A THERMAL RC MODEL INCLUDING THERMAL MASS AND SOLAR GAIN EFFECTS FOR BUILDING ENERGY SIMULATION

A Thesis

by

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ABSTRACT

Building Commissioning is important for evaluating energy and dollar savings in existing buildings. Energy Systems Lab of Texas A&M University has developed WinAM with the purpose of aiding that process. WinAM is a steady-state calculation engine tool that computes energy and dollar savings for commissioning purposes in existing buildings. However, the problem can rise with WinAM's simplified calculation method rendering inaccurate results. This research proposes a Resistance-Capacitance (RC) model be added to the current WinAM model that incorporates the effects of solar heat gains and thermal mass effects. The RC model is tested against 11 simulation cases with EnergyPlus™, a building energy simulation program, and the current WinAM version. Parameters are changed in all models to analyze the proposed RC model against EnergyPlus results. The results show that the RC model achieves better performance than WinAM when compared to EnergyPlus. The extreme case differs of 286% for annual heating consumption between the RC model and EnergyPlus, while WinAM differs in 4040% for annual heating consumption when compared to EnergyPlus. The RC model annual heating and cooling consumption results approximates better to EnergyPlus in more than 90% of the cases analyzed. Energy savings are estimated for the cases of temperature setback and dead-band temperature set points, for seven different weather conditions and three different building masses. A case study is also analyzed of a real building, each model is calibrated to the building's metered energy consumption, and applied energy efficiency measures (EEMs) to the models, comparing each model's estimated savings. For the case study, the estimated savings from all models when temperature set back and temperature dead-band are applied present similar estimated savings. The extreme cases are of WinAM over predicting savings for temperature set back such as 47% for annual heating consumption, while RC predicts 27% and EnergyPlus only predicts 6%, and WinAM under predicting savings for temperature dead-band such as 31% for annual heating consumption, while RC predicts 96%, and EnergyPlus predicts 99% savings. The RC model presents improvement from the current WinAM model in 53/55 of simulated cases of the estimated savings when compared to EnergyPlus esti-

mated savings.

DEDICATION

To God, to my beloved wife Laura, to family and friends. There is nothing more I could ask for.

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1. INTRODUCTION

1.1 Background

The hazards of Climate Change are increasingly well known [6] [7] resulting in a reduction of energy consumption and lowered carbon emissions.

Energy consumption for commercial and residential buildings is approximately 40% of U.S. total energy usage [8]. Consequently, the importance in reducing energy consumption for this sector, and hence the job of building commissioning is vital.

Building commissioning, according to ASHRAE's "The Strategic Guide to Commissioning"[9], is defined as: "a quality-focused process for enhancing the delivery of a new and existing building project". It also states: "Post-occupancy on-going commissioning can also contribute to sustaining optimal performance over time, delivering energy efficiency and operational savings".

The Energy Systems Laboratory (ESL) at Texas A&M University developed a unique building commissioning process called Continuous Commissioning®, or CC®[10]. Its main objective is to produce a rapid payback while improving occupant comfort using cost effective measures into existing buildings. One of the tools developed by ESL for this process is WinAM. This software provides a quick method to estimate energy consumption and Energy Efficiency Measures (EEMs) that can be applied to existing buildings, with the emphasis of using its existing equipment rather than proposing costly retrofits.

WinAM is a simplified building energy simulation. Its main features are fewer user-input parameters when compared to its peers, a calibration assistant that enables a user to perform a quick calibration of a model to the building's measured energy consumption data, and the ability to estimate savings when EEMs are applied to the calibrated model. Notably, due to WinAM's non-complex thermal model, it lacks a comprehensive physical modeling in some of its features, e.g. neglecting the effects of thermal mass and solar gains to the building's energy consumption, which can render misguided results, especially when estimating savings for a temperature setback

EEM [1].

Likins (2018) shows a comparison from WinAM and EnergyPlus™ performances when applying a temperature setback and proposes a correction factor. EnergyPlus is a building energy simulation program funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). Figure 1.1, from the author's thesis, shows a comparison of the estimated savings from the cooling coils for a heavy mass construction in College Station, Texas. The study shows that WinAM is over predicting energy and dollar savings when applying temperature setback EEM, thus becoming an ineffective EEM for use when using WinAM. This is highly damaging for the CC® process, as this EEM has great potential in generating energy and dollar savings, if estimated correctly. Although Linkin's correction factor has shown effectiveness for the case displayed in Figure 1.1 into adjusting the estimated savings from a temperature set back EEM, it has also been demonstrated that it is not a comprehensive model for all climate scenarios.

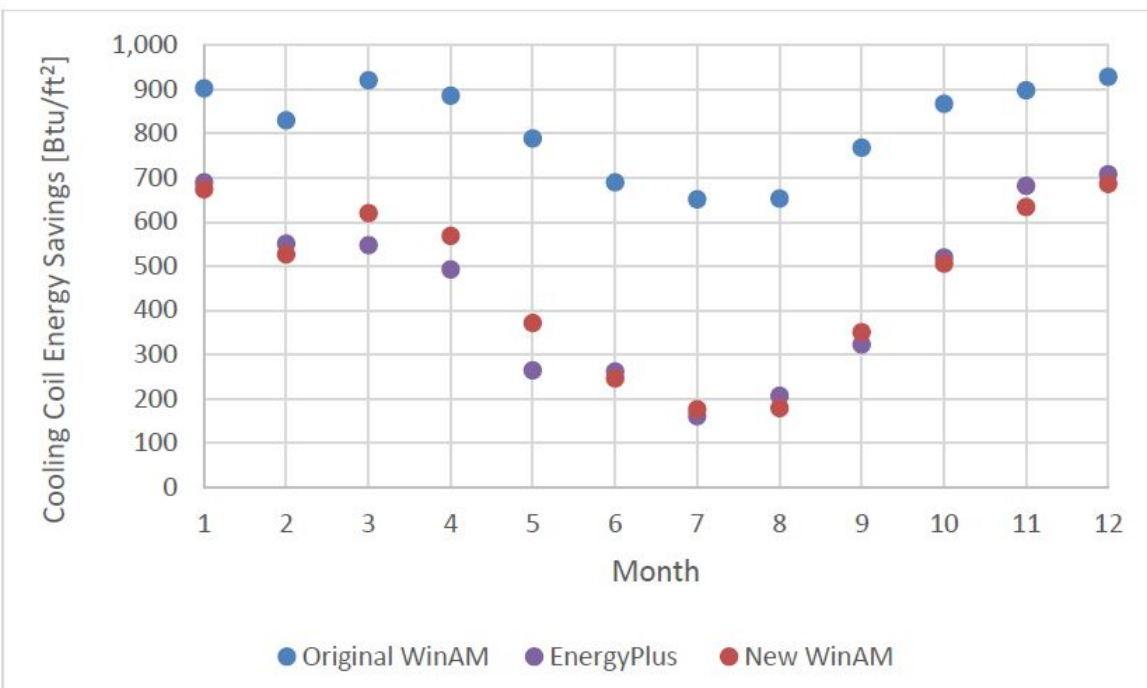


Figure 1.1: Monthly cooling coil energy savings for a heavy mass construction in College Station (Reprinted from [1])

Source: (Linkins, 2018)

1.2 Objective

The objective of this research is to test a Resistance-Capacitance (RC) model which incorporate thermal mass effects and solar gains, and to compare its effectiveness when applying EEM's, when compared to the savings obtained using EnergyPlus.

The testing is done against several EnergyPlus and WinAM simulations with buildings of similar parameters as the model's. It is also performed a case study for a real building, calibrating all three models to its measured data, and comparing the results when applied the proposed EEM's.

2. LITERATURE REVIEW

2.1 Energy Building Simulation

Since the energy crisis in the 1970's, a variety of building energy simulation programs were developed, with different calculation methods, yielding considerably different results when simulating the same building [11].

A comparison of several features of 20 major building energy simulation programs was made by Crawley et al. (2008), which included DOE2.1-E, EnergyPlus, eQuest, TRNSYS and others [12]. Notably although most programs deal with internal thermal mass, most perform design sizing calculation using only outside air dry bulb temperature, i.e. steady-state calculations. Although several features such as load calculations, economic evaluation and validation of reports are analyzed, they do not report on the ease of calibrating the simulation of an existing building to its metered energy consumption.

For building commissioning, it is of extreme importance to have a reliable physical model, in order to estimate energy and dollar savings. The challenge rises in building such a model when one needs to determine a series of building, loads, and system parameters.

Tiwari (2016) used the program eQuest to build an energy model for an existing building in Qatar, determining its Energy Utilization Index (EUI) and comparing it with a peer program, Visual DOE [13]. The results from eQuest's energy model more accurately reflect the building's physical reality, when compared with measured data, showing a deviation of only 8%, while the Visual DOE prediction is less than 57% of the measured EUI. However, the latter model was developed during the building's pre-occupancy phase, lacking comprehensive data, such as occupancy data. The study shows that since eQuest requires fewer inputs than other programs, it is more sensitive to its input parameters when compared to other detailed and complex programs such as EnergyPlus.

Ahmad & Culp (2006) emphasizes the importance of calibration for energy simulation of existing buildings [14]. Their research shows that an experienced energy simulation engineer, performing a detailed input of parameters of four buildings, had energy simulation results that ranged over +- 90% for individual components when compared to actual data. The discrepancies are due to the lack of efficiency in several real components of the building, as well as broken components that are hard to identify.

Lin et al. (2012) identifies that a second order RC model reproduces the input-output behavior of a 13th order model quite accurately [15], for predictive control using MPC (Model Predictive Control) control. Even a first order model is well fitted for the task.

In sum, even if a detailed energy modelling of an existing building is performed, it is still an arduous task to perform a calibration of the model to its measured consumption data. The studies demonstrate the importance of having a building energy simulation with real data assisting its parameters to more realistic values. Calibration of a building energy model is important due to its ability to predict energy consumption patterns when changing some of its parameters, e.g. loads, control operations, etc. However, to have a reliable calibrated model, it is more important for it to trend similarly to reality than for it to "fit" the data into the model.

2.2 Thermal Mass and Solar Gains

The thermal mass of a building is the capacity to store thermal energy, rather its sensible or latent, which has great influence in its indoor temperature, cooling/heating requirements and occupant comfort.

Reilly & Kinnane (2017) highlights that many engineers and architects focus primarily in the thermal resistances of buildings in the design stages, in making it energy efficient, disregarding its thermal mass[16]. In fact, this thinking is also incorporated into building design codes and regulations. Their study shows that substantial reductions in energy use are possible for a high mass building in hot climates, while for cold climates it would be a drawback.

Balars (1996) compared several analyzes done from different studies, and concluded that a high mass building has a smaller interior air temperature variation due to thermal mass effects compared to a low mass building [17]. For locations with large diurnal temperature fluctuations, the technique of energy storage is highly beneficial for reducing the energy consumption of mechanical systems, while maintaining occupant thermal comfort.

Braun (2003) highlights that many wrongly assume that building mass contributes to increase operation costs [18]. An assumption is often made that a massless building would require no time for pre-cooling or pre-heating, and it would have lower overall cooling loads than an actual building. However, it is possible to load shift the cooling required with the purpose of significantly reducing operational costs under proper circumstances. Braun compares different studies that have attempted to achieve optimal control strategies for reducing operational costs with load shifting due to thermal mass effects. Braun concludes that all strategies are sensitive to the following parameters: utility rate structure, type of equipment, occupancy schedule, building construction and climate conditions. Of these, the utility rate structure is the biggest factor. Most savings were achieved in east zones, and interior zones, indicating that solar gains as well as thermal mass effects in interior zones are dominant for these types of strategies. In Braun's overview, the studies found that by pre-cooling the building effectively taking into account its thermal mass, dollar savings were possible ranging from 10% to 50% cost reduction.

Belic (2016) investigates the accuracy and complexity of a buildings thermal model using a hybrid method combining the advantages of a first-principles model, where it is possible to understand its dynamics, and a data-driven model to estimate parameters more accurately, using an optimization tool [2]. The author proposes several different model structures, for a multizone, multistore building. First, the author builds an RC Model as in Figure 2.1. For this figure the author uses a 3R2C (three resistances and two capacitances) model, using tabulated values to build the initial model. Subsequently, an optimization tool is used to more accurately represent the model compared to the reference model result, minimizing error by changing the model parameters. Belic tested different complexity models, 4R3C, 3R2C and 2R1C to compare the impacts of the different models on results. In fact, the "non-optimized" model 4R3C was more accurate than the optimized 2R1C results, showing that the model structure is more important than the parameter estimation itself. Belic concluded that the best error function to be used in the optimization process, in which "best" is characterized by smallest difference compared to the reference model, is the RMSE (Root Mean Square Error) function. Lastly, Belic experimented reducing complexity of the existing models, by eliminating elements representing interior walls and fenestrations (doors and windows). The reduced models produced highly inaccurate results, demonstrating once again the importance of the model's structure. Belic stated: "the disadvantage of using RC method is that the resulting network grows in complexity for real buildings. (...) For example, relatively simple family house (...) with 14 rooms has 194 states and state matrix with 194 x 194 elements. For large commercial building, this number can be much larger".

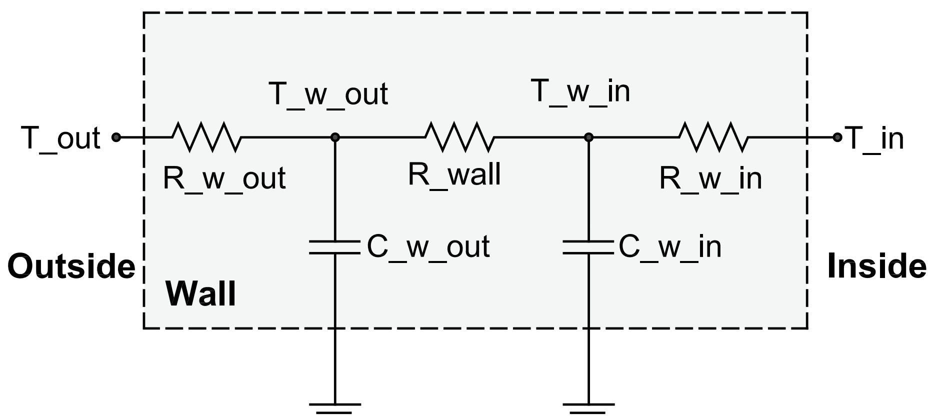


Figure 2.1: 3R2C Thermal Model (Reprinted from [2])

Source: Belic©[2016] IEEE

Scotton et al. (2013) propose three physics-based models for determining CO_2 level, indoor temperature and humidity of a room in the Q-building on Kungliga Tekniska Högskolan (KTH) Campus, Stockholm/Sweden [3]. For the temperature model, an energy balance equation was derived based on known heat transfer equations (general heat conduction and heat convection equations), having 11 parameters unknown. In this model, the authors do not account for the thermal capacitance of the walls and floor, although they do consider the thermal capacitance of the air. These parameters were established by using a set of measured data during 45 minutes in May 12,

2012. Subsequently, the authors validate their model by testing it against a different set of weather conditions in June of the same year as shown in Figure 2.2.

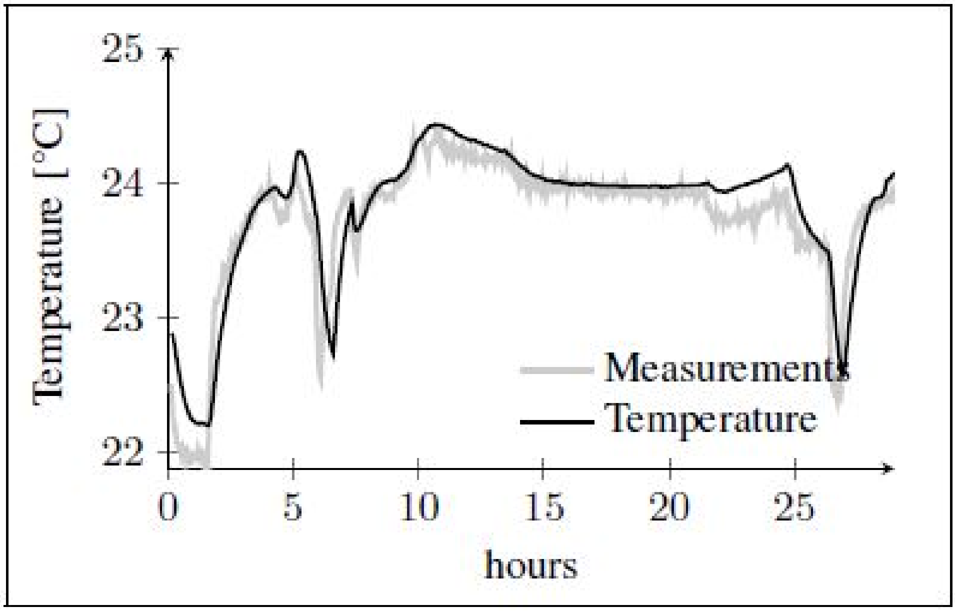


Figure 2.2: Scotton Simulation data against measured data (Reprinted from [3])

Source: Scotton©[2013] IEEE

Although the results are impressive when compared to experimental data, the authors recognize the model lacks testing against a different set of weather conditions. This model was customized for a specific lab room, and was not tested for a generic building.

Balasubramanya et al. (1992) found that when varying the parameters of buildings mass, aspect ratio, glass area ratio, internal load, control throttling range and thermostat setback, the SEAP (Simplified Energy Analysis Procedure) calculations from ASHRAE TC 4.7 results were significantly different when compared to a DOE-2 simulation [4]. It differentiates itself because it uses a simplified solar gain calculation and neglects the effects of thermal mass. The authors then develop a “modified SEAP” [19], in which maintains the basic premises of the SEAP, and adds the effects of solar heat gains and thermal mass, resulting in a RC Model as shown in Figure 2.3. This method was tested for 45 different cases against an hourly DOE-2 simulation. The results showed that in more than 80% of the cases the "modified SEAP" produced a better simulation than the original SEAP. The remaining cases are similar or have worsened.

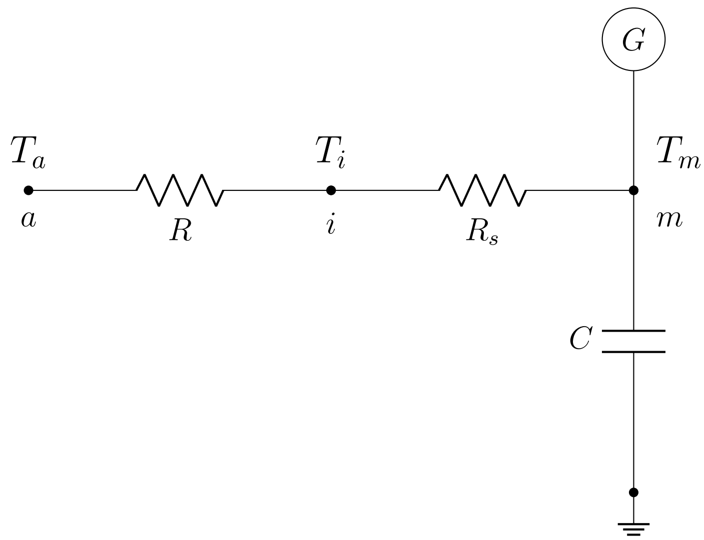


Figure 2.3: Thermal RC Model for the Modified SEAP (Adapted from [4])

Source: (Claridge, et al. 1992)

Kassas (2015) also proposes an RC Thermal Model, but considers heat transfer into the air as well as into the buildings mass, and having a capacitance attached to the air as well as the buildings mass, as in Figure 2.4 [5].

Kassas finds that there is little difference when using average daily outside air temperature and hourly outside air temperature, in terms of daily energy consumption through his simulation. He then proposes that the average daily outside air temperature could be used for estimating energy consumption for an entire residential area with this model based on an average outside air temperature for the summer period and an average outside air temperature for the winter period.

Similar to thermal mass effects, the solar heat gain is an important feature necessary to be incorporated in a building's thermal model. Yang et al. (2015) showed energy consumption is increased as the window/wall ratio is increased, becoming a sensitive parameter when estimating

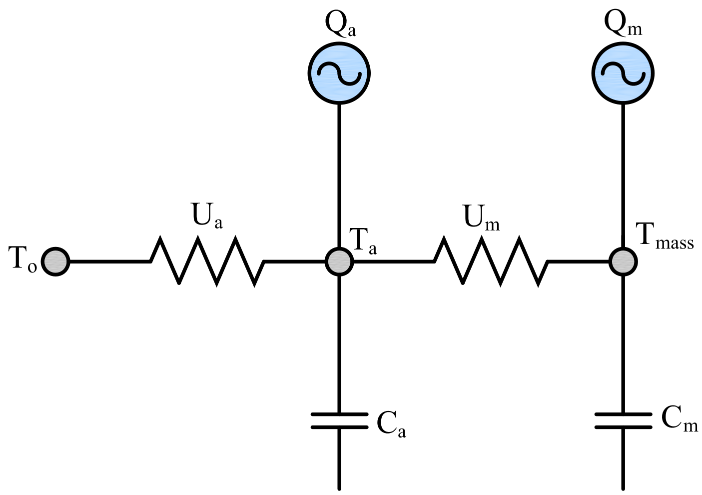


Figure 2.4: Kassas Thermal RC Model (Reprinted from [5])

Source: (Kassas, 2015)

energy consumption [20]. This sensitivity is increased if the fenestration surface is oriented west or east.

In sum, research studies show the importance of incorporating the effects of solar heat gains and the effects of thermal mass, or else the thermal model used would be incomplete and fail to achieve its purpose, especially in certain conditions described in the research studies.

3. METHODOLOGY

3.1 RC Model

This research proposes testing an RC building energy model to be used for evaluating its effectiveness when different building's mass are applied, and for different climates, especially for analysing setback temperature savings, when compared to the current model of WinAM and to EnergyPlus.

The current WinAM model, is an hourly steady-state calculation between the outside air and the inside air, as described in Figure 3.1.

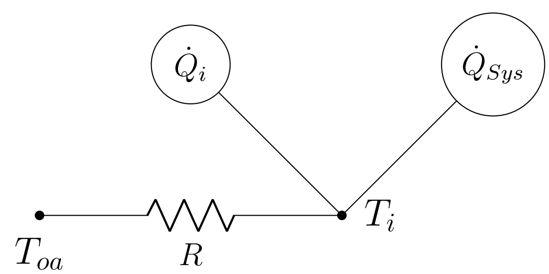


Figure 3.1: Resistance model of WinAM

In Figure 3.1, T_{oa} is outside air temperature, T_i is the zone's indoor temperature, R is the envelope resistance, $\dot{Q}_i$ is the internal heat gain from people, electrical equipment and lighting, and $\dot{Q}_{Sys}$ is the cooling or heating required to achieve the temperature set point. The envelope resistance is $R = \frac{1}{\sum_i^n U_i A_i}$, where U_i is the heat transfer coefficient for each surface of the zone, A_i is each surface area, and n is the number of zone surfaces (exterior walls and roof).

The proposed thermal model is inspired by the research studies mentioned on the literature review, but is different due to considering the internal heat gain sources (occupants, lighting and electrical equipment) primarily being transferred to the indoor air temperature (T_i), and secondarily heating up the mass of the building (walls, floors and furnishing). A diagram of this model is showed in Figure 3.2.

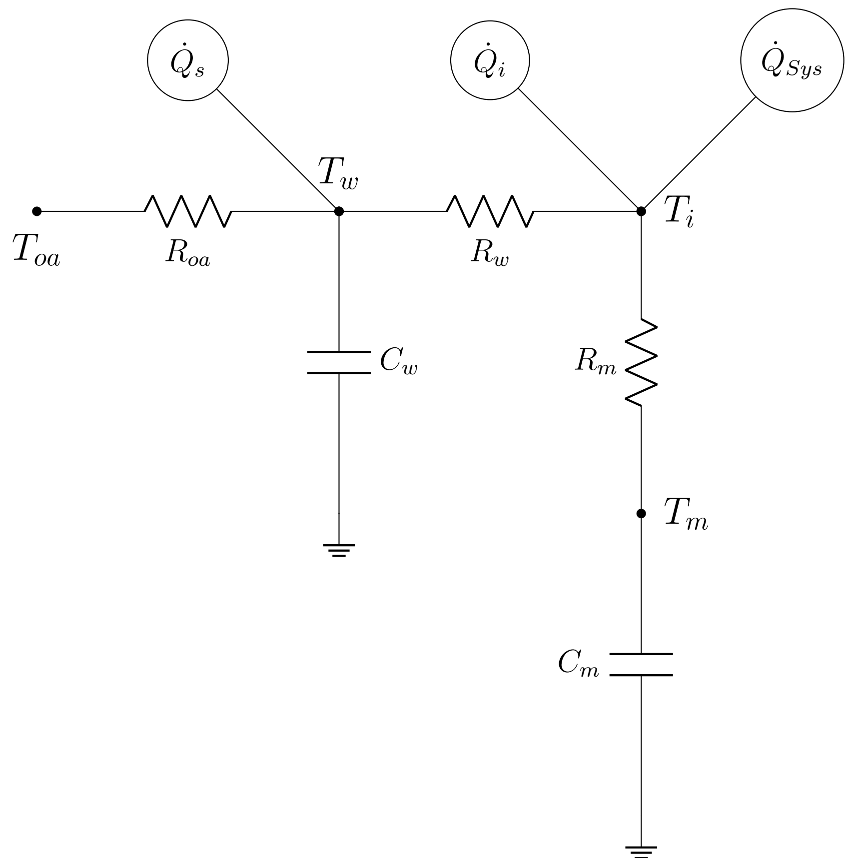


Figure 3.2: RC Model

The building's mass is represented by a temperature node (T_m) coupled with a single mass (C_m) and separated by a thermal resistance (R_m), which is the resistance of the air boundary layer and anything between the air and the floor, e.g. carpet, rug. The value of R_m was fixed as 0.5 hr·ft^2·°F/Btu through all cases in this research, which was achieved from a calibration process in simulation cases.

This model also considers that the solar heat gains are transferred primarily to the outside wall surface, and secondarily to the inside air temperature.

T_{oa} represents the outside air temperature and T_w represents the outside wall surface and mass temperature. R_{oa} represents the thermal resistance between the outside surface of the wall and the outside air, R_w represents the thermal resistance between the outside surface of the wall and the internal air, C_w represents the zone's walls thermal capacitance and C_m represents the zone's mass thermal capacitance.

The resistance values of R_{oa} and R_w were chosen as described in Equation 3.1. Therefore, for cases in which thermal mass and solar gains are not taken into account, the model reduces itself to the current WinAM model, as described in Figure 3.1. The values of R_{oa} and R_w were chosen to have R_{oa} much less than R_w, since its physical meaning is the resistance between the wall and the outside air temperature. Thus, the distribution chosen was $R_{oa} = \frac{1}{5}\frac{1}{\sum_i^n U_i A_i}$ and $R_w = \frac{4}{5}\frac{1}{\sum_i^n U_i A_i}$.

$$R_{oa} + R_w = \frac{1}{\sum_i^n U_i A_i} \tag{3.1}$$

The thermal capacitance is a term calculated as in Equation 3.2.

$$C = \sum_i^N \rho_i c_{p_i} V_i \tag{3.2}$$

where ρ_i is density, c_{p_i} is the specific heat and V_i is volume, of each layer of massive material that the thermal capacitance represents.

The thermal capacitance, based on the lumped capacitance model, is befitting to a real body when its Biot number is smaller than 0.1. For real wall buildings and floors, this is not the case. Hence, this is something to consider when analyzing the results of this model.

This model results in a differential equation, which becomes Equation 3.3 if written in terms of finite differences with terms of order $O((\Delta t)^2)$ neglected.

$$\begin{bmatrix} T_m^{p+1} \\ T_w^{p+1} \end{bmatrix} = \begin{bmatrix} 1 - \frac{\Delta t}{R_m C_m} & \frac{\Delta t}{R_m C_m} & 0 & 0 \\ 0 & \frac{\Delta t}{R_w C_w} & 1 - \frac{(R_w + R_{oa})\Delta t}{R_w R_{oa} C_w} & \frac{\Delta t}{R_{oa} C_w} \end{bmatrix} \begin{bmatrix} T_m^p \\ T_i \\ T_w^p \\ T_{oa} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{\Delta t}{C_w} \end{bmatrix} \begin{bmatrix} \dot{Q}_s \end{bmatrix} \tag{3.3}$$

The index p indicates the time step, and Δt indicates the duration of the time step. This is a simple matrix format that is not computationally expensive.

For a fixed T_i, $\dot{Q}_{Sys}$ can be calculated from an energy balance on the node T_i, as described in Equation 3.4.

$$\dot{Q}_{Sys} = \frac{R_m + R_w}{R_m R_w} T_i - \frac{1}{R_m} T_m - \frac{1}{R_w} T_w - \dot{Q}_i \tag{3.4}$$

Note that when the indoor air temperature is in the throttling range, i.e. between the heating and cooling set points, $\dot{Q}_{Sys}$ is not zero. The system still provides cooling at the cooling coil set point, with no reheat, operating at minimum flow.

3.2 Solar Calculations

It is well known that the solar irradiance on a surface is composed of three components: the direct beam, the diffuse radiation and the reflected radiation. For this research, ASHRAE's clear sky model is used to calculate all three components, where it is necessary to have the tables of the clear sky optical depth for beam irradiance and the clear sky optical depth for diffuse irradiance, for a given location, which are provided in 2017 ASHRAE Fundamentals. An example of the calculation for solar gains using this model is demonstrated in Appendix D. From these calculations, it is possible to determine the total hourly irradiance from the sun for a surface with a given orientation.

As an example, the values for the parameters described are displayed for day 21 of each month, in Table 3.1.

Table 3.1: Monthly Solar Parameters for College Station

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
τ_b	0.342	0.362	0.376	0.396	0.417	0.458	0.463	0.479	0.425	0.368	0.352	0.336
τ_d	2.391	2.298	2.267	2.223	2.211	2.088	2.09	2.029	2.226	2.413	2.415	2.463
$I_{b,N\ (Noon)}$ (W/m^2)	281	285	288	285	278	265	263	258	269	280	275	278
$I_{d,h\ (Noon)}$ (W/m^2)	33	39	42	45	46	52	52	54	43	34	32	30

In Table 3.1, τ_b is the clear sky optical depth for beam irradiance, τ_d is the clear sky optical depth for diffuse irradiance, $I_{b,N\ (Noon)}$ is the normal direct solar irradiance for a horizontal surface and $I_{d,h\ (Noon)}$ is the diffuse solar irradiance for a horizontal surface.

From interpolating the values from one month to another on a given day, a daily value for the clear sky optical depth for τ_b and τ_d can be calculated. Using these values, solar irradiation for wall surfaces oriented south, east, north, west, and parallel to the ground (roof) can be calculated. As an example, for College Station, the solar irradiation per unit area for each given surface can be seen as in Figures 3.3 and 3.4, for January 1 and July 1 respectively.

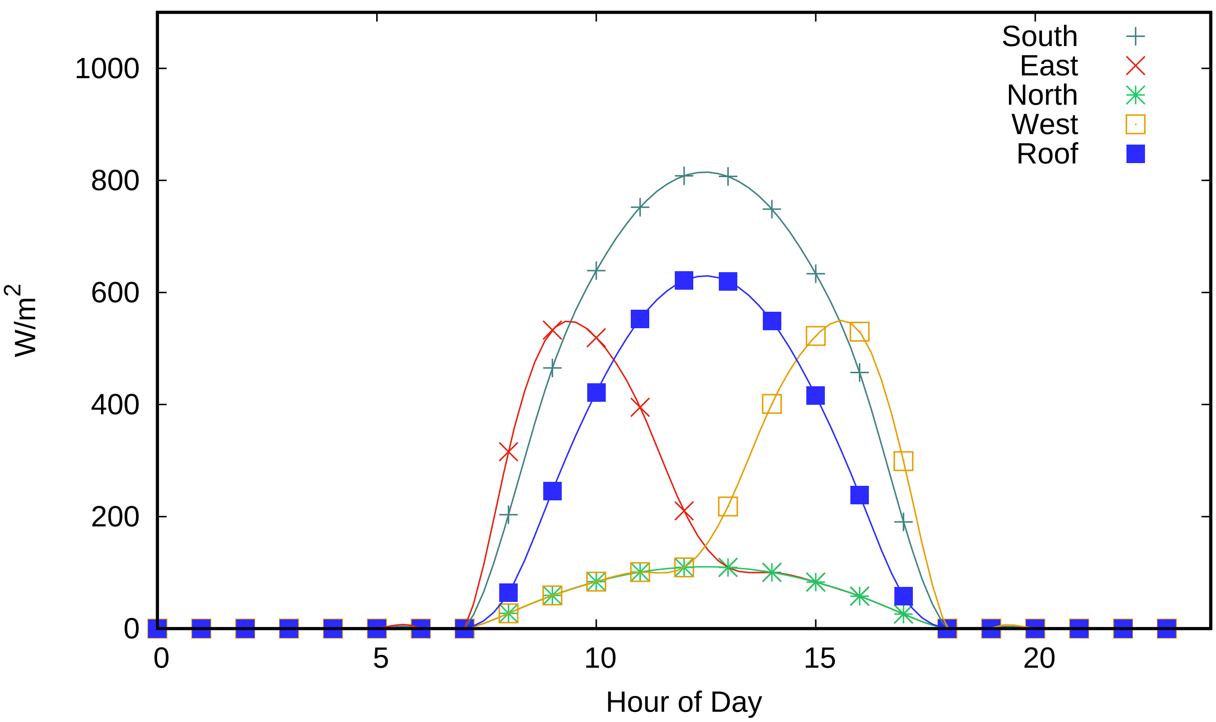


Figure 3.3: Solar Intensity for College Station January 1

In this research, the results for solar gains calculated using ASHRAE's Clear-sky radiation model are multiplied by a parameter σ_S, which can be interpreted as the wall's radiation absorptivity combined with the Window/Wall area ratio. The amount of solar heat gain is highly dependent

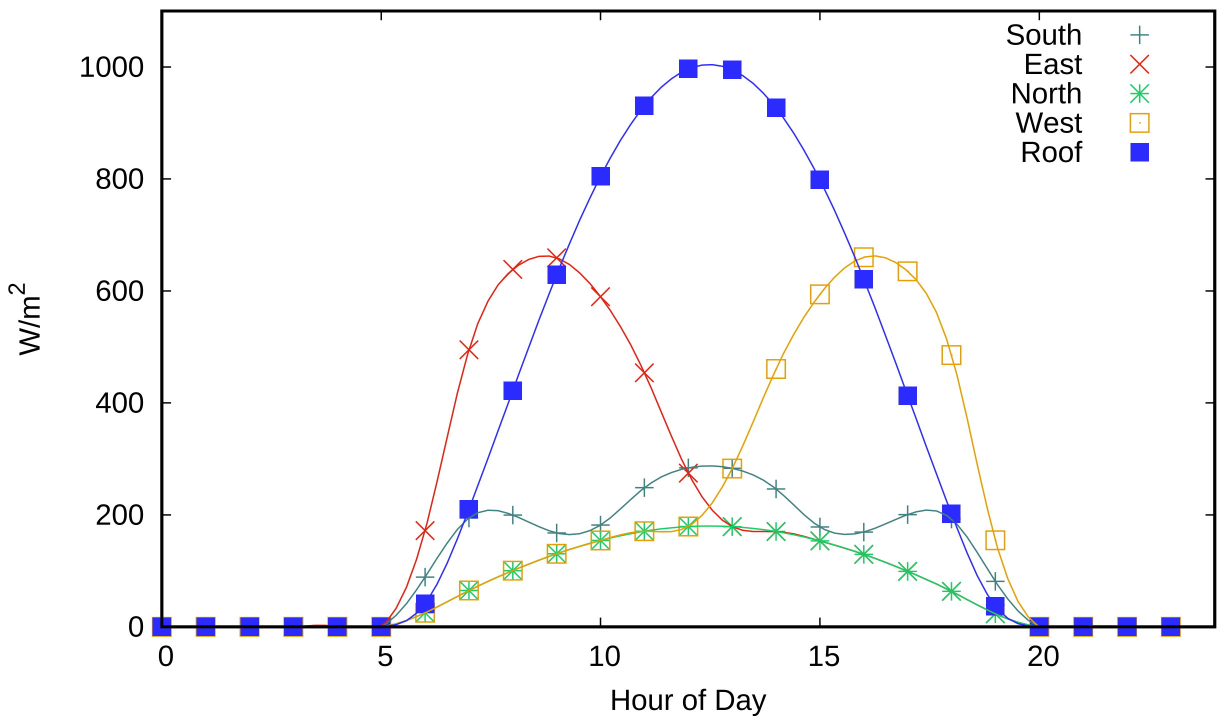


Figure 3.4: Solar Intensity for College Station July 1

on the window area of a building. This parameter σ_S was estimated when compared to EnergyPlus' results, in the simulations having solar effects. For the solar load heat gain calculations, for a given orientation of the building, it is necessary to account for different orientations then presented in Appendix B and C. This is done through a weighted sum, as described:

For a given orientation of the building the solar gain for a labeled orientation, will be given by the orientation of the building with respect to that label θ as follows:

1. If $\theta < 90°$, $W_1 = 1 - \frac{\theta}{90°}$, $W_2 = \frac{\theta}{90°}$, $W_3 = 0$, $W_4 = 0$.

2. If $90° < \theta < 180°$, $W_1 = 0$, $W_2 = 2 - \frac{\theta}{90°}$, $W_3 = \frac{\theta}{90°} - 1$, $W_4 = 0$.

3. If $180° < \theta < 270°$, $W_1 = 0$, $W_2 = 0$, $W_3 = 3 - \frac{\theta}{90°}$, $W_4 = \frac{\theta}{90°} - 2$.

4. If $270° < \theta < 360°$, $W_1 = \frac{\theta}{90°} - 3$, $W_2 = 0$, $W_3 = 0$, $W_4 = 4 - \frac{\theta}{90°}$.

where W_1, W_2, W_3, and W_4 are the weighted sum factors applied according to Equation 3.5 for the solar gain in the zone $\dot{Q}_{SZ}$.

$$\dot{Q}_{SZ} = W_1\dot{Q}_{SO} + W_2\dot{Q}_{SO+90^\circ} + W_3\dot{Q}_{SO+180^\circ} + W_4\dot{Q}_{SO+270^\circ} \tag{3.5}$$

where $\dot{Q}_{SO}$, $\dot{Q}_{SO+90^\circ}$, $\dot{Q}_{SO+180^\circ}$, $\dot{Q}_{SO+270^\circ}$, are the solar gains for the labeled orientation of the zone's labeled, 90° apart, 180° apart, and 270° apart, respectively.

As an example, the building described in the Case Study in Chapter 6 was considered oriented 150° from its labeled "North" to the true North orientation. Therefore, the solar gain in the labeled "North" zone is calculated as $\dot{Q}_{SZ} = 0.333\dot{Q}_{SE} + 0.666\dot{Q}_{SS}$, having in this case $W_1 = 0$, $W_2 = 0.333$, $W_3 = 0.666$, and $W_4 = 0$.

3.3 Simulation Cases

For this study, a series of building energy simulations is performed. The strategy is to add more complexity to each simulation and observe how the results from the proposed RC model compare to EnergyPlus, as well as comparing them to the results of WinAM[1]. Care must be taken to use the same weather data, building envelope, and system parameters, for an effective comparison.

For the initial simulation case, "Single Zone High R", a 1-Zone building is simulated in WinAM, the RC model, and EnergyPlus, with the geometry described in Appendix A. The purpose of this simulation is to observe if EnergyPlus, WinAM and the proposed RC model agree in a very basic case, with the conditions described in Table 3.2, and the floor plan described in Appendix A.

For the second simulation case, "5 Zones Normal R", a 5-Zone building is simulated in WinAM and EnergyPlus, with floor plan described in Appendix B. This case adds more complexity compared to "Single Zone High R ", adding more zones, having more realistic values for wall/roof resistance, minimum flow rate and internal heat gain loads, but still maintaining a massless building as described in Table 3.3.

The R-value for the wall is based on a lumped value from a typical building wall with an R-value of 10.0 hr·ft^2·°F/Btu, with 10% window area on the wall with an R-value of 1.89 hr·ft^2·°F/Btu,

[1]WinAM 5.2 and EnergyPlus 8.9 was used throughout this research

Table 3.2: Parameters for “Single Zone High R”

1 Zone
System: SDVAV
No OA (Outside Air)
No Sensible Heat Gain
No Latent Heat Gain
No Solar Heat Gain
No Infiltration
No mass effects
Adiabatic surface under floors
Temperature Setpoint: 75 °F
Wall Resistance: 40 hr·ft^2·°F/Btu
Roof Resistance: 40 hr·ft^2·°F/Btu
Design Flowrate: 1 CFM/ft^2
Minimum Flowrate: 0.01 CFM/ft^2
People/Lighting/Equipment Schedule: Always off
Weather: College Station/TX TMY3

Table 3.3: Parameters for “5 Zones Normal R”

5 Zones
System: SDVAV
25% OA (Outside Air)
Sensible Heat Gain per person: 250 Btu/hr
Peak Occupancy: 150 ft^2/person
Sensible Heat Gain from Lighting/Electrical Equipment: 2 W/ft^2
Latent Heat Gain per person: 200 Btu/hr
No Solar Heat Gain
No Infiltration
No Mass Effects
Adiabatic surface under floor
Preheat Temperature Setpoint: 35 °F
Heating Temperature Setpoint: 75 °F
Cooling Temperature Setpoint: 75 °F
Wall Resistance: 7.0 hr·ft^2·°F/Btu
Roof Resistance: 20.0 hr·ft^2·°F/Btu
Design Flow Rate: 1 CFM/ft^2
Minimum Flow Rate: 0.15 CFM/ft^2
People/Lighting/Equipment Schedule: Always 100%
Weather: College Station/TX TMY3

which is estimated for a triple glazed window with 1/4” air gap.

For the third simulation case, “Masses”, thermal mass is added to the walls and zones of the base model “5 Zones Normal R” while maintaining the original resistance values. This is simulated only with EnergyPlus and the proposed RC model since there is no input parameter that defines the property of thermal mass in WinAM. “Low mass”, “Medium mass”, and “High mass” buildings will be simulated, to analyze the energy consumption compared to the base model and see how the thermal mass affects the overall energy consumption.

Also, the results from Case 3 and all cases after it are used as a metered consumption data into WinAM. This is then used for a calibration process with the intent of noting which parameters WinAM suggests to adjust to be considered “calibrated”.

The wall and floors material to be used in the “Low mass”, “Medium mass” and “High mass” are described in Table 3.4. The capacitance of the walls and floors are calculated using the wall area and floor area of 1672.3 m^2 and 8361.3 m^2 respectively. Note that the thickness of the insulation material in the walls varies from one building type to another, in such a way to always maintain a wall resistance of 7.0 $hr \cdot ft^2 \cdot {}^\circ F/Btu$ (1.233 $m^2 \cdot K/W$).

