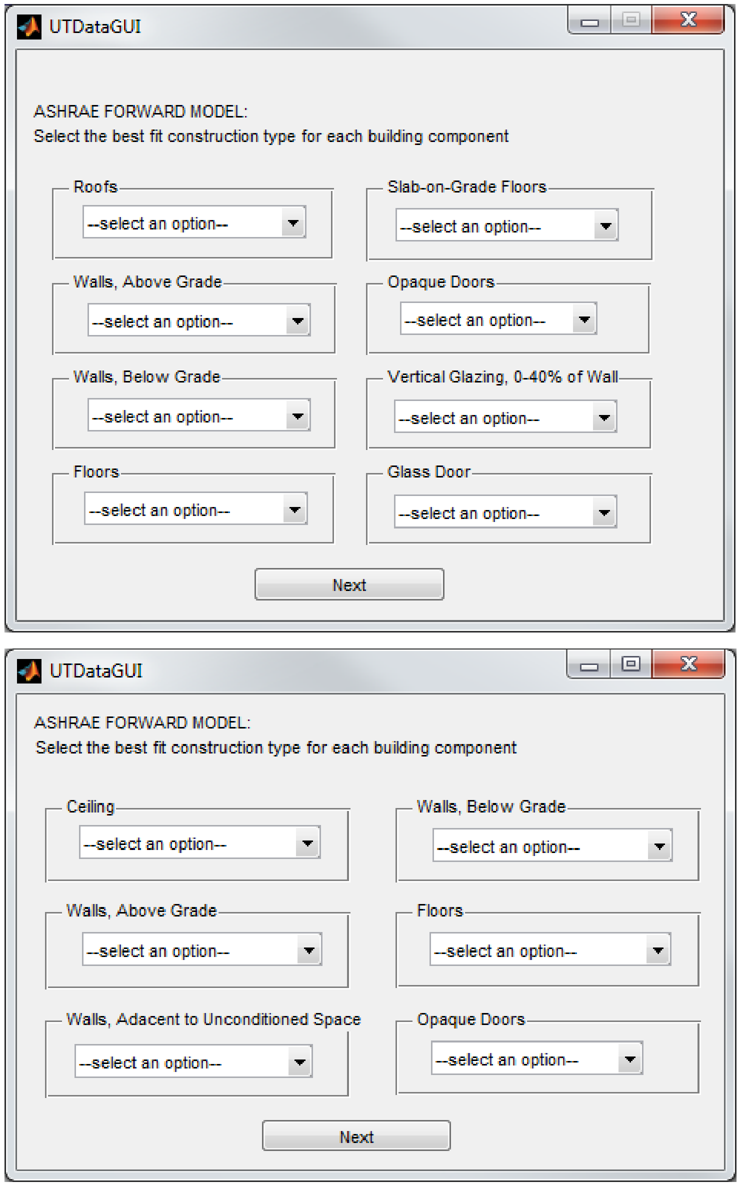

Figure 2.5: Fourth Window of BEAT

The fifth page is for inputting the actual assembly U or R values for the existing building BLC calculation. In addition, this page is where the user estimates the buildings "leakiness". The options: "tight", "average", and "leaky", correspond to infiltration air change rates of 0.5, 1.0, and 1.5 changes per hour. This parameter can be estimated by an auditor who has inspected various aspects of the building such as window and door seals. If no audit has been performed, the value can be estimated based on the age of the building. New construction would be "tight".

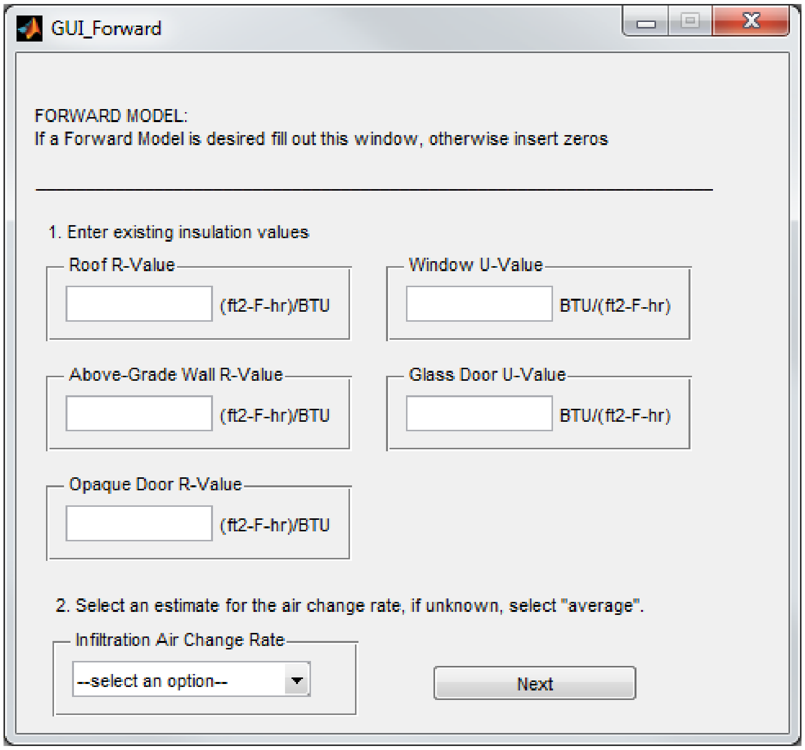

Figure 2.6: Fifth Window of BEAT

The final menus are for all above-grade exterior construction areas, as well as the building volume. The building volume will be used in conjunction with the air change rate to determine the mass flow rate of air ($\dot{m}_{inf}$) for the final BLC calculation.

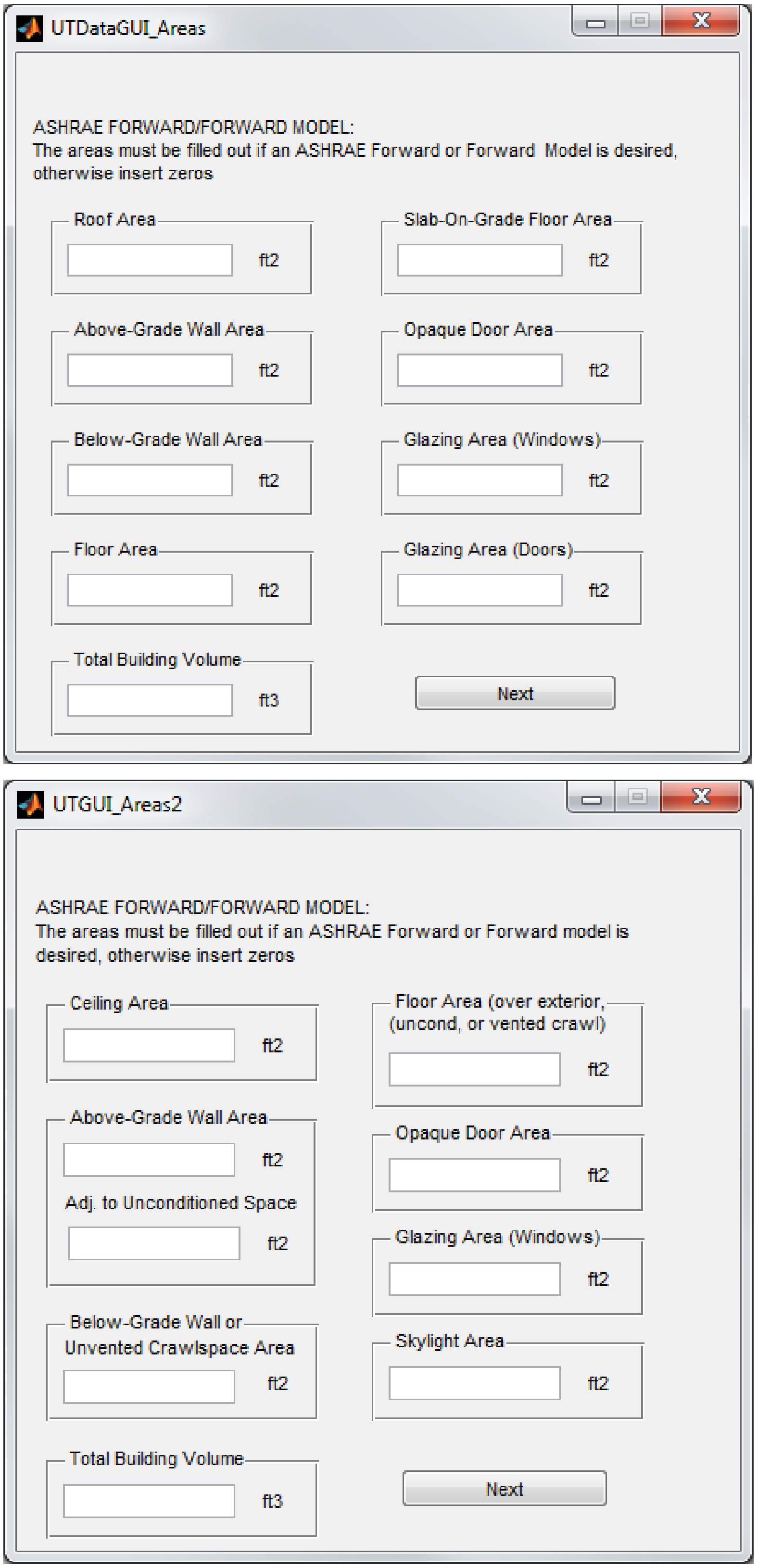

Figure 2.7: Sixth Window of BEAT

If only a pre-retrofit analysis was selected, this will be the final GUI page. If a pre- and post- retrofit comparison was selected, all of the pages, except for page 3 and 4, will pop up again for the input of post- retrofit efficiencies, utility data, and construction areas and U-values.

2.4 Forward Modeling Method

The forward modeling method is based on a physical description of the building energy systems. It can be used to determine energy end-uses and predict energy savings from ECMs. BEAT performs two forward modeling calculations: one for the actual building being tested, and one for an ASHRAE baseline building.

2.4.1 ASHRAE Baseline Building

For the ASHRAE baseline building, the prescriptive envelope requirements from Tables 5.5-1 through 5.5-8 in ANSI/ASHRAE/IES Standard 90.1-2010 for high-rise residential buildings (4 stories or above), and Table 5.2 from ANSI/ASHRAE/IES Standard 90.2-2007 for low-rise residential buildings (3 stories or below) were used to calculated an ASHRAE reference BLC. These tables can be found in Appendix A. This BLC is used as an efficiency ceiling to compare to the Forward and Inverse BLC. A lower BLC indicates better insulation values and a lower rate of infiltration. The BLC is calculated as follows (citation):

$$BLC = \sum_{j=1}^{N_E} U_{T,j} * A_j + \dot{m}_{inf} * c_{p,a} \qquad \textbf{Equation 2.1}$$

Where the exterior construction U-values ($U_{T,j}$) come from Standard 90.1 or Standard 90.2 based on the climate zone and the construction type, and the exterior construction areas (A_j) are a user input. The construction type, climate zone, and number of stories are also user inputs. The mass flow rate of infiltration is based on a user estimate of “leaky”, “average”, or “tight” corresponding to 1.5, 1.0, or 0.5 air changes per hour.

2.4.2 Actual Building

For the actual building, Equation 2.1 is used with one additional user input, the exterior construction U-values or R-values. The user may choose not to perform either the ASHRAE or Actual building Forward models by simply inputting zero into all numeric fields. However, performing both Forward and Inverse methods will yield more accurate results. `

2.5 INVERSE MODELING: CHANGE-POINT LINEAR MODELS

The change point model identifies the relationship between the building energy consumption and a weather dependent parameter; in this case, monthly average outdoor temperature. BEAT supports several types of regression models to accommodate various building energy use patterns resulting from different operation and system types. The types of models supported by the optimization tool are described below, with examples of the models shown in Figure 2.8. The inverse modeling method interpolates information about the building from historic annual energy consumption.

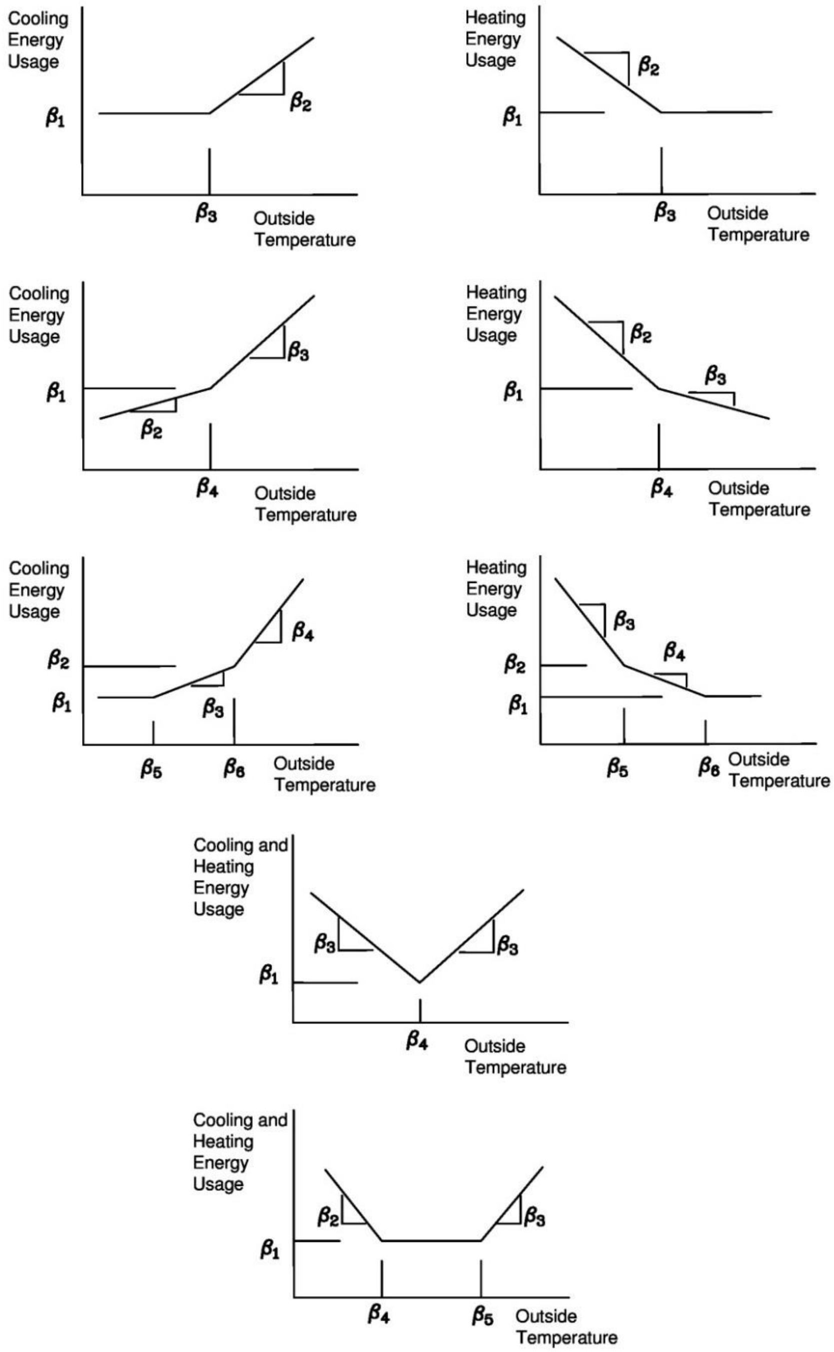

Figure 2.8: BEAT Change-Point Models

:Model types starting from the top left: 3P cooling (3PC), 3P heating (3PH), 4P cooling (4PC), 4P heating (4PH), 4P cooling type 2 (4PC2), 4P heating type 2 (4PH2), 4P cooling and heating combined (4PHC), 5P cooling and heating combined (5PHC)

2.5.1 Three-Parameter Change-Point

BEAT can find best-fit three- parameter change-point models described by the following equations:

$$Heating: E = \beta_1 + \beta_2 * (\beta_3 + T)^+$$ **Equation 2.2**

$$Cooling: E = \beta_1 + \beta_2 * (T - \beta_3)^+$$ **Equation 2.3**

In these equations, β_1 is the Y change point, β_2 is the slope, and β_3 is the X change-point. The ( ) + notation indicates that the value of the parenthetic term must be set to zero if the term turns negative (Krarti, 2011).

3P models should be used to model buildings with envelope-driven heating or cooling loads, such as are found in residential and small commercial buildings. 3PC models are often appropriate for modeling electricity use in residences with electric air conditioning. 3PH models are often used to model energy use in residences with conventional gas or oil heating (Kissock, Haberl, & Claridge, 2002).

In the code for 3PC models, β_1 is reported as the base load (BL), β_2 is the slope, (m), and β_3 is the balance temperature (T_b).

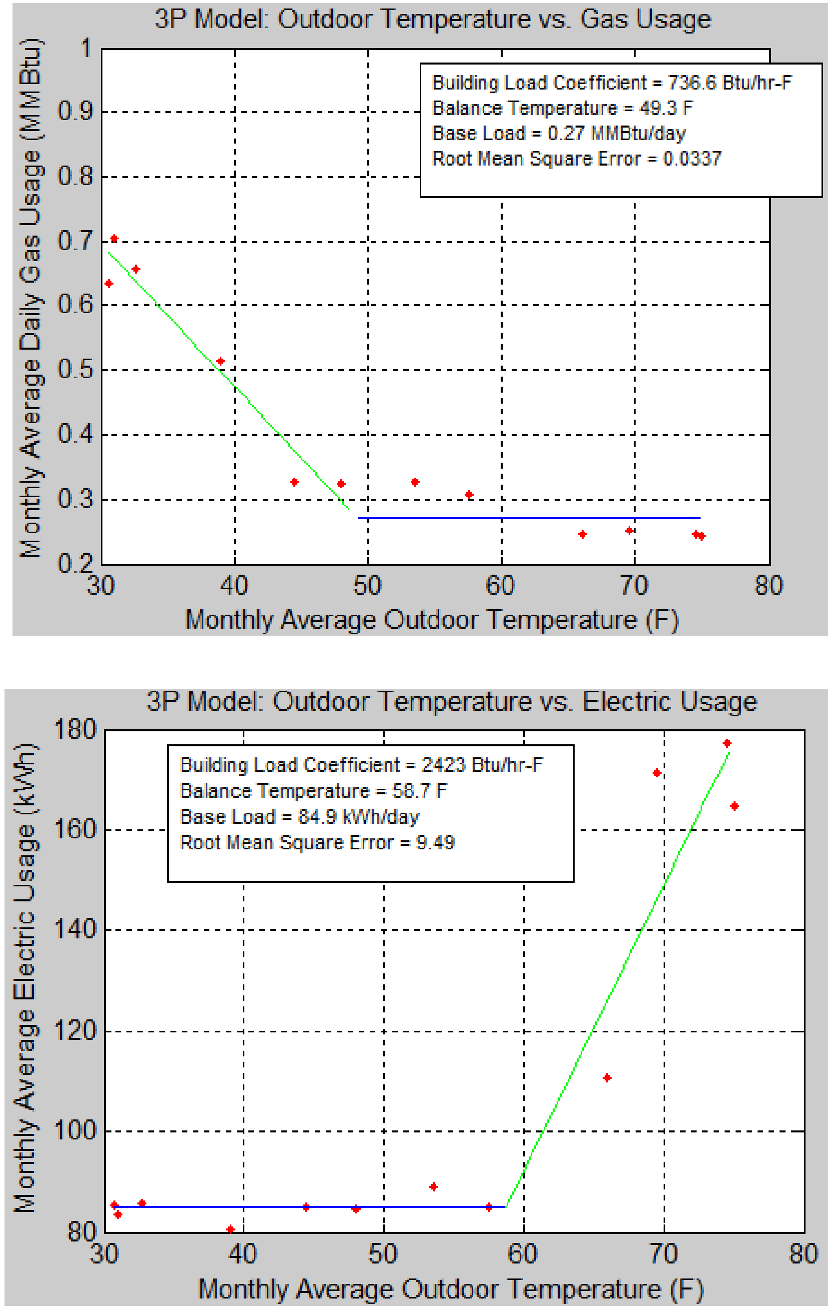

Figure 2.9*:* 3P Heating (a) and Cooling (b) Plots

2.5.2 Four-Parameter Change-Point

BEAT can find best-fit four- parameter change-point models described by the following equations:

$$E = \beta_1 + \beta_2 * (\beta_4 - T)^+ - \beta_3 * (T - \beta_4)^+$$ **Equation 2.4**

In these equations, β_1 is the Y change point, β_2 is the slope of the line to the left of the change point, β_3 is the slope of the line to the right of the change point, and β_4 is the X change-point.

4P models should be used to model buildings that use VAV systems, or for buildings with high latent loads. 4P models are also appropriate for systems with nonlinear control features such as hot-deck reset schedules and economizers (Kissock, Haberl, & Claridge, 2002). In rare occasions, 4P models can represent systems that switch between heating and cooling with no transition period. In this case, the left side of the model represents heating, and the right represents cooling.

In the code for 4P models, β_1 is reported as the Y change point (Y_CP), β_2 is the left slope (mL), β_3 is the right slope (mR), and β_4 is the balance temperature (T_b).

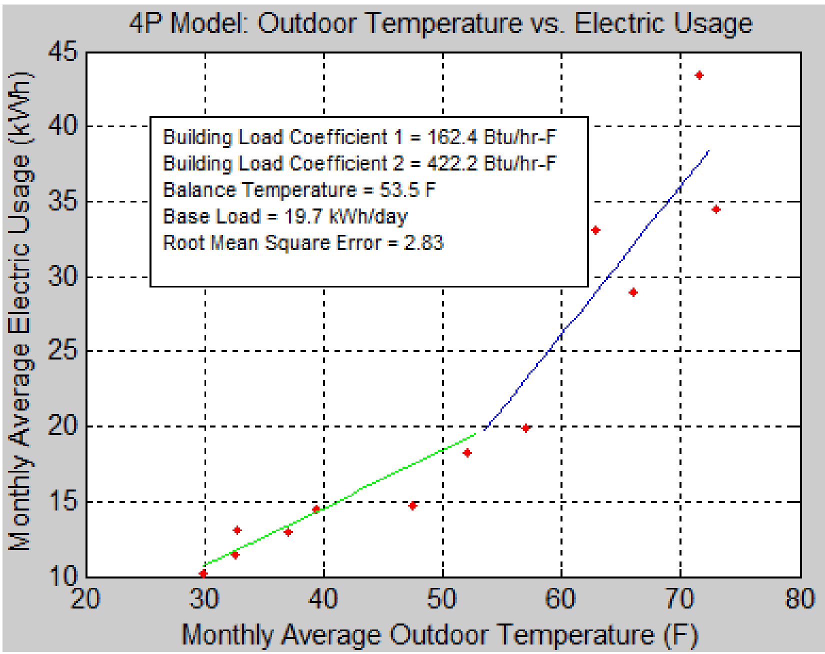

Figure 2.10: 4P Cooling Plot

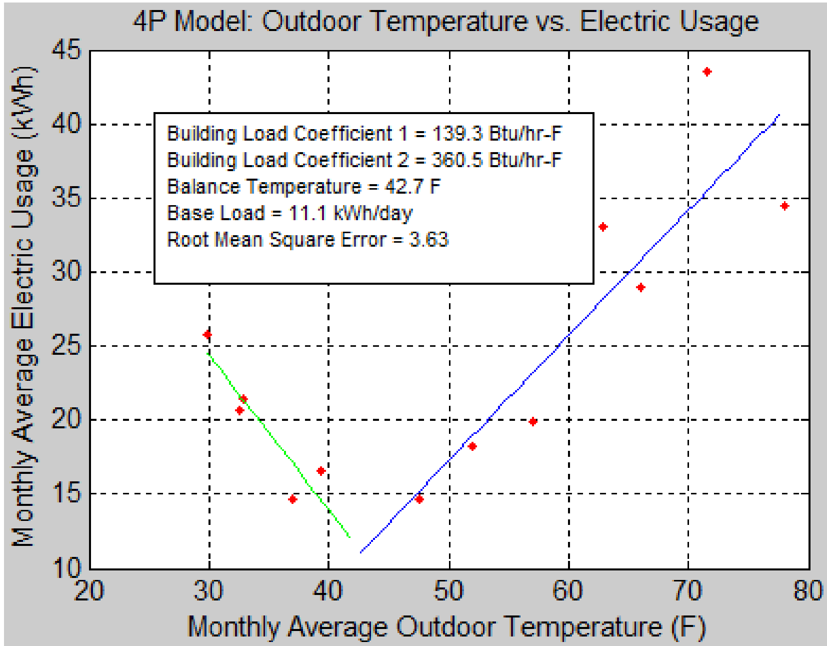

Figure 2.11:4P Combination Heating and Cooling Plot

2.5.3 Five-Parameter Change-Point

BEAT can find best-fit five- parameter change-point models described by the following equation:

$$E = \beta_1 + \beta_2 * (\beta_4 - T)^+ + \beta_3 * (T - \beta_5)^+ \quad \textbf{Equation 2.5}$$

In these equations, β_1 is the Y change point, β_2 is the slope of the line to the left of the change point, β_3 is the slope of the line to the right of the change point, β_4 is the left X change-point, and β_5 is the right X change-point. The left side of the model represents heating, and the right represents cooling, the middle section represents the transition period.

5P models should be used to model energy data which includes both heating and cooling, such as electricity data from buildings utilizing electric heat pumps or both electric chillers and electric resistive heating (Kissock, Haberl, & Claridge, 2002).

In the code for 5P models, β_1 is reported as the base load (BL), β_2 is the left slope (mL), β_3 is the right slope (mR), β_4 is the left balance temperature (T_{b1}), and β_5 is the right balance temperature (T_{b2}).

