# Statistical and Graphical Methods to Determine Importance and Interaction of Building Design Parameters to Inform and Support Design Decisions

by

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ABSTRACT

This research is aimed at studying the impact of building design parameters in terms of their importance and mutual interaction, and how these aspects vary across climates and HVAC system types. A methodology is proposed for such a study, by examining the feasibility and use of two different statistical methods to derive all realistic 'near-optimum' solutions which might be lost using a simple optimization technique.

DOE prototype medium office building compliant with ASHRAE 90.1-2010 was selected for the analysis and four different HVAC systems in three US climates were simulated.

The interaction between building design parameters related to envelope characteristics and geometry (total of seven variables) has been studied using two different statistical methods, namely the 'Morris method' and 'Predictive Learning via Rule Ensembles'.

Subsequently, a simple graphical tool based on sensitivity analysis has been developed and demonstrated to present the results from parametric simulations. This tool would be useful to better inform design decisions since it allows imposition of constraints on various parameters and visualize their interaction with other parameters.

It was observed that the Radiant system performed best in all three climates, followed by displacement ventilation system. However, it should be noted that this study did not deal with performance optimization of HVAC systems while there have been several studies which concluded that a VAV system with better controls can perform better than some of the newer HVAC technologies. In terms of building design parameters, it was observed that 'Ceiling Height', 'Window-Wall Ratio' and

‘Window Properties’ showed highest importance as well as interaction as compared to other parameters considered in this study, for all HVAC systems and climates.

Based on the results of this study, it is suggested to extend such analysis using statistical methods such as the ‘Morris method’, which require much fewer simulations to categorize parameters based on their importance and interaction strength. Usage of statistical methods like ‘Rule Ensembles’ or other simple visual tools to analyze simulation results for all combinations of parameters that show interaction would allow designers to make informed and superior design decisions while benefiting from large reduction in computational time.

# DEDICATION

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TABLE OF CONTENTS

Page

LIST OF TABLES ........ viii

LIST OF FIGURES ........ ix

CHAPTER

1. RESEARCH PLAN AND OVERVIEW ........ 1

1.1 Problem Statement ........ 1

1.2 Objective ........ 1

1.3 Introduction ........ 2

2. LITERATURE REVIEW ........ 5

3. THEORY ........ 12

3.1 Software Used ........ 12

3.1.1 EnergyPlus v8.2 ........ 12

3.1.2 GenOpt v3.1.0 ........ 12

3.1.3 R ........ 13

3.1.4 MS Excel ........ 13

3.2 Statistical Methods ........ 14

3.2.1 Morris Method ........ 14

3.2.2 Predictive Learning via Rule Ensembles ........ 15

4. METHODOLOGY ........ 18

4.1 DOE Prototype Building Description ........ 18

4.2 Climate Selection ........ 19

4.3 HVAC Systems ........ 22

4.3.1 VAV (ASHRAE 90.1 Base Model) ........ 22

4.3.2 VAV + Indirect Evaporative Cooling (Outdoor Air) ........ 23

4.3.3 Displacement Ventilation ........ 23

CHAPTER Page

4.3.4 Radiant Cooling System with DOAS ........ 24

4.4 Building Design Parameters and Their Ranges ........ 25

4.4.1 Aspect Ratio ‘AR’ ........ 25

4.4.2 Floor to Ceiling Height ‘CH’ ........ 25

4.4.3 Depth of Perimeter Zone ‘PZD’ ........ 25

4.4.4 Window-Wall Ratio ‘WWR’ ........ 26

4.4.5 Wall U-Value ‘WU’ ........ 26

4.4.6 Roof U-Value ‘RU’ ........ 26

4.4.7 Glass Type ‘WinU’ (A Combination of U-Value and SHGC) ........ 26

4.5 Utility Cost Structure ........ 28

5. RESULTS AND DISCUSSIONS ........ 29

5.1 HVAC Performance in Various Climates ........ 29

5.2 Importance and Interaction of Parameters ........ 30

5.2.1 Morris Method ........ 30

5.2.2 RuleFit Method ........ 34

6. PROPOSED VISUALIZATION TOOLS ........ 43

7. SAMPLE ANALYSIS ........ 48

8. CONCLUSIONS ........ 53

9. FUTURE WORK ........ 54

10. REFERENCES ........ 58

APPENDIX

A CHARTS FOR ELEMENTARY ANALYSIS USING MORRIS METHOD ........ 61

B CHARTS FOR IMPORTANCE AND INTERACTION STRENGTH USING ‘PREDICTIVE LEARNING VIA RULE ENSEMBLES’ ALGORITHM ........ 66

APPENDIX Page

C CHARTS FOR DETAILED INTERACTION OF A PARAMETER WITH OTHERS USING 'PREDICTIVE LEARNING VIA RULE ENSEMBLES' ALGORITHM .........................69

LIST OF TABLES

Table Page

1: Climate Classification, Source: Baechler et al (2010)..........20

2: Ranges for Input Parameters..........28

3: Relative Importance and Interaction Strengths for All Parameters for Memphis..........37

4: Relative Importance and Interaction Strengths for All Parameters for Phoenix..........38

5: Relative Importance and Interaction Strengths for All Parameters for Albuquerque..........39

LIST OF FIGURES

Figure Page

1: Error Comparison of Decision Tree Models for Regression (Friedman Et Al, 2005) ........ 17

2: Error Comparison of Decision Tree Models for Classification (Friedman Et Al, 2005) ........ 17

3: Building Geometry (Courtesy: PNNL Scorecard) ........ 18

4: Zoning Diagram (Courtesy: PNNL Scorecard) ........ 19

5: Bin Data for Phoenix (2B – Hot Dry) ........ 21

6: Bin Data for Memphis (3A – Mixed Humid) ........ 21

7: Bin Data for Albuquerque (4B – Mixed Dry) ........ 22

8: Utility Cost Vs CDD for Various HVAC Systems ........ 29

9: Memphis - VAV (48 Simulations) ........ 31

10: Memphis - VAV (200 Simulations) ........ 31

11: Memphis - VAV + Evap (200 Simulations) ........ 32

12: Memphis - Displacement Ventilation (200 Simulations) ........ 33

13: Memphis - DOAS + Radiant (200 Simulations) ........ 33

14: Importance Vs Interaction Strength of Parameters in Memphis ........ 35

15: Importance Vs Interaction Strength of Parameters for VAV System (Other Climates) ........ 36

16: Interaction with 'CH', for Memphis-VAV ........ 40

17: Interaction with 'AR', for Memphis-VAV ........ 40

18: Interaction with 'PZD', for Memphis-VAV ........ 41

19: Interaction with 'WWR', for Memphis-VAV ........ 41

20: Interaction with 'WU', for Memphis-VAV ........ 42

21: Interaction with 'RU', for Memphis-VAV ........ 42

Figure Page

22: Interaction with 'Winu', for Memphis-VAV ... 43

23: Simplified Visual Tool, Base Screen ... 44

24: Simplified Visual Tool, Saving Visualization ... 46

25: Simplified Visual Tool, Interaction Visualization ... 47

26: Memphis - VAV, All Parameters Floating ... 48

27: Memphis-VAV, 'AR' & 'PZD' Fixed ... 49

28: Memphis-VAV, 'CH' Fixed ... 49

29: Memphis-VAV, 'WWR' Fixed ... 50

30: Memphis-VAV, 'WWR' Fixed at 0.1 ... 52

31: Memphis-VAV, All but 'WWR' Fixed ... 52

32: Memphis VAV (All Parameters Including LPD) ... 55

33: HVAC System Performance for Memphis (Including Better VAV) ... 56

34: Morris Method (σ vs μ*) for Phoenix – VAV ... 62

35: Morris Method (σ vs μ*) for Phoenix – VAV + Evaporative ... 62

36: Morris Method (σ vs μ*) for Phoenix – Displacement Ventilation ... 63

37: Morris Method (σ vs μ*) for Phoenix – DOAS + Radiant Cooling ... 63

38: Morris Method (σ vs μ*) for Albuquerque – VAV ... 64

39: Morris Method (σ vs μ*) for Albuquerque – VAV + Evaporative ... 64

40: Morris Method (σ vs μ*) for Albuquerque – Displacement Ventilation ... 65

41: Morris Method (σ vs μ*) for Albuquerque – DOAS + Radiant Cooling ... 65

42: RuleFit Method - Importance Vs Interaction Strength for Phoenix ... 67

43: RuleFit Method - Importance Vs Interaction Strength for Albuquerque ... 68

44: RuleFit Method - Interaction Strengths with ‘CH’ and ‘AR’ for Memphis – VAV + Evaporative ... 70

Figure Page

45: RuleFit Method - Interaction Strengths with ‘PZD’ and ‘WWR’ for Memphis – VAV + Evaporative ........ 70

46: RuleFit Method - Interaction Strengths with ‘WU’ and ‘RU’ for Memphis – VAV + Evaporative ........ 71

47: RuleFit Method - Interaction Strengths with ‘WinU’ for Memphis – VAV + Evaporative ........ 71

48: RuleFit Method - Interaction Strengths with ‘CH’ and ‘AR’ for Memphis – Displacement Ventilation ........ 72

49: RuleFit Method - Interaction Strengths with ‘PZD’ and ‘WWR’ for Memphis – Displacement Ventilation ........ 72

50: RuleFit Method - Interaction Strengths with ‘WU’ and ‘RU’ for Memphis – Displacement Ventilation ........ 73

51: RuleFit Method - Interaction Strengths with ‘WinU’ for Memphis – Displacement Ventilation ........ 73

52: RuleFit Method - Interaction Strengths with ‘CH’ and ‘AR’ for Memphis – DOAS + Radiant Cooling ........ 74

53: RuleFit Method - Interaction Strengths with ‘PZD’ and ‘WWR’ for Memphis – DOAS + Radiant Cooling ........ 74

54: RuleFit Method - Interaction Strengths with ‘WU’ and ‘RU’ for Memphis – DOAS + Radiant Cooling ........ 75

55: RuleFit Method - Interaction Strengths with ‘WinU’ for Memphis – DOAS + Radiant Cooling ........ 75

56: RuleFit Method - Interaction Strengths with ‘CH’ and ‘AR’ for Phoenix – VAV ........ 76

57: RuleFit Method - Interaction Strengths with ‘CH’ and ‘WWR’ for Phoenix – VAV 76

58: RuleFit Method - Interaction Strengths with ‘WU’ and ‘RU’ for Phoenix – VAV ........ 77

Figure Page

59: RuleFit Method - Interaction Strengths with 'WinU' for Phoenix – VAV ............77

60: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Phoenix – VAV + Evaporative ............78

61: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Phoenix – VAV + Evaporative ............78

62: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Phoenix – VAV + Evaporative ............79

63: RuleFit Method - Interaction Strengths with 'WinU' for Phoenix – VAV + Evaporative ............79

64: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Phoenix – Displacement Ventilation ............80

65: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Phoenix – Displacement Ventilation ............80

66: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Phoenix – Displacement Ventilation ............81

67: RuleFit Method - Interaction Strengths with 'WinU' for Phoenix – Displacement Ventilation ............81

68: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Phoenix – DOAS + Radiant Cooling ............82

69: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Phoenix – DOAS + Radiant Cooling ............82

70: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Phoenix – DOAS + Radiant Cooling ............83

71: RuleFit Method - Interaction Strengths with 'WinU' for Phoenix – DOAS + Radiant Cooling ............83

Figure Page

72: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Albuquerque – VAV ....................................................................................................84

73: RuleFit Method - Interaction Strengths with 'CH' and 'WWR' for Albuquerque – VAV ................................................................................................84

74: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Albuquerque – VAV ....................................................................................................85

75: RuleFit Method - Interaction Strengths with 'WinU' for Albuquerque – VAV ......85

76: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Albuquerque – VAV + Evaporative ......................................................................................86

77: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Albuquerque – VAV + Evaporative ..............................................................................86

78: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Albuquerque – VAV + Evaporative ......................................................................................87

79: RuleFit Method - Interaction Strengths with 'WinU' for Albuquerque – VAV + Evaporative ...........................................................................................87

80: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Albuquerque – Displacement Ventilation ........................................................................88

81: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Albuquerque – Displacement Ventilation ........................................................................88

82: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Albuquerque – Displacement Ventilation ........................................................................89

83: RuleFit Method - Interaction Strengths with 'WinU' for Albuquerque – Displacement Ventilation ........................................................................89

84: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Albuquerque – DOAS + Radiant Cooling ........................................................................90

Figure Page

85: RuleFit Method - Interaction Strengths with ‘PZD’ and ‘WWR’ for Albuquerque – DOAS + Radiant Cooling ........................................................................ 90

86: RuleFit Method - Interaction Strengths with ‘WU’ and ‘RU’ for Albuquerque – DOAS + Radiant Cooling ........................................................................ 91

87: RuleFit Method - Interaction Strengths with ‘WinU’ for Albuquerque – DOAS + Radiant Cooling ............................................................................... 91

# 1. RESEARCH PLAN AND OVERVIEW

## 1.1 Problem Statement

Interaction of building design parameters while computing energy performance of buildings have always demanded special attention from designers. Designers generally address this challenging task either by setting up an optimization problem or by carrying out a parametric analysis.

Optimization programs are generally set up in a way to provide a unique optimum solution, where many of the potential sub-optimum solutions (or near-optimum solutions) whose performance lie very close to the optimum solution are lost. In many cases, such solutions may prove to be better alternatives, should other constraints such as financial or site-related be included. With parametric analysis, the interpretation and analysis become too complex due to the large number of parameters involved and the order in which the parameters are varied, because of mutual interaction effects between these parameters.

On the other hand, impact of building envelope and geometry on energy consumption differs with type of HVAC systems involved and the climate under consideration. This makes it difficult to anticipate the impact of various parameters from prior works, which forces the designer to run simulations for all combination of parameters.

## 1.2 Objective

This research is aimed at studying the impact of building design parameters (geometry and envelope characteristics) in terms of their importance and mutual interaction, and how these aspects vary across climates and HVAC system types. A methodology is proposed for such a study, by examining the feasibility and use of two different statistical methods, to inform design decision and derive all realistic 'near-optimum' solutions which might be lost using a simple optimization technique.

### 1.3 Introduction

Generally a process to determine design parameters is viewed by many researchers as an optimization problem. However in case of buildings, the number of design options and variables are so large that an exhaustive search to locate all such (optimum and sub-optimum) solutions become a very cumbersome if not impossible task.

In a simple parametric analysis, what has always been a matter of concern and required significant judgement, is the rank of various measures in ascertaining the cascade of measures for energy efficient design. Sensitivity analysis can play an important role in determining such an order in the cascade. Further, the number of parameters involved in building energy modeling is so large that parametric simulations for all such variations require very long computational as well as analysis times.

In the past, many studies have been performed to determine the importance of input design parameters in terms of first order (local) sensitivity analysis, higher order (global) sensitivity analysis, multiple regression analysis, etc. Local sensitivity analysis could be useful for determining the importance of a measure among various measures available, but does not provide a clear understanding of the possible savings when employed along with multiple measures and constraints, during the design process.

On the other hand, with advancements in technology and emergence of newer and more efficient HVAC systems and techniques, the interaction of building design parameters might not be similar for different system types and even climates. It is important to analyze the interaction of building design parameters with different types of HVAC system, rather than carrying out the study for building envelope and HVAC systems in isolation.

Though the methodology can be used for making design decisions for different types of buildings and different types of design parameters, this study uses a DOE prototype midrise office building model initially developed by US DOE, PNNL and NREL (Deru et al, 2011), with enhancements for various versions of ASHRAE 90.1 by PNNL (Goel et al, 2014). The building type selected is a three floor 'Medium Office' building, with floor area of '53,628 $ft^2$', aspect ratio of '1.5', floor to floor height of '13 ft.', floor to ceiling height of '9 ft.', and glazing fraction of '0.33'. Inputs for all parameters that are governed by ASHRAE 90.1 (Goel et al, 2014) have been taken from 2010 version. The building is described in more detail in the methodology section. The categorization of building types in the DOE's reference building models is based on CBECS 2003 database (Deru et al, 2011). CBECS is a survey of US buildings conducted by EIA about every four years. 2003 CBECS include data from field survey of non-mall commercial buildings with a sample size of 4,820. For each building, CBECS presents data on floor area, number of floors, census division, basic climate design criteria, principal building activity, number of employees, and other characteristics. (Griffith et al, 2007)

The range for variation of independent parameters selected in this study has been determined using engineering judgement, general practice, and prior works in this domain, making sure that the ranges for parameters that are governed by ASHRAE 90.1 covers all input recommendations across different vintages of ASHRAE 90.1 starting from pre 1980 construction inputs assumed by Deru et al (2011), until the ASHRAE 90.1-2010 vintage and the advanced design models proposed by ASHRAE for 50% saving design guide. The selection of ranges has been discussed below in the methodology section of this document.

The 50% Energy Saving Design Guide has been used as a source for system design parameters for some of the newer HVAC technologies included is this study, and the input recommendations for advanced design have been considered as the upper limit of the ranges for parametric variations.

Two statistical methods have been used for the analysis of parameter importance and interaction among parameters. The Morris method is used for global sensitivity analysis (elementary analysis for classification of parameters), which has proved to be a good method for such studies and requires moderate computational time as per Tian et al (2013) and Sanchez et al (2014). 'Predictive Learning via Rule Ensembles' technique has been utilized to analyze detailed interaction of parameters (Friedman et al, 2005). Further, this study proposes the use of a simplified tool based on sensitivity analysis to better inform design decisions during the early design stage.

## 2. LITERATURE REVIEW

Addison (1988) developed and demonstrated a computer based design methodology suitable for use with any energy simulation program and at any of the design phases. It is a multiple criteria satisficing strategy intended to benefit any building design professional who is not an expert in the design of energy-efficient buildings, and would especially be useful for reaching the critical energy related decisions made early in the programming and conceptual design stages.

Snyder et al (2013) proposed an automated design methodology to provide designers a decision support tool rather than an optimization tool, which generates numerous design alternatives rather than an optimum solution. This involved a relatively small number of parameters and adopted a design of experiments response surface approach.

Dutta (2013) proposed an interactive visualization approach which used regression based models to create dynamic interplays of how varying these important variables affect the multiple criteria, while providing a visual range or band of variation of the different design parameters using parallel coordinate representation. It was based on the application of Monte Carlo approaches to create a database of solutions using deterministic whole building energy simulations, along with data mining methods (random forest algorithm) to rank variable importance and reduce the multi-dimensionality of the problem.

The present study proposes alternative design methodology to the two prior studies and extends their scope by considering parameter interactions more explicitly and to different types of advanced HVAC systems and their effect in different climates.

Kao (1985) studied the extent to which energy consumption is dependent on HVAC systems. Using BLAST, Kao simulated four types of buildings: small office (30,000 ft2), large office (22,297 ft2), school (66,048 ft2) & retail store (153,600 ft2). A wide variety of HVAC system was selected and the study was conducted for six sites with varied climates. The study came up with suggestions on strategies for HVAC system controls based on heating and cooling degree days for different buildings. Medium Office building was not considered as a category and a similar study taking into account the newer HVAC technologies / practices, using more advanced simulation tools would have been useful. Moreover, impact of building characteristics on various different HVAC system types through sensitivity analysis would have been a good extension. The current study includes these aspects.

Griffith et al (2007) quantified the energy performance opportunities for a large set of building models derived from the 2003 CBECS data. Each building was modeled first as a baseline complying with ASHRAE 90.1-2004 and then modified with a set of technologies and practices that represent projections for improvements out to 2025. The study concluded that about 62% of the buildings (47% of commercial building floor area), can reach Net-Zero. Two primary scenarios were modeled to access the potential of becoming net-zero, the 'Base' and the 'Max Tech'. 'Base' is the reference with prescriptive measures from Standard 90.1-2004 and 'Max Tech' is the scenario includes best estimates for improvements in envelope, lighting, plug loads, HVAC, and on-site generation, based on projections for what could be available in the market in 2025. This study did not include change in building geometry or base topology of the HVAC system. Studying the effects of change in building geometry, envelope characteristics and various HVAC systems would be a good extension.

Deru et al (2011) characterized the commercial building stock in US and developed reference models for them. Fifteen commercial building types and one multifamily residential building were determined to represent approximately two-third of the commercial building stock. The input parameters for the building models came from several sources, some determined from ASHRAE 90.1, 62.1-2004, and 62-1999, 90.1-89 and the rest were determined from other studies of data and standard practices. National data from 2003 CBECS (EIA 2005) were used to determine the appropriate average mix of representative buildings, with an intension to represent 70% of US commercial building floor area. CBECS PBAplus information was used to map data from the 2003 CBECS datasets to the reference buildings. This study provided an exhaustive database to determine ranges of input parameters that have been in practice for a long time.

Lam et al (1996) described the basic principles of sensitivity methods for studying building energy performance and analyzed office buildings in Hong Kong. Different forms of sensitivity coefficients were discussed and the analysis was performed in terms of three different outputs (Annual electricity consumption, peak building demand and load profiles), by varying about 60 input parameters. The study was limited to single order sensitivity analysis and different types of HVAC system were not considered. Extending this study to higher order analysis and applied to various HVAC system types would be very useful.

Al-Homoud (1997) selected 14 important variables and carried out an optimization. The range for input parameters variation were well defined, but has been outdated in the current practice.  The U-values for roof / wall as per ASHRAE 90.1 are now out of those ranges. The basis for selection of these ranges for input parameters needs to be redefined.

The intent of Stocki et al (2007) was to provide a set of standardized parametric values of important design variables for typical commercial buildings. These sets of specifications were developed from the criteria in ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings

(ASHRAE 2004b), and prior published works outlining the typical use patterns and energy densities. These assumptions could be utilized for getting an initial base model, especially the ones that are not governed by ASHRAE 90.1.

Lam et al (2008) carried out a sensitivity analysis for 10 calibrated building models, with 10 parameters categorized under building envelope, HVAC system and HVAC plant. The study was limited to first order sensitivity analysis only and the type of HVAC systems considered were identical. The first order influence coefficient did not capture the interaction between parameters. Use of higher order sensitivity analysis with more HVAC system types would be a good extension. The number of parameters were also very limited. Parameters like lighting and equipment loads are known to have a direct impact on energy consumption of the HVAC system. More number of building envelope parameters and their interaction with different HVAC types could be useful to inform the designers about the interaction of envelope characteristics with different HVAC system.

Bichiou et at (2011) carried out a study to optimize building envelope and HVAC systems independently as well as simultaneously for few of the residential building types in five US locations based on minimizing the LCC and annual energy cost. They used three algorithms (Genetic Algorithm, Particle Swarm Algorithm and Sequential search algorithm) to come up with the most accurate optimization solutions. The study showed that Genetic algorithm was more efficient in terms of time taken for optimization. It also revealed that simultaneous optimization of envelope and HVAC resulted in better accuracy / optimization compared to the sequential approach.

Though optimization techniques provide an optimum solution, they do not provide the range of options which a designer would like to explore. Better design decisions should not be limited to minimizing one or two dependent functions.

Tian et al (2013) presented a review of sensitivity analysis methods in building energy analysis. The study summarizes the pros and cons of various methods and has categorized the methods under two basic categories, local sensitivity analysis and global sensitivity analysis. Few of the methods discussed are Regression method, Screening based method (Morris method is most widely used as screening method), Variance based method, and Meta-model based method. This review can be used for selection of the sensitivity analysis algorithm which provides a good trade-off between accuracy and computation time.

Daly et al (2014) conducted a sensitivity analysis for few building envelope and internal load parameters using single order parametric variation to determine the influence coefficient of each variable separately for two forms of buildings in Australia. Input ranges were determined from an exhaustive literature study for various parameters in international literature. This analysis did not take into account second order sensitivity to establish the interaction of building input parameters. The study captured eight climates and two building forms but was limited to a particular HVAC system (water cooled VAV with gas boiler). An extension of such a study for various HVAC systems while incorporating the higher order sensitivity analysis would be very useful.

Sanchez et al (2014) incorporated the use of first order and higher order sensitivity analysis applied to a building energy model (ESP-r), using the Morris method. The study was carried out for an apartment building and the usefulness of higher-order analysis was highlighted. A similar analysis for different kinds of HVAC systems could be useful to inform the designers about the interaction between building envelope and HVAC system for various kinds of technologies available in the market.

Engelmann et al (2014) performed a simulation based approach to determine the energy saving potential and comfort characteristics of few low energy cooling systems and passive cooling systems (Natural Ventilation, Mechanical (Night) Ventilation, Hybrid Ventilation with fan coil, Hybrid ventilation with Radiant ceiling panels, Hybrid ventilation with Radiant TABS) for four climate types / cities (Stockholm, Stuttgart, Rome, Seoul). They concluded that comfort conditions with purely passive technology are hard to achieve unless the building is designed with passive strategies. It was found that water based low-energy cooling can successfully be applied to office buildings in all climate zones and may be operated with additional active cooling. The study did not take into account the variation of building geometry and envelope characteristics while quantifying the energy savings and comfort conditions.

Hemsath et al (2015) presented a methodology to evaluate the impact of building forms and materials on the energy use of buildings sensitivity analysis. Both local sensitivity analysis and global sensitivity analysis (Mortis method) were reviewed. This study was however limited to a particular type of building and HVAC system.

Olsen et al (2003) carried out a validation of energy prediction for low energy cooling systems using EnergyPlus for newly built buildings in UK. The systems evaluated were chilled ceilings, displacement ventilation, natural ventilation, free cooling, and a traditional VAV system. It concluded that EnergyPlus provides sufficient accuracy for most energy simulation applications.

