ABSTRACT

Al GHARABLY, MAGED FAROUK. Multivariate Function-based Energy Assessment During Early Building Design. (Under the direction of Joseph DeCarolis, and Edward Jaselskis.)

Much of our global energy supply is ultimately consumed in buildings. In the U.S., buildings account for approximately 40% of domestic energy consumption. While significant opportunities exist to improve building energy performance, inflexibility and lack of practically effective energy assessment tools available for use during the early design process limit opportunities to explore energy efficient design alternatives. Particularly in the early stages of building design, when key decisions can have a strong effect on realized energy performance, architects lack tools that can inform building design with energy performance data. While energy simulation engines exist, they require the specification of relatively detailed building plans that require significant effort and time to setup and run; therefore such models are typically applied late in the design process to verify energy performance. As a result, building energy performance has served as a design outcome rather than a design goal.

A previous study used EnergyPlus, a whole building energy simulation engine, within a Monte Carlo simulation framework to develop a linear regression-based building energy model (LRBEM) that can predict building energy performance based on the specification of 27 parameters relevant to the early building design phases. The model was limited to medium-sized U.S. commercial office buildings with rectangular geometries in four different climate zones represented by the cities of Miami, Winston-Salem, Albuquerque, and Minneapolis. The goal of this thesis was to extend the applicability of the previously developed LRBEM to estimate the cooling and heating loads of commercial office buildings with arbitrarily complex geometries.

In the current analysis, the original LRBEM – based on rectangular geometries – was initially used to predict energy performance of buildings with complex geometries. Because the accuracy of the LRBEM was inconsistent across different building geometries, the model was reformed to include building wall area as an explanatory variable, which significantly improved its predictive capability. The revised model, LRBEM+, was exercised on a set of limiting cases designed to systemically test variations in building geometry. Finally, LRBEM+ was tested to examine how well it responds to changes in individual design parameters. With the exception of heating in Miami, the R^2 values obtained from the regression exceed 93%, which indicates an excellent fit to the EnergyPlus simulation results. LRBEM+ results indicate that the model works well for non-rectangular building geometries, and is capable of providing valuable energy-related feedback during the early design stages.

Multivariate Function-based Energy Assessment During Early Building Design

by
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DEDICATION

Dedicated to my parents, siblings, and friends for all of their support and care during my master's degree

BIOGRAPHY

Maged Farouk Al Gharably is from Gaza, Palestine, and grew up in Sharjah, United Arab Emirates (UAE). Witnessing the marvelous rise of the infrastructure in UAE, he went to study Civil and Environmental engineering at the American University of Sharjah. He graduated in June 2011 with a Bachelors of Science in Civil and Environmental Engineering alongside with a Minor in Engineering System Management. In May 2012, he started his Masters of Science in the Construction Engineering and Management at North Carolina State University, with emphasize on construction practices, energy modeling and assessment, and engineering economics. At the age of 22, he magnificently graduated with a 4.0 GPA in exactly 12 months. Upon graduation, he intends to go back to the industry with the intention of obtaining PhD in the close future.

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When thinking about names to thank, a lot of them come to my attention. I would like to start by thank Allah for all his blessing and generosity.

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Chapter 1 Introduction

In 2011, approximately 41% of total U.S. energy consumption (equivalent to 40 quadrillion BTU) was consumed in buildings (US EIA, 2012). This is equivalent to more than nearly18 times the total energy produced in the African continent for the year 2009 (US EIA, 2010). Significant potential for energy savings exist by optimizing building design in a way that minimizes the thermal cooling and heating loads, which constitute a major portion of the total energy consumed by buildings. Formal consideration of energy performance has typically been addressed by engineers in the later stages of the design process when much of the building design is already fixed. Thus building energy performance is currently viewed mostly as a design outcome rather than as a design target.

The AIA describes Building Energy Modeling (BEM) as a tool to predict the anticipated building energy usage and as a method to capture the corresponding energy savings compared to a baseline (AIA, 2012). However, utilizing the available suite of building energy simulation tools requires substantial time, information, and technical expertise that make effective use of BEM infeasible for architects in the early design stages. With increasing attention to energy performance modeling, design professionals are responding to contractual arrangements by conducting energy simulations towards the end of the design phase using tools such as DOE-2, EnergyPlus, IES Virtual Environment, and Carrier HAP (Maile et al., 2007). The design community still lacks practical tools, however, to perform a rigorous assessment of building energy performance during the conceptual design phase. Consequently, most design decisions that greatly influence building energy performance are frequently made in the absence of model-based energy estimates.

A recent study by the Association of Collegiate Schools of Architecture (ACSA) showed that most architects acknowledge the importance of interoperability between energy simulations and design (AIA, 2012). The AIA study calls for simplified simulation methods and/or improved user-interfaces for complex building energy simulation engines that are appropriately responsive to key early design variables. Such efforts could improve building energy performance by integrating energy analysis into all stages of design, as shown in Figure 1.1. Some notable efforts, such as ISO 13790 and MIT Design Advisor (Urban & Glicksman, 2007), have attempted to reduce the number of required inputs and to simplify the underlying model physics. A more recent approach, developed by Hygh et al. (2012), utilizes EnergyPlus, an existing whole building energy simulation engine, within a Monte Carlo framework to develop a linear regression-based building energy model (LRBEM) based on 27 building parameters relevant to the early design stages. The resultant LRBEM accurately predicts the energy performance of medium-sized, rectangular office buildings within four different U.S. climate zones represented by Miami, Winston-Salem, Albuquerque, and Minneapolis.

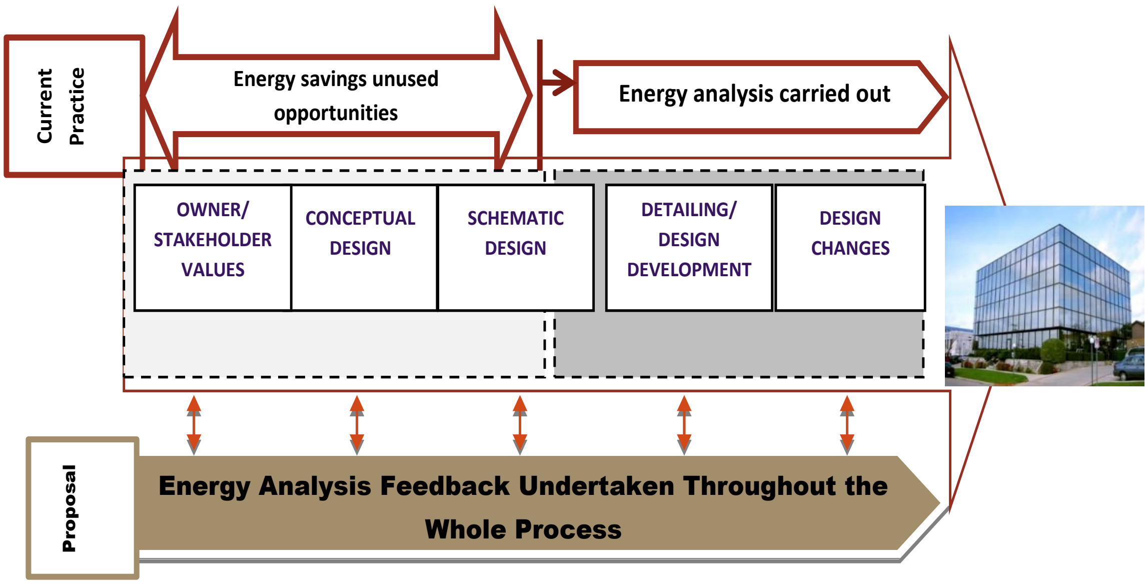

Figure 1.1: Current practice in which energy analysis occurs near the end of the design process contrasted with proposed practice where energy analysis occurs throughout the building design process.

This thesis expands on the work described by Hygh et al. (2012) and Hygh (2011) by testing and extending the functionality of the LRBEM. This thesis meets three research objectives: (1) test the existing LRBEM's accuracy in predicting energy loads for non-rectangular building geometries, (2) modify the LRBEM to better capture variation in building geometry, and (3) test the model's accuracy in capturing the effect of changes in early design parameters on building heating and cooling loads.

The thesis is organized as follows. Section 2 describes the overall approach to extend the LRBEM to capture non-rectangular geometries and to test the model's ability to capture changes in early design parameters. Section 3 presents results associated with the three research objectives. Section 4 outlines the insights and conclusions drawn from the analysis and provides recommendations on applying the revised LRBEM.

Chapter 2 Model development

2.1. Prior Model Development

The work in this thesis builds on previous work by Hygh (2011) and Hygh et al. (2012), which describe the development of the original LRBEM. In this previous work, 27 building design parameters relevant to the early architectural design process were selected. For reference, these parameters are provided below in Table 2.1

Table 2.1: Building design parameters relevant to the early design stages.

	Parameter	Unit	Minimum	Maximum
1	Total Building Area	Area (SF)	20,000	100,000
2	Depth	Ft	40 ft min; range governed by aspect ratio range	
3	Aspect Ratio	Length/Depth	1	10
4	Orientation (rotation)	Degrees	0	180
5	Roof Insulation	R-value(h·ft^2·°F/BTU)	15	50
6	Roof Color	Solar Absorptance	0.19	0.97
7	Roof Emissivity	Emissivity	0.86	0.95
8-11	Window R-value (N,S,E,W)	R-value (h·ft^2·°F/BTU)	1.1	4.3
12-15	Window SHGC (N,S,E,W)	SHGC	0.2	0.6
16-19	Wall Insulation (N,S,E,W)	R-value (h·ft^2·°F/BTU)	R-8	R-40
20-23	Shading Projection Factor (N,S,E,W)	Percentage of Window Height	5	100
24-27	Window to Wall Ratio (N,S,E,W)	%	2	90

While the design parameters listed in Table 2.1 are likely to have a strong effect on building energy performance, several other factors, including prevailing climate, building size, and geometry, are also likely to exhibit a strong effect. While these factors could be included in the regression as explanatory variables, their addition to the model makes the regression significantly more complex and is likely to reduce the model's predictive skill. As a result, Hygh (2011) made a set of assumptions exogenous to the model. A separate LRBEM was developed for four different U.S. climate zones as defined by (ASHRAE, 2007), which were selected to capture climatic extremes. Weather files from the following representative cities were utilized: Miami, FL (Zone 1A), Winston-Salem, NC (Zone 4A), Albuquerque, NM (Zone 4B), and Minneapolis, MN (Zone 6A). In addition, while building size is an explanatory variable in the LRBEM, it is limited to the range associated with a U.S. medium-size commercial office building type drawn from the DOE Commercial Reference Building Models (Deru, 2011). This particular building type was chosen based on its ubiquity in the U.S. commercial building market. Building geometry was limited to rectangular shapes, defined by building depth and aspect ratio.