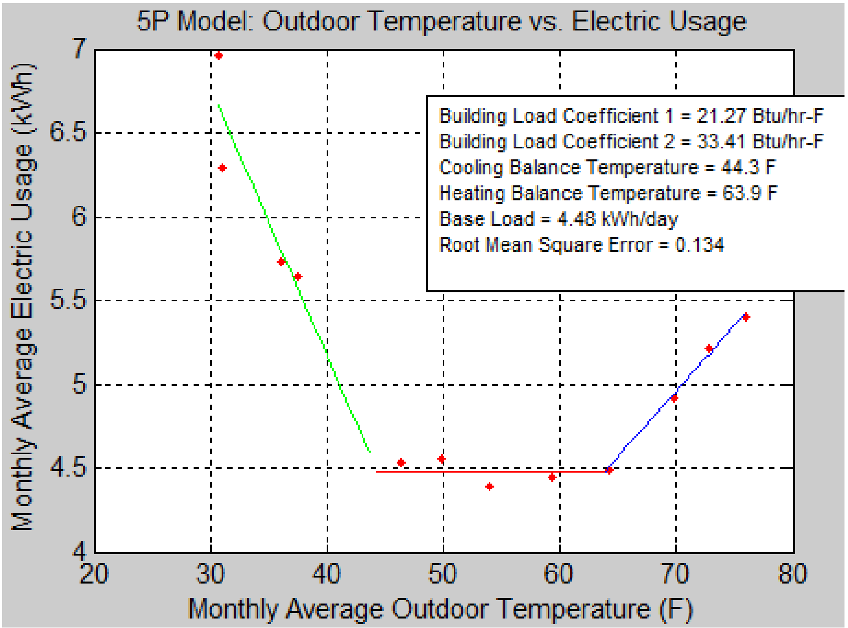

Figure 2.12: 5P Combination Heating and Cooling (b) Plots

2.6 Inverse Modeling Optimization Method

BEAT was created in the Matlab environment utilizing a variety of custom functions and scripts. Using utility data and system type as an input, it determines the optimum CPL model to describe the behavior of the building. There are three basic functions within BEAT that calculate the required information for the inverse modeling: Calc_X, Opt_X, and Graph_X, where "_X" represents the type of regression model (i.e. 3PgH, 4Pe, 5Pe), and the fuel type (gas "g", or electric "e"). Some models must be split into multiple functions based on fuel type and heating or cooling, while others can produce several models from one function. This process will be explained further in the optimization section.

2.6.1 Calculating RMSE

In the Calc_X type functions, for heating, the first section of code within this function defines the first section of the change-point model, to the left of the first X-axis separation-point (X_{SP}). The separation point is a place holder to separate the data to be regressed independently, such as in this section from the Calc_3PgH function:

```
% LEFT(=_L) PORTION OF THE 3P MODEL to the LEFT of the CHANGE POINT
% Extract data points for regression, anything less than or equal to X_SP
j = 1;
BTU_dayL = 0;
T_omL = 0;
for i = 1:length(T_om)
    if T_om(i) <= X_SP
        T_omL(j) = T_om(i);
        BTU_dayL(j) = BTU_day(i);
        j = j+1;
    end
end
```

Next, it defines the section of the model to the right of X_{SP}. This will either be a second sloped line (4P or 4P2) or a horizontal line (3P or 5P), such as in the following lines of code from the Cacl_5Pe function:

```
% STRAIGHT(=_S) PORTION OF THE 5P MODEL in between the two CHANGE POINTS
% Extract data points for the transition (horizontal) period
i = 1;
j = 1;
kWh_dayS = 0;
T_omS = 0;
while i <= length(T_om)
    if T_om(i) > X_SP1 && T_om(i) < X_SP2
        T_omS(j) = T_om(i);
        kWh_dayS(j) = kWh_day(i);
        j = j+1;
    end
i = i+1;
end
```

After splitting the data into appropriate sections, the model performs a linear regression on each section. From this regression, the slope of the regression (β_1) and the y-intercept (β_0) are calculated. Where a horizontal line is desired (such as in a 3P model), β_1 is set as zero. From this the error sum of squares (SSE) is determined for each section and in turn used to calculate the total root-mean-squared error (RMSE).

$$S_{xy} = \Sigma x_i y_i - (\Sigma x_i)(\Sigma y_i)/n \quad \textbf{Equation 2.6}$$

$$S_{xx} = \Sigma x_i^2 - (\Sigma x_i)^2/n \quad \textbf{Equation 2.7}$$

$$\beta_1 = \frac{S_{xy}}{S_{xx}} \quad \textbf{Equation 2.8}$$

$$\beta_0 = \frac{\Sigma y_i - \beta_1 \Sigma x_i}{n} \quad \textbf{Equation 2.9}$$

$$SSE = \Sigma y_i^2 - \beta_0 \Sigma y_i - \beta_1 \Sigma x_i y_i \quad \textbf{Equation 2.10}$$

$$RMSE = \frac{\sqrt{SSE_R + SSE_L + SSE_S}}{n} \quad \textbf{Equation 2.11}$$

2.6.2. Optimization

The Calc_X function is fed to the Opt_X function which optimizes the X separation-point(s) based on minimizing the RMSE. X_{SP} is tested at 0.5 °F increments from 20 to 80 °F until the lowest RMSE has been found. When the lowest RMSE is found, the optimization ends, and the RMSE, slope, and y-intercept are recorded. If there are two change points (5P or 4P2 model), the first (lowest) X separation point is tested at 0.5 °F increments from 20 to 60 °F, and the second (higher) X separation point is tested from 50 °F to 80 °F.

```
% For the specified range, calculate RMSE at 0.5 increments of X_SP
for X_SP1 = X_SP_Lmin:0.5:X_SP_Lmax;
    for X_SP2 = X_SP_Rmin:0.5:X_SP_Rmax;
        [RMSE,T_omL,T_omR,T_omS,kWh_dayL,kWh_dayR,kWh_dayS,...
            Beta1_L,Beta1_R,Beta1_S,Beta0_L,Beta0_R,Beta0_S]...
            = Calc_5Pe(T_om,kWh_day,X_SP1,X_SP2);
% Calculate the balance temperature from the intersection of regressions
        Tb_1 = (Beta0_L - Beta0_S)/(Beta1_S - Beta1_L);
        Tb_2 = (Beta0_S - Beta0_R)/(Beta1_R - Beta1_S);
% If the RMSE(n) is greater than  RMSE(n-1), then stop and retain X_SP(n-1)
        if RMSE < RMSE_5Pe && Beta1_R > 0 && (Tb_1 < 80 && Tb_2 < 80);
            RMSE_5Pe = RMSE;
            Beta1_5eL = Beta1_L;
            Beta1_5eR = Beta1_R;
            Beta1_5eS = Beta1_S;
            Beta0_5eL = Beta0_L;
            Beta0_5eR = Beta0_R;
            Beta0_5eS = Beta0_S;
```

```
            T_om5eL = T_omL;
            T_om5eR = T_omR;
            T_om5eS = T_omS;
            kWh_day5eL = kWh_dayL;
            kWh_day5eR = kWh_dayR;
            kWh_day5eS = kWh_dayS;
            Tb_5Pe1 = Tb_1;
            Tb_5Pe2 = Tb_2;
        end
    end
end
```

A check is included to ensure the balance temperature does not reach an obviously unreasonable value (80 F). T_b (β_4) is calculated as the intersection point of the regression lines to the left and right of the separation point. X_{SP} is often very close to T_b, but T_b will always be higher than X_{SP}.

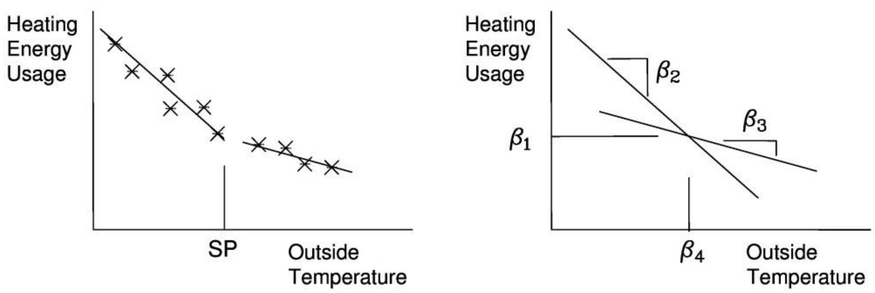

Figure 2.13: Optimization Procedure

After the variables have been optimized, the BLC and BL are calculated. For model types that do not include combined heating and cooling (same fuel for heating and cooling), these values are simply calculated using the following equations, where β_1 represents the slope:

$$Electric: BLC = ABS\left(\frac{\beta_1 * 24}{COP}\right) * 3412$$ **Equation 2.12**

$$Gas: BLC = ABS\left(\frac{\beta_1 * 24}{\eta}\right) * 1.0E6$$ **Equation 2.13**

$$T_b = \frac{\beta_{0,L} - \beta_{0,R}}{\beta_{0,R} - \beta_{0,L}}$$ **Equation 2.14**

$$Heating: BL = \beta_{0,R} + \beta_{1,R} * T_b$$ **Equation 2.15**

$$Cooling: BL = \beta_{0,L} + \beta_{1,L} * T_b$$ **Equation 2.16**

However, if the model includes combined heating and cooling, the model must check to see if the same equipment is used. If it is, the equations will use the combined heating and cooling equipment efficiency. If it is not separate efficiencies (i.e. an electric boiler and an electric chiller), in line with what the user entered in the program (see Figure 2.1), the following code will be used:

```
if COP_Comb == 0;
    BLC_5PeL = abs(Beta1_5eL*COP_H/24)*3412; % [Btu/hr-F]
    BLC_5PeR = abs(Beta1_5eR*COP_C/24)*3412; % [Btu/hr-F]
elseif COP_Comb > 0;
    BLC_5PeL = abs(Beta1_5eL*COP_Comb/24)*3412; % [Btu/hr-F]
    BLC_5PeR = abs(Beta1_5eR*COP_Comb/24)*3412; % [Btu/hr-F]
end
```

If, in Calc_X, the slope (β_1) a section is set to zero, in the Opt_X function, the resulting y-intercept (β_0) becomes the BL. The final function, Graph_X, graphs the data from Opt_X using the "plot" function built into Matlab.

2.7 BEAT Work Flow

The "START.m" file is the master file which sets the entire set of calculations in motion. It calls the GUI windows, as well as the appropriate functions to perform the required calculations. This script is the core of the program, where all functions are called and all variables are collected. All calculations are performed after the GUIs have been completed. The flow of the function and GUI calls is depicted in Figure 2.14.

After all of the GUIs have been called and the user input data has been collected (represented by the grey boxes in Figure 2.14), the calculations begin. First the "findRefBLC" function is called. This function takes the data collected in the "Optional User Inputs" section to calculate the Actual and ASHRAE Baseline BLC using Equation 2.1. For the ASHRAE Baseline BLC, the program looks up the appropriate U-value, based on the construction type and

ASHRAE climate zone, in a referenced excel file containing the tables in Appendix A: ASHRAE Standard 90 Tables.

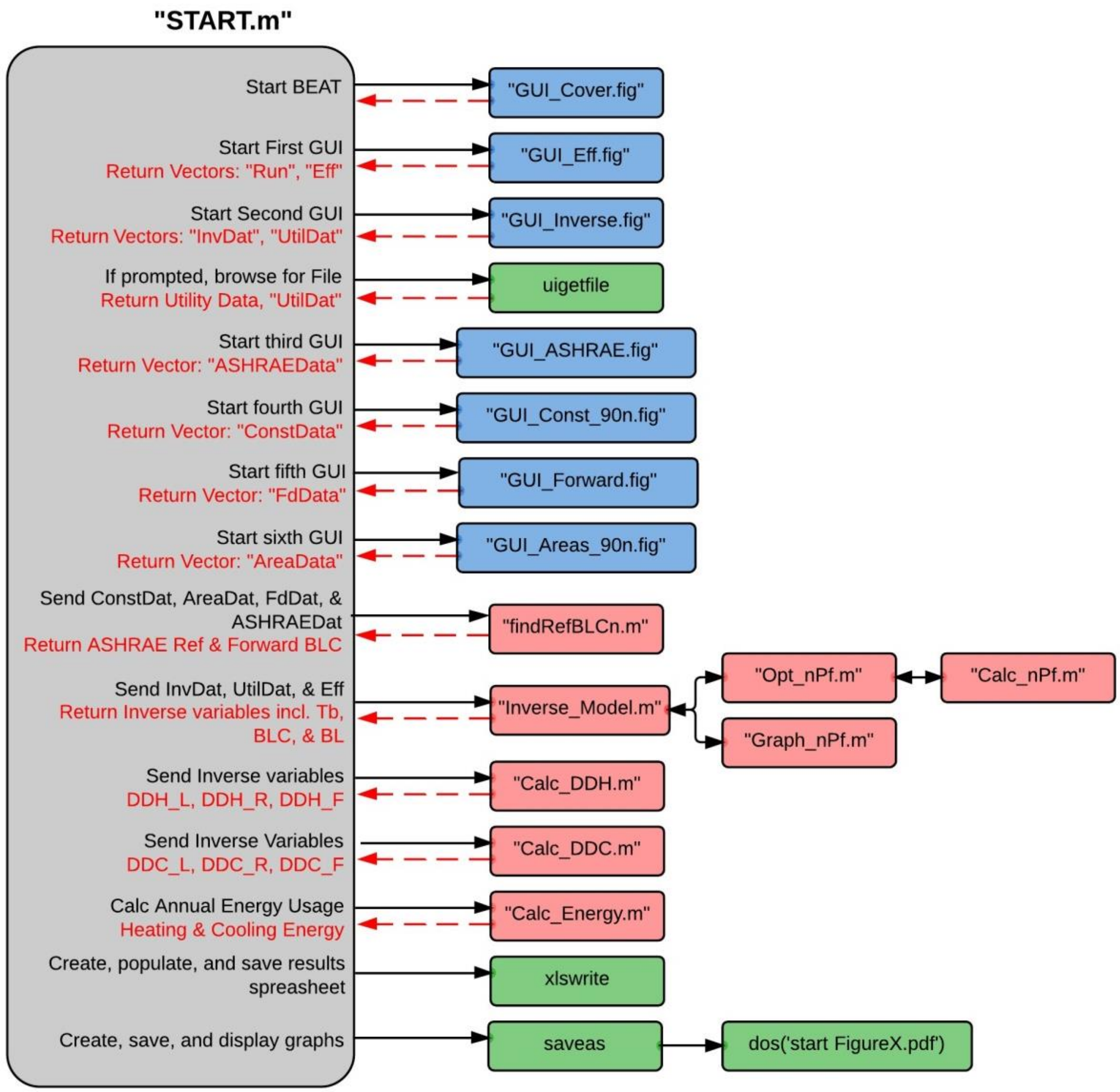

Figure 2.14: START file Workflow

Next, the "Inverse_Model" function is called. This function decides which CPL model best fits the building based on the HVAC system type and the RMSE. The handles from the GUI are converted into numbers, allowing easy identification of what option from each dropdown menu the user selected, as shown in Table 2-3.

```
InverseData(1,1) = get(handles.Heating_menu,'value')-1;
InverseData(1,2) = get(handles.Cooling_menu,'value')-1;
InverseData(1,3) = get(handles.AirDist_menu,'value')-1;
InverseData(1,4) = get(handles.Other_menu,'value')-1;
InverseData(1,5) = get(handles.Excel_menu,'value')-1;
```

Table 2-3: HVAC System Codes

Heating System	Cooling System	Air Distribution	Other Components
(1) Gas or oil w/ forced air	(1) Electric w/ forced air	(1) Constant Air Volume	(1) Economizer
(2) Gas or oil w/ baseboard or radiant	(2) Electric w/ baseboard or radiant	(2) Variable Air Volume	(2) Heat recovery ventilator
(3) Electric w/ forced air	(3) none	(3) none	(3) Enthalpy recovery ventilator
(4) Electric w/ baseboard or radiant			(4) none
(5) none			

Eight types of heating or combined heating and cooling models are identified within the code. The 3P type model will always be used to describe a system that does not contain any of the listed “other components”, and does not include heating and cooling with the same unit. A 4P model will always describe a system that features VAV, HRV, or ERV, and either a 4P or a 5P model will describe combined heating and cooling. The sections of the code which call the Opt_X and Graph_X functions have been replaced with “…”.

```
% Type 1: 3PHg: Heating w/ gas w/ forced air, & NO VAV/HRV/ERV
if (InvData(1,1) == 1 && (InvData(1,3) ~= 2 && InvData(1,4) == 4))
    ...
    P(1) = 1;
% Type 2: 4PHg or 4PHg2: Heating w/ gas w/ forced air, & VAV/HRV/ERV
elseif (InvData(1,1) == 1 && (InvData(1,3) == 2 || InvData(1,4) ~= 4))
    ...
    if (RMSE_4Pg < RMSE_4Pg2) || (Tb_5Pg2_2 >= S_min)
        ...
        P(1) = 2;
    elseif (RMSE_4Pg > RMSE_4Pg2)
        ...
        P(1) = 3;
    end
% Type 3: 3PHg: Heating w/ gas w/ water
elseif (InvData(1,1) == 2)
    ...
```

```
    P(1) = 1;
% Type 4: 3PHe: Heating w/ electric w/ forced air , NO cooling, & NO
VAV/HRV/ERV
elseif (InvData(1,1) == 3 && InvData(1,2) == 3 && (InvData(1,3) ~= 2 &&
InvData(1,4) == 4))
    ...
    P(1) = 1;
% Type 5: 4PHe or 4PHe2: Heating w/ electric w/ forced air, NO cooling, &
VAV/HRV/ERV
elseif (InvData(1,1) == 3 && InvData(1,2) == 3 && (InvData(1,3) == 2 ||
InvData(1,4) ~= 4))
    ...
    if (RMSE_4Pe < RMSE_4Pe2) || (Tb_4Pe2_2 >= S_min)
        ...
        P(1) = 2;
    elseif (RMSE_4Pe > RMSE_4Pe2)
        ...
        P(1) = 3;
    end
% Type 6: 3PHe: Heating w/ electric w/ water, NO cooling
elseif (InvData(1,1) == 4 && InvData(1,2) == 3)
    ...
    P(1) = 1;
% Type 7: 4PHCe or 5PHCe: Heating & cooling with electricity (heat pump, etc)
elseif (InvData(1,1) == 3 || InvData(1,1) == 4) && (InvData(1,2) == 1 ||
InvData(1,2) == 2)
    ...
    if (RMSE_4Pe < RMSE_5Pe)
        ...
        P(1) = 4;
        P(2) = 4;
    elseif (RMSE_4Pe > RMSE_5Pe)
        ...
        P(1) = 5;
        P(2) = 5;
    end
% Type 8a: No Heating & electric cooling
elseif (InvData(1,1) == 5 && (InvData(1,2) == 1 || InvData(1,2) == 2))
    ...
    P(1) = 6;
% Type 8b: No Heating & no cooling
elseif (InvData(1,1) == 0 && InvData(1,2) == 0 && InvData(1,3) == 0 &&
InvData(1,4) == 0);
    ...
    P(1) = 6;
else
    errordlg('No Heating System Detected','Bad Input','modal')
end
```

Similarly, there six types of cooling models identified, following the same selection guidelines as the heating models. In both sets of code, the types of model are assigned a code depending on whether they include three, four, or five parameters, whether there are one or two balance temperatures, and whether they are heating or cooling. There are 10 codes in all which are indicated in Table 2-4**: CPL Model Codes**.

Table 2-4: CPL Model Codes

P(1)	**P(2)**
1 = 3PH	7 = 3PC
2 = 4PH	8 = 4PC
3 = 5PH	9 = 5PC
4 = 4PHC	4 = 4PHC
5 = 5PHC	5 = 5PHC
6 = No heating	10 = No cooling

```
% Type 9: 3PCe: Cooling w/ electric w/ forced air, heating w/ gas or NO
heating, & NO VAV/HRV/ERV
if (InvData(1,2) == 1 && (InvData(1,1) == 1 || InvData(1,1) == 2 ||
InvData(1,1) == 5) && (InvData(1,3) ~= 2 && InvData(1,4) == 4))
    ...
    P(2) = 7;
% Type 10: 4PCe: Cooling w/ electric w/ forced air, heating w/ gas or NO
heating, & VAV/HRV/ERV
elseif (InvData(1,2) == 1 && (InvData(1,1) == 1 || InvData(1,1) == 2 ||
InvData(1,1) == 5) && (InvData(1,3) == 2 || InvData(1,4) ~= 4))
    ...
    if RMSE_4Pe < RMSE_5Pe2 || (Tb_5Pe2_2 <= S_max)
        ...
        P(2) = 8;
    elseif RMSE_4Pe > RMSE_5Pe2
        ...
        P(2) = 9;
    end
% Type 11: 3PCe: Cooling w/ electric w/ water, Heating w/ Gas
elseif (InvData(1,2) == 2 && (InvData(1,1) == 1 || InvData(1,1) == 2))
    ...
    P(2) = 7;
% Type 12: 4PHCe or 5Pe: Heating and cooling with electric (heat pump, etc)
elseif (InvData(1,2) == 1 || InvData(1,2) == 2) && (InvData(1,1) == 3 ||
InvData(1,1) == 4);
    ...
% Type 13: No Cooling & gas heating
elseif (InvData(1,2) == 3 && (InvData(1,1) == 1 || InvData(1,1) == 2));
    ...
    P(2) = 10;
% Type 14: No Cooling & electric heating
elseif (InvData(1,2) == 3 && (InvData(1,1) == 3 || InvData(1,1) == 4));
    ...
```

```
    P(2) = 10;
else
    errordlg('No Cooling System Detected','Bad Input','modal')
end
```

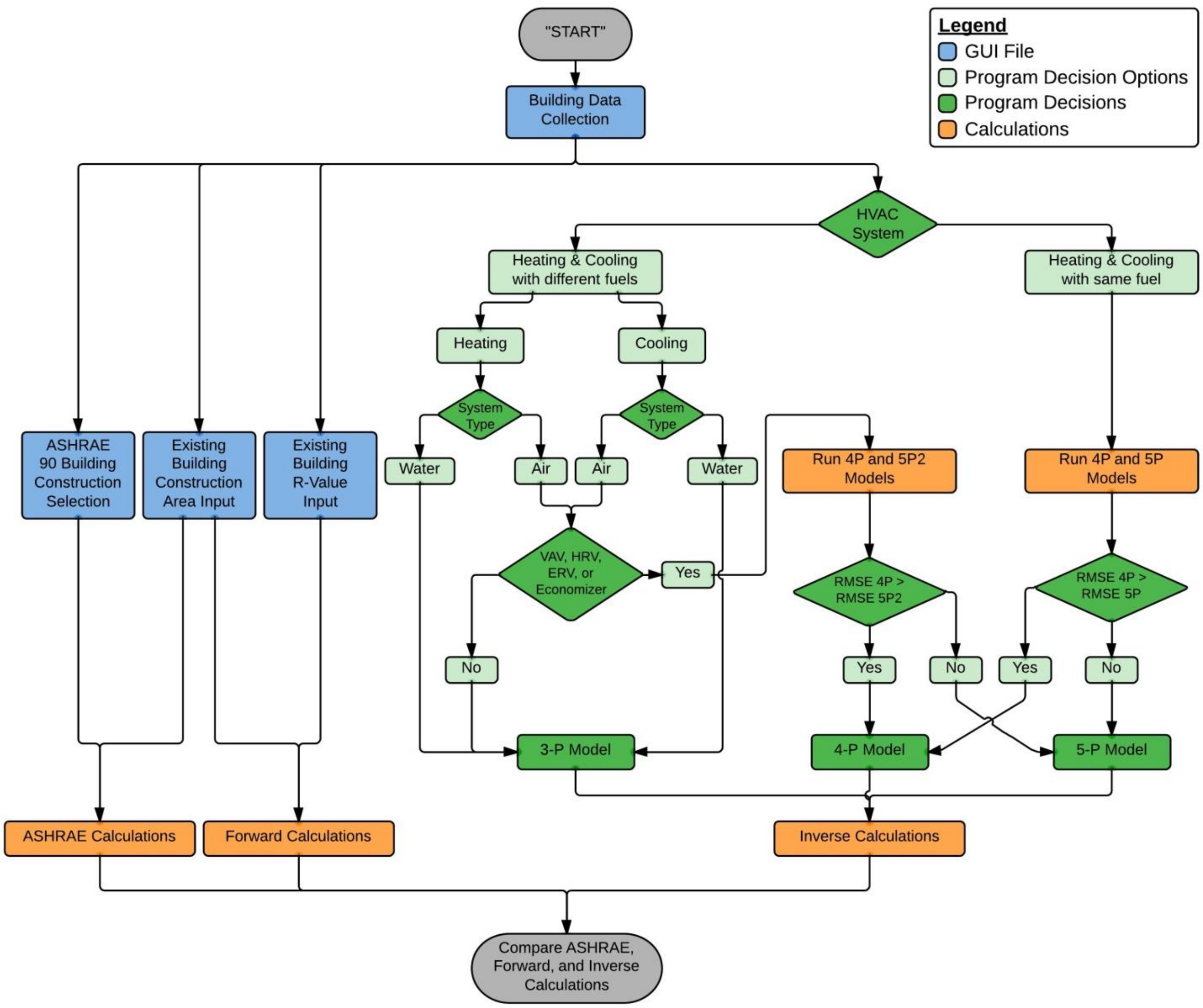

Figure 2.15: BEAT Optimization Workflow

If a model type that includes two heating or two cooling balance temperatures (Code 2, 3, 8, or 9), it also includes two BLCs. Therefore, the inverse model optimization must be rerun using a 3P model, to enable calculations to be performed using the forward model which always only produces one BLC. This new balance temperature will only be used with the forward model energy use calculations.

2.8 ANNUAL HEATING AND COOLING ENERGY USAGE

After the Inverse, Forward, and ASHRAE Forward BLCs are calculated, BEAT also breaks down the annual gas or electric energy usage use for heating and cooling. Energy usage is calculated using the following basic equations:

$$E_H = \frac{f * BLC * DDH(T_b)}{efficiency} \quad \textbf{Equation 2.17}$$

$$E_C = \frac{f * BLC * DDC(T_b)}{efficiency} \quad \textbf{Equation 2.18}$$

where “f” is the number of hours of operation per day. For the purpose of this study, “f” will be taken as 24 hrs/day. Efficiency would be either AFUE or COP for heating, and COP for cooling.

The heating degree days (DDH) are calculated using the simplified method proposed by Erbs, Klein, and Beckman (Equation 2.19), and cooling degree days (DDC) are calculated using the method proposed by Schoenau and Kehrig (Equation 2.20) (Krarti, 2011).

$$DD_H(T_b) = \sigma_m * N_m^{3/2} * \left[\frac{\theta}{2} + \frac{\ln(e^{-a*\theta} + e^{a*\theta})}{2 * a}\right] \quad \textbf{Equation 2.19}$$

$$DD_C(T_b) = \sigma_m * N_m * [Z_m * F(Z_m) + f(Z_m)] \quad \textbf{Equation 2.20}$$

Equation 2.17 and Equation 2.18 can be used for both Inverse and Forward models where there is only one change point for heating and for cooling (3P, 4PHC, 5PHC). However, where there are two change points, two degree day calculations must be made based on the two balance temperatures, and the following equations must be used to calculate energy usage:

$$E_H = \frac{f * [BLC_L * DDH(T_{b1})_L + BLC_R * DDH(T_{b2})_{R-L}]}{efficency} \quad \textbf{Equation 2.21}$$

$$E_C = \frac{f * [BLC_R * DDC(T_{b2})_R + BLC_L * DDC(T_{b1})_{L-R}]}{efficency} \quad \textbf{Equation 2.22}$$

where $DDH(T_b)_{R\text{-}L}$ and $DDC(T_b)_{L\text{-}R}$ are calculated as the difference between the degree days calculated form the right and left balance temperatures, respectively. This is done to ensure that no degree days are doubly accounted for. This also includes 4P models which, while technically have only one balance temperature, the second x change point must be used to calculate degree days for the secondary slope (BLC).