Thornton et al (2009) developed a technical support document for 50% energy savings design guide, for various building types, of which medium office is one of the building types. The document presents the analysis and results for a recommended package of every saving design feature highlighted in the ASHRAE design guide. It includes the design parameters and results for various newer HVAC systems including radiant cooling with DOAS system, which is one of the most popular energy saving HVAC technology included in this study. The guide presents a comparison of the input parameters and results for the baseline model as per ASHRAE 90.1-2004 and the recommended advanced model in terms of building envelope characteristics, internal loads and HVAC system. This document can be used as a good source to assign ranges for the parameters to be considered for the study. The HVAC system enhancements considered for the advanced design guide are DOAS system, Radiant Heating & Cooling system, Premium HVAC Equipment Efficiency, Demand Control Ventilation, Improved controls (Motorized OA dampers), and Alternative VAV systems with improved controls. The document also compares the cost of various system changes in baseline and advanced models.

# 3. THEORY

## 3.1 Software Used

### 3.1.1 EnergyPlus v8.2

EnergyPlus is an energy analysis and thermal load simulation program, with its root from BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programs. The principle differences between EnergyPlus and its parent tools during its release were (i) its capability to perform integrated simultaneous simulation where building response is tightly coupled with primary and secondary HVAC systems, (ii) heat balance based solution technique for building thermal loads that allow for simultaneous calculation of radiant and convective effects at both interior and exterior surface during each time step, and (iii) the capability to reduce the time step up to 1minute as against the traditional one hour. There are more advantages of using EnergyPlus, which came at the cost of higher modeling and run times. Over the years, various algorithms have been incorporated within EnergyPlus to allow modeling of complex and new HVAC systems like evaporative cooling, displacement ventilation and radiant systems.

### 3.1.2 GenOpt v3.1.0

GenOpt is an optimization program for minimization of a cost function that is evaluated by an external simulation program. The independent variable can be continuous, discrete or both. Constraints on dependent variables can be implemented using functions. GenOpt uses parallel computing to evaluate the simulations. It has a library of local and global multi-dimensional and one-dimensional optimization algorithms, and algorithms for doing parametric runs.

During this study, GenOpt has been used as a tool to run the parametric simulations using EnergyPlus. The intent of using GenOpt was to facilitate generation of input files and reading output files from EnergyPlus. The input files were parametrized to the extent of every single coordinate of the building including all the surfaces and daylight sensors, to achieve the variations in terms of 'ceiling height', 'perimeter zone depth', 'window-wall ratio', 'aspect ratio', etc., along with variation of other envelope characteristics like 'U-values' for roof, wall and window.

### 3.1.3 R

R is a language and environment for statistical computing and graphics. It is a GNU project developed at Bell Laboratories (formerly AT&T, now Lucent Technologies) by John Chambers and colleagues. R provides a wide variety of statistical and graphical techniques, and is highly extensible.

The algorithm used for this study has been based on 'Predictive Learning via Rule Ensembles'. General regression and classification models are constructed as linear combinations of simple rules derived from the data. Each rule consists of a conjunction of a small number of simple statements concerning the values of individual input variables. These rule ensembles are shown to provide predictive accuracy comparable to the best methods. Techniques used in this method allow for automatic identification of those variables that are involved in interactions with other variables, the strength and degree of those interactions, as well as the identities of the other variables with which they interact. (Friedman et al, 2005).

### 3.1.4 MS Excel

Microsoft excel (VBA Environment) was used to analyze the results using 'Morris Method' and develop a simplified tool for representation of importance and interaction between parameters based on sensitivity analysis to facilitate designers for making more informed decision.

## 3.2 Statistical Methods

### 3.2.1 Morris Method

This method is based on One-factor-at-a-time (OAT) screening methods, which identifies the subset of important input parameters among a large number of input parameters (Morris, 1991; Sanchez et al, 2014). The output function y(x) can be expressed as a function of vector of real input parameters with k coordinates, where k is the number of input parameters. Input variables are transformed into reduced dimensionless variables in the interval (0:1) as follows:

$$x_i' = (x_i - x_{min} / x_{max} - x_{min}), \tag{3.1}$$

where, $x_{min}$ and $x_{max}$ are the minimum and maximum values for a parameter.

A simulation trajectory can then be defined as a sequence of (k+1) points, with each point differing from the preceding one only by one coordinate. In a trajectory, each input parameter changes only once with pre-defined step $\Delta_i$. The function is evaluated for all points in the trajectory. First point of the trajectory is randomly selected, and thus multiple trajectories are initiated which differ from each other by randomly selected starting points. The elementary effect (EE) is thus calculated for all points in the trajectory using the following equation:

$$EE_i = \frac{y(x+e_i\Delta_i)-y(x)}{\Delta \mathrm{i}} \tag{3.2}$$

Each trajectory with (k+1) simulations, provide an estimate of k elementary effects for each of the variables. A set of r such different trajectories are defined which requires r x (k+1) simulation runs. The average and standard deviation of elementary effects are computed for each input variable as follow:

$$\mu_i = \frac{1}{r}\sum_{t=1}^{r} EE_{it} \quad (3.3)$$

$$\sigma_i = \sqrt{\frac{1}{(r-1)}\sum_{t=1}^{r}(EE_{it} - \mu_i)^2} \quad (3.4)$$

To eliminate the effects of non-monotonic models, it has been recommended that the average of absolute elementary effects be used given by the formula shown below:

$$\mu_i^* = \frac{1}{r}\sum_{t=1}^{r} |EE_{it}| \quad (3.5)$$

The criterion $\mu_i^*$ is a good indicator to classify the input variable by order of importance, despite the fact that information about sign of elementary effect is lost.

As per Morris method, plotting the two statistical indicators (σ and μ*), helps to identify the inputs that can be considered to have an effect (Sanchez et al, 2014) based on the following heuristics:

1) Negligible – Low Average (μ*) and Low Standard Deviation (σ)
2) Linear and additive – High Average (μ*) and Low Standard Deviation (σ)
3) Non-Linear or involved in interactions – High Standard Deviation (σ)

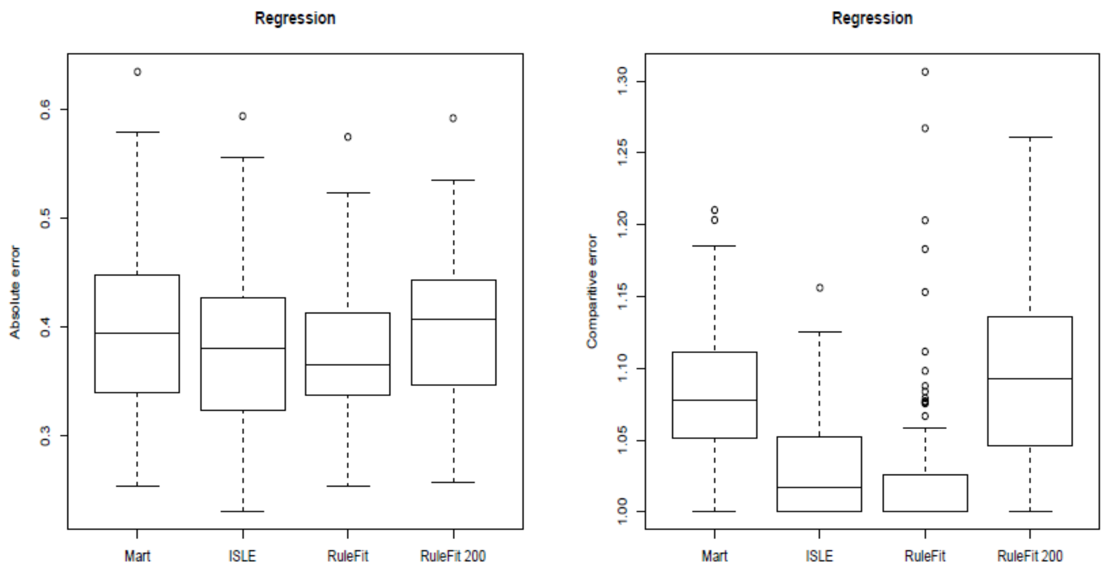
'Non-Linear' in this study refers to parameters for which the function (utility cost in this study), does not vary linearly with change in those parameters. It could be considered to have a 'higher-order linear' impact on the energy consumption or utility cost.

### 3.2.2 Predictive Learning via Rule Ensembles

General regression and classification models are constructed as linear combinations of simple rules derived from the data. Each rule consists of a conjunction of a small number of simple statements concerning the values of individual input variables. These rule ensembles are shown to produce predictive accuracy comparable to the best methods. Because of its simple form, each rule is easy to understand, as is its influence on individual predictions, selected subsets of predictions, or globally over the entire space of joint input variable values. Similarly, the degree of relevance of the respective input variables can be assessed globally, locally in different regions of the input space, or at individual prediction points (Friedman et al, 2005). The authors have presented techniques for automatically identifying those variables that are involved in interactions with other variables, the strength and degree of those interactions, as well as the identities of the other variables with which they interact. These algorithms have been adopted in the package for R statistical packages.

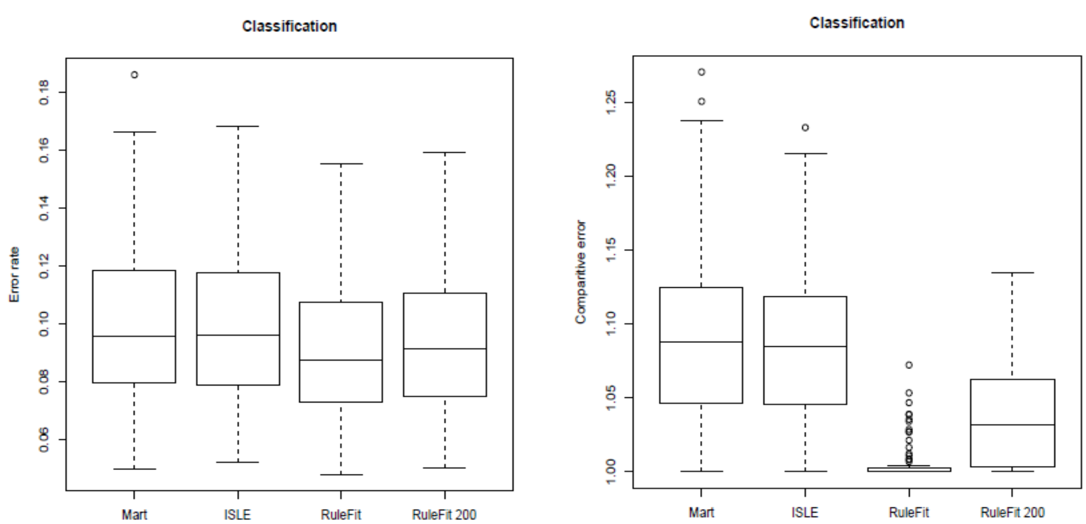
Friedman et al (2005) compared various decision tree based models for their prediction accuracy and the results have been shown in Figure 1-2. The simulation consisted of 100 data sets, each with 10000 observations and 40 input variables. These 100 target functions were themselves each randomly generated so as to produce a wide variety of different targets in terms of their dependence on the input variables. The input variables were randomly generated according to a standard Gaussian distribution.

'RuleFit' algorithm compared best among other decision tree based ensembles like 'Mart' and 'ISLE'. Figure 1 compares various decision tree models for 'Regression' and Figure 2 compares these models for 'Classification'. All the decision tree ensembles compared were with 500 trees, except one of the 'Rulefit' version with 200 trees. It should be observed that 'RuleFit' model with 500 decision trees performed best among others and 'RuleFit' model with 200 decision trees also compared well with other 500 trees models.




Average absolute error — Comparative absolute error

*Figure 1: Error Comparison of Decision Tree Models, for Regression (Friedman et al, 2005)*




Error rate — Comparative error rate

*Figure 2: Error Comparison of Decision Tree Models, for Classification (Friedman et al, 2005)*

# 4. METHODOLOGY

The study has been divided into three parts. The first part deals with performance evaluation of four different cooling systems in three climate zones of US. The analysis is based on total annual utility cost with utility rates taken from the EIA national average (Thornton et al, 2009). Second part deals with analysis of importance of parameters and their interaction among each other using two statistical techniques, ('Morris method' and 'Predictive Learning via Rule Ensembles' algorithm). Third part of the study proposes a simplified visualization tool to inform designers so as to make better decisions based on sensitivity analysis concepts using parametric simulations.

## 4.1 DOE Prototype Building Description

ASHRAE 90.1-2010 compliant models for Albuquerque (Zone 4B), Memphis (Zone 3B) and Phoenix (Zone 2B), developed by PNNL has been used for this study. It is a building with rectangular footprint (aspect ratio of 1:1.5) with three floors and total built-up area of 53,600 $ft^2$. The building geometry is shown in Figure 3.

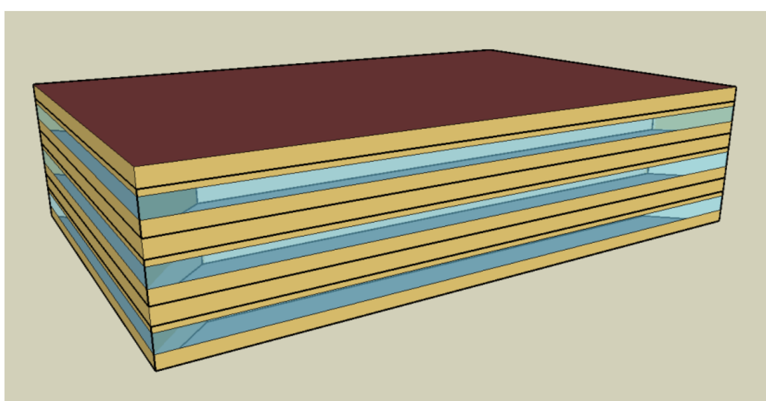


*Figure 3: Building Geometry (courtesy: PNNL Scorecard)*

The base model has a window-wall ratio of 0.33 with the windows distributed uniformly along all four sides of the building. The perimeter zone depth has been modeled as 15 ft., which results in a perimeter area of 40% and a core area of 60%. The zoning is illustrated in Figure 4.

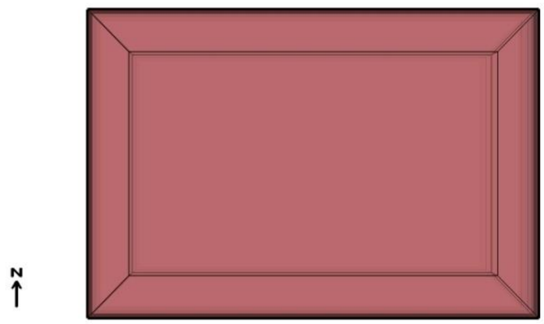



*Figure 4: Zoning Diagram (courtesy: PNNL Scorecard)*

The floor-to-floor height is assumed to be 13 ft., with 9 ft. floor-to-ceiling height and 4 ft. plenum. Sill height for the model is assumed to be 3.35 ft.

All the building characteristics have been modeled to be in compliance with ASHRAE 90.1-2010. The HVAC system for this base model is Packaged VAV, with cooling thermostat set-point of 75 $^{o}$F and heating thermostat set-point of 70 $^{o}$F.

For this study, small changes have been made to the models developed by PNNL, in terms of HVAC system sizing, which is set to size based on long term average weather file conditions with sizing ratio of 1.15 (Cooling) and 1.25 (Heating) as per ASHRAE 90.1-2010. The intent behind such change is to avoid any un-met hours.

## 4.2 Climate Selection

The first criteria in terms of climate selection for this study was to avoid cold climates that may not have much cooling requirement since this study primarily focuses on cooling systems rather than heating systems.

Baechler et al (2010) presented the categorization of various cities in the climate zones and the description of the type of climate corresponding to the climate zones in Table 1.

Table 1: Climate Classification, Source: Baechler et al (2010)

| Climate Type | IECC Zone |
|---|---|
| Subarctic | Zone 8 |
| Very Cold | Zone 7 |
| Cold | Zone 5 and 6 |
| Mixed-Humid | Zone 4A and 3A (above warm-humid line) |
| Mixed-Dry | Zone 4B |
| Hot-Humid | Zone 2A and 3A (below warm-humid line) |
| Hot-Dry | Zone 3B |

Zone 5, 6, 7, 8 can thus be rejected from the scope of this study. Also, Zone 1 covers a very negligible part of US (Hawaii, Guam, Puerto Rico and Virgin Islands), and was neglected for this study.

Further, the recommendations for building design parameters from ASHRAE 50% design guide and the site EUI's calculated for ASHRAE 90.1 models as per Thornton et al (2009) have been used to narrow down the selection of climate zones / cities for this study, by eliminating climates that had similar input recommendations and energy consumption. Based on these criteria, three climate types are chosen and the cities corresponding to those climate types as per the ASHRAE 90.1 prototype models from PNNL have been selected for the study. These cities are: Phoenix, Memphis and Albuquerque.

Of these three locations the climate summaries are shown in Figure 5-7. Charts for each climate represents the number of hours in each temperature bin (10 $^oF$ bins) and the coincident average relative humidity in the bins, read on the secondary y-axis.

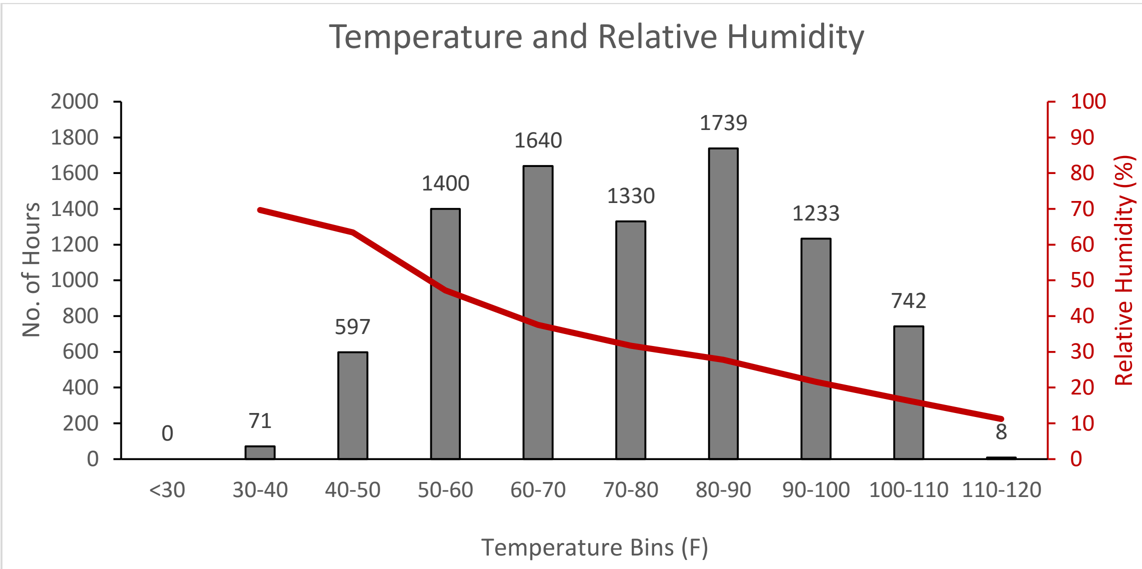



*Figure 5: Bin Data for Phoenix (2B- Hot and Dry)*

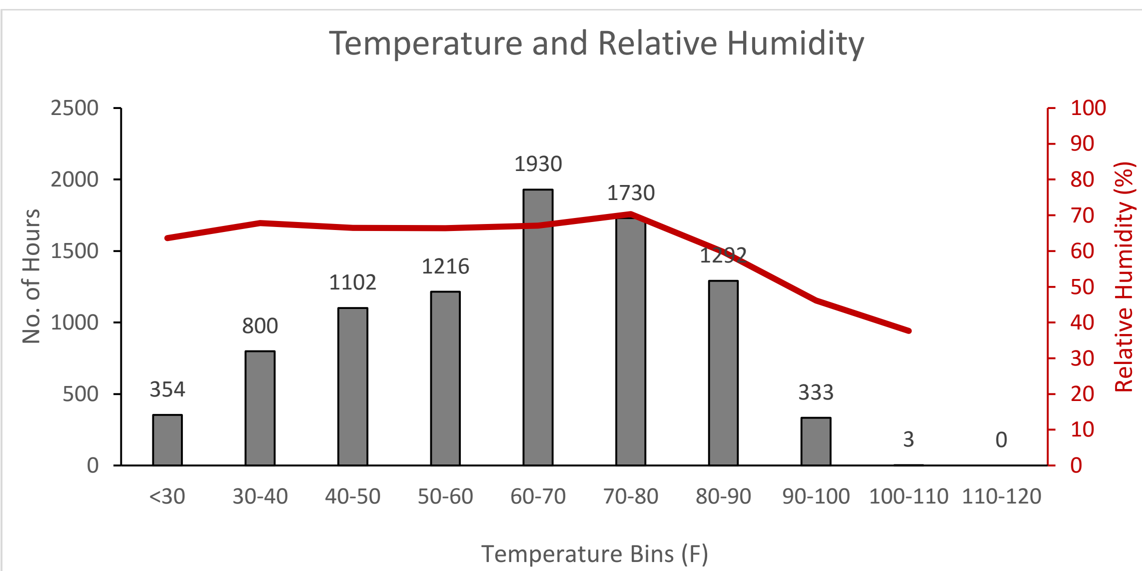



*Figure 6: Bin Data for Memphis (3A-Mixed Humid)*

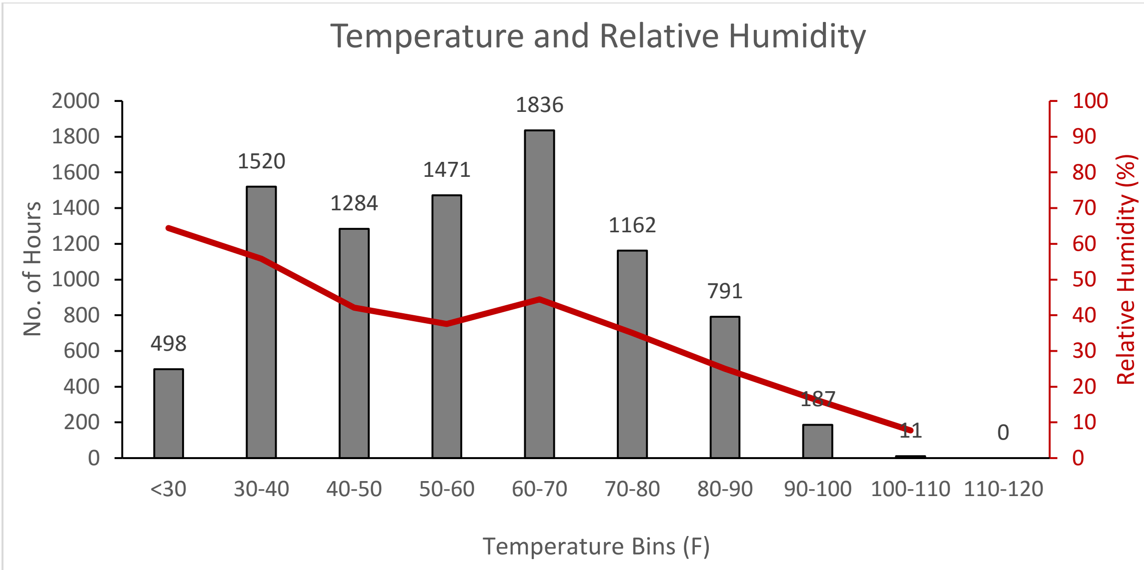



*Figure 7: Bin Data for Albuquerque (4B – Mixed Dry)*

### 4.3 HVAC Systems

Four different HVAC systems are selected in the study and no parametric variations for the HVAC system details have been considered. All the systems have been simulated with auto-sized system parameters.

#### 4.3.1 VAV (ASHRAE 90.1 Base Model)

This is the base model, adopted from PNNL's DOE prototype models for medium office buildings with ASHRAE 90.1-2010 compliance. The secondary system consists of packaged gas furnace used for heating and a DX system for cooling. There are three packaged units (one per floor), with each zone having a VAV terminal box with damper and electric reheat coil. The system has been set to auto-size based on design period using long term average TMY3 weather files. The sizing ratios have been set to 1.15 for cooling and 1.25 for heating equipment. The supply air temperature has been modeled as 104 $^{o}$F (heating) and 55 $^{o}$F (cooling). System efficiencies, economizer requirements are based on ASHRAE 90.1-2010 recommendations and varies depending on the climate. This system is modeled as the base system for this study that meets the minimum requirement for ASHRAE 90.1-2010, and should not be considered as the optimum representation of a VAV system. There have been studies which show that VAV systems with better controls are as good, if not superior to few of the newer technologies like Displacement Ventilation, Chilled Beam, etc. (Olsen et al, 2003 and Stein et al, 2013). This study's scope is not to run parametric simulations of HVAC systems and suggest a best performing system. It is rather intended to observe the impact of building design parameters on energy consumption of buildings with different cooling techniques.

### 4.3.2 VAV + Indirect Evaporative Cooling (Outdoor Air)

With the base VAV model, an indirect evaporative cooler is modeled to pre-cool the outdoor air. Three evaporative coolers have been modeled to serve each of the three packaged units. Each evaporative cooler is modeled with a cooling effectiveness of 0.63 and a 40W water circulation pump. The secondary fans have been modeled with an efficiency of 0.7 and a pressure drop of 0.75 inches of water column. The dew-point effectiveness factor for the indirect evaporative cooler is taken to be 0.9.