For the roof, it was assumed to have no significant mass, and therefore its capacitance was neglected for all cases in this research.

For the fourth simulation case, “Solar”, solar gains are added to the base model “5 Zones Normal R”. This is simulated only with EnergyPlus and the proposed RC model, since there is no input parameter that defines the property of solar gains in WinAM.

The fifth simulation case, “Mass & Solar” is the same as “Masses” + “Solar”, i.e. including solar gains and thermal mass effects combined and repeating the same analysis as before.

For the sixth simulation case, “Internal Load Variation”, schedules are added to “Mass & Solar” for internal load variation, i.e. people/lighting/equipment peak output heat values will be multiplied by the multiplier that varies as in Figure 3.5. The same analysis is repeated as before, except now the same load schedule is also added to the WinAM model, and this becomes the new base model for later simulations.

Table 3.4: Construction Layers for each type of Building for "Masses"

Surface	**Construction Layers From Outside to Inside**	**Density (kg/m^3)**	**Specific Heat (J/kg·K)**	**Length (m)**	**Conductivity (W/m·K)**	**Resistance (m^2·K/W)**	**Capacitance per Area (J/m^2·K)**
Light Mass							
Floor	4" Concrete	2300	750	0.102	1.5	0.068	175260
	Total	**-**	**-**	**0.102**	**-**	**0.068**	**175260**
Walls	Wood	608	1630	0.025	0.15	0.167	24776
	Insulation	43	1210	0.028	0.03	0.941	1469
	Gypsium	800	1090	0.020	0.16	0.125	17440
	Total	**-**	**-**	**0.073**	**-**	**1.233**	**43685**
Medium Mass							
Floor	8" Concrete	2300	750	0.203	1.5	0.135	350520
	Total	**-**	**-**	**0.203**	**-**	**0.135**	**350520**
Walls	4" Brick	1920	790	0.102	0.80	0.127	154107
	Wood	608	1630	0.025	0.15	0.167	24776
	Insulation	43	1210	0.024	0.03	0.814	1271
	Gypsium	800	1090	0.020	0.16	0.125	17440
	Total	**-**	**-**	**0.171**	**-**	**1.233**	**197594**
Heavy Mass							
Floor	12" Concrete	2300	750	0.305	1.50	0.203	525780
	Total	**-**	**-**	**0.305**	**-**	**0.203**	**525780**
Walls	12" Concrete	2300	750	0.305	1.50	0.203	525780
	Wood	608	1630	0.025	0.15	0.167	24776
	Insulation	43	1210	0.022	0.03	0.738	1152
	Gypsium	800	1090	0.020	0.16	0.125	17440
	Total	**-**	**-**	**0.372**	**-**	**1.233**	**569148**

For the seventh simulation case, "Temperature Setback", a temperature setback of 10°F is applied to "Internal Load Variation" during unoccupied hours, with a cooling set point of T_C = 85°F and a heating set point of T_H = 68°F. Unoccupied hours are defined from 7:00 PM to 5:00 AM of next day. This is also implemented in the WinAM model.

For the eight simulation case, "Temperature Deadband", the heating temperature set point is changed to 70°F and the cooling temperature set point to 76°F from "Internal Load Variation", during all hours. No temperature setback is applied for unoccupied hours. This is also implemented in the WinAM model.

For the ninth simulation case, "Setback % Deadband", this is the same as "Temperature Setback" + "Temperature Deadband", analyzing the combined effect of temperature throttling range and night-time temperature setback.

For the tenth simulation case, "10 Stories", this is the same as "Set Back & Deadband", except the building has 10 floors, maintaining the same total floor space as before, but reducing its internal

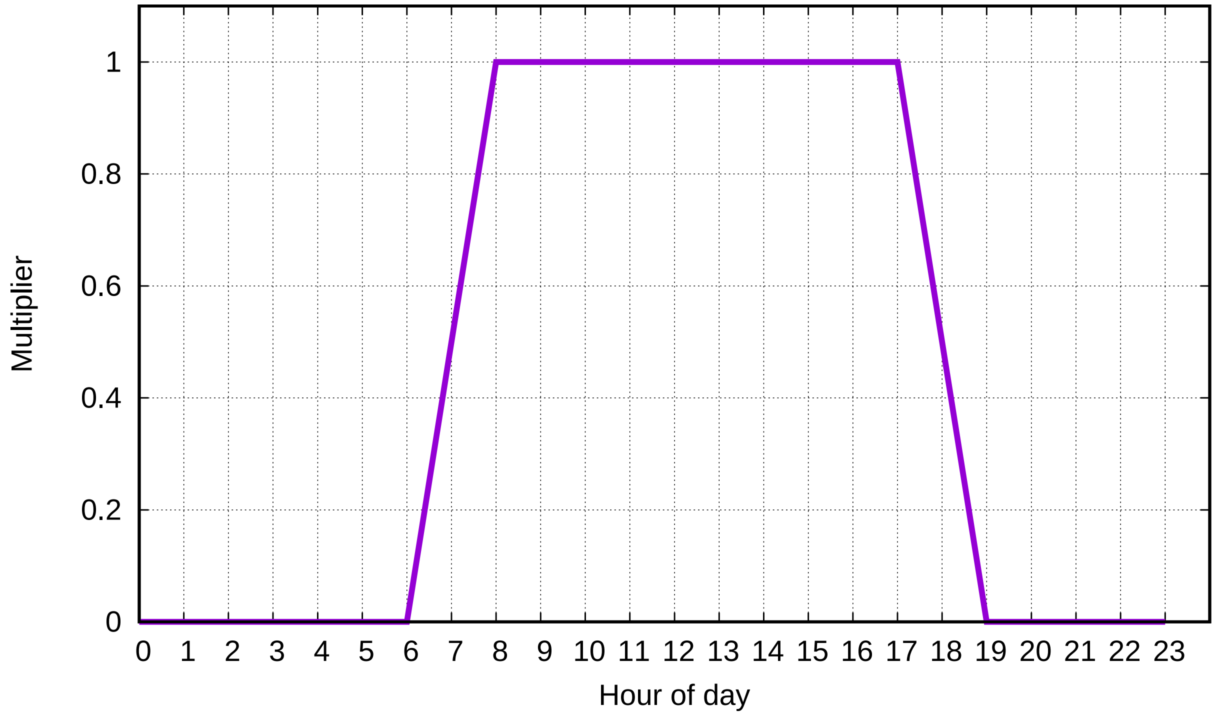


Figure 3.5: Daily Schedule Multiplier for Internal Loads

zone, as described in the floor plan in Appendix C. This will also be implemented in the WinAM model.

For the eleventh simulation case, “6 Climates”, two types of buildings will be tested for six different climates: El Paso - TX, Juneau - AK, New York - NY, Las Vegas - NV, Denver - CO, and Chicago - IL. Type 1 Building is the same as “Setback & Deadband”, and type 2 building is the same as “10 stories”.

3.4 Case Study

A case study is proposed to test its results against the Outpatient Clinic, located in New York City, that is undergoing the Continuous Commissioning® process. This test analyzes the behavior of the proposed findings in a real building with multiple floors.

WinAM, EnergyPlus, and RC models are generated and calibrated to real measured data. Subsequently, three EEM’s are applied to all models: reduction of minimum flow in the system’s fans, increasing the zone's temperature throttling range, and applying a night-time temperature setback. An analysis is made of the savings generated from each EEM.

3.5 WinAM Calibrations

From Simulation Case 3 forward, the WinAM baseline model is calibrated to the results of the modified EnergyPlus models results, treating the EnergyPlus simulation results as "Measured Data". The calibration process is one in which through engineering analysis, input parameters to the model are altered to approximate the modeled consumption results to the measured data.

The WinAM calibration assistant suggests to improve the TOTAL CV-RMSE (Coefficient of Variation of the Root Mean Square Error), which is a normalized version of the RMSE (Root Mean Square Error). Its calculation is described in Equations 3.6, 3.7, 3.8, and 3.9.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(ME_i - SE_i)^2}{n-1}} \tag{3.6}$$

$$MME = \frac{\sum_{i=1}^{n} ME_i}{n} \tag{3.7}$$

$$CV_{RMSE} = \frac{RMSE}{MME} \tag{3.8}$$

$$CV_{RMSET} = \sqrt{CV_{RMSECOOLING}{}^2 + CV_{RMSEHEATING}{}^2} \tag{3.9}$$

where ME is Measured Energy, SE is Simulation Energy, n is the number of data points, MME is the Mean Measured Energy, CV_{RMSET} is the Total CV-RMSE, and $MDEC$ is the Mean Daily Energy Consumption.

In all attempts, the calibration assistant tool from WinAM will follow the same protocol, as described:

1. The first suggestion shown to modify its parameter will be modified.
2. The value it suggests will be chosen.
3. If the program does not reach Calibration Status, repeat steps 1 and 2. If it does, check to see if the next suggestion improves the Total CV-RMSE by reducing it more than 2% of the

current CV-RMSE. If so, modify the parameter by its suggested value, then repeat step 3. If not, stop.

Even though this procedure is NOT recommended when applied to a real Commissioning project without engineering reasoning, the intent of performing this protocol is to analyze how WinAM “adjusts" itself to the effects of each case.

3.6 Air Handling Unit (AHU) System

3.6.1 Description

Through all Simulation Cases, the system will be the same: a Single Duct Variable Air Volume (SDVAV) with reheat, having a blow-through fan, as represented in Figure 3.6. Only one system is present in all simulation cases.

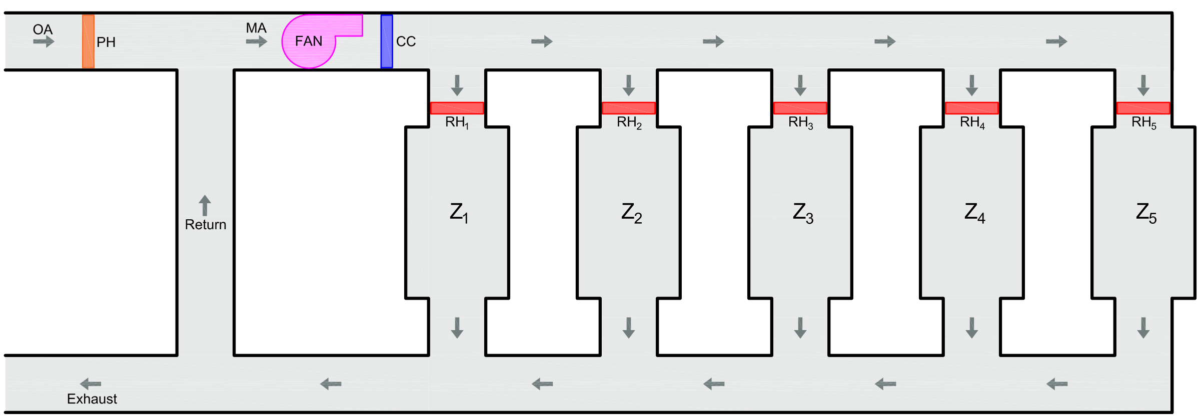


Figure 3.6: Single Duct Variable Air Volume (SDVAV) Diagram

The outside air (OA) is drawn through the pre-heat coil (PH) and mixed with the return air forming a mixed air (MA). The fan blows the mixed air through the cooling coil (CC) and branches into the different zones. Before the air reaches each zone, it passes through the reheat coil (RH) and is heated as necessary, entering each zone. The air gets heated or cooled in the zones from the internal load gains plus the heat transferred from the walls, floors and roof. The air leaves the zone, is mixed again in the return air, where some is exhausted out of the building, and the remainder is returned back to the system, completing a full cycle.

3.6.2 Calculation

All calculations from this project are based in the First Law of Thermodynamics applied to a control volume, as described in Equation 3.10.

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_g = \frac{dE}{dt} \tag{3.10}$$

where $\dot{E}_{in}$ is the rate of energy entering the control volume, $\dot{E}_{out}$ is the rate of energy leaving the control volume, $\dot{E}_g$ is the rate of energy generated inside the control volume and $\frac{dE}{dt}$ is the rate of energy change through time inside the control volume.

The calculations are considered steady-state for each hour with no internal heat generation for the following components: Pre-heat coil, Cooling Coil and each Reheat Coil, reduce Equation 3.10 to $\dot{E}_{in} = \dot{E}_{out}$, as shown in Equation 3.11.

$$\dot{Q}_{in} = \rho_{air} \dot{V}_{air} c_{p_{air}} (T_{outair} - T_{inair}) \tag{3.11}$$

where $\dot{Q}_{in}$ is the heat input (it will be negative for cooling) into the component, ρ_{air} is the density of air, $\dot{V}_{air}$ is the air volumetric flow, $c_{p_{air}}$ is the specific heat of air, T_{out} is the air temperature leaving the component and T_{inair} is the air entering the component. For the purpose of this research, ρ_{air} was always considered a constant value of 1.207 kg/m^3, and the air specific heat is 1.0 kJ/kg·K.

If Equation 3.11 is described in the imperial system, having $\dot{V}_{air}$ described in CFM (Cubic Feet per Minute), Equation 3.11 reduces to Equation 3.12.

$$\dot{Q}_{in} = 1.08 \dot{V}_{air} (T_{outair} - T_{inair}) \tag{3.12}$$

Similarly, the latent heat that is removed from the air in the cooling coil can be described as in

Equation 3.13.

$$\dot{Q}_{LAT} = \rho_{air} \dot{V}_{air} h_{vwater} (\omega_{MA} - \omega_{CL}) \tag{3.13}$$

where $\dot{Q}_{LAT}$ is the latent heat removal, h_{vwater} is the vaporization enthalpy of water, ω_{MA} is the mixed air humidity ratio, and ω_{CL} is the humidity ratio leaving the cooling coil.

The assumption made for the fan, for WinAM, the RC model and in EnergyPlus is that there is no heat gain across the fan and therefore ΔT_{fan} = 0. This is to assure a reliable comparison between models, since WinAM and EnergyPlus have different methods to calculate the heat gain through the fan.

When passing through the Cooling Coil, sensible and latent heat are removed from the air as described in Equations 3.12 and 3.13.

It is assumed that the return air temperature is a weighted average of the temperature leaving each zone with each zone air flow, as described in Equation 3.14.

$$T_R = \frac{\sum_{i=1}^{5} \dot{V}_i T_{Zi}}{\dot{V}_T} \tag{3.14}$$

where $\dot{V}_i$ is the air flow exhausted from each zone, and T_{Zi} is each zone's temperature. It is also assumed in this research that the leaving temperature of the zone is the zone's temperature, with no heat added in the air ducts.

The mixed air temperature is calculated as in Equation 3.15.

$$T_{MA} = X_{OA} T_{oa} + (1 - X_{oa}) T_R \tag{3.15}$$

where X_{OA} is the percentage of outside air of the total flow.

The preheat will be active when $T_{oa} < T_{ph}$, where T_{ph} is the preheat temperature set point. In the simulation cases, T_{ph} is 35°F.

For cases which jump from a wider temperature deadband to a narrower temperature deadband, an adjustment of calculation was observed necessary for T_s, T_m, and $\dot{V}_i$. For this research, this particular hour is called hour "C" (of Change). The supply air necessary now is as described in

Equations 3.16 and 3.17 (only for these hours of change). The necessary flow from Equation 3.16 is tested to see if it goes below minimum, in which case it is reset to the minimum flow. The temperature supply also is tested if it goes below the cooling coil set point temperature, in which case it is reset to the cooling coil set point temperature.

$$\dot{V}_i = \frac{\dot{Q}_T - C_m(T_C - T_m^{p-1})}{1.08(T_C - T_{CL})} \tag{3.16}$$

$$T_{s(C)} = T_H - \frac{\dot{Q}_T}{1.08\dot{V}_i} + \frac{C_m(T_H - T_m^{p-1})}{1.08\dot{V}_i} \tag{3.17}$$

where T_{CL} is the cooling coil set point temperature, T_C is the zone's cooling set point temperature, T_H is the zone's heating set point temperature, and $\dot{Q}_T$ is the sum of the internal gains with the total heat transferred from the walls and floors. In the hour "C", T_m is reset according to the following circumstances:

1. If T_m is lower than the heating set point, it is heated to the heating set point, being reset to T_H and calculated according to Equation 3.17.

2. If T_m is higher than the cooling set point, it will be cooled to the cooling set point, being reset to T_C and calculated according to Equation 3.17.

3. If T_m is between the cooling and heating set points, it will be calculated as usual (Equation 3.3).

3.7 Humidity Ratio Difference

The humidity ratio calculation in WinAM assumes a constant ambient pressure for its calculations. Therefore, in order to have similar comparisons, the weather file was modified for the weather input into WinAM and the RC model. The "new weather" adjusts its wet bulb and dew point temperatures, in order to match EnergyPlus' humidity ratio, which takes into account different ambient pressure for each hour.

From this, the humidity ratio matched for all cases except when the relative humidity went to approximate or exactly 100%, when no further adjustment can be made for the WinAM weather file, i.e. it is not possible to “fabricate” weather with relative humidity above 100%.

3.8 Time Step

The time step used in EnergyPlus and the RC model for the first 6 simulation cases is 1-time step per hour. This was made in order to be able to compare the results for each time step with WinAM, which uses 1-time step per hour.

Tests were made to see how the results were to be different with different time steps in “5 Zones Normal R”, where all simulations are expected to match. All the metrics errors were worsened with shorter time steps.

From the seventh simulation case forward, a time step of 6 per hour is used in EnergyPlus. Thus, its comparison is only made on a yearly basis, instead of a time step basis.

3.9 Comparison Tables

For all simulation cases, comparison tables are displayed between the models, showing the percentage difference between the consumption data for each model. This percentage difference is calculated as the largest value computed using Equations 3.18 and 3.19.

$$\%Difference = \frac{|M_1 - M_2|}{M_1} \tag{3.18}$$

$$\%Difference = \frac{|M_1 - M_2|}{M_2} \tag{3.19}$$

where M_1 and M_2 are the heating or cooling consumption results from two separate models.

4. SIMULATION CASES RESULTS AND DISCUSSIONS

4.1 Single Zone High R

For Single Zone High R case, the parameters used are described in Table 3.2. This case is to test and ensure that WinAM, EnergyPlus and the proposed RC model have approximate or exact results. Therefore, high R-values are used in the roof and walls. In sum, it's a 1 zone building with no Outside Air and no internal loads.

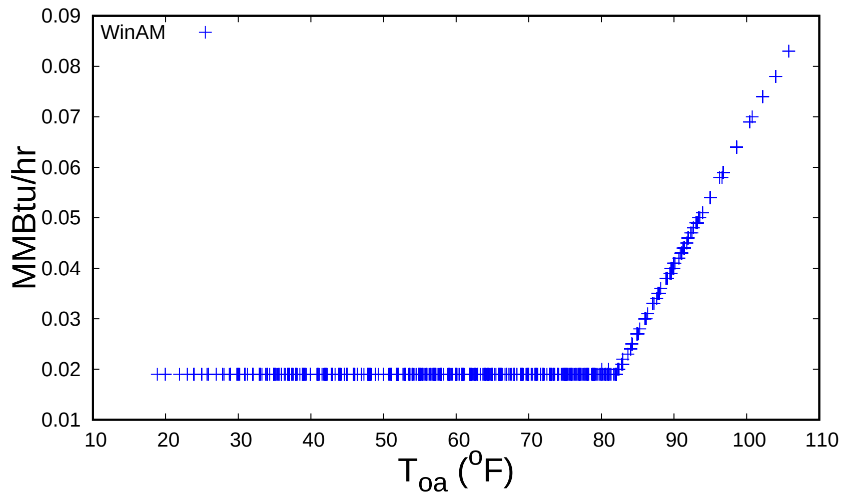
The maximum difference when comparing each data point between WinAM and the RC model is 0.36% for cooling and 0.00% for heating. The annual difference is 0.064% and 0.00% respectively. As these metrics indicates, the difference between the WinAM and RC model is too small for visual comparison. Thus, comparison will be displayed only between WinAM and EnergyPlus in Figures 4.1 and 4.2, for its system's hourly cooling and heating consumption respectfully. The comparison metrics between simulations are described in Table 4.1.

Table 4.1: Comparison between models for Single Zone High R

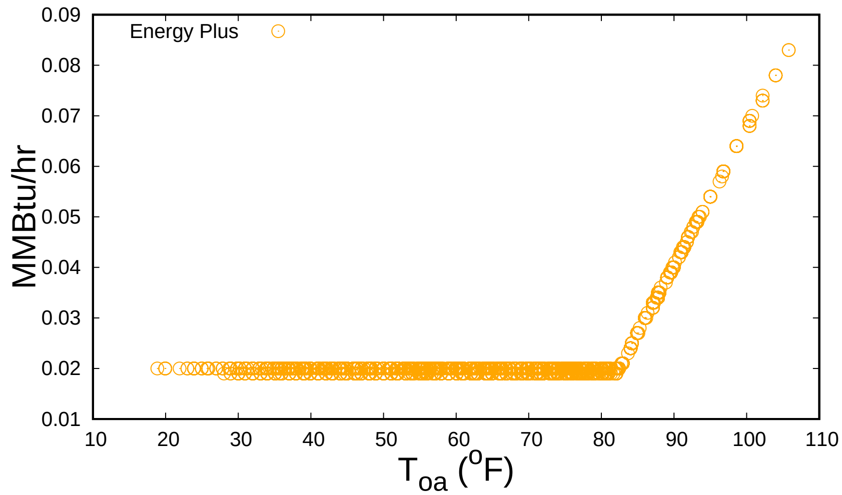
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.0194	0.0202	4.01%
Max. Difference Data Point for Heating (MMBTU)	0.00140	0.00151	7.51%
Annual Cooling (MMBTU)	194.00	194.38	0.19%
Annual Heating (MMBTU)	374.16	375.31	0.31%

From Figure 4.1, one can notice the slope of increase cooling when the temperature goes above 82 °F. This increase occurs because the fan increases flow above minimum, as the zone requires more cooling. Similarly, at Figure 4.2, the system requires no reheat when the system's flow is above minimum.

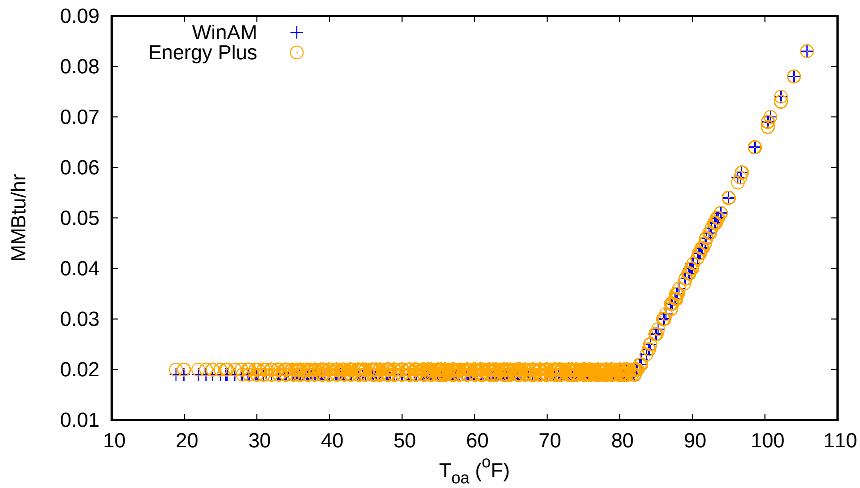
From Table 4.1, the results are considered satisfactory comparatively, achieving the proof of similarity through a simple energy balance for the building.



(a) WinAM Cooling Consumption

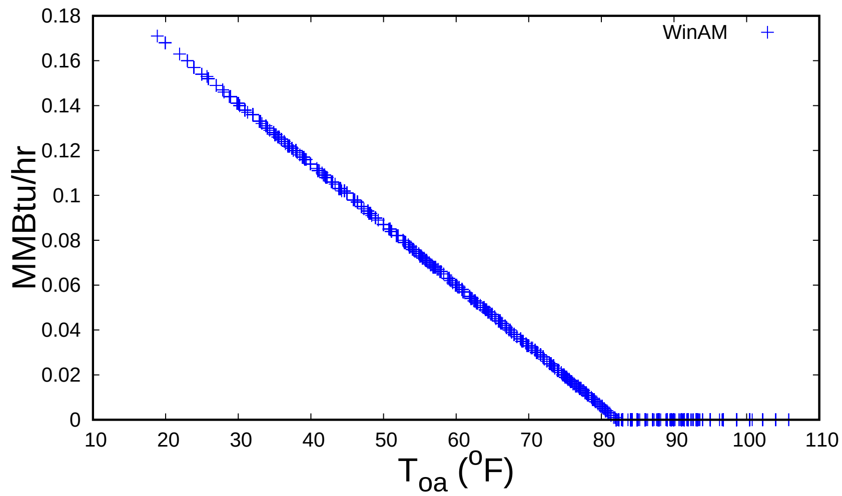


(b) EnergyPlus Cooling Consumption

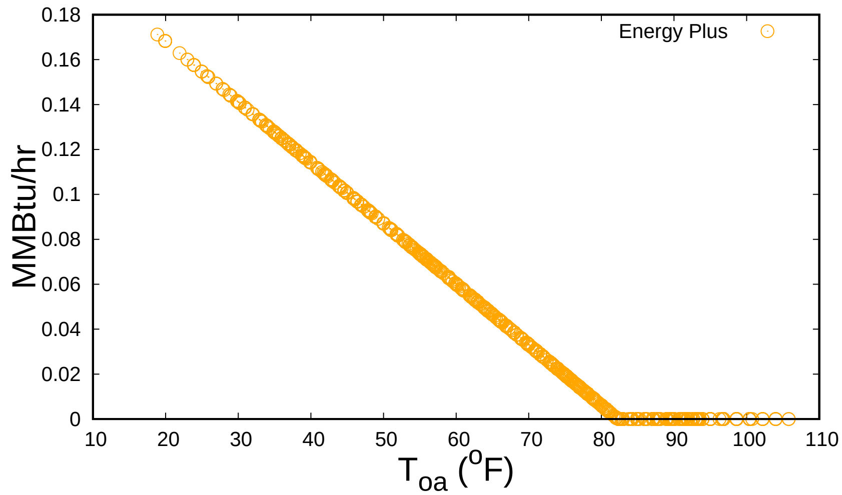


(c) WinAM and EnergyPlus Cooling Consumption

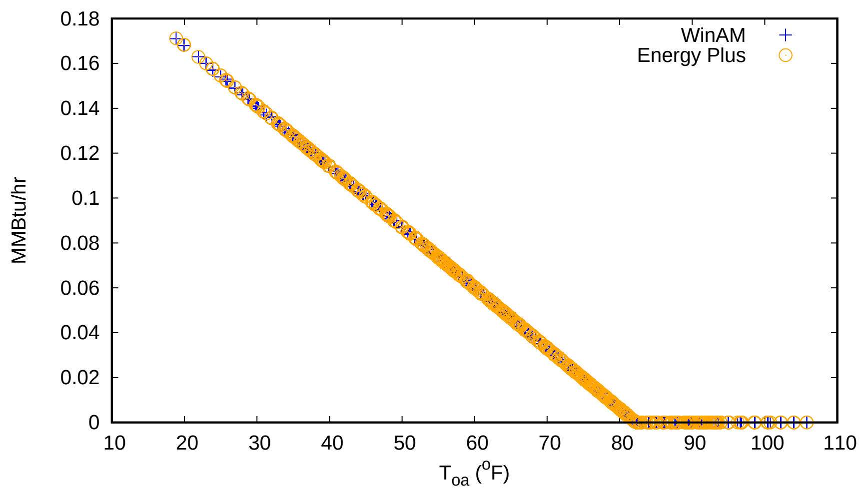
Figure 4.1: Single Zone High R - Cooling Consumption



(a) WinAM Cooling Consumption



(b) EnergyPlus Cooling Consumption



(c) WinAM and EnergyPlus Heating Consumption

Figure 4.2: Single Zone High R - Heating Consumption

4.2 5 Zones Normal R

For 5 Zones Normal R case, the parameters used were as described in Table 3.3. This simulation adds internal loads and intake of outside air when compared to the previous case. Note also that the walls and roof R-values are changed to a more common value encountered in commercial buildings. Lastly, although the same floor space is used as before, it is now braked down into a 5-zone building, instead of 1, as described in Appendix B. Since there isn't any solar loads or thermal mass effects, it is also expected for the results for each case to match.

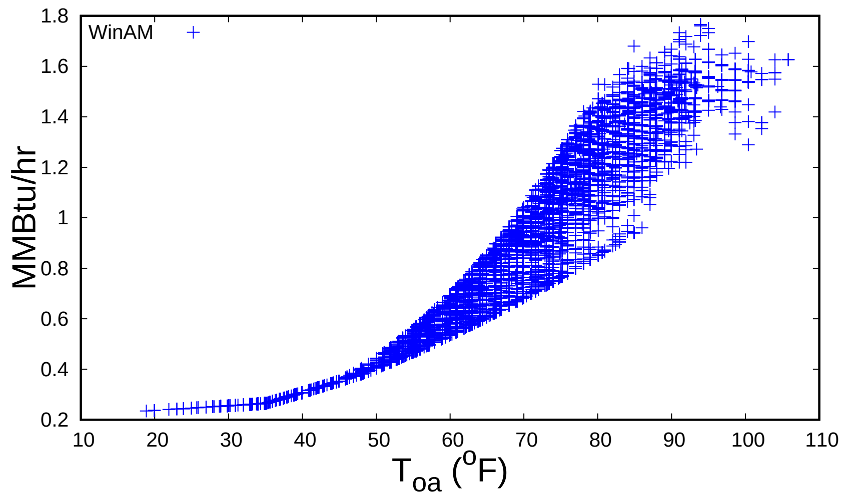
The maximum difference when comparing each data point between WinAM and the RC model is 0.26% for cooling and 0.00% for heating[1]. The annual difference is 0.15% for cooling and 0.00% for heating. Again, as these metrics indicates, the difference between the WinAM and RC model is too small for visual comparison. Thus, comparison is displayed only between WinAM and EnergyPlus in Figures 4.3 and 4.4, for its system's hourly cooling and heating consumption respectfully. The comparison metrics between simulations are described in Table 4.2.

Table 4.2: Comparison between models for 5 Zones Normal R

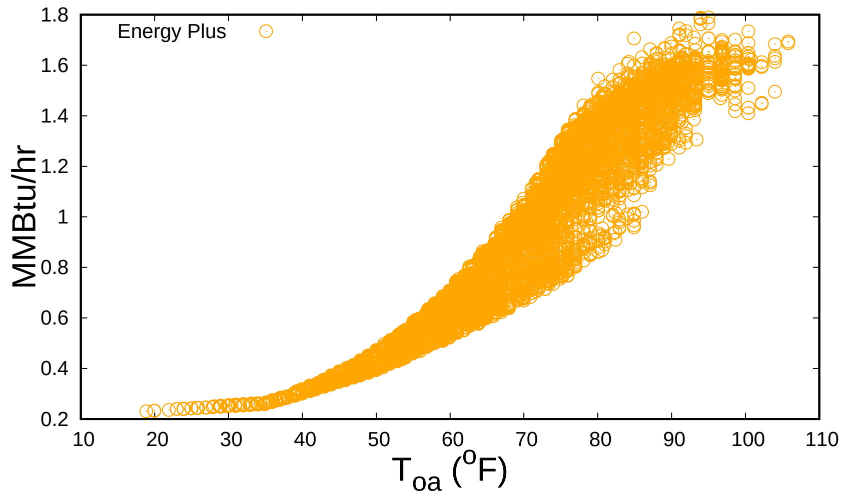
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.5780	0.6581	13.85%
Average Difference for Cooling	-	-	2.65%
Standard Deviation for Cooling	-	-	2.07%
Max. Difference Data Point for Heating (MMBTU)	0.00327	0.01104	237.46%
Average Difference for Heating	-	-	2.56%
Standard Deviation for Heating	-	-	12.05%
Annual Cooling (MMBTU)	7713.36	7895.69	2.37%
Annual Heating (MMBTU)	34.20	33.85	1.03%

From Figure 4.3, one can notice a linear increase of cooling until T_{OA} reaches approximately 35 °F. From there on, the latent loads generated by the people, as well as the outside air, gain considerable effect, generating the spread seen.

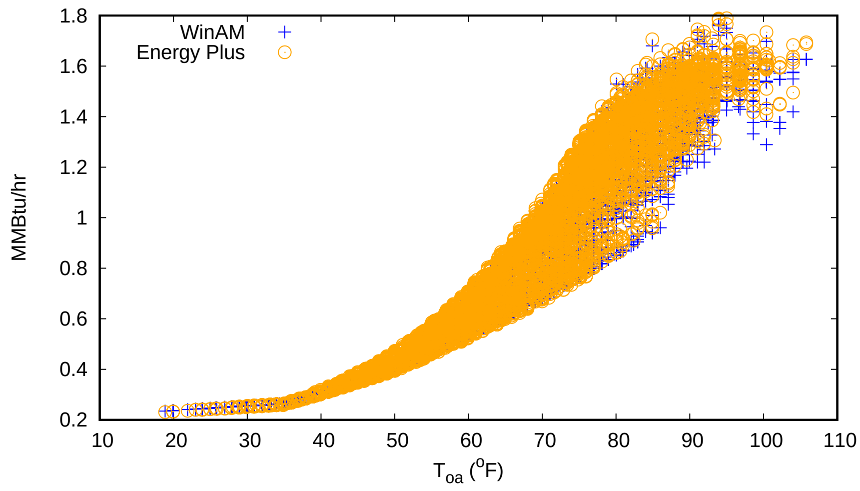
[1] The comparison for the data points in which the heating consumption was below 0.001 MMBtu was not considered in any analysis made throughout this research



(a) WinAM Cooling Consumption

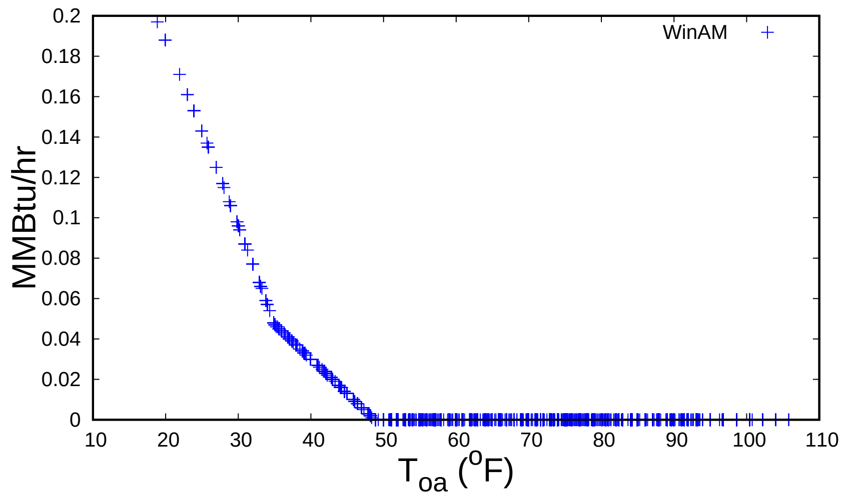


(b) EnergyPlus Cooling Consumption

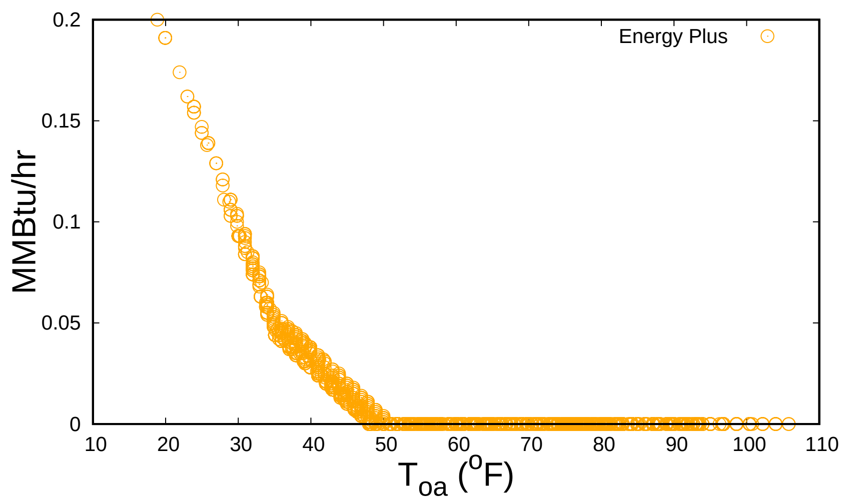


(c) WinAM and EnergyPlus Cooling Consumption

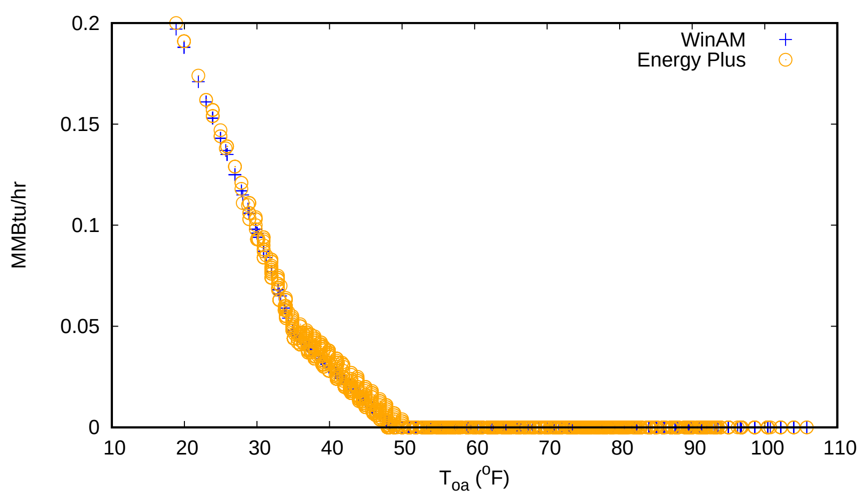
Figure 4.3: 5 Zones Normal R - Cooling Consumption



(a) WinAM Heating Consumption



(b) EnergyPlus Heating Consumption



(c) WinAM and EnergyPlus Heating Consumption

Figure 4.4: 5 Zones Normal R - Heating Consumption

From Figure 4.4, one can notice that heating only occurs in temperatures below 50°F, when minimum flow is achieved and the reheat starts. Then, the heating increases linearly until reaches 35°F, which is the pre heat set point. This first slope will be called as "Slope 1" for heating in the following simulation cases. Bellow that temperature, the slope is increased due to the sum of preheat and reheat. This second slope will be called "Slope 2" for heating in the following simulation cases. Note that the EnergyPlus trends in a zig-zag format along the mentioned first slope. This is due to the time step choice of 1 per hour, generating a small instability in the results. However, even with this instability, the results are considered comparable. The heating plot with EnergyPlus using a time step of 4 per hour is displayed in Figure 4.5 for a better visual comparison.

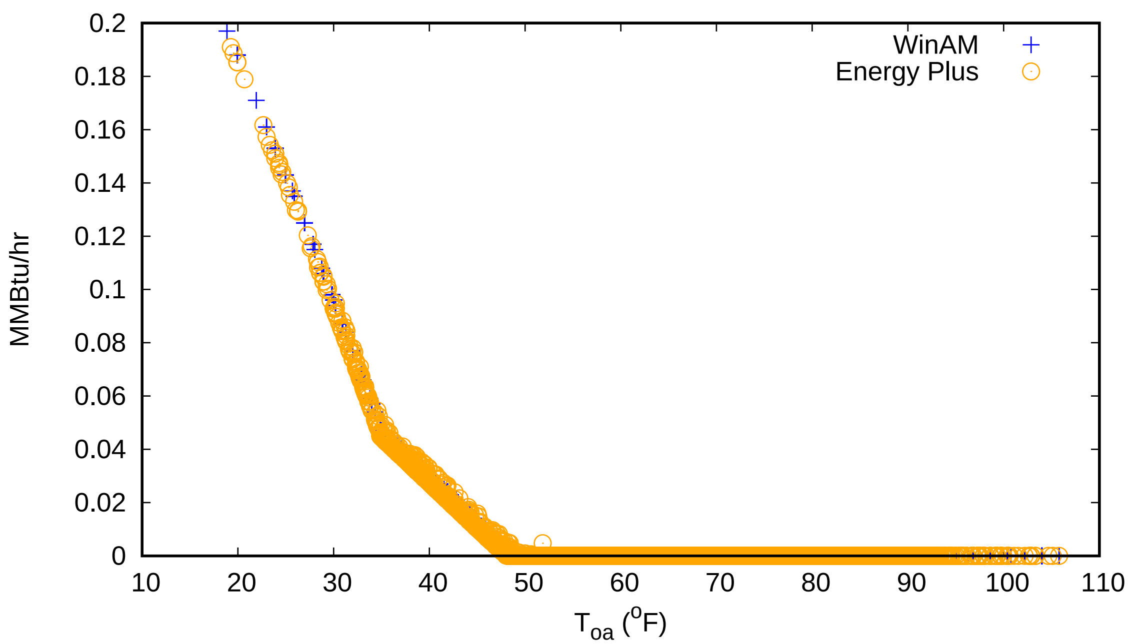


Figure 4.5: 5 Zones Normal R - Heating Consumption with 15 minutes time step for EnergyPlus

From Table 4.2, the results are again considered satisfactory comparable, achieving the proof of similarity through a simple energy balance for the building.

This simulation case is the base model comparison for simulation cases "Masses", "Solar", and "Mass & Solar", i.e. WinAM will not change any parameters. The results displayed are still low when looking at the annual cooling and heating consumption for all cases. The difference for each data point is of high value in the heating data points due to reaching very low values, in which the percentage comparison will still be high.

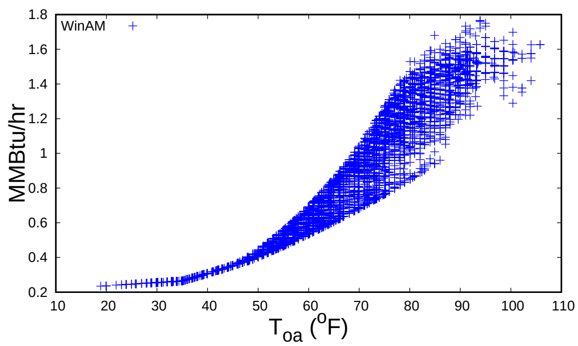
4.3 Masses

Masses adds mass into the walls and floors to the 5 Zones Normal R case, and is subdivided into three type of wall and floor constructions, as displayed in Table 3.4. Note that the overall resistance value for each type of wall is still the same as the WinAM model, making possible the comparison of solely the mass effect of each type of building, to WinAM, which does not take this effect into consideration. The comparison is made between the RC model results and EnergyPlus, as well as both with the baseline model of WinAM (5 Zones Normal R case). Then, the calibration assistant tool of WinAM is used to analyze what type of calibration steps its suggesting to represent the results from the EnergyPlus model.