The user is allowed to enter efficiency in the form of annual fuel utilization efficiency (AFUE) for heating with gas, and coefficient of performance (COP), energy efficiency ratio (EER), or seasonal energy efficiency ratio (SEER) for heating or cooling with electricity. The annual energy use calculations use AFUE and COP, so an input of EER or SEER must be converted to COP using the following equations:

$$COP = \frac{EER}{3.413}$$ **Equation 2.23**

$$EER = -0.02 * SEER^2 + 1.12 * SEER$$ **Equation 2.24**

If there are two change points, the calculation of heating degree days must be adjusted for the Forward models, since there is only one BLC. Therefore, in the cases where BEAT chooses a 4P or 5P2 model, a second optimization must be run resulting in a 3P model, and the Forward and ASHRAE Forward models will use the resulting balance temperature to calculate degree days, and, ultimately, energy usage.

2.9 OUTPUT DATA FILES

After the calculations are complete, BEAT will output an excel file entitled "BEATResults.xls" listing the following calculated parameters

Table 2-5: **BEAT Output Parameters**

Parameter	**Units**
Tb Heating 1	°F
Tb Heating 2	°F
Tb Cooling 1	°F
Tb Cooling 2	°F
Tb Combined	°F
Heating Degree Days	°F -day
Cooling Degree Days	°F -day
ASHRAE Reference BLC	Btu/hr-°F
Forward BLC	Btu/hr-°F
Gas Heating Left BLC	Btu/hr-°F
Gas Heating Right BLC	Btu/hr-°F
Electric Heating Left BLC	Btu/hr-°F
Electric Heating Right BLC	Btu/hr-°F
Electric Cooling Left BLC	Btu/hr-°F
Electric Cooling Right BLC	Btu/hr-°F
Gas Heating Base Load	MMBtu/day
Electric Heating Base Load	kWh/day
Electric Cooling Base Load	kWh/day
ASHRAE Heating Energy Usage	MMBtu/yr
Forward Heating Energy Usage	MMBtu/yr
Inverse Heating Energy Usage	MMBtu/yr
ASHRAE Cooling Energy Usage	MMBtu/yr
Forward Cooling Energy Usage	MMBtu/yr
Inverse Cooling Energy Usage	MMBtu/yr

At maximum, an output file will have four (4) balance temperatures, heating degree days, cooling, degree days, six (6) building load coefficients, two (2) base loads, and six (6) energy usages; for a total of 19 numbers. The rest of the rows in the results column will show zeros. At a minimum, an output file will have one (1) balance temperature, heating degree days, one (1) building load coefficient, one (1) base load, and one (1) energy usage; for a total of five (5) numbers.

BEAT will also output one to four graphs, entitled “Figure1.pdf”, “Figure2.pdf”, “Figure1_post.pdf” and “Figure2_post.pdf”. Figure 1 is a heating model, or a heating/cooling model, and Figure 2 is a cooling model only.

CHAPTER 3 : BEHAVIOR AND RETROFIT ANLAYSIS

One of the goals of iCAST's HUD EIF project is to target specific occupant behaviors and develop behavior conservation measures (BCMs) to ultimately decrease the amount of energy used by occupant interaction within the space. This includes opening and closing blinds, opening and closing windows, thermostat setpoints and setbacks, turning off lights when a room is unoccupied, taking shorter showers, washing machine and dishwasher operation, hang drying clothes, and using power strips or turning off electronics. However, it is not clear what the potential impact to building energy usage will be if these behaviors are implemented to varying degrees.

Therefore, a behavior sensitivity study was performed using eQuest. eQuest is a whole-building energy performance design tool running DOE-2.2; it is capable of modeling multiple zones in buildings of complex design The first step in this analysis was identifying reasonable ranges of values for the model parameters. A similar approach to what was used in Clevenger and Haymaker's research in this area was used: three values for each parameter were tested: low, medium, and high, and these parameters fall into two categories: occupant schedules, and occupant loads (Clevenger & Haymaker, 2006).

3.1 BUILDING ENERGY MODEL

The building being analyzed is the Sunnyside Retirement Village in Glenwood Springs, CO. The data for the building energy model was collected by the energy audit performed by iCAST and the resulting report. The 40,000 square foot, 4 story, residential building was constructed in 1981. It is occupied 24 hrs/day, and houses about 50-65 clients. No floor plan was available for the building, but exterior photos and Google Maps images were used to determine approximate locations of apartments and building geometry. It was estimated that the main building contains 41 apartments, and the "Club 60" building contains 8 apartments.

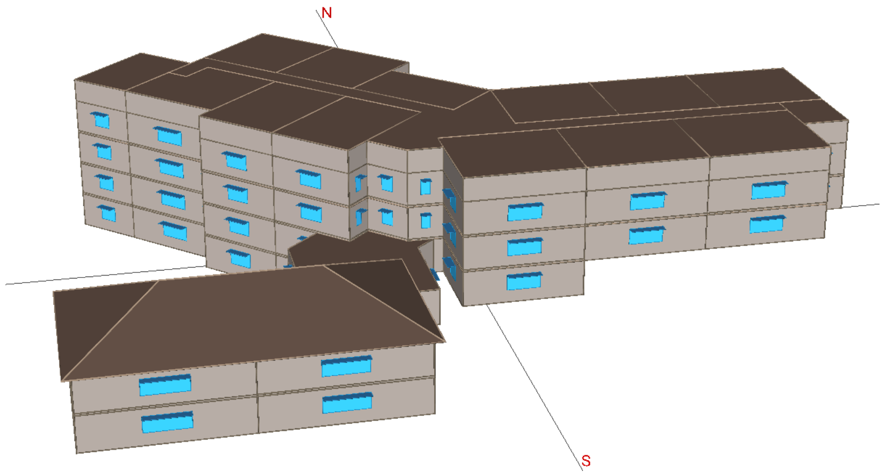

Figure 3.1: Sunnyside eQuest Model

Table 3-1: Sunnyside eQuest Baseline Inputs Summary

Parameter	Description	Value	Unit
Constructions			
Exterior Wall	2x6 steel frame, R-19 insulation between studs, stucco finish	0.118	U-value
Roof	Sloped with attic space, wood frame, R-19 insulated below deck	0.067	U-value
Window	Aluminum frame, double-pane	0.55 (COG)/1.0 (Frame), 0.76	U-value, SHGC
Overhangs	2' horizontal, 0' above, all windows		
HVAC System			
Apartments	Unit heaters, hydronic baseboards	see boilers	
Corridors	Packaged single zone, DX cooling with furnace	auto-sized	
Main Bldg Boiler	Manufacturer and model	(2) Burnham 809BWI	
	Efficiency	70	%
	Input	528,000	Btu/hr

	Output	411,000	Btu/hr
Club 60 Boiler	Manufacturer	(1) Burnham	
	Efficiency	70	%
	Input	130,000	Btu/hr
	Output	91,000	Btu/hr
DHW Equipment			
Main Bldg DHW	Manufacturer and model	x2: State SBF1002	
	Efficiency	60	%
	Input	260,000	Btu/hr
	Capacity	100	gallons
	Temperature setting	140	°F
	Supply flow rate	2.3	gpm
Club 60 DHW	Manufacturer	x1: State S8F7036ONEASMED	
	Efficiency	(60)	%
	Input	360,000	Btu/hr
	Capacity	75	gallons
	Temperature setting	140	°F
	Supply flow rate	0.5	gpm
Utility Cost			
	Electricity	0.076	$/kWh
	Natural gas	0.88	$/therm

Each apartment has a refrigerator and electric range. There is a laundry room on each floor with one washer and electric dryer, for a total of four of each. Only five of the apartments have window air conditioners. For the purposes of this study, these window AC units were ignored.

To determine the electricity usage of the appliances, the Energy Star Multifamily High Rise Program (MFHR) Simulation Guidelines (Energy Star, 2012) were referenced. The Performance Path Calculator Version 1.2 (Energy Star Performance Path Calculator Version 1.2), available on the MFHR website, calculates the power densities based on input information about the building including square footage, number of bedrooms, and quantity of each appliance. It also provides the recommended schedules for lighting, equipment, and domestic hot water (DHW), and required DHW flow rates in gallons per minute. The supply flow rate is based on a medium occupancy consumption of 25 gallons per person per day plus 16 gallons per day per clothes washer.

Table 3-2: Miscellaneous Equipment Loads

Parameter	kWh/yr	Quantity	W/ft^2	Location
Refrigerator	529	49	0.415	Apt
Clothes Washer	196	4	0.12	Common
Clothes Dryer (electric)	5398	4	0.85	Common
Range (electric)	604	49	0.474	Apt
Fixed misc. loads (electric)	1.05 (kWh/yr-ft^2)		0.5	Apt
Common area misc. loads			0.2	Common
Apartment lighting			1.0	Apt
Common area lighting			0.6	Common

Therefore, a total power density of 1.39 W/ft2 was entered into each apartment, and 0.97 for the laundry rooms. The equipment usage, including appliances and miscellaneous plug loads, is based on 5.8 hrs/day of full load operation for the apartments, and 9 hrs/day for common areas. The lighting usage is based on 2.34 hrs/day of full load operation for the apartments, and 24 hrs/day for common areas. The heating and cooling schedules are at setpoint from 6 am to 10 pm (16 hrs), with a setback from 10 pm to 6 am (8 hrs).

Three years of utility data was collected between January 2007 and January 2010. The model was calibrated to a reasonable accuracy. However, accepting a degree of inaccuracy, schedules were kept constant throughout the year to enable clear and concise adjustments for the sensitivity study.

Table 3-3: Schedules

Hour	DHW	Common Area Equip	Apartment Equip	Common Area Lighting	Apartment Lighting	Occupancy
1	0.05	0.1	0.05	0.159	0.015	0.9
2	0.05	0.1	0.05	0.159	0.015	0.9
3	0.05	0.1	0.05	0.159	0.015	0.9
4	0.05	0.1	0.05	0.159	0.015	0.9
5	0.05	0.1	0.05	0.159	0.015	0.9
6	0.05	0.3	0.05	0.159	0.015	0.9
7	0.3	0.45	0.05	0.795	0.077	0.7
8	0.5	0.45	0.05	1.430	0.139	0.4
9	0.4	0.45	0.5	1.430	0.139	0.4
10	0.3	0.45	0.5	1.113	0.108	0.2
11	0.3	0.3	0.5	1.113	0.108	0.2
12	0.35	0.3	0.5	1.113	0.108	0.2
13	0.4	0.3	0.3	0.795	0.077	0.2
14	0.35	0.3	0.5	0.795	0.077	0.2
15	0.35	0.3	0.5	0.795	0.077	0.2
16	0.3	0.3	0.5	0.795	0.077	0.3
17	0.3	0.3	0.5	0.795	0.077	0.5
18	0.5	0.3	0.5	1.113	0.108	0.5
19	0.5	0.6	0.35	2.225	0.217	0.5
20	0.4	0.8	0.05	2.225	0.217	0.7
21	0.35	0.9	0.05	2.225	0.217	0.7
22	0.45	0.8	0.05	2.225	0.217	0.8
23	0.3	0.6	0.05	1.907	0.186	0.9
24	0.05	0.3	0.05	0.159	0.015	0.9
Total	**6.7**	**9**	**5.8**	**24**	**2.34**	**13.9**

3.2 PARAMETERS TO BE STUDIED

In order to study the impact of occupant's impact on energy usage, low, medium, and high values were selected for each category. Lighting and equipment usage was varied from baseline (medium) values by 40%. The medium values are identical to the values used for calibration of the model.

Table 3-4: DOE2 Parameter Ranges

DOE-2 Parameter	Description	Ranges
LIGHTING-SCHEDULE	Hourly assignment of percentage of maximum lighting power in use	Low: 1.4 hrs/day (0.6 W/sf) Medium: 2.34 hrs/day (1.0 W/sf) High: 3.28 hrs/day (1.4 W/sf)
EQUIP-SCHEDULE	Hourly assignment of percentage of maximum equipment power in use	Low: 4.0 hrs/day (0.82W/sf) Medium: 5.8 hrs/day (1.36 W/sf) High: 7.5 hrs/day (1.90 W/sf)
PEOPLE-SCHEDULE	Hourly assignment of percentage of maximum num ber of people present	Low: 8.34 hrs/day (500 ft2/ppl) Medium: 13.9 hrs/day(700 ft2/ppl) High: 19.46 hrs/day (1167 ft2/ppl)
HEAT-TEMP-SCH	Hourly assignment of thermostat setpoint	Low: No setback Medium: 8 hr setback High: 13 hr setback
Weather File	Building location and climactic data	Wichita, KS (4A) Boulder, CO (5B) Gunnison County, CO (7B)
AIR-CHANGES/HR	Number of outdoor air changes from infiltration, also includes opening of windows and doors	Low: 0.2 Medium: 0.5 High: 2.0

Using 72 F as the highest temperature tested, three ranges of temperatures were tested for both the temperature setpoint and setback, as outlined in Table 3-5.

Table 3-5: Global Parameter Ranges

Parameter	Description	Equation
Change in setpoint	High temperature in the HEAT-TEMP-SCH	Low: 0 Medium: -2 High: -4
Change in setback	Low temperature in the HEAT-TEMP-SCH	Low: 0 Medium: -2 High: -4

The global parameters feature of eQuest was used to create a user input expression to calculate the sepoint and setback temperature based on the defined change in temperature measured from 72 F. The following user input expressions were used to define the HEAT-TEMP-SCH:

$$Setpoint: 72 + \#PA(\text{Setpoint})$$ **Equation 3.1**

$$Setback: 72 + \#PA(\text{Setpoint}) + \#PA(\text{Setback})$$ **Equation 3.2**

The four major ASHRAE climate zones in the state of Colorado were studied: Eagle (city of the closest available weather file), Boulder, and Gunnison. No weather files could be obtained for the "4B" area of Colorado, so Wichita, KS was selected (4A). Research shows that energy usage in buildings where heat loss dominates the load are more sensitive to thermostat settings, while buildings in climates where internal heat gain dominates are more responsive to occupant presence and activity level (Clevenger & Haymaker, 2006). It is then anticipate that the sensitivity analysis will show more sensitivity to thermostat settings than to other behaviors, such as occupancy and equipment schedules.

3.3 SENSITIVITY ANALYSIS

The sensitivity analysis was first performed on all 41 apartments in the building, assuming all occupants participated in the selected behavior. First, the behaviors were tested on the base building with no retrofits. Next, the same behaviors were tested on a building after it has been retrofitted. Finally, the variation in impact for different degrees of participation and for different climate zones was analyzed.

3.3.1. BCMs before ECMs

The baseline building was analyzed with the Eagle, CO weather file. First, each "high" and "low" behavior was varied one at a time off of the baseline, which includes all "medium" behaviors. Then, all of the low behaviors were combined, and again, all of the high behaviors. The "low" behaviors represent the lowest energy consumption actions, and the "high" parameters represent the highest energy consumption. All of these runs represent scenarios where occupant behavior is altered prior to any building retrofits and where 100% of the apartments participate in the selected behavior. The results show that internal gains had minimal effect on the building's normalized energy usage. However, when the energy use is broken down by fuel type, more pronounced effects can be seen.

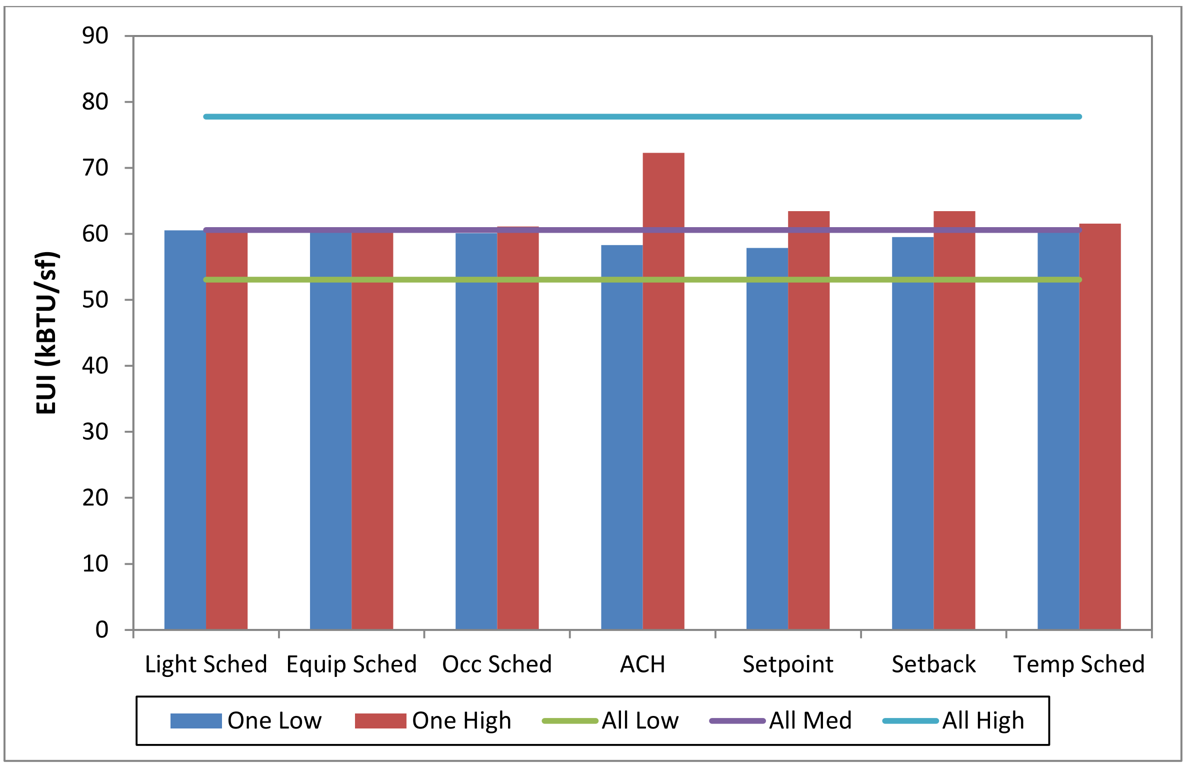

Figure 3.2: Whole-building EUI [kBtu/sf]

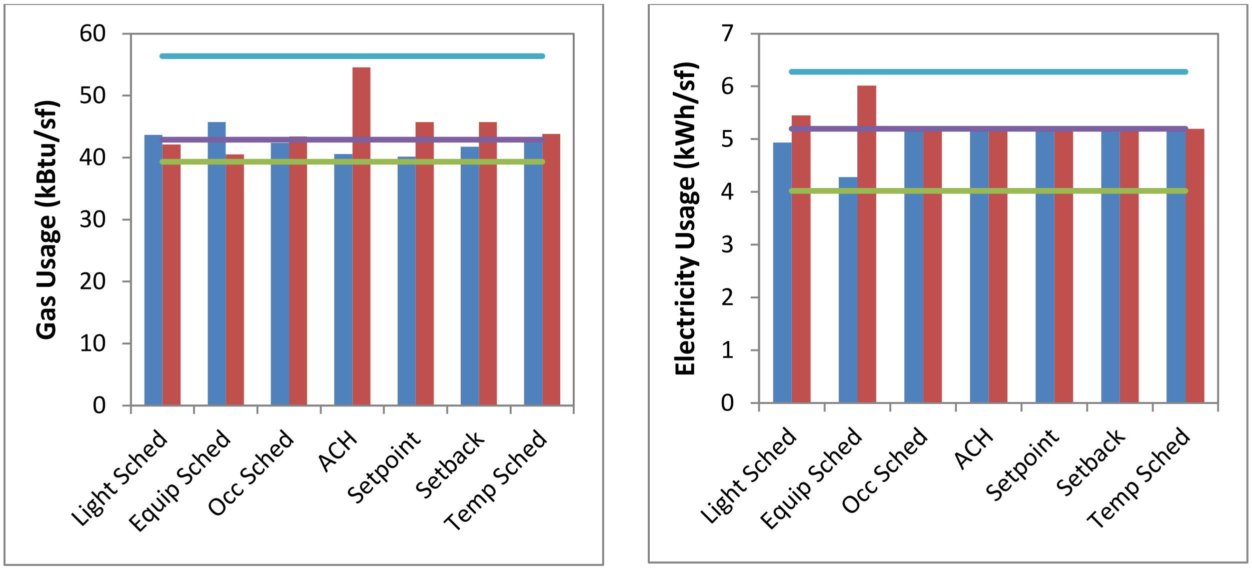

Figure 3.3: Gas EUI (a), and Electricity EUI (b)

The building analyzed is an old-vintage residential building in a cold climate. This type of building is typically skin-load-dominated, as opposed to internal-load-dominated. The reduction or increase of an internal gain, such as equipment power density, is met with the opposite behavior in required heating energy usage. Because the skin load has remained the same, a reduction of the internal loads does not reduce overall energy reduction, it only increases the heating energy usage required to offset the skin load. Only a couple measures affect electricity, while all measures affect gas (heating).

Since it is obvious that the temperature setpoint, setback, and schedule have a large impact on energy usage, these parameters were varied and combined to determine compounded effects. Figure 3.4 shows the relationship between setpoint, setback, and schedule and the EUI savings over the baseline buildings EUI. This plot shows the small difference in the 8hr and 13 hr setback, but also highlights the benefit of any setback over no setback at all.

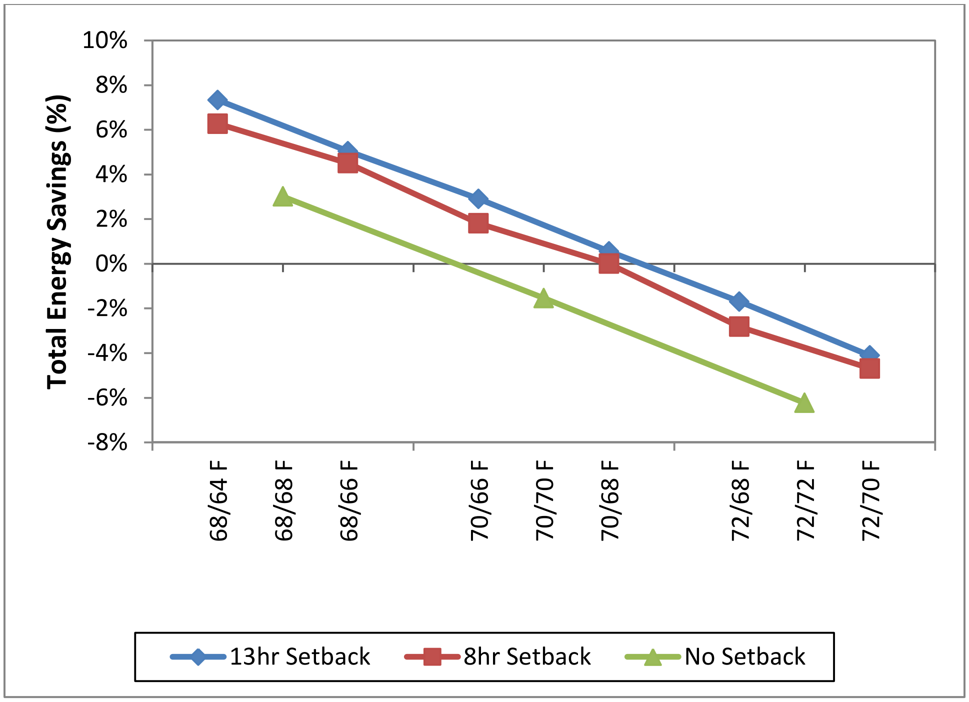

Figure 3.4: Setpoint/Setback and Schedule Combinations

From Figure 3.5, it can be seen that the length of setback yields diminishing returns. Despite this behavior, it can be estimated that for every hour of setback, 0.34% savings can be achieved with a "low" setback (-4F from the setpoint) and 0.16% savings can be achieved with a "medium" setback (-2F from the setpoint). The high setback is indicated by "0" on the x-axis.

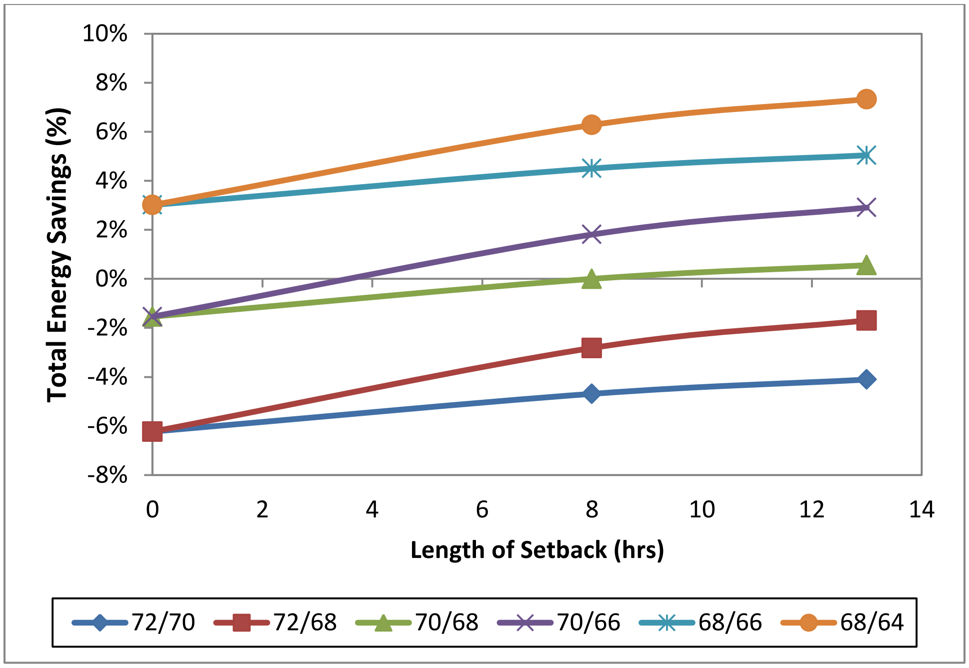

Figure 3.5: Setback Duration Savings [Setpoint/Setback (F)]

Next, the same combinations were run off of the baseline with a low ACH and a high ACH. The high ACH model used 10% to 27.5% more energy than the baseline, no matter what setpoint, setback, or schedule was applied. The low ACH model saved between 2% and 10%.