### 4.3.3 Displacement Ventilation

Displacement ventilation system has been modeled using the three node displacement ventilation model in EnergyPlus, which has been validated by a number of studies in the past (Mateus et al, 2015). This system is modeled to deliver a low velocity supply air at the floor level to minimize mixing and to establish a vertical temperature gradient. This means that the average room temperature can be higher than that used in conventional mixed air systems. The supply air temperature is set to 62.5 $^{o}$F, with fan pressure drop of 1 inch water column because of a low velocity discharge. The EER of the DX coil has been assumed to be 12.5 and the outdoor air requirement has been reduced by a factor of 0.83 (air distribution effectiveness of 1.2) due to better ventilation effectiveness of the displacement ventilation system, as compared to conventional VAV system. (Design Brief, 2005)

#### 4.3.4 Radiant Cooling System with DOAS

Radiant system has been identified as a good low-energy cooling alternative, with significant energy saving potential for many climates and facility types across the globe. For climates with higher humidity, it becomes necessary to use an additional system like DOAS to cater to the latent load in order to avoid condensation issues and maintain comfortable conditions (Didwania et al, 2014).  This system has been modeled as a combination of three HVAC systems serving the zones. These systems are sequenced in the following order. The DOAS system is given first priority which supplies 100% OA (as per OA requirement) at temperature 57 $^{o}$F to 60 $^{o}$F with an OA Reset, using a DX coil. This system is basically meant to cater to the latent load requirement of the space. However, along with the latent load, the system also meets a part of the sensible load. Following this system, the second priority is given to radiant cooling system which caters to the sensible loads. This is achieved through radiant panels attached to the ceiling having chilled water pipes circulating chilled water from the chiller supplied at 60.8 $^{o}$F. The radiant panels are modeled with dew point controls to avoid condensation problems. This control turns off the system at times when the panel temperature approaches the room air dew-point temperature. To meet the comfort requirement during these times, third system (PTAC for each zone) is modeled which switches on at times when there are un-met loads in the space. This system is modeled with DX coil efficiency of 11.94 EER. The space thermostats for such system is based on operative temperature set-point of 78.8 $^{o}$F. This operative temperature set-point was obtained using CBE comfort tool to match similar comfort conditions as of 75 $^oF$ air temperature set-point using convection based cooling systems and satisfying ASHRAE Standard 55 comfort requirement.

The ceiling panels are modeled with 0.5 inch thick PEX tubes with a spacing of 6 inches center-to-center. The chiller used has an efficiency of 0.33 kW/ton, which has been taken from the data sets available with EnergyPlus. The chilled water and condenser water pumps are modeled with a head of 33.5 Ft of water column.

### 4.4 Building Design Parameters and Their Ranges

The following section describes the building design variables considered for the study. The variables are related to building envelope design and not to the internal load characteristics.

#### 4.4.1 Aspect Ratio 'AR'

The aspect ratio describes the proportional relationship between width of the building foot-print along North-South (NS) axis and East-West (EW) axis. In this study, all aspect ratios are specified as ratio of width along NS:EW axis, and has been abbreviated as 'AR'.

#### 4.4.2 Floor to Ceiling Height 'CH'

As the name suggests, this is the distance between floor and ceiling of the zone (excluding plenum). It has been abbreviated to 'CH' in this document.

#### 4.4.3 Depth of Perimeter Zone 'PZD'

This is the distance between exterior wall and interior wall (that runs parallel to the exterior wall) of the perimeter zones. This has been abbreviated as 'PZD' in the following sections of this document.

#### 4.4.4 Window-Wall Ratio 'WWR'

This is the ratio of total window area to total exterior wall area of the building. In this study the windows are assumed to be distributed uniformly in all four directions of the building. This has been abbreviated to 'WWR' in the following sections.

#### 4.4.5 Wall U-Value 'WU'

U-Value or U-Factor is the overall heat transfer coefficient which takes into account the conduction of heat through all layers of the construction, including the air film resistances. Unit for U-Value is Btu/hr-Ft$^2$-F, and has been abbreviated as 'WU' in the succeeding sections.

#### 4.4.6 Roof U-Value 'RU'

Similar to the Wall U-Value, this represents the U-Value of the roof and has been abbreviated as 'RU' in the sections hereafter.

#### 4.4.7 Glass Type 'WinU' (A Combination of U-Value and SHGC)

The three most important characteristics of a glazing unit that influences building energy consumption are U-Value, Solar Heat Gain Coefficient (SHGC) and Visible Light Transmittance (VLT). SHGC and VLT ranges from 0 to 1. In general, including all combinations of SHGC and VLT are neither practical nor feasible. In this study, three combinations have been selected as discussed later in this document. However, in terms of normalization of the input range and result interpretation, U-Value is used at the criteria. This has been abbreviated as 'WinU' in the later sections of this document. It is identified as a limitation for this study, where the variations or range of parameters have been defined based on ASHRAE recommendations (as discussed later). For projects related to design of buildings, it is necessary to treat these properties (U-Value, SHGC and VLT) in isolation.

For all parameters, three discrete points are selected to represent the range for a given parameter, viz-a-viz, the minimum, base-case, and the maximum. The base case values for these parameters have been derived from ASHRAE 90.1-2010. The minimum value of these parameters have been defined based on the assumptions of pre 1980 constructions as per Deru et al (2011), while the maximum value of the range has been determined from the advanced design recommendations from ASHRAE 50% Savings design guide for medium office, or best industry practices (in case the values for a parameter is not governed by ASHRAE 90.1 or 50% savings design guide).

The recommendations for Wall and Roof insulation in Advanced 50% guide has been presented in terms of R-Value. These values have been converted to U-Values while taking into account the air film resistances, as per ASHRAE 90.1. For calculation of Roof U-Value, R-0.17 accounts for exterior air film resistance and R-0.61 for interior air film resistance. For the Wall U-Value, R-0.17 accounts for exterior air film resistance, R-0.68 for interior air film resistance and R-0.45 for 0.5 in. gypsum board. Window type variation has been limited to a combination of U-Value and SHGC (fixed VT). The study takes into account three types of windows for each climate zone and the representation is based on U-Value of the window.

Table 2 assembles the ranges for parameters considered for this study. The entries in bold fonts represent the base case values. Total number of simulation runs for this study is 26,244, since we consider four HVAC systems and three climate zones.

Table 2: Ranges for Input Parameters

| Parameters | Minimum | Intermediate | Maximum |
|---|---|---|---|
| Floor to Ceiling Ht. 'CH' | **9** | 12 | 15 |
| Aspect Ratio 'AR' | 1:1 | **1:1.5** | 1:3 |
| Depth of Perimeter Zone 'PZD' | 10 | **15** | 20 |
| Window-Wall Ratio 'WWR' | 0.1 | **0.33** | 0.4 |
| Wall U-Value 'WU' | | | |
| 2B - Phoenix | 0.24 | **0.124** | 0.046 |
| 3A - Memphis | 0.13 | **0.084** | 0.046 |
| 4B - Albuquerque | 0.1 | **0.064** | 0.046 |
| Roof U-Value 'RU' | | | |
| 2B - Phoenix | 0.23 | **0.048** | 0.039 |
| 3A - Memphis | 0.225 | **0.048** | 0.039 |
| 4B - Albuquerque | 0.184 | **0.048** | 0.032 |
| Glass Type 'WinU' | | | |
| 2B - Phoenix | U1.22-SHGC0.54 | **U0.75-SHGC0.25** | U0.51-SHGC0.25 |
| 3A - Memphis | U1.22-SHGC0.54 | **U0.65-SHGC0.25** | U0.51-SHGC0.25 |
| 4B - Albuquerque | U1.22-SHGC0.54 | **U0.5-SHGC0.4** | U0.44-SHGC0.26 |

### 4.5 Utility Cost Structure

Sensitivity of inputs are compared in terms of their impact on total utility cost calculated using the EIA national average natural gas rate of $1.16/therm ($0.41/m$^3$) and the national average electric rate of $0.0939/kWh (EIA 2006). These rates are the same that has being used by the SSPC 90.1 Committee in developing the 2010 version of Standard 90.1 (Thornton et al, 2009).

## 5. RESULTS AND DISCUSSIONS

### 5.1 HVAC Performance in Various Climates

Figure 8 illustrates the variation in annual utility cost ($/year) for four different HVAC systems in three climate zones as described earlier. The climate zones have been represented by their Cooling Degree Day (CDD), where, lowest CDD corresponds to 'Albuquerque', followed by 'Memphis' and 'Phoenix' respectively.

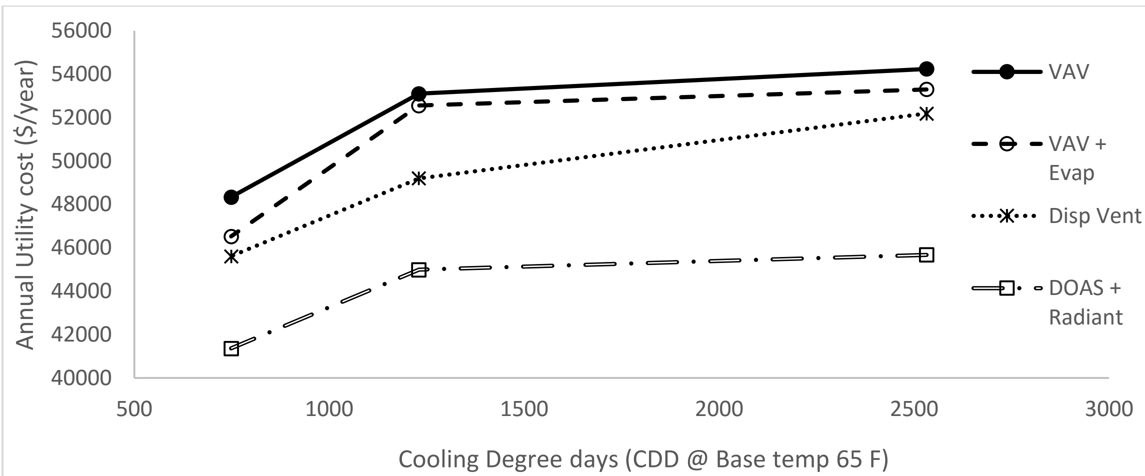



*Figure 8: Utility Cost Vs CDD for Various HVAC Systems*

With detailed simulations, it is unlikely that a perfect linear trend is found with degree day due to effects of solar radiation, heat capacitance, reheat requirements, humidity etc. Another reason for such non-linearity is that the building and system characteristics for ASHRAE 90.1-2010 case varies from climate to climate.

It can be noticed that for all climates, radiant system performs best, followed by displacement ventilation and VAV with evaporative cooling on the outdoor air.

Also, savings from VAV + Evaporative cooling in Memphis is not significant compared to VAV alone due to high humidity conditions in this climate (as can be seen in the climate analysis chart).

## 5.2 Importance and Interaction of Parameters

The major focus of this study is to investigate the interaction between various envelope parameters, validate statistical methods and suggest better visualization techniques for the designers to interpret the results and make better informed design suggestions.

### 5.2.1 Morris Method

Morris method (discussed earlier in Section 3.2.1) has been used for elementary screening of the results. This method is based on random sampling and requires less computational time for the elementary screening of parameters. As already discussed in the theory section, the number of simulation runs required for this analysis is [r x (k+1)], where 'r' is the number of simulation trajectories and 'k' is the number of parameters. Two charts have been plotted for σ vs μ*, one with six simulation trajectories (48 simulations) and the other with twenty five simulation trajectories (200 simulations), for VAV system in Memphis, as shown in Figures 9-10. Similar charts for other HVAC systems in Memphis (200 simulations) are shown in Figures 11-13. Charts for other climates are presented in Appendix A.

The area on the charts have been subdivided into 9 grids. Grids from bottom towards the top indicate an increase in interaction strength of the parameters (or the parameters might have non-linear impact on total utility cost), while the grids from left to right indicate an increase in the importance (i.e. sensitivity) of the parameters. For example the left bottom grid would contain the parameters that have least importance as well as interaction effects while the top-right grid would contain the parameters that showed highest importance as well as highest interactions.

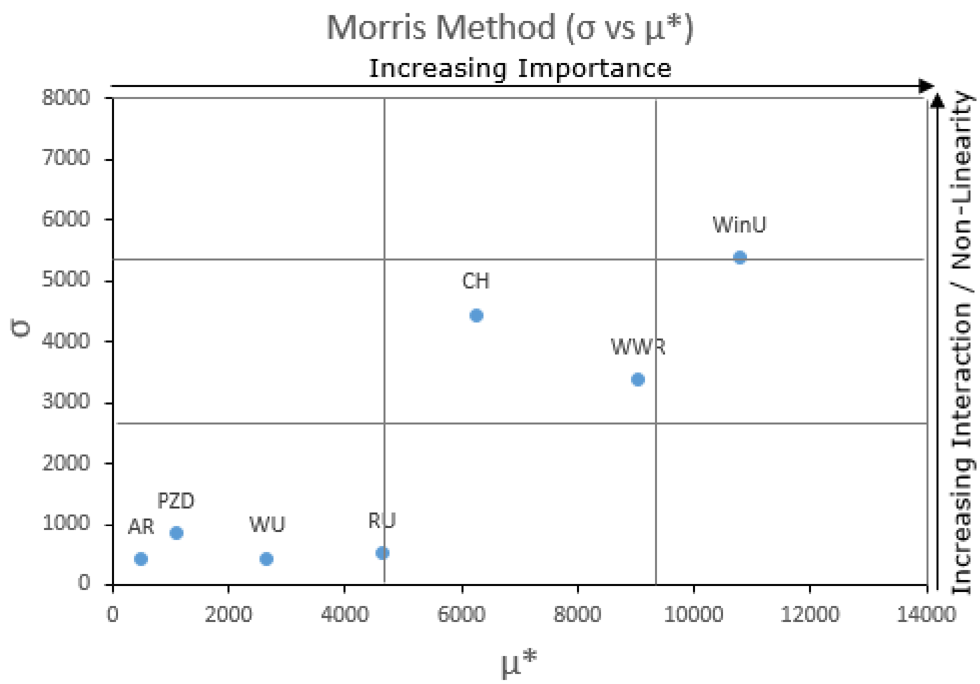



*Figure 9: Memphis - VAV (48 Simulations)*

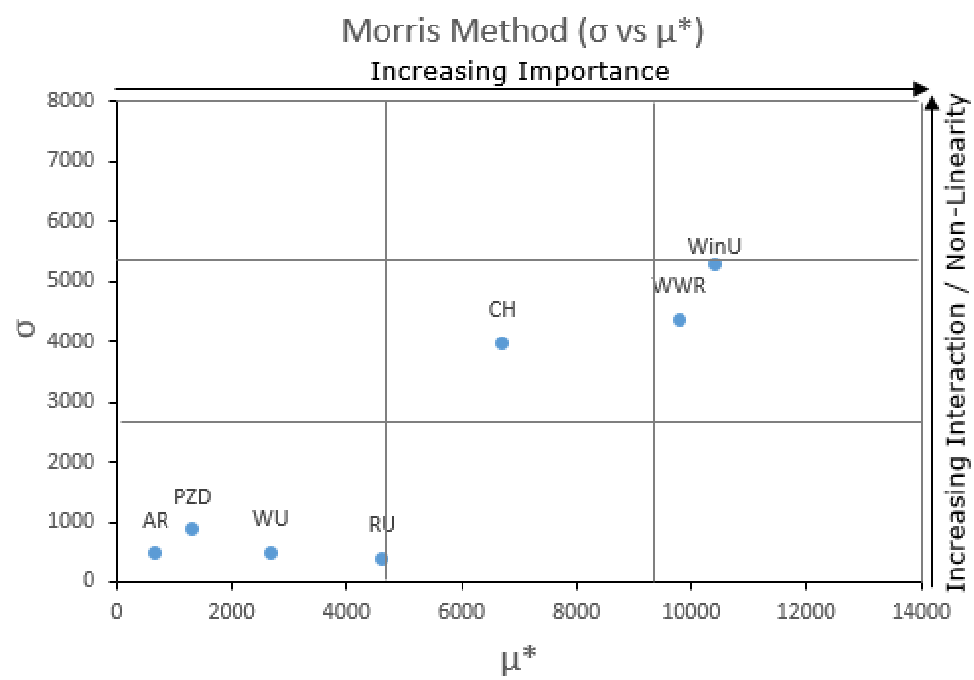



*Figure 10: Memphis - VAV (200 Simulations)*

It is observed that both charts show similar results thereby supporting the use of Morris method for elementary analysis with fewer simulation results. The results have also been compared to those from other statistical method (Predictive Learning via Rule Ensembles), which is based on decision tree model and takes into account the simulation results from all combination of parameters.

From Figure 10 and principles stated by Morris method we can state that 'AR (Aspect Ratio)', has the least effect, followed by 'PZD (Perimeter Zone Depth)', 'WU (Wall U-Value)', 'RU (Roof U-Value)' respectively, which show very little interaction with other parameters. Three of the parameters, 'WWR (Window-Wall Ratio)', 'CH (Ceiling Ht.)', and 'WinU (Window U-Value)' show high standard deviation along with high average values, indicating that these parameters have relatively more importance and also interact with each other.

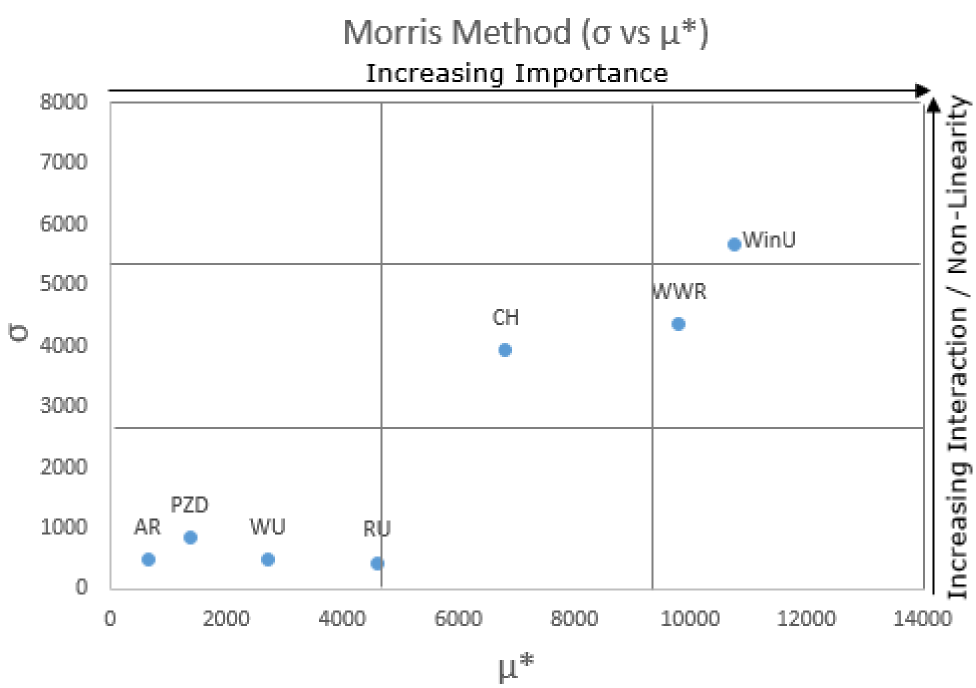



*Figure 11: Memphis - VAV + Evap (200 Simulations)*

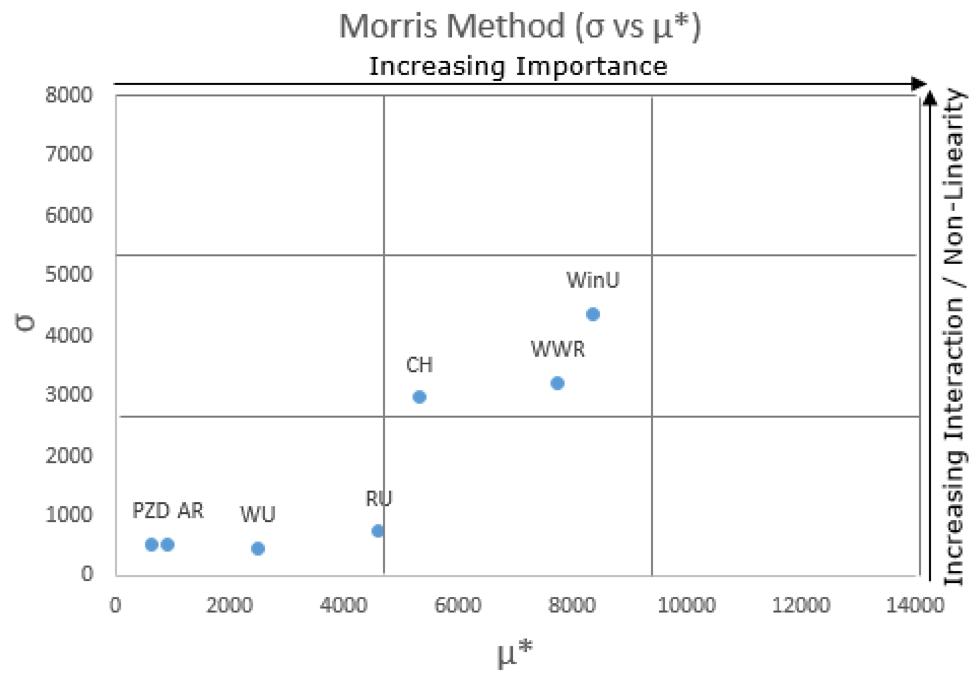



*Figure 12: Memphis - Displacement Ventilation (200 Simulations)*

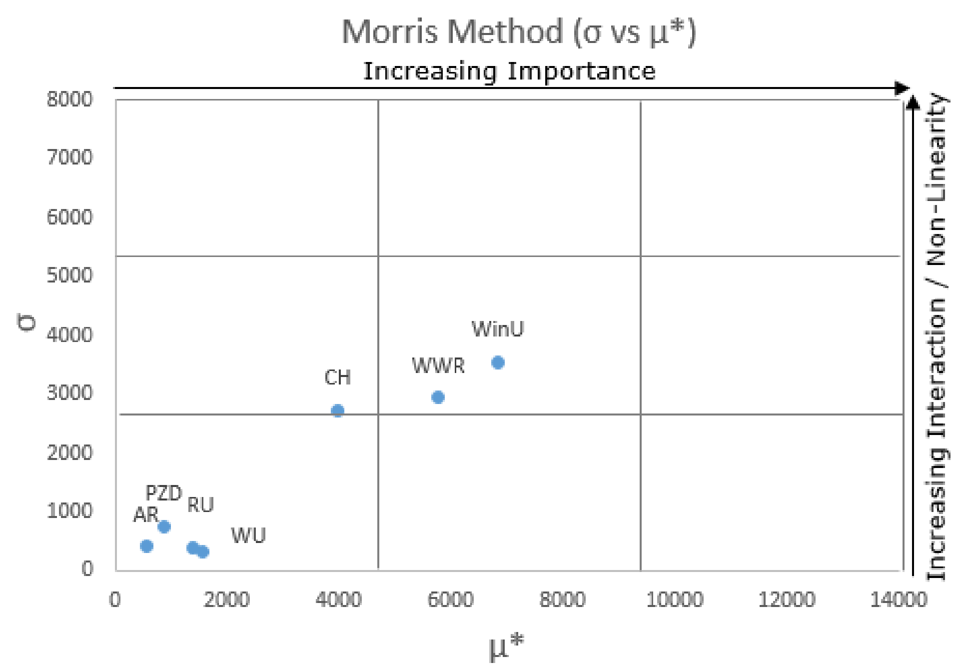



*Figure 13: Memphis - DOAS + Radiant (200 Simulations)*

Comparing the characteristics of the parameters across different HVAC system (Figures 10-13), it can be observed that for all parameters the importance as well as interaction strengths remain similar to those for 'VAV' and 'VAV + Evaporative' system, while both importance and interactions decrease for 'Displacement Ventilation' and are lowest for 'Radiant System'.

This method provides an excellent elementary screening opportunity at lesser computational cost to reduce the number of parameters and thereby the number of simulations needed for further analysis of the interactions.

### 5.2.2 RuleFit Method

For this study, the number of parameters were not reduced, in order to evaluate the methods against each other. However, we do propose to reduce the number of parameters after performing an elementary analysis in order to reduce the computational time while dealing with a large number of parameters.

Relative importance of parameters and their interaction have been determined using the 'RuleFit (Predictive Learning via Rule Ensembles)' algorithm in R statistical package, as discussed in Section 3. Figures 14-15 present the relative importance and interaction of various parameters with different HVAC systems in Memphis climate and for VAV system in different climates.