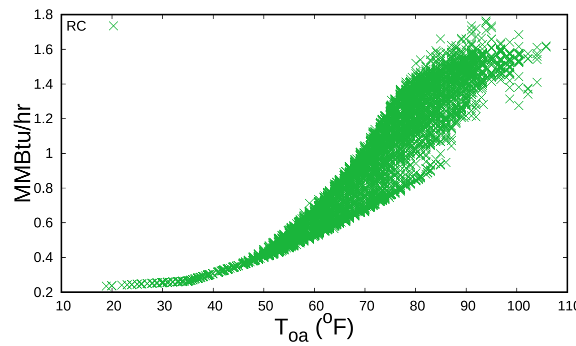
4.3.1 Light Mass

The cooling and heating results are displayed in Figures 4.6 and 4.7. For cooling, the light mass has little effect in its consumption. For heating however, a small spread occurs in the Slope 1, for the EnergyPlus and RC models, due to the heat storage that occurs in the walls. Figure 4.8 demonstrates how the wall temperature T_w from the RC model tracks the Outside Air Temperature (T_{oa}) for the first 1000 hours of the year. For this case, there is not a considerable difference between the two, showing that little heat storage is occurring in the walls.

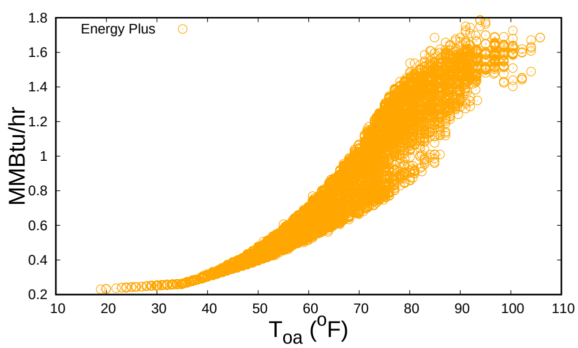
Table 4.3 displays the comparison metrics between the simulations for this case. Note that if only mass effects are included, and the building has little mass, the divergence in overall results is not that high.



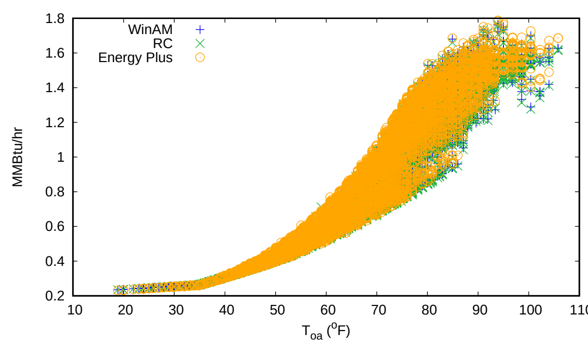
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption

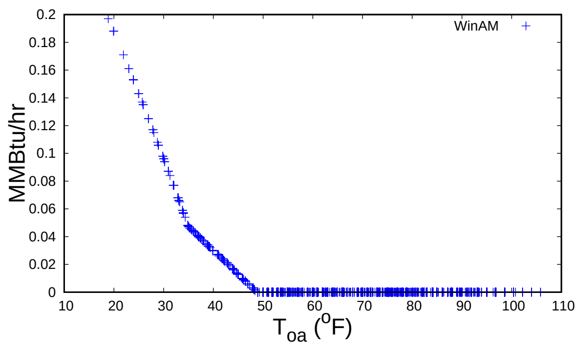


(c) EnergyPlus Cooling Consumption

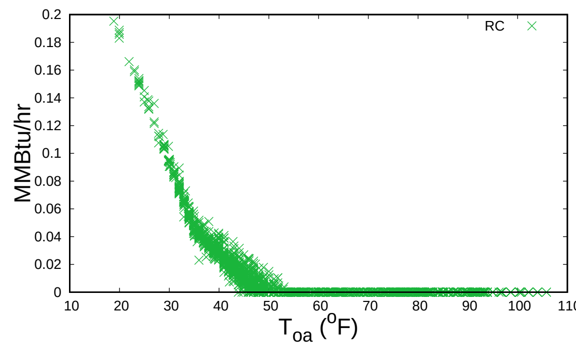


(d) WinAM, RC, and EnergyPlus Cooling Consumption

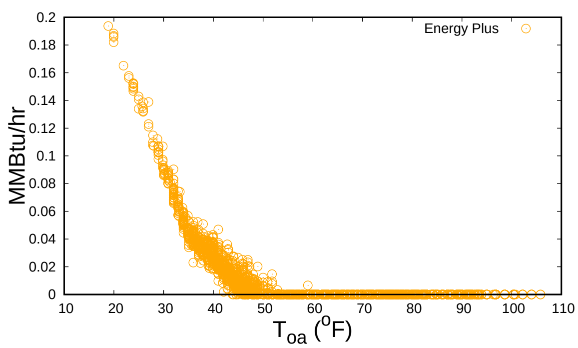
Figure 4.6: Masses - Light Mass - Cooling Consumption



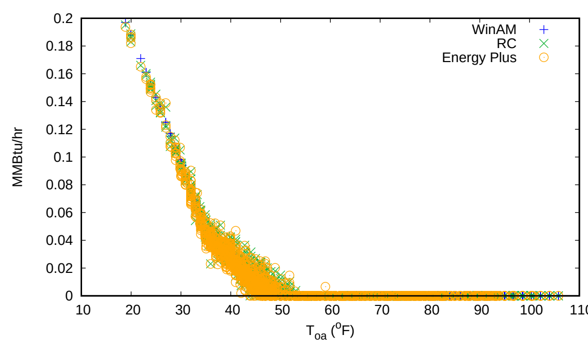
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.7: Masses - Light Mass - Heating Consumption

Table 4.3: Comparison between models for *Masses* - Light Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.665	0.712	7.15%
Average Difference for Cooling	-	-	0.48%
Standard Deviation for Cooling	-	-	0.47%
Max. Difference Data Point for Heating (MMBTU)	0.014	0.002	783.40%
Average Difference for Heating	-	-	3.95%
Standard Deviation for Heating	-	-	24.82%
Annual Cooling (MMBTU)	7713.36	7699.52	0.18%
Annual Heating (MMBTU)	34.20	33.01	3.60%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.554	0.647	16.80%
Average Difference for Cooling	-	-	2.70%
Standard Deviation for Cooling	-	-	2.02%
Max. Difference Data Point for Heating (MMBTU)	0.023	0.002	1140.87%
Average Difference for Heating	-	-	5.83%
Standard Deviation for Heating	-	-	34.36%
Annual Cooling (MMBTU)	7713.36	7896.75	2.38%
Annual Heating (MMBTU)	34.20	30.70	11.40%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.582	0.712	22.37%
Average Difference for Cooling	-	-	2.79%
Standard Deviation for Cooling	-	-	2.16%
Max. Difference Data Point for Heating (MMBTU)	0.001	0.006	515.69%
Average Difference for Heating	-	-	3.30%
Standard Deviation for Heating	-	-	17.12%
Annual Cooling (MMBTU)	7896.75	7699.52	2.56%
Annual Heating (MMBTU)	30.70	33.01	7.54%

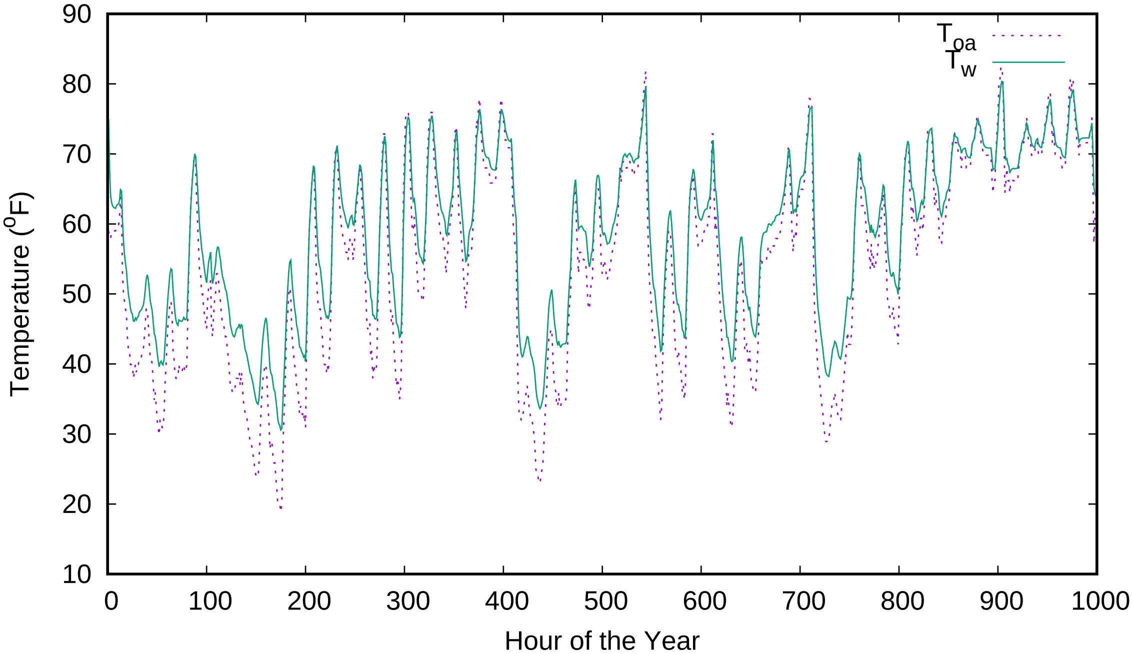


Figure 4.8: Masses - Light Mass - T_w vs T_{oa}

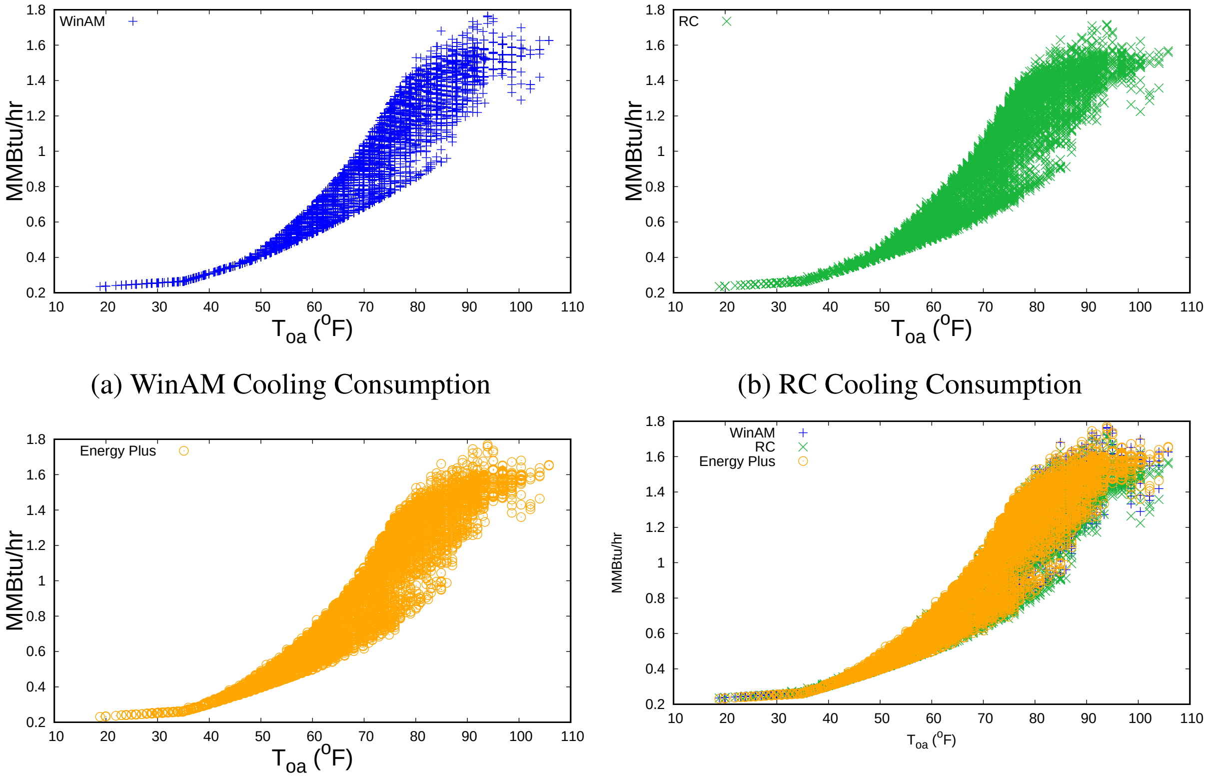
4.3.2 Light Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 is used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 21%. Only one step was made to complete the protocol, resulting a Total CV-RMSE of 11%. The step was:

- Increase the Conditioned Floor Area from 90000 ft^2 to 92728 ft^2, reducing the Total CV-RMSE from 21% to 11.4%.

4.3.3 Medium Mass

The cooling and heating results are displayed in Figures 4.9 and 4.10. For cooling, the medium mass also has little effect in its consumption. For heating however, a larger spread then before occurs in temperatures below 65°F, for the EnergyPlus and RC models, due to the heat storage that occurs in the walls. Figure 4.11 demonstrates how the wall temperature T_w from the RC model



(a) WinAM Cooling Consumption

(b) RC Cooling Consumption

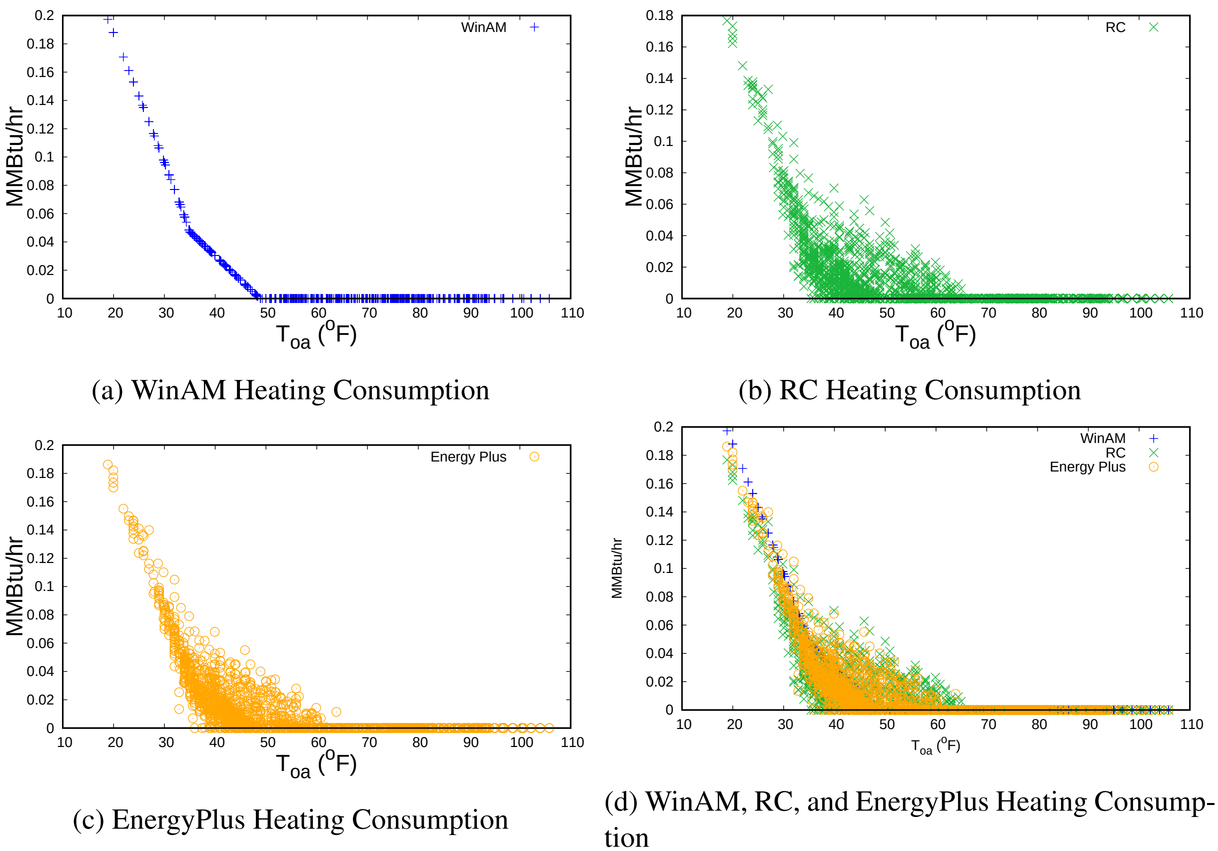
(c) EnergyPlus Cooling Consumption

(d) WinAM, RC, and EnergyPlus Cooling Consumption

Figure 4.9: Masses - Medium Mass - Cooling Consumption

tracks the Outside Air Temperature (T_{oa}) for the first 1000 hours. For this case, note that the wall temperature fluctuates less than before, presenting a higher mass effect from the walls.

Table 4.4 displays the comparison metrics between the simulations for this case. Note that now the results are presenting considerable difference for heating when compared to the baseline model of WinAM. Also, the RC is getting an approximate result with EnergyPlus.



(a) WinAM Heating Consumption

(b) RC Heating Consumption

(c) EnergyPlus Heating Consumption

(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.10: Masses - Medium Mass - Heating Consumption

Table 4.4: Comparison between models for *Masses* - Medium Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.763	0.685	11.35%
Average Difference for Cooling	-	-	1.88%
Standard Deviation for Cooling	-	-	1.58%
Max. Difference Data Point for Heating (MMBTU)	0.041	0.001	3202.26%
Average Difference for Heating	-	-	14.01%
Standard Deviation for Heating	-	-	93.14%
Annual Cooling (MMBTU)	7713.36	7682.34	0.40%
Annual Heating (MMBTU)	34.20	23.47	45.69%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.499	0.589	18.21%
Average Difference for Cooling	-	-	2.90%
Standard Deviation for Cooling	-	-	2.35%
Max. Difference Data Point for Heating (MMBTU)	0.033	0.001	2736.64%
Average Difference for Heating	-	-	11.94%
Standard Deviation for Heating	-	-	81.50%
Annual Cooling (MMBTU)	7713.36	7886.65	2.25%
Annual Heating (MMBTU)	34.20	26.56	28.73%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.579	0.712	22.98%
Average Difference for Cooling	-	-	2.92%
Standard Deviation for Cooling	-	-	2.27%
Max. Difference Data Point for Heating (MMBTU)	0.018	0.001	1349.90%
Average Difference for Heating	-	-	5.45%
Standard Deviation for Heating	-	-	37.31%
Annual Cooling (MMBTU)	7886.65	7682.34	2.66%
Annual Heating (MMBTU)	26.56	23.47	13.17%

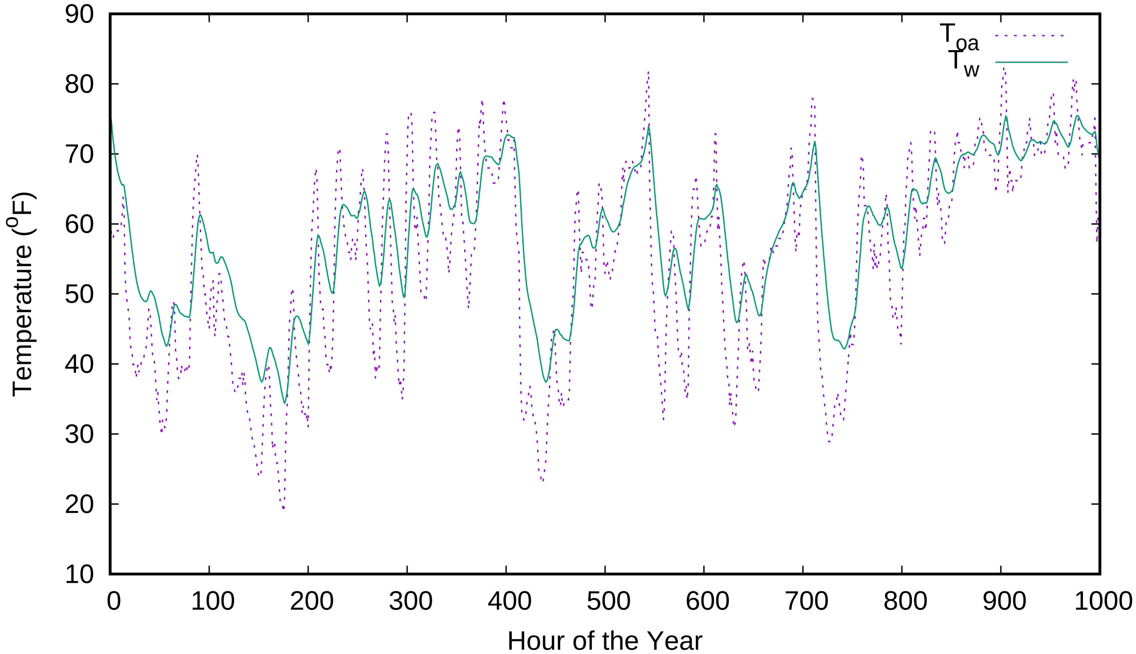


Figure 4.11: Masses - Medium Mass - T_w vs T_{oa}

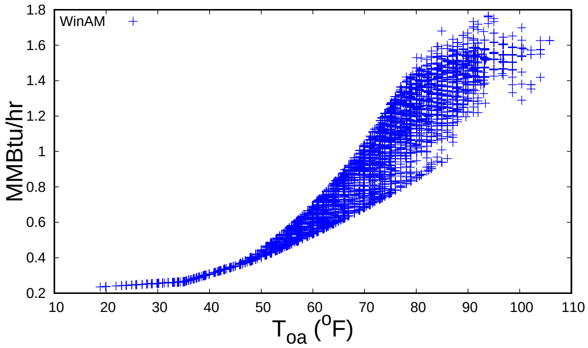
4.3.4 Medium Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 48%. Only one step was made to complete the protocol, resulting a Total CV-RMSE of 14%. The step was:

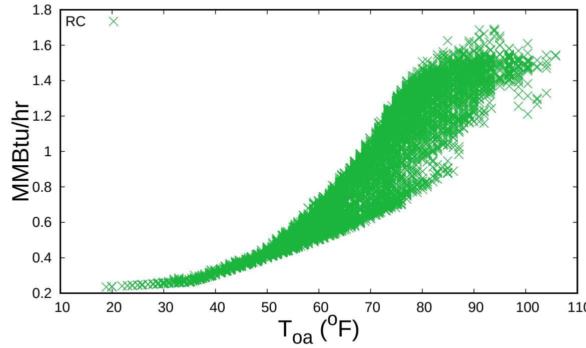
- Constant Cooling Coil Set Point from 55 °F to 57.8 °F, reducing the Total CV-RMSE from 48% to 14.3%.

4.3.5 Heavy Mass

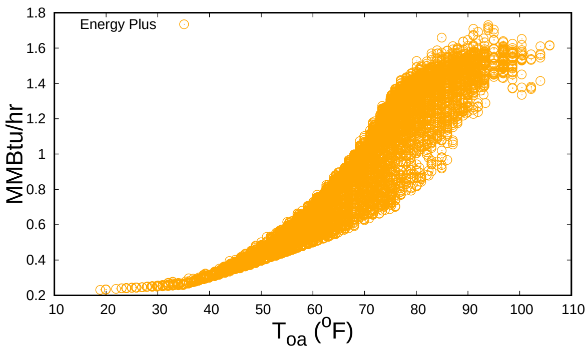
The cooling and heating results are displayed in Figures 4.12 and 4.13. For cooling, the high mass has little effect in its consumption, like previous cases. For heating however, a larger spread then before occurs in temperatures below 70°F, for the EnergyPlus and RC models. This is due to the heat storage that occurs in the walls. Figure 4.14 demonstrates how the wall temperature T_w



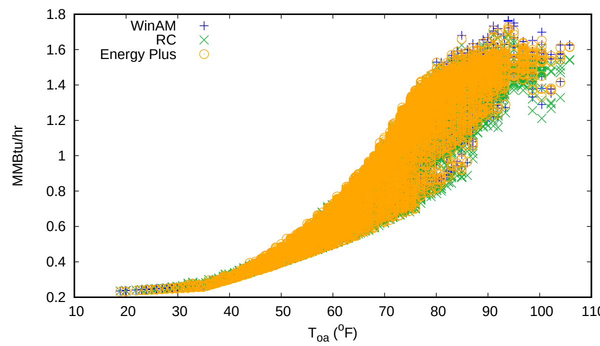
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



(c) EnergyPlus Cooling Consumption

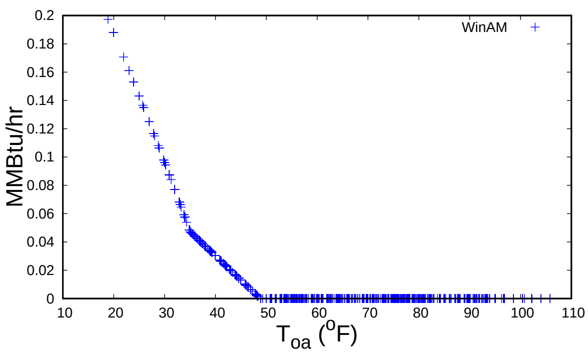


(d) WinAM, RC, and EnergyPlus Cooling Consumption

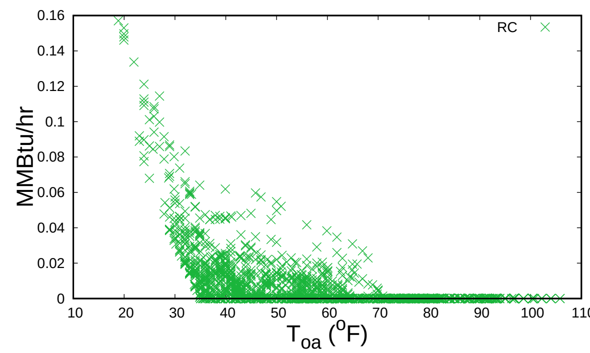
Figure 4.12: Masses - Heavy Mass - Cooling Consumption

from the RC model tracks the Outside Air Temperature (T_{oa}) for the first 1000 hours. For this case, note that the wall temperature fluctuates even less then before.

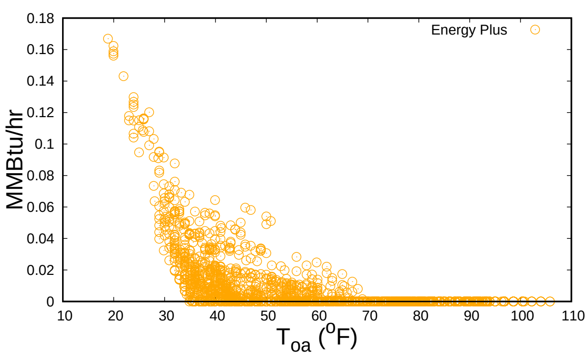
Table 4.5 displays the comparison metrics between the simulations for this case. Note that now the results are presenting considerable difference for heating when compared to the baseline model of WinAM. Also, the RC is getting an approximate result with EnergyPlus.



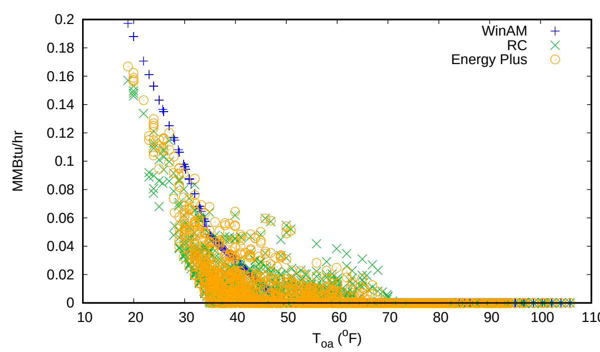
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.13: Masses - Heavy Mass - Heating Consumption

Table 4.5: Comparison between models for *Masses* - Heavy Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.763	0.683	11.75%
Average Difference for Cooling	-	-	2.41%
Standard Deviation for Cooling	-	-	1.95%
Max. Difference Data Point for Heating (MMBTU)	0.040	0.001	2754.43%
Average Difference for Heating	-	-	16.09%
Standard Deviation for Heating	-	-	108.08%
Annual Cooling (MMBTU)	7713.36	7669.04	0.58%
Annual Heating (MMBTU)	34.20	14.76	131.76%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.499	0.586	17.52%
Average Difference for Cooling	-	-	3.20%
Standard Deviation for Cooling	-	-	2.79%
Max. Difference Data Point for Heating (MMBTU)	0.040	0.001	2950.07%
Average Difference for Heating	-	-	17.05%
Standard Deviation for Heating	-	-	116.90%
Annual Cooling (MMBTU)	7713.36	7870.52	2.04%
Annual Heating (MMBTU)	34.20	17.22	98.63%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.590	0.712	20.69%
Average Difference for Cooling	-	-	2.96%
Standard Deviation for Cooling	-	-	2.17%
Max. Difference Data Point for Heating (MMBTU)	0.027	0.003	940.57%
Average Difference for Heating	-	-	5.09%
Standard Deviation for Heating	-	-	34.34%
Annual Cooling (MMBTU)	7870.52	7669.04	2.63%
Annual Heating (MMBTU)	17.22	14.76	16.68%

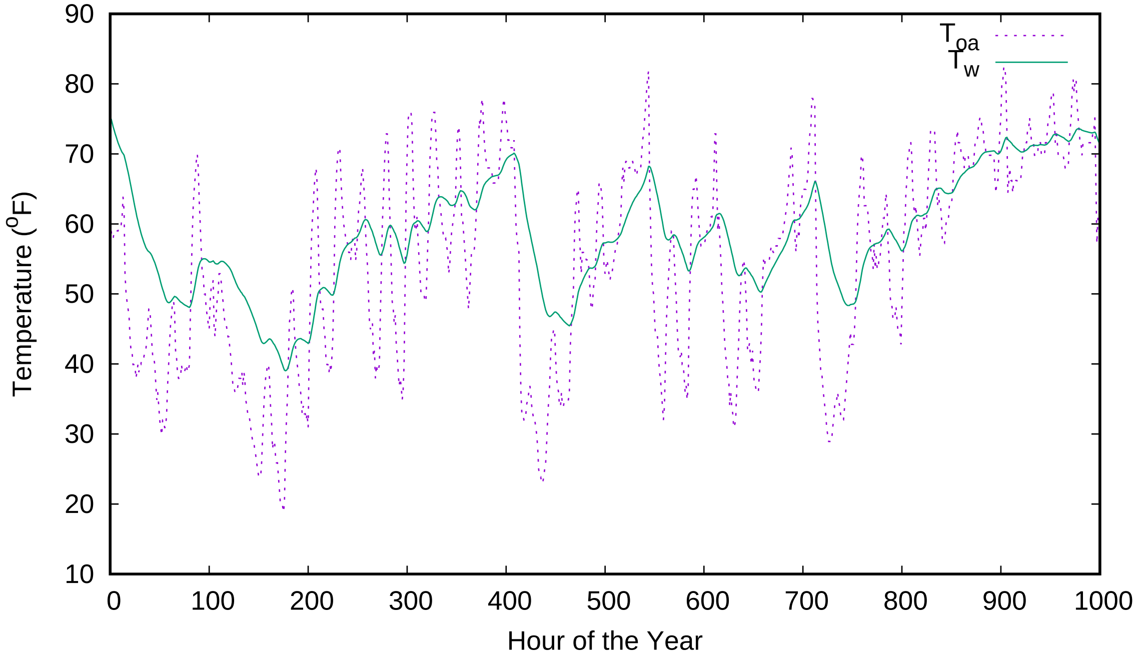
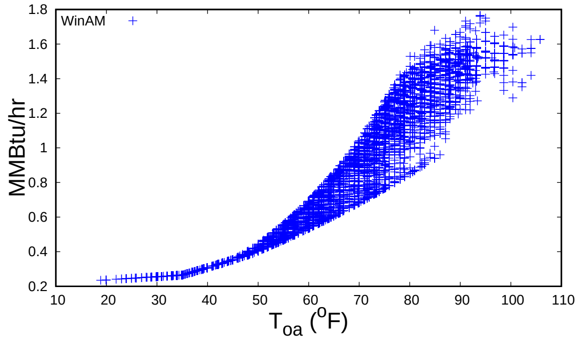


Figure 4.14: Masses - Heavy Mass - T_w vs T_{oa}

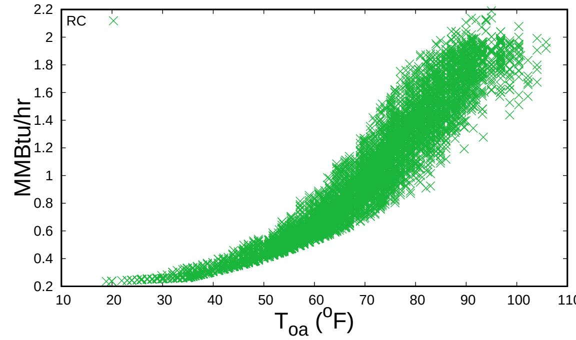
4.3.6 Heavy Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 170%. Two steps were made and no further suggestions were available from the Calibration Assistant, and the model was not considered calibrated. Therefore, the protocol was not able to be completed. The resulting Total CV-RMSE after these steps was 28%. The steps were:

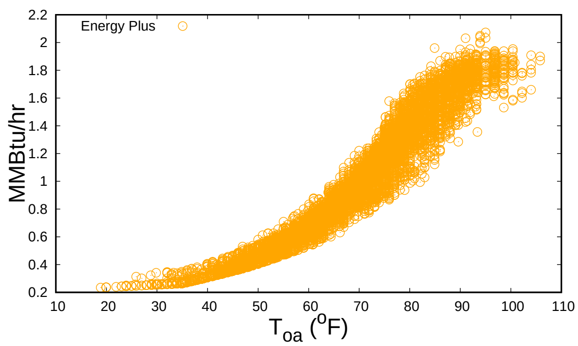
- Overall Zone Occupied Cooling Set Point from 75 °F to 72 °F, reducing the Total CV-RMSE from 170% to 29.5%.
- Constant Cooling Coil Set Point from 55 °F to 55.5 °F, reducing the Total CV-RMSE from 29.5% to 28.1%.



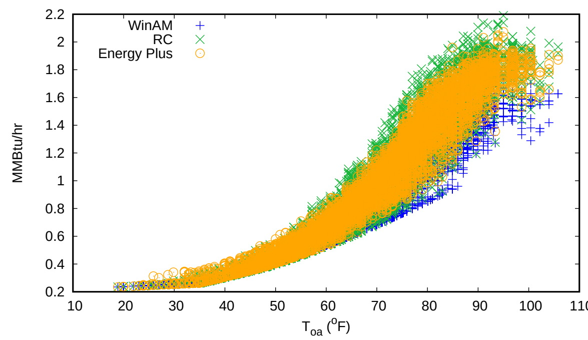
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



(c) EnergyPlus Cooling Consumption



(d) WinAM, RC, and EnergyPlus Cooling Consumption

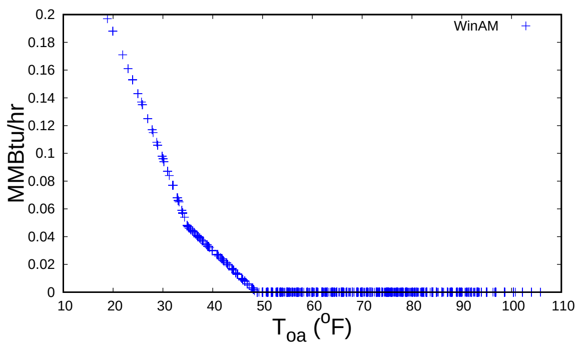
Figure 4.15: Solar - Cooling Consumption

4.4 Solar

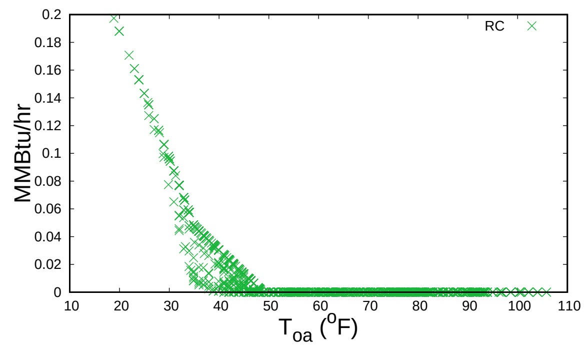
At first, when attempting to simulate the solar gains in EnergyPlus, only through adding the solar effects in the walls, it did not change hardly at all. Therefore, the EnergyPlus model was changed to have 10% window area in its external walls. In order to remain consistent with the same UA value from before, the wall now was made with an R-Value of 10 hr·°F·ft^2/Btu, and the window was made with an R-Value of 1.89 hr·°F·ft^2/Btu.

The cooling and heating results are displayed in Figures 4.15 and 4.16. For cooling, the solar effects have higher effects in its consumption. For heating, a small spread below the Slope 1 occurs in temperatures below 50°F, for the EnergyPlus and RC models. This is due to a decrease on the necessary heating, due to solar gains.

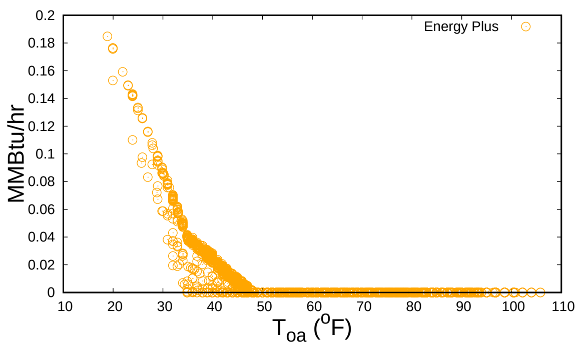
Table 4.6 displays the comparison metrics between simulations. Note that the heating con-



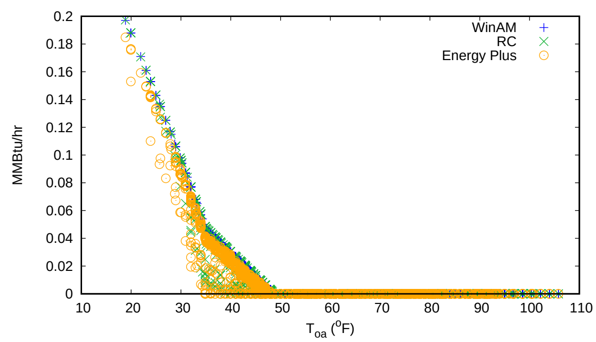
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.16: Solar - Heating Consumption

sumption has been reduced, and the cooling consumption has been increased, for the EnergyPlus and RC models, when compared to the baseline model of WinAM.

Table 4.6: Comparison between models for *Solar*

Difference between WinAM and RC			
	WinAM	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.450	0.624	38.75%
Average Difference for Cooling	-	-	7.89%
Standard Deviation for Cooling	-	-	9.90%
Max. Difference Data Point for Heating (MMBTU)	0.024	0.001	2190.67%
Average Difference for Heating	-	-	3.60%
Standard Deviation for Heating	-	-	50.09%
Annual Cooling (MMBTU)	7713.36	8389.34	8.76%
Annual Heating (MMBTU)	34.20	31.08	10.02%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.429	0.624	45.36%
Average Difference for Cooling	-	-	9.88%
Standard Deviation for Cooling	-	-	9.19%
Max. Difference Data Point for Heating (MMBTU)	0.040	0.002	2387.17%
Average Difference for Heating	-	-	7.95%
Standard Deviation for Heating	-	-	59.56%
Annual Cooling (MMBTU)	7713.36	8479.14	9.93%
Annual Heating (MMBTU)	34.20	23.68	44.39%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.624	0.452	38.12%
Average Difference for Cooling	-	-	4.89%
Standard Deviation for Cooling	-	-	5.00%
Max. Difference Data Point for Heating (MMBTU)	0.002	0.028	1619.47%
Average Difference for Heating	-	-	6.54%
Standard Deviation for Heating	-	-	41.14%
Annual Cooling (MMBTU)	8479.14	8389.34	1.07%
Annual Heating (MMBTU)	23.68	31.08	31.24%

4.4.1 Solar WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 86%. Two steps were made to complete the protocol, resulting a Total CV-RMSE of 15%. The steps were:

- Overall U-Value from 0.07 Btu/ft^2·°F·hr to 0.06 Btu/ft^2·°F·hr, reducing the Total CV-RMSE from 86% to 20.7%.

- Constant Preheat Coil Set Point from 35 °F to 34 °F, reducing the Total CV-RMSE from 20.7% to 15.2%.

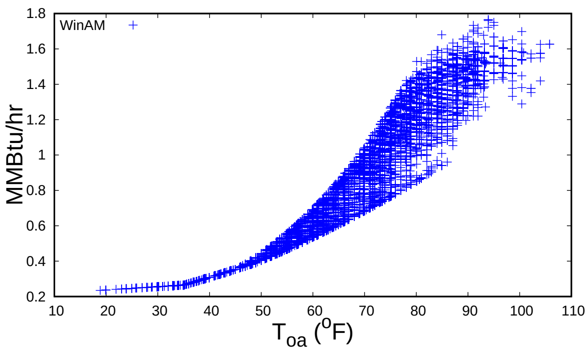
4.5 Mass & Solar

Mass & Solar case is the same as *Masses* with the added solar effects from Solar case. The comparison is made between the RC model results and EnergyPlus, as well as both with the baseline model of WinAM (5 Zones Normal R case).

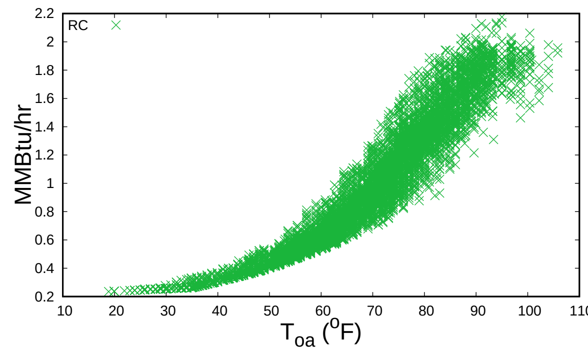
For this case, it is notable to see the combined effects for consumption of thermal mass and solar effects, for the RC and EnergyPlus models. A higher consumption occurs for cooling, mainly due to solar effects. For heating, as the mass increases, more spread is noted for temperatures near both heating slopes.

4.5.1 Light Mass

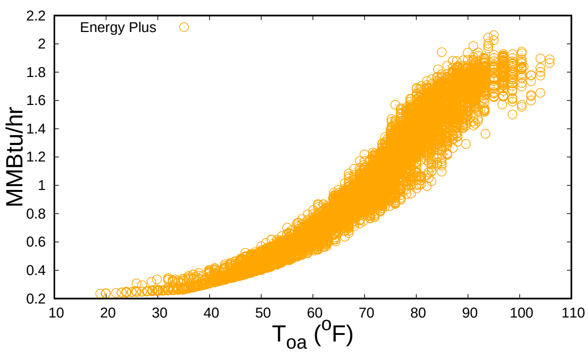
The cooling and heating results are displayed in Figures 4.17 and 4.18. Table 4.7 displays the comparison metrics between simulations.