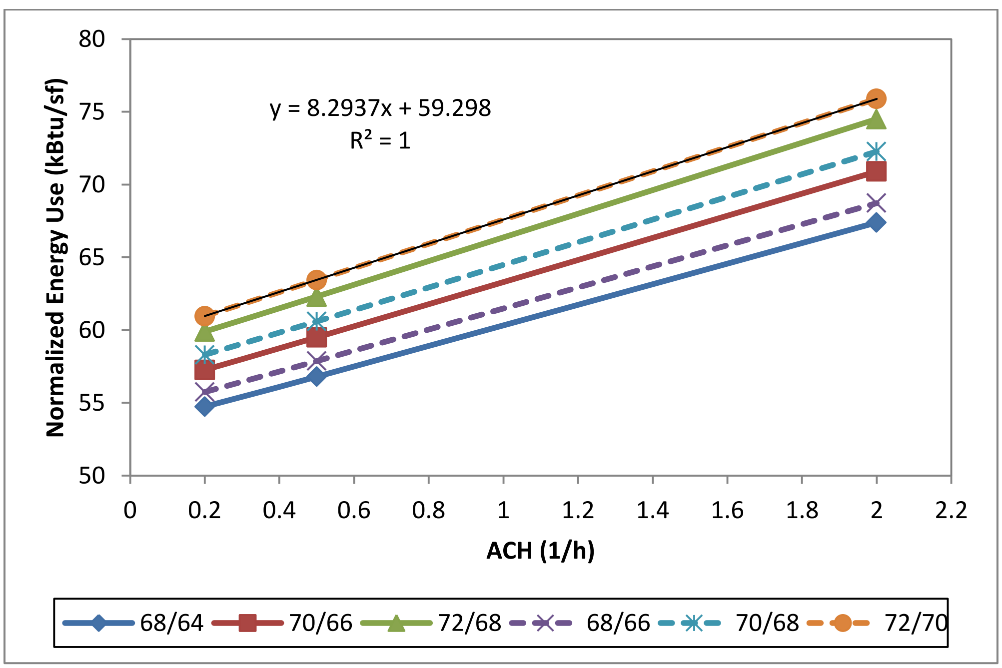

Figure 3.6: ACH Influence on Energy Use [Setpoint/Setback (F)]

Figure 3.6 shows the relationship between ACH and the building's energy use intensity (EUI). The EUI includes both electrical and gas energy usage, normalized based on the building's floor area. This relationship can also be described with a linear trendline: for every 1.0 ACH, there an increase of 8 kBtu/sf to the buildings EUI. Recall that ACH is meant to simulate the opening of windows and doors.

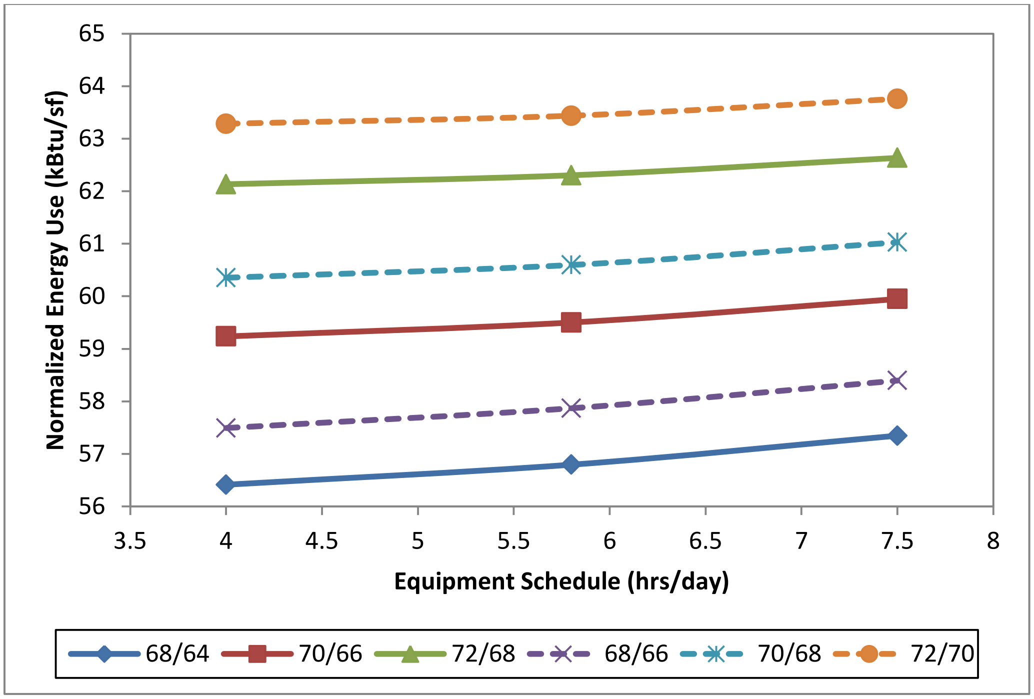

Figure 3.7: Equipment Schedule Influence on Energy Use [Setpoint/Setback (F)]

Finally, the combinations were run off of the baseline with a low equipment schedule and a high equipment schedule. The high (or long) schedule model used 1% to 6% less energy, and the low (or short) model used 2% to 8% less energy. Equipment schedule did not have a large impact on the buildings energy usage overall, because, as previously indicated, the decrease in electrical energy usage is simply met with an increase in heating energy usage.

3.3.2. Percent Participation

Next, the first sensitivity analysis was repeated to determine the effects of percent participation. Two options were tested: 30% (12 apartments) and 60% (25 apartments) participation, selected at random. Next, two more tests were performed, selecting all South or South-West facing apartments, and selecting all North or North-East apartments. Due to the symmetrical layout of the building, this corresponds to roughly 50% participation.

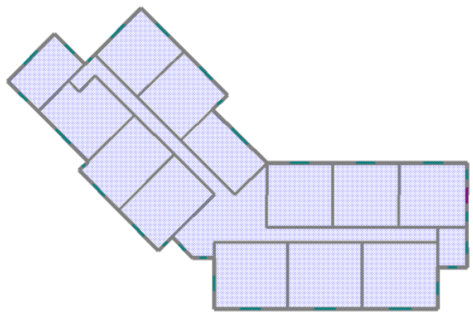

Figure 3.8: Main Building 2nd Floor Plan

To establish a baseline, the "all low" and "all high" measures were simulated with only one apartment participating.

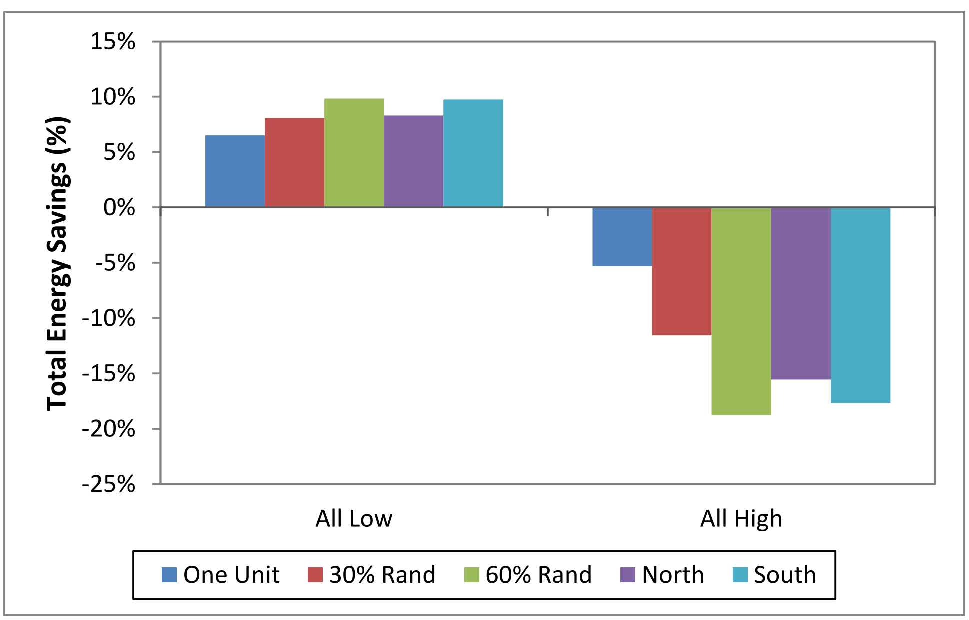

Figure 3.9: % Participation Impact on Energy Use

This study reveals that the fewer people who participate in a positive behavior which lowers total energy usage (electricity + gas), the more energy usage the building will consume. In addition, the fewer people who participate in a higher energy consuming behavior, the less energy the building will consume. Figure 3.9 shows the percent difference in energy usage relative to the baseline building, with 100% participation. Therefore, the “all low” category for 30% participation is compared to the “all low” category for 100% participation, and so on.

The “North” and “South” studies represent roughly 50% of the building each. 20 apartments fall on the north of the building, and 21 fall on the south. The apartments on the North use a disproportionate amount more energy than their South-facing counterparts. This is not surprising since South-facing apartments will require less heating energy usage.

The isolated effects of fluctuations in internal gains followed interesting behavior. Changing this behavior in one apartment showed dampened variation relative to magnifying the range to 100% or even 30% of occupants. Lowering the lighting schedule on only the North side had an insignificant benefit, while raising it had a more noticeable difference. The south-facing apartments, as well as the 100% participation scenario had the greatest sensitivity to changing lighting schedule .

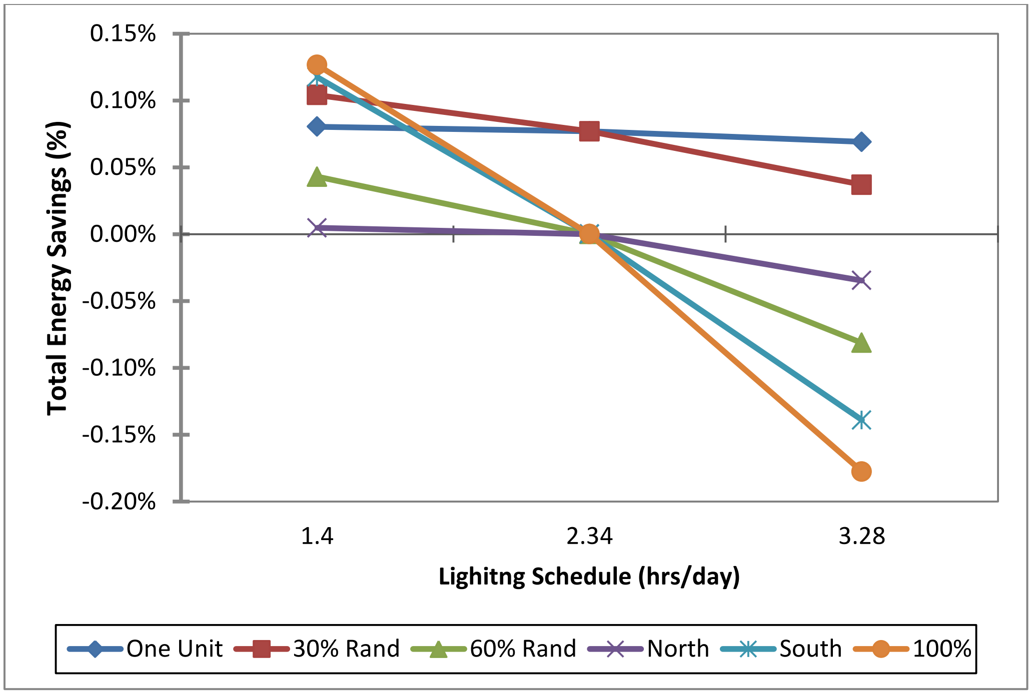

Figure 3.10: Lighting Schedule Impact for Various % Participation

3.3.3. Climate Zones

The first sensitivity analysis was repeated for three additional climate zones: 4A, 5B, and 7B. These zones were selected to represent all climate types present in the state of Colorado, which aligns with the scope of ICASTs study.

Table 3-6: Heating Degree Days for selected Climate Zones

Climate Zone	**4A**	**5B**	**6B**	**7B**
City	Witchita, KS	Boulder, CO	Eagle, CO	Gunnison, CO
HDD (base 65)	4791	5487	8222	9987

The variation in EUI between the climate zones was vastly dependent on the degree days. Variations in internal gains had little effect on electrical usage, but a notable effect on heating energy usage. This is expected due to the fact that the building being studied falls into the category of skin-load-dominated. The air changes per hour and setback, in particular, had the most dramatic differences between climate zones. For all parameters, climate zone 4A was the most sensitive to change, and 7B was the least sensitive. For all climate zones, a reduction in the lighting and equipment schedules equaled an increase in gas usage, and a reduction in the square foot per person led to a decrease in gas usage.

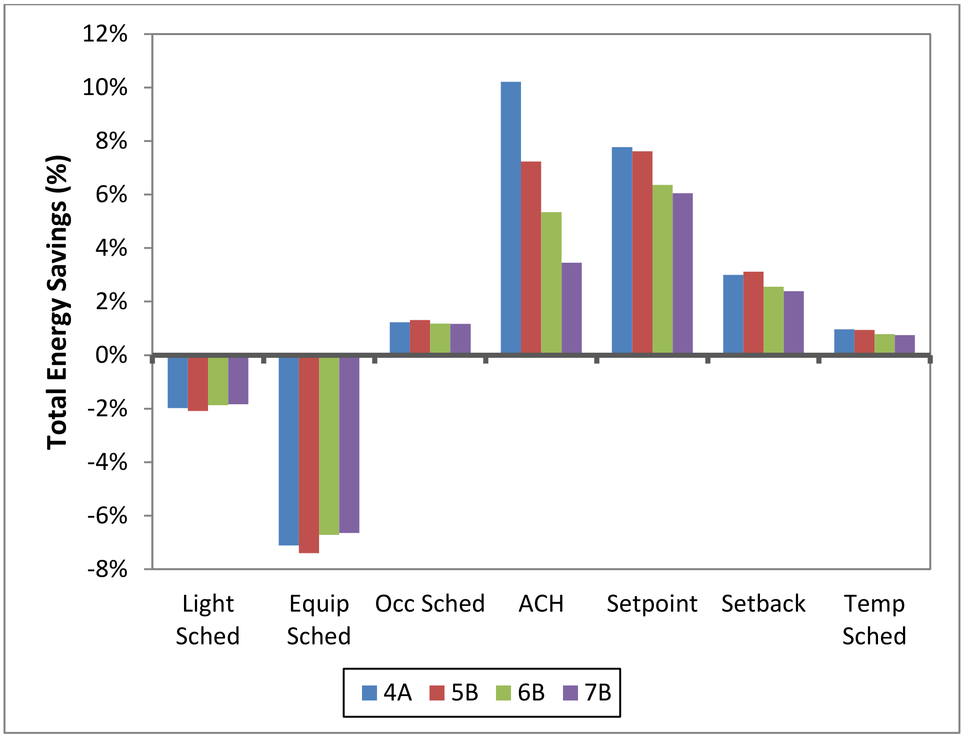

Figure 3.11: BCM Impact on Gas Energy Savings (One Low)

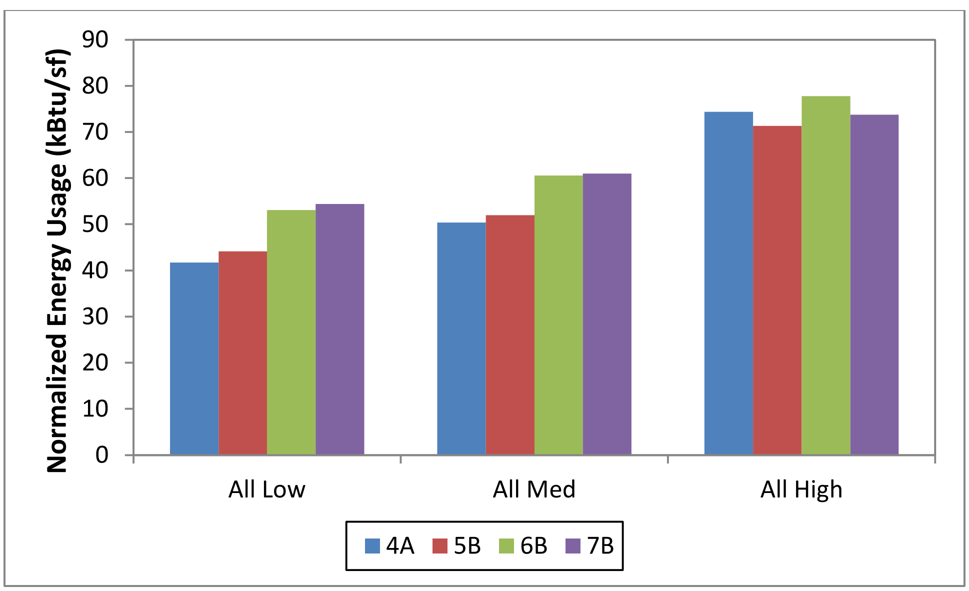

Figure 3.12: BCM Impact on EUI (kBtu/sf)

3.3.4. BCMs plus ECMs

There are a variety of ECMs implemented on the buildings in the HUD project. ECMs are tailored to the needs of each facility and will not be the same for any two buildings. Common measures include boiler replacement, domestic hot water heater replacement, addition of attic insulation, lighting updates, window replacement, and caulking/weather-stripping to reduce infiltration. For the Sunnyside retirement community, all of these ECMs were implemented. However, the lighting updates were only performed in the common areas and hallways. All of the updates but lighting were implemented in the baseline building to determine the new potential impact of occupant behavior. In addition, the impact of adding exterior wall insulation was studied.

To simulate these measures, the efficiency of the boilers was increased to standard values for new high-efficiency equipment. In addition, the water heater temperature was lowered to 120 F.

Table 3-7: Energy Conservation Measures

Parameter	**Description**	**Value**	**Unit**
Constructions			
Roof	wood frame, R-30 insulated below deck	0.034	U-value
Exterior Wall	2x6 steel frame, R-19 insulation between studs, R-5 c.i.	0.071	U-value
Window	Solarban 70 XL	0.29 (COG)/1.0 (Frame), 0.28	U-value, SHGC
HVAC System			
Main Bldg Boiler	Efficiency	80	%
Club 60 Boiler	Efficiency	80	%
DHW Equipment			
Main Bldg DHW	Efficiency	95	%

	Temperature setting	120	°F
Club 60 DHW	Efficiency	95	%
	Temperature setting	120	°F

The savings due to each retrofit individually, as well as for all retrofit measures combined was calculated. The "all medium" value, shown in Figure 3.13, indicates savings prior to any behavior sensitivity analysis. Interestingly, the window measure used slightly more energy (-0.5%) than the baseline building for this scenario. This is likely due to the decrease in solar heat gain coefficient (SHGC), and not to the decrease in assembly U-value. The lower SHGC reduces the amount of solar gain, thus increasing the demand for heating.

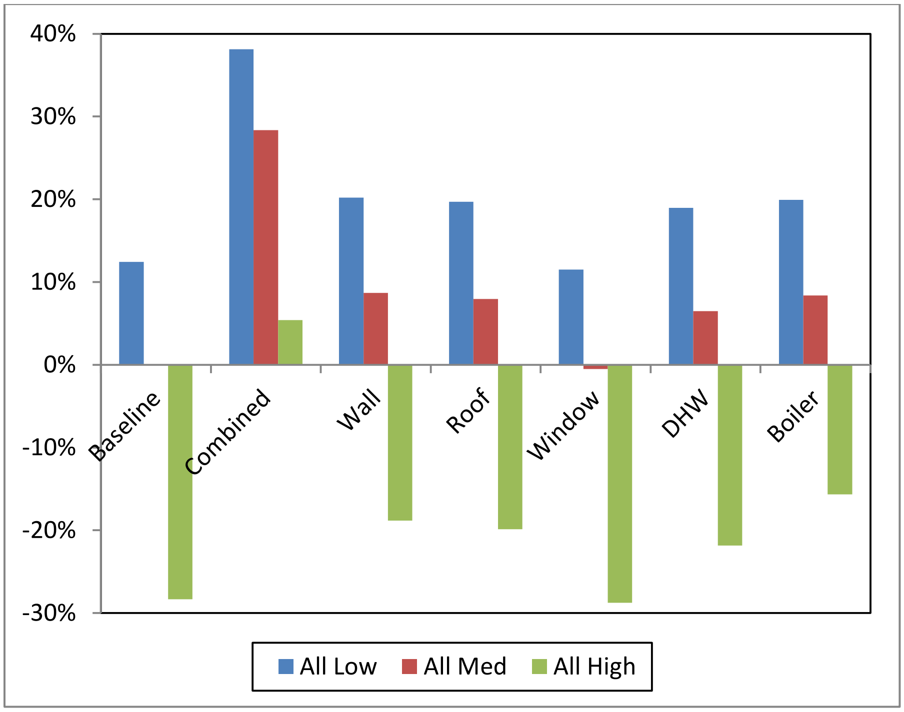

Figure 3.13: Retrofit Impact on Energy Savings

To further illustrate the relationship between BCMs and ECMs, the % savings for each ECM was plotted versus the combined energy savings of the ECM plus BCM (Figure 3.14, Figure 3.15). Recall, this is energy savings over the baseline building using all medium values.

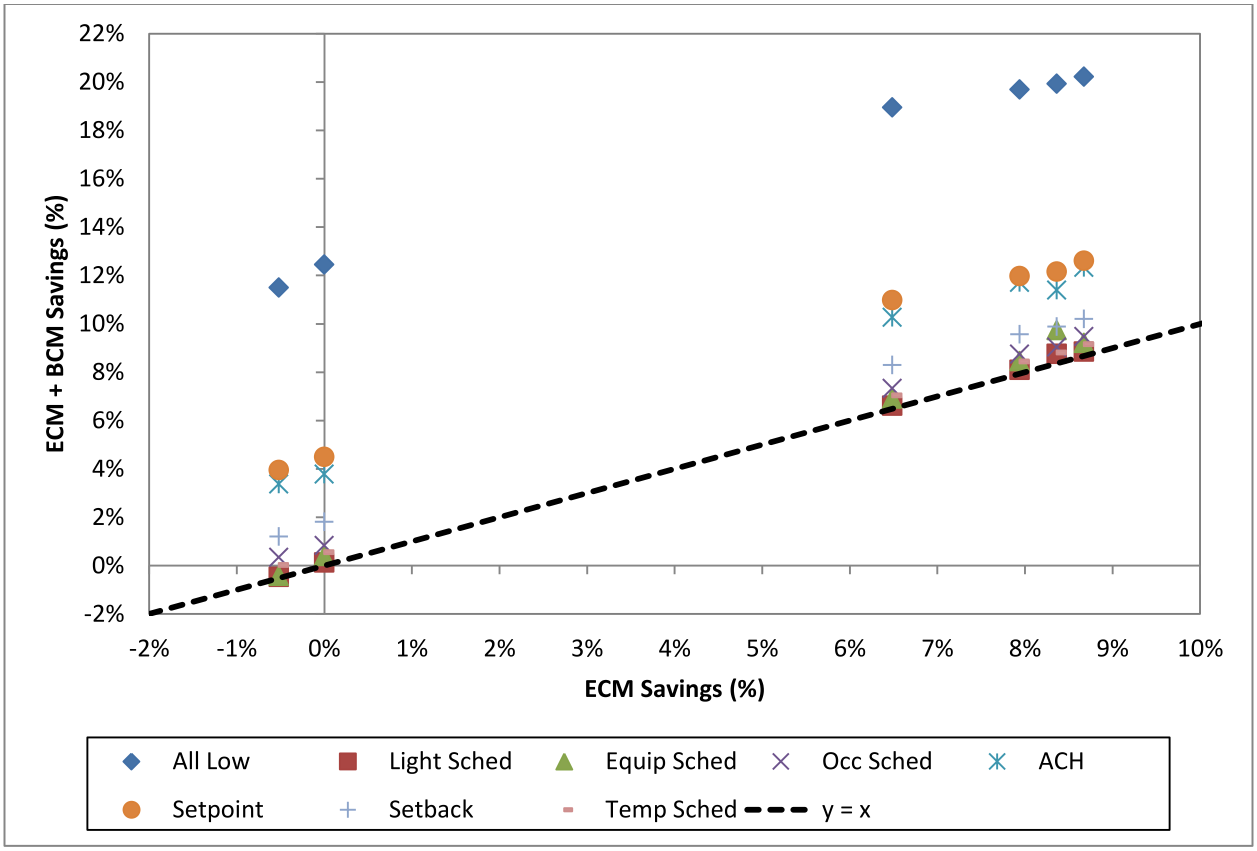

Figure 3.14: Compounded ECM and Low Case BCM Savings

For most ECMs, the "all low" BCM combination resulted in about a 12% increase in energy savings, the low setpoint temperature BCM saved 4.0%, and the low equipment schedule BCM saved 0.5%. The boiler measure benefitted more from the low equipment schedule than the other measures, saving 1.3%. This variation is likely due to a higher partial load performance and is dependent on the performance curves of the specific boiler. The window measure benefited more from the low setpoint temperature, saving 4.5%.

In contrast, the high behavior category shows that retrofitting the building cannot cancel out the higher associated energy consumption, for the more extreme cases. However, a 6.5% ECM savings , such as from updating the domestic hot water boiler, does allow the occupant to enjoy a higher setpoint temperature and still save more energy than the baseline building.