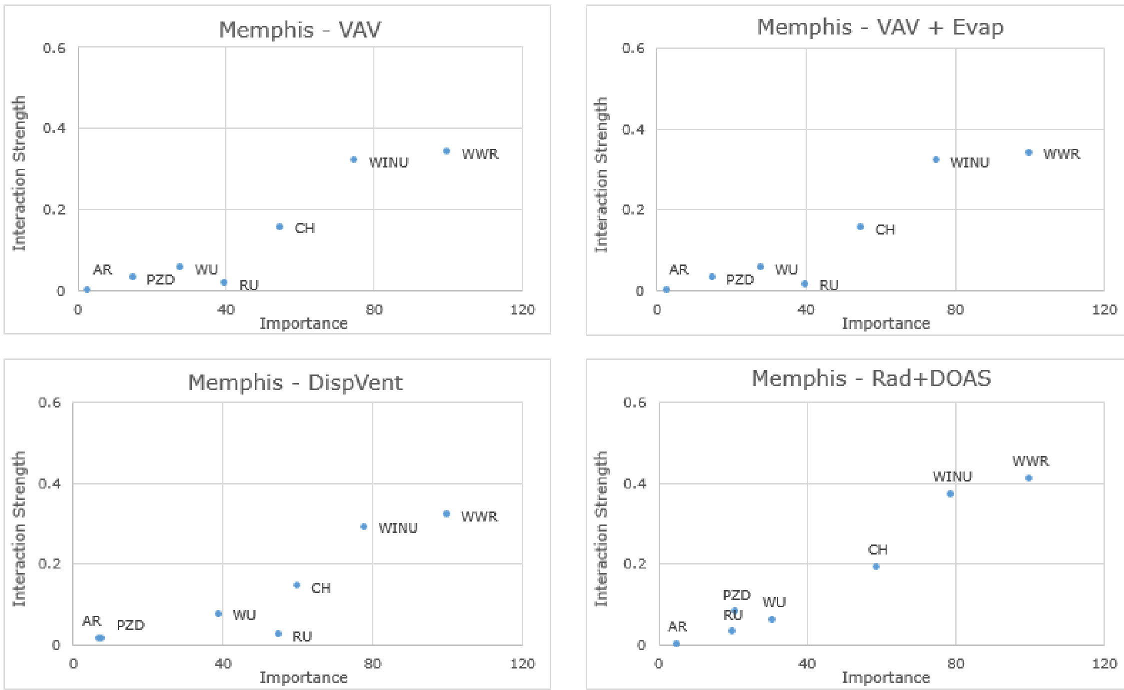



*Figure 14: Importance Vs Interaction Strength of Parameters in Memphis*

From Figure 14 for Memphis, it can be observed that the relative importance and interaction of parameters with VAV and VAV + Evaporative systems remain similar; this is not surprising since the cooling techniques are not really different. With the Displacement ventilation system, it is observed that while other parameters showed similar importance and interaction, 'WU' and 'RU' showed more importance while 'PZD' showed less importance, as compared to VAV system. For a radiant system, while the interaction strength of 'PZD', 'CH', 'WinU' and 'WWR' showed some increase, 'RU' showed a reduction in the relative importance, when compared to other system types. In general, for all the systems, 'WWR' is found to have the greatest interaction strength as well as relative importance, followed by 'WinU' and 'CH'.

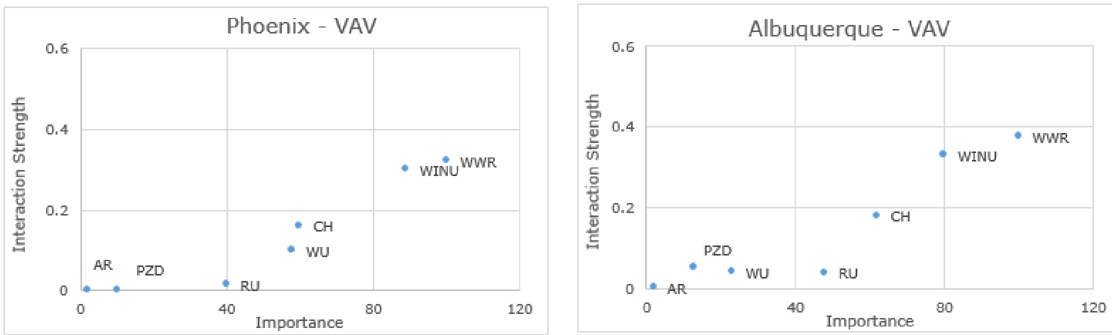



*Figure 15: Importance Vs Interaction Strength of Parameters for VAV System (other climates)*

This results suggest that a detailed interaction study is important for essentially three parameters, namely, 'WWR', 'WinU', 'CH'. Similar trends were observed in other climates with some differences (charts attached in Appendix B). From the charts (Figure 15) for Phoenix – VAV, it could be observed that the importance and interaction of 'WU' was significantly higher as compared to its importance and interaction for VAV systems in other climates, which could be attributed to higher temperature difference between indoor and outdoor environments in such climate.

Results from 'RuleFit' method appeared to be similar to those derived from the 'Morris method'. Both these methods show that 'WWR', 'WinU' and 'CH' have higher impact / importance and interact with each other.

Charts for other climate and system combinations are assembled in Appendix B. Tables 3-6 assemble the relative importance and interaction strengths for all parameters derived by use of the 'Rulefit' method.

Table 3: Relative Importance and Interaction Strengths for All Parameters for Memphis

| | **Parameter** | **Relative Importance (%)** | **Interaction Strength (Ratio)** |
|---|---|---|---|
| VAV | Ceiling Height 'CH' | 55 | 0.155 |
| | Aspect Ratio 'AR' | 3 | 0.0001 |
| | Perimeter Zone Depth 'PZD' | 15 | 0.03 |
| | Window-Wall Ratio 'WWR' | 100 | 0.34 |
| | Wall U-Value 'WU' | 28 | 0.055 |
| | Roof U-Value 'RU' | 40 | 0.015 |
| | Window Type 'WinU' | 75 | 0.32 |
| VAV + Evaporative | Ceiling Height 'CH' | 55 | 0.155 |
| | Aspect Ratio 'AR' | 3 | 0.0001 |
| | Perimeter Zone Depth 'PZD' | 15 | 0.03 |
| | Window-Wall Ratio 'WWR' | 100 | 0.34 |
| | Wall U-Value 'WU' | 28 | 0.055 |
| | Roof U-Value 'RU' | 40 | 0.015 |
| | Window Type 'WinU' | 75 | 0.32 |
| Displacement Ventilation | Ceiling Height 'CH' | 60 | 0.145 |
| | Aspect Ratio 'AR' | 7 | 0.015 |
| | Perimeter Zone Depth 'PZD' | 8 | 0.015 |
| | Window-Wall Ratio 'WWR' | 100 | 0.32 |
| | Wall U-Value 'WU' | 39 | 0.075 |
| | Roof U-Value 'RU' | 55 | 0.025 |
| | Window Type 'WinU' | 78 | 0.29 |
| DOAS + Radiant Cooling | Ceiling Height 'CH' | 59 | 0.19 |
| | Aspect Ratio 'AR' | 5 | 0.0001 |
| | Perimeter Zone Depth 'PZD' | 21 | 0.08 |
| | Window-Wall Ratio 'WWR' | 100 | 0.41 |
| | Wall U-Value 'WU' | 31 | 0.06 |
| | Roof U-Value 'RU' | 20 | 0.03 |
| | Window Type 'WinU' | 79 | 0.37 |

Table 4: Relative Importance and Interaction Strengths for All Parameters for Phoenix

| | Parameter | Relative Importance (%) | Interaction Strength (Ratio) |
|---|---|---|---|
| VAV | Ceiling Height 'CH' | 60 | 0.16 |
| | Aspect Ratio 'AR' | 2 | 0.001 |
| | Perimeter Zone Depth 'PZD' | 10 | 0.001 |
| | Window-Wall Ratio 'WWR' | 100 | 0.32 |
| | Wall U-Value 'WU' | 58 | 0.1 |
| | Roof U-Value 'RU' | 40 | 0.015 |
| | Window Type 'WinU' | 89 | 0.3 |
| VAV + Evaporative | Ceiling Height 'CH' | 61 | 0.16 |
| | Aspect Ratio 'AR' | 2 | 0.001 |
| | Perimeter Zone Depth 'PZD' | 12 | 0.001 |
| | Window-Wall Ratio 'WWR' | 100 | 0.32 |
| | Wall U-Value 'WU' | 59 | 0.1 |
| | Roof U-Value 'RU' | 39 | 0.015 |
| | Window Type 'WinU' | 90 | 0.3 |
| Displacement Ventilation | Ceiling Height 'CH' | 50 | 0.14 |
| | Aspect Ratio 'AR' | 4 | 0.001 |
| | Perimeter Zone Depth 'PZD' | 8 | 0.001 |
| | Window-Wall Ratio 'WWR' | 100 | 0.31 |
| | Wall U-Value 'WU' | 60 | 0.1 |
| | Roof U-Value 'RU' | 43 | 0.025 |
| | Window Type 'WinU' | 88 | 0.3 |
| DOAS + Radiant Cooling | Ceiling Height 'CH' | 57 | 0.18 |
| | Aspect Ratio 'AR' | 2 | 0.0001 |
| | Perimeter Zone Depth 'PZD' | 26 | 0.07 |
| | Window-Wall Ratio 'WWR' | 100 | 0.38 |
| | Wall U-Value 'WU' | 52 | 0.1 |
| | Roof U-Value 'RU' | 11 | 0.0001 |
| | Window Type 'WinU' | 93 | 0.37 |

Table 5: Relative Importance and Interaction Strengths for All Parameters for Albuquerque

| | Parameter | Relative Importance (%) | Interaction Strength (Ratio) |
|---|---|---|---|
| VAV | Ceiling Height 'CH' | 62 | 0.18 |
| | Aspect Ratio 'AR' | 2 | 0.001 |
| | Perimeter Zone Depth 'PZD' | 13 | 0.05 |
| | Window-Wall Ratio 'WWR' | 100 | 0.375 |
| | Wall U-Value 'WU' | 23 | 0.04 |
| | Roof U-Value 'RU' | 48 | 0.038 |
| | Window Type 'WinU' | 80 | 0.33 |
| VAV + Evaporative | Ceiling Height 'CH' | 62 | 0.18 |
| | Aspect Ratio 'AR' | 2 | 0.0001 |
| | Perimeter Zone Depth 'PZD' | 13 | 0.05 |
| | Window-Wall Ratio 'WWR' | 100 | 0.375 |
| | Wall U-Value 'WU' | 23 | 0.04 |
| | Roof U-Value 'RU' | 48 | 0.038 |
| | Window Type 'WinU' | 80 | 0.33 |
| Displacement Ventilation | Ceiling Height 'CH' | 52 | 0.16 |
| | Aspect Ratio 'AR' | 2 | 0.0001 |
| | Perimeter Zone Depth 'PZD' | 10 | 0.04 |
| | Window-Wall Ratio 'WWR' | 100 | 0.37 |
| | Wall U-Value 'WU' | 20 | 0.04 |
| | Roof U-Value 'RU' | 60 | 0.02 |
| | Window Type 'WinU' | 80 | 0.32 |
| DOAS + Radiant Cooling | Ceiling Height 'CH' | 52 | 0.23 |
| | Aspect Ratio 'AR' | 8 | 0.04 |
| | Perimeter Zone Depth 'PZD' | 12 | 0.07 |
| | Window-Wall Ratio 'WWR' | 100 | 0.48 |
| | Wall U-Value 'WU' | 22 | 0.04 |
| | Roof U-Value 'RU' | 28 | 0.038 |
| | Window Type 'WinU' | 88 | 0.43 |

Further, the interaction of a particular parameter with other parameters has been studied using ‘RuleFit’ technique. Figures 16-22 represent the interaction strength of a single parameter with other parameters for the VAV system in Memphis, while charts for other systems and climates are gathered in Appendix C.

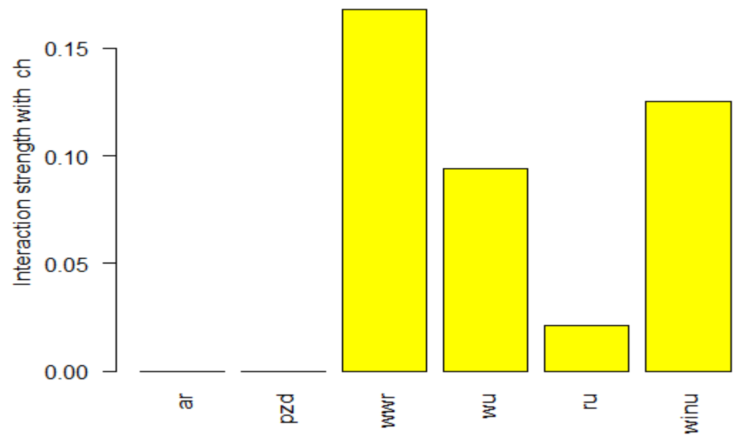



*Figure 16: Interaction with Ceiling Height 'CH', for Memphis-VAV*

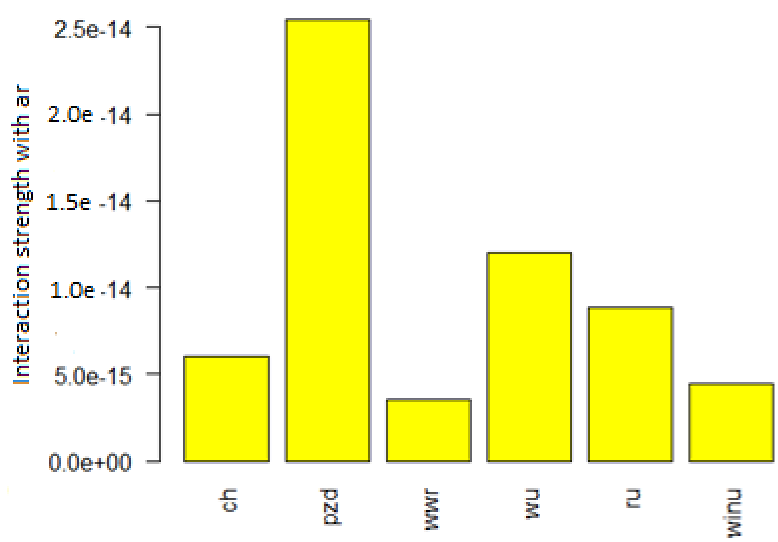



*Figure 17: Interaction with Aspect Ratio 'AR', for Memphis-VAV*

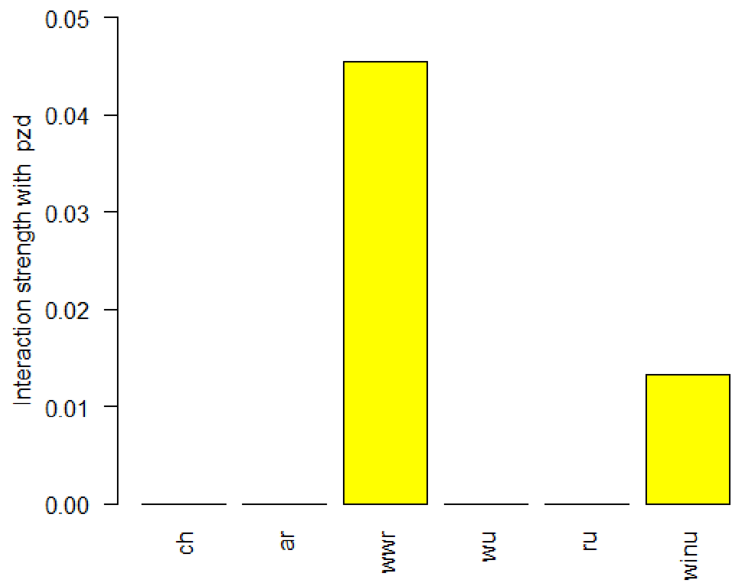



*Figure 18: Interaction with Perimeter Zone Depth 'PZD', for Memphis-VAV*

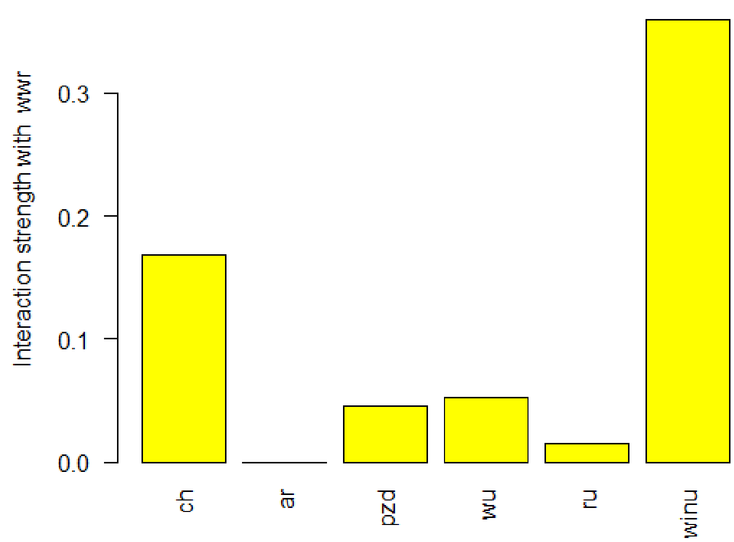



*Figure 19: Interaction with Window Wall Ratio 'WWR', for Memphis-VAV*

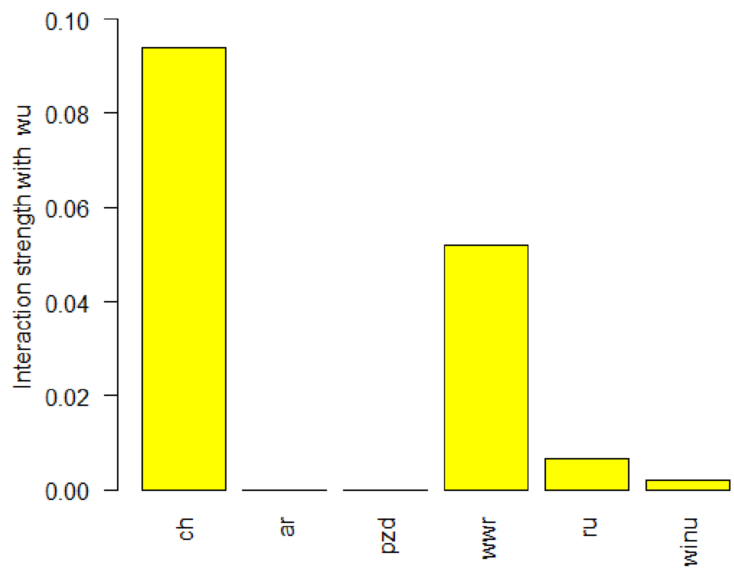



*Figure 20: Interaction with Wall U-Value 'WU', for Memphis-VAV*

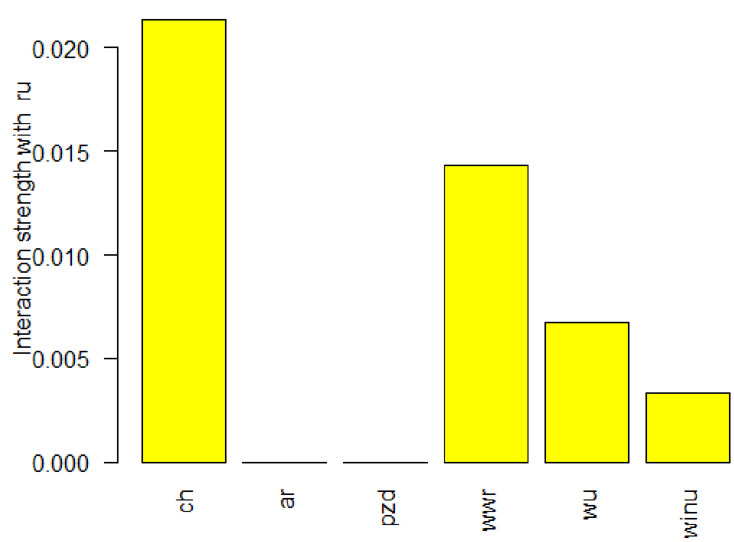



*Figure 21: Interaction with Roof U-Value 'RU', for Memphis-VAV*

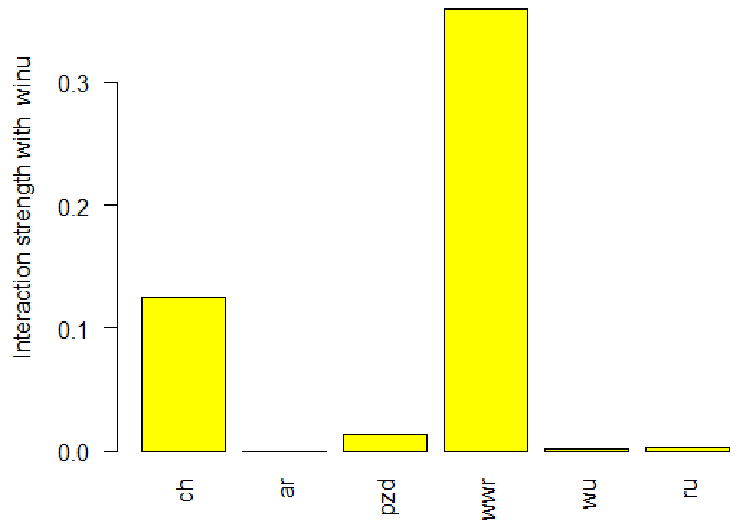



*Figure 22: Interaction with 'WinU', for Memphis-VAV*

It can be observed that parameter ‘CH’ shows maximum interaction with ‘WWR’ and ‘WinU’, while ‘AR’ shows maximum interaction with ‘PZD’, though the interaction strength between these is much lower as compared to interaction strengths of ‘CH’ with ‘WWR’ and ‘WinU’. The scales for interaction strength has not been fixed so as to get a proper sense of relative interaction strength of different parameters with all parameters, even when the magnitude of interaction strength for a parameter is much lower than the other. For example, the interaction strength of other parameters with ‘CH’ is about ‘0.1’, while that with ‘AR’ is much smaller, about ‘2 e-14’.

## 6. PROPOSED VISUALIZATION TOOLS

The methods discussed above for analyzing the impacts of parameters may be suitable for researchers. However for designers who may lack the statistical knowledge, it is very important to have a simple tool which allows them to visualize the interaction and analyze the savings potential due to change in a parameter. In this study, such a tool is proposed which allows one to analyze the results after an initial screening using 'Morris method' has been performed (recall that this requires fewer iterations / simulations). Parameters that do not show much impact and interaction may be dropped / fixed after elementary analysis, and combinations of the parameters that have higher impact and interaction should be considered for further analysis. This would save computational time considerably and speed up the analysis as a whole. Screenshots of the tool are shown in Figures 23-25, which represent the savings potential of a particular parameter in different ways.

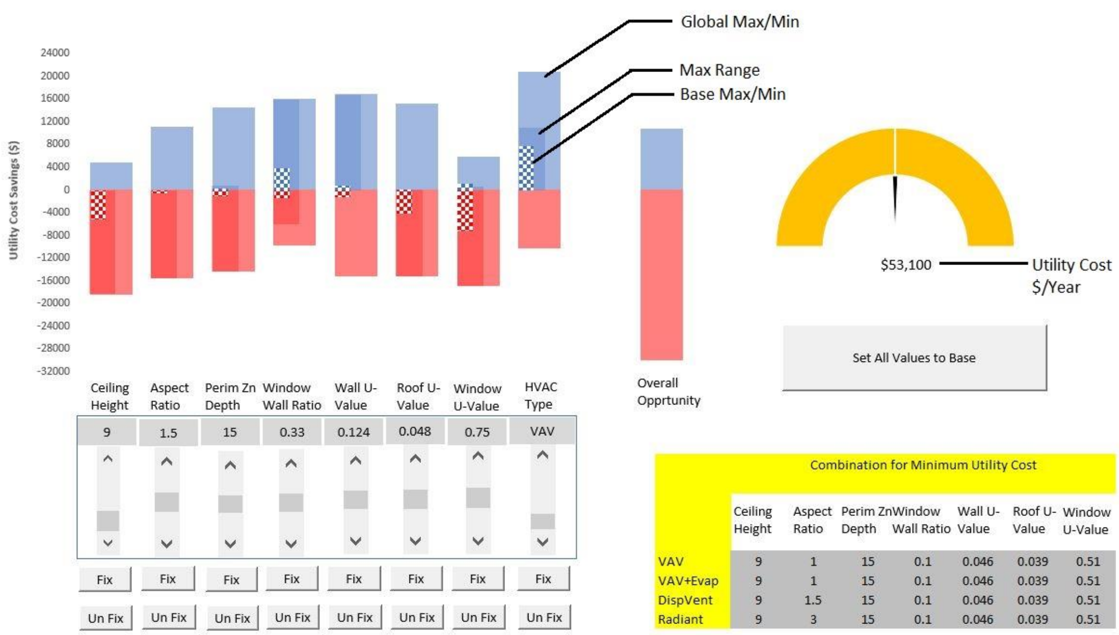



*Figure 23: Simplified Visual Tool, Base Screen*

Speedometer graphic presents the utility cost ($/year) for a particular combination of variable parameters adjusted using the slider bars for each of the parameters. Deviation of the pointer to the left indicates that there is a positive savings while the deviation to the right would symbolize a negative savings.

The column graph provides information about the possible savings when the parameter is changed from the base value. This can be visualized in three ways, where the thinnest / pattern filled columns represent the positive and negative savings achievable by altering that parameter from its base value, while all other parameters are fixed at their base value. The intermediate (thick) / dark colored column represents the positive and negative savings achievable by altering this parameter with other parameters fixed at a combination that can give the maximum range of positive / negative savings (i.e. the difference between maximum and minimum utility cost achievable by varying that parameter id maximized). The widest column (faded color) represents the global positive / negative savings, when other parameters are allowed to float at any value. This would mean that there could be two different combinations of other parameters, one when maximum positive savings from the parameter is achieved and the other at which the maximum negative savings from the parameter is achieved.


*Figure 24: Simplified Visual Tool, Saving Visualization*

Further, there are buttons located below the slider bars that allows one to fix / unfix one or more of the parameters at a particular value. This feature would help the designer to apply a constraint for one or more parameter and glean the impact it has on the saving potential of other parameter. This in turn gives a sense about the magnitude of interaction between parameters.

Figure 25 shows the interaction of ‘WWR’ with other parameters where the solid-filled columns represent the savings from the parameter in the same fashion described above, but with some of the parameters fixed at a particular value. The single line (whisker) now represents the amount of saving potential that could be achieved if the other parameter(s) were not fixed. In other words, it represents the interaction of the particular parameter with the parameter(s) that have been fixed. At this stage, a designer can choose to fix another parameter that has good potential for savings, keeping in mind other constraints involved in the design. The right most column represents the over-all saving potential available by variation of all the parameters considered in the study and the impact of fixing one or more parameters.