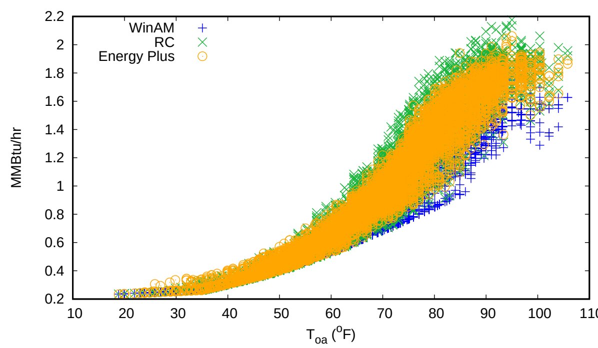
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption

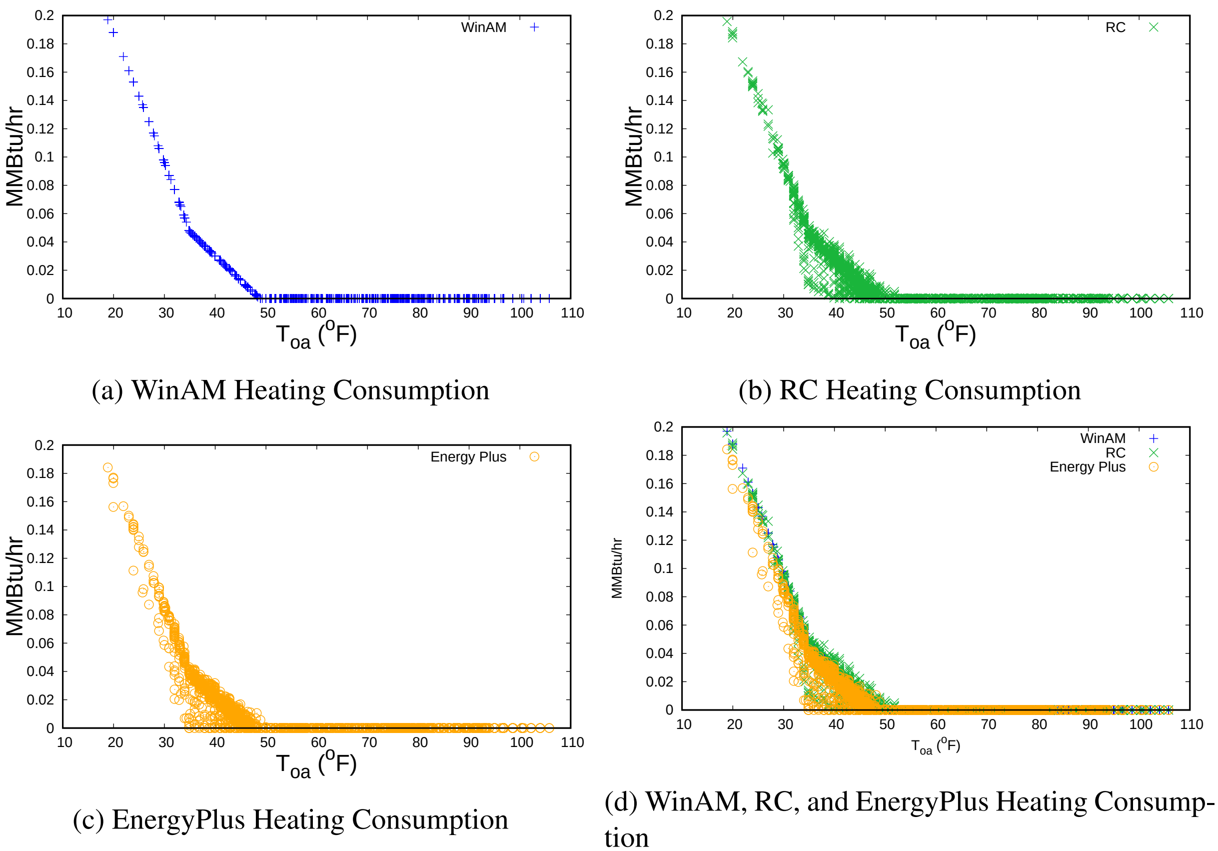


(c) EnergyPlus Cooling Consumption



(d) WinAM, RC, and EnergyPlus Cooling Consumption

Figure 4.17: Mass & Solar - Light Mass - Cooling Consumption



(a) WinAM Heating Consumption

(b) RC Heating Consumption

(c) EnergyPlus Heating Consumption

(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.18: Mass & Solar - Light Mass - Heating Consumption

Table 4.7: Comparison between models for *Mass & Solar* - Light Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.450	0.617	37.13%
Average Difference for Cooling	-	-	7.80%
Standard Deviation for Cooling	-	-	9.39%
Max. Difference Data Point for Heating (MMBTU)	0.027	0.001	1871.26%
Average Difference for Heating	-	-	7.08%
Standard Deviation for Heating	-	-	54.42%
Annual Cooling (MMBTU)	7713.36	8387.22	8.74%
Annual Heating (MMBTU)	34.20	30.05	13.81%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.429	0.616	43.54%
Average Difference for Cooling	-	-	9.36%
Standard Deviation for Cooling	-	-	8.69%
Max. Difference Data Point for Heating (MMBTU)	0.041	0.001	3731.64%
Average Difference for Heating	-	-	9.72%
Standard Deviation for Heating	-	-	80.35%
Annual Cooling (MMBTU)	7713.36	8438.70	9.40%
Annual Heating (MMBTU)	34.20	23.13	47.85%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.616	0.442	39.41%
Average Difference for Cooling	-	-	4.61%
Standard Deviation for Cooling	-	-	4.86%
Max. Difference Data Point for Heating (MMBTU)	0.001	0.029	2649.85%
Average Difference for Heating	-	-	6.43%
Standard Deviation for Heating	-	-	57.33%
Annual Cooling (MMBTU)	8438.70	8387.22	0.61%
Annual Heating (MMBTU)	23.13	30.05	29.92%

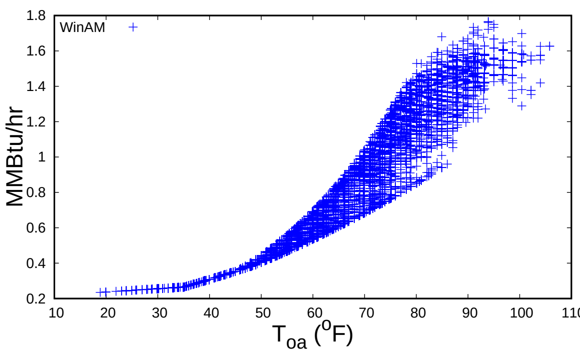
4.5.2 Light Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 91%. Two steps were made to complete the protocol, resulting a Total CV-RMSE of 15%. The steps were:

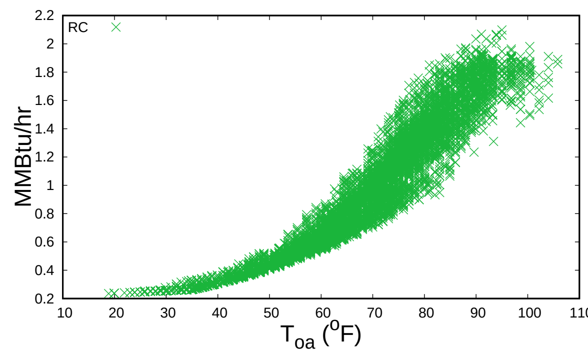
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.12 CFM/ft^2, reducing the Total CV-RMSE from 91% to 19.7%.
- Constant Preheat Coil Set Point from 35°F to 34°F, reducing the Total CV-RMSE from 19.7% to 15.1%.

4.5.3 Medium Mass

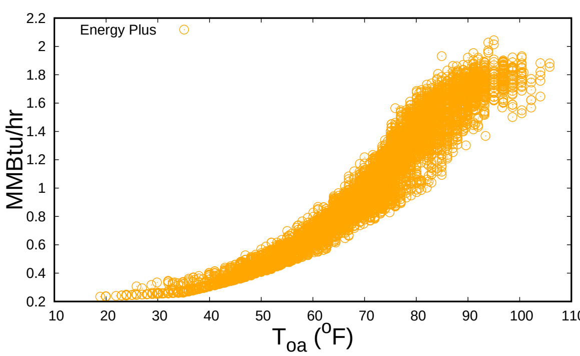
The cooling and heating results are displayed in Figures 4.19 and 4.20. Table 4.8 displays the comparison metrics between simulations.



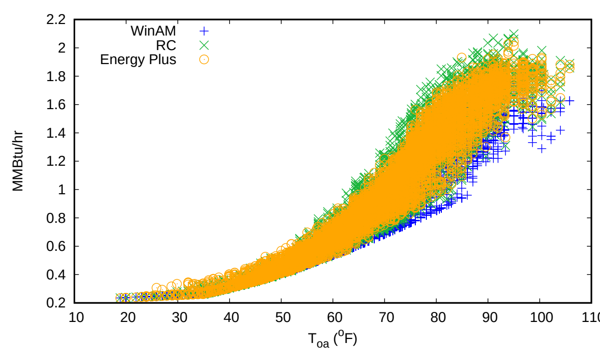
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption

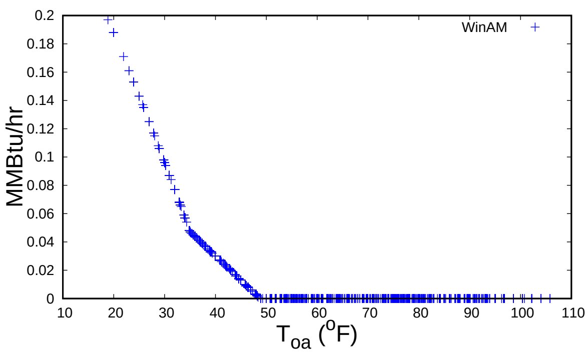


(c) EnergyPlus Cooling Consumption

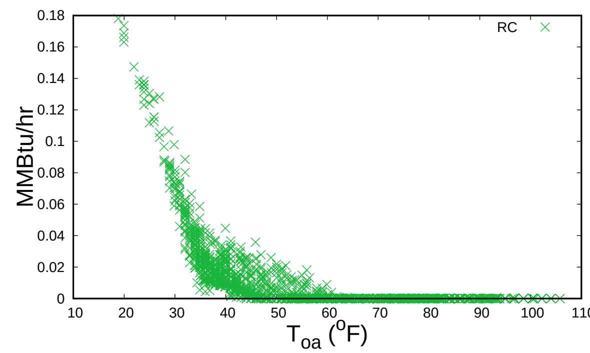


(d) WinAM, RC, and EnergyPlus Cooling Consumption

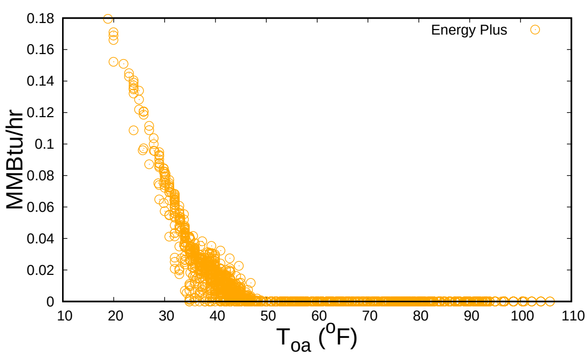
Figure 4.19: Mass & Solar - Medium Mass - Cooling Consumption



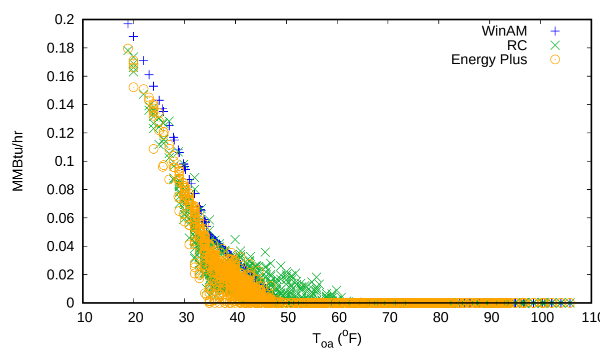
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.20: Mass & Solar - Medium Mass - Heating Consumption

Table 4.8: Comparison between models for *Mass & Solar* - Medium Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.382	0.517	35.08%
Average Difference for Cooling	-	-	7.69%
Standard Deviation for Cooling	-	-	7.20%
Max. Difference Data Point for Heating (MMBTU)	0.027	0.001	1759.63%
Average Difference for Heating	-	-	22.32%
Standard Deviation for Heating	-	-	81.87%
Annual Cooling (MMBTU)	7713.36	8366.84	8.47%
Annual Heating (MMBTU)	34.20	20.00	70.94%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.429	0.616	43.51%
Average Difference for Cooling	-	-	9.31%
Standard Deviation for Cooling	-	-	8.15%
Max. Difference Data Point for Heating (MMBTU)	0.048	0.001	4353.00%
Average Difference for Heating	-	-	14.68%
Standard Deviation for Heating	-	-	109.75%
Annual Cooling (MMBTU)	7713.36	8431.48	9.31%
Annual Heating (MMBTU)	34.20	19.08	79.19%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.616	0.451	36.47%
Average Difference for Cooling	-	-	4.22%
Standard Deviation for Cooling	-	-	4.75%
Max. Difference Data Point for Heating (MMBTU)	0.001	0.045	2940.70%
Average Difference for Heating	-	-	7.72%
Standard Deviation for Heating	-	-	68.82%
Annual Cooling (MMBTU)	8431.48	8366.84	0.77%
Annual Heating (MMBTU)	19.08	20.00	4.83%

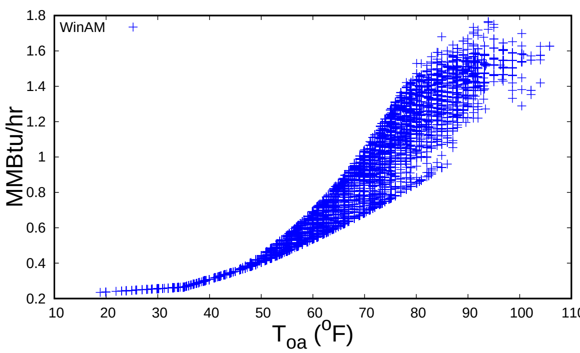
4.5.4 Medium Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 146%. Two steps were made to complete the protocol, resulting a Total CV-RMSE of 16%. The steps were:

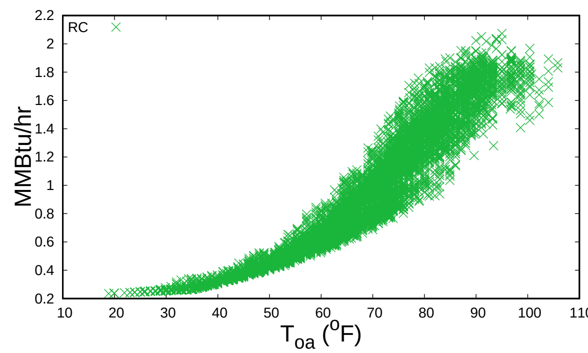
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.10 CFM/ft^2, reducing the Total CV-RMSE from 146% to 18.8%.
- Constant Cooling Coil Set Point from 55°F to 54.3°F, reducing the Total CV-RMSE from 18.8% to 16.5%.

4.5.5 Heavy Mass

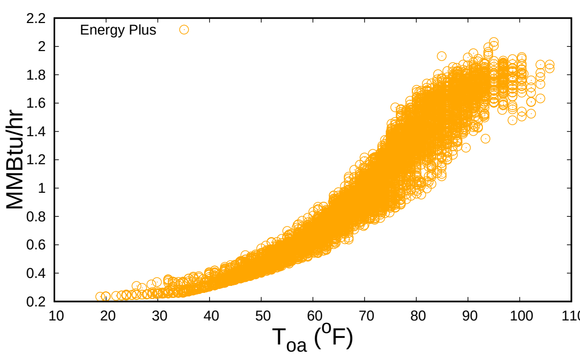
The cooling and heating results are displayed in Figures 4.21 and 4.22. Table 4.9 displays the comparison metrics between simulations.



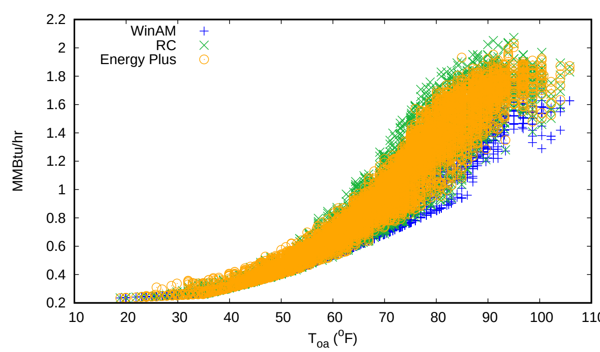
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption

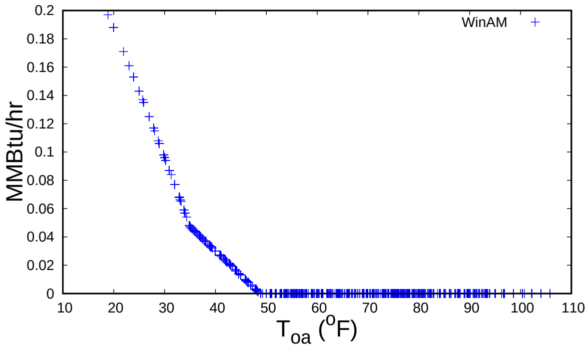


(c) EnergyPlus Cooling Consumption

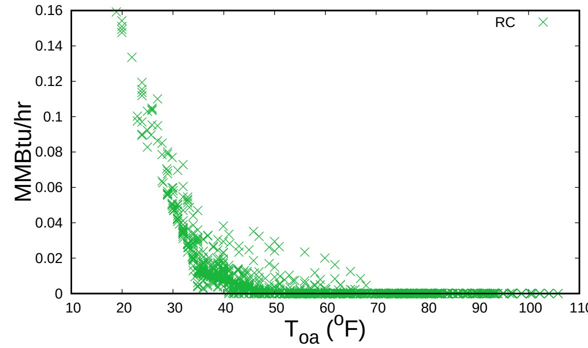


(d) WinAM, RC, and EnergyPlus Cooling Consumption

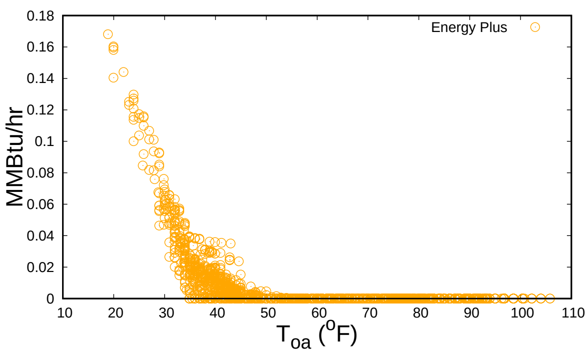
Figure 4.21: Mass & Solar - Heavy Mass - Cooling Consumption



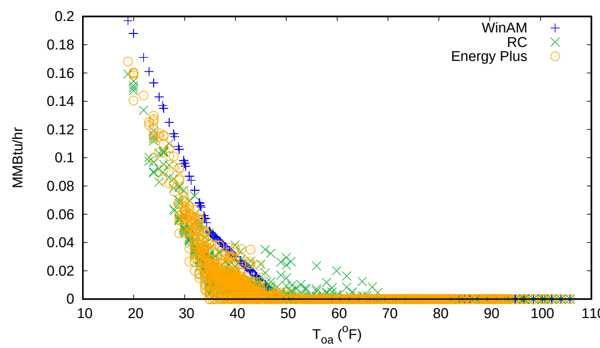
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.22: Mass & Solar - Heavy Mass - Heating Consumption

Table 4.9: Comparison between models for *Mass & Solar* - Heavy Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.382	0.521	36.33%
Average Difference for Cooling	-	-	7.72%
Standard Deviation for Cooling	-	-	6.96%
Max. Difference Data Point for Heating (MMBTU)	0.027	0.001	1871.26%
Average Difference for Heating	-	-	28.10%
Standard Deviation for Heating	-	-	95.62%
Annual Cooling (MMBTU)	7713.36	8355.38	8.32%
Annual Heating (MMBTU)	34.20	14.32	138.76%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.429	0.620	44.50%
Average Difference for Cooling	-	-	9.28%
Standard Deviation for Cooling	-	-	8.12%
Max. Difference Data Point for Heating (MMBTU)	0.041	0.002	2411.52%
Average Difference for Heating	-	-	15.51%
Standard Deviation for Heating	-	-	101.80%
Annual Cooling (MMBTU)	7713.36	8422.69	9.20%
Annual Heating (MMBTU)	34.20	14.38	137.89%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.620	0.460	34.92%
Average Difference for Cooling	-	-	4.23%
Standard Deviation for Cooling	-	-	4.69%
Max. Difference Data Point for Heating (MMBTU)	0.001	0.023	1763.49%
Average Difference for Heating	-	-	4.92%
Standard Deviation for Heating	-	-	42.94%
Annual Cooling (MMBTU)	8422.69	8355.38	0.81%
Annual Heating (MMBTU)	14.38	14.32	0.37%

4.5.6 Heavy Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 253%. Seven steps were made to complete the protocol, altering four parameters, resulting a Total CV-RMSE of 16%. The steps were:

- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.08 CFM/ft^2, reducing the Total CV-RMSE from 253% to 21.4%.

- Constant Cooling Coil Set Point from 55 °F to 53.8 °F, reducing the Total CV-RMSE from 21.4% to 19.6%.

- Constant Preheat Coil Set Point from 35 °F to 34.6 °F, reducing the Total CV-RMSE from 19.6% to 18.9%.

- Constant Cooling Coil Set Point from 53.8 °F to 53.1 °F, reducing the Total CV-RMSE from 18.9% to 18.1%.

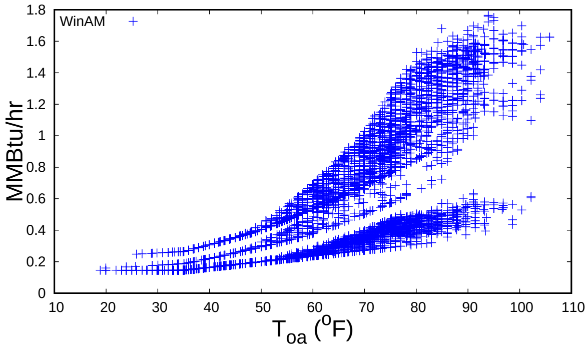
- Constant Fan Static Pressure Set Point from 0 inH_2O to 1.0 inH_2O, reducing the Total CV-RMSE from 18.1% to 17.3%.

- Constant Preheat Coil Set Point from 34.6 °F to 34.2 °F, reducing the Total CV-RMSE from 17.3% to 16.9%.

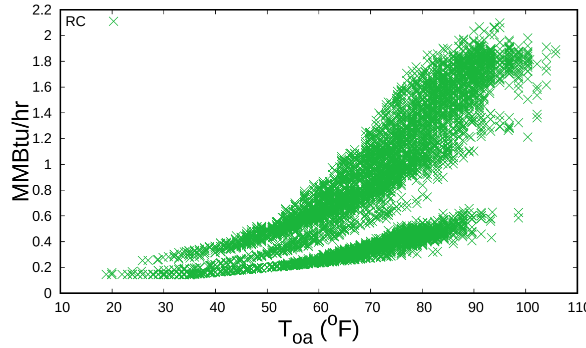
- Constant Cooling Coil Set Point from 53.1 °F to 52.4 °F, reducing the Total CV-RMSE from 16.9% to 15.6%.

4.6 Internal Load Variation

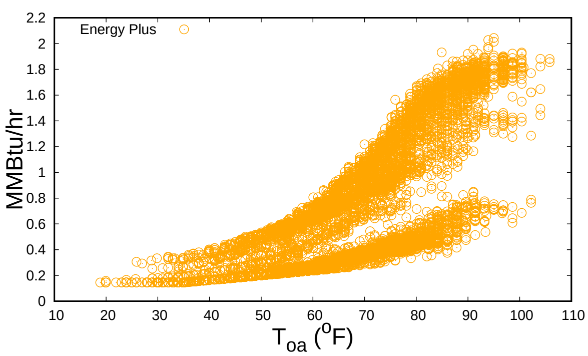
This case analyzes the effects of internal load variation in the different models. The internal loads are going to vary according to the multiplier times the peak load (maintained as before), as described in Figure 3.5. This parameter change is added to Mass & Solar case. This load variation is also added in the WinAM model.



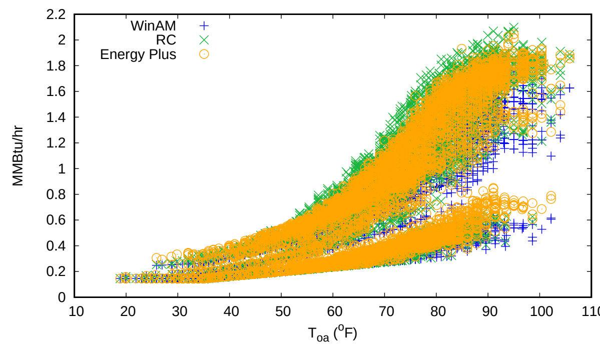
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



(c) EnergyPlus Cooling Consumption



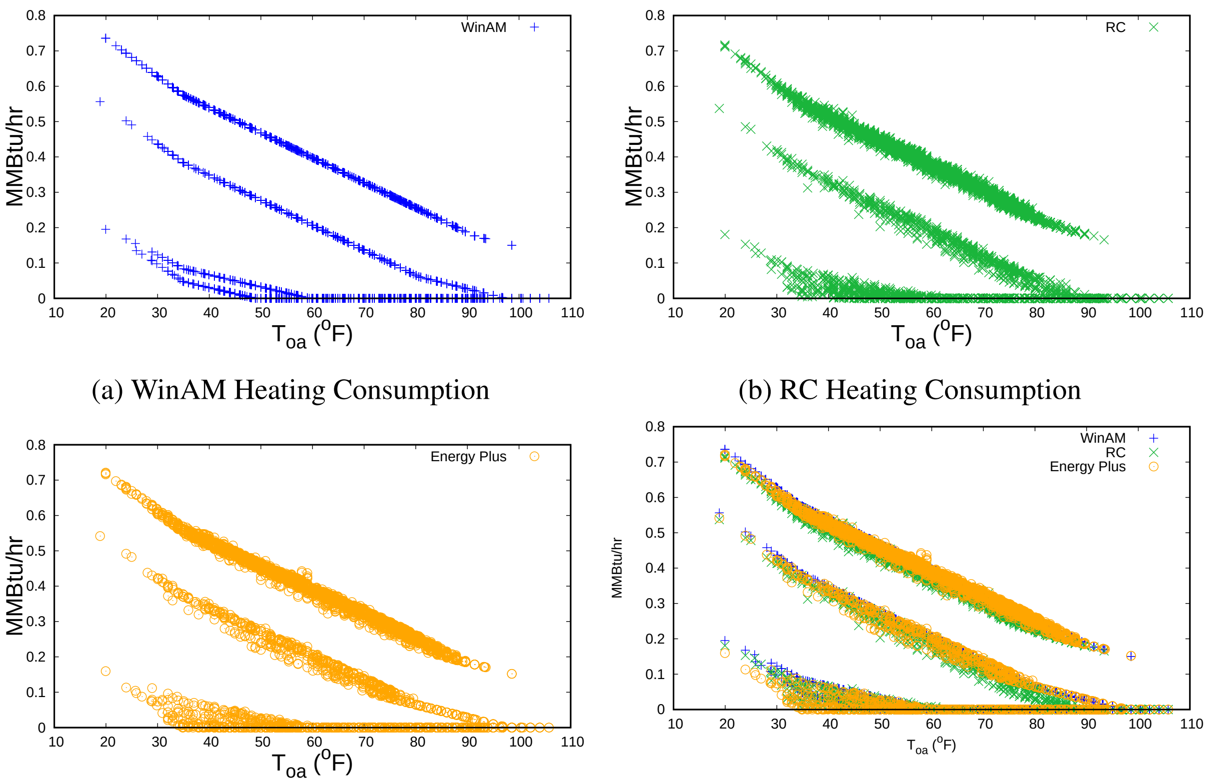
(d) WinAM, RC, and EnergyPlus Cooling Consumption

Figure 4.23: Internal Load Variation - Medium Mass - Cooling Consumption

For Internal Load Variation case, only the "Medium Mass" case is analyzed, due to represent a more typical building construction, and to not have so much repetitive results.

4.6.1 Medium Mass

The cooling and heating results are displayed in Figures 4.23 and 4.24. It is possible to note separate regions of heating and cooling due to load variation. For heating, it is also possible to notice a spread in the EnergyPlus and RC models due to thermal mass effects. Table 4.10 displays the comparison metrics between simulations.



(a) WinAM Heating Consumption

(b) RC Heating Consumption

(c) EnergyPlus Heating Consumption

(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.24: Internal Load Variation - Medium Mass - Heating Consumption

Table 4.10: Comparison between models for Internal Load Variation case - Medium Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.444	1.125	153.14%
Average Difference for Cooling	-	-	14.16%
Standard Deviation for Cooling	-	-	25.97%
Max. Difference Data Point for Heating (MMBTU)	0.001	0.202	15110.35%
Average Difference for Heating	-	-	42.59%
Standard Deviation for Heating	-	-	397.08%
Annual Cooling (MMBTU)	5113.63	5700.23	11.47%
Annual Heating (MMBTU)	1632.75	1540.75	5.97%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Max. Difference Data Point for Cooling (MMBTU)	0.830	0.414	100.44%
Average Difference for Cooling	-	-	10.21%
Standard Deviation for Cooling	-	-	10.00%
Max. Difference Data Point for Heating (MMBTU)	0.048	0.001	4431.88%
Average Difference for Heating	-	-	10.22%
Standard Deviation for Heating	-	-	103.14%
Annual Cooling (MMBTU)	5113.63	5729.06	12.04%
Annual Heating (MMBTU)	1632.75	1592.51	2.53%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Max. Difference Data Point for Cooling (MMBTU)	1.178	0.496	137.54%
Average Difference for Cooling	-	-	11.31%
Standard Deviation for Cooling	-	-	21.02%
Max. Difference Data Point for Heating (MMBTU)	0.001	0.225	16790.96%
Average Difference for Heating	-	-	40.49%
Standard Deviation for Heating	-	-	374.69%
Annual Cooling (MMBTU)	5729.06	5700.23	0.51%
Annual Heating (MMBTU)	1592.51	1540.75	3.36%

4.6.2 Medium Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Curiously, the model was already considered calibrated, with a Total CV-RMSE of 12%. However, according to the protocol, it could be improved. Therefore, the following step was made resulting in a CV-RMSE of 2%.

- Overall Lighting and Plug Electric Usage from 2 W/ft^2 to 2.46 W/ft^2, reducing the Total CV-RMSE from 12% to 1.8%.

4.7 Temperature Setback

For Temperature Setback case, a night-time temperature setback of 10°F is applied to Internal Load Variation case. The heating and cooling set points during that period is 65°F and 85°F respectively.

Also, for the EnergyPlus model, the time step was change for 6 per hour, to ensure stability in its results, due to thermal mass effects, especially in the hour of change of temperature set point.

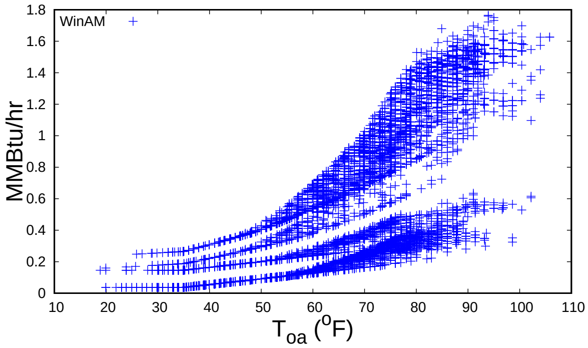
A novelty aspect is introduced in this model that neither the RC model, or the WinAM was capturing its effect. When the night-time temperature setback is over at 05:00 AM, the system in EnergyPlus heats not only the space, but also its mass.

At first, the effects of the sudden heating were not accounted for in the RC model, it tried to heat up the air temperature, without taking to account the elevation of the mass' temperature. This yielded a difference as high as 162% in the heating consumption for the Heavy Mass building, between the RC model and EnergyPlus.

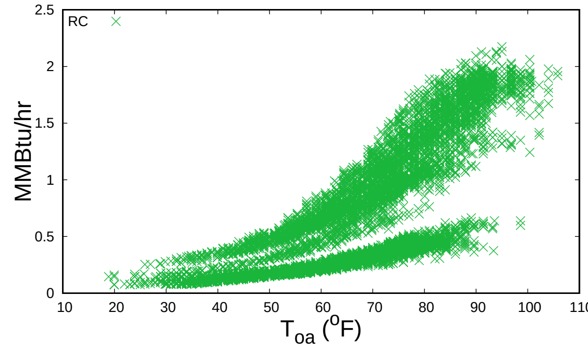
Thus, in order to capture this effect, an adjustment of the RC model's calculation was made on those hours in which the temperature set point jumps from 65°F to 75°F, which are described in Section 3.6.2.

4.7.1 Light Mass

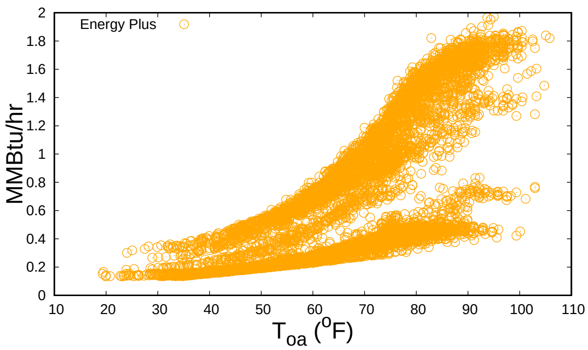
The cooling and heating results are displayed in Figures 4.25 and 4.26. Note a considerable difference in the heating consumption in all three models. The higher values of heating for En-



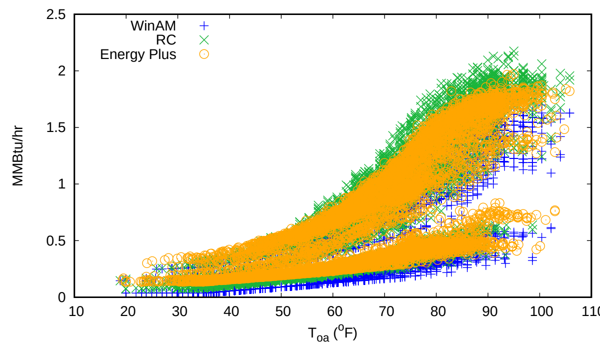
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



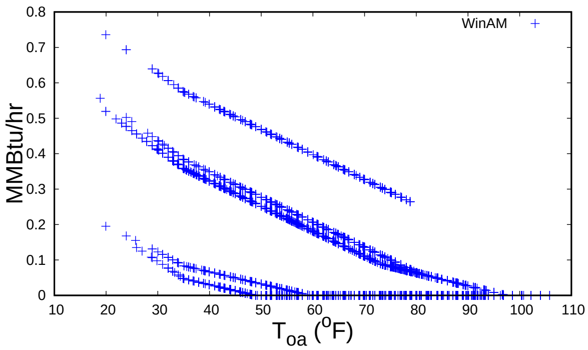
(c) EnergyPlus Cooling Consumption



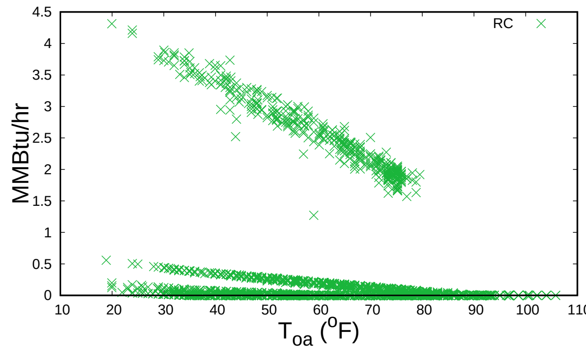
(d) WinAM, RC, and EnergyPlus Cooling Consumption

Figure 4.25: Temperature Setback - Light Mass - Cooling Consumption

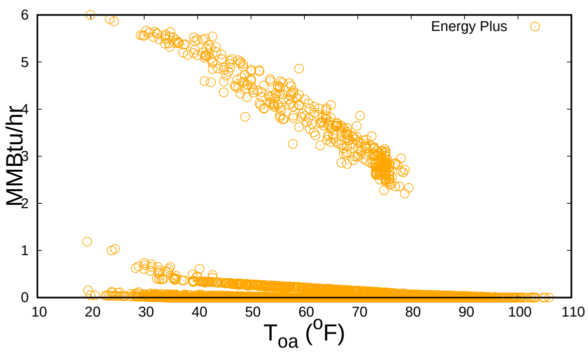
ergyPlus and the RC model represent the hours in which the temperature set point is reset to the daytime set point. Table 4.11 displays the comparison metrics between simulations.



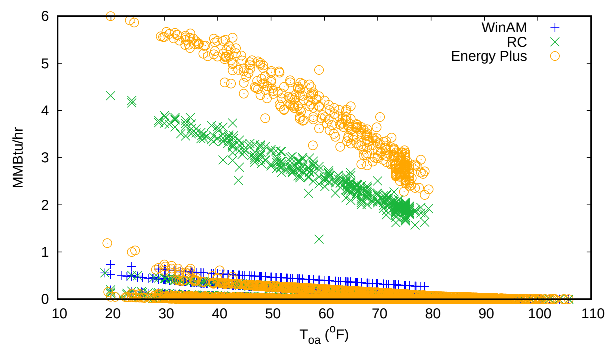
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.26: Temperature Setback - Light Mass - Heating Consumption

Table 4.11: Comparison between models for Temperature Setback case - Light Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4722.04	5688.14	20.46%
Annual Heating (MMBTU)	865.27	1056.60	22.11
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4722.04	5633.84	19.31%
Annual Heating (MMBTU)	865.27	1526.13	76.37%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	5633.84	5688.14	0.96%
Annual Heating (MMBTU)	1526.13	1056.60	44.44%

4.7.2 Light Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 48%. Three steps were made to complete the protocol, resulting a Total CV-RMSE of 3%. The steps were:

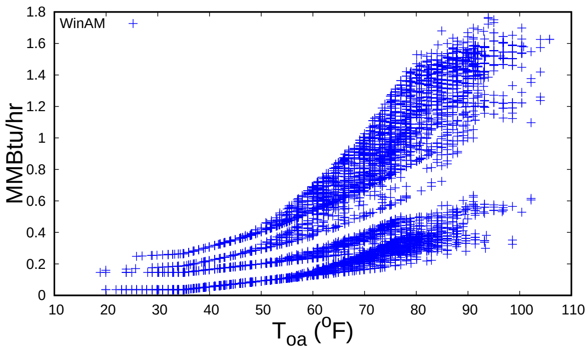
- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.32 CFM/ft^2, reducing the Total CV-RMSE from 48% to 7.9%.

- Constant Cooling Coil Set Point from 55°F to 54.3°F, reducing the Total CV-RMSE from 7.9% to 5.7%.

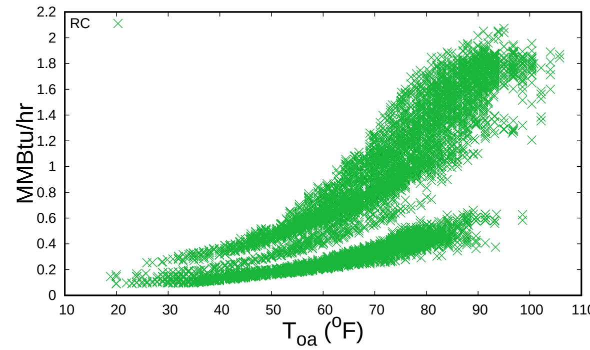
- Minimum Occupied Outside Air from 25% to 20.3%, reducing the Total CV-RMSE from 5.7% to 3.3%.

4.7.3 Medium Mass

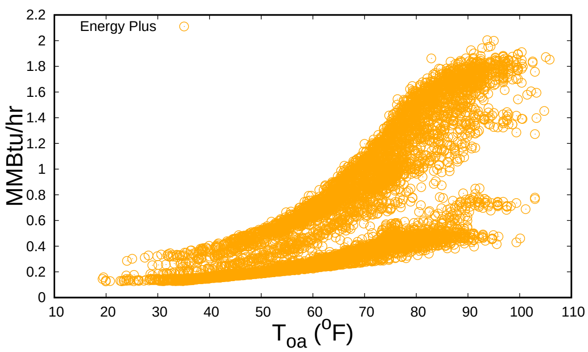
The cooling and heating results are displayed in Figures 4.27 and 4.28. Table 4.12 displays the comparison metrics between simulations. As more mass is added, the models for RC and EnergyPlus approximate their results more then before.