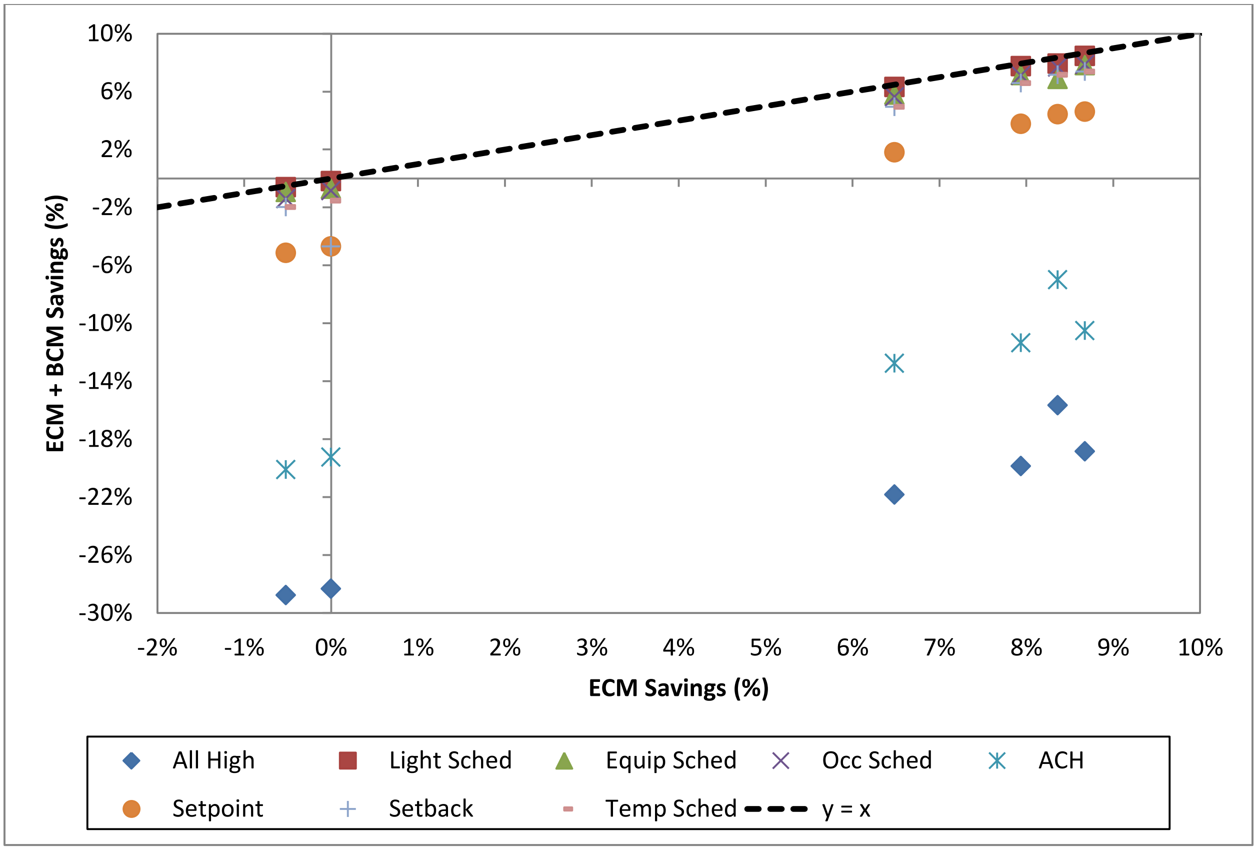

Figure 3.15: Compounded ECM and High Case BCM Savings

To further illustrate the effect of high and low-case BCMs, a select number of behaviors, high and low, were included on the same plot. Figure 3.16 clearly shows that the low behaviors save an additional percentage over the ECMs, while the high behaviors cause the initial benefit of the ECM to drop by an equivalent percentage.

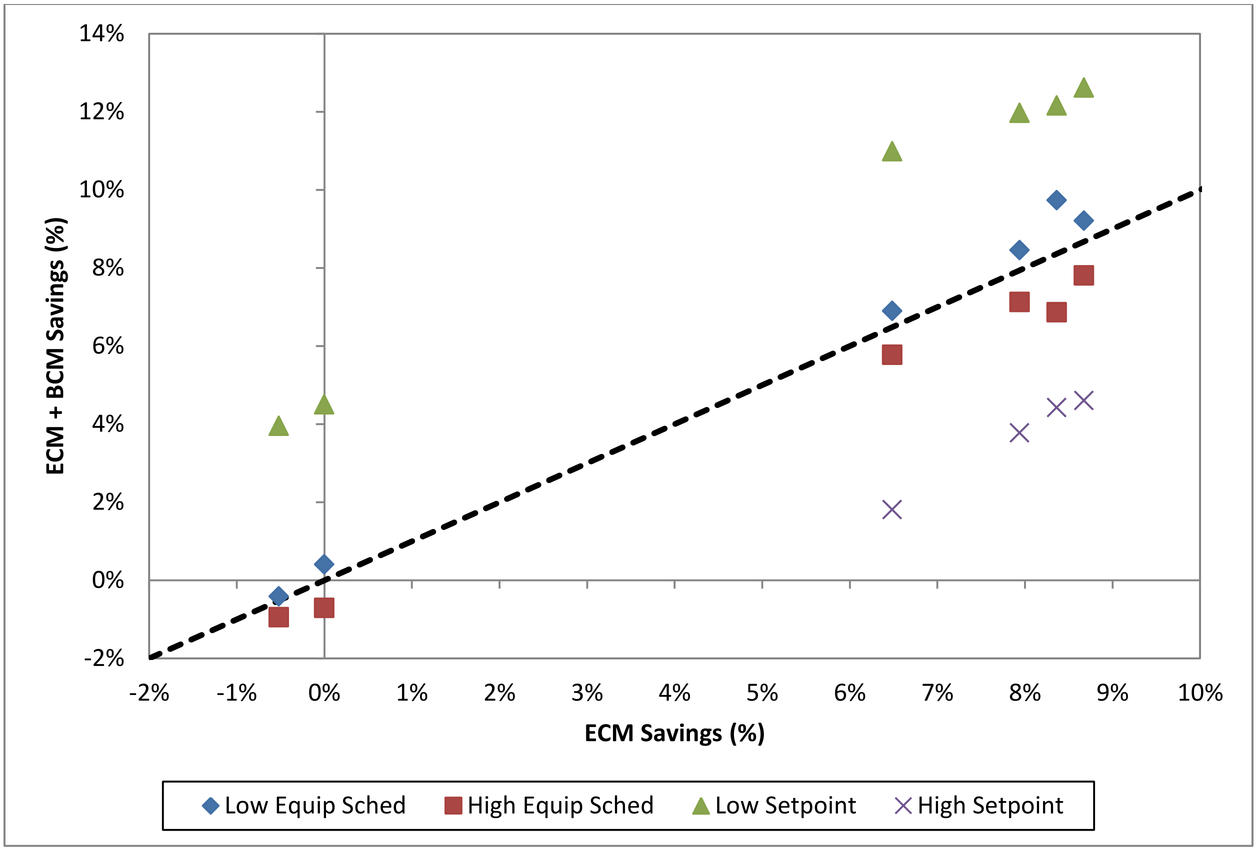

Figure 3.16: Select High and Low BCM Combinations

3.4 OBSERVATIONS

Analysis shows that the same behaviors impact energy usage in multi-family housing in the same way, but in varying degrees. Before ECMs were implemented, the individual parameters that normalized energy usage (EUI) was most sensitive to was ACH (+3.8% / -19%) and setpoint (+4.5% / -4.7%). Electricity usage (kWh) was most sensitive to equipment schedule (+18%/ -16%). These same parameters had the highest impact for all climate zones.

Table 3-8: BCM Sensitivity without ECMs

Parameter	BCM Alone
Ventilation Rate (High)	-19.3%
Setpoint (High)	-4.7%
Setback (High)	-4.7%
Setpoint (Low)	+4.5%
Ventilation Rate (Low)	+3.8%

Table 3-9: BCM Sensitivity after ECMs

Parameter	Combined ECMs plus BCM
Ventilation Rate (High)	-22.0%
Setback (High)	-4.1%
Occ Schedule (High)	-4.1%
Ventilation Rate (Low)	+4.2%
Setpoint (High)	+4.0%

Overall, it can be seen that installing retrofits is not able to significantly reduce (or increase) the percent impact that occupant behavior has on the building. The major impacts on energy usage are from internal gains and the opening of windows and doors which forces the heating system to condition more air. The setback and setpoint, however, do have a small impact. When the temperature is set back at night before ECMs, the windows were letting out much more heat requiring the heating system to keep turning on. However, after the retrofits, the building is much tighter and does not lose as much heat at night, dampening the negative impact of a high setpoint or high (no) setback by a small amount (0.7%).

From observing Figure 3.14 through Figure 3.16, it appears that the individual ECMs combined with individual, or multiple, BCMs results in a linear relationship. This was tested by plotting the results of the eQuest simulation of ECMs with BCMs versus the value obtained by adding the ECM savings alone to the BCM savings alone. The combined effects of individual BCMs and individual ECMs behaved farily linearly, with the simulation, at times, predicting more savings than simple addition.

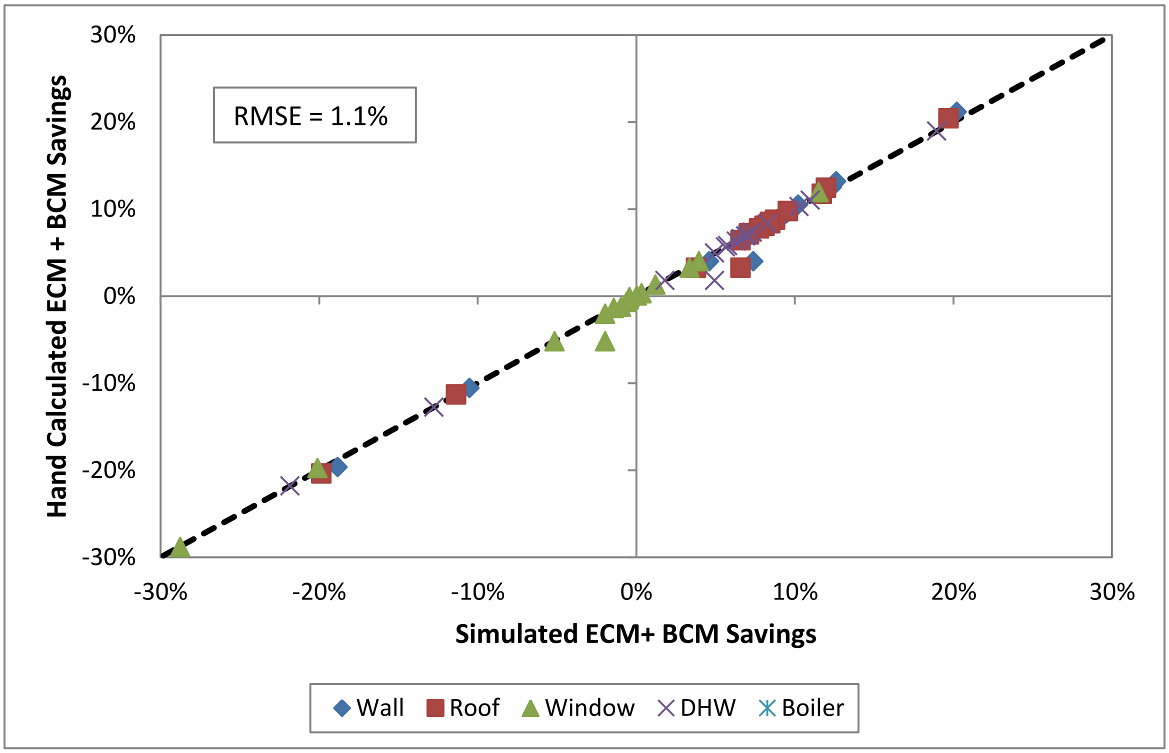

Figure 3.17: Simulated vs Calculated Individual ECM + BCM Savings

This is a rather useful relationship which can be used to easily predict the additional savings that can be expected by modifying occupant behavior. Recall that the all low BCM pacakge can save up to 12.5%, and the ECM package can save up to 28.3%. Added together, this savings is 40.8% which is very close to the savings predicted by the simulation: 38.1 %.

One cannot, however, add the savings of individual ECMs together and end up with the combined savings. While this may work some of the time, as a rule, it does not account for interactive effects of different ECMs and will not be accurate.

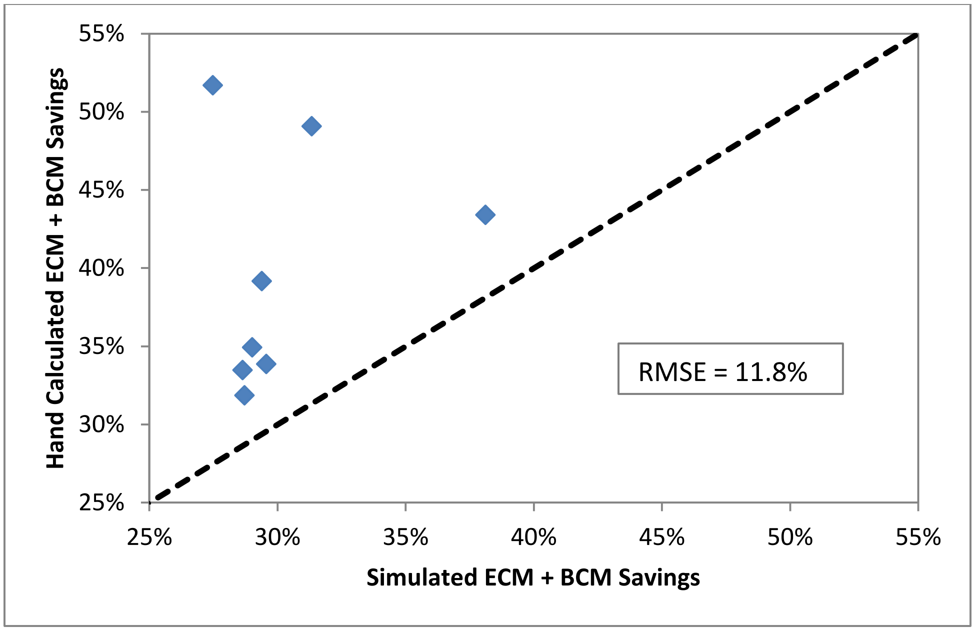

Figure 3.18: Simulated vs Calculated Combined ECM + BCM Savings

However, if the combined savings of the ECMs is known, the linear relationship between the BCMs and the combined ECMs holds true: combined savings can be added to individual BCM savings.

3.4.1. Cooling Dominated Climate

Additional analysis was performed to determine if the observed linear relationship between ECMs and BCMs persists for mild or cooling-dominated climates. Miami, FL was selected as the climate to simulate. The model was left unchanged except for the addition of cooling in the apartments. ASHRAE 90.1 Appendix G procedures were used to select the type and efficiency of cooling equipment, which was a packaged terminal air conditioning (PTAC) system with DX cooling. The setpoint and setback BCMs were implemented in the same manner, but used 70 as the base temperature and increased the setpoint to simulate a decrease in energy usage, or a “low” behavior, as shown in Table 3-10. The same equations were used in cooling schedules: Equation 3.1 and Equation 3.2.

Table 3-10: Global Parameter Ranges (cooling)

Parameter	Description	Equation
Change in setpoint	Low temperature in the COOL-TEMP-SCH	Low: +4 Medium:+2 High: 0
Change in setback	High temperature in the COOL-TEMP-SCH	Low: +4 Medium: +2 High: 0

The relationship between ECMs and BCMs was found to be very similar for this climate as with the heating-dominated climates. The itial plots show the expected results: high energy using behaviors cause a decrease in energy savings when added to ECMs, and low energy using behaviors cause an increase, as shown in Figure 3.19.

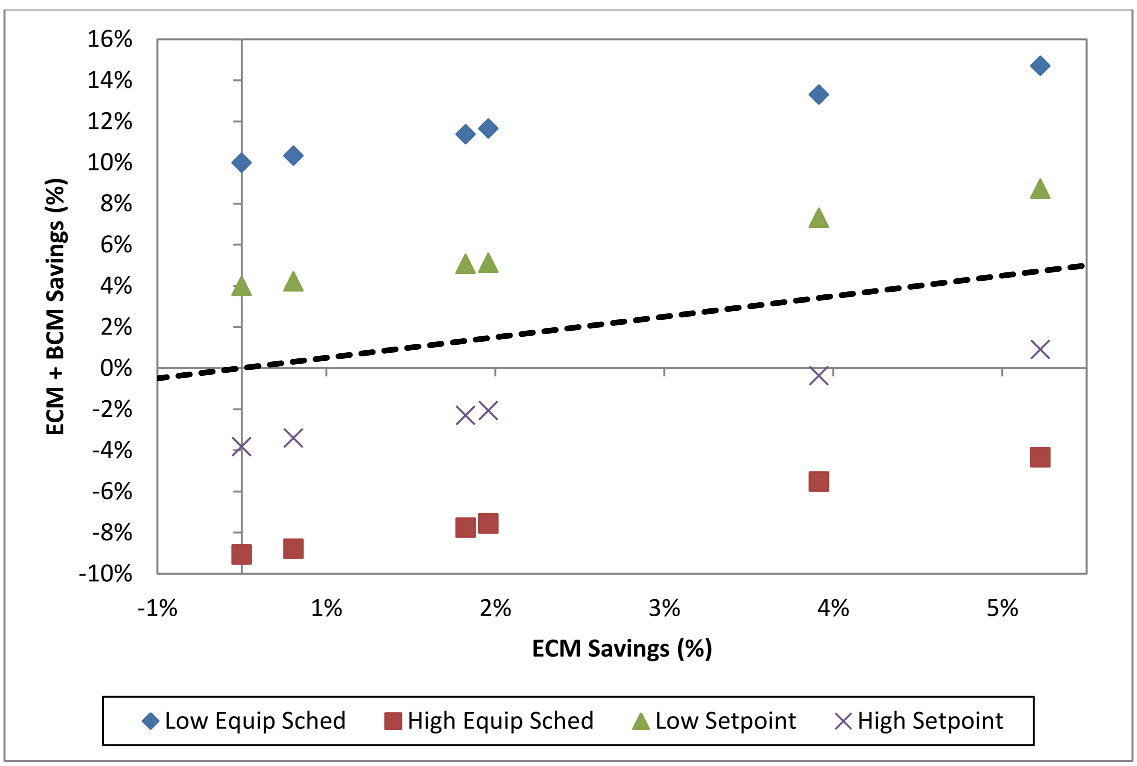

Figure 3.19: Select High and Low BCM Combinations (cooling)

As can be guessed from Figure 3.19, the combined effects of individual BCMs and individual ECMs behaved extremely linearly. The RMSE is 0.1%. This means that adding behavoirs to energy conservation measures in this cooling-dominated climate yields very accurate predictions of energy savings.

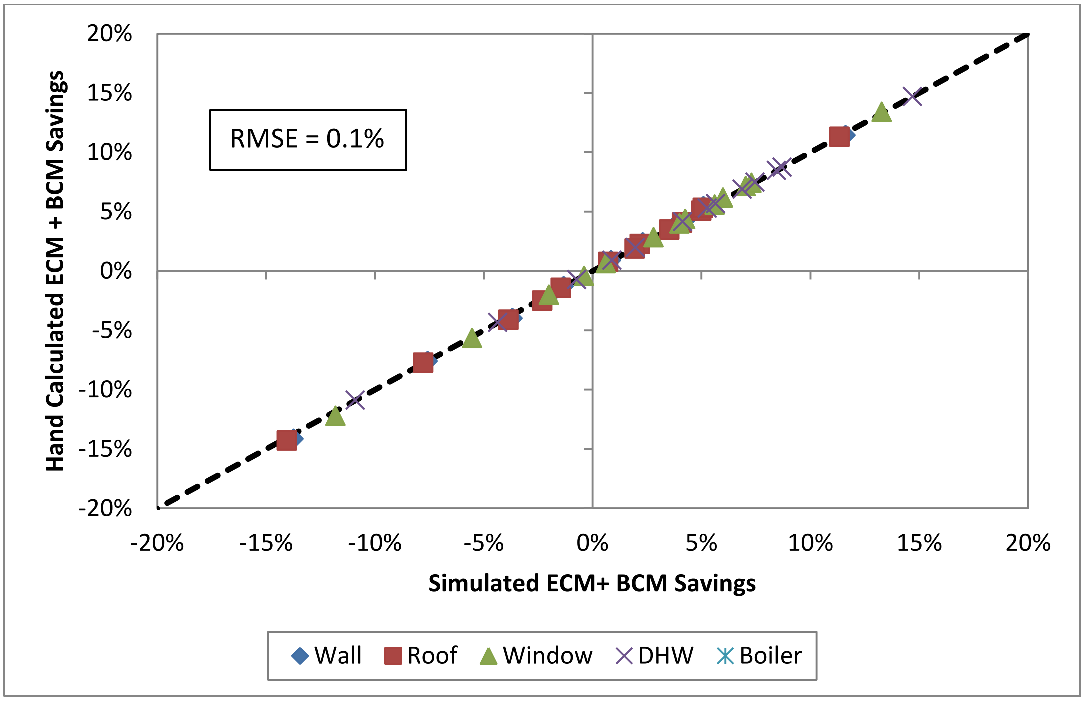

Figure 3.20: Simulated vs Calculated Individual ECM + BCM Savings (cooling)

In addition, this climate also does not follow a linear relationship when ECMs are compounded, as shown in Figure 3.21.

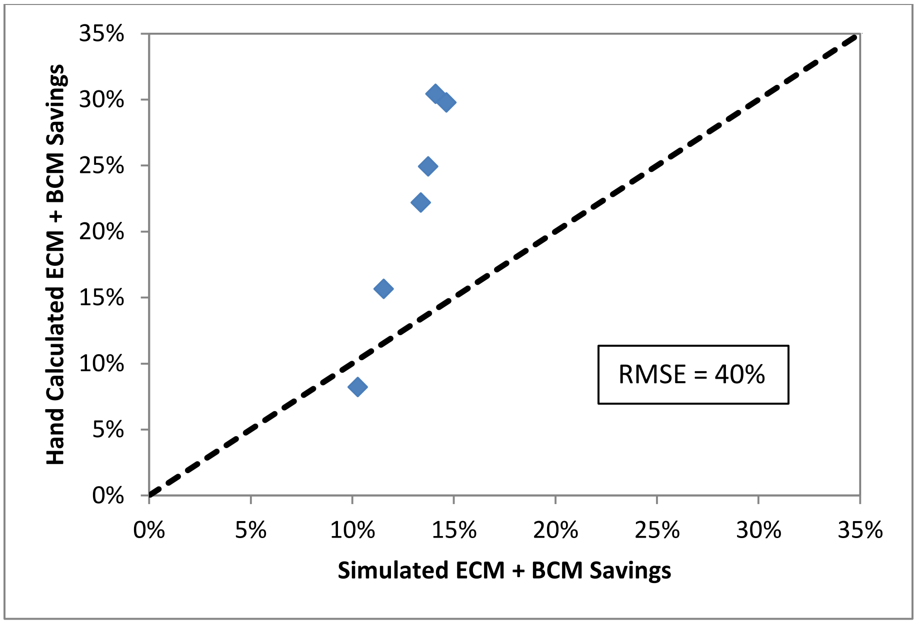

Figure 3.21: Simulated vs Calculated Combined ECM + BCM Savings (cooling)

Overall, in Miami, FL, this bilding can save 11.0% on the combined ECM package, and 26.7% on the all low BCM package alone. Combined, this yields 37.0% savings. Interestingly, this is the opposite effect from the cooling-dominated climate: BCMs have more of an impact than ECMs.

3.5 Implementation Package

Based on the limited simulation performed, a rough guideline has been developed to determine maximum savings measures for real-world implementation. While a higher occupant density does affect energy usage (+0.8%), it is not a practical conservation measure and will not be considered as such. Due to the linear relationship of the combination of ECMs and BCMs, any number of BCMs can be added together with an individual ECM to predict combined savings. However, multiple ECMs cannot be added together to eachother or to BCMs. This relationship is not linear and will not yield accurate results.

3.5.1 Heating Dominated Climate

For any building, the first behaviors to be targeted are setpoint, setback, and temperature schedule. In addition, ensure occupant are not fighting a the heating system with opening windows, due to system malfunction or lack of user expertise.

Table 3-11: Individual BCM Rankings (Heating)

Rank	Parameter	Savings	Description
1	Setpoint	4.5%	Lower temperature setpoint by 4°F
2	ACH	3.8%	Keep windows closed when heating system is in operation
3	Setback	1.8%	Use a setback of at least 4°F lower than the setpoint
4	Schedule	0.6%	Use a setback of at least 8-13 hours
5	Equipment	0.4%	Turn off all equipment when not in use
6	Lights	0.1%	Turn off all lights when not in use

Setpoint, setback, and schedule combined make up 7.3% of the BCM package savings, naturally it is best to have the lowest setpoint, lowest setback, and longest setback as possible, but some tradeoffs can be made. A "medium" setback (8 hours) can save nearly as much as a "low" setback of 13 hours. The most important parameter is to have a low setpoint, as shown in Table 3-12.

Table 3-12: Temperature Schedule, Setpoint, and Setback Rankings

Rank	Parameters (Schedule/Setpoint/Setback)	Savings
1	Low/Low/Low	7.3%
2	Medium/Low/Low	6.3%
3	Low/Low/Medium	5.0%
4	Medium/Low/Medium	4.5%
5	Low/Medium/Low	2.9%
6	Medium/Medium/Low	1.8%

The retrofit, or energy conservation, measures have a much more significant impact on energy usage, however, it is difficult to recommend highest-savings measures due to high variability in existing building constructions and HVAC equipment. In general, additional insulation and higher efficiency equipment will yield significant savings. ASHRAE 90.1 recommends an assembly U-value of 0.048 for roofs with insulation entirely above deck and 0.064 for steel framed walls in climate zones 4-7. Additional savings can often be achieved by exceeding these minimum values, as was done in the example analysis. The existing construction U-values were increased about 200%, resulting in 8.7% savings from a decrease in wall conduction, and 7.9% from the roof. It should be noted that additional insulation results in diminishing returns around R-30 for roofs and R-15 for walls.

Table 3-13: Individual ECM Rankings

Rank	Parameter	Savings
1	Wall	8.7%
2	Boiler	8.4%
3	Roof	7.9%
4	DHW	6.5%
Combined		28.3%

Inefficienct existing boiler or furnace systems can be replaced with typical ASHRAE 90.1 recommended furnaces or boilers (79- 82% efficient), or high performance condensing boilers with efficiencies inexcess of 90%. Domestic hot water boiler supply temperature should always be reduced to 120°F and may be replaced with high performance equpment (95% efficient).

3.5.2. Cooling Dominated Climate

In the cooling dominated climate, BCMs had a much more pronounced effect than ECMs, so targeting behaviors should be a focus of any retrofit program. Reducing the equipment and lighting schedules had a very large impact on energy usage. Unlike in heating dominated climates, a decrease in interior gains does not equal an increase in heating energy usage. It is instead met with a further decrease in cooling energy usage. In addition, setpoint and setbacks had a significant impact, as can be expected.