In Hygh (2011) a base EnergyPlus model was developed to represent a medium-sized commercial office building in each of the four specified climate zones. The early design parameters were assigned numerical ranges, shown in Table 2.1, that collectively span a broad segment of the design space. Next, a Mont Carlo simulation was performed in which random draws from a uniform distribution associated with each parameter range were made to create an instance of the commercial building model. The Monte Carlo simulation was used to create 20,000 building model instances, which were run through EnergyPlus to produce estimates of idealized heating and cooling loads for each model instance. A stepwise linear multivariate regression model was developed using 16,000 model instances, and the remaining 4,000 instances were used to verify the model. In addition to the early design parameters, several derived parameters were developed to increase the accuracy of the model. For example, total window area, based on the product of wall area and window-to-wall ratio, could potentially explain some of the variance in building energy performance. This enabled the inclusion of potentially useful non-linear terms in a linear regression model. Both the original 27 early building design parameters and derived parameters were treated as potential explanatory variables in the stepwise regression model. The stepwise regression procedure added explanatory variables to the regression model if it reduced the residual error in model prediction. A separate LRBEM was developed to predict heating, cooling, and total loads in each of the four climate zones, resulting in 12 separate regression models. Parameters included and excluded by stepwise regression procedure are provided in the appendix to Hygh et al. (2012). Building design parameters and the additional parameters derived from them became explanatory variables in the LRBEM if retained by the stepwise regression.

2.2 Initial Investigations to Test Applicability of LRBEM to New Building Geometries

A series of procedures were first tested to explore different ways to apply LRBEM to buildings that are not rectangular but are nonetheless rectilinear and have right-angled corners. The underlying basis for these procedures was that a non-rectangular rectilinear building could be represented by equivalent rectangle-shaped units for which the LRBEM is applicable. These procedures are summarized in Table 2.2. They were tested for several different instances of buildings in the four climate zones studied by Hygh et al. (2012). Overall, these procedures did not yield prediction performances that were comparable to the energy load prediction accuracy, especially for heating, reported by Hygh et al. (2012).

Table 2.2: Methods used to estimate heating and cooling loads using the LRBEM developed by Hygh et al. (2012).

Method	Brief description of the estimation procedure	Reference
Combinations of rectangles	Predict energy performance for several rectangular shapes that would build up the shape that the user intends to predict.	Appendix I
Floor Area Preserved	Predict energy performance for a rectangular geometry that has the same floor area as the building shape the user intends to predict.	Appendix II
Perimeter Preserved	Predict energy performance for a rectangular geometry that has the same perimeter as the building shape the user intends to predict.	Appendix III
Bigger Rectangle With Area Factor	Predict the energy performance for a rectangular shape that can enclose the shape the user intends to predict, but is corrected by a ratio represented the rectangular floor area to the true floor area.	Appendix IV

Although we did not develop a sufficiently accurate procedure for applying the LRBEM to non-rectangular buildings, we observed that the heating prediction performance could be improved by: (1) making the building envelope properties cardinal-direction-specific in the regression model inputs; and (2) incorporating roof area as a separate explanatory variable. In the LRBEM developed by Hygh et al. (2012), the constant floor height of 15 feet and the rectangular building shape enabled the wall area to be directly correlated to floor and roof areas for a given building aspect ratio (i.e., length of the shorter side of the rectangular floor area divided by that of the longer side). In the LRBEM, the wall properties (such as wall area, window-to-wall ratio, R-value) were assumed to be the same for all sides of the building. As a result, the wall parameters were represented in the LRBEM by a single set of variables that were not specific to the wall in each cardinal direction. These observations led to a reexamination of the LRBEM model structure (i.e., the explanatory variables that describe the energy load). The following section describes the development and testing of an improved LRBEM.

2.3 Development and Testing of a New Linear Regression-based Building Energy Model (LRBEM+).

The simulation data used to develop the original LRBEM were used to develop a revised regression model, LRBEM+, which included five new parameters: wall area by cardinal direction and roof area. This approach enabled the development of a revised model without redoing the EnergyPlus simulation conducted by Hygh et al. (2012). For each of the four climate zones, the stepwise linear regression procedure (using the StepWiseFit function in MATLAB) was applied to the dataset consisting of 80% (16,000) simulations, chosen randomly, out of the complete set the 20,000 energy simulations. The remaining 4,000 the simulations were saved to conduct the model testing and performance assessment.

The stepwise regression was initiated with 30 design parameters as well as an additional set of 48 terms derived from the design parameters, as potential explanatory variables in the linear regression model (see Table 5.3 in the Appendix). The 30 building design parameters include 25 of the original 27 parameters from Hygh et al. (2012): aspect ratio and depth parameters were excluded but roof area and wall areas by cardinal direction were added. Details on the new explanatory variables in LRBEM+ are provided in Table 2.3

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Table 2.3: Changes in the set of parameters considered in the new regression model.

Parameter	Original LRBEM		LRBEM+	
Aspect ratio	$\frac{Length}{Depth}$		Excluded	
Depth	The shorter dimension in the rectangular floor plan		Excluded	
Wall Areas (N,S,E,W)	$\frac{Floor\ Area}{\frac{stories}{depth}}$	$\frac{Floor\ Area}{\frac{stories}{depth*aspect\ ratio}}$	$\left(\frac{FloorArea}{\frac{Stories}{Depth}}\right) * 4.57^{1} * stories$	$\left(\frac{FloorArea}{\frac{Stories}{Depth*Aspect\ Ratio}}\right) * 4.57 * stories$
Roof Area	$\frac{Area}{Number\ of\ Stories}$		$\frac{FloorArea}{Stories}$	

For each climate zone, the resulting regression model, based on the 16,000 data points, consisted of a reduced set of explanatory variables identified by the stepwise regression process; 48 explanatory variables were included in the final model for heating load and 35 explanatory variables in the model for cooling load. See Table 5.1and Table 5.2 in the Appendix for the resulting sets of explanatory variables and their corresponding

[1] The 4.57 represents the metric floor to floor height that was used in the baseline model of the Monte Carlo simulation framework

coefficients for heating and cooling, respectively, in each climate zone. For the datasets used for the model development, the LRBEM+ prediction for heating energy load in each climate zone yielded an R^2 value between 0.765 and 0.965, and for cooling a value between 0.956 and 0.9926. The test datasets (i.e., the random set of 4,000 energy simulations not used in the LRBEM+ development) were used to first evaluate the ability of the newly developed regression models to predict the energy loads for rectangular buildings. The energy loads predicted with LRBEM+ were compared against the corresponding EnergyPlus simulation results. Table 2.4 and Table 2.5 show the values for coefficient of variance of root mean square error (CVRMSE), average percent error, and R^2 for heating and cooling regression equations.

Table 2.4:LRBEM+ performance in predicting heating energy loads for buildings in four climate zones; the errors represent the difference between LRBEM+ predictions and EnergyPlus simulations.

Location	Miami	Winston-Salem	Albuquerque	Minneapolis
Climate Zone	1A	4A	4B	6A
R-squared	0.765	0.9584	0.9359	0.9645
RMSE (GJ)	1.6	28.8	44.2	74.1
CV (RMSE)	71.90%	9.50%	12.50%	5%
Mean Absolute Error	123%	7.8%	10.9%	6.1%
Standard Deviation	-	6.7%	9.8%	5.5%

Table 2.5: LRBEM+ performance in predicting cooling energy loads for buildings in four climate zones; the errors represent the difference between LRBEM+ predictions and EnergyPlus simulations.

Location	Miami	Winston-Salem	Albuquerque	Minneapolis
Climate Zone	1A	4A	4B	6A
R-squared	0.9926	0.980	0.956	0.9715
RMSE (GJ)	31.2	27.1	34.7	203.0
CV (RMSE)	3%	5.70%	8.70%	6.80%
Mean Absolute Error	2.6%	4.7%	7.0%	5.8%

Figure 1.1 includes a set of scatterplots that demonstrate the linear relationship between heating and cooling loads predicted by the LRBEM+ versus EnergyPlus. Overall, the prediction performance of LRBEM+ is strong and comparable to performance reported by Hygh et al. (2012) for rectangular-shaped buildings.

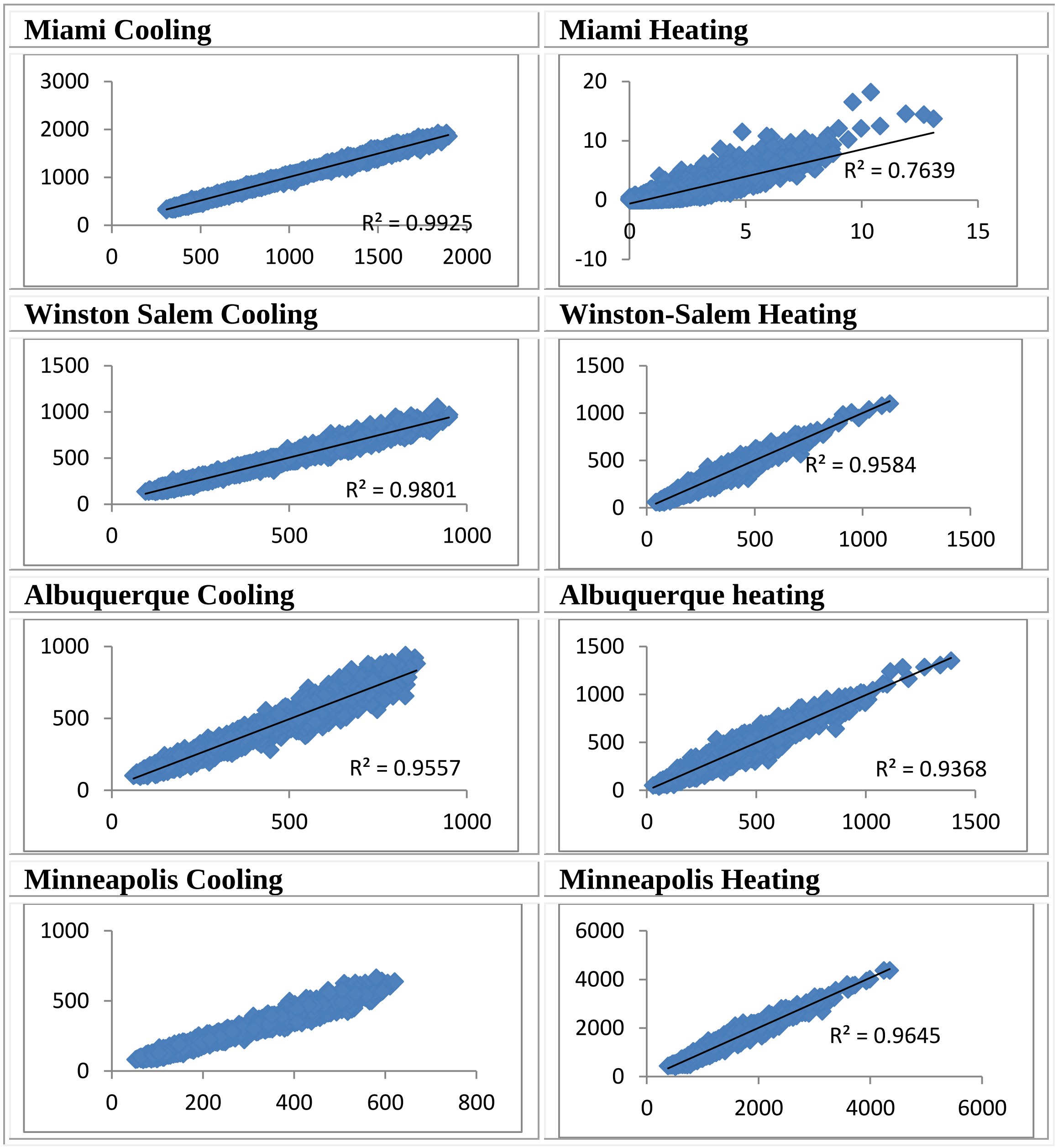


Figure 2.1: Scatterplots demonstrating the linear relationship between LRBEM+ (horizontal axis) and EnergyPlus (vertical axis) predictions for cooling (left column) and heating loads (right column). Each of the 4 rows represents results from one of the test locations.