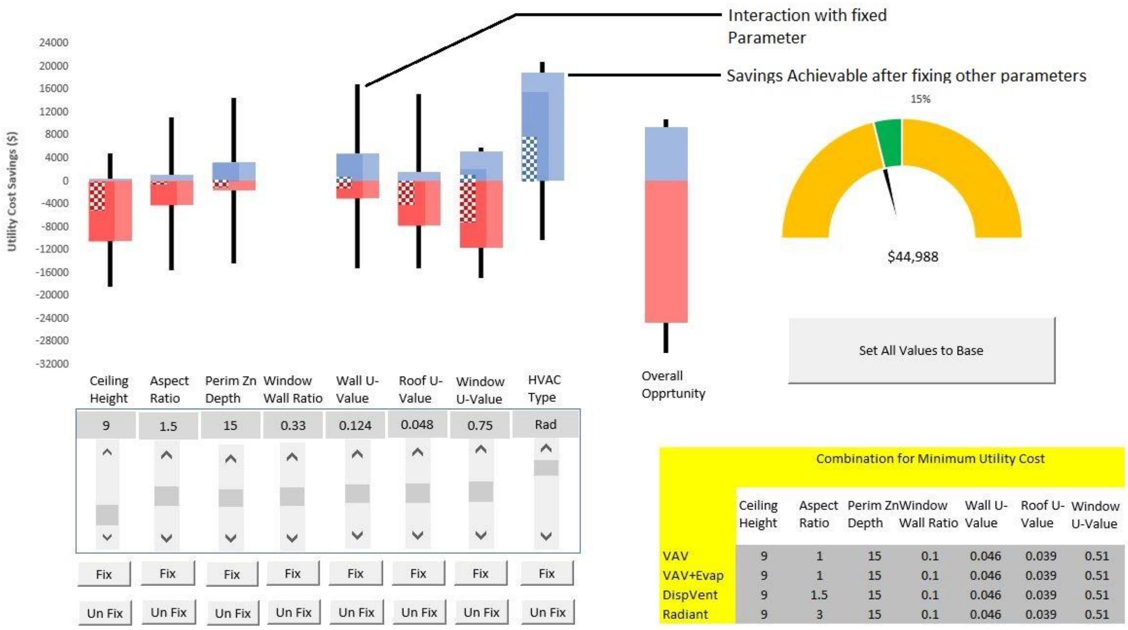



*Figure 25: Simplified Visual Tool, Interaction Visualization*

This computational aspect of the tool is based on an exhaustive search in MS Excel (VBA), and thus the time taken to navigate through the results increases with increase in the number of parameters. It is therefore suggested to narrow down the number of parameters using elementary analysis methods before using such a simplified tool. This is because the effect of parameters that are not involved in interaction and demonstrate linear impact on energy consumption, essentially do not require such visualization.

Statistical methods, such as multiple regression, can be used to enhance the subsequent speed of such a visualization tool but it is not recommended because even with good regression fits (say standard errors in the range of 3-5 %) the errors may distort potential saving estimates of certain parameters.

## 7. SAMPLE ANALYSIS

This section presents a sample case to demonstrate the use of the simplified visualization tool for analyzing design alternatives. The first three parameters (CH, AR, WWR) are likely to be highly influenced by the building's functional requirement and site constraints. Also, from Figure 26, 'AR' and 'PZD' seem to have very little latitude for savings and thus these could easily be fixed at the onset.

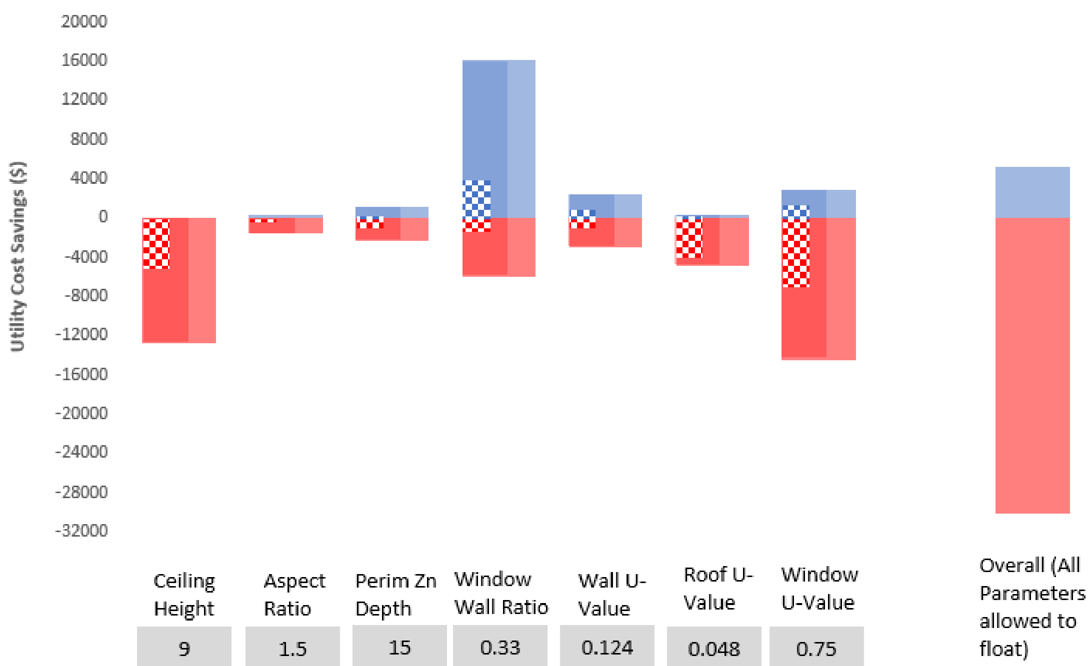



*Figure 26: Memphis - VAV, All Parameters Floating*

Fixing these parameters to their base values, as shown in Figure 27, leads us to conclude that their interaction with other parameters is not significant as well. The parameter, 'CH' can have a negative impact if it is changed from its base value; this should be the next best parameter to constrain keeping in mind other existing site or functional constraints.

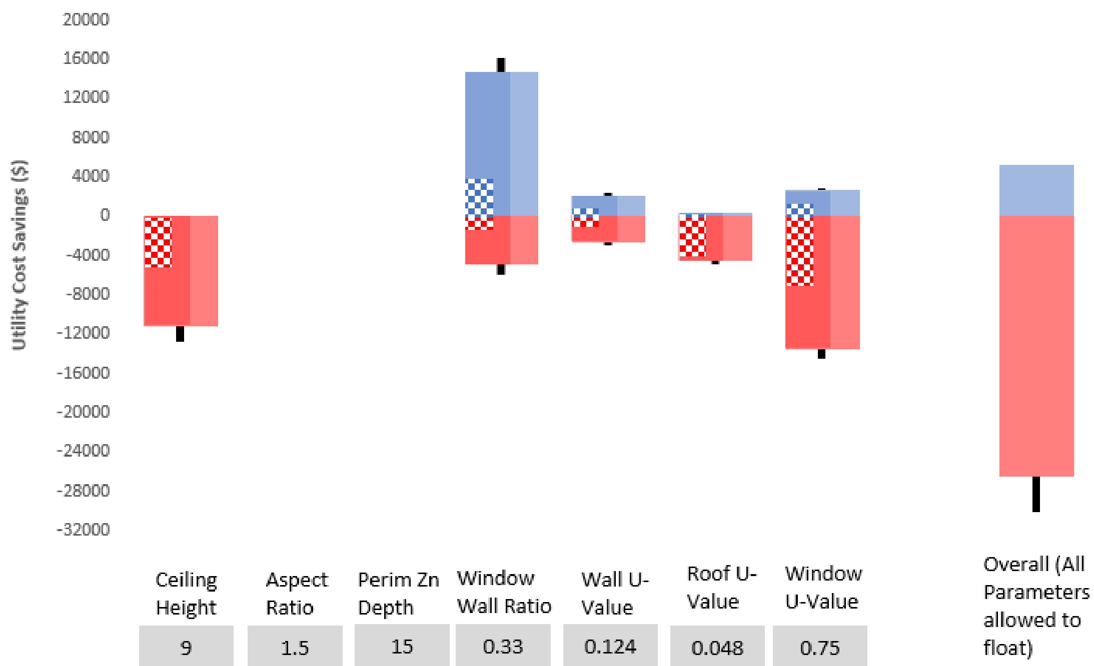



*Figure 27: Memphis-VAV, 'AR' & 'PZD' Fixed*

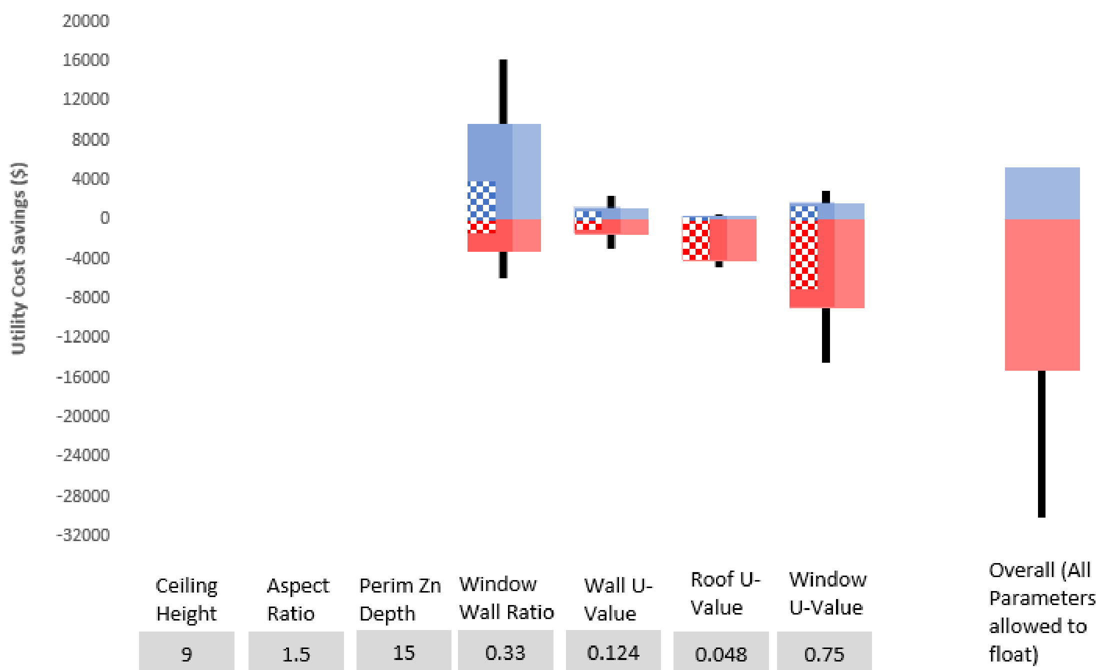



*Figure 28: Memphis-VAV, 'CH' Fixed*

Fixing 'CH' to its base value, as shown in Figure 28, some latitude in achieving savings due to improvement in 'WWR' is lost, but is still not comparable to the negative savings that changing 'CH' would have incurred. Also, as discussed earlier, 'CH' would probably be influenced by other functional constraints.

Since this study used inputs based on either ASHRAE 90.1 recommendations or the inputs that were used in modeling of ASHRAE 90.1 models by PNNL, the next step of the analysis makes an attempt to inform the user on the benefits in savings offered by various recommendations of ASHRAE 90.1 that have been considered in this study. ASHRAE 90.1 limits 'WWR' of 0.4. If we fix 'WWR' at its base value (0.33), that was assumed for ASHRAE 90.1 models, we can see that the impact of improvements made in terms of suggested properties for wall, roof and window since 1980 through various vintages of ASHRAE 90.1 is not very significant.

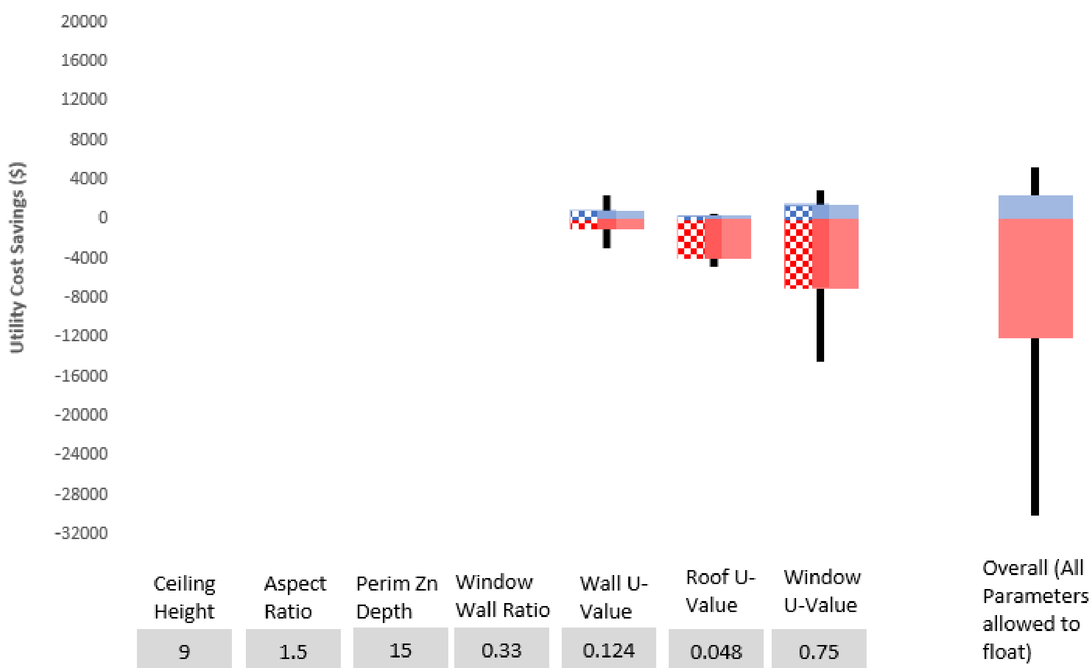



Figure 29: Memphis-VAV, 'WWR' Fixed

From Figure 29, the column representing overall saving potential indicates that the amount of savings achieved by moving from the worst case values of parameters left in the study to their base case values (red portion of the column), are smaller than those achieved by fixing the other parameters at their base case (bottom whisker portion of the column). Also, it can be noticed that the interactions between three remaining parameters in the study are not significant (since there is no visible difference between the heights of pattern filled columns and solid filled columns). However, there was significant interaction between 'WU' and 'WinU' with some parameters that have been fixed (whisker portion of the column). This implies that a decision regarding any of the parameters can now be made as per their saving potential without being concerned about the other parameters remaining in the study.

It could be observed that changes in 'WU' suggested in ASHRAE 90.1 from 1980's until ASHRAE 90.1-2010 did not actually result in much savings. 'RU' and 'WinU' did result in significant savings (as discussed in the earlier sections of this document, 'WinU' does not mean change in U-Value of window only, but it is accompanied by change in SHGC of the window as well). However, from the previous step (Figure 28), it is worth noticing that 'WWR' has a significant potential to increase savings by changing it from base value. This points toward an important observation that rather than imposing stringencies in Wall U-Values and Roof U-Values, stringent requirements in terms of reducing 'WWR' or enforcing use of some shading devices to avoid heat gain through windows in such a climate, would prove to be a wise strategy to propose in future revisions of ASHRAE 90.1.

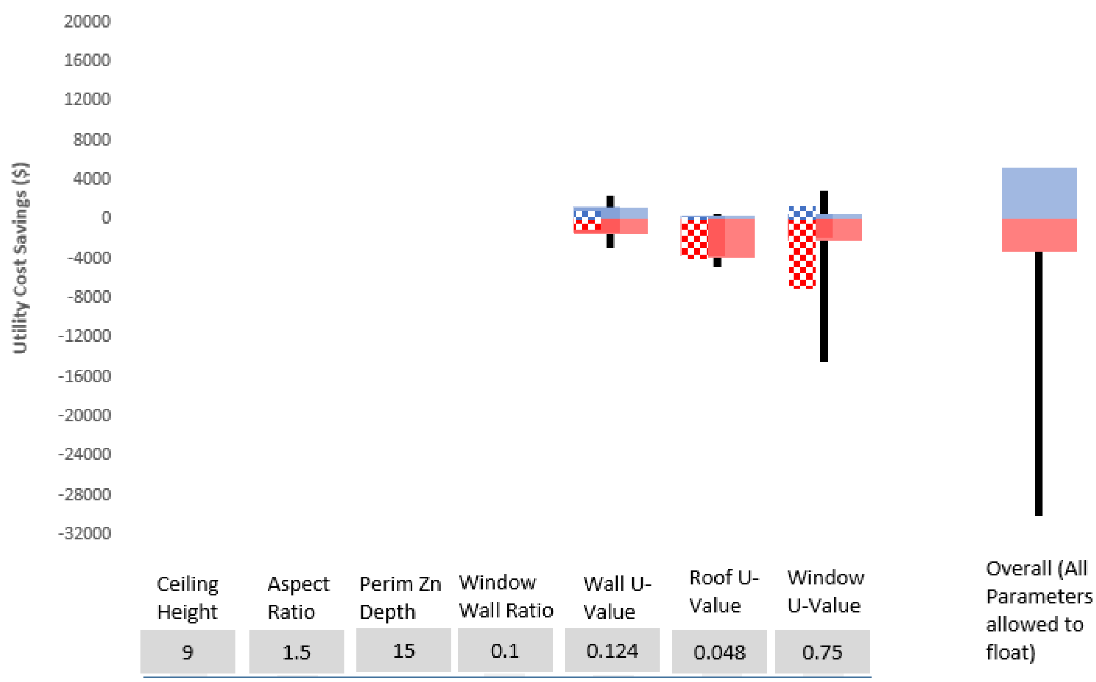



*Figure 30: Memphis-VAV, 'WWR' fixed at 0.1*

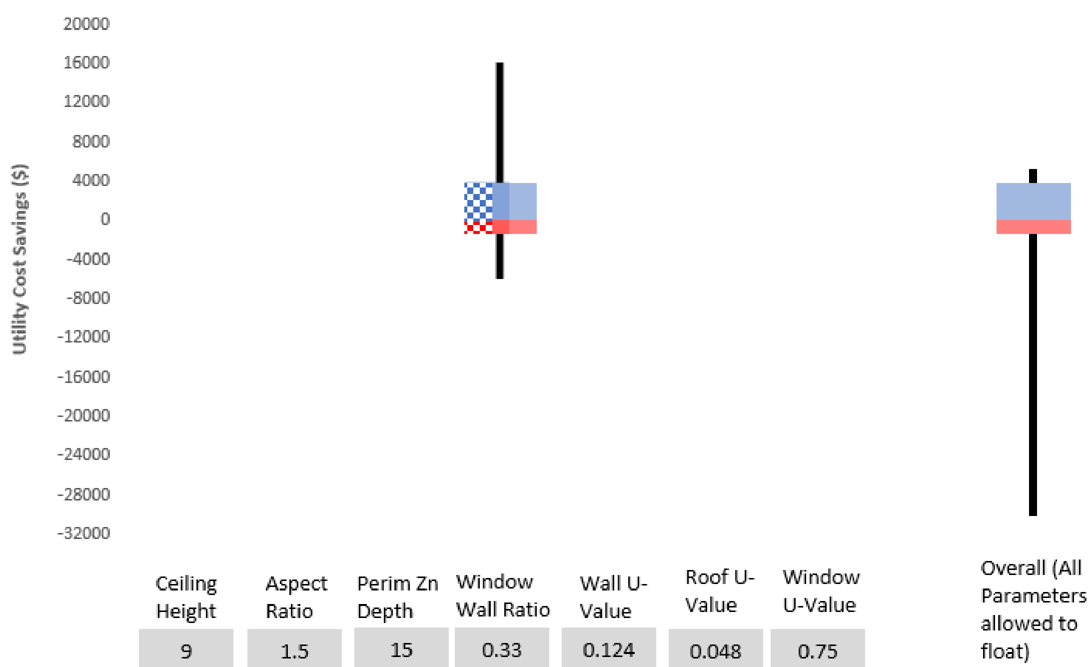



*Figure 31: Memphis-VAV, All but 'WWR' Fixed*

Figure 30 shows that on fixing 'WWR' at its best case (assumed to be 0.1), there is not much latitude left for improving savings from 'WinU'. This is very much expected since there is very little window area left in the building. The positive savings (represented by the column for overall savings) show a higher value than the cumulative savings resulting from other individual parameters remaining in the analysis since the savings since the savings are relative to the base value of that parameter while other parameters are fixed at any possible value. However for overall savings column, the savings is always relative to base case values for all parameters, which gives a sense of actual total savings including the effects of fixed parameters at any value.

Finally, if all parameters except ‘WWR’ are fixed (at their base values), the savings value represented by individual column for ‘WWR’ becomes very similar to that represented by column for overall savings, as shown in Figure 31.

## 8. CONCLUSIONS

The Radiant cooling system with DOAS is found to perform best in all three climates studied, followed by Displacement ventilation and Evaporative cooling on OA with a base case VAV system respectively. Evaporative cooling did not show significant savings in a climate with higher humidity (which is to be expected). As an example, with a VAV system in Memphis, the annual utility cost is about $53,100, as compared to $52,556, $49,197 and $44,988 for ‘VAV + Evaporative’ system, ‘Displacement Ventilation’ system and ‘DOAS + Radiant cooling’ system respectively.

As discussed earlier, many studies in the past have shown that VAV systems with better controls could perform much better than some of the other systems; however optimization of individual secondary systems and their control was not in the scope of this study. The aim for this study was more towards analyzing the interaction effects of building envelope design parameters for a selected few of the promising and emerging HVAC technologies, and suggesting a convenient analysis and visualization methodology for real projects.

As a general observation, the parameters ‘CH’, ‘WWR’ and ‘WinU’ showed maximum impact and interaction in all climates and for all system type, of which ‘WWR’ had maximum importance and interaction with ‘WinU’.

In terms of methodology we found that ‘Morris method’ is able to provide a very good categorization of input parameters at low computational requirements with regards to simulation run time. It is highly recommended to perform such elementary analysis in order to reduce the number of parameters; this is achieved by removing the parameters with very less importance and interaction effects.

Use of visualization tool with an exhaustive search is recommended during final analysis with a reduced parameter set because it provides better understanding and user-friendliness to the designers, without introducing needless uncertainty or errors in prediction. Use of regression methods have shown good results but even an error of 3-5% could be substantial for such studies where the savings for some of the parameters might fall in that range.

## 9. FUTURE WORK

This study was limited to input parameters related to building geometry and envelope characteristics. Considering more number of parameters related to internal loads, HVAC system, operation types and schedules would be a good extension.

A sample study was conducted to identify the level of interaction and importance of ‘Lighting Power Density (LPD)’ as compared to other parameters considered in this study for the model with ‘VAV system’ in ‘Memphis’ climate. The variation in ‘LPD’ considered for this study was 0.45 W/ft$^2$, 0.9 W/ft$^2$ (base LPD as per ASHRAE 90.1-

2010) and 1.35 W/ft$^2$. The result using 'Morris Method' has been shown in Figure 32. 'LPD' showed medium importance and interaction effects, which is as expected due to its interaction with 'WWR', since the daylighting controls is turned 'ON'.

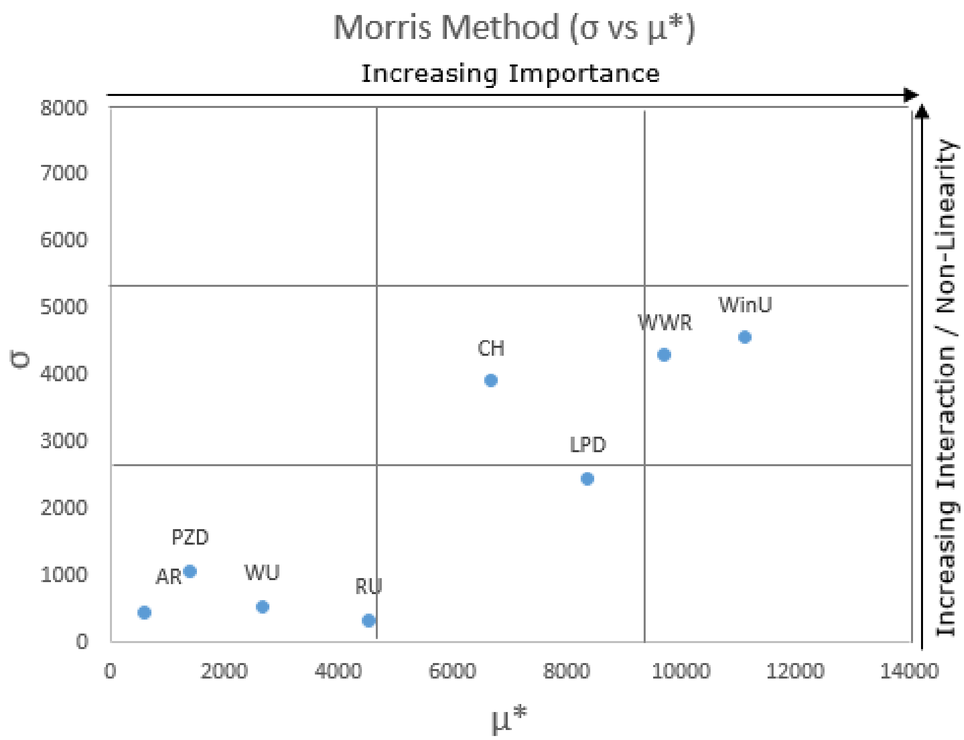



*Figure 32: Memphis VAV (All parameters including LPD)*

Also, a more efficient VAV system was modeled (termed as 'Better VAV') to allow comparing its performance with other efficient systems included in this study, so as to give an insight of the necessity of a study involving more HVAC parameters. The improvements made in this system as compared to the base VAV system are:

1) Fan Static Pressure set to 2'' inches of water column as against 5.5'' in the base system.
2) DX Cooling Coil EER set to 12.5 against 11.5 in the base system.
3) Cooling supply air temperature reset based on 'Warmest' from 55 $^oF$ to 65 $^oF$, against fixed set-point of 55 $^oF$.