Table 3-14: Individual BCM Rankings

Rank	Parameter	Savings	Description
1	Equipment	10.0%	Turn off all equipment when not in use
2	Setpoint	4.0%	Lower temperature setpoint by 4°F
3	ACH	3.7%	Keep windows closed when heating system is in operation
4	Lights	2.7%	Turn off all lights when not in use
5	Setback	2.2%	Use a setback of at least 4°F lower than the setpoint
6	Schedule	0.9%	Use a setback of at least 8-13 hours

High efficiency, low-e windows play an important role to reduce heat gain in the space. Domestic hot water is also a large load in residential buidngs and continues to be an area of significant savings. While added insulation to the walls and roof did have some impact, it was not as pronounced in the heating climate. ASHRAE 90.1 recommends a minimum U-value of 0.124 for steel-framed walls in climate zone 1A (Miami) and a U-0.048 roof. This climate reaches the point of diminishing returns more quickly than the heating climate.

Table 3-15: Individual ECM Rankings

Rank	Parameter	Savings
1	DHW	4.7%
2	Window	3.4%
3	Wall	1.5%
4	Roof	1.3%
5	Boiler	0.3%
Combined		11.0%

CHAPTER 4 : TESTING AND VERIFICATION

Each algorithm of BEAT was verified to identify any errors or discrepancies in the program. In addition, BEAT was used to assess pre- and post- ECM as well as pre- and post- BCM data, as generated in Chapter 3.

4.1 VERIFICATION

Each algorithm of BEAT was put through a verification process. There are eleven types of model that BEAT can produce, as shown in Table 4-1. For each of these models, the balance temperature, building load coefficient, and base load were selected, and the utility data was then reverse-generated. The weather data was obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center and represents a 3 year average for Boulder, CO. Boulder was selected over Eagle, CO due to its higher summer temperatures, allowing better simulation of the cooling CPL models.

Table 4-1: Types of Algorithms

Heating	Cooling	Combined
3PeH	3PeC	5PeHC
3PgH	4PeC	4PeHC
4PeH	4PeC2	
4PgH		
4PeH2		
4PgH2		

First, a balance temperature, monthly base load, and slope was selected. These set parameters are shown in Table 4-2. Based on these values, the monthly energy usage was determined as shown in Figure 4.1. If the outdoor temperature was greater than the balance temperature, the gas usage was set to the base load. Similarly, in Figure 4.2, if outdoor temperature was less than the balance temperature, electricity usage was set to the base load.

Table 4-2: Set Parameters

	3PgH	3PeC	3PeH	4PgH	4PeH	4PeC	4PgH2	4PeH2	4PeC2	4PeHC	5PeHC
Tb_L (°F)	62.0	58.0	53.0	55	55	49	45		40	49	45
Tb_R (°F)							64		52		62
BL (Therms/Month)	85.0	322.6	322.6	85	85	100	85		85	100	85
Slope_L	-2.23	3.53	-7.82	-35	-35	2	-30		30	-14	-10
Slope_R				-5	-5	20	-8		8	8	10

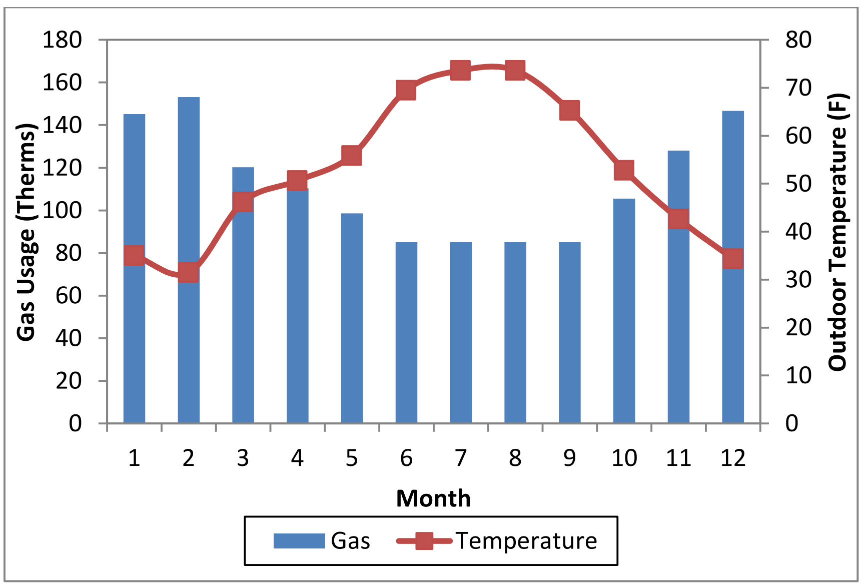

Figure 4.1: Sample of generated gas data

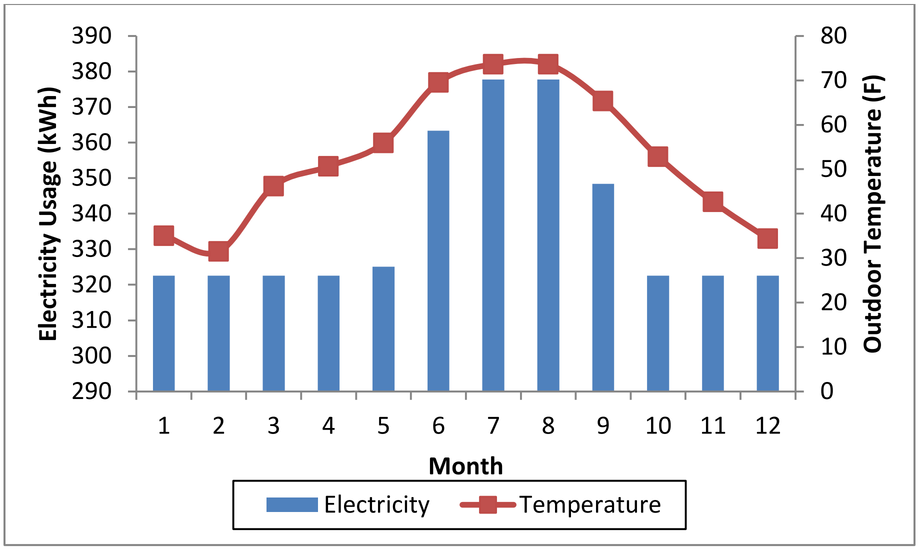

Figure 4.2: Sample of generated electricity data

Since BEAT uses monthly daily energy usage (MMBtu/day) as an input, prior to plotting energy usage versus outdoor temperature, the monthly energy usage was divided by the number of days in the billing period and converted to million BTUs. However, since the way the utility data is generated does not account for variation in length of billing period, a constant value of 30 days was used. To calculate BLC, an AFUE of 80% and a COP of 3.0 was used.

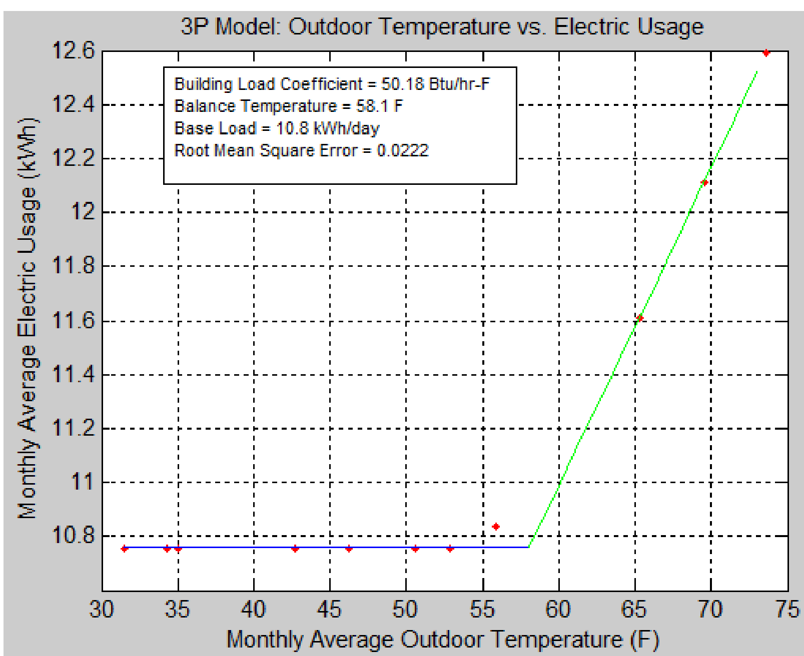

Figure 4.3: Example BEAT CPL Plot

Table 4-3 and Figure 4.4 outline the results of these tests. All variations were under 3.0% with root mean squared errors as shown in Figure 4.4. The major differences occurred between the set and calculated balance temperature. This is not surprising, since BEAT uses a fine-stepped optimization to arrive at a balance temperature. In essence, BEAT is determining that for the utility and weather data entered, the resulting Tb which minimizes RMSE.

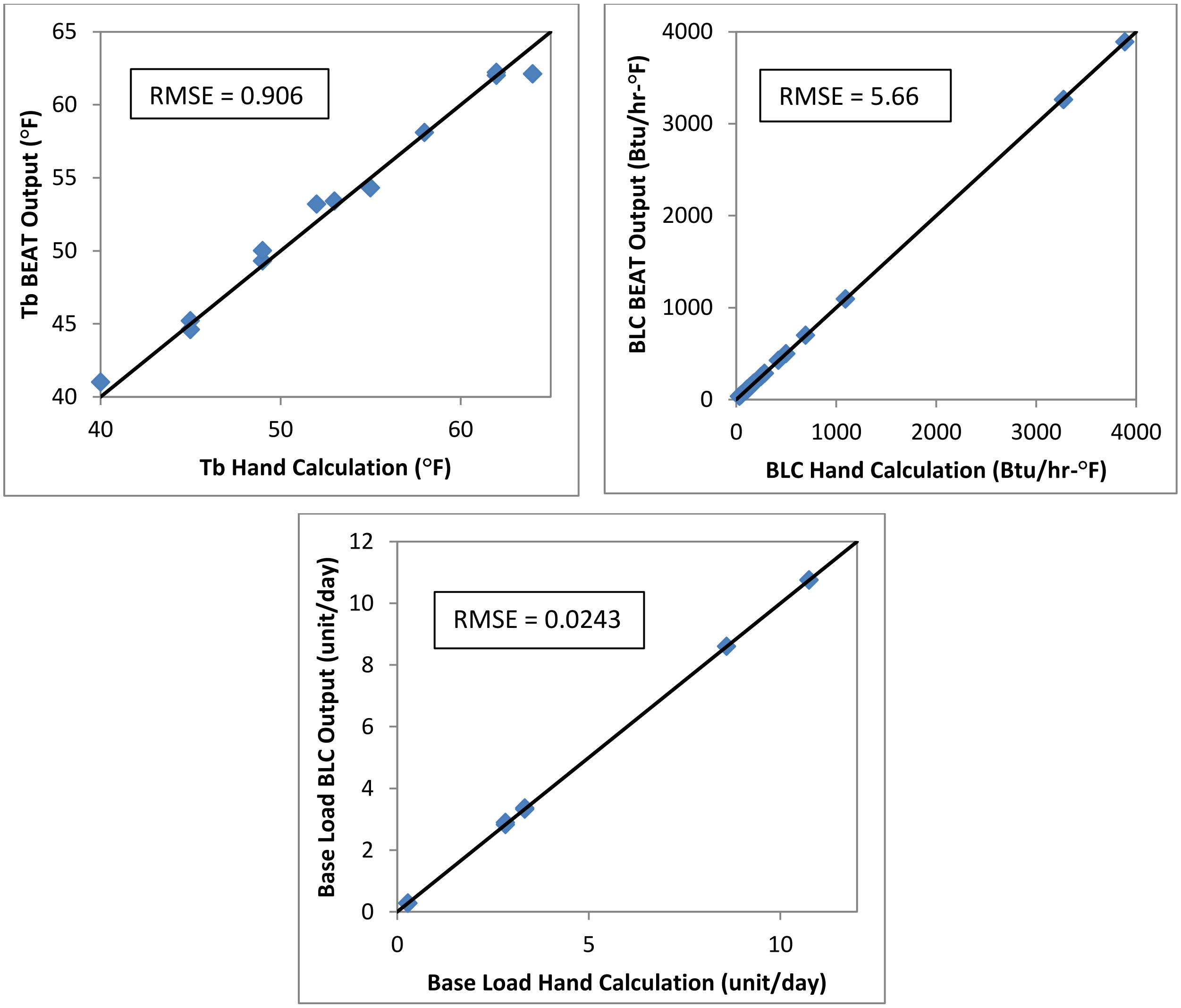

Figure 4.4: Hand Calculations vs. BEAT Output

Table 4-3: Verification Results

		Tb_L (°F)	Tb_R (°F)	BL (MMBtu/day or kWh/day)	BLC_L	BLC_R
3PgH	**Hand**	62		0.283	247.8	
	BEAT	62		0.283	247.8	
	% Diff	0.00%		0.00%	0.00%	
3PeC	**Hand**	58		10.753	50.18	
	BEAT	58.1		10.754	50.18	
	% Diff	-0.17%		-0.01%	0.00%	
3PeH	**Hand**	53		10.75	111.2	
	BEAT	53.4		10.75	108.4	
	% Diff	-0.75%		0.00%	2.52%	
4PgH	**Hand**	55		0.283	3890	696.7
	BEAT	54.3		0.283	3889	698.2
	% Diff	1%		0%	0%	0%
4PeH	**Hand**	55		8.6	497.6	89.35
	BEAT	54.3		8.6	497.6	89.34
	% Diff	1.27%		0.00%	0.00%	0.01%
4PeC	**Hand**	49		3.33	34.59	283.6
	BEAT	49.3		3.33	34.59	283.6
	% Diff	-0.61%		0.00%	0.00%	0.00%
4PgH2	**Hand**	64	45	0.283	3277	1093
	BEAT	62.1	44.6	0.285	3260	1092
	% Diff	2.97%	0.89%	-0.71%	0.52%	0.09%
4PeH2	**Hand**	64	45	0.283	3277	1093
	BEAT	62.1	44.6	0.285	3260	1092
	% Diff	2.97%	0.89%	-0.71%	0.52%	0.09%
4PeC2	**Hand**	52	40	2.83	153.5	422.3
	BEAT	53.2	41	2.83	153	426.5
	% Diff	-2.31%	-2.50%	0.00%	0.33%	-0.99%
4PeHC	**Hand**	49		3.33	178.2	112.9
	BEAT	50		3.37	178.2	112.8
	% Diff	-2.04%		-1.20%	0.00%	0.09%
5PeHC	**Hand**	45	62	2.83	137.9	142.2
	BEAT	45.2	62.2	2.9	137.9	142.2
	% Diff	-0.44%	-0.32%	-2.47%	0.00%	0.00%

4.2 Case Studies

The results from two eQuest models were studied in BEAT to determine the degree of accuracy in predicting post-retrofit and post-BCM energy usage. The same model and results obtained in Chapter 3 were used for this study. The average monthly outdoor temperature was obtained from the EAGLE-CO.bin typical meteorological year (TMY2) weather file used in the eQuest models. The 100% participation in the “all low” behaviors was implemented for this study.

As shown in Table 4-4, for the BCM analysis, every component from the Inverse modeling decreased. The balance temperature decreased by 2%, meaning that the building does not require heating until a lower outdoor temperature. The heating degree days, which are calculated from Tb, decreased by 5%, meaning that there are fewer hours in the year that the building requires heating in the first place. Finally, the annual energy usage for heating dropped by 11%.

Table 4-4: Pre- and Post- BCM Results

	Pre-BCM	Post-BCM	% Diff
CPL Model Type	3PgH	3PgH	
Tb (°F)	56.75	55.67	1.9%
DDH (°F-day)	5987	5694	4.9%
ASHRAE BLC (Btu/hr-°F)	8620	8620	0.0%
Forward BLC (Btu/hr-°F)	9794	9794	0.0%
Inverse BLC (Btu/hr-°F)	6403	6024	5.9%
Gas Base Load (MMBtu/day)	0.970	0.972	-0.1%
ASHRAE Annual Heating (MMBtu/yr)	1769	1683	4.9%
Forward Annual Heating (MMBtu/yr)	2010	1912	4.9%
Inverse Annual Heating (MMBtu/yr)	1314	1176	10.5%

The Forward modeling results are within the same range as the Inverse model, but predict much higher BLCs and, therefore, higher annual heating energy usage. The Inverse model is a much more accurate calculation because it removes a degree of inaccuracy incurred by estimating the assembly U-values and areas of an existing building. Many of these buildings are old and do not have construction documents available. Therefore, the results of the Forward model are only as accurate as the inputs to that model. With that being said, the results are still as expected. Since no changes were made to the envelope, the Forward model BLC stayed the same. The Tb, and therefore DDH, did change, which in turn decreased the annual heating energy usage by the same about (5%).

While not the main focus of this thesis, the pre- and post- ECM scenario was also tested to ensure BEAT functions as expected. Table 4-5 shows the results from this analysis. All components decreased in the same manner as the BCM analysis. The baseload dropped drastically, as did the predicted heating energy usage. It is interesting to note that the difference between the pre- and post- heating energy usage is the same for the Forward and Inverse models.

Table 4-5: Pre- and Post-ECM Results

	Pre-ECM	Post-ECM	% Diff
CPL Model Type	3PgH	3PgH	
Tb (°F)	56.75	55.85	1.6%
DDH (°F-day)	5987	5743	4.1%
ASHRAE BLC (Btu/hr-°F)	8620	8620	0.0%
Forward BLC (Btu/hr-°F)	9794	6933	29.2%
Inverse BLC (Btu/hr-°F)	6403	4526	29.3%
Gas Base Load (MMBtu/day)	0.970	0.603	37.8%
ASHRAE Annual Heating (MMBtu/yr)	1769	1485	16.1%
Forward Annual Heating (MMBtu/yr)	2010	1194	40.6%
Inverse Annual Heating (MMBtu/yr)	1314	780	40.7%

When comparing these predictions of heating energy usage to the predictions from the calibrated eQuest models, the results are very close. The differences are around 4% for the pre- and post- ECM and BCM predictions, and the change is less than 1.0%.

Table 4-6: eQuest vs BEAT Annual Heating Energy Use [MMBtu/yr]

	eQuest	BEAT	% Diff
Pre-BCM	1268	1314	-3.7%
Post-BCM	1129	1176	-4.2%
Change	138.5	138.0	0.5%
Pre-ECM	1268	1314	-3.7%
Post-ECM	750.1	779.8	-4.0%
% Diff	517.4	534.2	0.3%

The results of these studies show, with confidence, that BEAT accurately separates the heating energy usage from the provided utility bills. It also provides an extra layer of confirmation for the accuracy of the calibrated eQuest model.

4.3 Limitations and Areas for Improvement

Currently, BEAT cannot calculate 2-parameter type models, such as variable-based degree-day models. This will cause a degree of error, as indicated in Section 3.1 during the testing of the tool.

Some feedback was provided by the employees at iCAST. They pointed out some user-friendliness issues, some of which were fixed, and some of which were not. One limitation that was not improved upon was the ability for the user to go back and edit data after proceeding onto the next window. This is something not achievable by this type of simple program.

BEAT also relies on the user to take the data it outputs and calculate the savings. The addition of a demand calculation and incorporation of energy costs and utility rate structures would greatly add to the usefulness of the program.

CHAPTER 5 : CONCLUSIONS

A tool was created to analyze pre- and post-retrofit/education data to determine the degree of savings incurred. This tool, BEAT, was tested using two case studies: pre- and post- BCMs and pre- and post- ECMs, and was proven to an accuracy of less than 4% when compared to an eQuest model. In a heating-dominated climate, it predicted a heating energy use savings of 10% when 100% of occupants adopted low-energy usage behaviors, and a savings of 40% when these behaviors were combined with a whole-building retrofit. In a cooling-dominated climate, behavior modification resulted in 27% savings, and 37% savings when those behaviors were combined with a retrofit.

A detailed sensitivity analysis was performed to determine what occupant behaviors have the most impact on building energy usage. In a heating-dominated climate, the number of air changes per hour, the setpoint, and the setback had the most significant savings. The lighting schedule and equipment schedule had a significant impact on electrical energy use, which was met by the opposite and equivalent impact on heating energy usage.

The highest average impact one behavior had was an increase or decrease in energy usage by 4.0%-5.0%. In a large apartment building, this can magnify to a significant amount. Ventilation rate had the highest impact by far, resulting in 22% more energy usage due to occupants who leave windows or doors open. This is likely to occur in old apartments where heating systems are in need of retro commissioning, or where the occupant does not know how to properly operate their system.

In a cooling-dominated climate, equipment schedule, setpoint, and the number of air changes per hour has the most significant savings. The lighting schedule and setback were also significant. The highest impact one behiavor had (equipment schedule) was a decrease in energy usage by 10%. Overall, more energy could be saved from modifying occupant behavior in the cooling-dominated climate than by whole-building retrofits.

Climate zone had a noticeable relationship with behavior. The higher the heating degree days, the less sensitive the building was. Percent participation and apartment orientation also played a part. Southern exposed apartments are more sensitive to changes than North facing apartments.

This thesis completes Phase I in a continuing area of research with iCAST and the HUD EIF project. After iCAST implements the ECMs and BCMs and collects utility data before and after each implementation, BEAT will be used to assess the energy savings from these measures. Further research will also utilize occupant surveys and actual education programs implemented by iCAST to better assess the impact that the occupant's behavior has on the energy usage in the building. The surveys of the occupants will allow a more refined definition of behavior and occupancy schedules. This thesis serves as a starting point to determine the potential impact of iCAST's program.

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APPENDIX A: ASHRAE STANDARD 90 TABLES

ASHRAE 90.1 TABLES 5.5-1 TO 5.5-8

TABLE 5.5-1 Building Envelope Requirements for Climate Zone 1 (A, B)*

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.063	R-15.0 c.i.	U-0.048	R-20.0 c.i.	U-0.218	R-3.8 ci
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-1.280	NR
Attic and Other	U-0.034	R-30.0	U-0.027	R-38.0	U-0.081	R-13.0
Walls, Above-Grade						
Mass	U-0.580	NR	U-0.151[a]	R-5.7 c.i.[a]	U-0.580	NR
Metal Building	U-0.113	R-13.0	U-0.113	R-13.0	U-1.180	NR
Steel-Framed	U-0.124	R-13.0	U-0.124	R-13.0	U-0.352	NR
Wood-Framed and Other	U-0.089	R-13.0	U-0.089	R-13.0	U-0.292	NR
Walls, Below-Grade						
Below-Grade Wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.322	NR	U-0.322	NR	U-0.322	NR
Steel-Joist	U-0.350	NR	U-0.350	NR	U-0.350	NR
Wood-Framed and Other	U-0.282	NR	U-0.282	NR	U-0.282	NR
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.730	NR	F-0.730	NR
Heated	F-1.020	R-7.5 for 12 in.	F-1.020	R-7.5 for 12 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.700		U-0.700	
Nonswinging	U-1.450		U-1.450		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-1.20		U-1.20		U-1.20	
Metal framing (curtainwall/storefront)[c]	U-1.20	SHGC-0.25 all	U-1.20	SHGC-0.25 all	U-1.20	SHGC-NR all
Metal framing (entrance door)[c]	U-1.20		U-1.20		U-1.20	
Metal framing (all other)[c]	U-1.20		U-1.20		U-1.20	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.98	$SHGC_{all}$–0.36	U_{all}–1.98	$SHGC_{all}$–0.19	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.98	$SHGC_{all}$–0.19	U_{all}–1.98	$SHGC_{all}$–0.16	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–1.90	$SHGC_{all}$–0.34	U_{all}–1.90	$SHGC_{all}$–0.27	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.90	$SHGC_{all}$–0.27	U_{all}–1.90	$SHGC_{all}$–0.27	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–1.36	$SHGC_{all}$–0.36	U_{all}–1.36	$SHGC_{all}$–0.19	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.36	$SHGC_{all}$–0.19	U_{all}–1.36	$SHGC_{all}$–0.19	U_{all}–1.36	$SHGC_{all}$–NR

*The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.

[a]Exception to Section A3.1.3.1 applies.

[b]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.