The LRBEM+ was able to predict more complex, non-rectangular building forms by considering 30 parameters in the stepwise regression, yet did not add more than 3% to the mean absolute error in cooling or heating at any location. Moreover, the addition of derived parameters and the displacement of some of the original design parameters in the stepwise regressions indicate that the new interaction between wall, window, and roof areas with their material properties is significant and should be accounted for in this analysis.

When analyzing the error sources within the regression model, several outliers were found, which tend to be focused on the heating prediction in the Miami climate zone. The justification behind the outliers is that the mean biased error calculation fails to take into consideration the order of magnitude of the value being predicted. Heating in Miami follows the statistics in Table 2.6 developed for the verification set, and when compared to heating in Winston-Salem, we can observe that the lower Miami heating value produces significantly higher error. This occurs because even a small deviation in absolute terms from a low value for predicted absolute energy can drive high relative errors. Moreover, the observation is still applicable when analyzing the error prediction outliers in other regions, whether for cooling or heating loads.

Table 2.6: Comparison between heating in Miami and Winston-Salem for the verification set; energy values were obtained using LRBEM+.

	Heating Miami (Mwh)	Heating in Winston-Salem (Mwh)
First Quartile	0.0591	43.3
Average	0.315	64.9
Third Quartile	0.428	81.7

Chapter 3 LRBEM+ applications to buildings with different configurations

3.1 LRBEM+ performance assessment procedure

This section describes the extended testing that was conducted to assess the performance of LRBEM+. Three types of testing were carried out: (1) rectilinear buildings; (2) buildings with a limiting shape factor as described in Section 3.3 (e.g., angle of building corners, non-uniform floor area in each story); and (3) a building that has a combination of shape factors. The following sections describe the applications of LRBEM+ to each of these cases and compare its prediction performance with energy values obtained using EnergyPlus.

3.2 Non-rectangular-shaped buildings with right-angled corners

Several different rectilinear-shaped buildings with right-angled corners were modeled and their heating and cooling energy loads in the four climate zones were estimated using EnergyPlus. An example of such a building is shown in Figure 3.1. The parameter values for all these buildings were chosen to be within the ranges (Table 2.1) used for generating the rectangular buildings that formed the datasets for developing the regression models. This ensured that the prediction performance could then be attributed to only the changes in the shape (i.e., purely rectangular to non-rectangular rectilinear). Overall prediction performance is good: all errors were the same or lower than the errors reported in

Table 2.4 and Table 2.5. For the example building shown in Figure 3.1, the mean-biased errors did not exceed 5%.

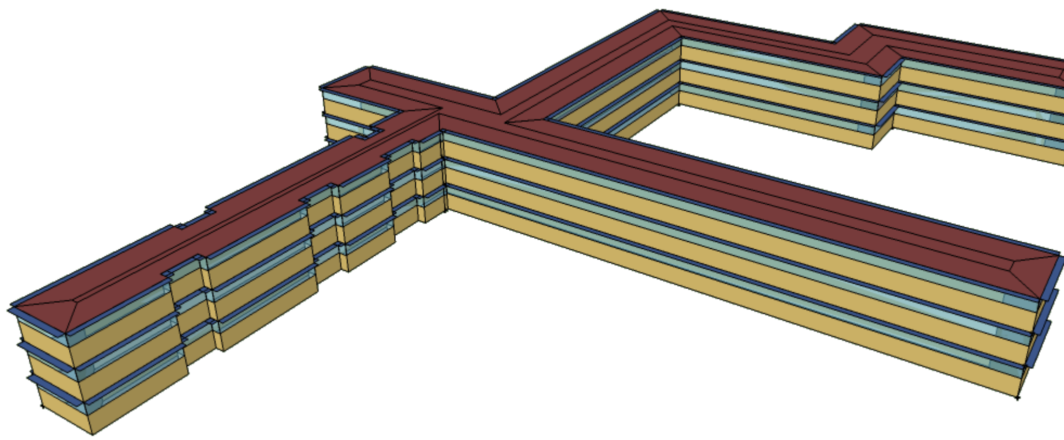


Figure 3.1: An example of a rectilinear-shaped, non-rectangular building with right-angled corners that was used to test the predictability of LRBEM+.

3.3 Buildings with one different shape factor

In another set of tests, the purely rectangular shape of a building was distorted by one shape factor at a time. These factors were chosen to represent the following deviations from the purely rectangular-shaped buildings: (1) buildings with open areas in the middle that result in self-shading effects, as shown in Figure 3.2 and Figure 3.3; (2) buildings with corners that are not at right angles, as shown in Figure 3.4 and Figure 3.5; (3) buildings with non-uniform roof heights, as shown in Figure 3.6 and Figure 3.7; and (4) building with non-uniform floor to floor heights for Winston-Salem climate zone, as shown in Figure 3.8.

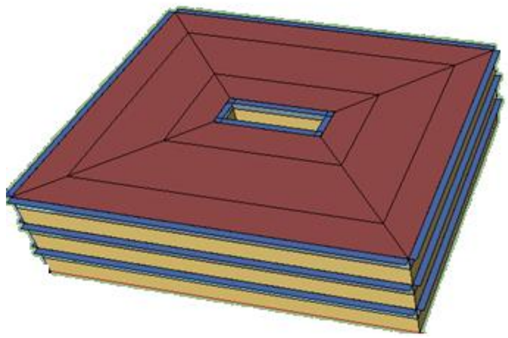


Figure 3.2: An example building with open areas in the middle that cause self-shading effects (Case A-1: a small court yard).

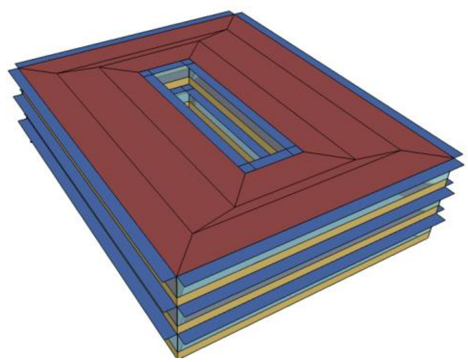


Figure 3.3: An example building with open areas in the middle that cause self-shading effects (Case A-2: a large court yard).

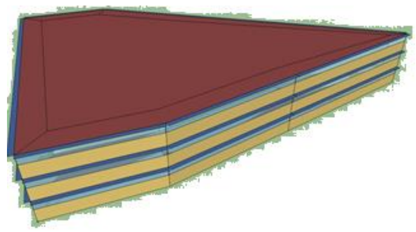


Figure 3.4: An example building with corners that are not right angled (Case B-1: corners with acute angles).

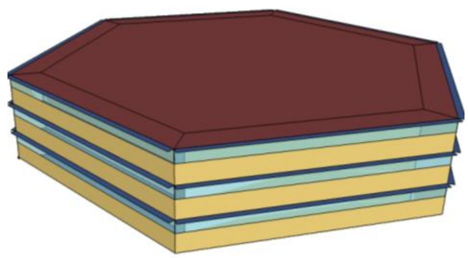


Figure 3.5: An example building with corners that are not right angled (Case B-2: corners with obtuse angles).

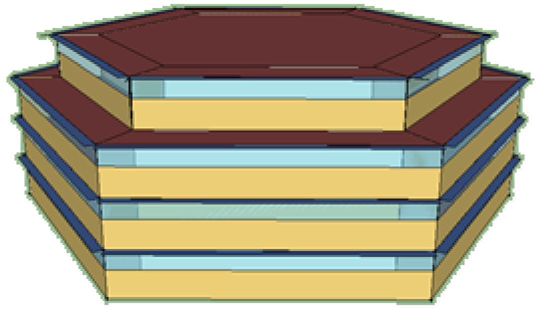


Figure 3.6: An example building with non-uniform roof heights (Case C-1).

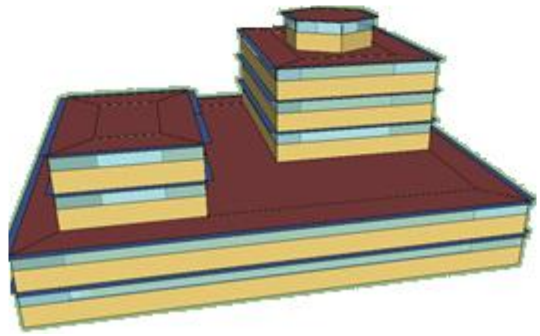


Figure 3.7: An example building with non-uniform roof heights (Case C-2).

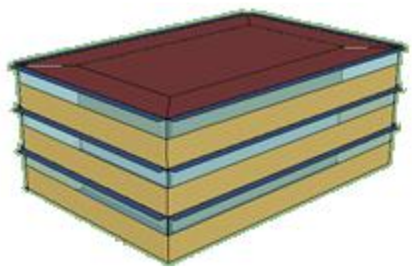


Figure 3.8: Building A with non-uniform floor heights (Case D).

Cases A1 and A2 (Figure 3.2 and Figure 3.3, respectively) represent two buildings with an interior courtyard with 3.9% and 15%, respectively, of the ground floor area. This deviation from a purely rectangular building leads to different amounts of self-shading on the building that could potentially affect the heating and cooling loads. The heating and cooling energy loads in the four climate zones for these two cases were estimated using LRBEM+ and EnergyPlus, and the prediction errors are shown in Table 3.1.

Cases B1 and B2 represent two buildings with non-right-angled corners; Case B1 includes corners with acute and obtuse angled corners, and Case B2 includes obtuse angled corners only. These cases have more than four corners, unlike the rectangular building that was used to generate the simulation data for LRBEM+. The prediction errors between LRBEM+ and EnergyPlus estimates of energy loads for these cases are reported also in Table 3.1.

Cases C1 and C2, which include buildings with different roof heights, were also tested. The errors between energy load estimates by LRBEM+ and EnergyPlus are also shown in Table 3.1.

For Case D, the floor to floor height was varied from the default value of 15 ft used in the datasets used for developing LRBEM+. The energy loads in the Winston-Salem climate zone were simulated using EnergyPlus and predicted using LRBEM+ for floor to floor heights ranging from 11 ft to 19 ft, in 1 ft increments. The resulting prediction errors are plotted in Figure 3.9. In all these cases where one building parameter was changed, all the other building parameters were set to be within the ranges of values that were used when generating the Monte Carlo simulations of building energy for the purely rectangular-shaped buildings (i.e., the chosen parameter values in Table 5.5 are within the ranges specified in table 2.1. Therefore, the prediction errors shown in Table 3.1 are attributed to the changes in shape-factors corresponding to each case. The table suggests that our regression model accurately predicts the courtyard system of design, which possesses the maximum shading effect. Additionally, energy loads for buildings with non-right angles are also predicted with a suitable mean-biased error. Finally, non-uniform roof heights, such as the architectural setback scenarios, are predicted with an acceptable level of accuracy. Figure 3.9 shows the cooling and heating energy loads prediction errors with the floor-to-floor heights varying from 10ft to 19 ft. The graph suggests that LRBEM+ predicts the heating and cooling loads with acceptable error for the cases with floor to floor height between 11 ft. and 18 ft.

Table 3.1: Prediction mean-biased error for heating and cooling in the four climate regions for the different shape-factor cases A1, A2, B1, B2, C1, and C3.