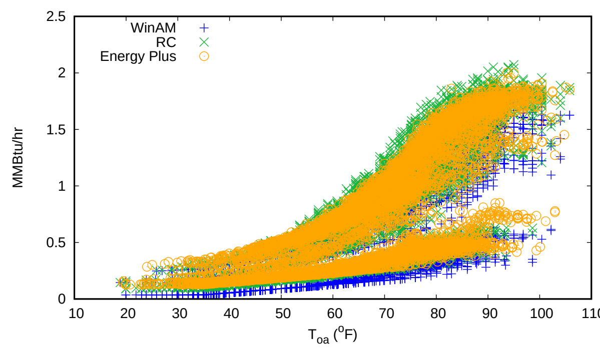
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



(c) EnergyPlus Cooling Consumption



(d) WinAM, RC, and EnergyPlus Cooling Consumption

Figure 4.27: Temperature Setback - Medium Mass - Cooling Consumption

Table 4.12: Comparison between models for Temperature Setback case - Medium Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4722.04	5584.21	18.26%
Annual Heating (MMBTU)	865.27	1085.29	25.43%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4722.04	5651.07	19.67%
Annual Heating (MMBTU)	865.27	1507.26	74.20%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	5651.07	5584.21	1.20%
Annual Heating (MMBTU)	1507.26	1085.29	38.88%

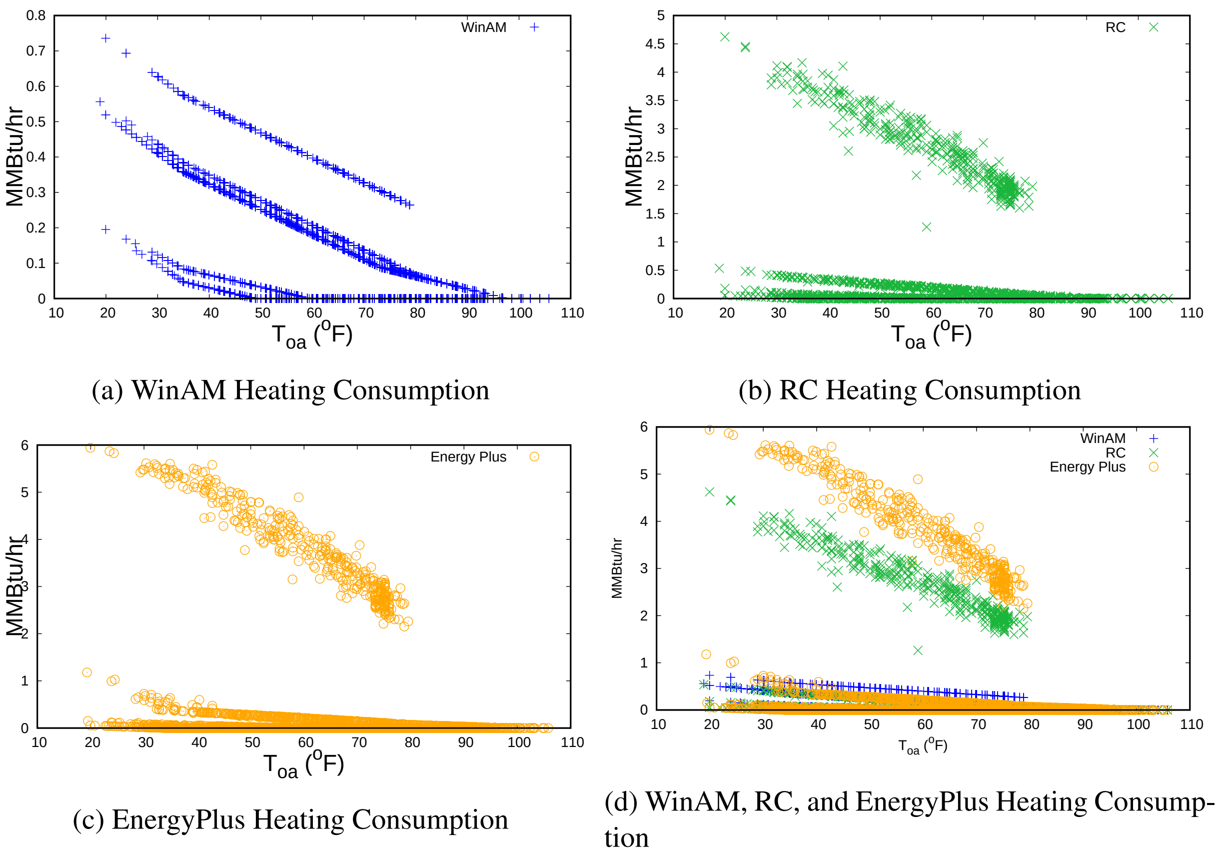


Figure 4.28: Temperature Setback - Medium Mass - Heating Consumption

4.7.4 Medium Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 48%. One step was made to complete the protocol, resulting a Total CV-RMSE of 6%. The step was:

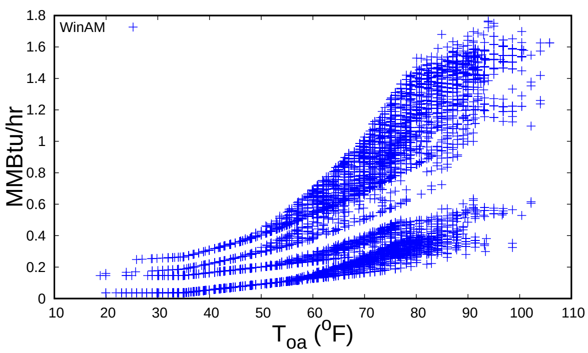
- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.32 CFM/ft^2, reducing the Total CV-RMSE from 48% to 6.3%.

4.7.5 Heavy Mass

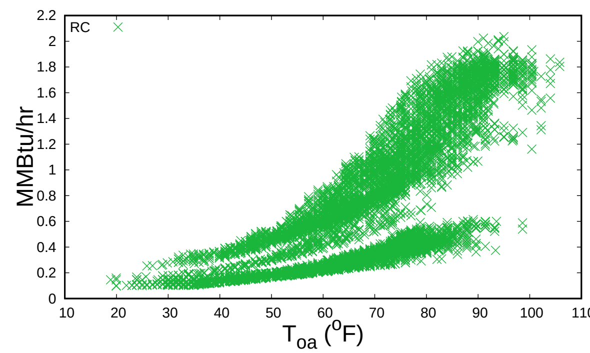
The cooling and heating results are displayed in Figures 4.29 and 4.30. Table 4.13 displays the comparison metrics between simulations. As more mass is added, the models for RC and EnergyPlus approximate their results more then before.

Table 4.13: Comparison between models for Temperature Setback case - Heavy Mass

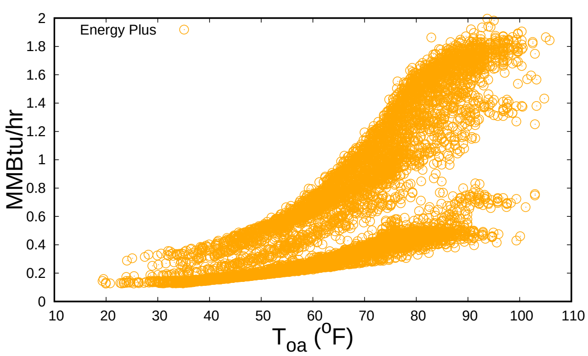
Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4722.04	5561.81	17.78%
Annual Heating (MMBTU)	865.27	1107.09	27.95%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4722.04	5647.61	19.60%
Annual Heating (MMBTU)	865.27	1505.01	73.94%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	5647.61	5561.81	1.54%
Annual Heating (MMBTU)	1505.01	1107.09	35.94%



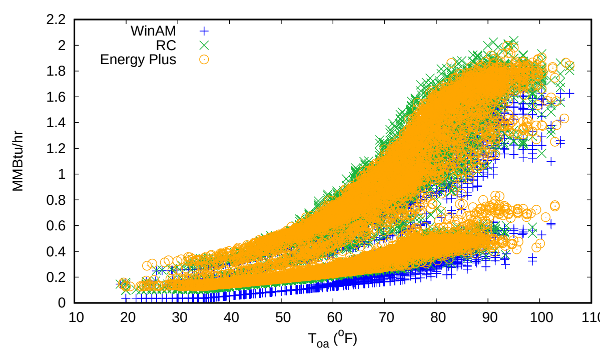
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption

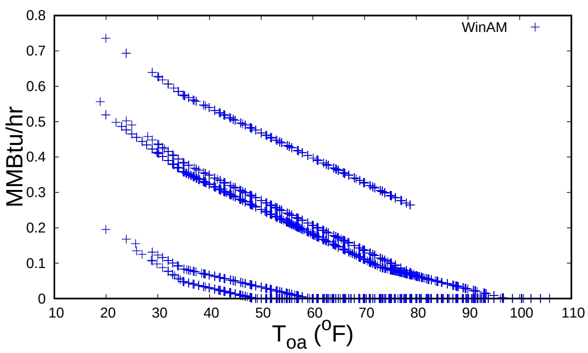


(c) EnergyPlus Cooling Consumption

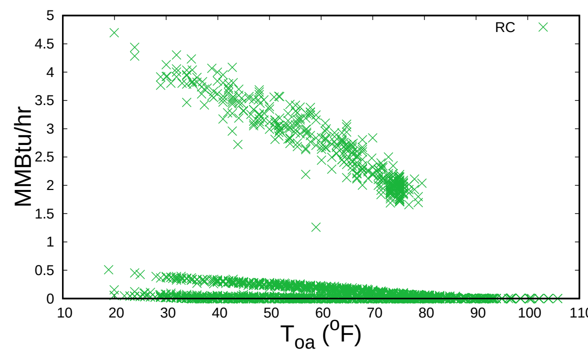


(d) WinAM, RC, and EnergyPlus Cooling Consumption

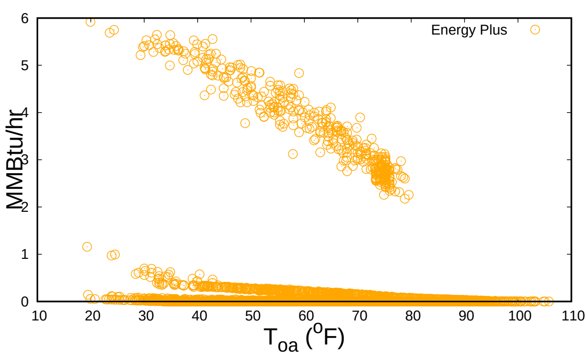
Figure 4.29: Temperature Setback - Heavy Mass - Cooling Consumption



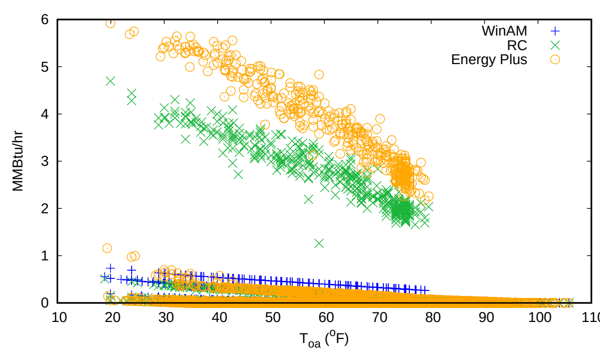
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.30: Temperature Setback - Heavy Mass - Heating Consumption

4.7.6 Heavy Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 48%. One step was made to complete the protocol, resulting a Total CV-RMSE of 4%. The step was:

- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.32 CFM/ft^2, reducing the Total CV-RMSE from 48% to 6.2%.

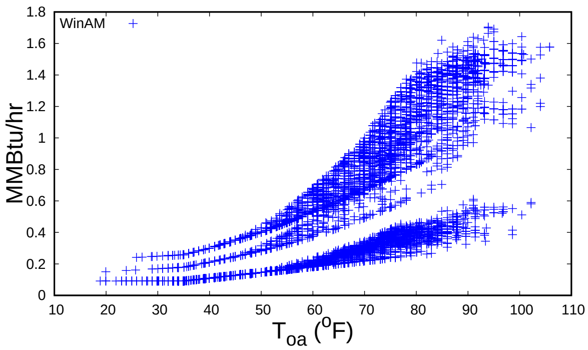
4.8 Temperature Deadband

This case analyzes the effects of a temperature throttling range (or temperature deadband) applied to all hours of the day, with no temperature setback. The heating set point is changed to 70°F, and the cooling set point is changed to 76°F.

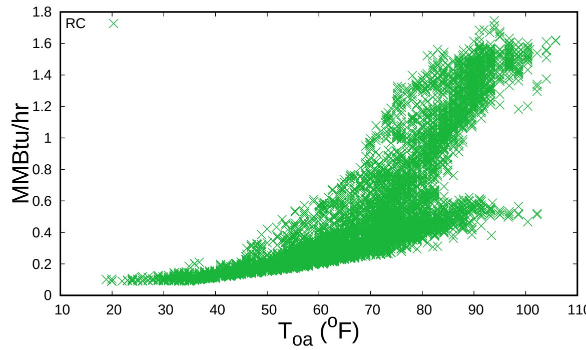
For Temperature Deadband case, only the "Medium Mass" case is analyzed, due to represent a more typical building construction, and to not have so much repetitive results.

4.8.1 Medium Mass

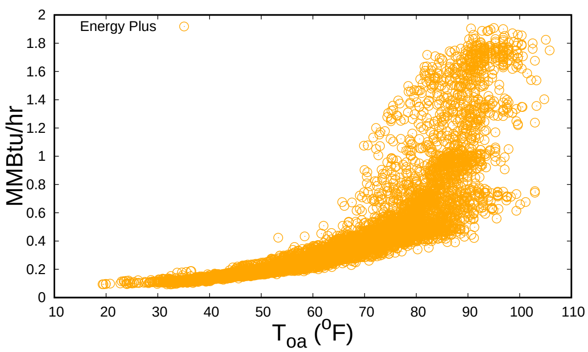
The cooling and heating results are displayed in Figures 4.31 and 4.32. Table 4.14 displays the comparison metrics between simulations. WinAM's heating consumption stands out in this case, when compared to the other models. Since, WinAM only includes steady-state calculations, it fails to consider all the energy stored in the building's mass, which would delay the necessary heating when the internal heat gains are decreased.



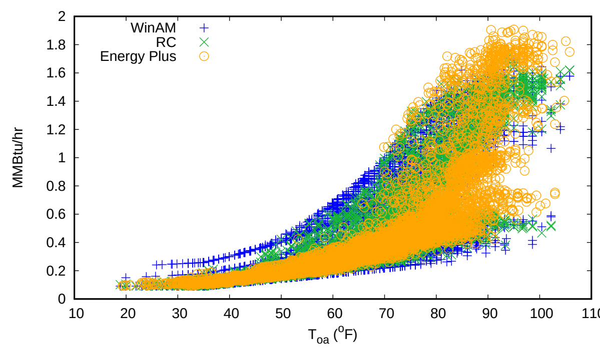
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



(c) EnergyPlus Cooling Consumption

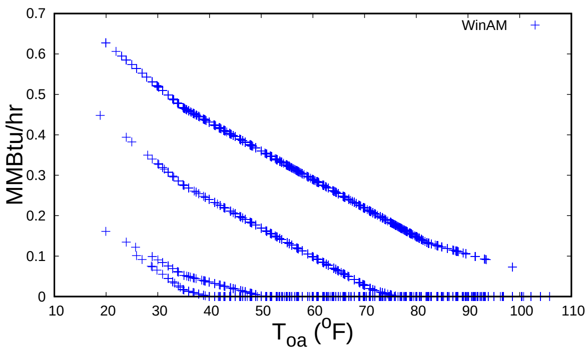


(d) WinAM, RC, and EnergyPlus Cooling Consumption

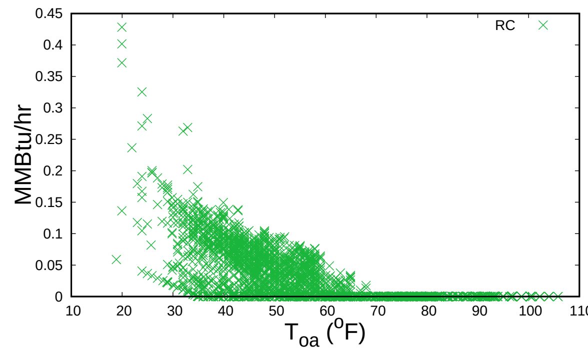
Figure 4.31: Temperature Deadband - Medium Mass - Cooling Consumption

Table 4.14: Comparison between models for Temperature Deadband case - Medium Mass

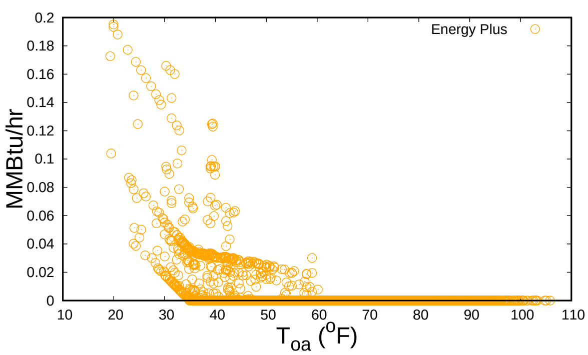
Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4765.26	4154.93	14.69%
Annual Heating (MMBTU)	1124.28	75.82	1382.89%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4765.26	3953.33	20.54%
Annual Heating (MMBTU)	1124.28	16.02	6918.02%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	3953.33	4154.93	5.10%
Annual Heating (MMBTU)	16.02	75.82	373.27%



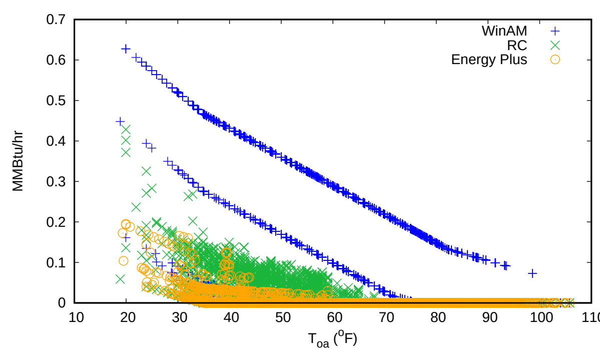
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.32: Temperature Deadband - Medium Mass - Heating Consumption

4.8.2 Medium Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 7596%. Eleven steps were made, changing nine parameters, and no further suggestions were available from the Calibration Assistant, and the model was not considered calibrated. Therefore the protocol was not able to be completed. The resulting Total CV-RMSE after these steps was 20%. The steps were:

- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.00 CFM/ft^2, reducing the Total CV-RMSE from 7596% to 2545.2%.
- Night Electric Load Ratio from 0.00 to 0.15, reducing the Total CV-RMSE from 2545.2% to 915.9%.
- Interior Zone Percentage from 81% to 100%, reducing the Total CV-RMSE from 915.9% to 72.5%.
- Zone Occupied Heating Set Point from 70°F to 67.9°F, reducing the Total CV-RMSE from 72.5% to 31.8%.
- Constant Preheat Coil Set Point from 35°F to 38°F, reducing the Total CV-RMSE from 31.8% to 24.9%.
- Constant Cooling Coil Set Point from 55°F to 57.8°F, reducing the Total CV-RMSE from 24.9% to 21.4%.
- Minimum Occupied Outside Air from 25% to 28.1%, reducing the Total CV-RMSE from 21.4% to 20.7%.
- Zone Occupied Cooling Set Point from 76°F to 76.6°F, reducing the Total CV-RMSE from 20.7% to 20.4%.

- Constant Cooling Coil Set Point from 57.8°F to 58.2°F, reducing the Total CV-RMSE from 20.4% to 20.3%.
- Conditioned Floor Area from 90000 ft^2 to 89646 ft^2, reducing the Total CV-RMSE from 20.3% to 20.2%.
- Constant Cooling Coil Set Point from 58.2°F to 58.6°F, reducing the Total CV-RMSE from 20.2% to 20.1%.

4.9 Setback & Deadband

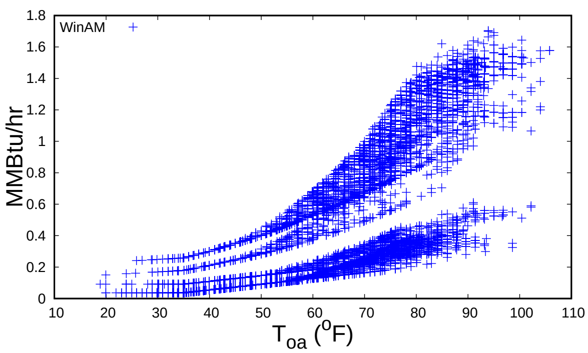
For Setback & Deadband case, the combined effects of Temperature Setback and Temperature Deadband cases are analyzed. It is noticeable that the necessary heating increase for all the change hours in EnergyPlus is now decreased when compared to the RC model.

4.9.1 Light Mass

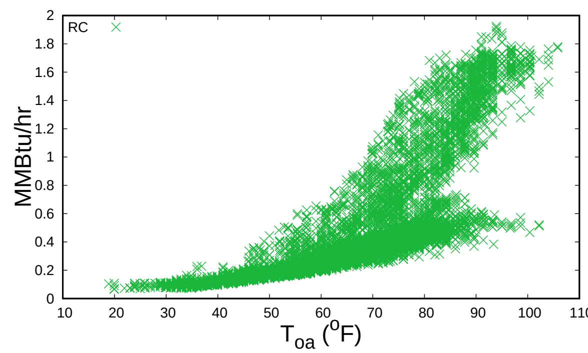
The cooling and heating results are displayed in Figures 4.33 and 4.34. Table 4.15 displays the comparison metrics between simulations.

Table 4.15: Comparison between models for Setback & Deadband case - Light Mass

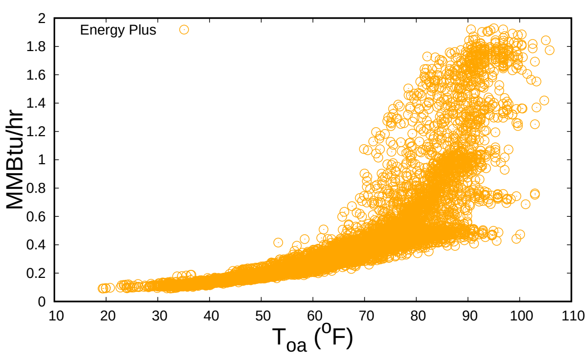
Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4572.46	4221.13	8.32%
Annual Heating (MMBTU)	749.48	54.32	1279.81%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4572.46	3955.02	15.61%
Annual Heating (MMBTU)	749.48	16.38	4476.81%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	3955.02	4221.13	6.73%
Annual Heating (MMBTU)	16.38	54.32	231.70%



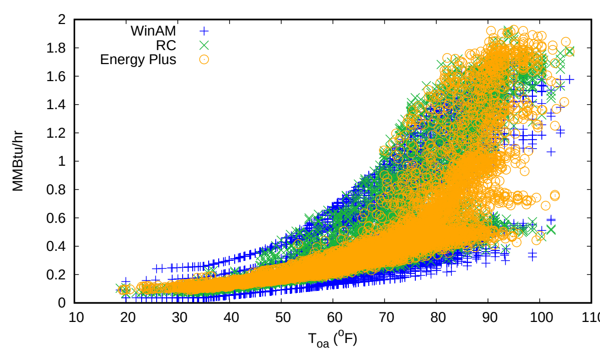
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption

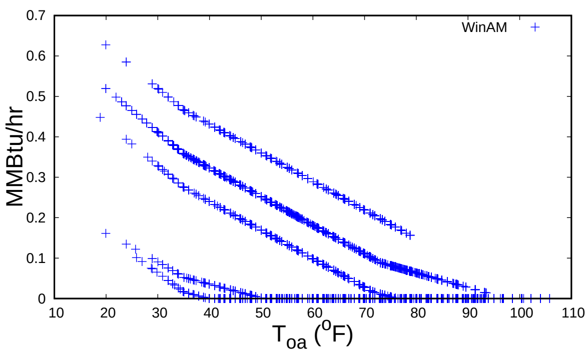


(c) EnergyPlus Cooling Consumption

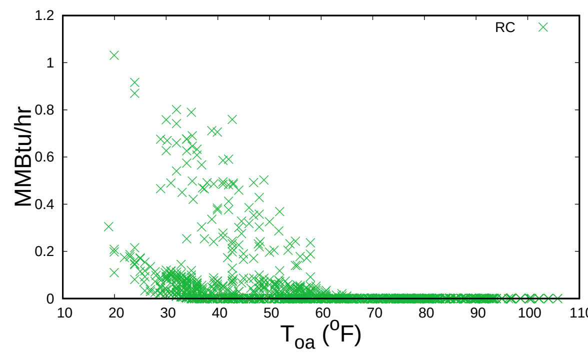


(d) WinAM, RC, and EnergyPlus Cooling Consumption

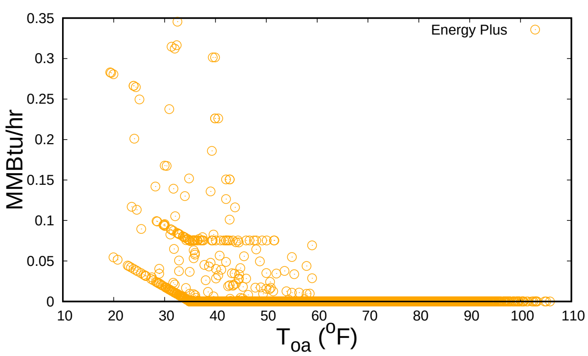
Figure 4.33: Setback & Deadband - Light Mass - Cooling Consumption



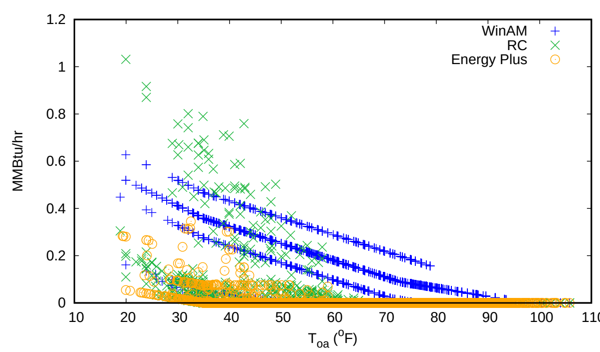
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



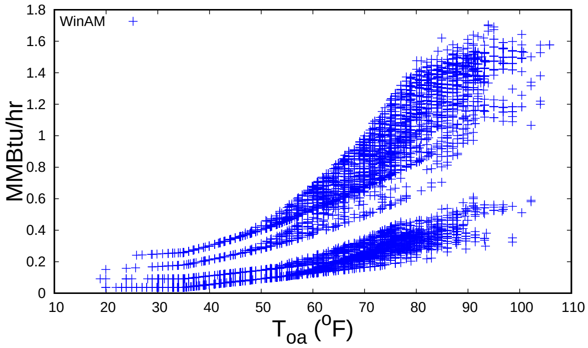
(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.34: Setback & Deadband - Light Mass - Heating Consumption

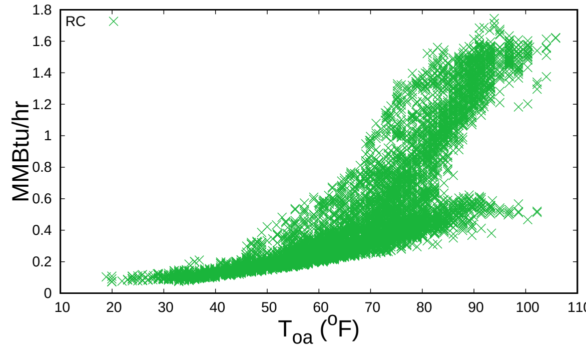
4.9.2 Light Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 5147%. Fifty steps were made, changing fourteen parameters, and no further suggestions were available from the Calibration Assistant, and the model was not considered calibrated. Therefore the protocol was not able to be completed. The resulting Total CV-RMSE after these steps was 21%. The steps are displayed in Appendix **??**. The initial and final result of each parameter changed is displayed below:

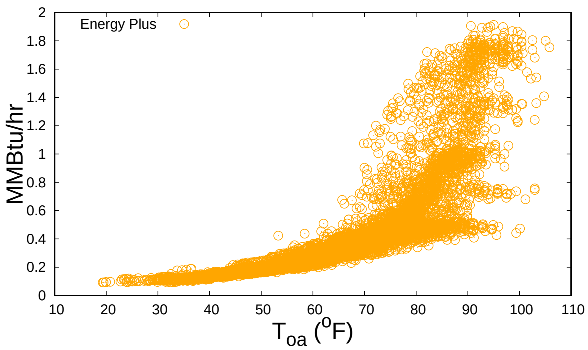
- Conditioned Floor Area from 90000 ft^2 to 52195 ft^2
- Maximum Primary Flow from 1 CFM/ft^2 to 0.98 CFM/ft^2
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.01 CFM/ft^2
- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.00 CFM/ft^2
- Constant Cooling Coil Set Point from 55°F to 73.0°F
- Constant Preheat Coil Set Point from 35°F to 36.2°F
- Peak Occupancy from 150 ft^2/person to 17 ft^2/person
- Night Electric Load Ratio from 0.00 to 0.15
- Interior Zone Percentage from 81% to 68%
- Overall U-Value from 0.07 Btu/$ft^2\cdot$°F·hr to 0.05 Btu/$ft^2\cdot$°F·hr
- Zone Unoccupied Cooling Set Point from 85°F to 109.0°F
- Zone Occupied Cooling Set Point from 76°F to 85.0°F
- Zone Occupied Heating Set Point from 70°F to 64.7°F
- Zone Unoccupied Heating Set Point from 65°F to 64.6°F



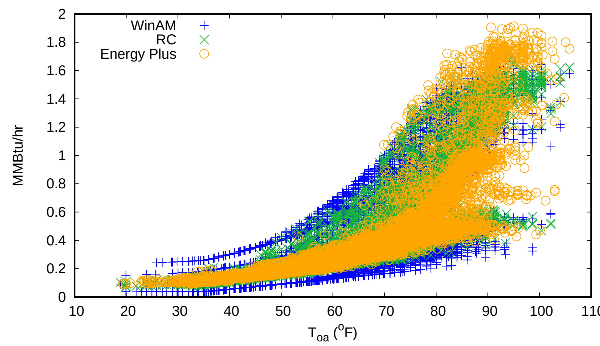
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



(c) EnergyPlus Cooling Consumption

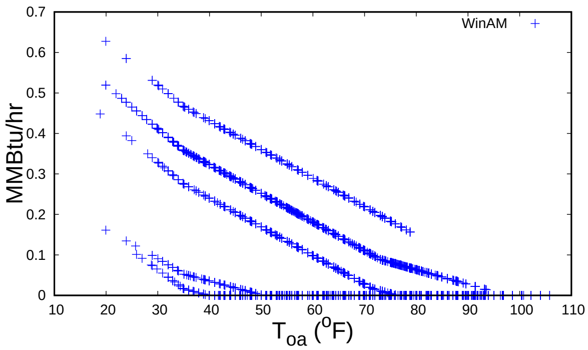


(d) WinAM, RC, and EnergyPlus Cooling Consumption

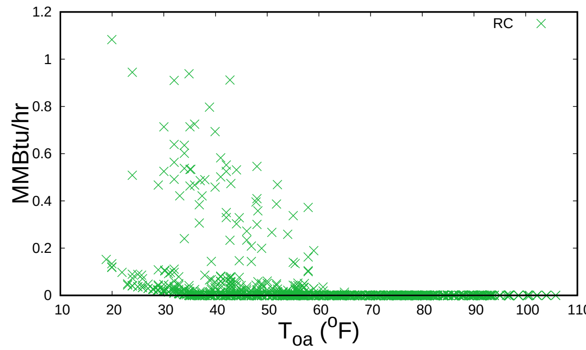
Figure 4.35: Setback & Deadband - Medium Mass - Cooling Consumption

4.9.3 Medium Mass

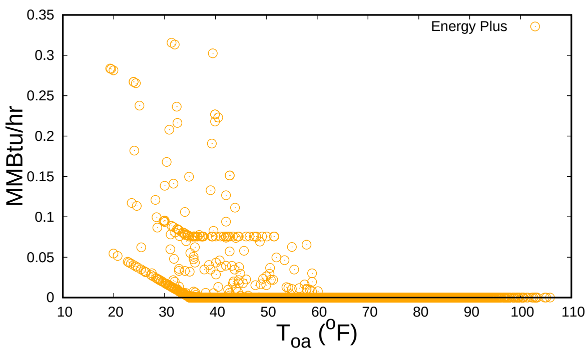
The cooling and heating results are displayed in Figures 4.35 and 4.36. Table 4.16 displays the comparison metrics between simulations.



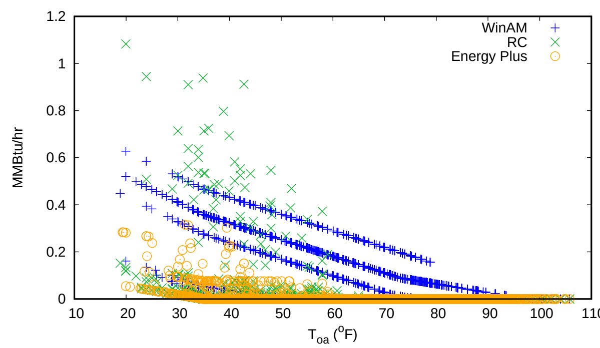
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.36: Setback & Deadband - Medium Mass - Heating Consumption

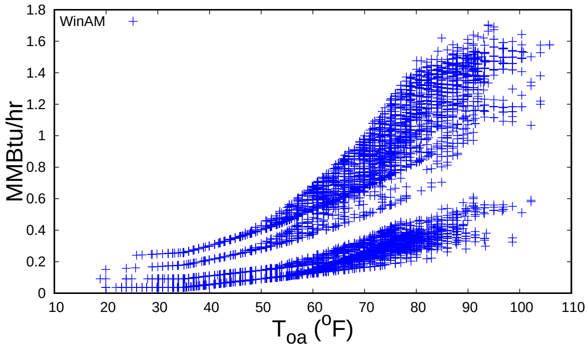
Table 4.16: Comparison between models for Setback & Deadband case - Medium Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4572.46	4150.84	10.16%
Annual Heating (MMBTU)	749.48	37.44	1901.75%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4572.46	3952.45	15.69%
Annual Heating (MMBTU)	749.48	15.53	4724.46%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	3952.45	4150.84	5.02%
Annual Heating (MMBTU)	15.53	37.44	141.01%

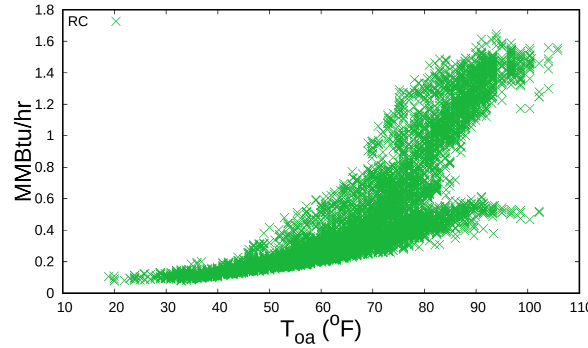
4.9.4 Medium Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 5434%. Fifty-seven steps were made, changing thirteen parameters, and no further suggestions were available from the Calibration Assistant, and the model was not considered calibrated. Therefore, the protocol was not able to be completed. The resulting Total CV-RMSE after these steps was 20%. The steps are displayed in Appendix **??**. The initial and final result of each parameter changed is displayed below:

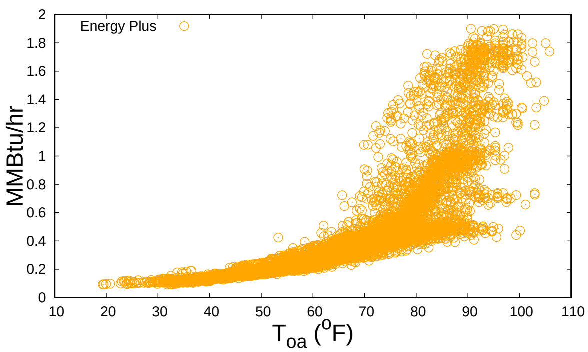
- Conditioned Floor Area from 90000 ft^2 to 48898 ft^2
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.00 CFM/ft^2
- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.00 CFM/ft^2
- Minimum Unoccupied Outside Air from 25% to 7%
- Constant Cooling Coil Set Point from 55°F to 72.9°F
- Peak Occupancy from 150 ft^2/person to 16 ft^2/person
- Night Electric Load Ratio from 0.00 to 0.15
- Static Pressure Set Point from 0 inH_2O to 0.15 inH_2O
- Interior Zone Percentage from 81% to 51%
- Zone Unoccupied Cooling Set Point from 85°F to 106.0°F
- Zone Occupied Cooling Set Point from 76°F to 85.3°F
- Zone Occupied Heating Set Point from 70°F to 61.0°F
- Zone Unoccupied Heating Set Point from 65°F to 60.9°F



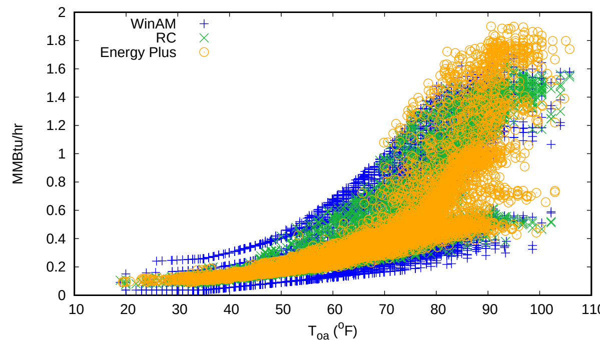
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



(c) EnergyPlus Cooling Consumption

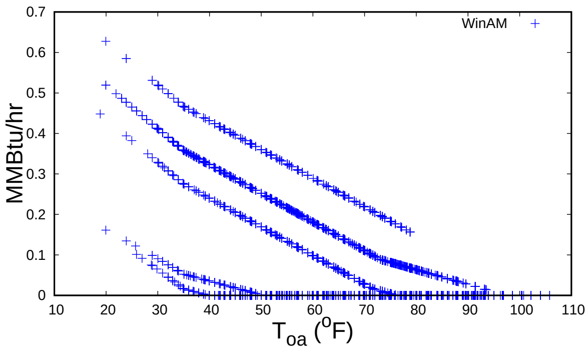


(d) WinAM, RC, and EnergyPlus Cooling Consumption

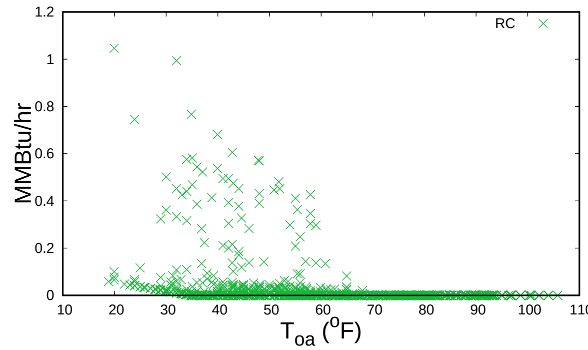
Figure 4.37: Setback & Deadband - Heavy Mass - Cooling Consumption

4.9.5 Heavy Mass

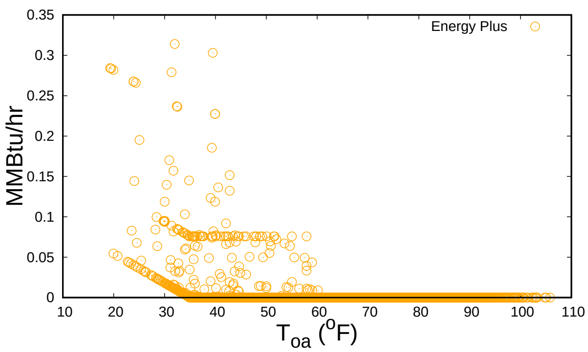
The cooling and heating results are displayed in Figures 4.37 and 4.38. Table 4.17 displays the comparison metrics between simulations.



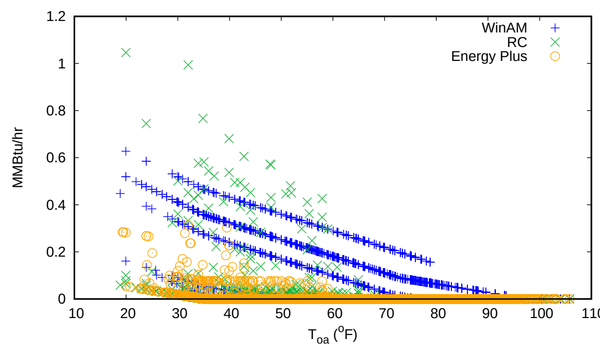
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.38: Setback & Deadband - Heavy Mass - Heating Consumption

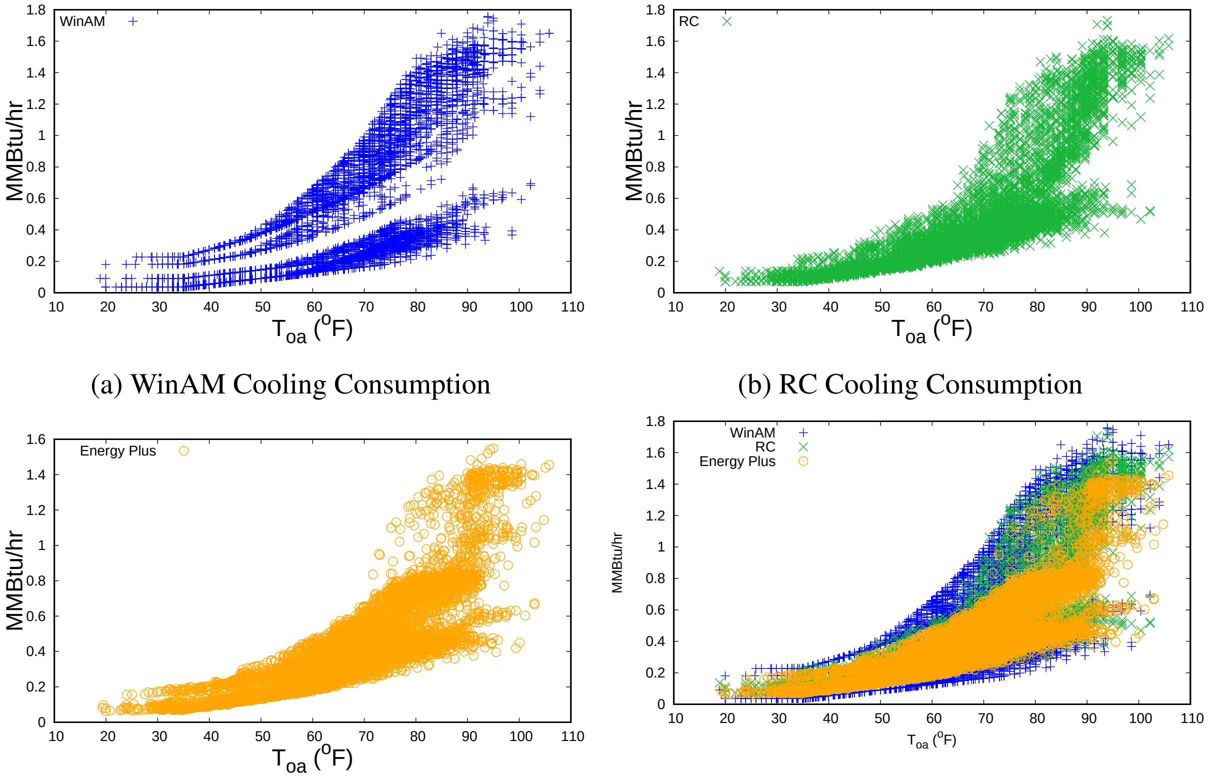
Table 4.17: Comparison between models for Setback & Deadband case - Heavy Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4572.46	4127.58	10.78%
Annual Heating (MMBTU)	749.48	31.52	2277.78%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4572.46	3951.86	15.70%
Annual Heating (MMBTU)	749.48	14.67	5010.16%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	3951.86	4127.58	4.45%
Annual Heating (MMBTU)	14.67	31.52	114.91%

4.9.6 Heavy Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 5765%. Forty-one steps were made, and thirteen parameters changed, and no further suggestions were available from the Calibration Assistant, and the model was not considered calibrated. Therefore, the protocol was not able to be completed. The resulting Total CV-RMSE after these steps was 17%. The steps are displayed in Appendix **??**. The initial and final result of each parameter changed is displayed below:

- Conditioned Floor Area from 90000 ft^2 to 60084 ft^2
- Maximum Primary Flow from 1 CFM/ft^2 to 2.00 CFM/ft^2
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.03 CFM/ft^2
- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.00 CFM/ft^2
- Constant Cooling Coil Set Point from 55°F to 72.7°F
- Constant Preheat Coil Set Point from 35°F to 35.4°F
- Peak Occupancy from 150 ft^2/person to 22 ft^2/person
- Night Electric Load Ratio from 0.00 to 0.15
- Interior Zone Percentage from 81% to 58%
- Overall U-Value from 0.07 Btu/ft^2·°F·hr to 0.05 Btu/ft^2·°F·hr
- Zone Unoccupied Cooling Set Point from 85°F to 100.0°F
- Zone Occupied Cooling Set Point from 76°F to 85.0°F
- Zone Occupied Heating Set Point from 70°F to 65.2°F



(a) WinAM Cooling Consumption

(b) RC Cooling Consumption

(c) EnergyPlus Cooling Consumption

(d) WinAM, RC, and EnergyPlus Cooling Consumption

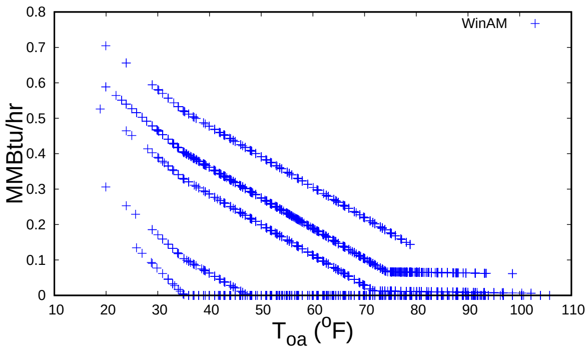
Figure 4.39: 10 Stories - Light Mass - Cooling Consumption

4.10 10 Stories

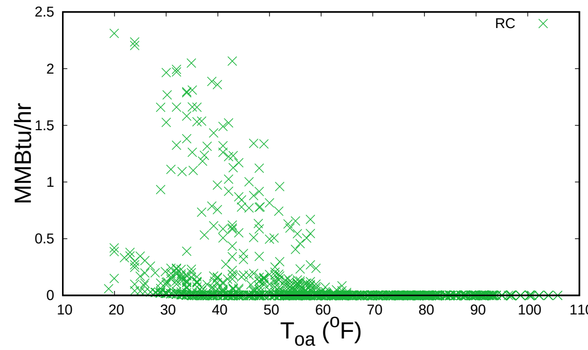
For 10 Stories case, a building of 10 stores is analyzed, with the same system and load properties as Setback & Deadband case, changing only the floor plan for each store (see Appendix C). This case essentially changes the interior/exterior area ratio, while maintaining the same parameters as before. This alteration improves the overall results of the RC model when compared to WinAM, showing its effectiveness for buildings with high external areas.