[c]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

TABLE 5.5-2 Building Envelope Requirements for Climate Zone 2 (A, B)*

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.218	R-3.8 c.i.
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-0.167	R-6.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.081	R-13.0
Walls, Above-Grade						
Mass	U-0.151[a]	R-5.7 c.i.[a]	U-0.123	R-7.6 c.i.	U-0.580	NR
Metal Building	U-0.113	R-13.0	U-0.113	R-13.0	U-0.184	R-6.0
Steel-Framed	U-0.124	R-13.0	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.089	R-13.0	U-0.089	R-13.0	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.107	R-6.3 c.i.	U-0.087	R-8.3 c.i.	U-0.322	NR
Steel-Joist	U-0.052	R-19.0	U-0.052	R-19.0	U-0.069	R-13.0
Wood-Framed and Other	U-0.051	R-19.0	U-0.033	R-30.0	U-0.066	R-13.0
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.730	NR	F-0.730	NR
Heated	F-1.020	R-7.5 for 12 in.	F-1.020	R-7.5 for 12 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.700		U-0.700	
Nonswinging	U-1.450		U-0.500		U-1.450	

Fenestration	Assembly Max. U	Assembly Max. SHGC	Assembly Max. U	Assembly Max. SHGC	Assembly Max. U	Assembly Max. SHGC
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-0.75	SHGC-0.25 all	U-0.75	SHGC-0.25 all	U-1.20	SHGC-NR all
Metal framing (curtainwall/storefront)[c]	U-0.70		U-0.70		U-1.20	
Metal framing (entrance door)[c]	U-1.10		U-1.10		U-1.20	
Metal framing (all other)[c]	U-0.75		U-0.75		U-1.20	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.98	$SHGC_{all}$–0.36	U_{all}–1.98	$SHGC_{all}$–0.19	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.98	$SHGC_{all}$–0.19	U_{all}–1.98	$SHGC_{all}$–0.19	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–1.90	$SHGC_{all}$–0.39	U_{all}–1.90	$SHGC_{all}$–0.27	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.90	$SHGC_{all}$–0.34	U_{all}–1.90	$SHGC_{all}$–0.27	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–1.36	$SHGC_{all}$–0.36	U_{all}–1.36	$SHGC_{all}$–0.19	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.36	$SHGC_{all}$–0.19	U_{all}–1.36	$SHGC_{all}$–0.19	U_{all}–1.36	$SHGC_{all}$–NR

*The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.
[a]Exception to Section A3.1.3.1 applies.
[b]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[c]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

TABLE 5.5-3 Building Envelope Requirements for Climate Zone 3 (A, B, C)[a]

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.173	R-5.0 c.i.
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-0.097	R-10.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.053	R-19.0
Walls, Above-Grade						
Mass	U-0.123	R-7.6 c.i.	U-0.104	R-9.5 c.i.	U-0.580	NR
Metal Building	U-0.113	R-13.0	U-0.113	R-13.0	U-0.184	R-6.0
Steel-Framed	U-0.084	R-13.0 + R-3.8 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.089	R-13.0	U-0.089	R-13.0	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.107	R-6.3 c.i.	U-0.087	R-8.3 c.i.	U-0.322	NR
Steel-Joist	U-0.052	R-19.0	U-0.052	R-19.0	U-0.069	R-13.0
Wood-Framed and Other	U-0.051	R-19.0	U-0.033	R-30.0	U-0.066	R-13.0
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.730	NR	F-0.730	NR
Heated	F-0.900	R-10 for 24 in.	F-0.900	R-10 for 24 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.700		U-0.700	
Nonswinging	U-1.450		U-0.500		U-1.450	

Fenestration	Assembly Max. U	Assembly Max. SHGC	Assembly Max. U	Assembly Max. SHGC	Assembly Max. U	Assembly Max. SHGC
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-0.65	SHGC-0.25 all	U-0.65	SHGC-0.25 all	U-1.20	SHGC-NR all
Metal framing (curtainwall/storefront)[c]	U-0.60		U-0.60		U-1.20	
Metal framing (entrance door)[c]	U-0.90		U-0.90		U-1.20	
Metal framing (all other)[c]	U-0.65		U-0.65		U-1.20	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.17	$SHGC_{all}$–0.39	U_{all}–1.17	$SHGC_{all}$–0.36	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.17	$SHGC_{all}$–0.19	U_{all}–1.17	$SHGC_{all}$–0.19	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–1.30	$SHGC_{all}$–0.65	U_{all}–1.30	$SHGC_{all}$–0.27	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.30	$SHGC_{all}$–0.34	U_{all}–1.30	$SHGC_{all}$–0.27	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–0.69	$SHGC_{all}$–0.39	U_{all}–0.69	$SHGC_{all}$–0.36	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.69	$SHGC_{all}$–0.19	U_{all}–0.69	$SHGC_{all}$–0.19	U_{all}–1.36	$SHGC_{all}$–NR

[a] The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.
[b] Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[c] Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

TABLE 5.5-4 Building Envelope Requirements for Climate Zone 4 (A, B, C)*

Opaque Elements	Nonresidential Assembly Maximum	Nonresidential Insulation Min. R-Value	Residential Assembly Maximum	Residential Insulation Min. R-Value	Semiheated Assembly Maximum	Semiheated Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.173	R-5.0 c.i.
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-0.097	R-10.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.053	R-19.0
Walls, Above-Grade						
Mass	U-0.104	R-9.5 c.i.	U-0.090	R-11.4 c.i.	U-0.580	NR
Metal Building	U-0.113	R-13.0	U-0.113	R-13.0	U-0.134	R-10.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.089	R-13.0	U-0.064	R-13.0 + R-3.8 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-1.140	NR	C-0.119	R-7.5 c.i.	C-1.140	NR
Floors						
Mass	U-0.087	R-8.3 c.i.	U-0.074	R-10.4 c.i.	U-0.137	R-4.2 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.038	R-30.0	U-0.069	R-13.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.066	R-13.0
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.540	R-10 for 24 in.	F-0.730	NR
Heated	F-0.860	R-15 for 24 in.	F-0.860	R-15 for 24in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.700		U-0.700	
Nonswinging	U-1.500		U-0.500		U-1.450	

Fenestration	Nonresidential Assembly Max. U	Nonresidential Assembly Max. SHGC	Residential Assembly Max. U	Residential Assembly Max. SHGC	Semiheated Assembly Max. U	Semiheated Assembly Max. SHGC
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-0.40	SHGC-0.40 all	U-0.40	SHGC-0.40 all	U-1.20	SHGC-NR all
Metal framing (curtainwall/storefront)[c]	U-0.50		U-0.50		U-1.20	
Metal framing (entrance door)[c]	U-0.85		U-0.85		U-1.20	
Metal framing (all other)[c]	U-0.55		U-0.55		U-1.20	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.17	$SHGC_{all}$–0.49	U_{all}–0.98	$SHGC_{all}$–0.36	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.17	$SHGC_{all}$–0.39	U_{all}–0.98	$SHGC_{all}$–0.19	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–1.30	$SHGC_{all}$–0.65	U_{all}–1.30	$SHGC_{all}$–0.62	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.30	$SHGC_{all}$–0.34	U_{all}–1.30	$SHGC_{all}$–0.27	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–0.69	$SHGC_{all}$–0.49	U_{all}–0.58	$SHGC_{all}$–0.36	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.69	$SHGC_{all}$–0.39	U_{all}–0.58	$SHGC_{all}$–0.19	U_{all}–1.36	$SHGC_{all}$–NR

*The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.
[b]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[c]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

TABLE 5.5-5 Building Envelope Requirements for Climate Zone 5 (A, B, C)*

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.119	R-7.6 c.i.
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-0.097	R-10.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.053	R-19.0
Walls, Above-Grade						
Mass	U-0.090	R-11.4 c.i.	U-0.080	R-13.3 c.i.	U-0.151[a]	R-5.7 c.i.[a]
Metal Building	U-0.113	R-13.0	U-0.057	R-13.0 + R-13.0	U-0.123	R-11.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.064	R-13.0 + R-3.8 c.i.	U-0.051	R-13.0 + R-7.5 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-0.119	R-7.5 c.i.	C-0.119	R-7.5 c.i.	C-1.140	NR
Floors						
Mass	U-0.074	R-10.4 c.i.	U-0.064	R-12.5 c.i.	U-0.137	R-4.2 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.038	R-30.0	U-0.052	R-19.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.051	R-19.0
Slab-On-Grade Floors						
Unheated	F-0.730	NR	F-0.540	R-10 for 24 in.	F-0.730	NR
Heated	F-0.860	R-15 for 24 in.	F-0.860	R-15 for 24 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.500		U-0.700	
Nonswinging	U-0.500		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-0.35		U-0.35		U-1.20	
Metal framing (curtainwall/storefront)[c]	U-0.45	SHGC-0.40 all	U-0.45	SHGC-0.40 all	U-1.20	SHGC-NR all
Metal framing (entrance door)[c]	U-0.80		U-0.80		U-1.20	
Metal framing (all other)[c]	U-0.55		U-0.55		U-1.20	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.17	$SHGC_{all}$–0.49	U_{all}–1.17	$SHGC_{all}$–0.49	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.17	$SHGC_{all}$–0.39	U_{all}–1.17	$SHGC_{all}$–0.39	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–1.10	$SHGC_{all}$–0.77	U_{all}–1.10	$SHGC_{all}$–0.77	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.10	$SHGC_{all}$–0.62	U_{all}–1.10	$SHGC_{all}$–0.62	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–0.69	$SHGC_{all}$–0.49	U_{all}–0.69	$SHGC_{all}$–0.49	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.69	$SHGC_{all}$–0.39	U_{all}–0.69	$SHGC_{all}$–0.39	U_{all}–1.36	$SHGC_{all}$–NR

*The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.
[a]Exception to Section A3.1.3.1 applies.
[b]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[c]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

TABLE 5.5-6 Building Envelope Requirements for Climate Zone 6 (A, B)*

Opaque Elements	Nonresidential Assembly Maximum	Nonresidential Insulation Min. R-Value	Residential Assembly Maximum	Residential Insulation Min. R-Value	Semiheated Assembly Maximum	Semiheated Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.093	R-10.0 c.i.
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-0.097	R-10.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.034	R-30.0
Walls, Above-Grade						
Mass	U-0.080	R-13.3 c.i.	U-0.071	R-15.2 c.i.	U-0.151[a]	R-5.7 c.i.[a]
Metal Building	U-0.113	R-13.0	U-0.057	R-13.0 + R-13.0	U-0.113	R-13.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.064	R-13.0 + R-7.5 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.051	R-13.0 + R-7.5 c.i.	U-0.051	R-13.0 + R-7.5 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-0.119	R-7.5 c.i.	C-0.119	R-7.5 c.i.	C-1.140	NR
Floors						
Mass	U-0.064	R-12.5 c.i.	U-0.057	R-14.6 c.i.	U-0.137	R-4.2 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.032	R-38.0	U-0.052	R-19.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-.0051	R-19.0
Slab-On-Grade Floors						
Unheated	F-0.540	R-10 for 24 in.	F-0.520	R-15 for 24 in.	F-0.730	NR
Heated	F-0.860	R-15 for 24 in.	F-0.688	R-20 for 48 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.700		U-0.500		U-0.700	
Nonswinging	U-0.500		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-0.35	SHGC-0.40 all	U-0.35	SHGC-0.40 all	U-0.65	SHGC-NR all
Metal framing (curtainwall/storefront)[c]	U-0.45		U-0.45		U-0.60	
Metal framing (entrance door)[c]	U-0.80		U-0.80		U-0.90	
Metal framing (all other)[c]	U-0.55		U-0.55		U-0.65	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.17	$SHGC_{all}$–0.49	U_{all}–0.98	$SHGC_{all}$–0.46	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.17	$SHGC_{all}$–0.49	U_{all}–0.98	$SHGC_{all}$–0.36	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–0.87	$SHGC_{all}$–0.71	U_{all}–0.74	$SHGC_{all}$–0.65	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.87	$SHGC_{all}$–0.58	U_{all}–0.74	$SHGC_{all}$–0.55	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–0.69	$SHGC_{all}$–0.49	U_{all}–0.58	$SHGC_{all}$–0.49	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.69	$SHGC_{all}$–0.49	U_{all}–0.58	$SHGC_{all}$–0.39	U_{all}–1.36	$SHGC_{all}$–NR

*The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.
[a]Exception to Section A3.1.3.1 applies.
[b]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[c]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

TABLE 5.5-7 Building Envelope Requirements for Climate Zone 7[a]

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.093	R-10.0 c.i.
Metal Building	U-0.065	R-19.0	U-0.065	R-19.0	U-0.097	R-10.0
Attic and Other	U-0.027	R-38.0	U-0.027	R-38.0	U-0.034	R-30.0
Walls, Above-Grade						
Mass	U-0.071	R-15.2 c.i.	U-0.071	R-15.2 c.i.	U-0.123	R-7.6 c.i.
Metal Building	U-0.057	R-13.0 + R-13.0	U-0.057	R-13.0 + R-13.0	U-0.113	R-13.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.042	R-13.0 + R-15.6 c.i.	U-0.124	R-13.0
Wood-Framed and Other	U-0.051	R-13.0 + R-7.5 c.i.	U-0.051	R-13.0 + R-7.5 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-0.119	R-7.5 c.i.	C-0.092	R-10.0 c.i.	C-1.140	NR
Floors						
Mass	U-0.064	R-12.5 c.i.	U-0.051	R-16.7 c.i.	U-0.107	R-6.3 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.032	R-38.0	U-0.052	R-19.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.051	R-19.0
Slab-On-Grade Floors						
Unheated	F-0.520	R-15 for 24 in.	F-0.520	R-15 for 24 in.	F-0.730	NR
Heated	F-0.843	R-20 for 24in.	F-0.688	R-20 for 48 in.	F-0.900	R-10 for 24 in.
Opaque Doors						
Swinging	U-0.500		U-0.500		U-0.700	
Nonswinging	U-0.500		U-0.500		U-1.450	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-0.35	SHGC-0.45 all	U-0.35	SHGC-NR all	U-0.65	SHGC-NR all
Metal framing (curtainwall/storefront)[c]	U-0.40		U-0.40		U-0.60	
Metal framing (entrance door)[c]	U-0.80		U-0.80		U-0.90	
Metal framing (all other)[c]	U-0.45		U-0.45		U-0.65	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}–1.17	$SHGC_{all}$–0.68	U_{all}–1.17	$SHGC_{all}$–0.64	U_{all}–1.98	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–1.17	$SHGC_{all}$–0.64	U_{all}–1.17	$SHGC_{all}$–0.64	U_{all}–1.98	$SHGC_{all}$–NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}–0.87	$SHGC_{all}$–0.77	U_{all}–0.61	$SHGC_{all}$–0.77	U_{all}–1.90	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.87	$SHGC_{all}$–0.71	U_{all}–0.61	$SHGC_{all}$–0.77	U_{all}–1.90	$SHGC_{all}$–NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}–0.69	$SHGC_{all}$–0.68	U_{all}–0.69	$SHGC_{all}$–0.64	U_{all}–1.36	$SHGC_{all}$–NR
2.1%–5.0%	U_{all}–0.69	$SHGC_{all}$–0.64	U_{all}–0.69	$SHGC_{all}$–0.64	U_{all}–1.36	$SHGC_{all}$–NR

[a]The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.
[b]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[c]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

TABLE 5.5-8 Building Envelope Requirements for Climate Zone 8[a]

Opaque Elements	Nonresidential Assembly Maximum	Nonresidential Insulation Min. R-Value	Residential Assembly Maximum	Residential Insulation Min. R-Value	Semiheated Assembly Maximum	Semiheated Insulation Min. R-Value
Roofs						
Insulation Entirely above Deck	U-0.048	R-20.0 c.i.	U-0.048	R-20.0 c.i.	U-0.063	R-15.0 c.i.
Metal Building	U-0.049	R-13.0 + R-19.0	U-0.049	R-13.0 + R-19.0	U-0.072	R-16.0
Attic and Other	U-0.021	R-49.0	U-0.021	R-49.0	U-0.034	R-30.0
Walls, Above-Grade						
Mass	U-0.071	R-15.2 c.i.	U-0.052	R-25.0 c.i.	U-0.104	R-9.5 c.i.
Metal Building	U-0.057	R-13.0 + R-13.0	U-0.057	R-13.0 + R-13.0	U-0.113	R-13.0
Steel-Framed	U-0.064	R-13.0 + R-7.5 c.i.	U-0.037	R-13.0 + R-18.8 c.i.	U-0.084	R-13.0 + R-3.8 c.i.
Wood-Framed and Other	U-0.036	R-13.0 + R-15.6 c.i.	U-0.036	R-13.0 + R-15.6 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-0.119	R-7.5 c.i.	C-0.075	R-12.5 c.i.	C-1.140	NR
Floors						
Mass	U-0.057	R-14.6 c.i.	U-0.051	R-16.7 c.i.	U-0.087	R-8.3 c.i.
Steel-Joist	U-0.032	R-38.0	U-0.032	R-38.0	U-0.052	R-19.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.033	R-30.0
Slab-On-Grade Floors						
Unheated	F-0.520	R-15 for 24 in.	F-0.510	R-20 for 24 in.	F-0.730	NR
Heated	F-0.688	R-20 for 48 in.	F-0.688	R-20 for 48 in.	F-0.900	R-10.0 for 24 in.
Opaque Doors						
Swinging	U-0.500		U-0.500		U-0.700	
Nonswinging	U-0.500		U-0.500		U-0.500	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[b]	U-0.35	SHGC-0.45 all	U-0.35	SHGC-NR all	U-0.65	SHGC-NR all
Metal framing (curtainwall/storefront)[c]	U-0.40		U-0.40		U-0.60	
Metal framing (entrance door)[c]	U-0.80		U-0.80		U-0.90	
Metal framing (all other)[c]	U-0.45		U-0.45		U-0.65	
Skylight with Curb, Glass, % of Roof						
0%–2.0%	U_{all}-0.98	$SHGC_{all}$-NR	U_{all}-0.98	$SHGC_{all}$-NR	U_{all}-1.30	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-0.98	$SHGC_{all}$-NR	U_{all}-0.98	$SHGC_{all}$-NR	U_{all}-1.30	$SHGC_{all}$-NR
Skylight with Curb, Plastic, % of Roof						
0%–2.0%	U_{all}-0.61	$SHGC_{all}$-NR	U_{all}-0.61	$SHGC_{all}$-NR	U_{all}-1.10	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-0.61	$SHGC_{all}$-NR	U_{all}-0.61	$SHGC_{all}$-NR	U_{all}-1.10	$SHGC_{all}$-NR
Skylight without Curb, All, % of Roof						
0%–2.0%	U_{all}-0.58	$SHGC_{all}$-NR	U_{all}-0.58	$SHGC_{all}$-NR	U_{all}-0.81	$SHGC_{all}$-NR
2.1%–5.0%	U_{all}-0.58	$SHGC_{all}$-NR	U_{all}-0.58	$SHGC_{all}$-NR	U_{all}-0.81	$SHGC_{all}$-NR

[a] The following definitions apply: c.i. = continuous insulation (see Section 3.2), NR = no (insulation) requirement.
[b] Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[c] Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.

ASHRAE 90.2 TABLE 5.2

Table 5.2 Prescriptive Envelope Criteria

Climate Zone No.	Ceilings: Attic Space, Wood, Cavity R	Ceilings: Attic Space, Steel, Cavity R	Ceilings: Without Attic Space (Cathedral or Flat Roof), Wood, Cavity R	Ceilings: Without Attic Space (Cathedral or Flat Roof), Steel, Cavity R	Walls: Above-Grade Frame, Wood, Cavity R	Walls: Above-Grade Frame, Wood, Cont. Ins. R	Walls: Above-Grade Frame, Steel, Cavity R	Walls: Above-Grade Frame, Steel, Cont. Ins. R	Walls: Frame Adjacent to Unconditioned Space, Cavity R	Walls: Above-Grade Mass Exterior Insulation, Continuous Insulation R	Walls: Above-Grade Mass Interior Insulation, Interior Insulation R	Walls: Below-Grade Exterior Insulation[a], Continuous Insulation R	Walls: Below-Grade Interior Insulation[a], Interior Insulation R	Walls: Unvented Crawlspace, Interior Insulation R	Floors: Frame Over Exterior, Wood, Cavity R	Floors: Frame Over Exterior, Steel, Cavity R	Floors: Frame Over Unconditioned Space and Vented Crawlspace, Wood, Cavity R	Floors: Frame Over Unconditioned Space and Vented Crawlspace, Steel, Cavity R	Floors: Slab-on-Grade, Perimeter Insulation R[b]	Doors: Non-Wood U	Fenestration: Vertical Glazed Assemblies U	Fenestration: Vertical Glazed Assemblies SHGC	Fenestration: Skylights U	Fenestration: Skylights SHGC[b]
1	30	30	13	19	13	0	15	0	0	0	0	0	0	0	15	22	13	15	NR	0.39	0.67	0.37	1.60	0.4
2	30	30	22	19	15	0	21	0	0	0	0	0	0	0	19	22	13	15	NR	0.39	0.67	0.37	1.05	0.4
3A,B	30	30	22	22	15	0	15	7.5	11	0	4	0	0	13	19	30	19	30	NR	0.39	0.47	0.40	0.90	0.4
3C	30	30	22	22	15	0	15	7.5	11	0	4	0	0	13	19	30	19	30	NR	0.39	0.47	0.40	0.90	NR
4	38	38	22	22	15	5	15	7.5	13	3	4	0	0	21	21	38	19	30	NR	0.39	0.35	NR	0.60	NR
5	43	43	26	30	21	0	21	10	13	3	4	5.4	11	30	25	38	25	38	NR	0.39	0.35	NR	0.60	NR
6	49	49	38	38	15	10	21	10	15	6	15	8.1	11	30	25	38	25	38	NR	0.39	0.35	NR	0.60	NR
7	49	49	38	38	21	10	21	10	15	6	15	10.8	11	30	38	38	30	38	NR	0.39	0.35	NR	0.60	NR
8	52	52	38	38	21	10	21	10	15	6	21	10.8	11	30	38	38	30	38	NR	0.39	0.35	NR	0.60	NR

[a] Either the below-grade exterior insulation or the below-grade interior insulation requirements must be met. Insulation must extend the full height of the wall.
[b] NR = No requirement.

APPENDIX B: UTILITY DATA TEMPLATE

Month	Electric Billed Days	kWh	Gas Billed Days	Therms	Avg. Monthly Outdoor Temp
1	34	3160	34	240	26
2	29	2680	29	174	35
3	28	2720	28	180	32
4	31	2920	31	99	42
5	30	2720	30	86	49
6	32	2920	32	86	58
7	30	5680	30	70	69
8	29	5680	29	72	73
9	29	5160	29	73	73
10	32	4200	32	75	68
11	28	2640	28	88	55
12	31	2560	31	153	40
1	34	2640	34	199	35
2	29	2400	29	181	31
3	29	2480	29	180	35
4	32	2440	32	108	47
5	30	2360	30	109	47
6	32	2520	32	111	57
7	30	4600	30	81	70
8	29	4600	29	70	76
9	28	4240	28	66	77
10	32	2880	32	82	64
11	29	2440	29	99	52
12	33	2600	33	177	38
1	32	2560	32	265	32
2	31	2520	31	211	26
3	28	2080	28	198	31
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0

APPENDIX C: RUNNING AND INSTALLING BEAT

BEAT can run on any computer with a Windows operating system. The program has only been tested on computers running Windows 7. Matlab is not required to run the program. First, unzip the folder entitled “BEATv03”. It contains the following files:

1. Executable file: BEATv03.exe

2. Text file: readme.txt

The “readme” file includes instructions on how to download and install Matlab Runtime Compiler (MCR) which is required to run BEAT on a computer that does not have Matlab installed. These instructions are as follows:

1. Verify the MATLAB Compiler Runtime (MCR) is installed and ensure you have installed version 8.0 (R2012b).

2. Download the Windows 64-bit version of the MCR for R2012b from the MathWorks Web site

After you have verified that MCR is installed, you may run the executable file “BEATv03.exe” by double clicking on the file name. The cover page will automatically pop up. Follow the instructions to guide you through the program. If desired, the utility data can be entered into the provided template in Appendix B: Utility Data Template.

After the last window has been completed, the program will indicate that it is calculating. When the calculations are complete, the graphed results will pop up, and will also be accessible in the Results folder, along with an excel file of the numerical outputs. These outputs, such as annual heating and cooling energy usage, can then be used to determine pre- versus post- retrofit savings, as well as savings over ASHRAE 90.1 or 90.2. These graphs must be either closed or renamed before running the program again. If a graph of the same name is open while the program is attempting to create a new graph, it will crash.

The output data files will be saved in the following directory on the computer running BEAT: C:\Beat\Results. If this path does not already exist on the computer, BEAT will create the folder at this specified location.

APPENDIX D: BEAT USER MANUAL

1. INTRODUCTION

BEAT is a simulation tool which enables the user to estimate the savings between pre- and post-retrofit utility data without the need for weather normalization. It also provides a comparison to an ASHRAE 90.1 or 90.2 baseline building, allowing the user to determine the degree of efficiency of the building performance relative to a national standard, both pre- and post-retrofit.

BEAT performs this analysis using two methods: inverse and forward modeling. Inverse modeling is the core to the calculation, providing all of the information required. Forward modeling adds an extra degree of accuracy to compare the inverse model against. The ASHRAE Baseline is also calculated using a Forward model which uses the prescriptive envelope criteria from Standard 90.1 and 90.2

2. INVERSE MODEL INPUTS

In order to perform an inverse model, utility data is required to calculate the building's balance temperature(s) which is then used to determine heating degree days, and cooling degree days specific to the building being modeled. The balance temperature and degree days will be further explained in the Outputs section.

The basic methodology for the inverse model is to plot exterior air temperature against energy usage and use the relationship between the two variables to determine a best-fit regression which provides characteristics about the building which can then be used to predict energy usage for any given weather year.

1.1 UTILITY DATA

The utility data can be input into BEAT directly, or imported through an excel template. The excel template format must stay the same as in the template provided; otherwise BEAT will not be able to read the data properly. The following information is required, and all of it can typically be found on monthly utility bills:

- Number of days in billing period for electricity usage**
- Monthly electricity usage (kWh)
- Number of days in billing period for gas usage**
- Monthly gas usage (therms)
- Average monthly outdoor temperature*

*This information can usually be found on Xcel utility bills. Otherwise, it can be gathered here through the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center. The "MNTM" column shows the monthly mean [outside air] temperature.

** The number of billing days is essential to proper functioning of the program. If billing days are unknown, either enter the number of days in the month. It is always better to obtain the actual billing days, otherwise the program will not produce the most accurate results.

1.2 HVAC DATA

Certain information about the heating, ventilation, and air-conditioning (HVAC) system is required to determine the best type of fit for the data. For example, if the heating and cooling system both use electricity, as the outside air temperature increases or decreases from the balance temperature(s) there will be an increase in electricity usage. In another example, if the system is water (baseboard) it will always be one type of fit, but if it is air, it could be several different fits based on the operation of the system (i.e. economizer, VAV).

The following information about the HVAC system is required:

- Fuel type (electricity, gas, oil)
- System delivery type (water, air)
- System efficiency (for electric systems COP or EER is most accurate)
- Additional options (Constant volume, variable volume, economizer, heat recover ventilator, enthalpy recovery ventilator, etc)

<table>
<tr><th></th><th>Gas/Oil</th><th>Electricity</th></tr>
<tr><td>Heating</td><td>AFUE (%)</td><td rowspan="3">COP/EER (Preferred)
SEER (Third Option)</td></tr>
<tr><td>Cooling</td><td>not an option</td></tr>
<tr><td>Combined</td><td>not an option</td></tr>
</table>

3. FORWARD MODEL INPUTS

The forward modeling method uses the U-values and areas of the building's exterior constructions to calculate the building's load coefficient (BLC). For the ASHRAE forward model, the maximum U-value from Tables 5.5-1 through 5.5-8 in ANSI/ASHRAE/IES Standard 90.1-2010 for high-rise residential buildings (4 stories or above), and Table 5.2 from ANSI/ASHRAE/IES Standard 90.2-2007 for low-rise residential buildings (3 stories or below) is used in place of the actual construction U-value. These U-values vary based on climate zone.

The following information is required for a Forward model:

- Exterior construction U-values
- Exterior construction areas
- Whole building volume
- Approximate leakiness (leaky, average, tight)

For leakiness, these values roughly correspond to the age of the building. For new construction, choose tight, for older buildings, choose leaky or average based on the quality of the windows and doors. Make sure to only enter data for exterior constructions and for constructions that are applicable to the building being studied. "Adjacent to unconditioned space" refers to an enclosed area, like a garage, not ambient air.

The following information is required for an ASHRAE Forward model:

- ASHRAE climate zone*
- Number of stories*
- Exterior construction type
- Exterior construction areas
- Whole building volume
- Approximate leakiness (leaky, average, tight)

*Even if an ASHRAE Forward model is not performed, the climate zone and number of stories is required for formatting reasons.