	Miami		Winston-Salem		Albuquerque		Minneapolis	
	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating
A1 (Fig. 3.5)	1%	-	7%	4%	4%	8%	8%	4%
A2 (Fig. 3.6)	2%	-	4%	1%	4%	3%	2%	11%
B1 (Fig. 3.7)	2%	-	4%	7%	18%	20%	10%	6%
B2 (Fig. 3.8)	3%	25%	4%	12%	7%	3%	8%	7%
C1 (Fig. 3.9)	2%	12%	7%	16%	6%	6%	2%	12%
C2 (Fig. 3.10)	5%	9%	9%	15%	3%	5%	7%	0%

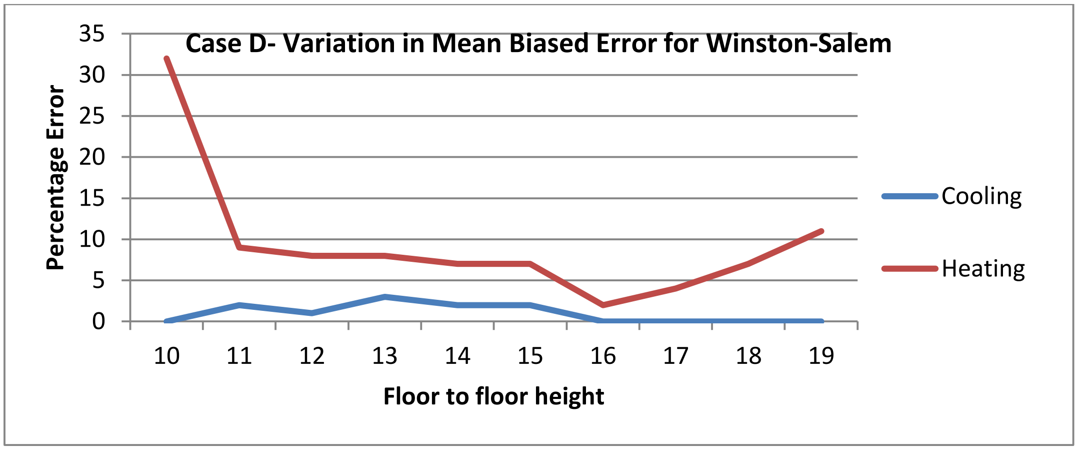


Figure 3.9: Absolute percentage error versus floor-to-floor height for a building in Winston-Salem. Percentage error was obtained by comparing energy predictions from LRBEM+ with EnergyPlus simulation results.

3.4 A building with many different shape factors

To assess the predictive performance of LRBEM+ for a building with multiple changes simultaneously affecting the energy loads, a building that constitutes all the changes reflected by Cases A, B, C, and D (described in the previous section) was designed as Case E (Figure 3.10). It includes the self-shading effect due to the presence of a courtyard. Non-uniform roof heights are incorporated by having 58.6% of the first floor area cover by roof, in addition to the roof on the top floor. This building also includes varying floor heights; the first floor height is 17 ft, while the other floors are 15 ft high. The shape of the building was changed by including on the first floor two right-angled corners, two corners at 102.9°, and another at 154.2°.

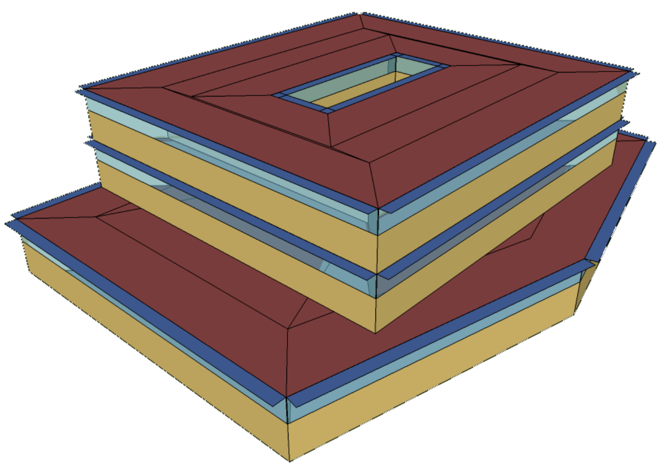


Figure 3.10: A building with several shape factors simultaneously changed to deviate from the pure rectangular-shaped building (Case E).

The performance of LRBEM+ was evaluated in terms of the predicted change in heating and cooling loads in comparison to that simulated by EnergyPlus associated with a change in the value of a single explanatory variable. For example, the change is heating energy load was predicted using LRBEM+ when one building parameter is incremented from a baseline value. The increase from the baseline set of values for each parameter was set to 25% of the Monte Carlo simulation ranges presented in Table 2.1. Table 3.2 lists the building parameters that were changed, and the corresponding baseline and incremented values for each parameter. This evaluation was conducted for each climate zone.

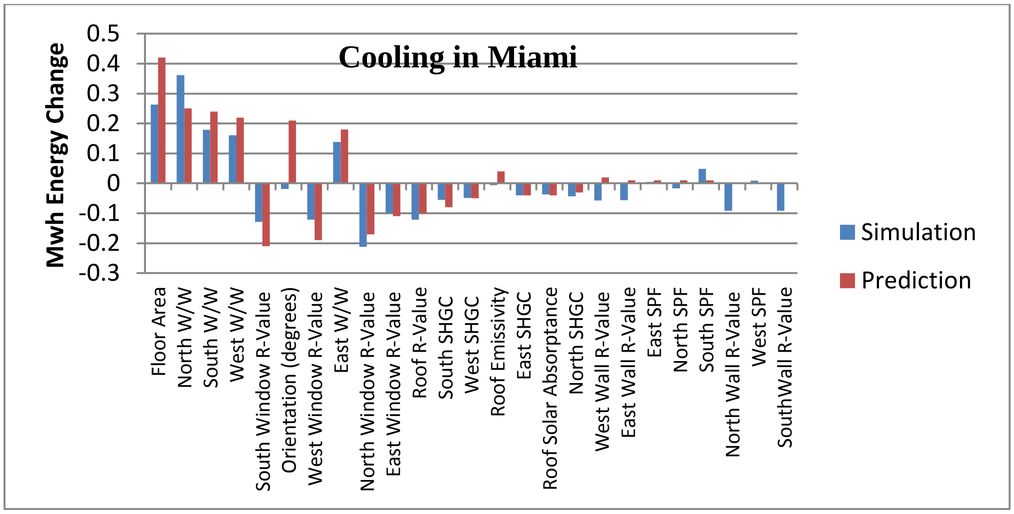
Table 3.2: Building parameter values for the baseline and the increased value of each building parameter used to test the LRBEM+ energy prediction for Case E.

	Baseline	25% Increase on Monte Carlo range
Building Floor Area (m2)	3,724	5,574
Orientation (degrees)	0	45.0
Roof Emissivity	0.90	0.923
Roof Solar Absorptance	0.70	0.895
Roof R-Value	25.8	34.6
Window SHGC (N,S,E,W)	0.35	0.45
Window R-Value (N,S,E,W)	2.22	3.02
Wall R-Value (N,S,E,W)	18.3	26.3
Shading Projection Factor (N,S,E,W)	0.50	0.738
Window-to-Wall Ratio (N,S,E,W)	40%	62%

The baseline energy load for Winston-Salem predicted by LRBEM+ and EnergyPlus is 56.66 MWh and 63.78 MWh, respectively, for heating, and 76.07 MWh and

71.05 MWh, respectively, for cooling. Figure 3.12 shows the relative change in energy loads in response to the change in each parameter for the Case E building (shown in Figure 3.9). This bar chart compares the LRBEM+ predictions of energy load changes for the Winston-Salem case with EnergyPlus simulated changes. Similar comparisons were conducted for the other climate zones, and the results are presented in Figure 3.11, Figure 3.13, and Figure 3.14.

In Winston-Salem, the changes in heating energy load corresponding to most parameters predicted by LRBEM+ and EnergyPlus match in direction, except for the Wall R parameter value. The bars associated with each parameter in Figure 3.12 are arranged left to right in decreasing order of effect on building energy load, as predicted by the LRBEM+ . The floor area parameter, which exhibits the largest effect on heating and cooling loads, implicitly includes roof area and wall areas in (N, S, E, W) orientations. In Figure 3.12we can observe that there is an inverse correlation between the level of importance of a building parameter and the discrepancy in the prediction of direction and magnitude. This suggests that changes in the most influential parameter values properly capture the changes in the energy loads; also, any errors arising due inaccurate energy load predictions for less influential parameters are negligible.



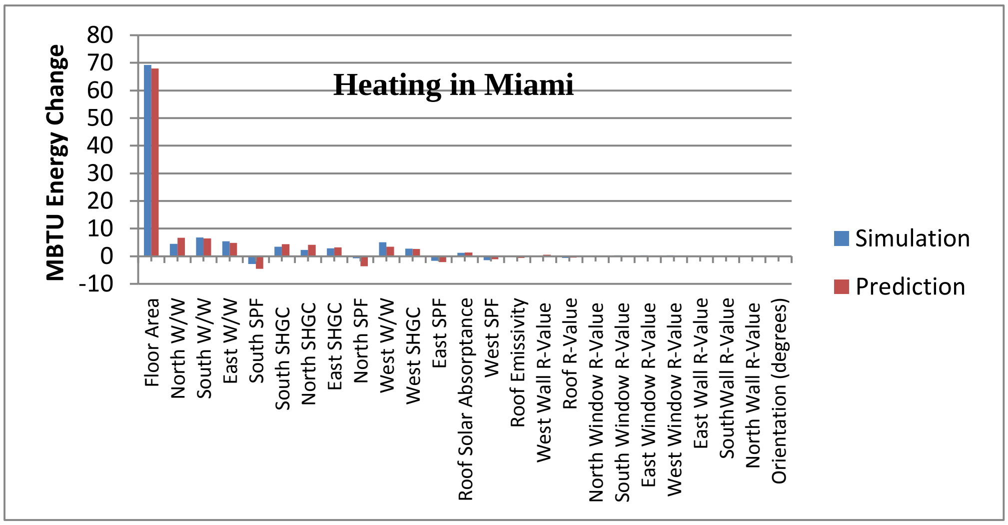


Figure 3.11: Comparison of relative change is cooling and heating energy loads (for Miami) predicted by LRBEM+ (red) and EnergyPlus (blue) in response to incremental change in each building parameter (Table 7). Parameters on x-axis are ranked by level of importance (left being most influential).