4.10.1 Light Mass

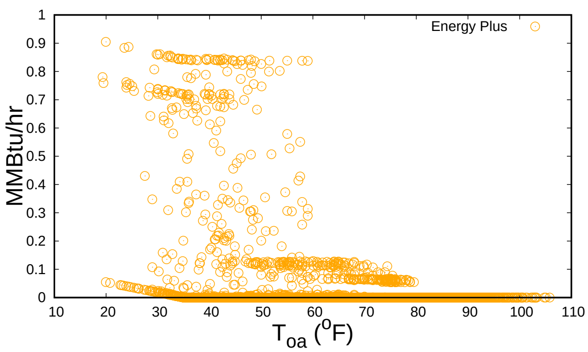
The cooling and heating results are displayed in Figures 4.39 and 4.40. Table 4.18 displays the comparison metrics between simulations.



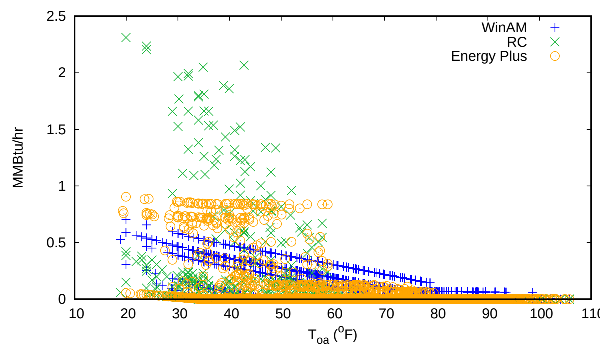
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.40: 10 Stories - Light Mass - Heating Consumption

Table 4.18: Comparison between models for 10 Stories case - Light Mass

Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4597.66	3877.40	18.58%
Annual Heating (MMBTU)	797.55	122.06	553.44%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4597.66	3640.54	26.29%
Annual Heating (MMBTU)	797.55	158.79	402.26%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	3640.54	3877.40	6.51%
Annual Heating (MMBTU)	158.79	122.06	30.10%

4.10.2 Light Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 455%. Six steps were made, changing five parameters, to complete the protocol, resulting a Total CV-RMSE of 14.8%. The steps were:

- Night Electric Load Ratio from 0.00 to 0.30, reducing the Total CV-RMSE from 455% to 58.0%.

- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.08 CFM/ft^2, reducing the Total CV-RMSE from 58.0% to 35.5%.

- Conditioned Floor Area from 90250 ft^2 to 82045 ft^2, reducing the Total CV-RMSE from 35.5% to 25.9%.

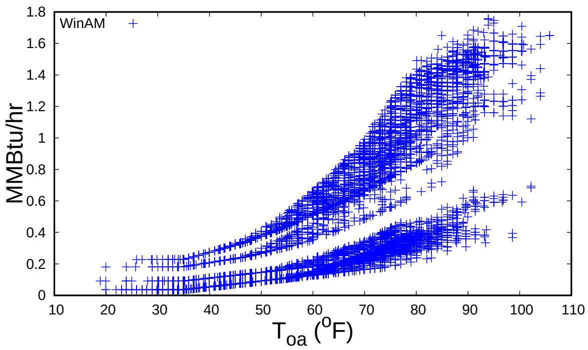
- Zone Occupied Cooling Set Point from 76°F to 79.0°F, reducing the Total CV-RMSE from 25.9% to 20.4%.

- Constant Cooling Coil Set Point from 55°F to 56.2°F, reducing the Total CV-RMSE from 20.4% to 17.1%.

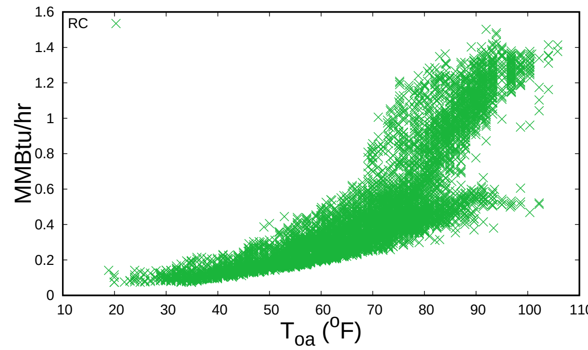
- Zone Occupied Cooling Set Point from 79.0°F to 82.0°F, reducing the Total CV-RMSE from 17.1% to 14.8%.

4.10.3 Medium Mass

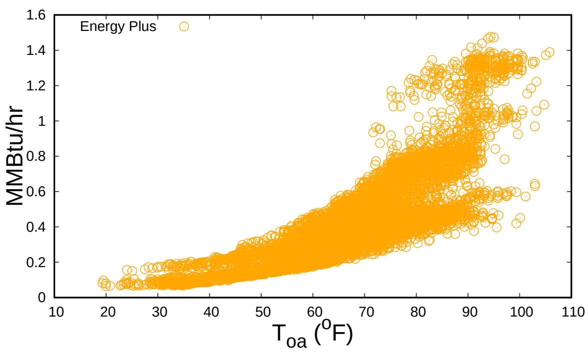
The cooling and heating results are displayed in Figures 4.41 and 4.42. Table 4.19 displays the comparison metrics between simulations.



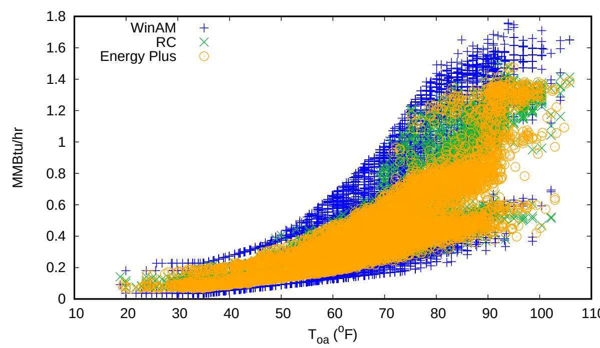
(a) WinAM Cooling Consumption



(b) RC Cooling Consumption



(c) EnergyPlus Cooling Consumption

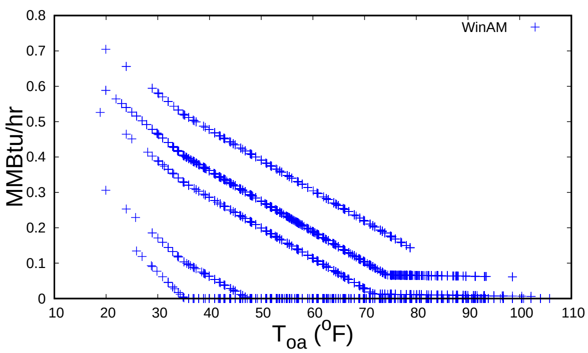


(d) WinAM, RC, and EnergyPlus Cooling Consumption

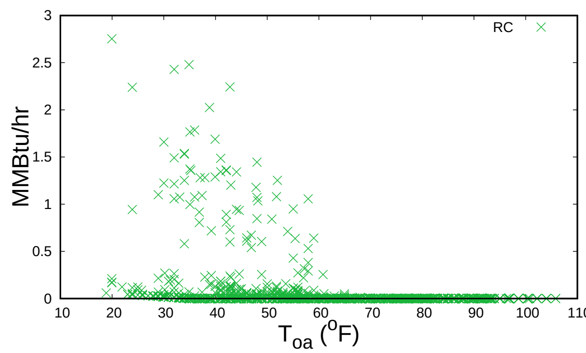
Figure 4.41: 10 Stories - Medium Mass - Cooling Consumption

Table 4.19: Comparison between models for 10 Stories case - Medium Mass

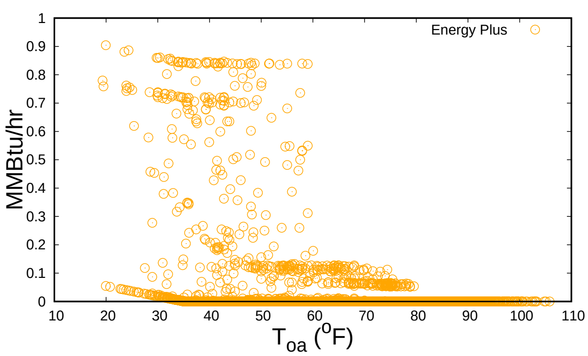
Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4597.66	3798.77	21.03%
Annual Heating (MMBTU)	797.55	181.43	92.25%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4597.66	3633.73	26.53%
Annual Heating (MMBTU)	797.55	154.14	417.44%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	3633.73	3798.77	4.54%
Annual Heating (MMBTU)	154.14	92.25	67.08%



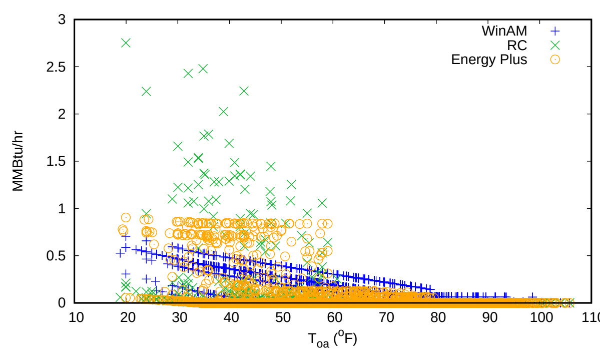
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.42: 10 Stories - Medium Mass - Heating Consumption

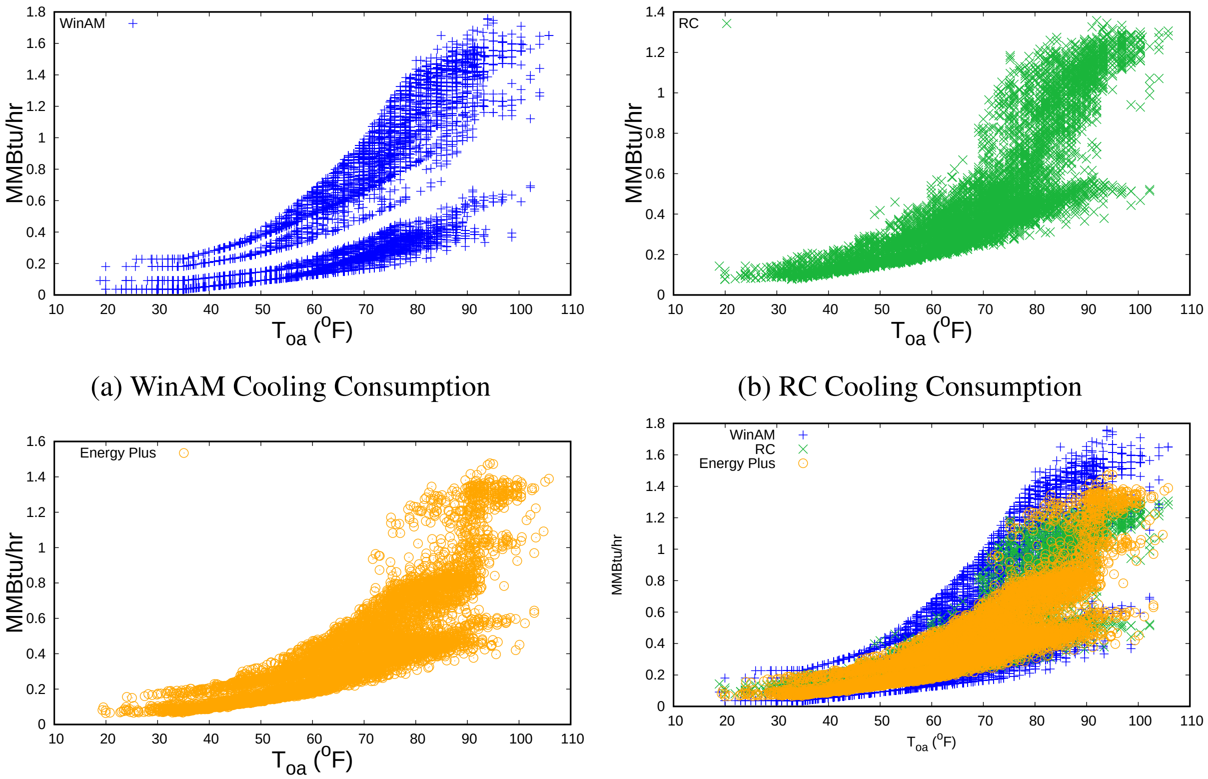
4.10.4 Medium Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 472%. Five steps were made to complete the protocol, resulting a Total CV-RMSE of 16%. The steps were:

- Night Electric Load Ratio from 0.00 to 0.30, reducing the Total CV-RMSE from 472% to 62.1%.
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.08 CFM/ft^2, reducing the Total CV-RMSE from 62.1% to 35.8%.
- Zone Occupied Cooling Set Point from 76°F to 85.0°F, reducing the Total CV-RMSE from 35.8% to 19.2%.
- Conditioned Floor Area from 90250 ft^2 to 86440 ft^2, reducing the Total CV-RMSE from 19.2% to 18.1%.
- Constant Cooling Coil Set Point from 55°F to 56.2°F, reducing the Total CV-RMSE from 18.1% to 15.8%.

4.10.5 Heavy Mass

The cooling and heating results are displayed in Figures 4.43 and 4.44. Table 4.20 displays the comparison metrics between simulations.



(a) WinAM Cooling Consumption

(b) RC Cooling Consumption

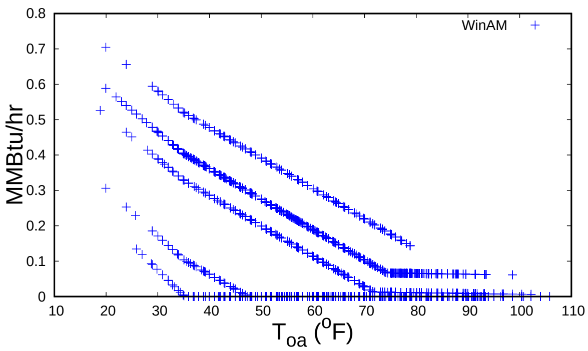
(c) EnergyPlus Cooling Consumption

(d) WinAM, RC, and EnergyPlus Cooling Consumption

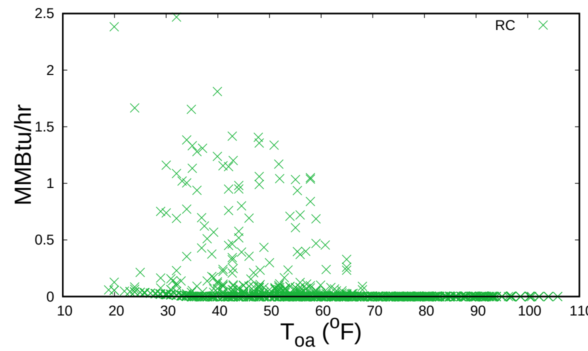
Figure 4.43: 10 Stories - Heavy Mass - Cooling Consumption

Table 4.20: Comparison between models for 10 Stories case - Heavy Mass

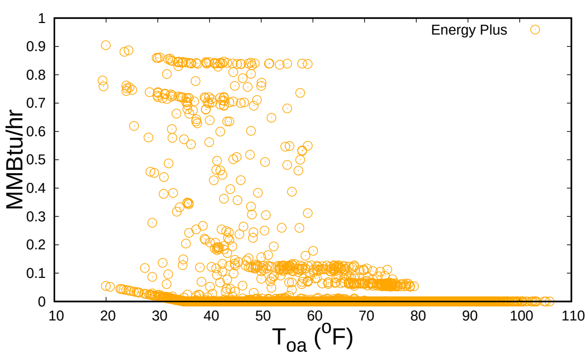
Difference between WinAM and RC			
	WinAM	RC	% Difference
Annual Cooling (MMBTU)	4597.66	3768.06	22.02%
Annual Heating (MMBTU)	797.55	76.24	946.07%
Difference between WinAM and EnergyPlus			
	WinAM	EnergyPlus	% Difference
Annual Cooling (MMBTU)	4597.66	3633.73	26.53%
Annual Heating (MMBTU)	797.55	154.14	417.44%
Difference between EnergyPlus and RC			
	EnergyPlus	RC	% Difference
Annual Cooling (MMBTU)	3633.73	3768.06	3.70%
Annual Heating (MMBTU)	154.14	76.24	102.16%



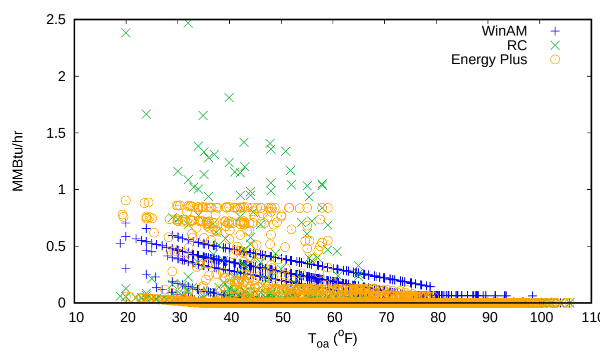
(a) WinAM Heating Consumption



(b) RC Heating Consumption



(c) EnergyPlus Heating Consumption



(d) WinAM, RC, and EnergyPlus Heating Consumption

Figure 4.44: 10 Stories - Heavy Mass - Heating Consumption

4.10.6 Heavy Mass WinAM Calibration

Using WinAM's Calibration Assistant tool, protocol described in Section 3.5 was used to calibrate WinAM's model to EnergyPlus results. Initially, the model was not considered calibrated, with a Total CV-RMSE of 489%. Four steps were made to complete the protocol, resulting a Total CV-RMSE of 15%. The steps were:

- Night Electric Load Ratio from 0.00 to 0.30, reducing the Total CV-RMSE from 489% to 65.9%.
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.05 CFM/ft^2, reducing the Total CV-RMSE from 65.9% to 34.4%.
- Conditioned Floor Area from 90250 ft^2 to 82045 ft^2, reducing the Total CV-RMSE from 34.4% to 22.7%.
- Zone Occupied Cooling Set Point from 76°F to 82.0°F, reducing the Total CV-RMSE from 22.7% to 15.5%.

4.11 6 Climates

For this case, the building with the parameters from Setback & Deadband case, which will be called building type 1, and the building with the parameters from 10 Stories case, which will be called building type 2, is simulated in 6 other weather conditions, for the Light Mass, Medium Mass and Heavy Mass types of constructions. The cities chosen for simulation are: El Paso - TX, Juneau - AK, New York - NY, Las Vegas - NV, Denver - CO, and Chicago - IL. The results for each type of building, for each simulation program, for each city, is presented in Appendix F.

Tables 4.21 and 4.22 presents the results for the highest differences between each pair of programs used, for each type of construction, for each type of building geometry.

Notice that the highest differences in heating consumption between models occurs mostly in hot weathers, and the highest differences in cooling consumption occurs mostly in cool weath-

Table 4.21: Type 1 Building Highest Differences

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	18.72%	993.22%	30.65%	4040.95%	13.01%	286.47%
Medium Mass	21.81%	1319.43%	30.72%	4146.21%	9.93%	202.71%
Heavy Mass	22.72%	1388.02%	30.77%	4249.81%	9.25%	192.68%
Highest Percentage and Type of Construction it Occurs						
	22.72%	1388.02%	30.77%	4249.81%	13.01%	286.47%
	Heavy Mass	Heavy Mass	Heavy Mass	Heavy Mass	Light Mass	Light Mass
City Where the Highest Percentage Occur						
	Juneau	Las Vegas	Juneau	El Paso	Denver	El Paso

Table 4.22: Type 2 Building Highest Differences

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	21.56%	436.36%	36.37%	420.24%	12.19%	22.71%
Medium Mass	24.44%	531.78%	36.77%	437.43%	9.91%	36.43%
Heavy Mass	25.34%	574.42%	36.82%	445.71%	9.16%	43.42%
Highest Percentage and Type of Construction it Occurs						
	25.34%	574.42%	36.82%	445.71%	12.19%	43.42%
	Heavy Mass	Heavy Mass	Heavy Mass	Heavy Mass	Light Mass	Heavy Mass
City Where the Highest Percentage Occur						
	Denver	Las Vegas	Denver	El Paso	Denver	Las Vegas

ers. This is reflective of the low quantity that is necessary for heating and cooling in the weather conditions described, yielding a higher percentage difference.

It is also noticeable that the RC model present lower percentage differences with EnergyPlus in all cases when compared to WinAM's percentage differences with EnergyPlus, as shown in more details in Appendix F. The extreme case being a 4250% difference between WinAM's and EnergyPlus results, for heating consumption in El Paso, for a Heavy Mass construction building. In contrast, the highest difference between EnergyPlus and the RC model occurs for heating consumption in a Light Mass construction building in El Paso.

5. SIMULATION CASES SAVINGS FOR TEMPERATURE SETBACK AND TEMPERATURE DEADBAND

Internal Load Variation, Temperature Setback, and Temperature Deadband cases were runned for all models, for all types of constructions (light mass, medium mass, and high mass), and for all climates from 6 Climates, as well as College Station, TX. The savings generated from a night-time temperature setback, from Internal Load Variation case to Temperature Setback case, and the savings generated from a temperature deadband, from Internal Load Variation case to Temperature Deadband case, are analyzed as follows.

5.1 Highest Savings From Temperature Setback and Temperature Deadband

Tables 5.1, 5.2, 5.3, and 5.4 describes the highest savings achieved by the different models for percentage consumption savings and energy consumption savings. They also display the cities in which these occur, and what type of construction. Appendix G displays all consumption savings, for all cities.

Table 5.1: Highest Percentage Savings From Night-time Temperature Setback

	WinAM	RC	EnergyPlus
Cooling	17.11%	5.81%	2.40%
Construction		Light Mass	Light Mass
City	Juneau	Juneau	Juneau
Heating	47.01%	35.19%	6.42%
Contruction		Light Mass	Light Mass
City	College Station	Las Vegas	El Paso

Table 5.2: Highest Percentage Savings From Temperature Deadband

	WinAM	RC	EnergyPlus
Cooling	12.16%	38.69%	44.89%
Construction		Heavy Mass	Light Mass
City	Juneau	Juneau	Juneau
Heating	31.14%	95.58%	99.05%
Contruction		Heavy Mass	Heavy Mass
City	College Station	College Station	College Station

Table 5.3: Highest Consumption Savings From Night-time Temperature Setback

	WinAM	RC	EnergyPlus
Cooling	399	149	123
Construction		Light Mass	Light Mass
City	Juneau	Juneau	College Station
Heating	790	819	125
Contruction		Light Mass	Light Mass
City	Juneau	Juneau	Juneau

Table 5.4: Highest Consumption Savings From Temperature Deadband

	WinAM	RC	EnergyPlus
Cooling	348	1565	1801
Construction		Light Mass	Light Mass
City	College Station	College Station	College Station
Heating	583	1803	1888
Contruction		Heavy Mass	Light Mass
City	Juneau	Juneau	Juneau

5.2 Temperature Setback Savings

For the temperature setback savings, there is only one case in which the results of the RC model is worse than the WinAM model, when compared to EnergyPlus for this EEM. That is the predicting of heating savings for a Light Mass Building, in Juneau. All other cases the RC model has reached more approximate results to EnergyPlus. Results could be improved if the interior/exterior area ratio is decreased, as seen in 6 Climates, from the previous chapter. A bar plot of energy generated savings is displayed in figures 5.1 and 5.2 for cooling and heating consumption respectively.

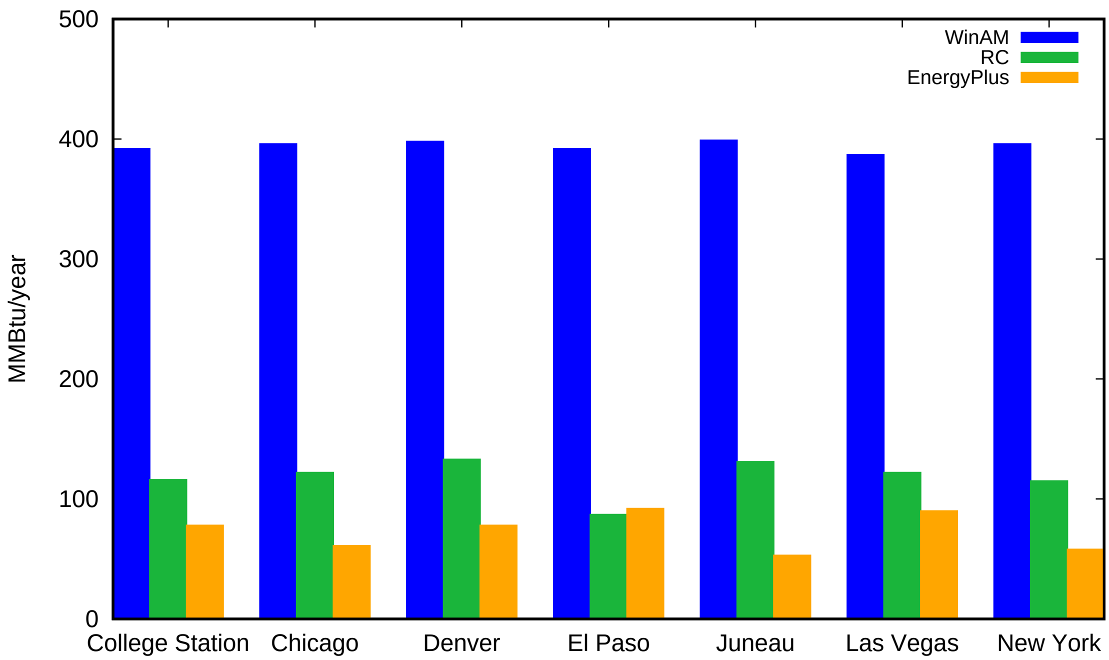


Figure 5.1: Annual Cooling Coil Savings for Medium Mass Building of 90,000 ft^2 for Temperature Setback

In general, WinAM over predict savings when compared to EnergyPlus, mainly due to not considering the large amount of heating or cooling necessary in the hours of changing the temperature set point to occupied hours, due to the building's mass. Take the case of the savings in heating consumption on Juneau for temperature setback. While WinAM is predicting 790 MMBtu of annual

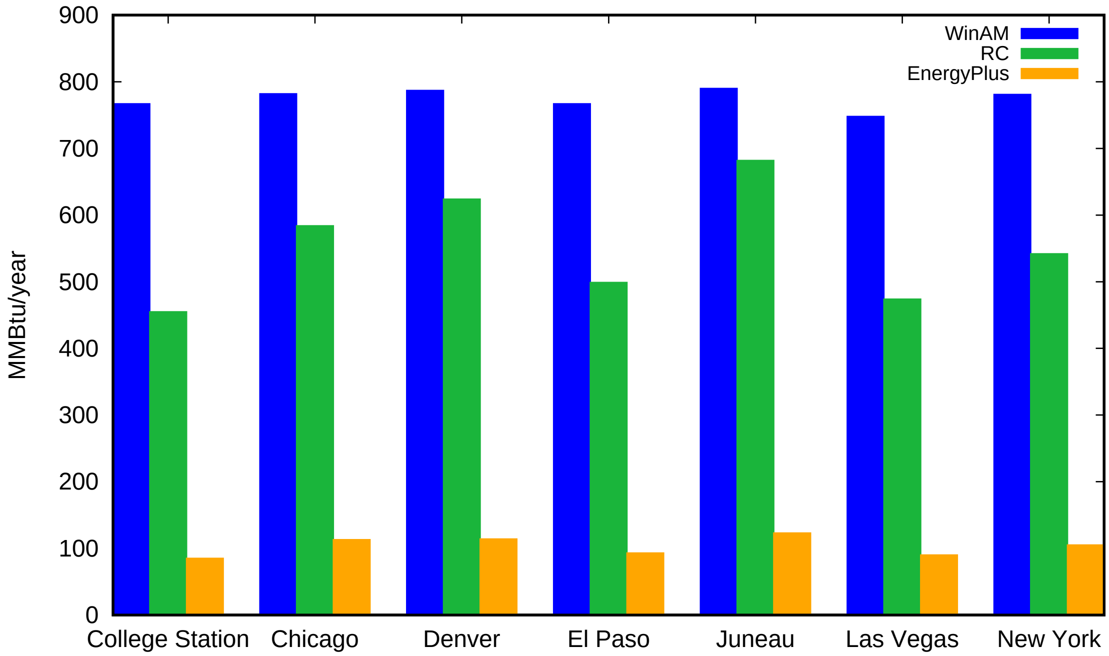


Figure 5.2: Annual Heating Coil Savings for Medium Mass Building of 90,000 ft^2 for Temperature Setback

heating savings, EnergyPlus is predicting only 125 MMBtu of savings, less then 1/5 of WinAM. This would be a difference of 665 MMBtu of heating, making it a $3325.00 difference in a 90000 ft^2 building, considering a price of $5.00 per MMBtu of heating.

5.3 Temperature Deadband Savings

For the Temperature deadband savings, the generated savings from WinAM is considerably lower than the ones predicted from RC and EnergyPlus, mainly due to the calculation that occurs in WinAM, always considering that the zone's temperature is either at the heating set point, or the cooling set point, and will increase the heating or cooling accordingly. This is not the case for the RC and EnergyPlus models, where there are hours in which the zone's temperature fluctuates in the deadband temperature range, operating at minimum flow, with no additional heating or cooling. As an example, for Juneau, as WinAM predicts 583 MMBtu of heating savings, both EnergyPlus and the RC model predicts over 1800 MMBtu's of savings for a heavy mass building, more then 3 times of WinAM's predictions. This case represents a difference of 1305 MMBtu of cooling, when compared to the Light Mass EnergyPlus model, making it a $13,050.00 difference in a 90,000 ft^2 building, considering a price of $10.00 per MMBtu of cooling. A bar plot of energy generated savings is displayed in figures 5.3 and 5.4 for cooling and heating consumption respectively.

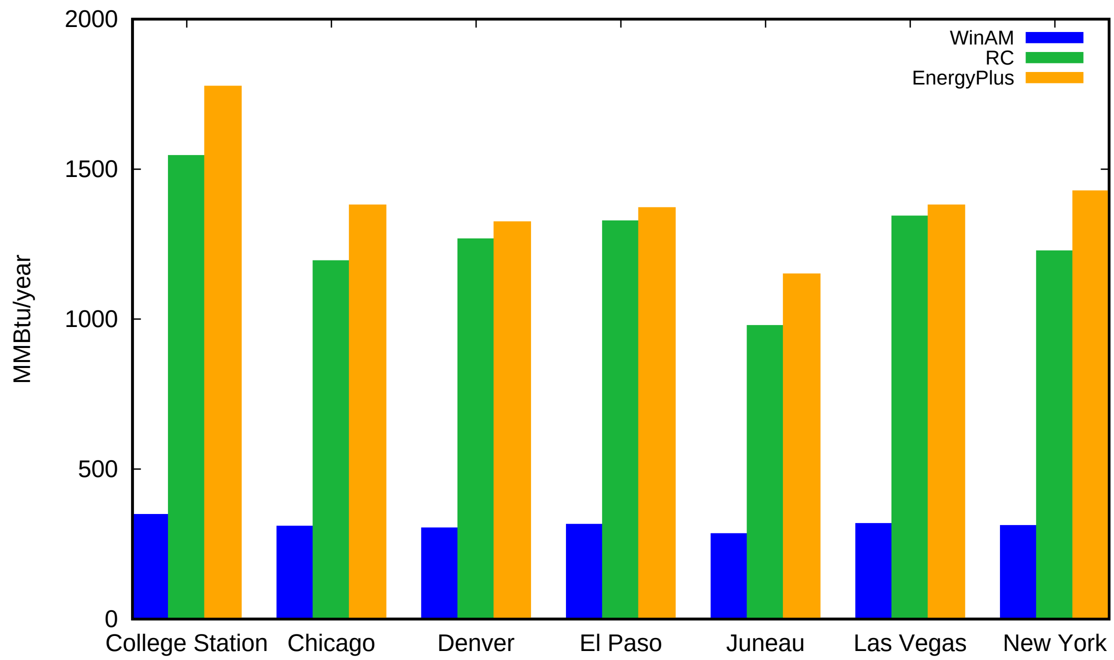


Figure 5.3: Annual Cooling Coil Savings for Medium Mass Building of 90,000 ft^2 for Temperature Deadband

For the cities of El Paso, the RC model is over predicting savings in heating consumption for all construction types, but not in terms of percentage of consumption reduction, since the initial model (Internal Load Variation) have different consumptions, and the difference does not go beyond 55 MMBtu in a total of energy savings of 1528 MMBtu.

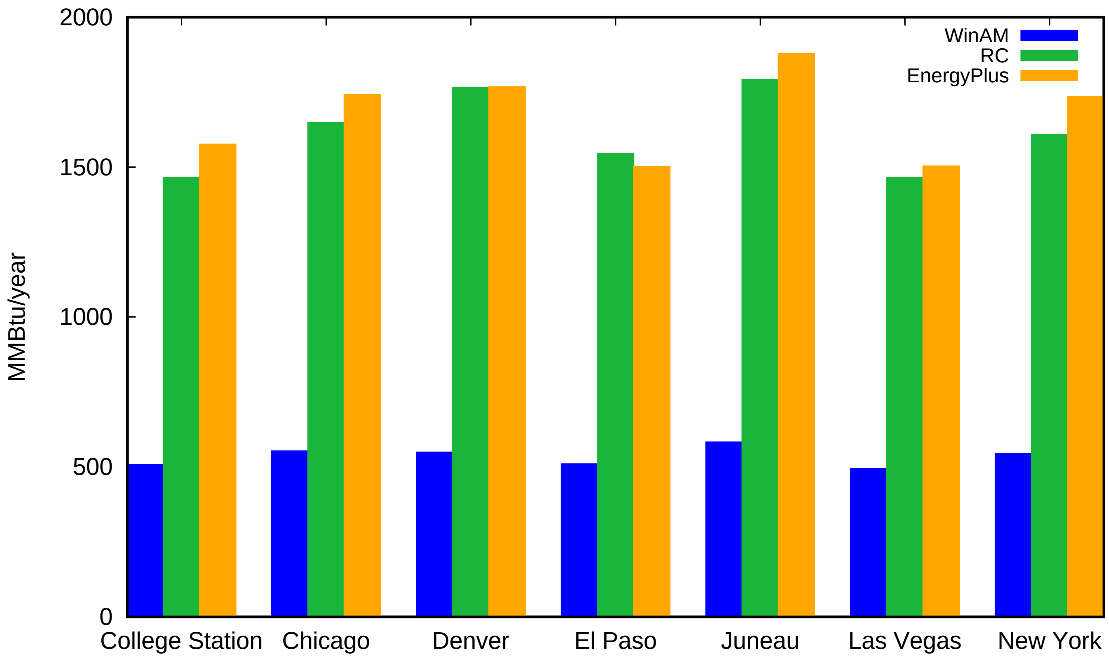


Figure 5.4: Annual Heating Coil Savings for Medium Mass Building of 90,000 ft^2 for Temperature Deadband

6. CASE STUDY: NEW YORK VETERANS ASSOCIATION OUTPATIENT CLINIC

The Outpatient Clinic is a 3-story building with 156,500 ft^2, in which 133,000 ft^2 is conditioned. The building was built in year 2000 and is primarily used for clinic and support space, incorporating spaces for police, pharmacy and offices. It is located at 800 Poly Place, Brooklyn, NY 11209. It is shown as Building 15 on the map of the Brooklyn Veterans Administration Medical Center, shown in Figure 6.1.

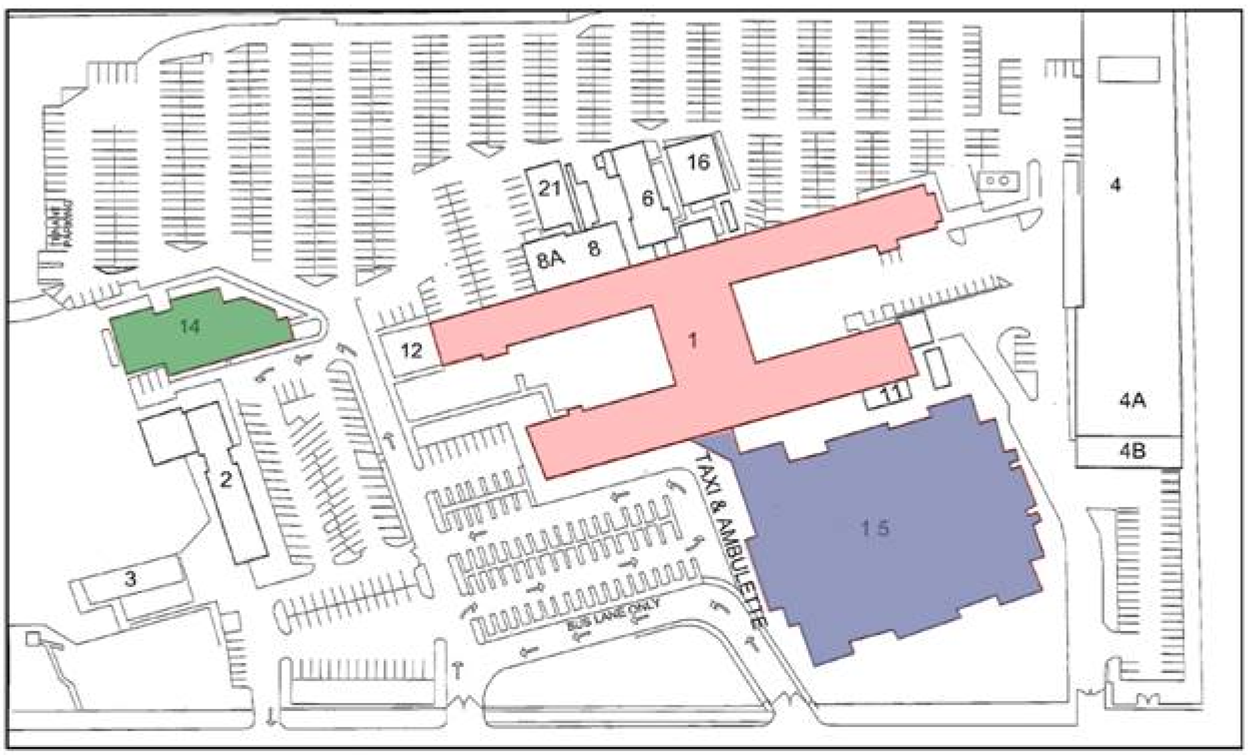


Figure 6.1: Brooklyn Veterans Administration Medical Center

The space breakdown is displayed in Table 6.1.

Table 6.1: Space Usages

Floor	Space Function
Basement	Pharmacy
	File Room
	Building Management Service
	Electrical and Mechanical rooms
First Floor	Ambulatory Care Clinics
Second Floor	Cystoscopy
	Procedures Room
	Eye Clinic
	Ambulatory Care Clinic

6.1 HVAC Systems and Plant

The building is served by 12 AHUs. The model created simulated eight AHUs where similar AHUs were combined into a single AHU. There are two types of AHUs present in the building:

1. Single Duct Variable Air Volume (SDVAV) with reheat.
2. Single Duct Constant Air Volume (SDCAV) with 100% outside air.

The area each AHU serves, as well as the modelled occupancy schedule is described in Table 6.2. Each AHU was modelled to operate 24 hours a day, seven days per week. For EnergyPlus and RC models, the exterior zones were further divided, in order to capture solar effects according to each orientation.

A ramp up and ramp down of 1 hour was simulated for the occupancy during its period. Figure 6.2 displays the occupancy for AHU 15-AC-3 as an example. The electrical/equipment loads were modelled following the same schedule for the occupancy, except 15% of its peak load remained on during unoccupied hours, as exemplified in Figure 6.3.

The preheat set point is 49°F. The cooling coil set point if 55°F. For the zone temperature, a constant set point of 72°F is used.

The electric/lighting peak load is 3 W/ft^2, and the peak occupancy is 250 ft^2/person.