The utility costs for the systems are shown in Figure 33. It can be observed that a 'Better VAV' system performs similar to 'Displacement Ventilation' system and the percentage improvement as compared to base VAV system is 7.5%.

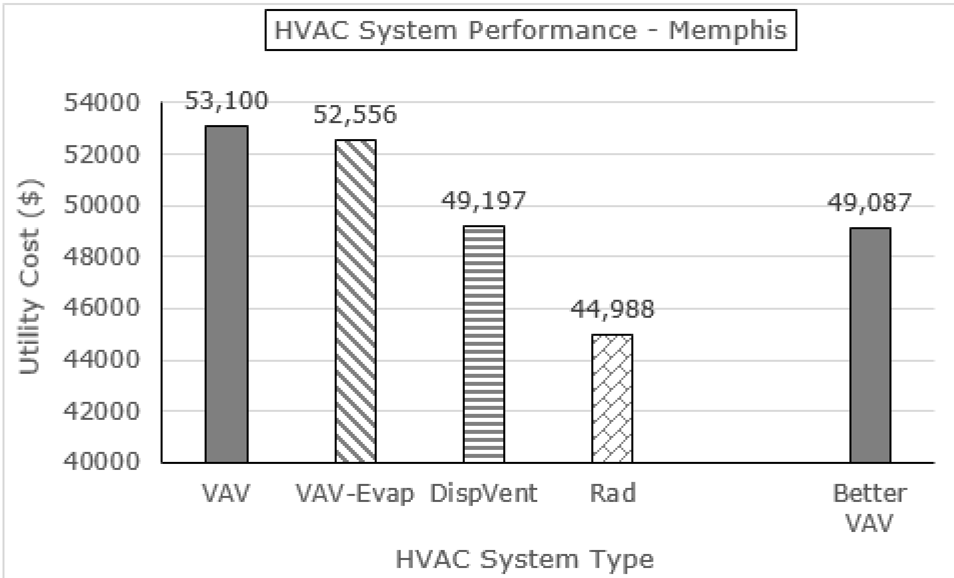



*Figure 33: HVAC System performance for Memphis (Including Better VAV)*

Therefore, a future study incorporating more variables related to internal loads, building types and HVAC system should be undertaken which will include a range of variations for various HVAC system to make better design decisions.

The methodology proposed in this research could be used to categorize buildings at a campus level based on parameters that show interaction effects and non-linear impacts on energy consumption. This could lead to a large reduction in the number of detailed simulations needed for a representative building in the group rather than simulating each and every individual building. This approach would be useful for future ASHRAE 90.1 work and also for use by design firms.

Incorporating similar approach into simulation tools to simplify and reduce the number of input parameters needed to set up initial simulation model would be beneficial.

## 10. REFERENCES

Addison, M.S. (1988). A Multiple Criteria Satisficing Methodology For the Design of Energy-Efficient Buildings, Masters' Thesis, Arizona State University, Tempe.

AL-Homoud, M.S. (1997). Optimum Design of Office Buildings, International Journal of Energy Research, Vol. 21, 941-957.

Baechler, M.C., Williamson, J., Gilbride, T., Cole, P., Hefty, M., & Love, P. (2010). Guide to determining Climate Regions by County, Building America Best Practices Series, Volume 7.1.

Bichiou, Y., & Krarti, M. (2011). Optimization of envelope and HVAC systems selection for residential buildings, Energy and Buildings 43 (2011) 3373-3382

Daly, D., Cooper, P., & Ma, Z. (2014). Understanding the risks and uncertainties introduced by common assumptions in energy simulation for Australian commercial buildings, Energy and Buildings 75, 382-393.

Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halverson, M., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J., & Crawley, D. (2011). US Department of Energy Commercial Reference Building Models of the National Building Stock, Technical Report, NREL/TP-5500-46861

Design Brief (2005), for Energy Design Resources, by Architectural Energy Corporation.

Didwania, S.K., Rawal, R., Shukla, Y., & Bansal, N.K. (2014), Relevance of radiant space cooling in Indian context, Conference Proceeding by ASHRAE, First International Conference on Energy and Indoor Environment for Hot Climates, Doha, Qatar.

Displacement Ventilation, Design Brief, Energy Design Resources.

Dutta, R. (2013). A Visual Analytics Based Decision Support Methodology For Evaluating Low Building Design Alternatives, Masters' Thesis, Arizona State University, Tempe.

Engelmann, P., Kalz, D., & Salvalai, G. (2014). Cooling Concepts for non-residential buildings: A comparison of cooling concepts in different climate zones, Energy and Buildings 82, 447-456.

Friedman, J.H., Popescu, B.E. (2005), Predictive Learning via Rule Ensembles.

GenOpt User Manual, v3.1.0. Retrieved from https://simulationresearch.lbl.gov/GO/download/manual-3-1-0.pdf

Getting Started with EnergyPlus. Retrieved from http://nrel.github.io/EnergyPlus/GettingStarted/GettingStarted/

Goel, S., Rosenberg, M., Athalye, R., Xie, Y., Wang, W., Hart, R., Zhang, J., & Mendon, V. (2014). Enhancements to ASHRAE Standard 90.1 Prototype Building Models, Technical Report, PNNL-23269.

Griffith, B., Long, N., Torcellini, P., Judkoff, R., Crawley, D., & Ryan, J. (2007). Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector, Technical Report, NREL/TP-550-41957.

Hemsath, T.L., & Bandhosseini, K.A. (2015). Sensitivity analysis evaluating basic building geometry's effect on energy use, Renewable Energy 76, 526-538.

Kao, J.Y. (1985). Control Strategies and Building Energy Consumption, ASHRAE Trans., pt. 2B, 810.

Lam, J.C., & Hui, S.C.M. (1996). Sensitivity Analysis of Energy Performance of Office Buildings, Building and Environment, Vol. 31, No. 1, pp. 27-39.

Lam, J.C. (2008). Sensitivity analysis and energy conservation measures implications, Energy Conversion and Management 49, 3170-3177.

Mateus, N.M., & Carrilho da Graca, G. (2015), A validated three-node model for displacement ventilation, Building and Environment 84, 50-59.

Morris, M.D. (1991). Factorial Sampling Plans for Preliminary Computational Experiments, Technometrics, Vol. 33, No. 2, pp. 161-174.

Olsen, E.L., & Chen, Q. (2003). Energy consumption and comfort analysis for different low-energy cooling systems in a mild climate, Energy and Buildings 35, 561-571.

Sanchez, D.G., Lacarriere, B., & Bourges, B. (2014). Application of sensitivity analysis in building energy simulations: Combining first and second order elementary effects methods, Energy and Buildings 68, 741-750.

Snyder, S.C., Reddy, T.A., & Addison, M.S. (2013). Automated Design of Buildings: Need, Conceptual Approach, and Illustrative Example, ASHRAE Transactions, Volume 119, Issue 1, p1.

Stein, J., & Taylor, T. (2013). VAV Reheat Versus Active Chilled Beams & DOAS, ASHRAE Journal, Vol 55, no. 5.

Stocki, M., Curcija, D.C., & Bhandari, M.S. (2007). The Development of Standardized Whole-Building Simulation Assumptions for Energy Analysis for a Set of Commercial Buildings, ASHRAE Transactions, Volume 113, Part 2.

Thornton, B.A., Wang, W., Lane, M.d., Rosenberg, M.I., & Liu, B. (2009). Technical Support Document: 50% Energy Savings Design Technology Packages for Medium Office Buildings, PNNL-19004.

Tian, W. (2013). A review of sensitivity analysis methods in building energy analysis, Renewable and Sustainable Energy Reviews 20, 411-419.

What is R? Retrieved from https://www.r-project.org/about.html

# APPENDIX A

## CHARTS FOR ELEMENTARY ANALYSIS USING MORRIS METHOD

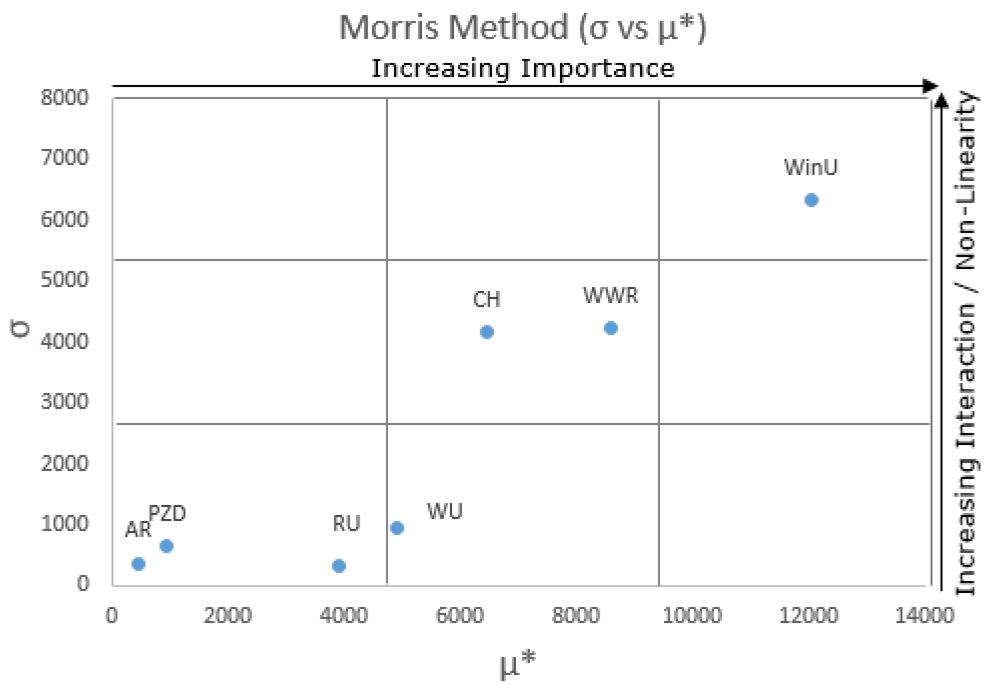



*Figure 34: Morris Method (σ vs μ*) for Phoenix - VAV*

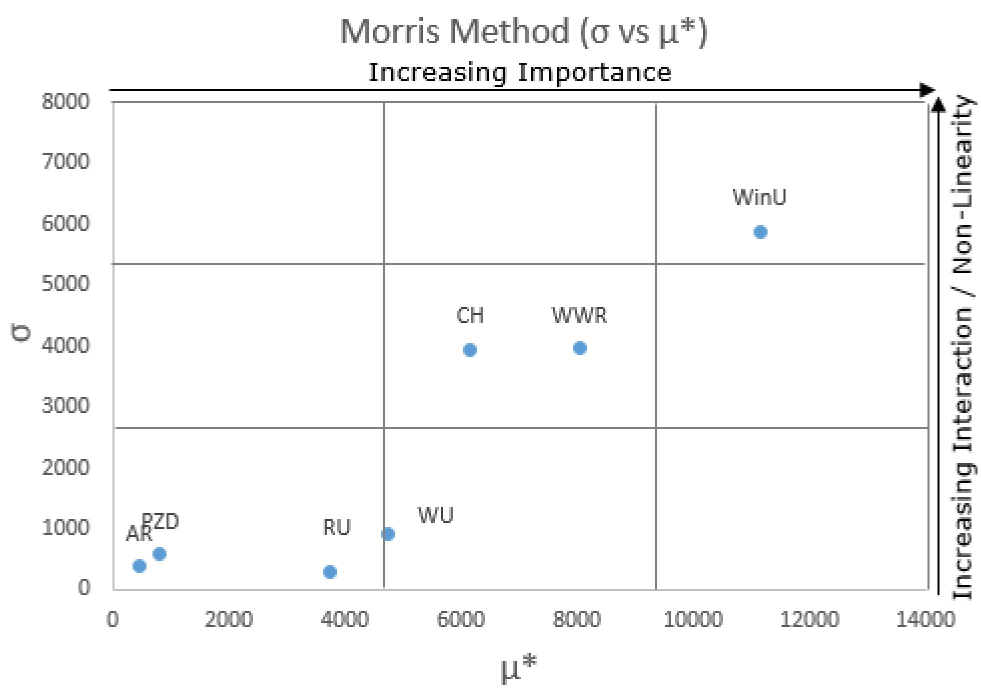



*Figure 35: Morris Method (σ vs μ*) for Phoenix – VAV + Evaporative*

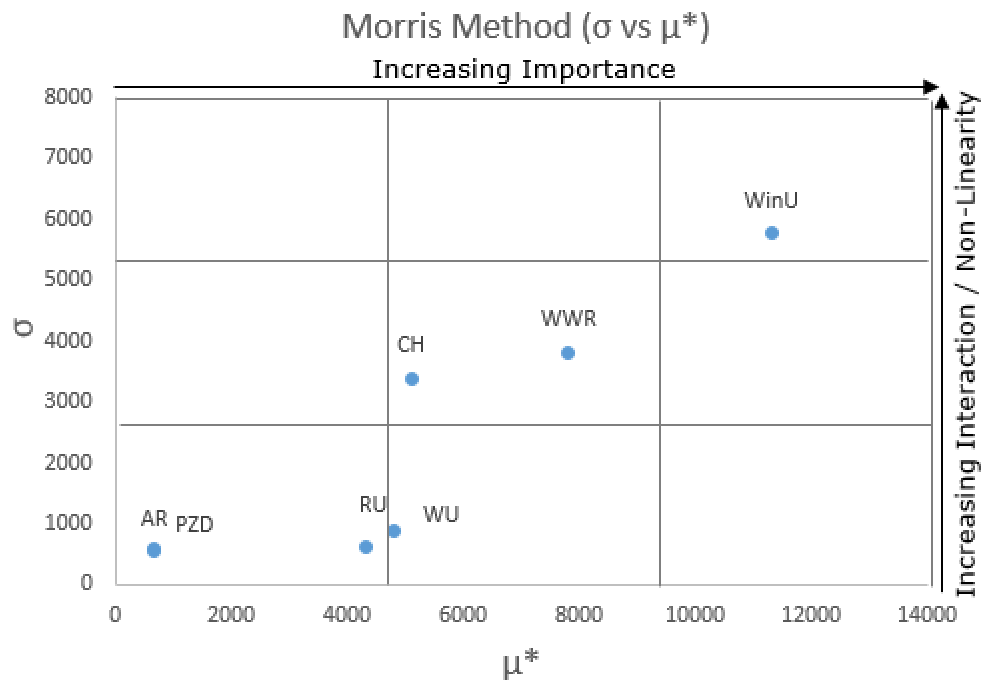



*Figure 36: Morris Method (σ vs μ*) for Phoenix – Displacement Ventilation*

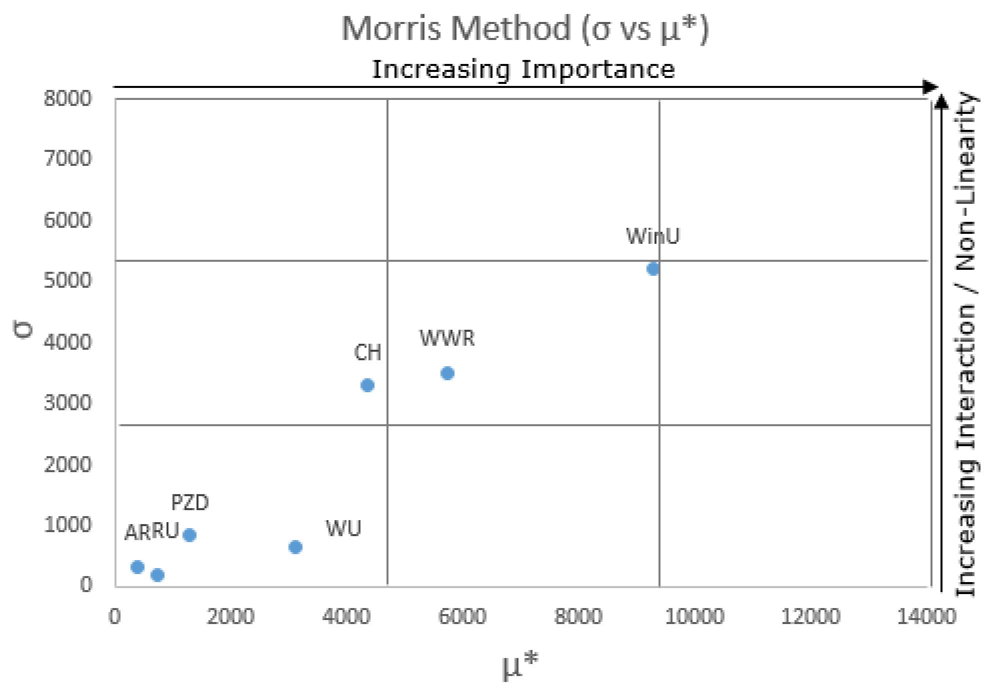



*Figure 37: Morris Method (σ vs μ*) for Phoenix – DOAS + Radiant Cooling*

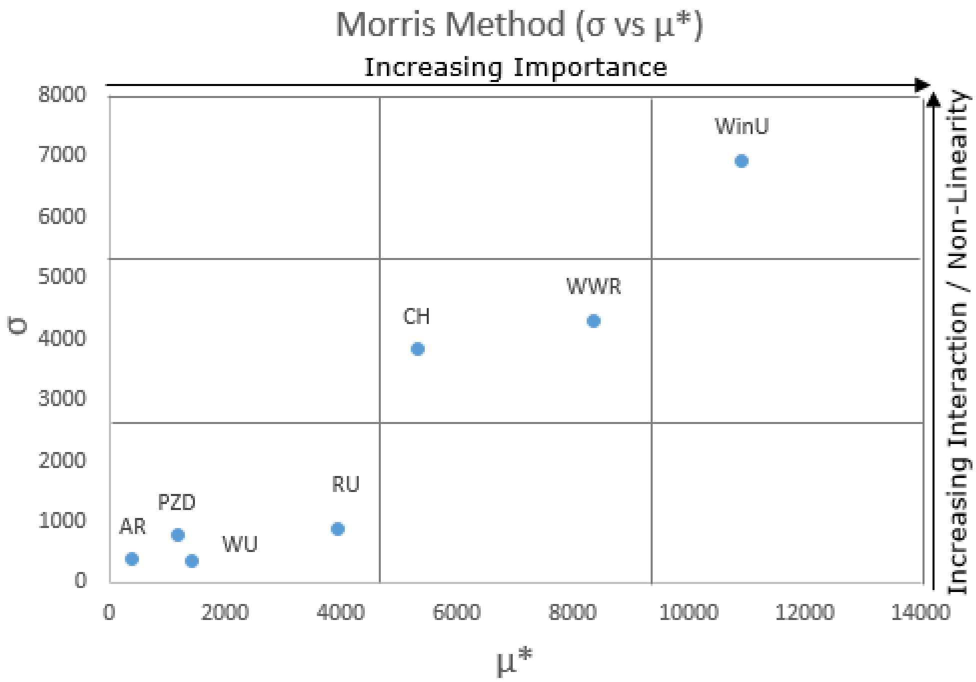



*Figure 38: Morris Method (σ vs μ*) for Albuquerque - VAV*

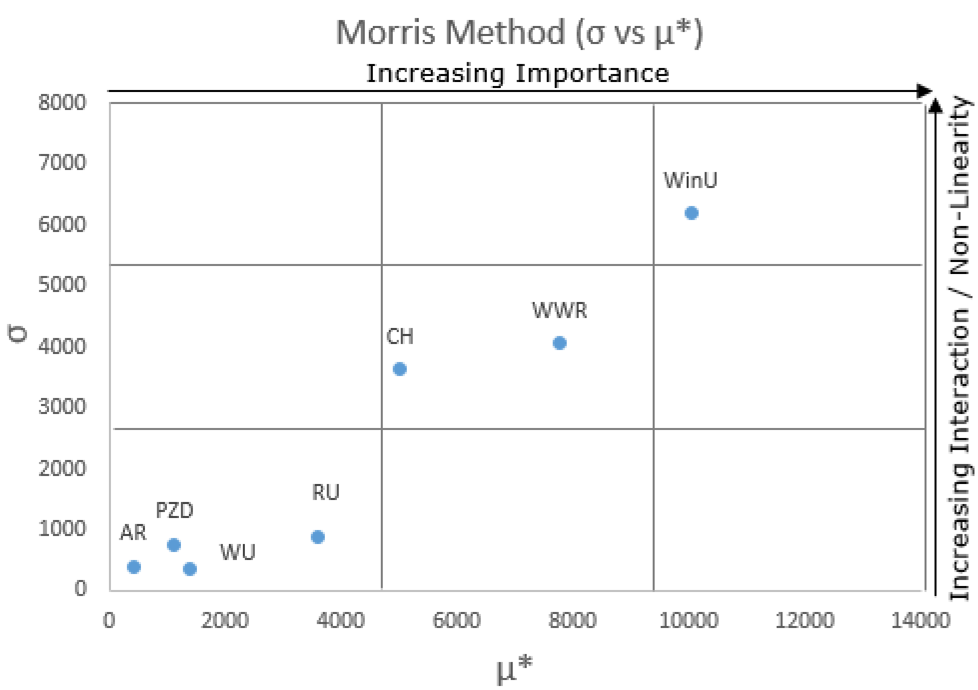



*Figure 39: Morris Method (σ vs μ*) for Albuquerque – VAV + Evaporative*

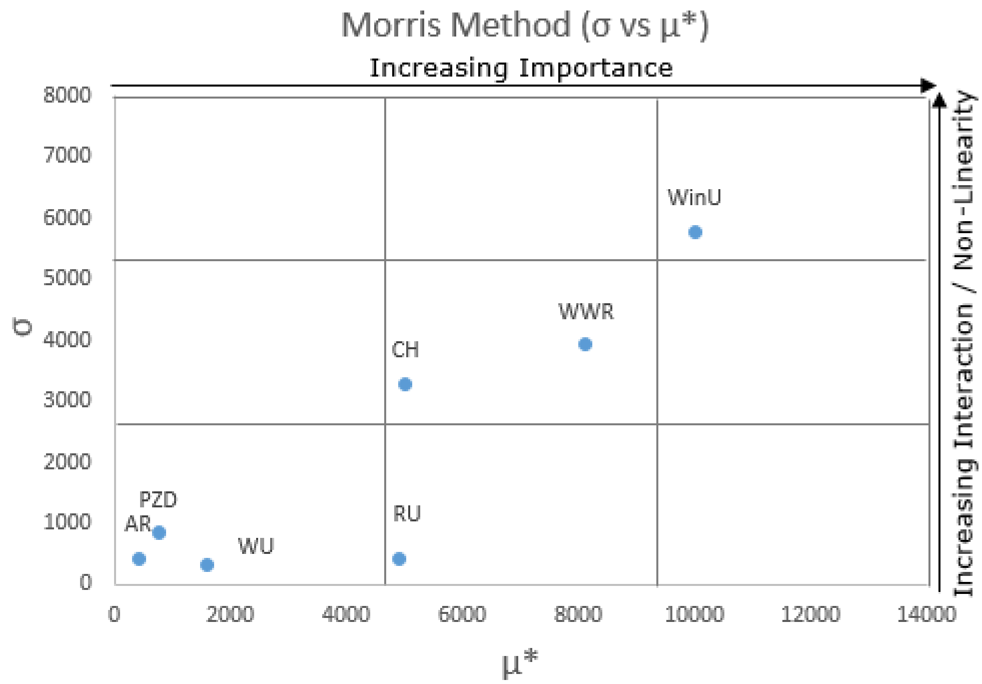



*Figure 40: Morris Method (σ vs μ*) for Albuquerque – Displacement Ventilation*

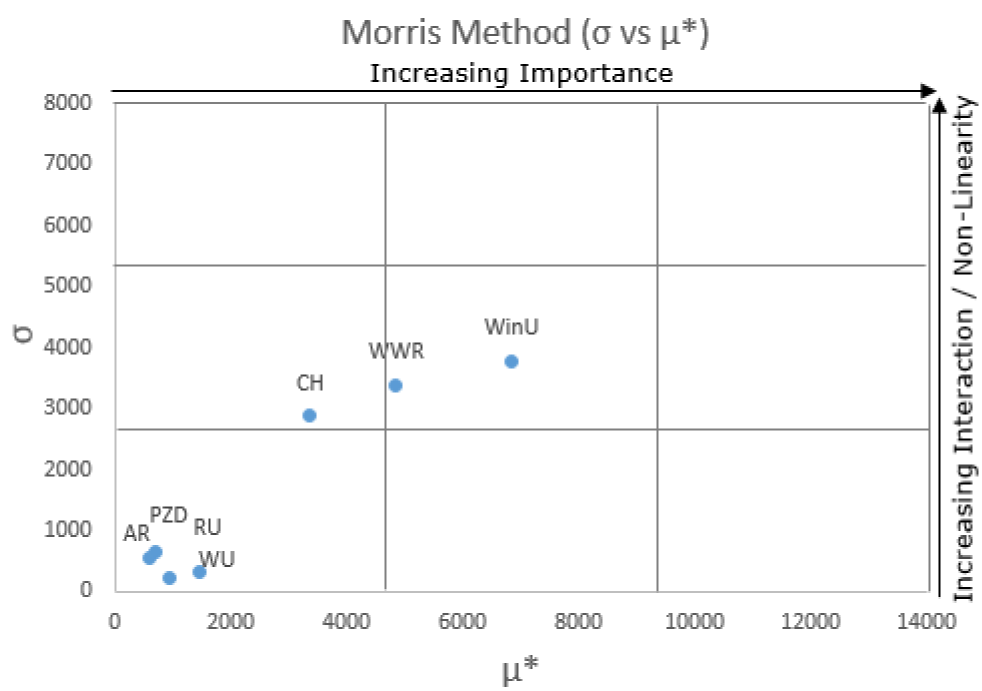



*Figure 41: Morris Method (σ vs μ*) for Albuquerque – DOAS + Radiant Cooling*

# APPENDIX B

## CHARTS FOR IMPORTANCE AND INTERACTION STRENGTH USING ‘PREDICTIVE LEARNING VIA RULE ENSEMBLES’ ALGORITHM

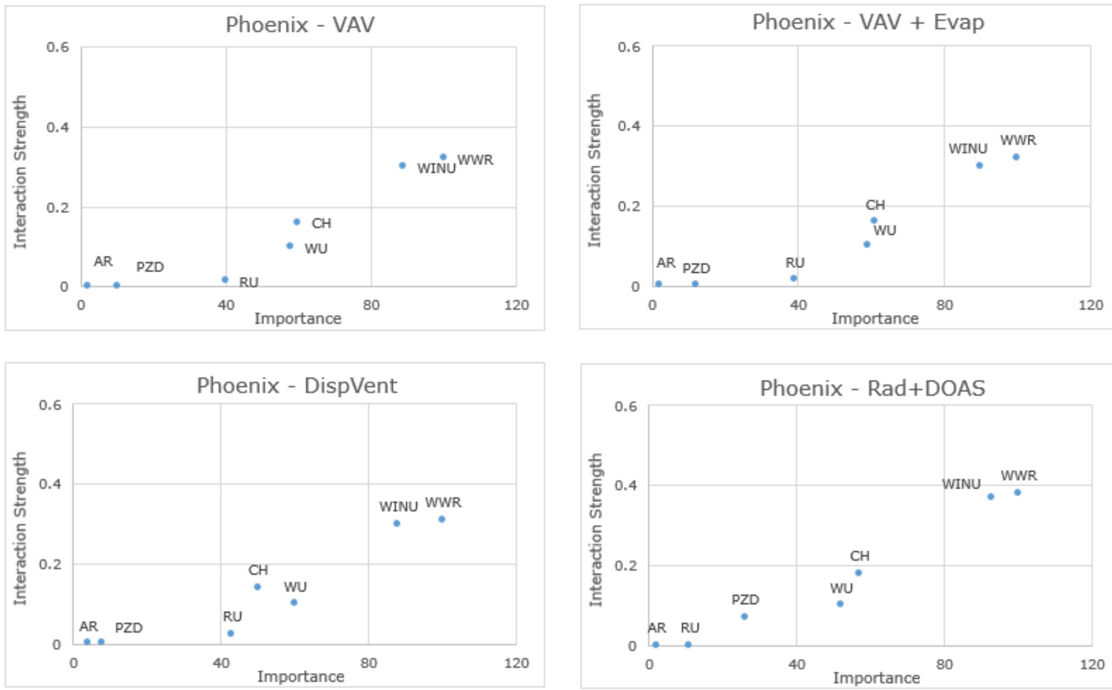



*Figure 42: RuleFit Method - Importance Vs Interaction Strength for Phoenix*

For Phoenix climate, it is noticed that there was an increase in the relative importance and interaction for parameter 'WU' as compared to other climates. This is attributed to increased temperature difference between indoor and outdoor environment in this climate.