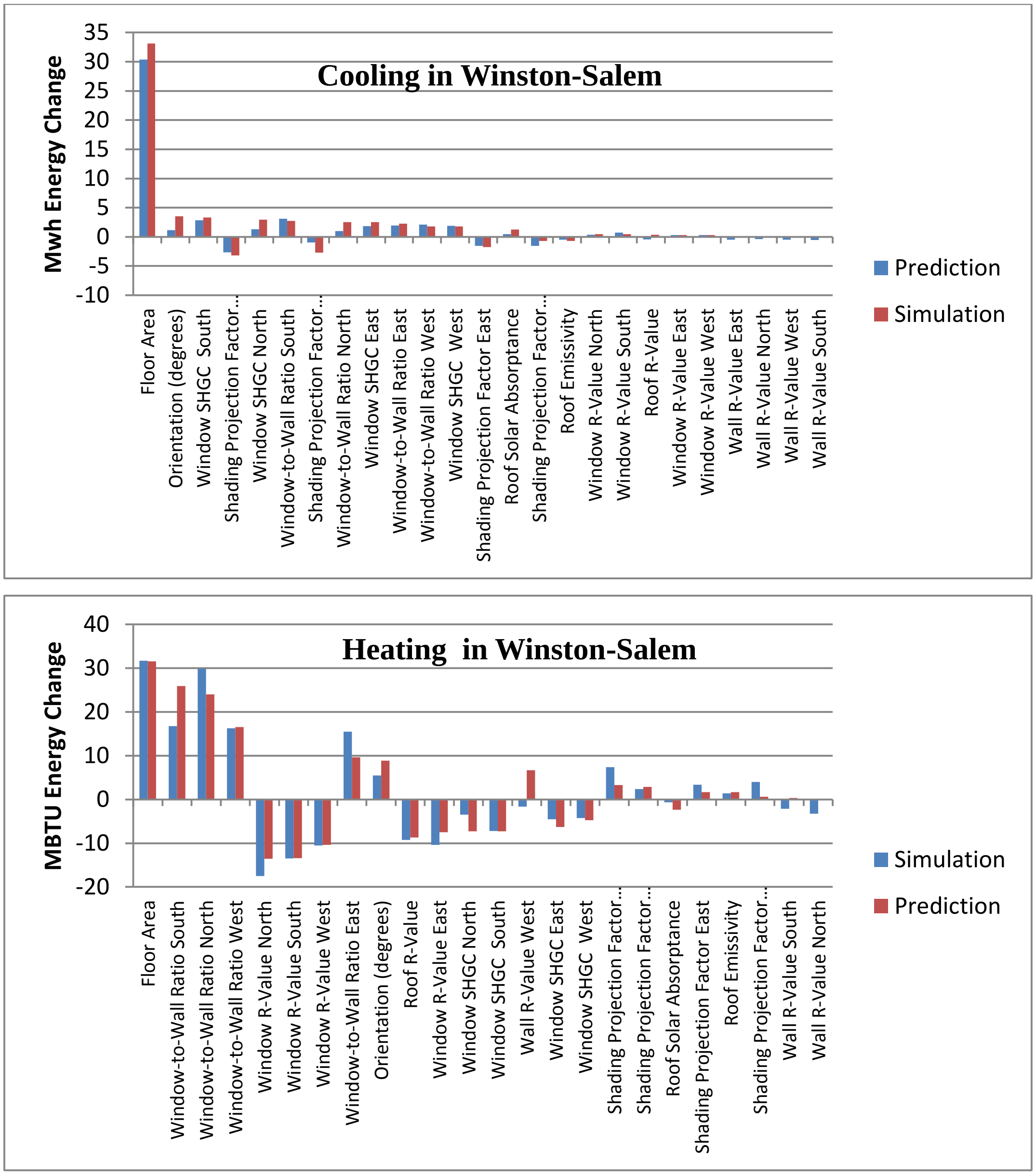


Figure 3.12: Comparison of relative change is cooling and heating energy loads (for Winston-Salem) predicted by LRBEM+ (red) and EnergyPlus (blue) in response to the incremental change in each building parameter (Table 7). Parameters on x-axis are ranked by level of importance (left being most influential).

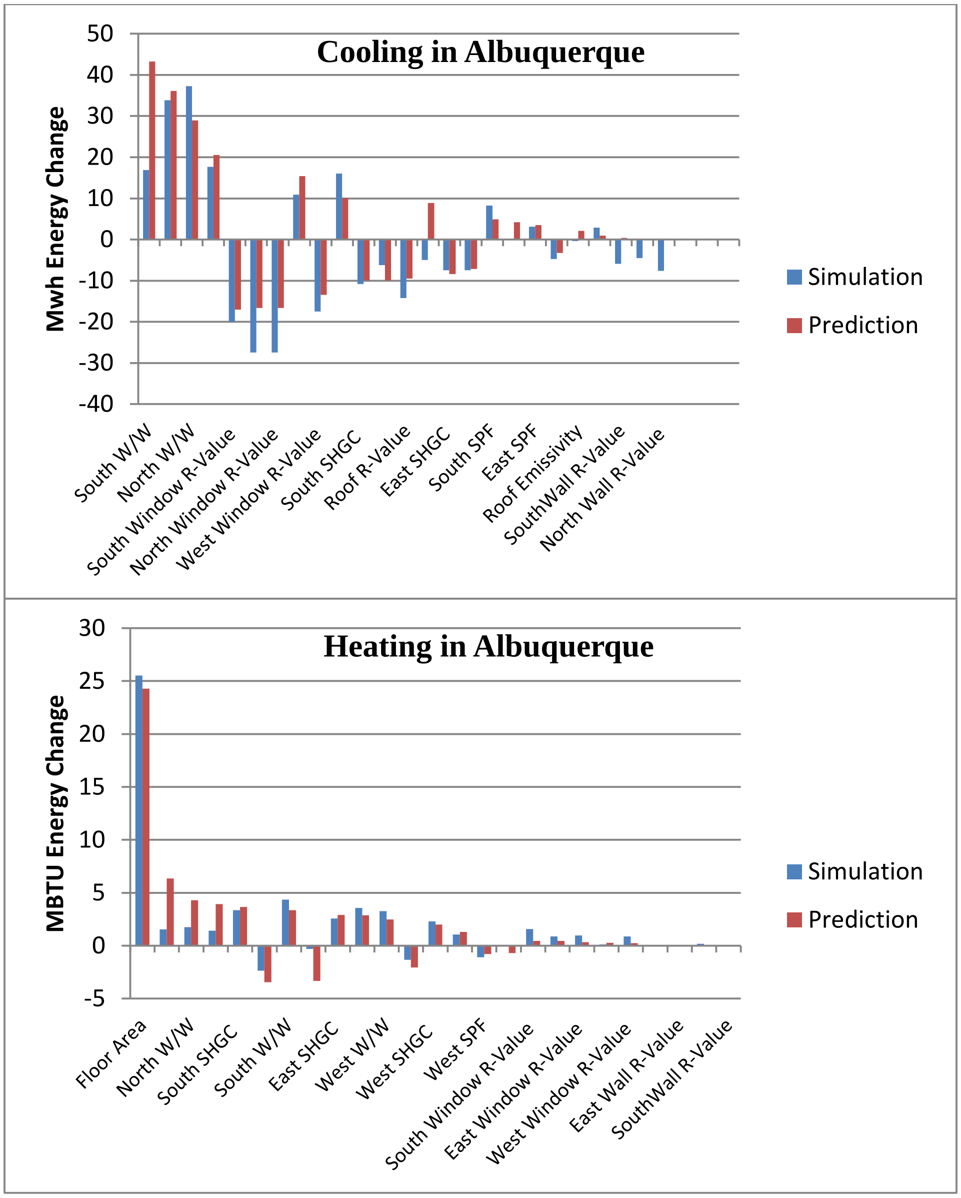
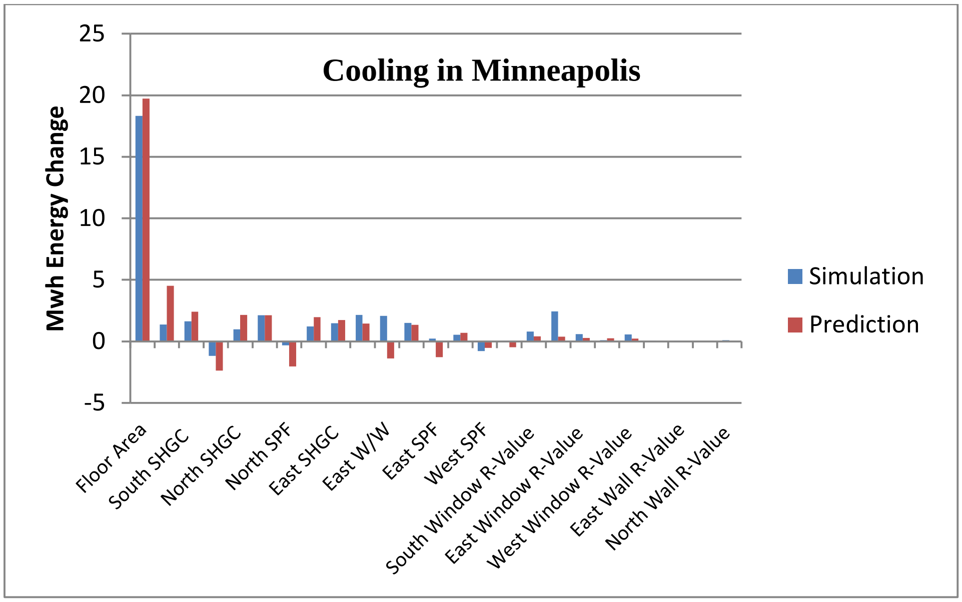


Figure 3.13: Comparison of relative change is heating energy load (for Albuquerque) predicted by LRBEM+ (red) and EnergyPlus (blue) in response to incremental change in each building parameter (Table 7). Parameters on x-axis are ranked by level of importance (left being most influential).



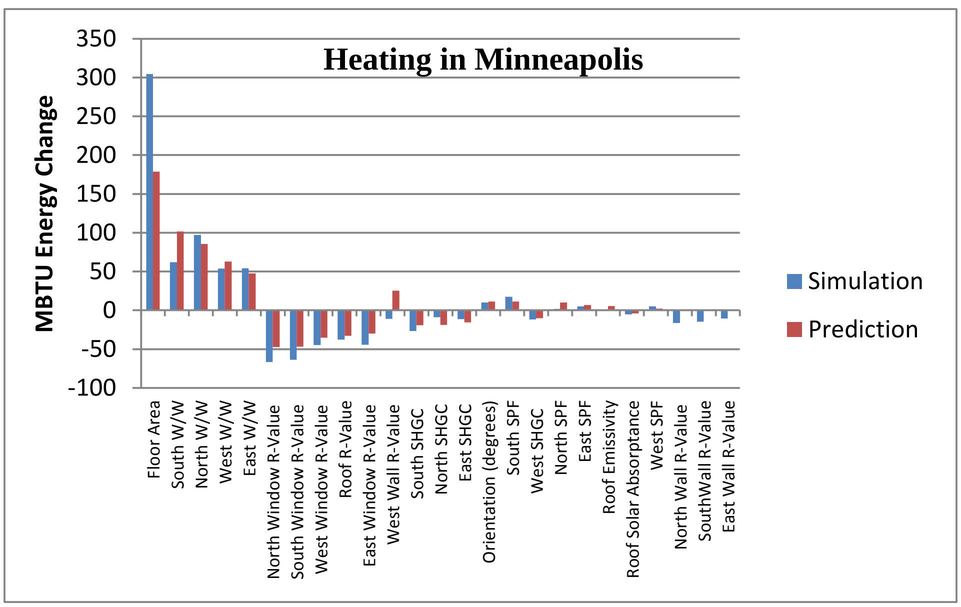


Figure 3.14: Comparison of relative change is heating energy load (for Minneapolis) predicted by LRBEM+ (red) and EnergyPlus (blue) in response to incremental change in each building parameter (Table 7). Parameters on x-axis are ranked by level of importance (left being most influential).

Chapter 4 Outcome and Discussion

Rapid feedback on building energy performance during the early design stages can help guide sustainable and efficient building design. Existing building energy simulation models require detailed building specifications and are complex to operate. Such models are of little value during the early design stages when architects are experimenting with massing, orientation, and fenestration. In previous work, a linear regression-based building energy model (LRBEM) was developed by iterating EnergyPlus within a Monte Carlo framework (Hygh et al, 2012). While LRBEM provided rapid and accurate estimates of heating and cooling loads, it was limited to rectangular, medium-sized office buildings.