Table 6.2: System's Description

AHU	Type	Conditioned Area (ft^2)	Interior Zone (%)	Window + Wall Area (ft^2)	Window Percentage (%)	Roof Area (ft^2)	Occupancy Schedule
15-AC-1A	SDVAV	15,568	100	0	0	0	6 AM to 6 PM on weekdays
15-AC-1B	SDCAV	4,597	100	0	0	0	7 AM to 5 PM on weekdays
15-AC-2	SDCAV	12,366	62	5115	30	0	24 hours per day, 7 days a week
15-AC-3	SDCAV	12,684	86	1970	30	0	6 AM to 6 PM on weekdays
15-AC-4	SDCAV	12,366	80	2585	30	0	6 AM to 6 PM on weekdays
15-AC-5	SDCAV	24,733	62	10230	10	24733	7 AM to 6 PM on weekdays
15-AC-6	SDCAV	24,733	86	3930	10	24733	7 AM to 6 PM on weekdays
15-AC-7	SDCAV	24,733	80	5170	10	24733	7 AM to 6 PM on weekdays

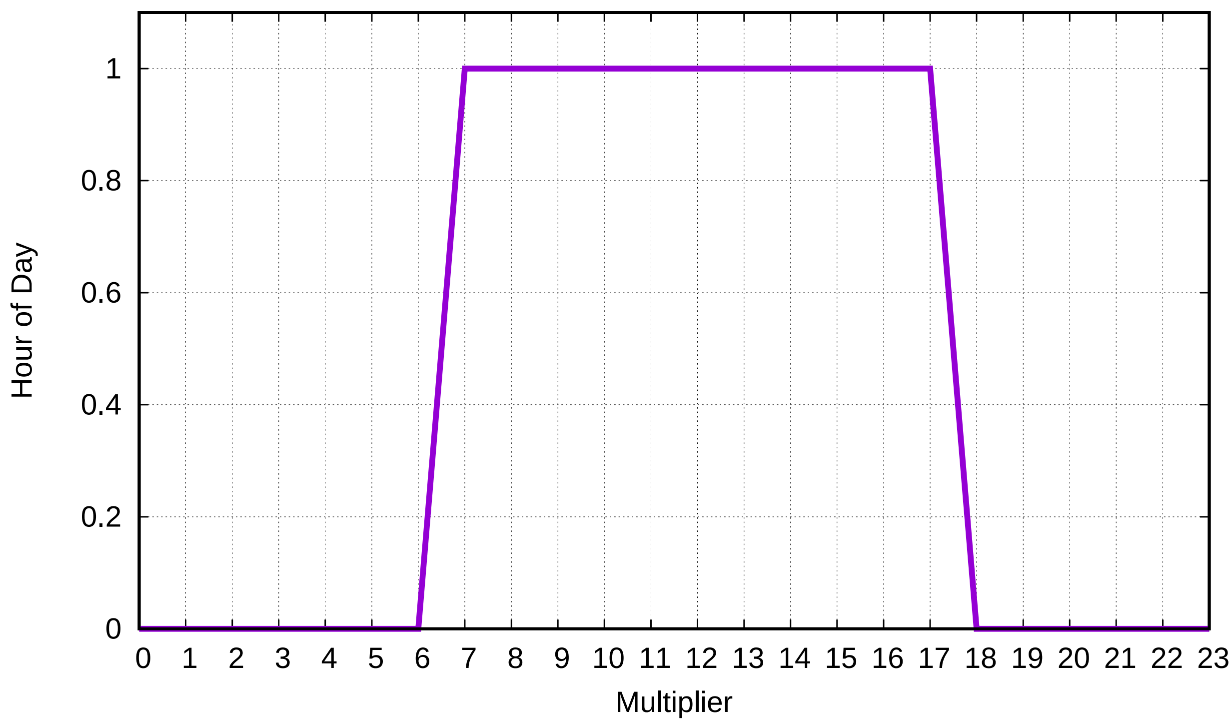


Figure 6.2: Occupancy Schedule Multiplier for AHU 15-AC-3

The building's mass is assumed to have walls and floors the same as the "Medium Mass" construction materials used in simulations, for the RC and EnergyPlus models. The plant consists of two chillers with nominal capacities of 900 tons each, with full-load efficiencies of 0.6 kW/ton each, and 1 boiler of nominal capacity of 32,000 kBtu/hr, with full-load efficiency of 71%.

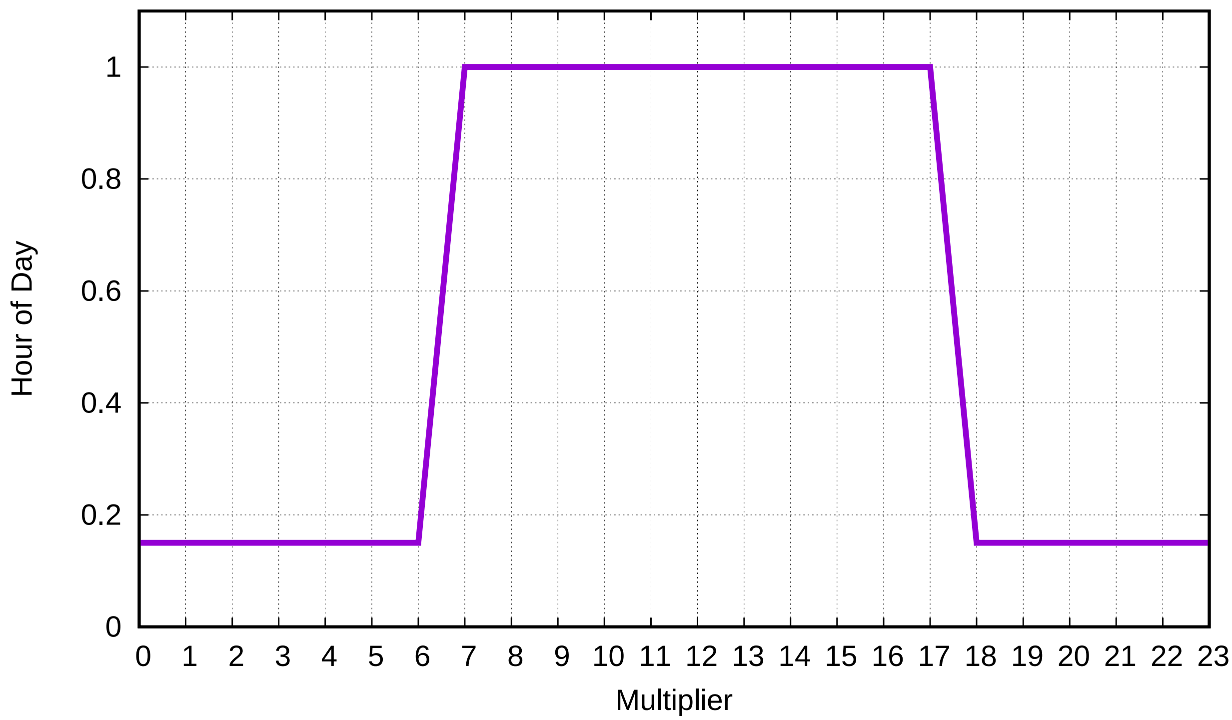


Figure 6.3: Electrical Equipment and Lighting Schedule Multiplier for AHU 15-AC-3

6.2 First Simulation Comparison

Initially, the heating and cooling results were as displayed in Figures 6.4 and 6.5. The annual cooling and annual heating are similar, as displayed in Table 6.3.

Table 6.3: Annual Uncalibrated Cooling and Heating Consumption

	Annual Cooling (MMBtu)	Annual Heating (MMBtu)
WinAM	18,461	25,219
RC	18,458	25,360
EnergyPlus	19,454	24,993

The consumption data was given for each billing period, according to Tables 6.4 and 6.5.

The COP for the Chiller is initially assumed as 0.6 kW/ton, or 5.86 kW of cooling per electrical kW. The boiler efficiency is initially assumed as 71%. These assumptions are made based on the

Table 6.4: Outpatient Clinic Electric Consumption

Start Date (inclusive)	End Date (exclusive)	kWh
9/13/2016	10/13/2016	418767
10/13/2016	11/10/2016	325942
11/10/2016	12/14/2016	266120
12/14/2016	1/13/2017	266739
1/13/2017	2/14/2017	385859
2/14/2017	3/16/2017	275176
3/16/2017	4/14/2017	220560
4/14/2017	5/12/2017	235173
5/12/2017	6/13/2017	407945
6/13/2017	7/13/2017	695493
7/13/2017	8/11/2017	802640
8/11/2017	9/12/2017	714556

Table 6.5: Outpatient Clinic Natural Gas Consumption

Start Date (inclusive)	End Date (exclusive)	MMBtu
9/26/2016	10/25/2016	1596
10/25/2016	11/23/2016	2537
11/23/2016	12/23/2016	3585
12/23/2016	1/25/2017	4363
1/25/2017	2/23/2017	3589
2/23/2017	3/27/2017	4446
3/27/2017	4/26/2017	2470
4/26/2017	5/25/2017	1415
5/25/2017	6/26/2017	1338
6/26/2017	7/26/2017	1106
7/26/2017	8/25/2017	1134
8/25/2017	9/25/2017	1235

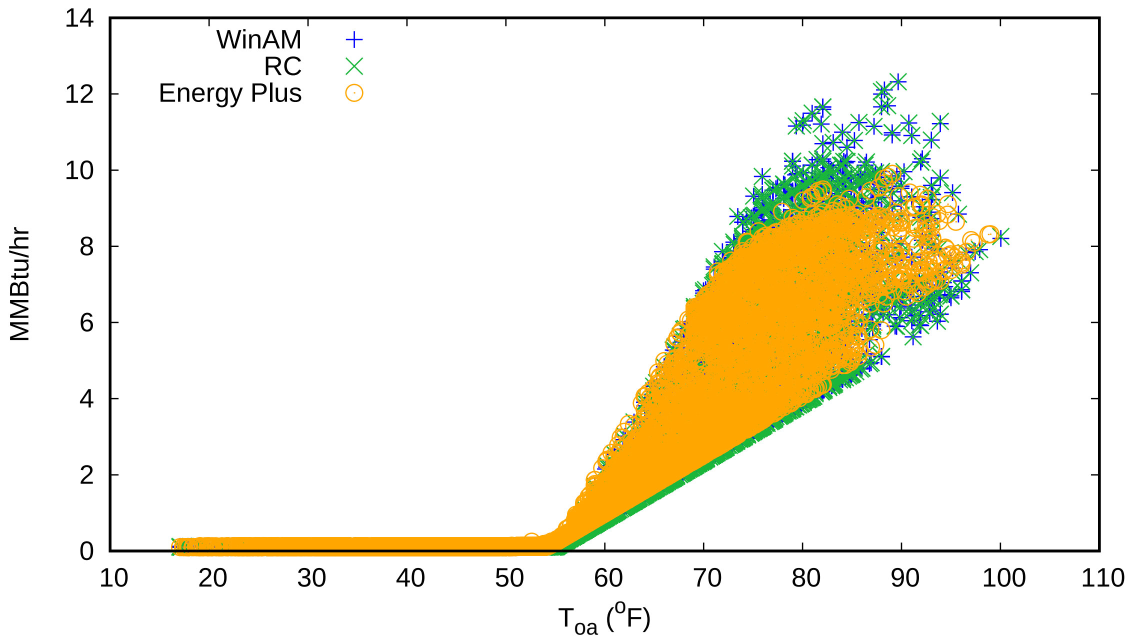


Figure 6.4: Outpatient Clinic Simulated Cooling Consumption

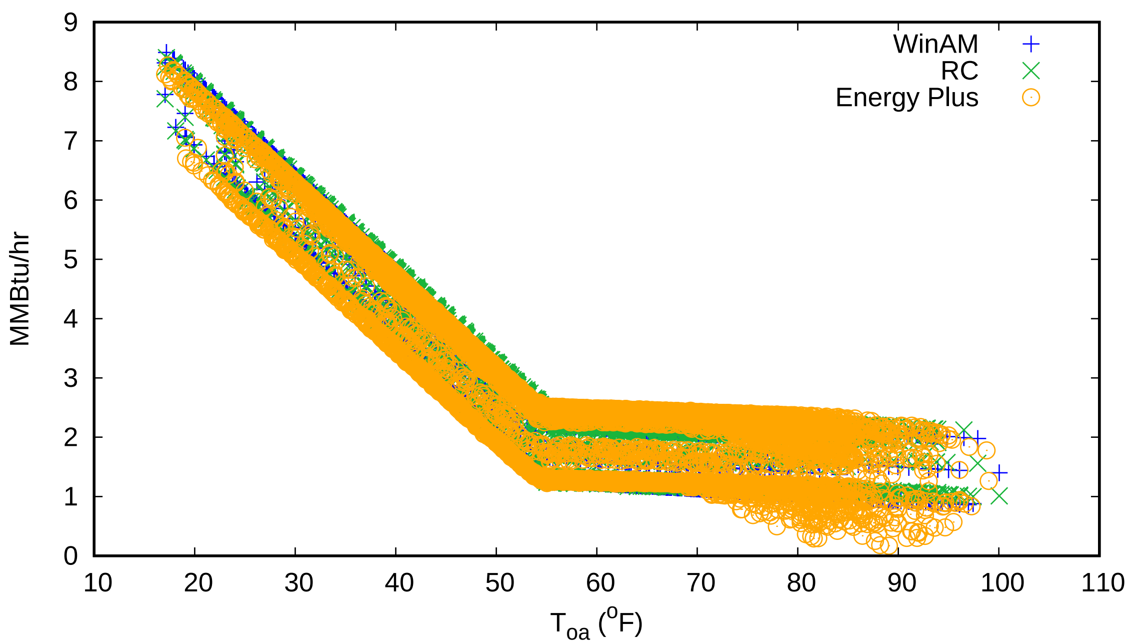


Figure 6.5: Outpatient Clinic Simulated Heating Consumption

Table 6.6: Uncalibrated Annual Energy Consumption

Model	Electricity (kWh)	Natural Gas (MMBtu)
WinAM	3,389,544	35,027
RC	3,308,452	35,659
EnergyPlus	5,528,743	35,598
Measured Data	4,833,505	28,813

CC® staff from their research on the facility. WinAM and EnergyPlus each gives total electric and natural gas consumption outputs.

For the RC model, some assumptions were made in order to calculate the plant and system electrical consumption. It is assumed a constant pump electric consumption of 21.81 kW for the circulation of chilled water and hot water, which is almost a constant observed value in the WinAM output through the year. The system's fan electrical consumption is calculated by $P = \dot{V}\Delta p$, where P is the electrical power, $\dot{V}$ is the air flow, and Δp is the pressure difference across the fan, which is assumed a constant 4 inH_2O for all fans. The cooling tower fan is assumed a constant 18.81 kW, based its average value in the WinAM output.

The initial annual electric and natural gas consumption for each model and the measured data is displayed in table 6.6. The Total CV-RMSE for each model is calculated according to Equations 3.8 and 3.9, and is displayed in Table 6.7, leading to a calibration process.

Table 6.7: Uncalibrated Model's CV-RMSE

Model	Electricity CV-RMSE	Natural Gas CV-RMSE	Total CV-RMSE
WinAM	46%	25%	52%
RC	46%	27%	53%
EnergyPlus	169%	26%	171%

Table 6.8: Calibrated Energy Consumption

Model	Electricity (kWh)	Natural Gas (MMBtu)
WinAM	5,106,665	29,409
RC	4,665,394	29,785
EnergyPlus	5,610,318	29,968
Measured Data	4,833,505	28,813

6.3 Calibration Process

For WinAM, the calibration assistant tool was used, and the protocol described in Section 3.5 was used in order to calibrate its model, with focus on the plant and system parameters alteration suggestions. The calibration steps adopted were: alter the COP of the chiller from 0.6 kW/ton to 1.4 kW/ton (or COP of 2.5), alter the Boiler efficiency from 72% to 82%, and alter the pressure rise across the fan from 2 inH_2O to 4 inH_2O.

For the RC model, in light of the calibration from WinAM, the chiller's COP was changed from 5.86 to 2.23.

For the EnergyPlus model, the calibration required more steps, as follows: Chiller COP was changed from 5.86 to 2.5, the primary pump for the chilled water and for the heating water were changed to have a head of 179 kPa, the boiler efficiency was changed to 82%, and the systems fans changed from having a 0 pressure difference across the fan to 1000 Pa.

After the calibration process was complete, the energy consumption and the Total CV-RMSE for each model gave the results shown in Tables 6.8 and 6.9 respectively. Note that, even though these inputs in EnergyPlus yielded high error values, it was the best possible outcome without using a calibration assistant tool as exists in WinAM. Comparison charts are displayed in Figures 6.6 and 6.7, showing that the models trend similarly to the real consumption.

Table 6.9: Calibrated Model's CV-RMSE

Model	Electricity CV-RMSE	Natural Gas CV-RMSE	Total CV-RMSE
WinAM	14%	13%	19%
RC	15%	15%	21%
EnergyPlus	33%	15%	37%

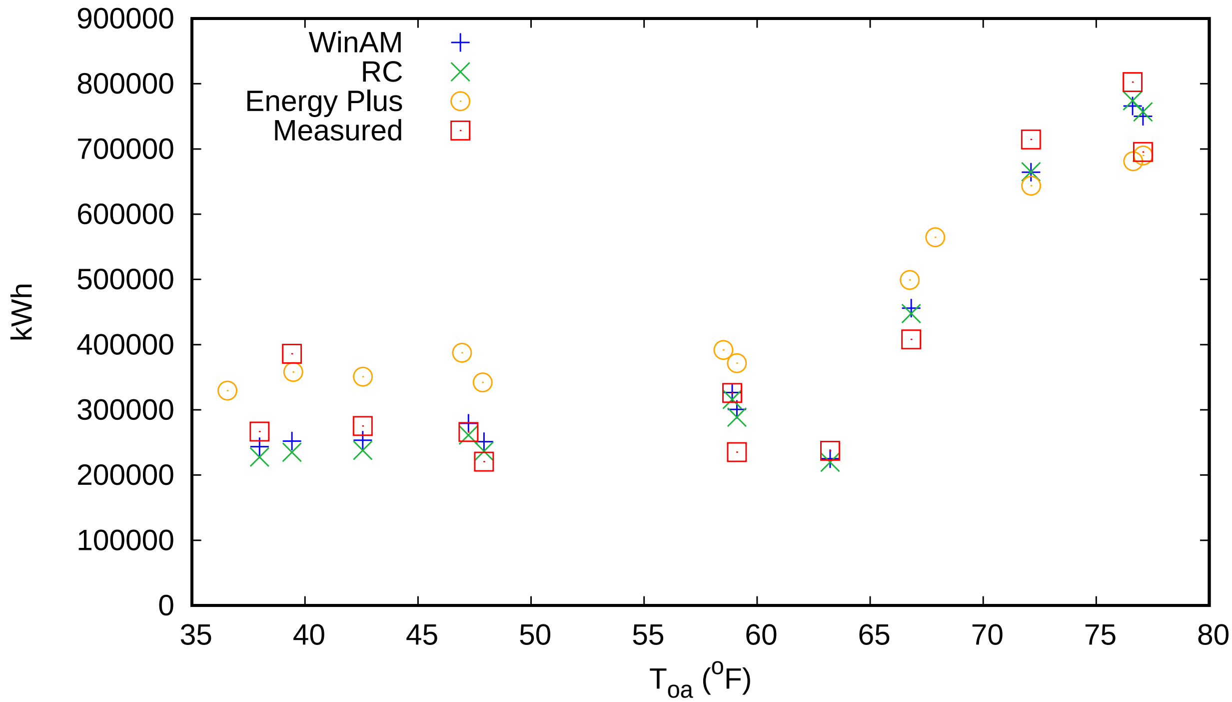


Figure 6.6: Outpatient Clinic Calibrated Monthly Electric Consumption

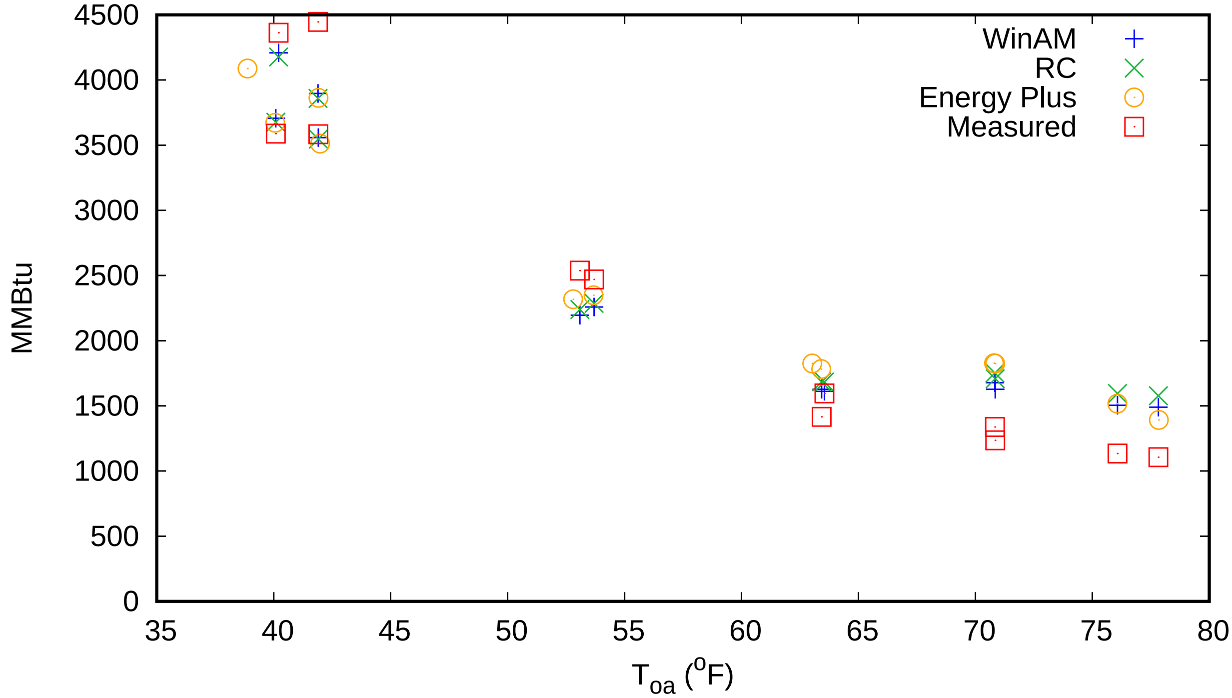


Figure 6.7: Outpatient Clinic Calibrated Monthly Natural Gas Consumption

6.4 EEM's applied to models

Three EEM's were applied to each model, yielding different results for comparison and analysis. Each EEM was applied individually and its energy and dollar savings analyzed, compared to the calibrated model.

6.4.1 First EEM: VFD Retrofit

Each model had each AHU altered to a VAV, allowing it to reduce its flow to 50% of its design flow. Note that this already was possible only for AHU 15-AC-1A, which is unaltered for this EEM. This yielded the energy and dollar savings displayed in Table 6.10.

Table 6.10: Energy Use and Savings Summary for VFD Retrofit

WinAM							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/(ft^2·year)**	**kBtu/(ft^2·year)**
Baseline Model	5,106,665	$510,667	29,409	$147,044	**$657,711**	$4.99	355
Model with VFD Retrofit	3,501,622	$350,162	14,001	$70,005	**$420,167**	$3.19	197
Savings	1,605,043	$160,504	15,408	$77,040	**$237,544**	$1.80	158
	31%		**52%**		**36%**		**45%**
RC							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/(ft^2·year)**	**kBtu/(ft^2·year)**
Model with VFD Retrofit	4,665,394	$466,539	29,785	$148,927	**$615,466**	$4.67	347
Proposed Model	3,443,428	$344,343	12,802	$64,009	**$408,352**	$3.10	186
Savings	1,221,966	$122,197	16,984	$84,918	**$207,115**	$1.57	161
	26%		**57%**		**34%**		**46%**
EnergyPlus							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/(ft^2·year)**	**kBtu/(ft^2·year)**
Baseline Model	5,610,318	$561,032	29,968	$149,841	**$710,873**	$5.39	373
Model with VFD Retrofit	4,485,761	$448,576	13,625	$68,125	**$516,701**	$3.92	220
Savings	1,124,556	$112,456	16,343	$81,716	**$194,171**	$1.47	153
	20%		**55%**		**27%**		**41%**

It is concerning that the RC model is over-estimating natural gas savings from this EEM. However, its total dollar and energy savings more closely approximates EnergyPlus estimated percentage savings.

6.4.2 Second EEM: Temperature Deadband

The heating and cooling set points for each model were changed to 75°F and 70°F respectively. This yielded the energy and dollar savings displayed in Table 6.11.

Table 6.11: Energy Use and Savings Summary for Temperature Deadband

WinAM							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/ft^2·year**	**kBtu/ft^2·year**
Baseline Model	5,106,665	$510,667	29,409	$147,044	**$657,711**	$4.99	355
Model with Deadband	4,912,842	$491,284	27,800	$139,001	**$630,285**	$4.78	338
Savings	193,824	$19,382	1,609	$8,044	**$27,426**	$0.21	17
	4%		**5%**		**4%**		**5%**
RC							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/ft^2·year**	**kBtu/ft^2·year**
Baseline Model	4,665,394	$466,539	29,785	$148,927	**$615,466**	$4.67	347
Model with Deadband	4,639,249	$463,925	25,636	$128,181	**$592,106**	$4.49	315
Savings	26,145	$2,615	4,149	$20,746	**$23,360**	$0.18	32
	1%		**14%**		**4%**		**9%**
EnergyPlus							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/ft^2·year**	**kBtu/ft^2·year**
Baseline Model	5,610,318	$561,032	29,968	$149,841	**$710,873**	$5.39	373
Model with Deadband	5,612,733	$561,273	26,392	$131,960	**$693,233**	$5.26	346
Savings	-2415	-$242	3,576	$17,881	**$17,640**	$0.13	27
	-0.04%		**12%**		**2%**		**7%**

This EEM does not provide substantial savings, due to still having seven SDCAV AHUs. The highest savings in energy consumption is in heating, which the RC and EnergyPlus models present similar results, 14% and 12% respectively, while WinAM under-estimates it with 5% savings. The RC presents an under-estimate of electricity savings that can partially be attributed to its calculation methods to determine electricity from pumps, fans and chiller.

6.4.3 Third EEM: Temperature Setback

A temperature setback was applied for each model. The schedule it followed was always one hour after occupancy hours ended, and the temperature setback ended one hour before occupancy hours started, respectively for each AHU. Note that AHU 15-AC-2 was maintained unaltered for this EEM. For the night-time temperature setback hours, the cooling and heating setpoints were changed to 85°F and 60°F respectively. This yielded the energy and dollar savings displayed in Table 6.12.

Table 6.12: Energy Use and Savings Summary for Temperature Setback

WinAM							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**\$/year**	**MMBtu/year**	**\$/year**	**\$/year**	**\$/(ft^2·year)**	**kBtu/(ft^2·year)**
Baseline Model	5,106,665	\$510,667	29,409	\$147,044	**\$657,711**	\$4.99	355
Model with Setback	5,049,188	\$504,919	20,897	\$104,485	**\$609,404**	\$4.62	289
Savings	57,478	\$5,748	8,512	\$42,559	**\$48,307**	\$0.37	66
	1%		**29%**		**7%**		**19%**
RC							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**\$/year**	**MMBtu/year**	**\$/year**	**\$/year**	**\$/(ft^2·year)**	**kBtu/(ft^2·year)**
Baseline Model	4,665,394	\$466,539	29,785	\$148,927	**\$615,466**	\$4.67	347
Model with Setback	4,665,394	\$466,539	20,757	\$103,787	**\$570,327**	\$4.33	278
Savings	0	\$0	9,028	\$45,140	**\$45,140**	\$0.34	69
	0%		**30%**		**7%**		**20%**
EnergyPlus							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**\$/year**	**MMBtu/year**	**\$/year**	**\$/year**	**\$/(ft^2·year)**	**kBtu/(ft^2·year)**
Baseline Model	5,610,318	\$561,032	29,968	\$149,841	**\$710,873**	\$5.39	373
Model with Setback	5,601,948	\$560,195	20,039	\$100,193	**\$660,388**	\$5.01	297
Savings	8,370	\$837	9,930	\$49,648	**\$50,485**	\$0.38	76
	0%		**33%**		**7%**		**20%**

The savings on electricity consumption is barely present in all models, mainly due to having constant air volume fans, with 100% outside air. The savings for natural gas are similar for all models.

6.5 All EEMs Applied

When all three EEM's are applied, it results in the estimated energy savings presented in table 6.13.

When all EEMs are applied, the estimated savings for all models are similar. RC slighty improved its dollar percentage savings to EnergyPlus estimated savings from the current WinAM model.

Table 6.13: Energy Use and Savings Summary after all EEMs are applied

WinAM							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/(ft^2·year)**	**kBtu/(ft^2·year)**
Baseline Model	5106665	$510,667	29409	$147,044	**$657,711**	$4.99	355
Proposed Model	3402297	$340,230	7163	$35,816	**$376,046**	$2.85	142
Savings	1704368	$170,437	22246	$111,228	**$281,665**	$2.14	213
	33%		**76%**		**43%**		**60%**
RC							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/(ft^2·year)**	**kBtu/(ft^2·year)**
Baseline Model	4665394	$466,539	29785	$148,927	**$615,466**	$4.67	347
Proposed Model	3347513	$334,751	7073	$35,365	**$370,117**	$2.81	140
Savings	1317882	$131,788	22712	$113,562	**$245,350**	$1.86	206
	28%		**76%**		**40%**		**60%**
EnergyPlus							
	Electricity		**Natural Gas**		**Total**	**ECI**	**EUI**
	kWh/year	**$/year**	**MMBtu/year**	**$/year**	**$/year**	**$/(ft^2·year)**	**kBtu/(ft^2·year)**
Baseline Model	5610318	$561,032	29968	$149,841	**$710,873**	$5.39	373
Proposed Model	3905614	$390,561	8656	$43,279	**$433,841**	$3.29	167
Savings	1704704	$170,470	21312	$106,562	**$277,032**	$2.10	206
	30%		**71%**		**39%**		**55%**

7. CONCLUSION AND FUTURE WORK

7.1 Conclusion

From the Simulation Case results, it's important to highlight that the RC model presented improved results compared to WinAM in 53 out of 55 cases, when percentage comparisons are made with EnergyPlus, with the exception of the annual cooling consumptions in *Masses*, and the annual heating consumption in Internal Load Variation, but with less than 2% differences in these cases.

It was also important to capture the "heat effect" in the hour "C" described in Section 3.6.2, that occurs in Temperature Setback and subsequent cases. No mention of this effect was found in the literature review.

From the comparison of energy savings from the simulation cases, notably the WinAM model is generally over predicting savings for temperature setback, and under predicting savings for temperature deadband, especially for annual heating consumption. The extreme cases are of WinAM over predicting savings for temperature setback such as 47% for annual heating consumption, while RC predicts 27% and EnergyPlus only predicts 6%, for the building in College Station, and WinAM under predicting savings for temperature deadband such as 31% for annual heating consumption, while RC predicts 96%, and EnergyPlus predicts 99% savings, for College Station. The RC model presents improvement from the current WinAM model in more than 95% of the estimated savings when compared to EnergyPlus estimated savings, having worsened only for a light mass building in Juneau. Tables 7.1, 7.2, 7.3, and 7.4 present the overall savings comparison for all cases analyzed in the simulation cases.

Table 7.1: Average Cooling and Heating Savings Percentage for Temperature Setback

	WinAM	RC	EnergyPlus
Cooling	11%	3%	2%
Heating	39%	29%	6%

Table 7.2: Average Cooling and Heating Savings Percentage for Temperature Deadband

	WinAM	RC	EnergyPlus
Cooling	9%	32%	35%
Heating	27%	84%	90%

Table 7.3: Average Cost Savings for Temperature Setback

	WinAM	RC	EnergyPlus
Saving	\$7,816	\$4,067	\$1,245

Table 7.4: Average Cost Savings for Temperature Deadband

	WinAM	RC	EnergyPlus
Saving	\$5,797	\$20,807	\$22,439

From the Case Study, the RC displayed a slight improvement in the savings consumption when analyzing the major energy source savings for each EEM. The remainder results are similar. Overall, the RC results that had a considerable improvement for the estimated savings, but rather all models had similar results when all EEMs are applied. This is due to this case not having high mass and solar impacts that could increase the difference between its cases.

The RC model shows effective results, keeping its format simple, with the addition of few parameters when compared to WinAM's current model for the user: the building's orientation θ, the solar factor σ_S, the external wall's capacitance C_w and the building's mass capacitance C_m.

The estimated savings are better approximated with EnergyPlus for the majority of cases presented here, when temperature setback and an increase of the temperature throttling range is presented. This work shows the importance of including these effects in WinAM, which is a program designed to estimate savings from simple measures as mentioned.

7.2 Future Work

From this RC model, further case studies is suggested to analyze the model's weaknesses and strengths, and the ease of estimating the additional parameters when compared to the current WinAM model. A study of different comparison with a different simulation tool besides EnergyPlus is also suggested to compare if the results are consistent with the ones presented here.

A stability analysis for the Equation 3.3 is proposed, since it uses an explicit algorithm, due to fast computation. While it did not present any instabilities for the cases studied in this research, it is important to know for what values of R·C and timesteps it becomes unstable.

It would be of high value to analyze which model has better savings predictions with measured data from post-EEMs applied.

An analysis of difference on other EEMs is also suggested for the RC model, to analyze the impact of thermal mass and solar gains in its energy savings predictions.

An improvement in the model's parameters is also a suggested study, such as the values of R_m, and the solar gains calculation method, in which based on the literature, has many drawbacks[21].

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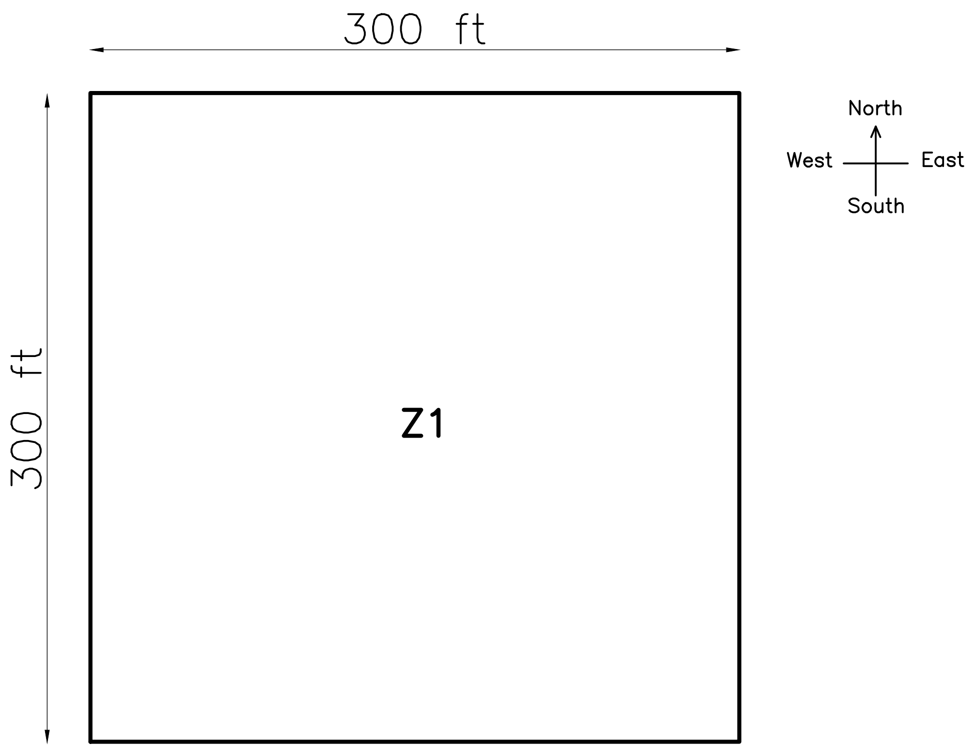
APPENDIX A

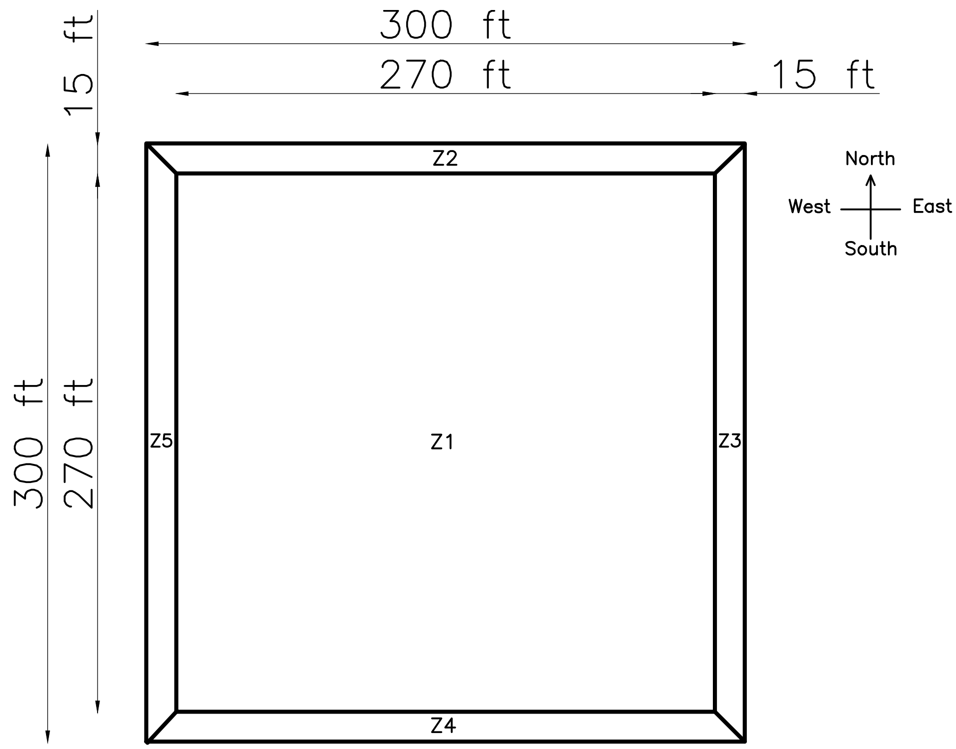
SINGLE ZONE HIGH R FLOOR PLAN



Number of Floors	1
Number of Zones	1
Height of Each Floor	15 ft
Total Floor Area	90000 ft^2

APPENDIX B

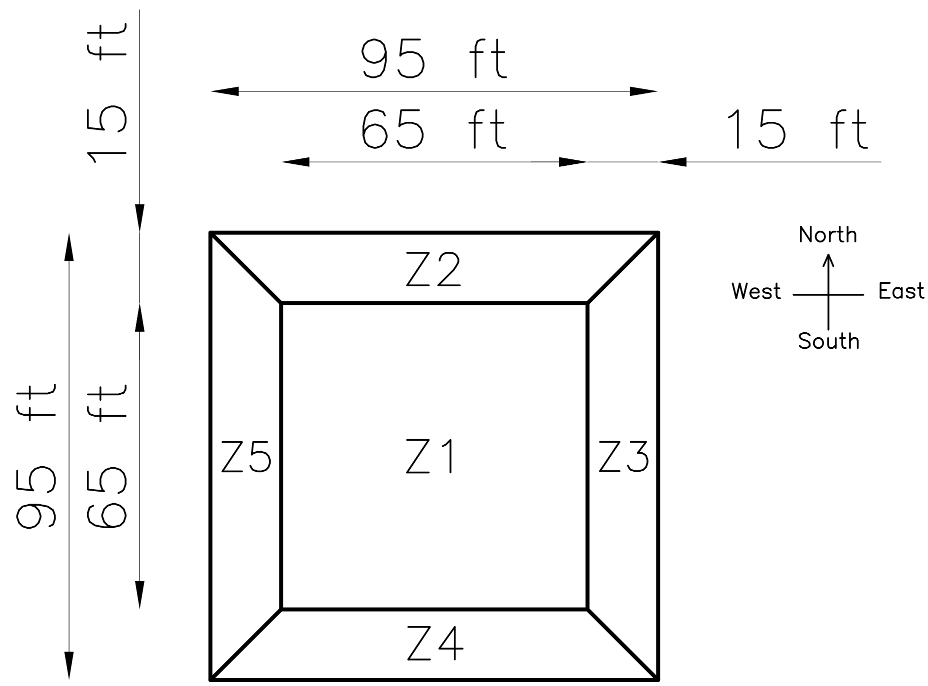
5 ZONES NORMAL R FLOOR PLAN



Number of floors	1
Number of zones per floor	5
Height of each floor	15 ft
Total floor area	90000 ft^2
Interior zone floor area	72900 ft^2
Each exterior zone floor area	4275 ft^2
Interior Zone	Z1
Exterior Zones	Z2, Z3, Z4, Z5

APPENDIX C

10 STORIES FLOOR PLAN



Number of floors	10
Number of zones per floor	5
Height of each floor	15 ft
Total floor area	90250 ft^2
Sum of interior zones floor area	42250 ft^2
Sum of each oriented exterior zone floor area	12000 ft^2
Interior Zone	Z1
Exterior Zones	Z2, Z3, Z4, Z5

APPENDIX D

EXAMPLE OF SOLAR RADIATION CALCULATION FROM ASHRAE'S CLEAR-SKY RADIATION MODEL

For an East Wall Surface at College Station TX, calculate the solar radiation received at 08:00 a.m. (Local Standard Time - LST) on March 6.

Given College Station's location, Latitude (L) = 30.596 N, Longitude (l_{local})= 96.307 W, and l_{st} = 90 W, where l_{st} is the standard time meridian.

For March 6, n = 65 (day of the year).

From these inputs, as well as the reference values from Table 3.1, all the following parameters are calculated: declination angle (δ_S), equation of time (ET), solar time (ST), hour angle (h_s), solar altitude angle (α), solar azimuth angle (a_S), the air mass (m), beam and diffuse air mass exponents (b and d).

$$\delta_s = 23.45^o sin\Big[\frac{360}{365}(284+n)\Big] = 23.45^o sin\Big[\frac{360}{365}(284+65)\Big] = -6.38^o \tag{D.1}$$

$$ET\,(min) = 9.87sin2B - 7.53cosB - 1.5sinB = -12.01\,min \tag{D.2}$$

Where $B = 360(n-81)/364$ degrees = -15.82 degrees.

$$ST = LST + ET + (l_{st} - l_{local})\frac{4min}{degree} = 08:22\,a.m. \tag{D.3}$$

$$h_s = (ST-12)\frac{15^o}{hr} = -54.31^o \tag{D.4}$$

$$sin\alpha = cos\,\delta_s cos\,h_s + sin\,\delta_s sin\,L \tag{D.5}$$

$$sina_s = cos\delta_s sinh_s/cos\alpha \tag{D.6}$$

Yielding $\alpha = 26.27^o$ and $a_s = -64.17^o$.

$$m = \frac{1}{sin\alpha + 0.50572(6.07995 + \alpha)^{-1.6364}} \tag{D.7}$$

Interpolating the values for τ_b and τ_d from Table 3.1, we can calculate b and d.

$$b = 1.219 - 0.043\tau_b - 0.151\tau_d - 0.204\tau_b\tau_d = 0.6867 \tag{D.8}$$

$$d = 0.202 + 0.852\tau_b - 0.007\tau_d - 0.357\tau_b\tau_d = 0.1996 \tag{D.9}$$

Solar radiation (I_c) on a tilted surface is the sum of the direct beam ($I_{b,c}$), sky diffuse ($I_{d,c}$), and ground reflected ($I_{r,c}$) solar radiation, as described in Equation D.10.

$$I_c = I_{b,c} + I_{d,c} + I_{r,c} \tag{D.10}$$

The extraterritorial solar radiation is given by Equation D.11.

$$I = I_O\Big[1 + 0.034cos\Big(\frac{360n}{365.25}\Big)^o\Big] = 1366.1\Big(\frac{360 \times 65}{365.25}\Big)^o\Big] = 1386\,W/m^2 \tag{D.11}$$

Where I_O is the solar constant.