In terms of HVAC system, it is observed that while the importance and interaction of most of the parameters remained the similar, the parameter 'CH' showed a decrease in relative importance for Displacement Ventilation system, and the parameter 'RU' showed a significant decrease in its relative importance for DOAS + Radiant Cooling system.

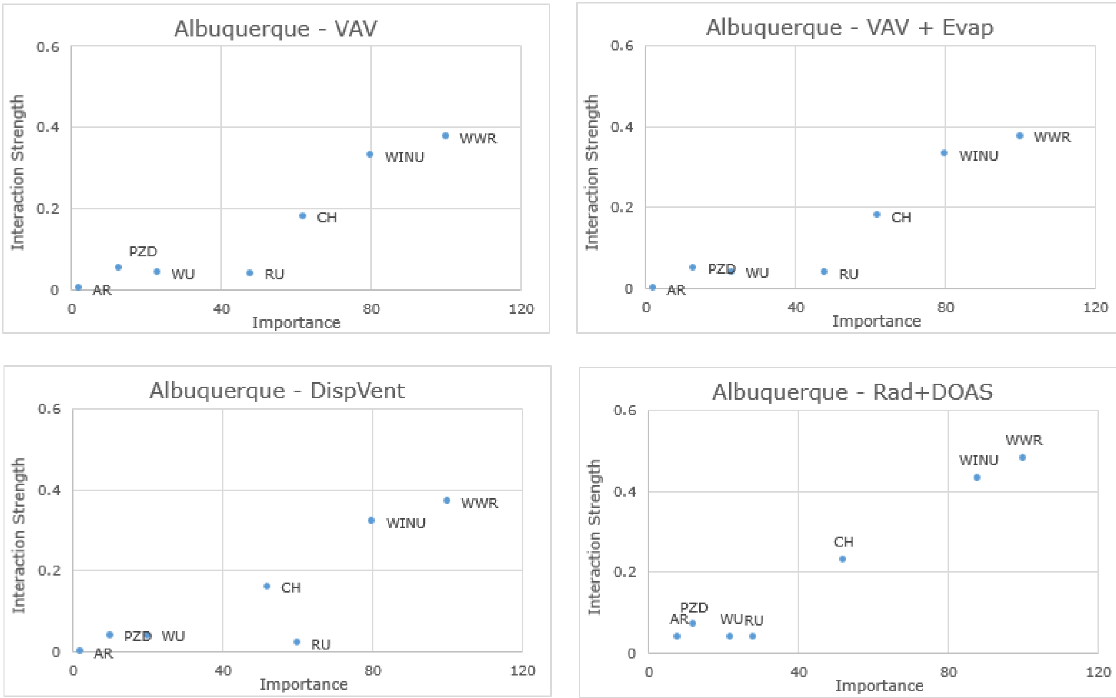



*Figure 43: RuleFit Method - Importance Vs Interaction Strength for Albuquerque*

Similar to other climates, the parameter 'RU' had a reduced importance for DOAS + Radiant Cooling system. It can also be noticed that the parameters 'WWR' and 'WinU' demonstrated slight increase in interaction strength in case of DOAS + Radiant Cooling system.

# APPENDIX C

## CHARTS FOR DETAILED INTERACTION OF A PARAMETER WITH OTHERS USING 'PREDICTIVE LEARNING VIA RULE ENSEMBLES' ALGORITHM

Similar trends (with minor differences) were noticed for interaction strength of parameters with respect to a particular parameter for various combinations of climate and HVAC system. Figures 44-87 illustrates these interaction strengths for all HVAC system and climate combinations that were not shown in the results section.

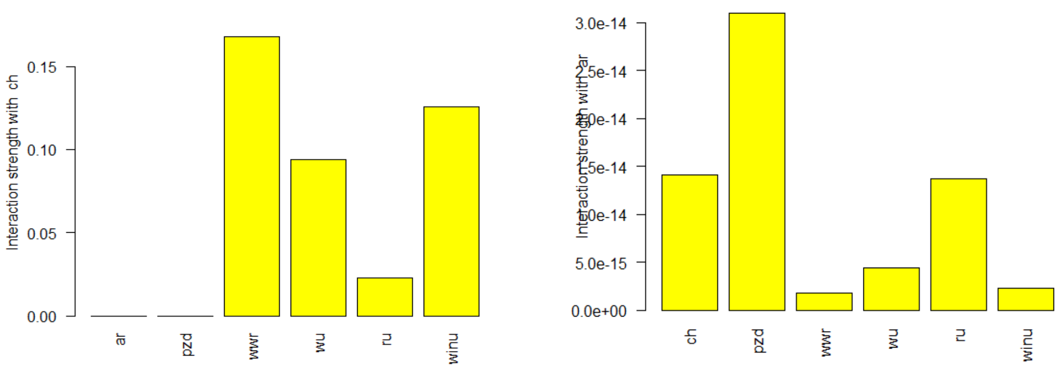



*Figure 44: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Memphis – VAV + Evaporative*

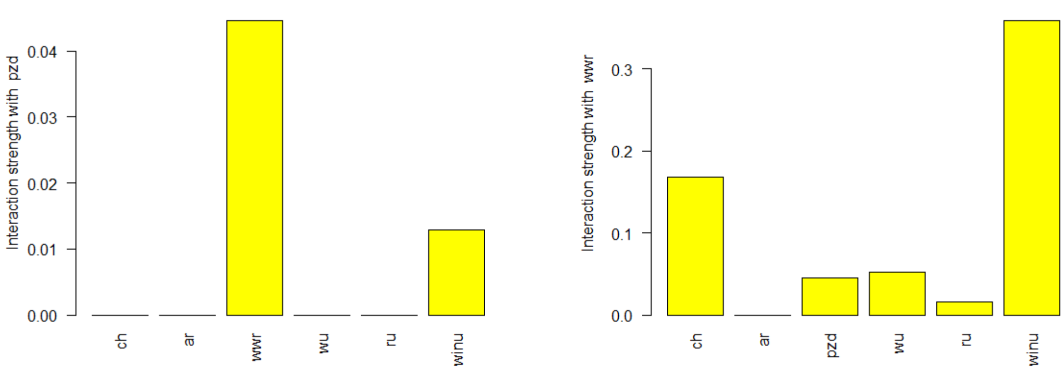



*Figure 45: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Memphis – VAV + Evaporative*

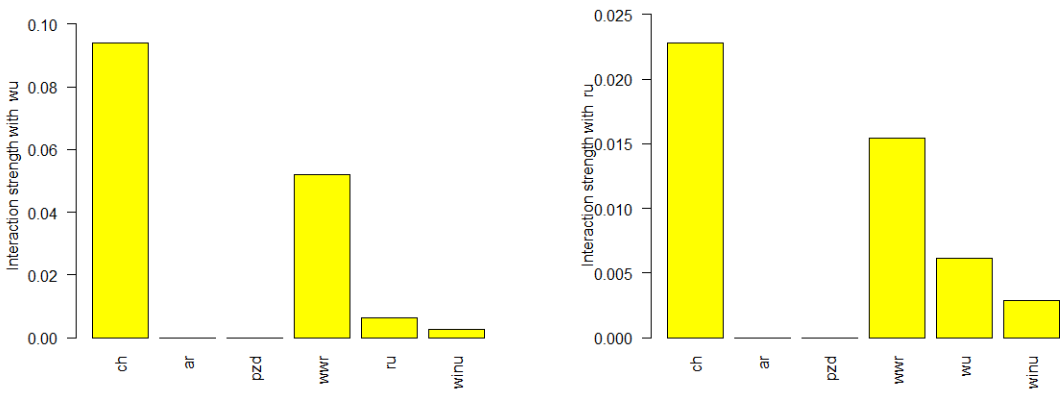



*Figure 46: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Memphis – VAV + Evaporative*

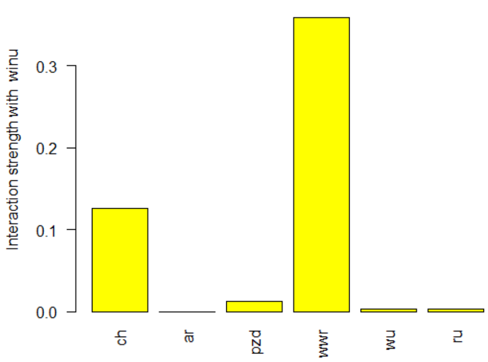



*Figure 47: RuleFit Method - Interaction Strengths with 'WinU' for Memphis – VAV + Evaporative*

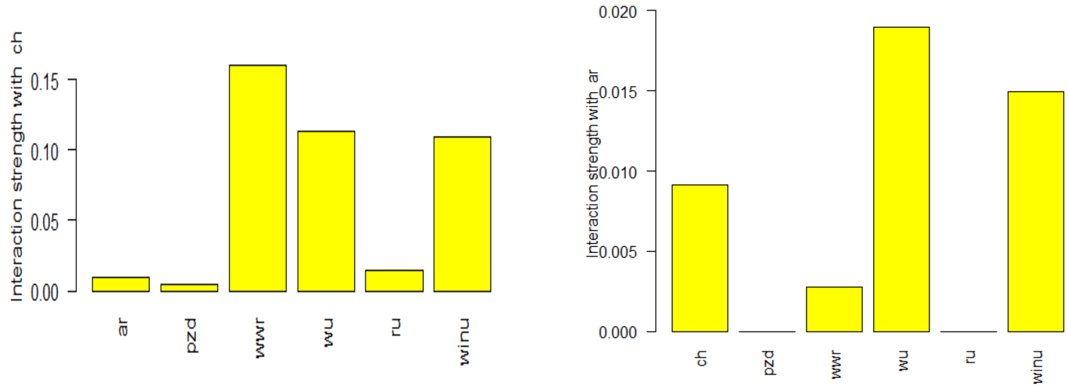



*Figure 48: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Memphis – Displacement Ventilation*

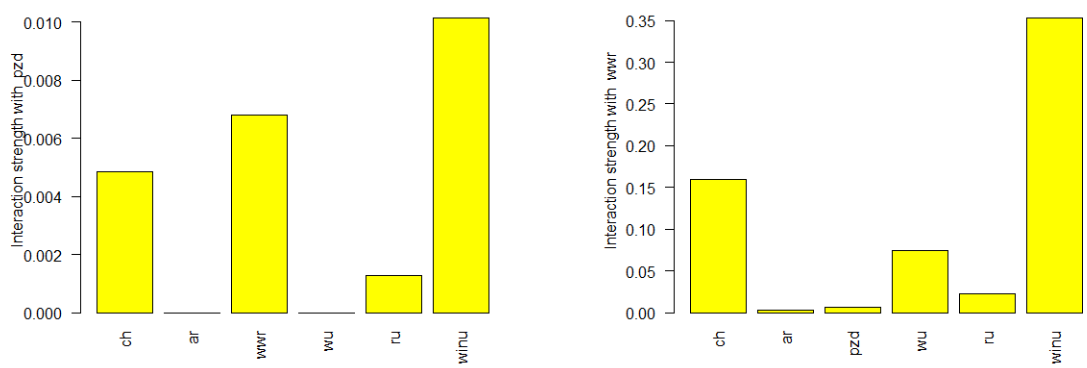



*Figure 49: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Memphis – Displacement Ventilation*

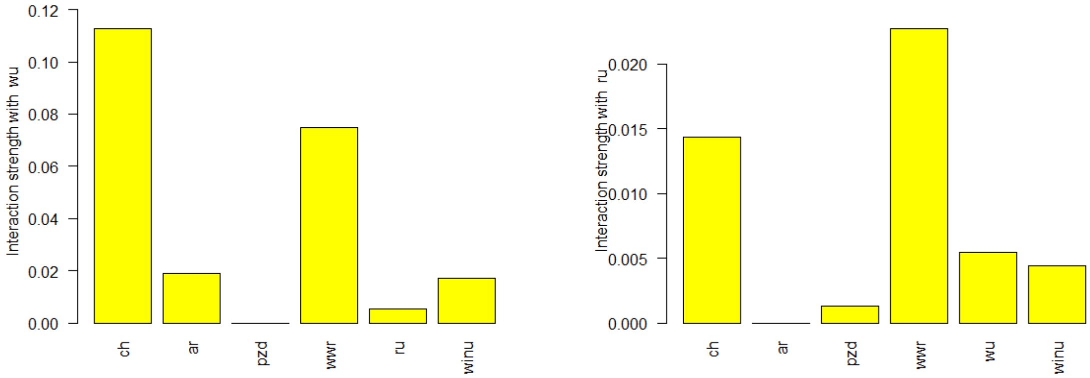



*Figure 50: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Memphis – Displacement Ventilation*

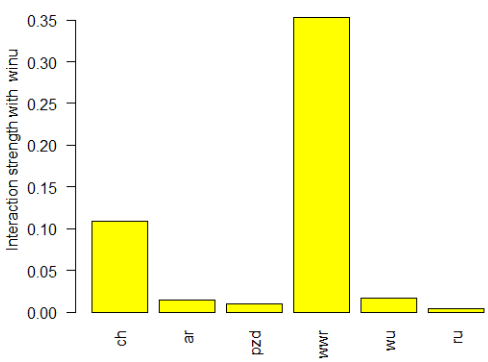



*Figure 51: RuleFit Method - Interaction Strengths with 'WinU' for Memphis – Displacement Ventilation*

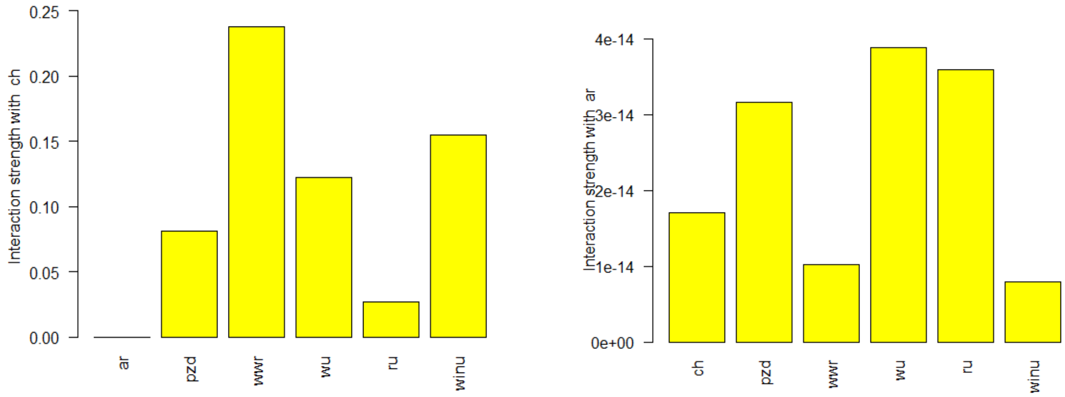



*Figure 52: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Memphis – DOAS + Radiant Cooling*

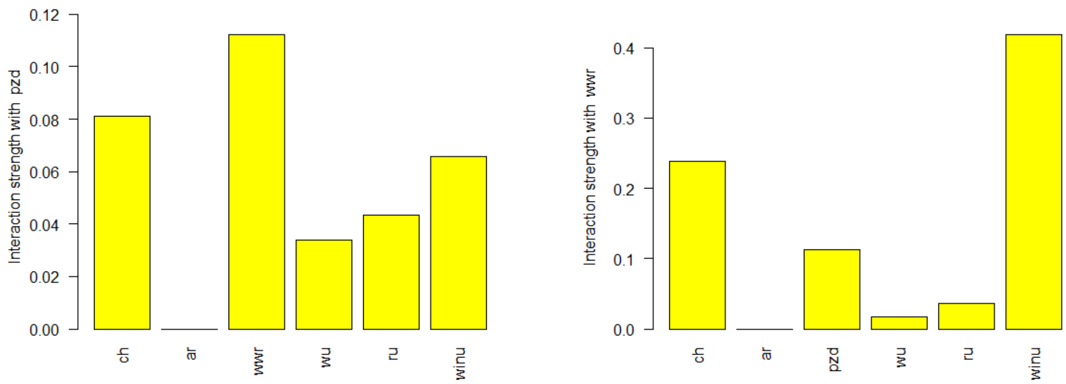



*Figure 53: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Memphis – DOAS + Radiant Cooling*

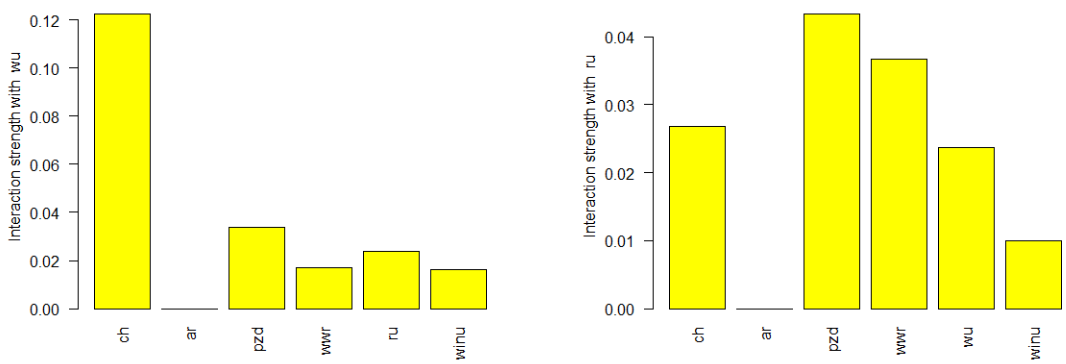



*Figure 54: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Memphis – DOAS + Radiant Cooling*

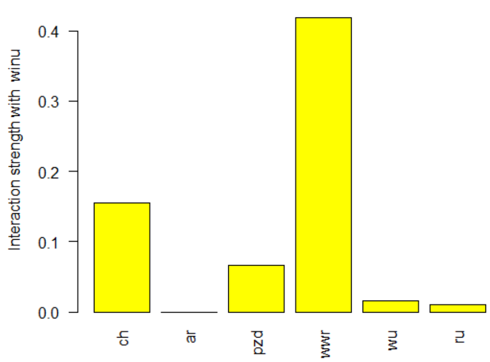



*Figure 55: RuleFit Method - Interaction Strengths with 'WinU' for Memphis – DOAS + Radiant Cooling*

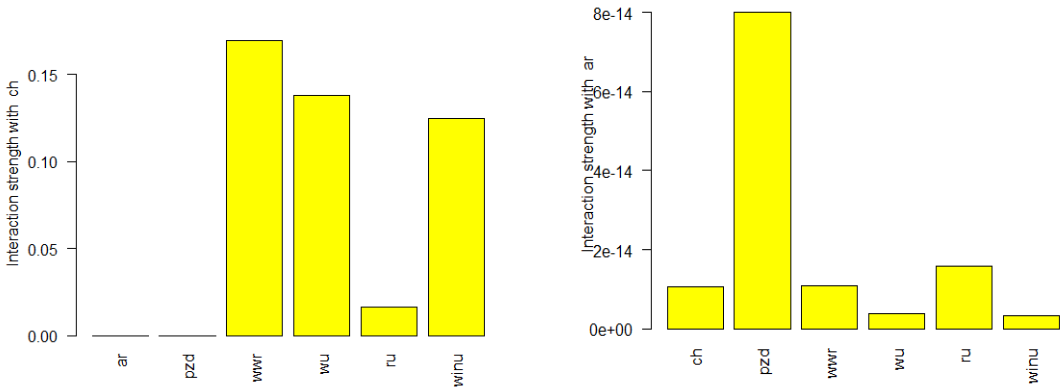



*Figure 56: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Phoenix – VAV*

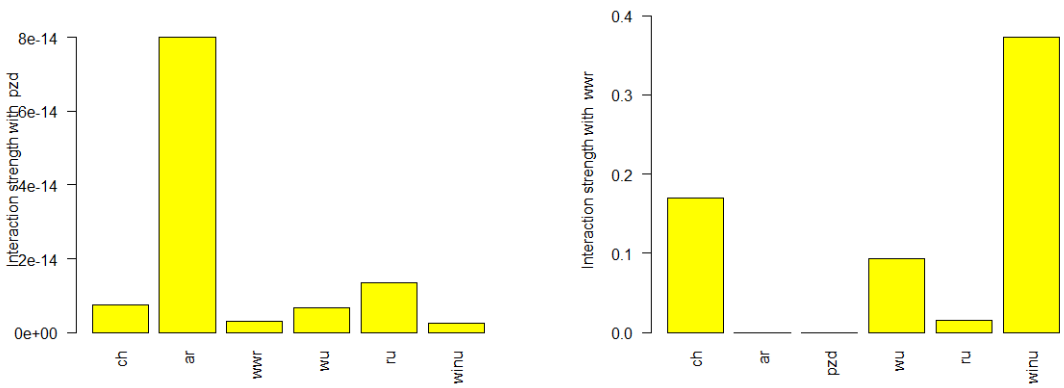



*Figure 57: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Phoenix – VAV*

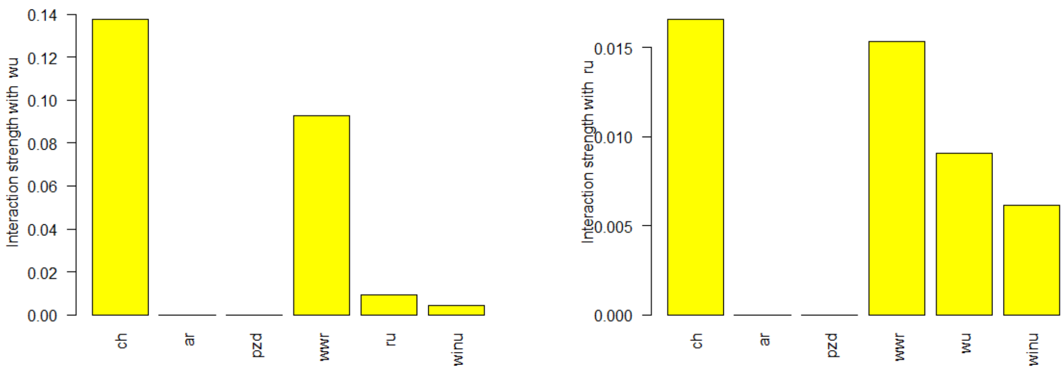



*Figure 58: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Phoenix – VAV*

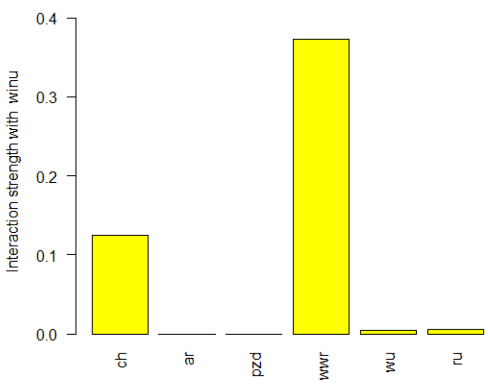



*Figure 59: RuleFit Method - Interaction Strengths with 'WinU' for Phoenix – VAV*