The work presented in this thesis represents a significant extension of LRBEM by generalizing the prediction capability to medium-sized commercial buildings with any arbitrary geometry. The updated model, referred to as LRBEM+, represents a revised multivariate linear regression equation based on 30 early building design parameters using results from the original 20,000 Monte Carlo realizations. The new model, LRBEM+, can accurately predict the heating and cooling loads associated with complex building geometries, including courtyards, arbitrary rectilinear forms, polygons, various floor-to-floor heights, and non-uniform roof heights. Moreover, LRBEM+ was able to predict the direction and magnitude associated with changes to at least the 5 most influential explanatory variables in all four location for cooling and heating. With the exception of heating in Miami where the absolute value of the heating load is less than 1 MWh, the R^2 values obtained from LRBEM+ exceed 93%, which indicates an excellent fit to the EnergyPlus simulation results.

LRBEM+ could serve as a practical substitute for building energy simulation engines in early building design stages by providing instantaneous feedback on energy performance through the specification of a limited number of early design parameters. Like LRBEM, the new model LRBEM+ is currently limited to four climate zones in the United States represented by the cities Winston-Salem, Miami, Albuquerque, and Minneapolis, which are meant to span the climatic extremes within the continental U.S. Future work could extend LRBEM+ development beyond these four climate zones. In addition, the model could be extended to predict different building categories, such as large and small sized office buildings, hotels, high and low raise residential, warehouses, malls, and retail stores. Another extension would be the application of formal search techniques to help identify optimal design solutions. Such solutions could be reached by allowing users to optimize a subset of their design decisions to minimize heating and cooling loads. Availability of LRBEM+ is significant because it can serve as a practical decision support tool for architects during the early design stages, where building design decisions have strong implications on realized energy performance yet tools to assess energy are most lacking. By targeting the early design phase, the intention of LRBEM+ is to transform the perception of building energy performance from a design outcome to a design target.

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Chapter 5 APPENDICES

❖ **Appendix I**

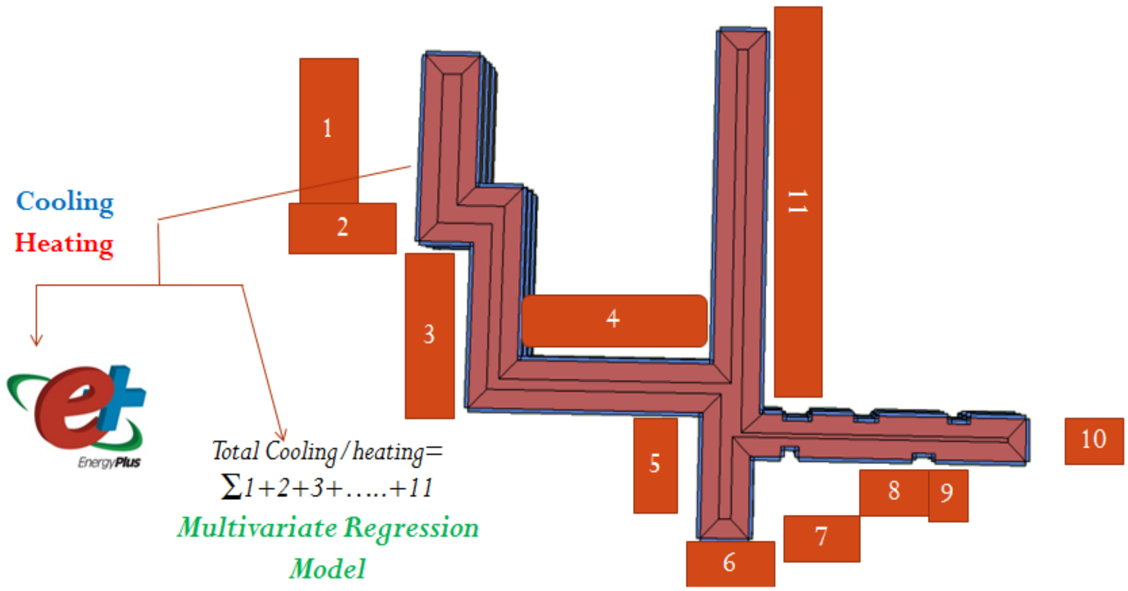

Figure 5.1: Framework of method "combination of rectangles".

The total floor areas of buildings 1 through 11 are equal to the floor area of the Case Study geometry (presented with red at top view). To obtain the cooling/ heating energy performance, the user would predict buildings 1, 2, 3… 11 and then add energies per cooling or heating. The rationale behind the attempt was that any complex geometry could behave thermally in a similar manner to a series of rectangle buildings that make up the same shape. This method proved to be inaccurate when thermal energies are compared with EnergyPlus simulation results.

- **Appendix II**

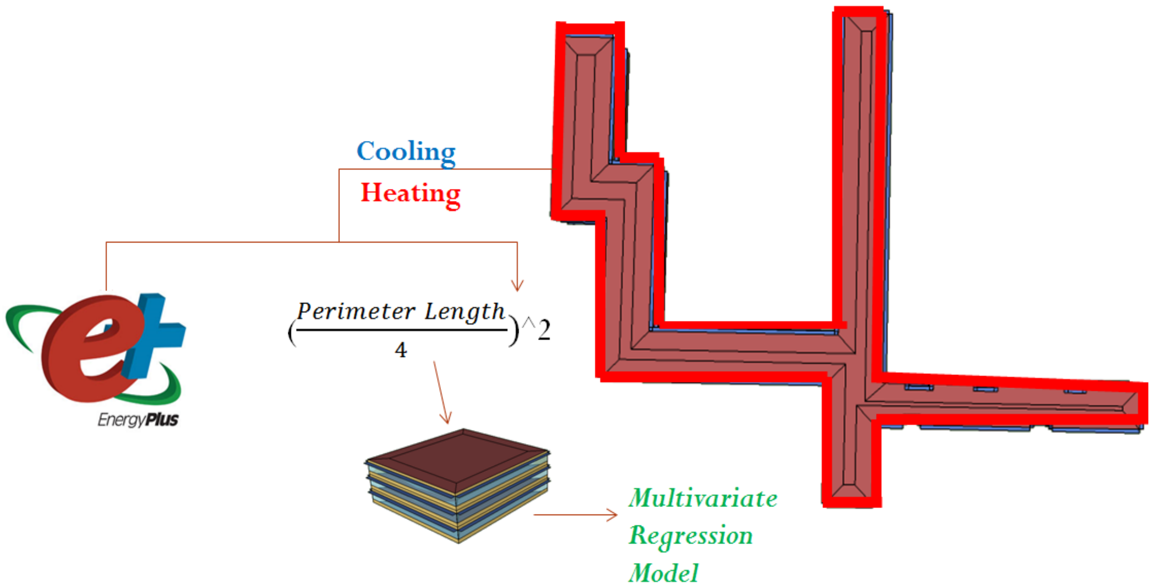

Figure 5.2: Framework of method "Perimeter Preserved".

The length of the perimeter highlighted in red is reshaped into the square buildings shown. The rationale is the square building would behave in a similar thermal manner. The multivariate regression model is used to predict the square shape (that has a similar perimeter as the case study). When compared to EnergyPlus, high errors were observed.

❖ **Appendix III**

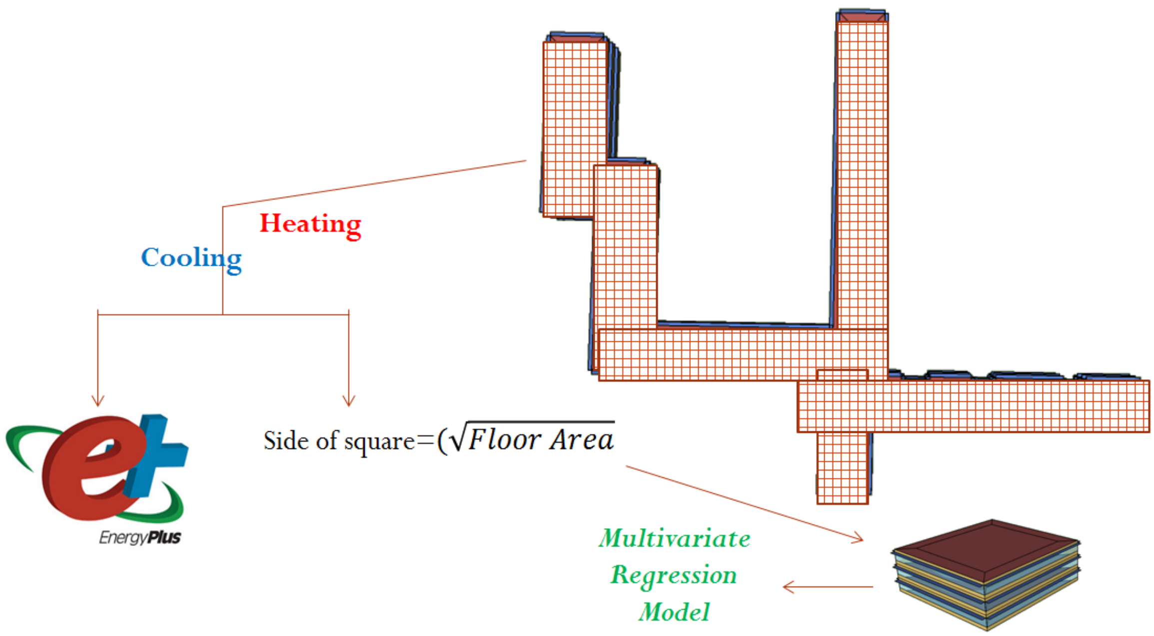

Figure 5.3: The framework for "Floor Area Preserved".

In this method, the floor area of the case study would be determined and reshaped into a rectangular building. The LRBEM would then predict the rectangle shape. The resultant errors were high for heating when compared with EnergyPlus.

❖ Appendix IV

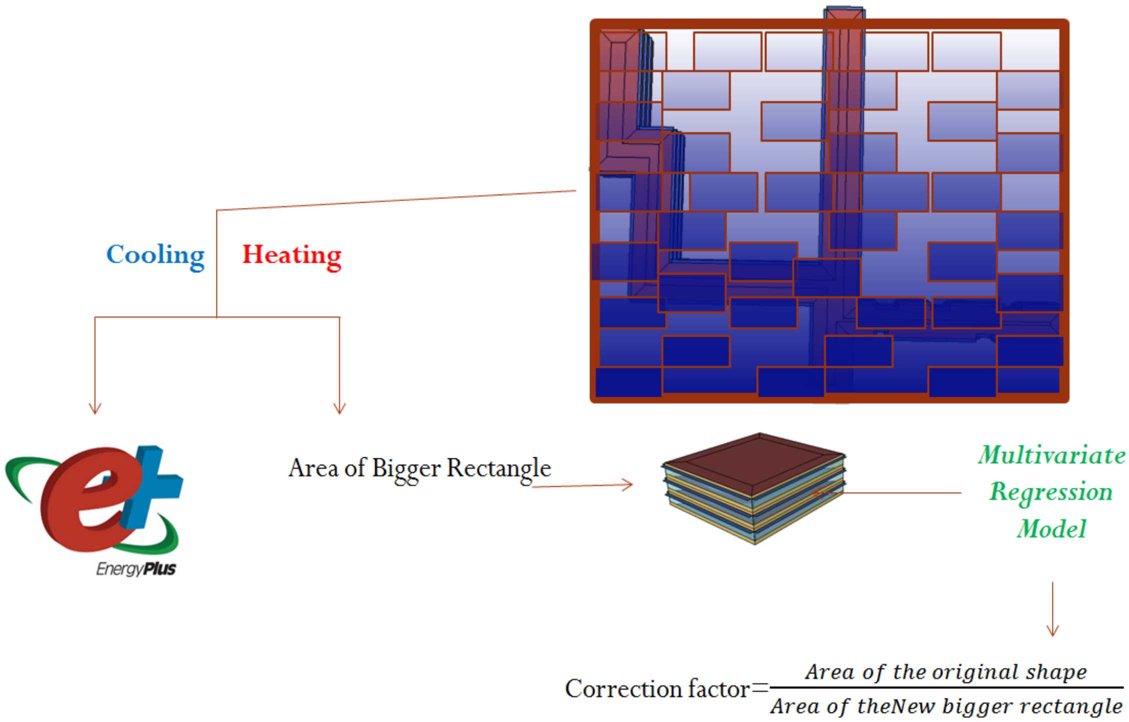

Figure 5.4: the Framework for "Bigger Rectangular with Area Factor".