The direct solar radiation component is described in Equation D.12.

$$I_{b,N} = Ie^{-\tau_b m^b} = 729\,W/m^2 \tag{D.12}$$

The diffuse solar radiation in a horizontal surface is described in Equation D.13.

$$I_{d,h} = Ie^{-\tau_d m^d} = 95\,W/m^2 \tag{D.13}$$

The angle of incidence i is defined as in Equation D.14.

$$cos\,i = cos\alpha cos(a_s - a_w)sin\beta + sin\alpha cos\beta \tag{D.14}$$

Yielding $i = 36.18$ degrees for an east surface, where β is the surface inclination (90 degrees).

Thus, the bem radiation is as described in Equation D.15.

$$I_{b,c} = I_{b,N}\, cos\, i = 588.14\, W/m^2 \tag{D.15}$$

The diffuse radiation on the surface is obtained by multiplying the sky diffuse radiation on a horizontal surface by the view factor between sky and surface (Equation D.16).

$$I_{d,c} = I_{d,h}\, cos^2\left(\frac{\beta}{2}\right) = 47.29\, W/m^2 \tag{D.16}$$

Assuming, the surface is surrounded by ordinary ground or grass, then $\rho = 0.2$.

$$I_{r,c} = \rho(I_{b,N}\, sin\alpha + I_{d,h})sin^2\left(\frac{\beta}{2}\right) = 41.70\, W/m^2 \tag{D.17}$$

Therefore, $I_c = I_{b,c} + I_{d,c} + I_{r,c} = 588.14 + 47.29 + 41.270 = 677.13\, W/m^2$.

APPENDIX E

WINAM CALIBRATION STEPS FOR SETBACK & DEADBAND

E.1 Light Mass Building

- Night Electric Load Ratio from 0.00 to 0.15, reducing the Total CV-RMSE from 5147% to 2535.3%.
- Peak Occupancy from 150 ft^2/person to 10 ft^2/person, reducing the Total CV-RMSE from 2535.3% to 465.9%.
- Conditioned Floor Area from 90000 ft^2 to 81818 ft^2, reducing the Total CV-RMSE from 465.9% to 429.1%.
- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.00 CFM/ft^2, reducing the Total CV-RMSE from 429.1% to 390.5%.
- Peak Occupancy from 10 ft^2/person to 16 ft^2/person, reducing the Total CV-RMSE from 390.5% to 314.8%.
- Overall U-Value from 0.07 Btu/$ft^2\cdot$°F·hr to 0.05 Btu/$ft^2\cdot$°F·hr, reducing the Total CV-RMSE from 314.8% to 232.0%.
- Conditioned Floor Area from 81818 ft^2 to 74380 ft^2, reducing the Total CV-RMSE from 232.0% to 208.1%.
- Constant Cooling Coil Set Point from 55°F to 59.0°F, reducing the Total CV-RMSE from 208.1% to 191.0%.
- Conditioned Floor Area from 74380 ft^2 to 67618 ft^2, reducing the Total CV-RMSE from 191.0% to 171.8%.

- Constant Cooling Coil Set Point from 59.0°F to 63.0°F, reducing the Total CV-RMSE from 171.8% to 152.4%.
- Zone Occupied Cooling Set Point from 76°F to 79.0°F, reducing the Total CV-RMSE from 152.4% to 142.2%.
- Constant Cooling Coil Set Point from 63.0°F to 65.8°F, reducing the Total CV-RMSE from 142.2% to 128.1%.
- Zone Occupied Cooling Set Point from 79°F to 82.0°F, reducing the Total CV-RMSE from 128.1% to 119.2%.
- Constant Cooling Coil Set Point from 65.8°F to 69.8°F, reducing the Total CV-RMSE from 119.2% to 98.2%.
- Interior Zone Percentage from 81% to 75.4%, reducing the Total CV-RMSE from 98.2% to 88.7%.
- Conditioned Floor Area from 67618 ft^2 to 61471 ft^2, reducing the Total CV-RMSE from 88.7% to 73.8%.
- Zone Occupied Cooling Set Point from 82°F to 85.0°F, reducing the Total CV-RMSE from 73.8% to 70.3%.
- Constant Cooling Coil Set Point from 69.8°F to 71.1°F, reducing the Total CV-RMSE from 70.3% to 60.6%.
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.10 CFM/ft^2, reducing the Total CV-RMSE from 60.6% to 56.6%.
- Constant Cooling Coil Set Point from 71.7 °F to 72.9°F, reducing the Total CV-RMSE from 56.6% to 51.3%.

- Minimum Occupied Supply Air Flow from 0.10 CFM/ft^2 to 0.03 CFM/ft^2, reducing the Total CV-RMSE from 56.6% to 47.1%.
- Peak Occupancy from 16 ft^2/person to 17 ft^2/person, reducing the Total CV-RMSE from 47.1% to 43.5%.
- Zone Occupied Heating Set Point from 70°F to 67.0°F, reducing the Total CV-RMSE from 43.5% to 41.0%.
- Conditioned Floor Area from 67471 ft^2 to 59777 ft^2, reducing the Total CV-RMSE from 41.0% to 39.8%.
- Interior Zone Percentage from 75.4% to 74.1%, reducing the Total CV-RMSE from 39.8% to 37.5%.
- Conditioned Floor Area from 59777 ft^2 to 58130 ft^2, reducing the Total CV-RMSE from 37.5% to 36.5%.
- Interior Zone Percentage from 74.1% to 72.8%, reducing the Total CV-RMSE from 36.5% to 34.4%.
- Conditioned Floor Area from 58130 ft^2 to 57142 ft^2, reducing the Total CV-RMSE from 34.4% to 33.7%.
- Interior Zone Percentage from 72.8% to 71.5%, reducing the Total CV-RMSE from 33.7% to 32.4%.
- Conditioned Floor Area from 57142 ft^2 to 56171 ft^2, reducing the Total CV-RMSE from 32.4% to 31.4%.
- Zone Occupied Heating Set Point from 67.0°F to 65.6°F, reducing the Total CV-RMSE from 41.4% to 30.7%.

- Constant Cooling Coil Set Point from 72.9°F to 73.0°F, reducing the Total CV-RMSE from 30.7% to 30.1%.
- Interior Zone Percentage from 71.5% to 70.2%, reducing the Total CV-RMSE from 30.1% to 29.3%.
- Conditioned Floor Area from 56171 ft^2 to 54624 ft^2, reducing the Total CV-RMSE from 29.3% to 28.0%.
- Interior Zone Percentage from 70.2% to 68.9%, reducing the Total CV-RMSE from 28.0% to 26.7%.
- Conditioned Floor Area from 54624 ft^2 to 54110 ft^2, reducing the Total CV-RMSE from 26.7% to 26.3%.
- Zone Occupied Heating Set Point from 65.6°F to 65.0°F, reducing the Total CV-RMSE from 26.3% to 26.1%.
- Constant Preheat Coil Set Point from 35°F to 35.4°F, reducing the CV-RMSE from 26.1% to 25.9%.
- Zone Unoccupied Cooling Set Point from 85°F to 109.0°F, reducing the Total CV-RMSE from 25.9% to 24.1%.
- Constant Preheat Coil Set Point from 35.4°F to 35.8°F, reducing the CV-RMSE from 24.1% to 23.9%.
- Minimum Occupied Supply Air Flow from 0.03 CFM/ft^2 to 0.01 CFM/ft^2, reducing the Total CV-RMSE from 23.9% to 23.3%.
- Conditioned Floor Area from 54110 ft^2 to 53601 ft^2, reducing the Total CV-RMSE from 23.3% to 23.1%.

- Interior Zone Percentage from 68.9% to 67.6%, reducing the Total CV-RMSE from 23.3% to 22.7%.
- Conditioned Floor Area from 53601 ft^2 to 52690 ft^2, reducing the Total CV-RMSE from 22.7% to 21.9%.
- Zone Unoccupied Heating Set Point from 65°F to 64.9°F, reducing the Total CV-RMSE from 21.9% to 21.7%.
- Constant Preheat Coil Set Point from 35.8°F to 36.2°F, reducing the CV-RMSE from 21.7% to 21.6%.
- Zone Unoccupied Heating Set Point from 64.9°F to 64.6°F, reducing the Total CV-RMSE from 21.6% to 21.2%.
- Conditioned Floor Area from 52690 ft^2 to 52195 ft^2, reducing the Total CV-RMSE from 21.2% to 20.8%.
- Zone Occupied Heating Set Point from 65.0°F to 64.7°F, reducing the Total CV-RMSE from 20.8% to 20.7%.

- Maximum Primary Flow from 1 CFM/ft^2 to 0.98 CFM/ft^2, reducing the Total CV-RMSE from 20.7% to 20.6%.

E.2 Medium Mass Building

- Night Electric Load Ratio from 0.00 to 0.15, reducing the Total CV-RMSE from 5434% to 2682.0%.
- Peak Occupancy from 150 ft^2/person to 10 ft^2/person, reducing the Total CV-RMSE from 2682.0% to 472.5%.

- Conditioned Floor Area from 90000 ft^2 to 81818 ft^2, reducing the Total CV-RMSE from 472.5% to 438.1%.
- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.00 CFM/ft^2, reducing the Total CV-RMSE from 438.1% to 391.7%.
- Peak Occupancy from 10 ft^2/person to 16 ft^2/person, reducing the Total CV-RMSE from 391.7% to 330.6%.
- Interior Zone Percentage from 81% to 51.0%, reducing the Total CV-RMSE from 330.6% to 233.1%.
- Conditioned Floor Area from 81818 ft^2 to 74380 ft^2, reducing the Total CV-RMSE from 233.1% to 209.1%.
- Constant Cooling Coil Set Point from 55°F to 59.0°F, reducing the Total CV-RMSE from 209.1% to 189.1%.
- Conditioned Floor Area from 74380 ft^2 to 67618 ft^2, reducing the Total CV-RMSE from 189.1% to 169.3%.
- Constant Cooling Coil Set Point from 59.0°F to 63.0°F, reducing the Total CV-RMSE from 169.3% to 146.9%.
- Zone Occupied Cooling Set Point from 76°F to 79.0°F, reducing the Total CV-RMSE from 146.9% to 136.5%.
- Constant Cooling Coil Set Point from 63.0°F to 65.8°F, reducing the Total CV-RMSE from 136.5% to 122.8%.
- Zone Occupied Cooling Set Point from 79.0°F to 82.0°F, reducing the Total CV-RMSE from 122.8% to 113.4%.

- Constant Cooling Coil Set Point from 65.8°F to 69.8°F, reducing the Total CV-RMSE from 113.4% to 96.5%.
- Zone Occupied Cooling Set Point from 82.0°F to 85.0°F, reducing the Total CV-RMSE from 96.5% to 88.5%.
- Constant Cooling Coil Set Point from 69.8°F to 71.7°F, reducing the Total CV-RMSE from 88.5% to 84.5
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.05 CFM/ft^2, reducing the Total CV-RMSE from 84.5% to 71.9%.
- Constant Cooling Coil Set Point from 71.7°F to 72.9°F, reducing the Total CV-RMSE from 71.9% to 63.6
- Zone Unoccupied Heating Set Point from 65°F to 64.4°F, reducing the Total CV-RMSE from 63.6% to 62.5%.
- Conditioned Floor Area from 67618 ft^2 to 64763 ft^2, reducing the Total CV-RMSE from 62.5% to 58.9%.
- Zone Unoccupied Heating Set Point from 64.4°F to 63.0°F, reducing the Total CV-RMSE from 58.9% to 55.3%.
- Conditioned Floor Area from 64763 ft^2 to 62029 ft^2, reducing the Total CV-RMSE from 58.9% to 50.9%.
- Minimum Occupied Supply Air Flow from 0.05 CFM/ft^2 to 0.00 CFM/ft^2, reducing the Total CV-RMSE from 50.9% to 48.1%.
- Conditioned Floor Area from 62029 ft^2 to 60320 ft^2, reducing the Total CV-RMSE from 48.1% to 45.4%.

- Zone Occupied Heating Set Point from 70°F to 67.0°F, reducing the Total CV-RMSE from 45.4% to 44.0%.
- Conditioned Floor Area from 60320 ft^2 to 58658 ft^2, reducing the Total CV-RMSE from 44.0% to 41.9%.
- Zone Unoccupied Heating Set Point from 63.0°F to 62.4°F, reducing the Total CV-RMSE from 41.9% to 40.0%.
- Conditioned Floor Area from 58658 ft^2 to 57661 ft^2, reducing the Total CV-RMSE from 40.0% to 38.7%.
- Zone Occupied Heating Set Point from 67.0°F to 64.9°F, reducing the Total CV-RMSE from 38.7% to 37.7%.
- Conditioned Floor Area from 57661 ft^2 to 56681 ft^2, reducing the Total CV-RMSE from 37.7% to 36.5%.
- Zone Unoccupied Heating Set Point from 62.4°F to 61.8°F, reducing the Total CV-RMSE from 36.5% to 35.5%.
- Conditioned Floor Area from 56681 ft^2 to 55119 ft^2, reducing the Total CV-RMSE from 35.5% to 33.6%.
- Zone Occupied Heating Set Point from 64.9°F to 61.9°F, reducing the Total CV-RMSE from 33.6% to 32.3%.
- Conditioned Floor Area from 55119 ft^2 to 54182 ft^2, reducing the Total CV-RMSE from 32.3% to 31.0%.
- Zone Unoccupied Heating Set Point from 61.8°F to 61.5°F, reducing the Total CV-RMSE from 31.0% to 30.4%.

- Conditioned Floor Area from 54182 ft^2 to 53261 ft^2, reducing the Total CV-RMSE from 30.4% to 29.6%.
- Zone Unoccupied Heating Set Point from 61.5°F to 61.2°F, reducing the Total CV-RMSE from 29.6% to 28.8%.
- Conditioned Floor Area from 53261 ft^2 to 52760 ft^2, reducing the Total CV-RMSE from 28.8% to 28.5%.
- Zone Unoccupied Heating Set Point from 61.2°F to 60.9°F, reducing the Total CV-RMSE from 28.5% to 27.9%.
- Conditioned Floor Area from 52760 ft^2 to 51863 ft^2, reducing the Total CV-RMSE from 27.9% to 27.5%.
- Minimum Unoccupied Outside Air from 25% to 20.3%, reducing the Total CV-RMSE from 27.5% to 26.7%.
- Zone Unoccupied Cooling Set Point from 85°F to 94.0°F, reducing the Total CV-RMSE from 26.7% to 25.4%.
- Zone Occupied Cooling Set Point from 85.0°F to 85.3°F, reducing the Total CV-RMSE from 25.4% to 25.1%.
- Conditioned Floor Area from 51863 ft^2 to 50981 ft^2, reducing the Total CV-RMSE from 25.1% to 23.8%.
- Static Pressure Set Point from 0 inH_2O to 0.15 inH_2O, reducing the Total CV-RMSE from 23.8% to 23.3%.
- Zone Unoccupied Cooling Set Point from 94.0°F to 103.0°F, reducing the Total CV-RMSE from 23.3% to 22.7%.

- Conditioned Floor Area from 50981 ft^2 to 50780 ft^2, reducing the Total CV-RMSE from 22.7% to 22.5%.
- Zone Occupied Heating Set Point from 61.9°F to 61.0°F, reducing the Total CV-RMSE from 22.5% to 22.2%.
- Conditioned Floor Area from 50780 ft^2 to 50303 ft^2, reducing the Total CV-RMSE from 22.5% to 21.9%.
- Minimum Unoccupied Outside Air from 20.3% to 16.5%, reducing the Total CV-RMSE from 21.9% to 21.5%.
- Conditioned Floor Area from 50303 ft^2 to 49830 ft^2, reducing the Total CV-RMSE from 21.5% to 21.2%.
- Minimum Unoccupied Outside Air from 16.5% to 13.4%, reducing the Total CV-RMSE from 21.2% to 20.9%.
- Conditioned Floor Area from 49830 ft^2 to 49362 ft^2, reducing the Total CV-RMSE from 20.9% to 20.7%.
- Minimum Unoccupied Outside Air from 13.4% to 9.3%, reducing the Total CV-RMSE from 20.7% to 20.4%.
- Conditioned Floor Area from 49362 ft^2 to 48898 ft^2, reducing the Total CV-RMSE from 20.4% to 20.1%.
- Minimum Unoccupied Outside Air from 9.3% to 6.5%, reducing the Total CV-RMSE from 20.1% to 19.9%.
- Zone Unoccupied Cooling Set Point from 103.0°F to 106.0°F, reducing the Total CV-RMSE from 19.9% to 19.8%.

E.3 Heavy Mass Building

- Night Electric Load Ratio from 0.00 to 0.15, reducing the Total CV-RMSE from 5765% to 2851.0%.
- Peak Occupancy from 150 ft^2/person to 10 ft^2/person, reducing the Total CV-RMSE from 2851.0% to 480.1%.
- Minimum Unoccupied Supply Air Flow from 0.15 CFM/ft^2 to 0.00 CFM/ft^2, reducing the Total CV-RMSE from 480.1% to 441.5%.
- Peak Occupancy from 10 ft^2/person to 16 ft^2/person, reducing the Total CV-RMSE from 441.5% to 339.8%.
- Overall U-Value from 0.07 Btu/ft^2·°F·hr to 0.05 Btu/ft^2·°F·hr, reducing the Total CV-RMSE from 339.8% to 265.1%.
- Conditioned Floor Area from 90000 ft^2 to 74380 ft^2, reducing the Total CV-RMSE from 265.1% to 217.5%.
- Constant Cooling Coil Set Point from 55°F to 63.0°F, reducing the Total CV-RMSE from 217.5% to 176.5%.
- Conditioned Floor Area from 74380 ft^2 to 67618 ft^2, reducing the Total CV-RMSE from 176.5% to 162.7%.
- Interior Zone Percentage from 81% to 71.9%, reducing the Total CV-RMSE from 162.7% to 145.1%.
- Peak Occupancy from 16 ft^2/person to 22 ft^2/person, reducing the Total CV-RMSE from 145.1% to 122.1%.
- Interior Zone Percentage from 71.9% to 58.0%, reducing the Total CV-RMSE from 122.1% to 97.9%.

- Constant Cooling Coil Set Point from 63°F to 65.8°F, reducing the Total CV-RMSE from 97.9% to 84.8%.
- Zone Occupied Cooling Set Point from 76°F to 79.0°F, reducing the Total CV-RMSE from 84.8% to 76.9%.
- Conditioned Floor Area from 67618 ft^2 to 61471 ft^2, reducing the Total CV-RMSE from 76.9% to 65.9%.
- Zone Occupied Cooling Set Point from 79.0°F to 82.0°F, reducing the Total CV-RMSE from 65.9% to 56.5%.
- Zone Occupied Heating Set Point from 70°F to 67.0°F, reducing the Total CV-RMSE from 56.5% to 51.5%.
- Constant Cooling Coil Set Point from 65.8°F to 68.6°F, reducing the Total CV-RMSE from 51.5% to 47.1%.
- Zone Occupied Cooling Set Point from 82.0°F to 85.0°F, reducing the Total CV-RMSE from 47.1% to 41.2%.
- Minimum Occupied Supply Air Flow from 0.15 CFM/ft^2 to 0.12 CFM/ft^2, reducing the Total CV-RMSE from 41.2% to 38.2%.
- Constant Cooling Coil Set Point from 68.6°F to 70.5°F, reducing the Total CV-RMSE from 38.2% to 33.8%.
- Minimum Occupied Supply Air Flow from 0.12 CFM/ft^2 to 0.10 CFM/ft^2, reducing the Total CV-RMSE from 33.8% to 31.1%.
- Constant Cooling Coil Set Point from 70.5°F to 71.2°F, reducing the Total CV-RMSE from 31.1% to 29.5%.

- Minimum Occupied Supply Air Flow from 0.10 CFM/ft^2 to 0.08 CFM/ft^2, reducing the Total CV-RMSE from 29.5% to 28.1%.
- Constant Cooling Coil Set Point from 71.2°F to 72.4°F, reducing the Total CV-RMSE from 28.1% to 25.6%.
- Minimum Occupied Supply Air Flow from 0.08 CFM/ft^2 to 0.06 CFM/ft^2, reducing the Total CV-RMSE from 25.6% to 23.0%.
- Maximum Primary Flow from 1 CFM/ft^2 to 1.50 CFM/ft^2, reducing the Total CV-RMSE from 23.0% to 22.1%.
- Constant Cooling Coil Set Point from 72.4°F to 72.6°F, reducing the Total CV-RMSE from 22.1% to 21.5%.
- Zone Unoccupied Cooling Set Point from 85°F to 88.0°F, reducing the Total CV-RMSE from 21.5% to 21.2%.
- Maximum Primary Flow from 1.50 CFM/ft^2 to 2.00 CFM/ft^2, reducing the Total CV-RMSE from 21.2% to 20.9%.
- Minimum Occupied Supply Air Flow from 0.06 CFM/ft^2 to 0.05 CFM/ft^2, reducing the Total CV-RMSE from 20.9% to 20.3%.
- Constant Preheat Coil Set Point from 35°F to 35.4°F, reducing the Total CV-RMSE from 20.3% to 19.9%.
- Zone Unoccupied Cooling Set Point from 88.0°F to 94.0°F, reducing the Total CV-RMSE from 19.9% to 19.5%.
- Zone Occupied Heating Set Point from 67.0°F to 66.1°F, reducing the Total CV-RMSE from 19.5% to 19.3%.

- Conditioned Floor Area from 61471 ft^2 to 60893 ft^2, reducing the Total CV-RMSE from 19.3% to 19.0%.

- Minimum Occupied Supply Air Flow from 0.05 CFM/ft^2 to 0.04 CFM/ft^2, reducing the Total CV-RMSE from 19.0% to 18.5%.

- Conditioned Floor Area from 60893 ft^2 to 60321 ft^2, reducing the Total CV-RMSE from 18.5% to 18.2%.

- Minimum Occupied Supply Air Flow from 0.04 CFM/ft^2 to 0.03 CFM/ft^2, reducing the Total CV-RMSE from 18.2% to 17.9%.

- Constant Cooling Coil Set Point from 72.6°F to 72.7°F, reducing the Total CV-RMSE from 17.9% to 17.5%.

- Zone Occupied Heating Set Point from 66.1°F to 65.2°F, reducing the Total CV-RMSE from 17.5% to 17.4%.

- Conditioned Floor Area from 60321 ft^2 to 60084 ft^2, reducing the Total CV-RMSE from 17.4% to 17.2%.

- Zone Unoccupied Cooling Set Point from 94.0°F to 100.0°F, reducing the Total CV-RMSE from 17.2% to 17.0%.

APPENDIX F

COMPARISON TABLES FOR EACH CITY FROM 6 CLIMATES

Table F.1: Annual Consumption for Chicago: Type 1 Building

WinAM Total Cooling (MMBTU)	2913
WinAM Total Heating (MMBTU)	1344
RC LightMass Total Cooling (MMBTU)	2614
RC LightMass Total Heating (MMBTU)	389
RC MediumMass Total Cooling (MMBTU)	2563
RC MediumMass Total Heating (MMBTU)	353
RC HeavyMass Total Cooling (MMBTU)	2546
RC HeavyMass Total Heating (MMBTU)	343
EnergyPlus LightMass Total Cooling (MMBTU)	2462
EnergyPlus LightMass Total Heating (MMBTU)	420
EnergyPlus MediumMass Total Cooling (MMBTU)	2460
EnergyPlus MediumMass Total Heating (MMBTU)	418
EnergyPlus HeavyMass Total Cooling (MMBTU)	2458
EnergyPlus HeavyMass Total Heating (MMBTU)	416

Table F.2: Annual Consumption for Chicago: Type 2 Building

WinAM Total Cooling (MMBTU)	2891
WinAM Total Heating (MMBTU)	1531
RC LightMass Total Cooling (MMBTU)	2473
RC LightMass Total Heating (MMBTU)	677
RC MediumMass Total Cooling (MMBTU)	2431
RC MediumMass Total Heating (MMBTU)	636
RC HeavyMass Total Cooling (MMBTU)	2410
RC HeavyMass Total Heating (MMBTU)	616
EnergyPlus LightMass Total Cooling (MMBTU)	2352
EnergyPlus LightMass Total Heating (MMBTU)	747
EnergyPlus MediumMass Total Cooling (MMBTU)	2348
EnergyPlus MediumMass Total Heating (MMBTU)	744
EnergyPlus HeavyMass Total Cooling (MMBTU)	2344
EnergyPlus HeavyMass Total Heating (MMBTU)	742

Table F.3: Comparison Between Models for Chicago: Type 1 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	11.48%	245.80%	18.33%	220.30%	6.15%	7.96%
Medium Mass	13.67%	281.00%	18.43%	221.76%	4.18%	18.41%
Heavy Mass	14.44%	291.89%	18.51%	223.38%	3.55%	21.19%

Table F.4: Comparison Between Models for Chicago: Type 2 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	16.92%	126.09%	22.95%	104.87%	5.15%	10.35%
Medium Mass	18.94%	140.76%	23.13%	105.80%	3.53%	16.99%
Heavy Mass	19.97%	148.44%	23.35%	106.32%	2.81%	20.41%

Table F.5: Annual Consumption for Denver: Type 1 Building

WinAM Total Cooling (MMBTU)	2657
WinAM Total Heating (MMBTU)	1412
RC LightMass Total Cooling (MMBTU)	2305
RC LightMass Total Heating (MMBTU)	339
RC MediumMass Total Cooling (MMBTU)	2239
RC MediumMass Total Heating (MMBTU)	287
RC HeavyMass Total Cooling (MMBTU)	2223
RC HeavyMass Total Heating (MMBTU)	275
EnergyPlus LightMass Total Cooling (MMBTU)	2040
EnergyPlus LightMass Total Heating (MMBTU)	204
EnergyPlus MediumMass Total Cooling (MMBTU)	2037
EnergyPlus MediumMass Total Heating (MMBTU)	202
EnergyPlus HeavyMass Total Cooling (MMBTU)	2035
EnergyPlus HeavyMass Total Heating (MMBTU)	200

Table F.6: Annual Consumption for Denver: Type 2 Building

WinAM Total Cooling (MMBTU)	2627
WinAM Total Heating (MMBTU)	1592
RC LightMass Total Cooling (MMBTU)	2161
RC LightMass Total Heating (MMBTU)	625
RC MediumMass Total Cooling (MMBTU)	2111
RC MediumMass Total Heating (MMBTU)	564
RC HeavyMass Total Cooling (MMBTU)	2096
RC HeavyMass Total Heating (MMBTU)	545
EnergyPlus LightMass Total Cooling (MMBTU)	1926
EnergyPlus LightMass Total Heating (MMBTU)	584
EnergyPlus MediumMass Total Cooling (MMBTU)	1921
EnergyPlus MediumMass Total Heating (MMBTU)	578
EnergyPlus HeavyMass Total Cooling (MMBTU)	1920
EnergyPlus HeavyMass Total Heating (MMBTU)	575

Table F.7: Comparison Between Models for Denver: Type 1 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	15.27%	316.57%	30.26%	592.18%	13.01%	66.16%
Medium Mass	18.67%	391.61%	30.46%	599.08%	9.93%	42.20%
Heavy Mass	19.51%	413.99%	30.57%	604.25%	9.25%	37.02%

Table F.8: Comparison Between Models for Denver: Type 2 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	21.56%	154.53%	36.37%	172.33%	12.19%	6.99%
Medium Mass	24.44%	182.33%	36.77%	175.36%	9.91%	2.53%
Heavy Mass	25.34%	192.14%	36.82%	176.70%	9.16%	5.58%

Table F.9: Annual Consumption for El Paso: Type 1 Building

WinAM Total Cooling (MMBTU)	3551
WinAM Total Heating (MMBTU)	872
RC LightMass Total Cooling (MMBTU)	3246
RC LightMass Total Heating (MMBTU)	81
RC MediumMass Total Cooling (MMBTU)	3187
RC MediumMass Total Heating (MMBTU)	62
RC HeavyMass Total Cooling (MMBTU)	3170
RC HeavyMass Total Heating (MMBTU)	59
EnergyPlus LightMass Total Cooling (MMBTU)	3076
EnergyPlus LightMass Total Heating (MMBTU)	21
EnergyPlus MediumMass Total Cooling (MMBTU)	3073
EnergyPlus MediumMass Total Heating (MMBTU)	21
EnergyPlus HeavyMass Total Cooling (MMBTU)	3074
EnergyPlus HeavyMass Total Heating (MMBTU)	20

Table F.10: Annual Consumption for El Paso: Type 2 Building

WinAM Total Cooling (MMBTU)	3558
WinAM Total Heating (MMBTU)	949
RC LightMass Total Cooling (MMBTU)	2994
RC LightMass Total Heating (MMBTU)	182
RC MediumMass Total Cooling (MMBTU)	2930
RC MediumMass Total Heating (MMBTU)	154
RC HeavyMass Total Cooling (MMBTU)	2911
RC HeavyMass Total Heating (MMBTU)	144
EnergyPlus LightMass Total Cooling (MMBTU)	2695
EnergyPlus LightMass Total Heating (MMBTU)	182
EnergyPlus MediumMass Total Cooling (MMBTU)	2690
EnergyPlus MediumMass Total Heating (MMBTU)	177
EnergyPlus HeavyMass Total Cooling (MMBTU)	2692
EnergyPlus HeavyMass Total Heating (MMBTU)	174

Table F.11: Comparison Between Models for El Paso: Type 1 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	9.38%	971.49%	15.45%	4040.95%	5.55%	286.47%
Medium Mass	11.43%	1302.73%	15.53%	4146.21%	3.68%	202.71%
Heavy Mass	12.00%	1386.18%	15.52%	4249.81%	3.15%	192.68%

Table F.12: Comparison Between Models for El Paso: Type 2 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	18.87%	422.44%	32.02%	420.24%	11.07%	0.42%
Medium Mass	21.43%	517.11%	32.28%	437.43%	8.94%	14.83%
Heavy Mass	22.26%	560.65%	32.17%	445.71%	8.11%	21.06%

Table F.13: Annual Consumption for Juneau: Type 1 Building

WinAM Total Cooling (MMBTU)	1850
WinAM Total Heating (MMBTU)	1681
RC LightMass Total Cooling (MMBTU)	1558
RC LightMass Total Heating (MMBTU)	525
RC MediumMass Total Cooling (MMBTU)	1519
RC MediumMass Total Heating (MMBTU)	474
RC HeavyMass Total Cooling (MMBTU)	1507
RC HeavyMass Total Heating (MMBTU)	460
EnergyPlus LightMass Total Cooling (MMBTU)	1416
EnergyPlus LightMass Total Heating (MMBTU)	652
EnergyPlus MediumMass Total Cooling (MMBTU)	1415
EnergyPlus MediumMass Total Heating (MMBTU)	651
EnergyPlus HeavyMass Total Cooling (MMBTU)	1415
EnergyPlus HeavyMass Total Heating (MMBTU)	650

Table F.14: Annual Consumption for Juneau: Type 2 Building

WinAM Total Cooling (MMBTU)	1783
WinAM Total Heating (MMBTU)	1926
RC LightMass Total Cooling (MMBTU)	1569
RC LightMass Total Heating (MMBTU)	925
RC MediumMass Total Cooling (MMBTU)	1550
RC MediumMass Total Heating (MMBTU)	864
RC HeavyMass Total Cooling (MMBTU)	1543
RC HeavyMass Total Heating (MMBTU)	841
EnergyPlus LightMass Total Cooling (MMBTU)	1549
EnergyPlus LightMass Total Heating (MMBTU)	1076
EnergyPlus MediumMass Total Cooling (MMBTU)	1548
EnergyPlus MediumMass Total Heating (MMBTU)	1072
EnergyPlus HeavyMass Total Cooling (MMBTU)	1547
EnergyPlus HeavyMass Total Heating (MMBTU)	1072

Table F.15: Comparison Between Models for Juneau: Type 1 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	18.72%	219.95%	30.65%	157.91%	10.05%	24.05%
Medium Mass	21.81%	254.37%	30.72%	158.20%	7.31%	37.25%
Heavy Mass	22.72%	265.54%	30.77%	158.51%	6.56%	41.40%

Table F.16: Comparison Between Models for Juneau: Type 2 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	13.66%	108.22%	15.07%	78.90%	1.24%	16.39%
Medium Mass	15.05%	122.83%	15.20%	79.54%	0.13%	24.11%
Heavy Mass	15.57%	128.89%	15.25%	79.58%	0.28%	27.46%

Table F.17: Annual Consumption for Las Vegas: Type 1 Building

WinAM Total Cooling (MMBTU)	3705
WinAM Total Heating (MMBTU)	814
RC LightMass Total Cooling (MMBTU)	3421
RC LightMass Total Heating (MMBTU)	74
RC MediumMass Total Cooling (MMBTU)	3349
RC MediumMass Total Heating (MMBTU)	57
RC HeavyMass Total Cooling (MMBTU)	3333
RC HeavyMass Total Heating (MMBTU)	55
EnergyPlus LightMass Total Cooling (MMBTU)	3323
EnergyPlus LightMass Total Heating (MMBTU)	24
EnergyPlus MediumMass Total Cooling (MMBTU)	3320
EnergyPlus MediumMass Total Heating (MMBTU)	23
EnergyPlus HeavyMass Total Cooling (MMBTU)	3320
EnergyPlus HeavyMass Total Heating (MMBTU)	23

Table F.18: Annual Consumption for Las Vegas: Type 2 Building

WinAM Total Cooling (MMBTU)	3756
WinAM Total Heating (MMBTU)	902
RC LightMass Total Cooling (MMBTU)	3206
RC LightMass Total Heating (MMBTU)	168
RC MediumMass Total Cooling (MMBTU)	3130
RC MediumMass Total Heating (MMBTU)	143
RC HeavyMass Total Cooling (MMBTU)	3109
RC HeavyMass Total Heating (MMBTU)	134
EnergyPlus LightMass Total Cooling (MMBTU)	2919
EnergyPlus LightMass Total Heating (MMBTU)	199
EnergyPlus MediumMass Total Cooling (MMBTU)	2911
EnergyPlus MediumMass Total Heating (MMBTU)	195
EnergyPlus HeavyMass Total Cooling (MMBTU)	2911
EnergyPlus HeavyMass Total Heating (MMBTU)	192

Table F.19: Comparison Between Models for Las Vegas: Type 1 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	8.30%	993.22%	11.48%	3282.34%	2.94%	209.39%
Medium Mass	10.61%	1319.43%	11.57%	3367.96%	0.87%	144.32%
Heavy Mass	11.15%	1388.02%	11.57%	3461.36%	0.38%	139.34%

Table F.20: Comparison Between Models for Las Vegas: Type 2 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	17.16%	436.36%	28.67%	352.35%	9.83%	18.57%
Medium Mass	19.99%	531.78%	29.02%	363.08%	7.53%	36.43%
Heavy Mass	20.79%	574.42%	29.03%	370.25%	6.82%	43.42%

Table F.21: Annual Consumption for New York: Type 1 Building

WinAM Total Cooling (MMBTU)	3096
WinAM Total Heating (MMBTU)	1093
RC LightMass Total Cooling (MMBTU)	2785
RC LightMass Total Heating (MMBTU)	218
RC MediumMass Total Cooling (MMBTU)	2738
RC MediumMass Total Heating (MMBTU)	187
RC HeavyMass Total Cooling (MMBTU)	2721
RC HeavyMass Total Heating (MMBTU)	177
EnergyPlus LightMass Total Cooling (MMBTU)	2647
EnergyPlus LightMass Total Heating (MMBTU)	228
EnergyPlus MediumMass Total Cooling (MMBTU)	2646
EnergyPlus MediumMass Total Heating (MMBTU)	227
EnergyPlus HeavyMass Total Cooling (MMBTU)	2645
EnergyPlus HeavyMass Total Heating (MMBTU)	225

Table F.22: Annual Consumption for New York: Type 2 Building

WinAM Total Cooling (MMBTU)	3064
WinAM Total Heating (MMBTU)	1207
RC LightMass Total Cooling (MMBTU)	2628
RC LightMass Total Heating (MMBTU)	425
RC MediumMass Total Cooling (MMBTU)	2583
RC MediumMass Total Heating (MMBTU)	385
RC HeavyMass Total Cooling (MMBTU)	2562
RC HeavyMass Total Heating (MMBTU)	368
EnergyPlus LightMass Total Cooling (MMBTU)	2514
EnergyPlus LightMass Total Heating (MMBTU)	521
EnergyPlus MediumMass Total Cooling (MMBTU)	2510
EnergyPlus MediumMass Total Heating (MMBTU)	518
EnergyPlus HeavyMass Total Cooling (MMBTU)	2508
EnergyPlus HeavyMass Total Heating (MMBTU)	516

Table F.23: Comparison Between Models for New York: Type 1 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	11.16%	400.46%	16.93%	380.12%	5.19%	4.24%
Medium Mass	13.07%	485.18%	17.00%	382.19%	3.48%	21.36%
Heavy Mass	13.78%	517.67%	17.05%	386.39%	2.88%	26.99%

Table F.24: Comparison Between Models for New York: Type 2 Building

Building Construction	WinAM and RC Cooling	WinAM and RC Heating	WinAM and EnergyPlus Cooling	WinAM and EnergyPlus Heating	RC and EnergyPlus Cooling	RC and EnergyPlus Heating
Light Mass	16.60%	184.24%	21.89%	131.63%	4.54%	22.71%
Medium Mass	18.62%	213.45%	22.05%	133.01%	2.90%	34.52%
Heavy Mass	19.59%	228.44%	22.16%	133.87%	2.14%	40.44%

APPENDIX G

COMPARISON TABLES FOR SAVINGS FROM NIGHT-TIME TEMPERATURE SETBACK AND FROM TEMPERATURE DEADBAND

Table G.1: Annual Energy Savings for each City with Temperature Setback

College Station Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	392	106	123	392	116	78	392	118	72
Heating	767	563	89	767	455	85	767	418	82
Chicago Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	396	129	27	396	122	61	396	121	58
Heating	782	705	122	782	584	113	782	539	111
Denver Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	398	136	81	398	133	78	398	132	71
Heating	787	756	120	787	624	114	787	574	108
El Paso Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	392	81	98	392	87	92	392	88	86
Heating	767	614	100	767	499	93	767	460	88
Juneau Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	399	149	53	399	131	53	399	125	51
Heating	790	819	125	790	682	123	790	629	121
Las Vegas Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	387	112	96	387	122	90	387	122	83
Heating	748	585	95	748	474	90	748	435	84
New York Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	396	121	60	396	115	58	396	113	56
Heating	781	661	107	781	542	105	781	499	104

Table G.2: Annual Energy Savings for each City with Temperature Deadband

College Station Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	348	1565	1801	348	1545	1776	348	1548	1767
Heating	508	1504	1598	508	1465	1576	508	1458	1572
Chicago Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	309	1199	1393	309	1194	1380	309	1197	1377
Heating	553	1656	1753	553	1648	1741	553	1652	1740
Denver Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	303	1271	1346	303	1267	1324	303	1267	1316
Heating	549	1762	1792	549	1764	1767	549	1764	1759
El Paso Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	315	1349	1397	315	1327	1371	315	1326	1366
Heating	510	1583	1528	510	1544	1501	510	1534	1498
Juneau Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	284	974	1156	284	978	1150	284	979	1149
Heating	583	1773	1888	583	1791	1879	583	1803	1878
Las Vegas Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	318	1353	1406	318	1343	1380	318	1342	1371
Heating	494	1498	1530	494	1465	1503	494	1457	1497
New York Savings (MMBtu/year)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	311	1231	1438	311	1227	1427	311	1232	1425
Heating	544	1615	1746	544	1609	1735	544	1613	1736

Table G.3: Savings Percentage for each City for Night-time Temperature Setback

College Station Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	7.7%	1.8%	2.1%	7.7%	2.0%	1.4%	7.7%	2.1%	1.3%
Heating	47.0%	34.7%	5.5%	47.0%	29.6%	5.4%	47.0%	27.4%	5.2%
Chicago Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	11.6%	3.4%	0.7%	11.6%	3.2%	1.6%	11.6%	3.2%	1.5%
Heating	34.2%	31.4%	5.6%	34.2%	26.7%	5.2%	34.2%	24.8%	5.1%
Denver Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	12.6%	3.8%	2.4%	12.6%	3.8%	2.3%	12.6%	3.8%	2.1%
Heating	33.4%	32.8%	6.0%	33.4%	28.0%	5.8%	33.4%	26.0%	5.5%
El Paso Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	9.6%	1.7%	2.2%	9.6%	1.9%	2.1%	9.6%	1.9%	1.9%
Heating	43.6%	35.0%	6.4%	43.6%	30.0%	6.1%	43.6%	27.9%	5.8%
Juneau Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	17.1%	5.8%	2.1%	17.1%	5.2%	2.0%	17.1%	4.9%	2.0%
Heating	29.7%	31.5%	4.9%	29.7%	26.6%	4.8%	29.7%	24.6%	4.8%
Las Vegas Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	9.2%	2.3%	2.0%	9.2%	2.6%	1.9%	9.2%	2.6%	1.8%
Heating	44.7%	35.2%	6.1%	44.7%	30.0%	5.9%	44.7%	27.8%	5.5%
New York Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	11.0%	3.0%	1.5%	11.0%	2.9%	1.4%	11.0%	2.9%	1.4%
Heating	38.6%	33.4%	5.4%	38.6%	28.1%	5.3%	38.6%	26.0%	5.3%

Table G.4: Savings Percentage for each City for Temperature Deadband

College Station Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	6.8%	27.0%	31.3%	6.8%	27.1%	31.0%	6.8%	27.3%	30.9%
Heating	31.1%	92.9%	99.0%	31.1%	95.1%	99.0%	31.1%	95.6%	99.0%
Chicago Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	9.0%	31.3%	36.1%	9.0%	31.6%	35.9%	9.0%	31.8%	35.9%
Heating	24.2%	73.9%	80.4%	24.2%	75.3%	80.3%	24.2%	75.8%	80.4%
Denver Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	9.6%	35.3%	39.7%	9.6%	35.9%	39.4%	9.6%	36.0%	39.2%
Heating	23.3%	76.5%	89.6%	23.3%	79.3%	89.6%	23.3%	79.8%	89.7%
El Paso Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	7.8%	29.1%	31.2%	7.8%	29.2%	30.8%	7.8%	29.3%	30.8%
Heating	29.0%	90.3%	98.6%	29.0%	92.8%	98.6%	29.0%	93.1%	98.6%
Juneau Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	12.2%	38.0%	44.9%	12.2%	38.6%	44.8%	12.2%	38.7%	44.7%
Heating	21.9%	68.3%	74.0%	21.9%	69.9%	73.9%	21.9%	70.6%	73.9%
Las Vegas Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	7.5%	28.3%	29.7%	7.5%	28.6%	29.3%	7.5%	28.6%	29.2%
Heating	29.5%	90.1%	98.4%	29.5%	92.6%	98.4%	29.5%	93.1%	98.4%
New York Savings (%)									
	Light Mass			Medium Mass			Heavy Mass		
	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus	WinAM	RC	EnergyPlus
Cooling	8.6%	30.5%	35.2%	8.6%	30.8%	35.0%	8.6%	31.0%	35.0%
Heating	26.9%	81.5%	88.3%	26.9%	83.4%	88.3%	26.9%	83.9%	88.4%