4. OUTPUTS

The outputs from BEAT fall into the following categories:

- Balance Temperature (Tb, °F)
- Degree Days (DD, °F-day)
- Building Load Coefficient (BLC, Btu/hr-°F)
- Base Load (BL, kWh/day[1] or MMBtu/day[1])
- Energy Usage (kWh/yr or MMBtu/yr)

[1] Conversions: 1 kWh = 3,412.142 Btu; 1 MMBtu = 1,000,000 Btu = 10 therms

The balance temperature and degree days are calculated from the Inverse model. The balance temperature is the outside temperature below which the building requires heating, or above which the building requires cooling. A building can have more than one balance temperature (i.e. two for heating, and two for cooling, or one for heating and one for cooling). The outdoor temperature between the heating and cooling balance temperature is the “transition period” or the time at which the building requires neither heating nor cooling. Balance temperature is essentially the point at which the heat gains and losses of the building are at equilibrium with the outdoor temperature. Tb includes the net heat gains due to solar radiation, internal gains, and ground losses.

The heating degree days (DDH) reflects the demand for energy needed to heat the building. It is derived from the difference between the outdoor temperature and the balance temperature. For example, when the outdoor temperature is below the heating balance temperature, it contributes to an increase in the number of DDH. The cooling degree days reflect the demand for energy to cool the building. The standard way of calculating degree days uses one balance temperature at 65 F. As you will see in the outputs from the program, this Tb is not accurate for most buildings.

The building load coefficient (BLC) characterizes the sum of the total heat transmission of the entire building and the building's infiltration losses. It accounts for all the above-grade building envelope components. Therefore, changes in the building envelope will change the building's load coefficient. A lower building coefficient equals a more efficient and tight envelope. The For the forward model, BLC is calculated using Equation . The inverse model BLC is calculated from Equation 2and Equation 3, where β is the slope of the line created by plotting monthly heating energy usage (from the utility bills) versus monthly outdoor temperature, as shown in Figure 1.

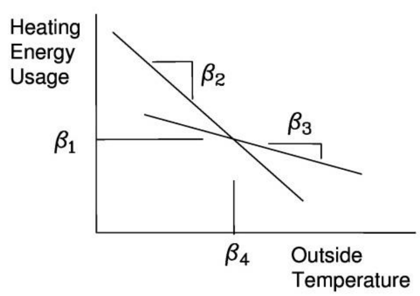


Figure 1: Heating Energy Usage versus Outdoor Temperature

$$BLC = \sum_{j=1}^{N_E} U_{T,j} * A_j + \dot{m}_{inf} * c_{p,a}$$ **Equation 1**

$$Electric: BLC = ABS\left(\frac{\beta_2 * 24}{COP}\right) * 3412$$ **Equation 2**

$$Gas: BLC = ABS\left(\frac{\beta_2 * 24}{\eta}\right) * 1.0E6$$ **Equation 3**

The base load is simply the constant energy usage, or the usage which is independent of exterior temperature. This is energy used for domestic hot water, internal plug loads, appliances, etc.

Finally, the annual energy usage is calculated using Tb, DD, and BLC. It predicts the amount of energy usage for heating (or cooling) only. The program will also output 2-4 graphs, depending on whether or not pre- and post-retrofit analysis was performed. These graphs must be either closed or renamed before running the program again. If a graph of the same name is open while the program is attempting to create a new graph, it will crash.

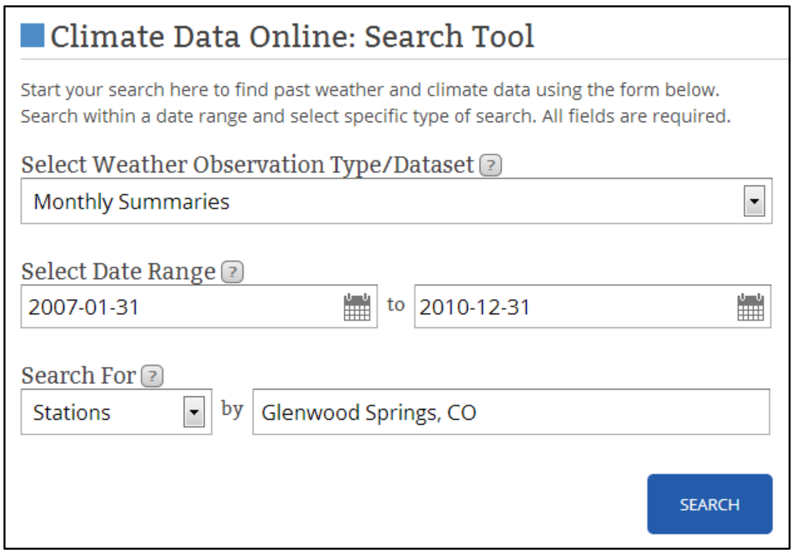
5. PRE AND POST RETROFIT ANALYSIS

In order to capture the most accurate changes in both interior loads and envelope retrofits, utility data is required. However, the Forward model can be used to conservatively predict the impact of envelope retrofits or HVAC efficiency updates on the building energy usage. It will use constant Tb and DDH, which, in actuality, will change after the retrofits. Theoretically, the impact of the retrofits will have a greater impact than predicted since (i.e., for heating) the Tb will increase and the DDH will decrease.

No weather normalization is required in this program. Once pre-retrofit balance temperature and BLC are calculated, the post-retrofit weather data is used in conjunction with the pre-retrofit balance temperature to calculated degree days. This in turn is used to predict energy usage in the post-retrofit weather year as though the retrofit had never occurred.

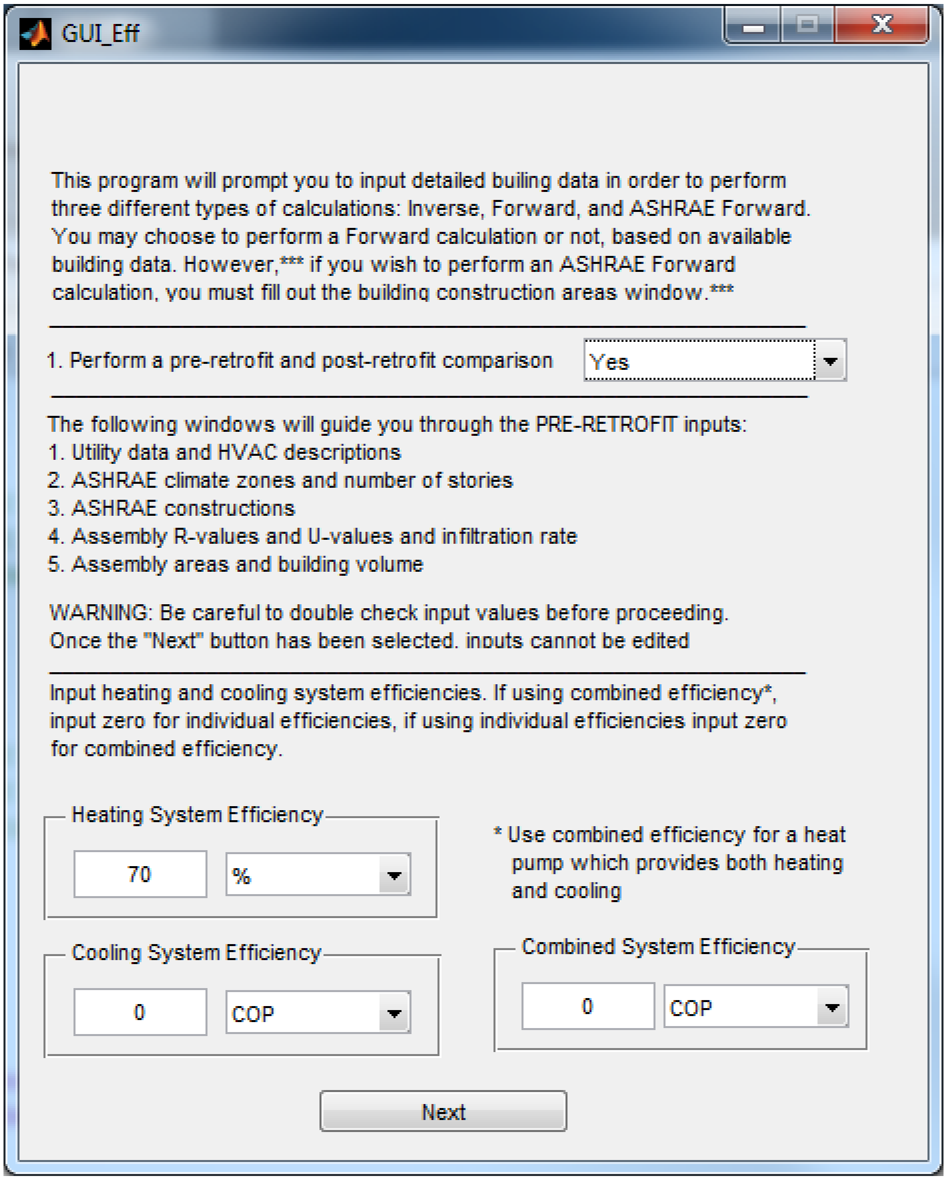
6. *TUTORIAL*

This tutorial will guide you through a case study using Sunnyside Retirement Village in Glenwood Springs, CO. The pre-retrofit utility data was obtained through historic utility bills, and the post-retrofit utility data was generated using a calibrated eQuest model. The average monthly outdoor temperature was obtained from the NOAA NCDC website:

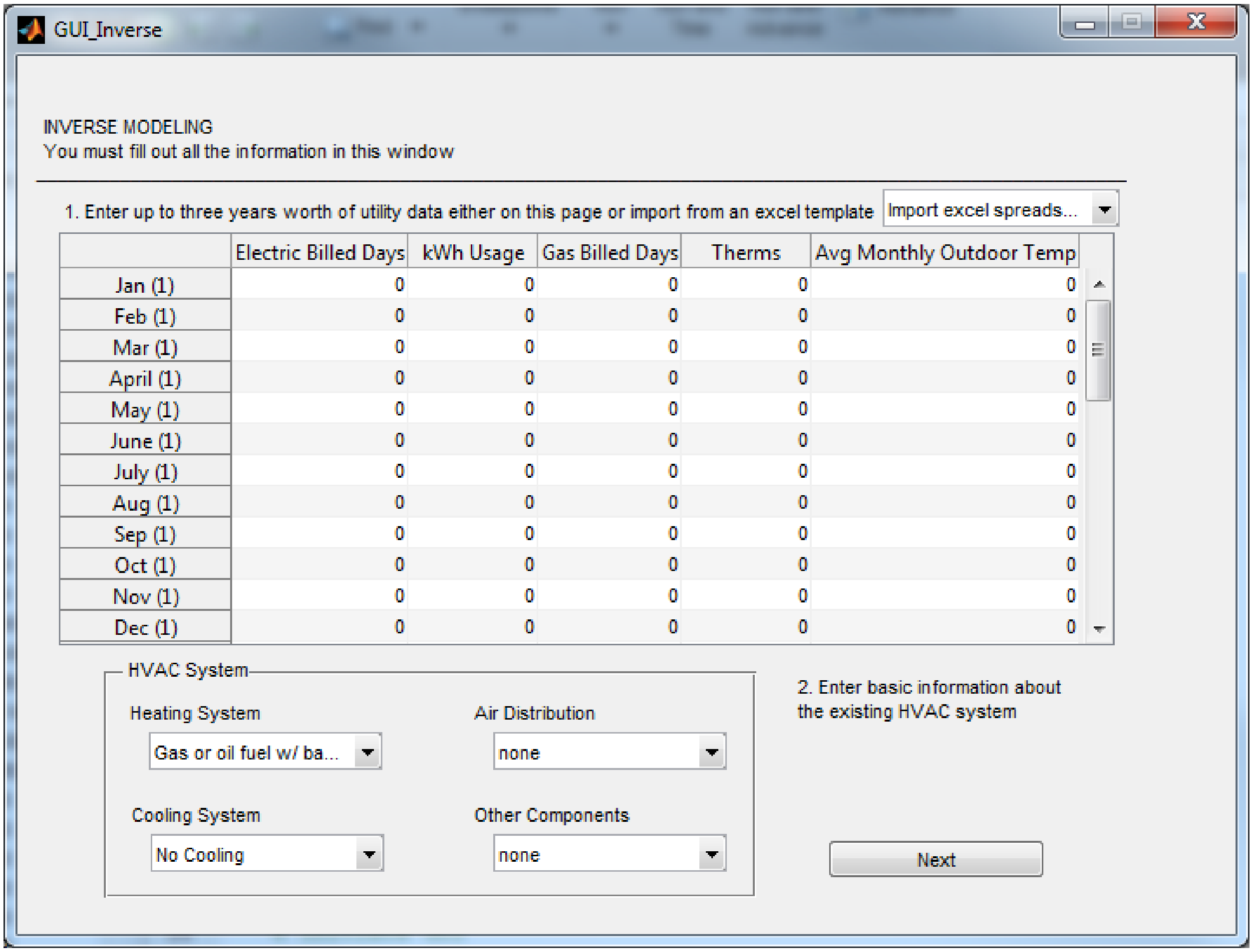


This pulls up a search for weather stations which have data between those years. You may have to check several stations before finding one that includes temperature. This will typically be a station that includes several decades of data, indicating a main station. To check, simply click a station, click "view details", select the year you want to look at, and click "view data". After it has been verified that this station includes the information required (MNTM), select "add to cart". Shortly, the NCDC will send you a link to enable you to download the requested data, free of charge: Next, all of the utility data and the weather data was entered into the utility data template to prepare for import into BEAT.

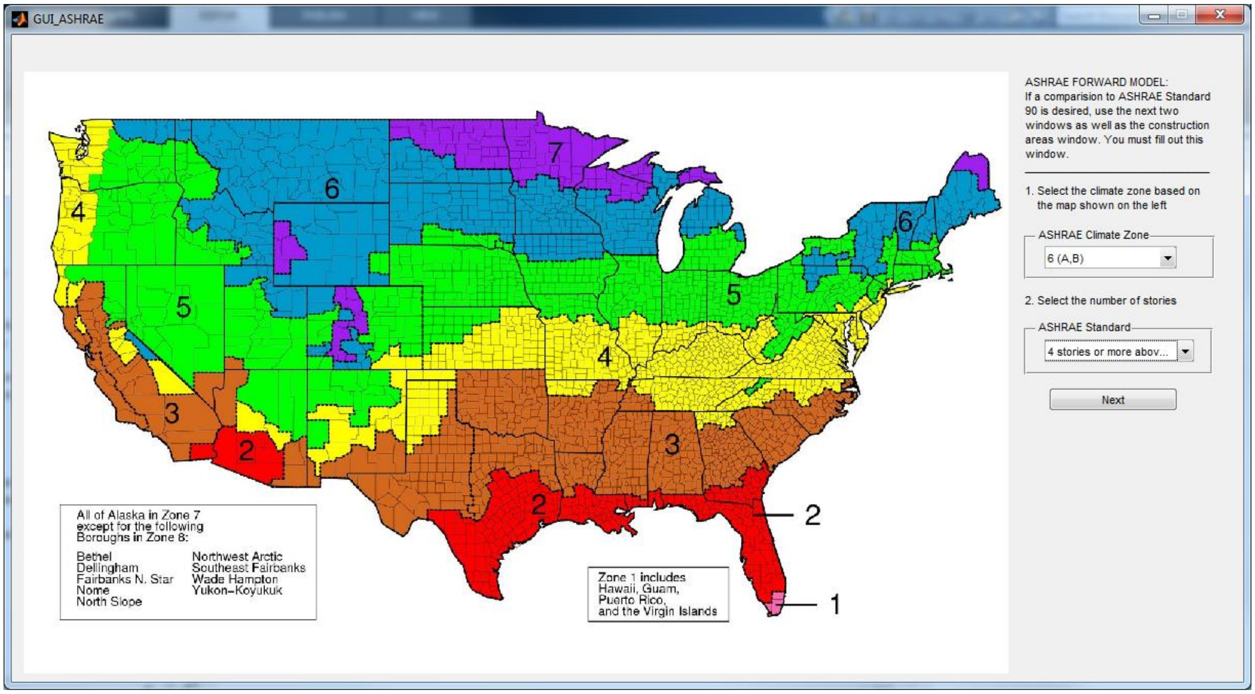
Click “Start” to begin the calculations. The first window includes some instructions, and allows you to input pre-retrofit heating and cooling system efficiency



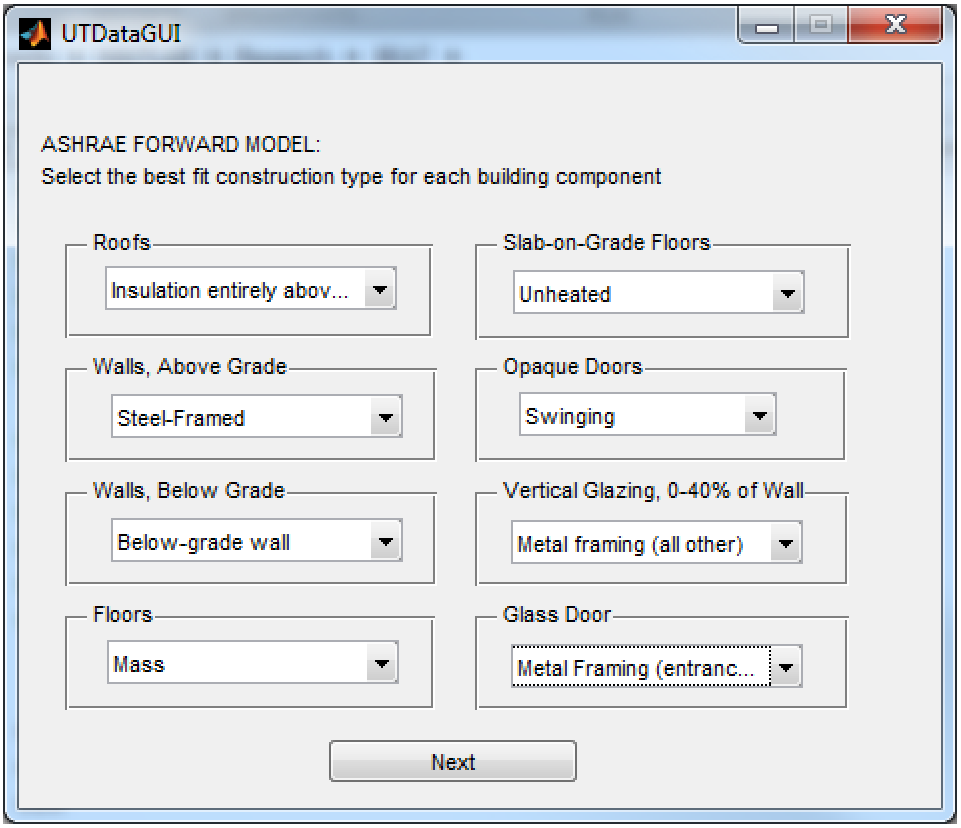
The second window prompts you for utility data, as well as basic defining information about the heating, ventilation, and air conditioning (HVAC) system:



If you selected "import excel spreadsheet" a navigator will pop up allowing you to select the appropriate import file. Next, the ASHRAE climate zone and number of stories in the building are selected:

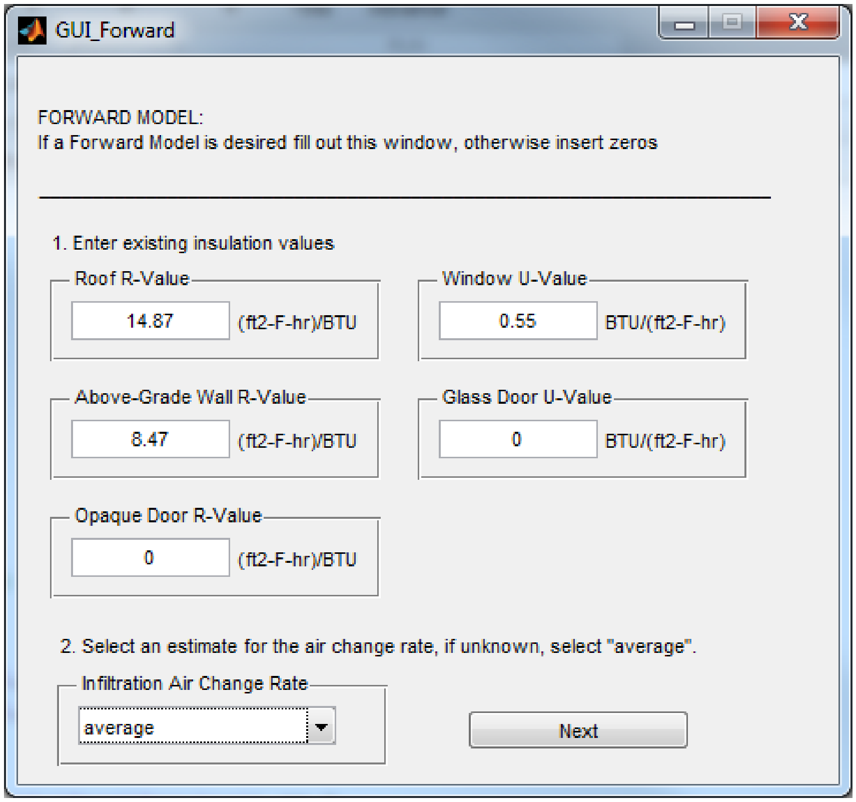


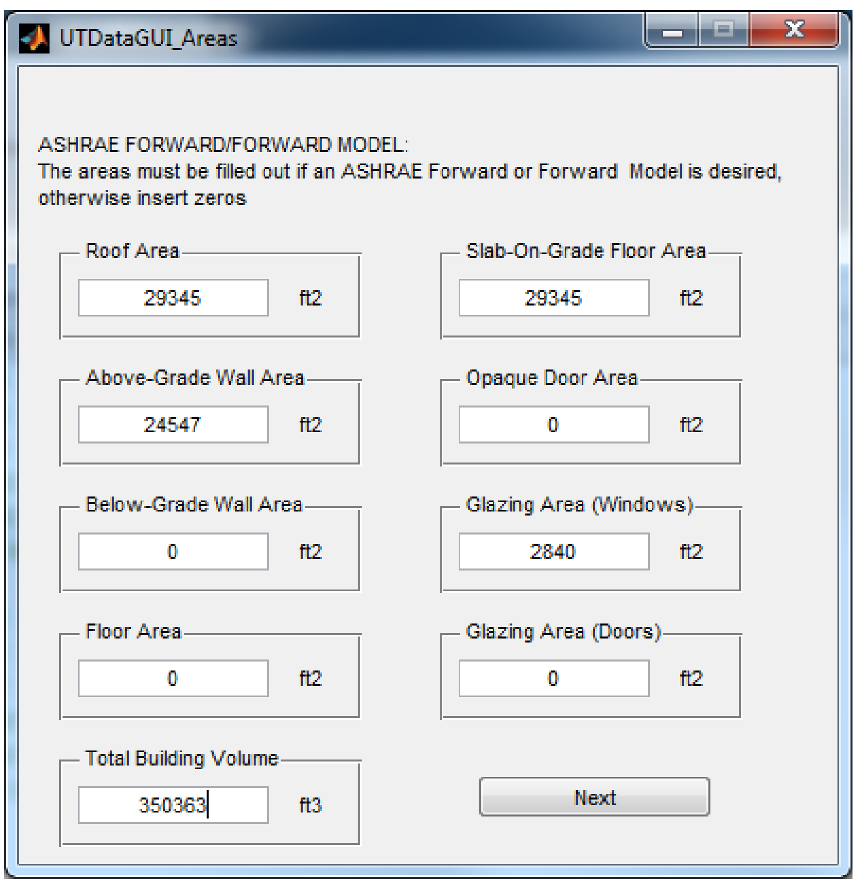
And the ASHRAE baseline construction types are selected. If the building component does not exist, you will be able to input zero for the area in a later window:



Next, the actual U-values and R-values of the existing building are inputted. Alternatively, you may enter all zeros in this window if a comparison to ASHRAE is not desired.

The areas of exterior constructions only are entered in the following window. For example, if your building does not have any below-grade walls, enter zero. "Floor" area is referring to any floor exposed to ambient air, not to internal floors that separate conditioned space from conditioned space.


GUI_Forward
FORWARD MODEL:
If a Forward Model is desired fill out this window, otherwise insert zeros
1. Enter existing insulation values
Roof R-Value
14.87
(ft2-F-hr)/BTU
Window U-Value
0.55
BTU/(ft2-F-hr)
Above-Grade Wall R-Value
8.47
(ft2-F-hr)/BTU
Glass Door U-Value
0
BTU/(ft2-F-hr)
Opaque Door R-Value
0
(ft2-F-hr)/BTU
2. Select an estimate for the air change rate, if unknown, select "average".
Infiltration Air Change Rate
average
Next


UTDataGUI_Areas
ASHRAE FORWARD/FORWARD MODEL:
The areas must be filled out if an ASHRAE Forward or Forward Model is desired, otherwise insert zeros
Roof Area
29345
ft2
Slab-On-Grade Floor Area
29345
ft2
Above-Grade Wall Area
24547
ft2
Opaque Door Area
0
ft2
Below-Grade Wall Area
0
ft2
Glazing Area (Windows)
2840
ft2
Floor Area
0
ft2
Glazing Area (Doors)
0
ft2
Total Building Volume
350363
ft3
Next

After this window, if a post-retrofit comparison was selected, four of the windows will repeat themselves to allow you to enter changes in the HVAC system type or efficiency, post-retrofit utility data, building u-value and R-values, and construction areas.

Once the inputs are completed, the program will calculate the results. When the calculations are completed, one to four graphs will pop up, depending on whether the building contains both heating and cooling, or if a post-retrofit comparison was performed.

These graphs will also be saved in the folder: C:\BEAT\Results, along with an excel file containing the calculation values. The following table includes a summary of the results for this example:

	Pre-ECM	**Post-ECM**	**% Diff**
CPL Model Type	3PgH	3PgH	
Tb (°F)	56.75	55.85	1.6%
DDH (°F-day)	5987	5743	4.1%
ASHRAE BLC (Btu/hr-°F)	8620	8620	0.0%
Forward BLC (Btu/hr-°F)	9794	6933	29.2%
Inverse BLC (Btu/hr-°F)	6403	4526	29.3%
Gas Base Load (MMBtu/day)	0.970	0.603	37.8%
ASHRAE Annual Heating (MMBtu/yr)	1769	1485	16.1%
Forward Annual Heating (MMBtu/yr)	2010	1194	40.6%
Inverse Annual Heating (MMBtu/yr)	1314	780	40.7%