Looking at the building from the top view, users would fit a rectangle (purple rectangle) over the case study geometry (presented in red). To obtain the cooling/ heating energy performance, the user would predict the bigger rectangle (purple) and then then apply a correction factor that would scale the floor area to the value associated with the building's actual geometry. This method lacks consistency because it showed promising results in certain cases, while it lacked accuracy in others, when compared with EnergyPlus simulation results.

❖ **Appendix V**

Table 5.1: Final cross product parameters, as well as their values that were included in the heating equation for the LRBEM+.

1A-Miami	**4A-Winston-Salem**	**4B-Albuquerque**	**6A-Minneapolis**	
4.99E+08	3.84E+09	2.85E+09	5.69E+10	Intercept
-2.17E+05	-9.35E+06	-1.24E+07	-1.73E+07	Area in m2
-1.75E+05	3.19E+07	3.37E+07	1.98E+08	Wall A w
-4.65E+05	2.46E+07	2.17E+07	1.85E+08	Wall A S
-1.75E+05	3.19E+07	3.37E+07	1.98E+08	Wall A E
-4.65E+05	2.46E+07	2.17E+07	1.85E+08	Wall A N
-7.76E+08	-1.39E+11	-1.72E+11	-4.89E+11	Wall U-Value West
-9.08E+07	-5.03E+09	-6.56E+09	4.77E+09	Wall U-Value South
-7.78E+07	5.98E+08	2.30E+09	-1.26E+09	Wall U-Value East
-2.89E+07	1.17E+09	6.84E+08	6.76E+09	Wall U-Value North
-1.19E+08	-3.23E+09	-5.29E+09	-1.38E+10	Window-to-Wall Ratio West
-1.21E+09	5.48E+09	2.68E+09	2.23E+10	Window-to-Wall Ratio South
1.90E+07	-1.64E+10	-2.52E+10	-5.66E+10	Window-to-Wall Ratio East
-1.03E+09	-6.02E+09	-1.49E+10	-1.05E+10	Window-to-Wall Ratio North
-3.30E+05	1.84E+07	3.44E+07	2.18E+07	window Area West
1.17E+06	3.50E+07	6.08E+07	5.91E+07	Window Area South
1.81E+05	5.55E+07	8.16E+07	1.64E+08	Window Area East
8.18E+05	4.22E+07	6.82E+07	8.30E+07	Window Area North
1.23E+06	6.28E+07	7.75E+07	2.42E+08	West Win U-value * Window Area
8.80E+05	6.02E+07	7.54E+07	2.22E+08	South U-value * Window Area
6.88E+05	5.58E+07	6.66E+07	2.14E+08	East U-value * Window Area
7.65E+05	6.26E+07	7.75E+07	2.21E+08	North U-value * Window Area
9.39E+05	4.31E+07	5.43E+07	1.45E+08	Roof Emissivity * Roof Area/number of stories
-1.42E+05	-7.27E+06	-1.07E+07	-1.35E+07	Roof Solar Absorptance * Roof Area
-7.57E+05	-6.79E+07	-7.40E+07	-2.56E+08	Roof R-value * Roof Area/Number of Stories
-2.91E+06	-3.26E+08	-5.03E+08	-8.89E+08	West SHGC * Window Area

Continue Table 5.1

-2.96E+06	-2.25E+08	-3.34E+08	-6.10E+08	South SHGC * Window Area
-2.31E+06	-2.51E+08	-3.53E+08	-6.33E+08	East SHGC * Window Area
-8.34E+05	-2.22E+08	-3.17E+08	-5.94E+08	North SHGC * Window Area
2.06E+07	7.44E+09	1.03E+10	2.28E+10	West Shading Project Factor * window-to-wall ratio
1.01E+08	3.67E+10	5.44E+10	1.24E+11	South Shading Project Factor * window-to-wall ratio
1.07E+08	2.50E+10	3.84E+10	7.56E+10	East Shading Project Factor * window-to-wall ratio
9.87E+07	3.24E+10	4.66E+10	1.11E+11	North Shading Project Factor * window-to-wall ratio
1.91E+08	8.78E+09	1.69E+10	4.81E+09	sin(orientation)+abs(cos(orientation))
1.28E+05	1.06E+07	1.78E+07	6.57E+06	West U-value * Window Area * sin(O)+abs(cos(O))
8.81E+04	3.12E+06	5.11E+06	-1.35E+06	South U-value * Window Area * sin(O)+abs(cos(O))
5.41E+04	-3.01E+06	-4.86E+06	-7.42E+05	East U-value * Window Area * sin(O)+abs(cos(O))
4.72E+04	8.19E+05	7.83E+05	-1.42E+05	North U-value * Window Area * sin(O)+abs(cos(O))
9.05E+05	-1.15E+08	-1.55E+08	-4.52E+08	West Wall U-value * Opaque Wall Area
7.48E+04	-6.35E+06	-7.17E+06	-2.75E+07	South Wall U-value * Opaque Wall Area
-3.97E+05	-2.12E+06	-6.96E+05	-2.43E+06	East Wall U-value * Opaque Wall Area
-5.67E+04	1.71E+06	1.57E+06	1.03E+07	North Wall U-value * Opaque Wall Area
3.63E+05	1.01E+08	1.59E+08	4.01E+08	West SHGC * Window Area * sin(O)+abs(cos(O))
5.51E+05	8.35E+06	1.59E+07	8.93E+05	South SHGC * Window Area * sin(O)+abs(cos(O))
3.63E+05	-3.43E+07	-5.08E+07	-1.15E+08	East SHGC * Window Area * sin(O)+abs(cos(O))
-1.59E+06	1.57E+07	3.42E+07	-1.11E+07	North SHGC * Window Area * sin(O)+abs(cos(O))

Table 5.2: Final cross product parameters, as well as their values that were included in the cooling equation for the LRBEM+.

1A-Miami	**4A-Winston-Salem**	**4B-Albuquerque**	**6A-Minneapolis**	
-2.71E+10	-1.38E+10	-2.38E+10	-1.49E+10	intercept
1.38E+08	8.57E+07	6.88E+07	5.46E+07	Area in m2
4.76E+07	-4.89E+06	-9.00E+06	-6.57E+06	Wall A w
3.94E+07	-8.77E+06	-1.40E+07	-9.46E+06	Wall A S
4.76E+07	-4.89E+06	-9.00E+06	-6.57E+06	Wall A E
3.94E+07	-8.77E+06	-1.40E+07	-9.46E+06	Wall A N
2.53E+10	1.96E+10	2.13E+10	1.50E+10	Window-to-Wall Ratio West
8.52E+10	5.70E+10	6.28E+10	4.39E+10	Window-to-Wall Ratio South
4.22E+10	3.66E+10	4.18E+10	2.64E+10	Window-to-Wall Ratio East
9.70E+10	6.26E+10	7.89E+10	4.61E+10	Window-to-Wall Ratio North
-6.63E+07	-3.83E+07	-3.73E+07	-2.61E+07	window Area West
-6.33E+07	-4.99E+07	-5.14E+07	-3.22E+07	Window Area South
-5.82E+07	-6.34E+07	-6.73E+07	-3.78E+07	Window Area East
-7.35E+07	-5.66E+07	-6.51E+07	-3.69E+07	Window Area North
3.58E+06	-7.15E+06	-5.80E+06	-5.67E+06	West Win U-value * Window Area
4.63E+06	-7.58E+06	-7.35E+06	-6.45E+06	South U-value * Window Area
6.07E+06	-7.80E+06	-8.14E+06	-6.65E+06	East U-value * Window Area
5.17E+06	-7.54E+06	-7.09E+06	-5.91E+06	North U-value * Window Area
-5.44E+07	-5.93E+07	-6.20E+07	-4.20E+07	Roof Emissivity * Roof Area
1.54E+07	1.38E+07	1.46E+07	7.71E+06	Roof Solar Absorptance * Roof Area
-1.31E+07	1.01E+07	7.52E+06	6.68E+06	Roof R-value * Roof Area
5.77E+08	4.16E+08	4.62E+08	2.83E+08	West SHGC * Window Area
4.44E+08	3.22E+08	3.34E+08	2.29E+08	South SHGC * Window Area
4.25E+08	3.11E+08	3.49E+08	2.22E+08	East SHGC * Window Area
4.46E+08	3.20E+08	4.26E+08	2.32E+08	North SHGC * Window Area
-3.98E+10	-2.70E+10	-3.00E+10	-2.08E+10	West Shading Project Factor * window-to-wall ratio
-1.49E+11	-1.20E+11	-1.30E+11	-8.98E+10	South Shading Project Factor * window-to-wall ratio
-8.04E+10	-6.60E+10	-7.84E+10	-4.88E+10	East Shading Project Factor * window-to-wall ratio

Continue Table 5.2

-1.36E+11	-1.03E+11	-1.26E+11	-7.61E+10	North Shading Project Factor * window-to-wall ratio
-8.29E+08	-1.78E+09	-2.12E+09	-8.41E+07	sin(orientation)
4.09E+10	2.57E+10	4.26E+10	2.93E+10	sin(orientation) squared
-1.30E+08	1.52E+07	2.46E+06	1.28E+07	West Wall U-value * Opaque Wall Area
1.02E+06	3.24E+06	2.61E+06	1.21E+06	South Wall U-value * Opaque Wall Area
2.21E+06	7.45E+05	2.18E+06	2.28E+06	East Wall U-value * Opaque Wall Area
4.65E+05	-2.18E+06	-9.77E+05	-7.65E+05	North Wall U-value * Opaque Wall Area
-1.45E+08	-1.27E+08	-1.37E+08	-6.35E+07	West SHGC * Window Area * sin(O)+abs(cos(O))
3.42E+07	4.27E+07	6.53E+07	3.53E+07	South SHGC * Window Area * sin(O)+abs(cos(O))
9.38E+07	9.85E+07	1.34E+08	6.35E+07	East SHGC * Window Area * sin(O)+abs(cos(O))
3.15E+07	2.24E+07	2.14E+07	1.74E+07	North SHGC * Window Area * sin(O)+abs(cos(O))

Table 5.3: List of building parameters and derived parameters that went into the Stepwise Regression.

Building Parameter Terms	
1	Area in m2
2	Wall A w
2	Wall A S
4	Wall A E
5	Wall A N
6	Surface Area
7	Orientation
8	Roof Emissivity
9	Roof Solar Absorptance
10	Roof R-Value
11	Window SHGC West
12	Window SHGC South
13	Window SHGC East
14	Window SHGC North
15	Window U-Value West
16	Window U-Value South
17	Window U-Value East
18	Window U-Value North
19	Wall U-Value West
20	Wall U-Value South
21	Wall U-Value East
22	Wall U-Value North
23	Shading Projection West
24	Shading Projection South
25	Shading Projection East
26	Shading Projection North
27	Window-to-Wall Ratio West
28	Window-to-Wall Ratio South
29	Window-to-Wall Ratio East
30	Window-to-Wall Ratio North

Continue Table 5.3

Derived Parameters- Cross Multiplied Terms	
31	Window Area West
32	Window Area South
32	Window Area East
34	Window Area North
35	West Window Area * cos(rotation)
36	South Window Area * cos(rotation)
37	East Window Area * cos(rotation)
38	North Window Area * cos(rotation)
39	West Win U-value * Window Area
40	South U-value * Window Area
41	East U-value * Window Area
42	North U-value * Window Area
43	Roof Emissivity * Roof Area
44	Roof Solar Absorptance * Roof Area
45	Roof R-value * Roof Area
46	Roof Emissivity * Roof Area / Number of Stories
47	Roof Solar Absorptance * Roof Area / Number of Stories
48	Roof R-value * Roof Area / Number of Stories
49	West SHGC * Window Area
50	South SHGC * Window Area
51	East SHGC * Window Area
52	North SHGC * Window Area
53	West Shading Project Factor * window-to-wall ratio
54	South Shading Project Factor * window-to-wall ratio
55	East Shading Project Factor * window-to-wall ratio
56	North Shading Project Factor * window-to-wall ratio
57	north window area^2
58	south window area^2
59	sin(orientation)
60	cos(orientation)
61	abs(cos(orientation))
62	sin(orientation) squared

Continue Table 5.3

63	cos(orientation) squared
64	sin(orientation)+abs(cos(orientation))
65	West U-value * Window Area * sin(O)+abs(cos(O))
66	South U-value * Window Area * sin(O)+abs(cos(O))
67	East U-value * Window Area * sin(O)+abs(cos(O))
68	North U-value * Window Area * sin(O)+abs(cos(O))
69	3-[sin(orientation) + abs(cos(orientation))]
70	West Window Area * [sin(O) + abs(cos(O))]
71	South Window Area * [sin(O) + abs(cos(O))]
72	East Window Area * [sin(O) + abs(cos(O))]
73	North Window Area * [sin(O) + abs(cos(O))]
74	West Wall U-value * Opaque Wall Area
75	South Wall U-value * Opaque Wall Area
76	East Wall U-value * Opaque Wall Area
77	North Wall U-value * Opaque Wall Area
78	West SHGC * Window Area * sin(O)+abs(cos(O))
79	South SHGC * Window Area * sin(O)+abs(cos(O))
80	East SHGC * Window Area * sin(O)+abs(cos(O))
81	North SHGC * Window Area * sin(O)+abs(cos(O))
82	West Shading Project Factor * window-to-wall ratio * sin(O)+abs(cos(O))
83	South Shading Project Factor * window-to-wall ratio * sin(O)+abs(cos(O))
84	East Shading Project Factor * window-to-wall ratio * sin(O)+abs(cos(O))
85	North Shading Project Factor * window-to-wall ratio * sin(O)+abs(cos(O))
86	Roof Area

Table 5.4: Building in Figure 3.1 parameter definitions.

Parameter	**Value**
Total Floor Area	8926 (m2)
Envelop Area/ Floor Area	0.89
Orientation	0
Stories	3
Window/Wall ratio (N,S, E,W)	40%
Shading Projection Factor (N,S, E,W)	0.5
Window SHGC (N,S, E,W)	0.35
Window R Value (N,S, E,W)	2.22
Wall R Value (N,S, E,W)	18.3
Roof Emissivity	0.9
Roof Solar Absorptance	0.7
Roof R Value	25.8

Table 5.5: Experiments A through C parameter definitions.

R Values are in (BTU/hft^2f), Areas in Meter	**A1**	**A2**	**B1**	**B2**	**C1**	**C2**	**Units**
Building Floor Area	5,775	5,217	2,174	6,535	7,223	9,751	M²
Roof Area	1,925	1,739	725	2,178	3,313	4,579	M²
Orientation	-	-	-	-	-	-	Degrees
West Wall Area	617	672	334	397	962	1,165	M²
South Wall Area	891	1,083	591	794	481	1,097	M²
East Wall Area	617	672	-	397	962	1,165	M²
North Wall Area	891	1,083	591	794	481	1,097	M²
Roof Emissivity	0.9	0.9	0.9	0.9	0.9	0.9	-
Roof Solar Absorptance	0.7	0.7	0.7	0.7	0.7	0.7	-
Roof R-Value	25.8	25.8	25.8	25.8	25.8	25.8	(BTU/hft^2f),

Continue table 5.5

West Window SHGC	0.35	0.35	0.35	0.35	0.35	0.35	-
South Window SHGC	0.35	0.35	0.35	0.35	0.35	0.35	-
East Window SHGC	0.35	0.35	0.35	0.35	0.35	0.35	-
North Window SHGC	0.35	0.35	0.35	0.35	0.35	0.35	-
West Window R-Value	2.22	2.22	2.22	2.22	2.22	2.22	(BTU/hft^2f)
South Window R-Value	2.22	2.22	2.22	2.22	2.22	2.22	(BTU/hft^2f)
East Window R-Value	2.22	2.22	2.22	2.22	2.22	2.22	(BTU/hft^2f)
North Window R-Value	2.22	2.22	2.22	2.22	2.22	2.22	(BTU/hft^2f)
West Wall R-Value	18.30	18.30	18.30	18.30	18.30	18.30	(BTU/hft^2f)
South Wall R-Value	18.30	18.30	18.30	18.30	18.30	18.30	(BTU/hft^2f)
East Wall R-Value	18.30	18.30	18.30	18.30	18.30	18.30	(BTU/hft^2f)
North Wall R-Value	18.30	18.30	18.30	18.30	18.30	18.30	(BTU/hft^2f)
West Shading Projection Factor	0.500	0.500	0.500	0.500	0.500	0.500	% of window height
Shading Projection Factor South	0.500	0.500	0.500	0.500	0.500	0.500	% of window height
East Shading Projection Factor	0.500	0.500	0.500	0.500	0.500	0.500	% of window height
North Shading Projection Factor	0.500	0.500	0.500	0.500	0.500	0.500	% of window height
West Window-to-Wall Ratio	40.00%	40.00%	40.00%	40.00%	40.00%	40.00%	%

Continue Table 5.5

South Window-to-Wall Ratio	40.00%	40.00 %	40.00 %	40.0 0%	40. 00 %	40. 00 %	%
East Window-to-Wall Ratio	40.00%	40.00 %	40.00 %	40.0 0%	40. 00 %	40. 00 %	%
North Window-to-Wall Ratio	40.00%	40.00 %	40.00 %	40.0 0%	40. 00 %	40. 00 %	%

Table 5.6: Ranking of the 30 parameters according to their importance in heating in the four climate zones, knowing that the importance of wall, roof, floor areas are aggregated with parameter term areas.

Miami	Winston-Salem	Albuquerque	Minneapolis
Areas	Areas	South W/W	Areas
North W/W	Window-to-Wall Ratio South	Areas	South W/W
South W/W	Window-to-Wall Ratio North	North W/W	North W/W
West W/W	Window-to-Wall Ratio West	West W/W	West W/W
South Window R-Value	Window R-Value North	South Window R-Value	East W/W
Orientation (degrees)	Window R-Value South	East Window R-Value	North Window R-Value
West Window R-Value	Window R-Value West	North Window R-Value	South Window R-Value
East W/W	Window-to-Wall Ratio East	Orientation (degrees)	West Window R-Value
North Window R-Value	Orientation (degrees)	West Window R-Value	Roof R-Value
East Window R-Value	Roof R-Value	East W/W	East Window R-Value
Roof R-Value	Window R-Value East	South SHGC	West Wall R-Value
South SHGC	Window SHGC North	North SHGC	South SHGC
West SHGC	Window SHGC South	Roof R-Value	North SHGC

Continue Table 5.6

Roof Emissivity	Wall R-Value West	West Wall R-Value	East SHGC
East SHGC	Window SHGC East	East SHGC	Orientation (degrees)
Roof Solar Absorptance	Window SHGC West	West SHGC	South SPF
North SHGC	Shading Projection Factor South	South SPF	West SHGC
West Wall R-Value	Shading Projection Factor North	North SPF	North SPF
East Wall R-Value	Roof Solar Absorptance	East SPF	East SPF
East SPF	Shading Projection Factor East	Roof Solar Absorptance	Roof Emissivity
North SPF	Roof Emissivity	Roof Emissivity	Roof Solar Absorptance
South SPF	Shading Projection Factor West	West SPF	West SPF
North Wall R-Value	Wall R-Value South	SouthWall R-Value	North Wall R-Value
West SPF	Wall R-Value North	East Wall R-Value	SouthWall R-Value
SouthWall R-Value	Wall R-Value East	North Wall R-Value	East Wall R-Value

Table 5.7: Ranking of the 30 parameters according to their importance in cooling in the four climate zones, knowing that the importance of wall, roof, floor Areas are aggregated with Areas.

Miami	**Winston-Salem**	**Albuquerque**	**Minneapolis**
Areas	Areas	Areas	Areas
North W/W	Orientation (degrees)	Orientation (degrees)	Orientation (degrees)
South W/W	Window SHGC South	North W/W	South SHGC
East W/W	Shading Projection Factor South	North SHGC	South SPF
South SPF	Window SHGC North	South SHGC	North SHGC
South SHGC	Window-to-Wall Ratio South	South SPF	South W/W
North SHGC	Shading Projection Factor North	South W/W	North SPF
East SHGC	Window-to-Wall Ratio North	North SPF	North W/W
North SPF	Window SHGC East	East SHGC	East SHGC
West W/W	Window-to-Wall Ratio East	East W/W	West W/W
West SHGC	Window-to-Wall Ratio West	West W/W	East W/W
East SPF	Window SHGC West	East SPF	West SHGC
Roof Solar Absorptance	Shading Projection Factor East	West SHGC	East SPF
West SPF	Roof Solar Absorptance	Roof Solar Absorptance	Roof Solar Absorptance
Roof Emissivity	Shading Projection Factor West	West SPF	West SPF
West Wall R-Value	Roof Emissivity	Roof Emissivity	Roof Emissivity
Roof R-Value	Window R-Value North	South Window R-Value	South Window R-Value
North Window R-Value	Window R-Value South	North Window R-Value	North Window R-Value
South Window R-Value	Roof R-Value	East Window R-Value	East Window R-Value
East Window R-Value	Window R-Value East	Roof R-Value	Roof R-Value

Continue Table 5.7

West Window R-Value	Window R-Value West	West Window R-Value	West Window R-Value
East Wall R-Value	Wall R-Value East	West Wall R-Value	West Wall R-Value
South Wall R-Value	Wall R-Value North	East Wall R-Value	East Wall R-Value
North Wall R-Value	Wall R-Value West	North Wall R-Value	South Wall R-Value
Orientation (degrees)	Wall R-Value South	South Wall R-Value	North Wall R-Value