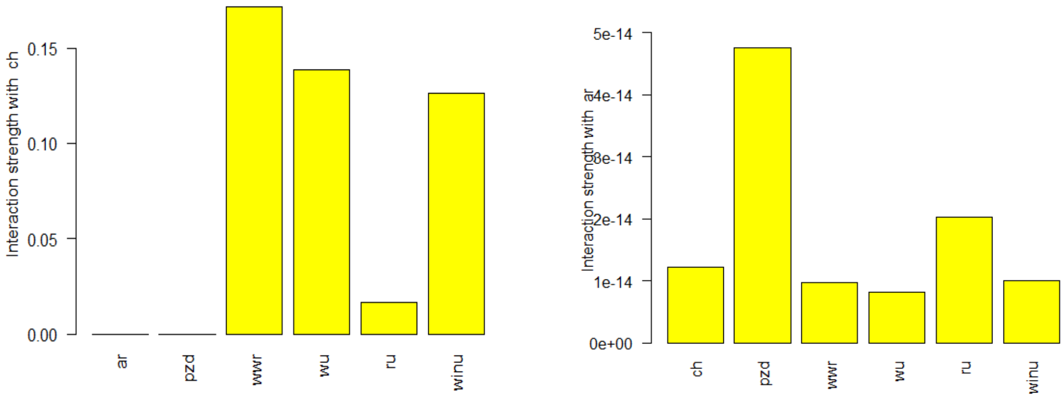



*Figure 60: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Phoenix – VAV + Evaporative*

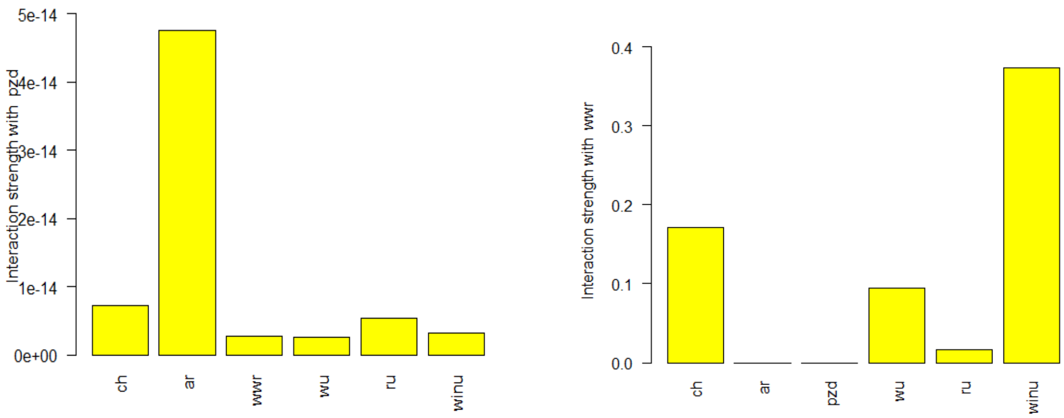



*Figure 61: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Phoenix – VAV + Evaporative*

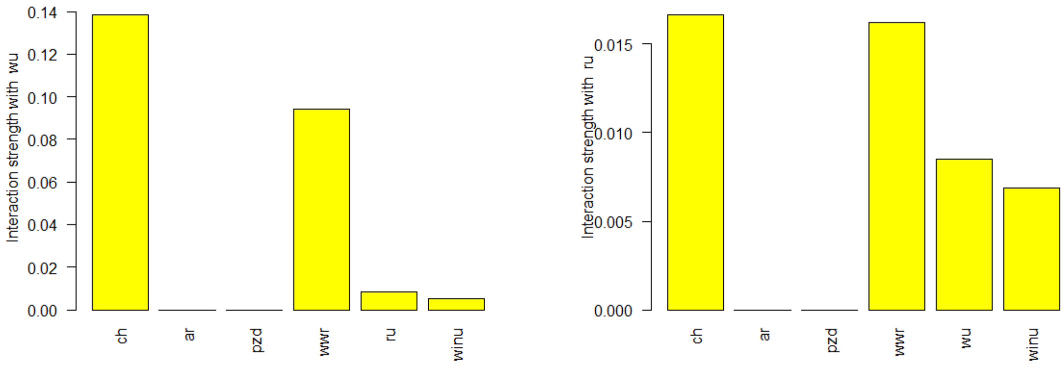



*Figure 62: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Phoenix – VAV + Evaporative*

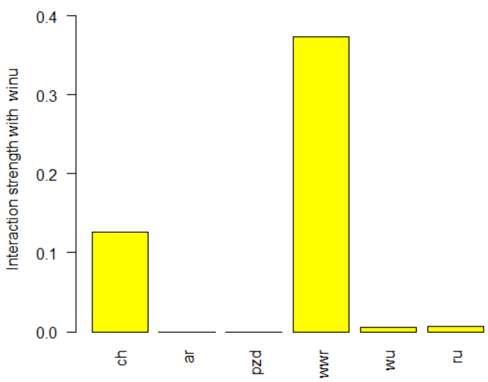



*Figure 63: RuleFit Method - Interaction Strengths with 'WinU' for Phoenix – VAV + Evaporative*

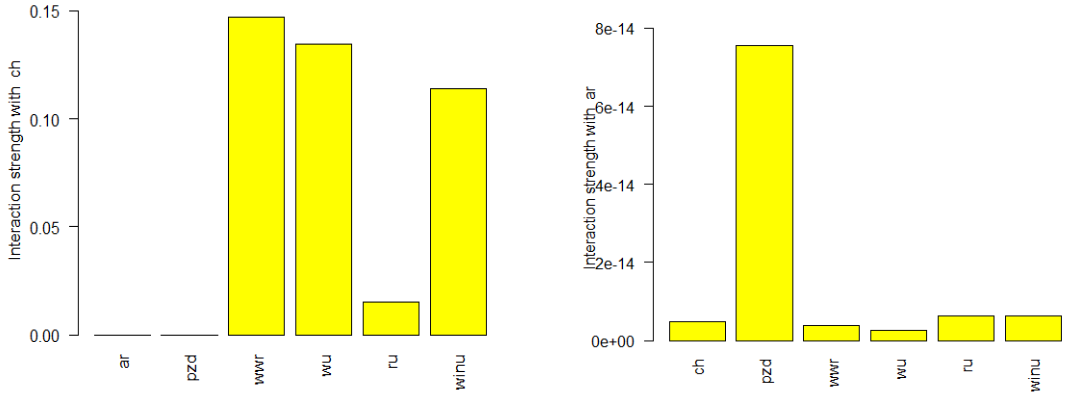



*Figure 64: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Phoenix – Displacement Ventilation*

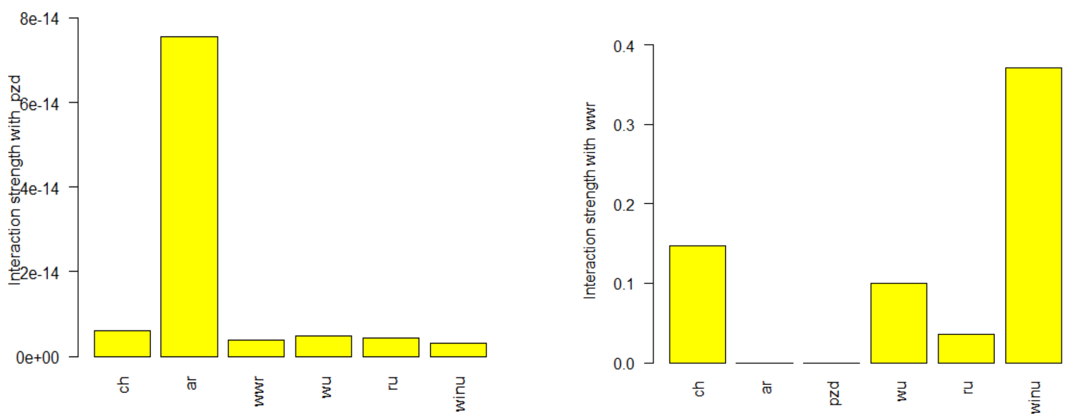



*Figure 65: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Phoenix – Displacement Ventilation*

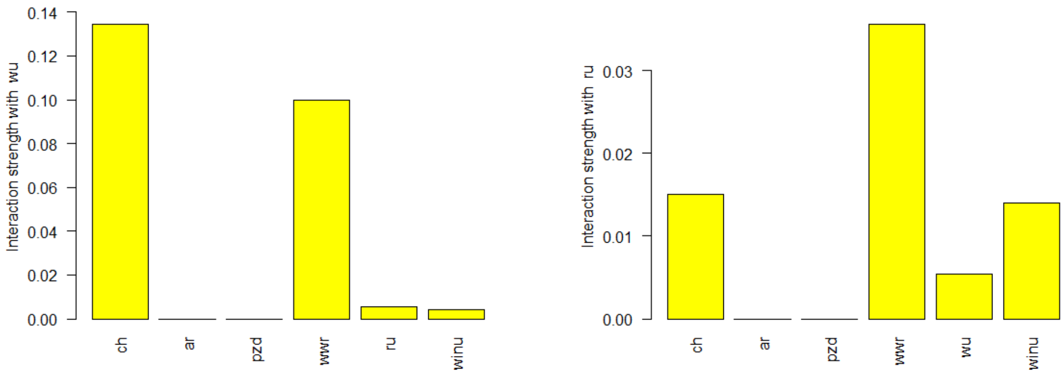



*Figure 66: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Phoenix – Displacement Ventilation*

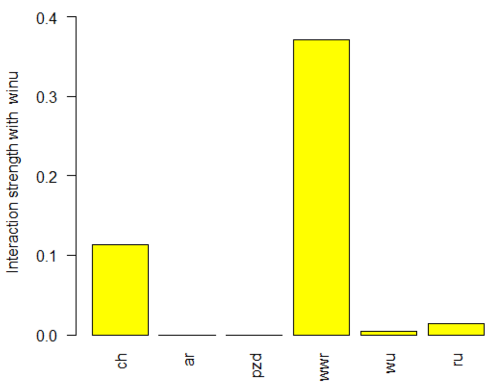



*Figure 67: RuleFit Method - Interaction Strengths with 'WinU' for Phoenix – Displacement Ventilation*

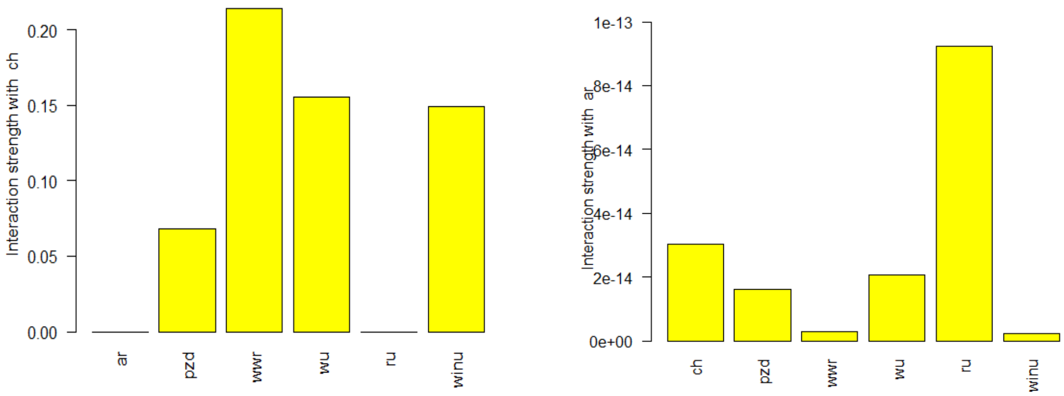



*Figure 68: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Phoenix – DOAS + Radiant System*

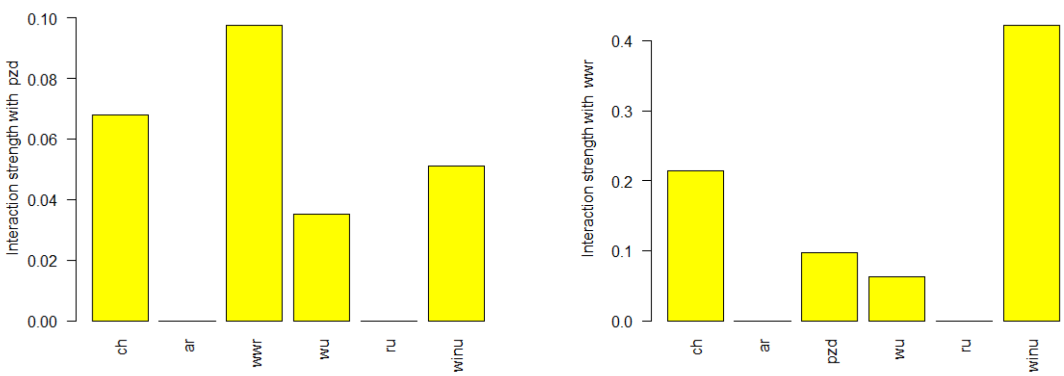



*Figure 69: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Phoenix – DOAS + Radiant System*

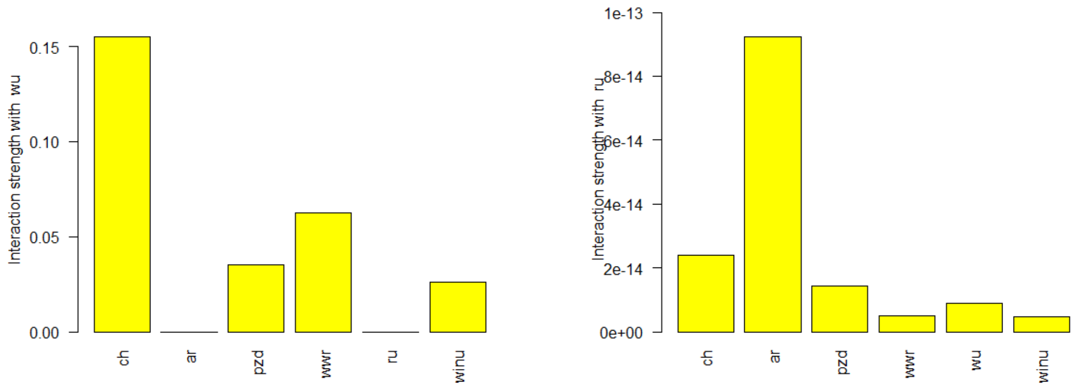



*Figure 70: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Phoenix – DOAS + Radiant System*

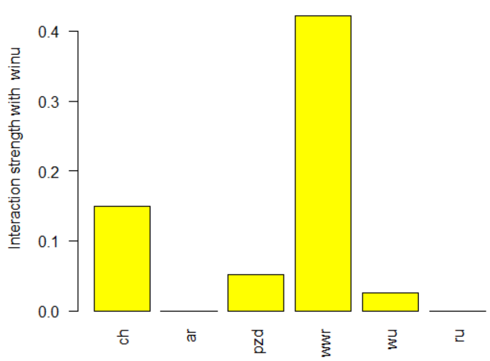



*Figure 71: RuleFit Method - Interaction Strengths with 'WinU' for Phoenix – DOAS + Radiant System*

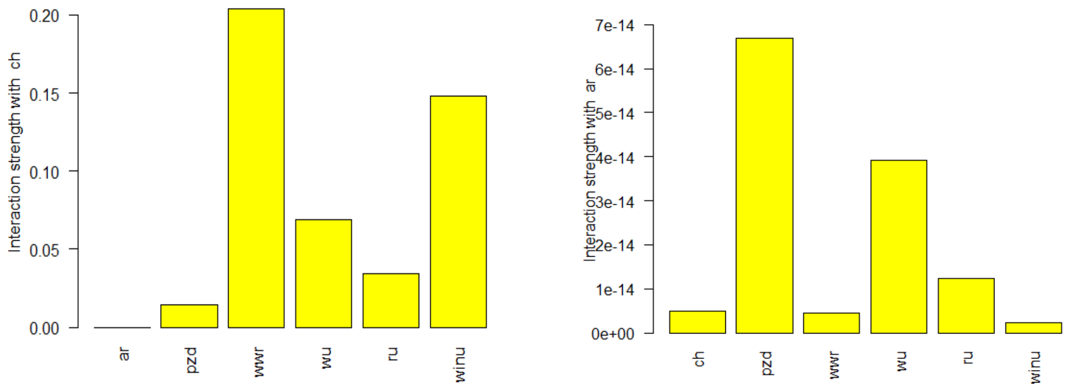



*Figure 72: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Albuquerque – VAV*

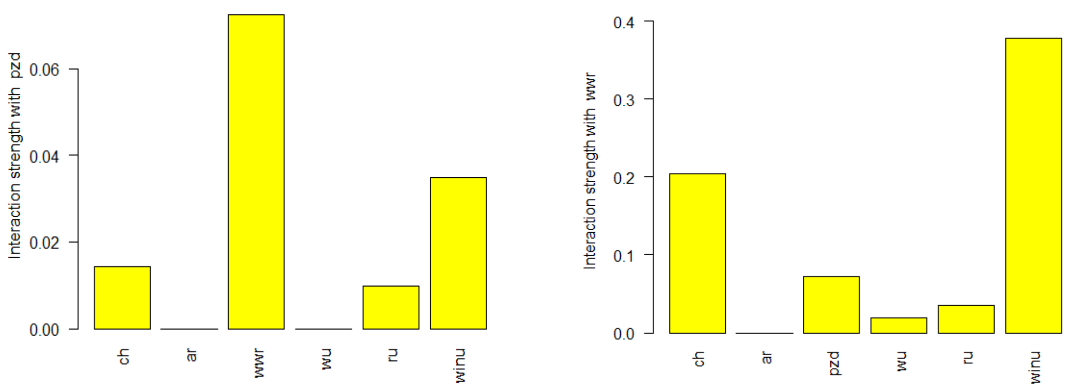



*Figure 73: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Albuquerque – VAV*

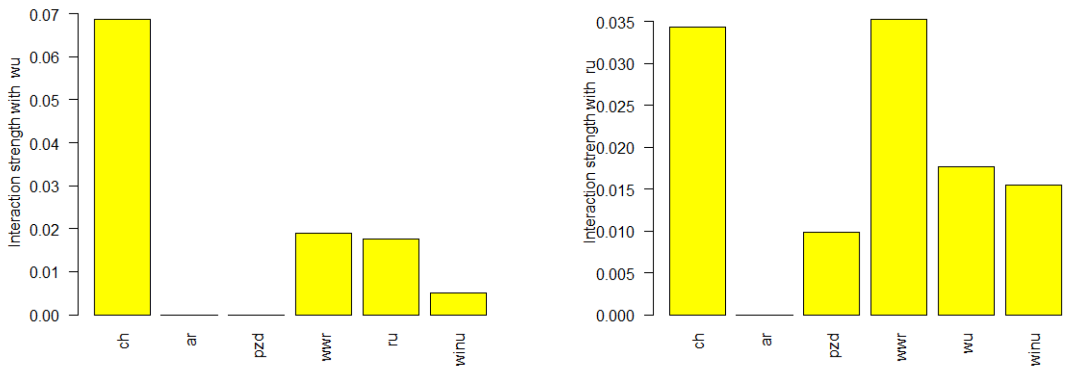



*Figure 74: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Albuquerque – VAV*

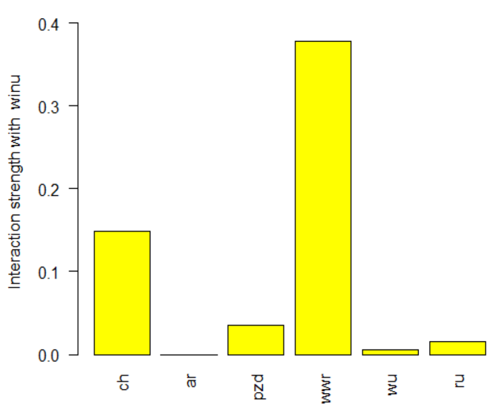



*Figure 75: RuleFit Method - Interaction Strengths with 'WinU' for Albuquerque – VAV*

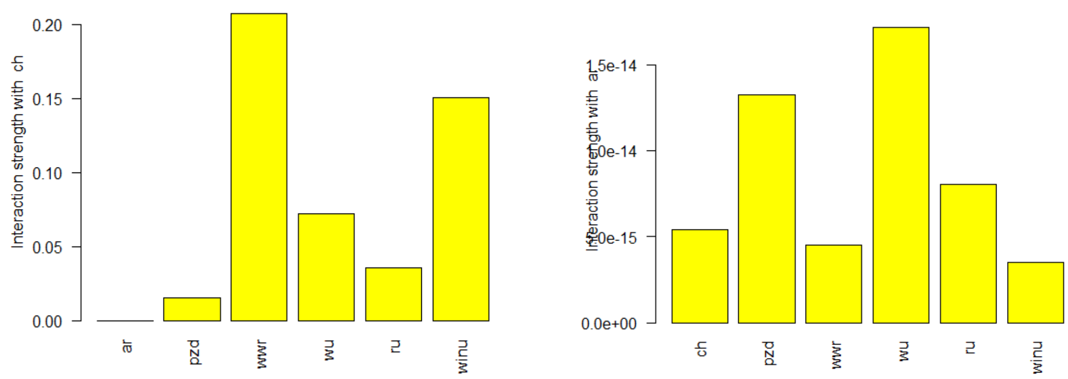



*Figure 76: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Albuquerque – VAV + Evaporative*

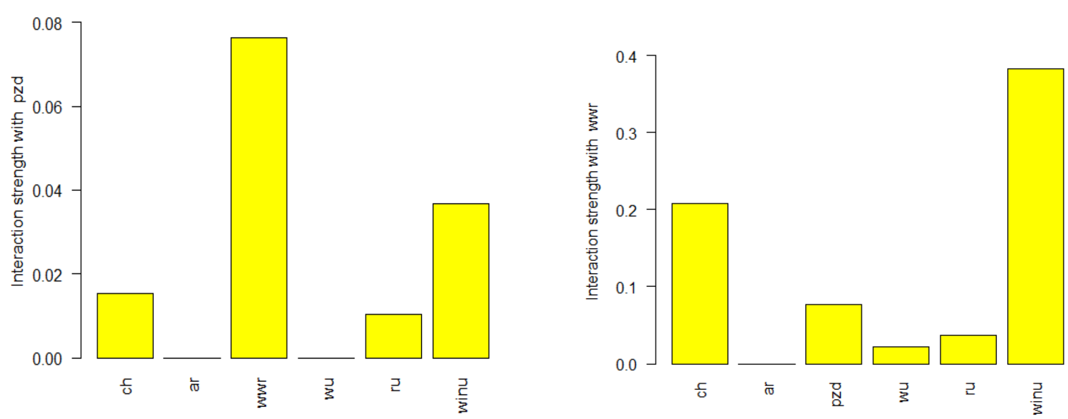



*Figure 77: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Albuquerque – VAV + Evaporative*

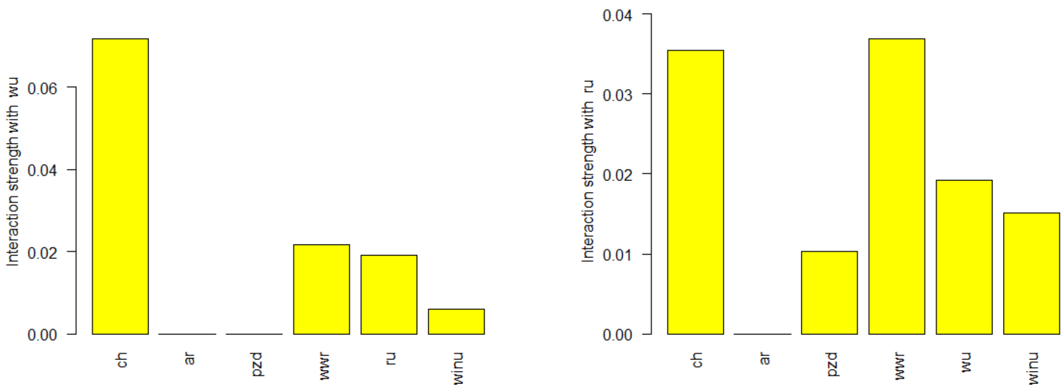



*Figure 78: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Albuquerque – VAV + Evaporative*

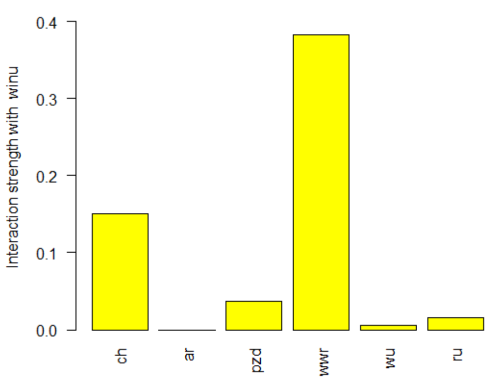



*Figure 79: RuleFit Method - Interaction Strengths with 'WinU' for Albuquerque – VAV + Evaporative*

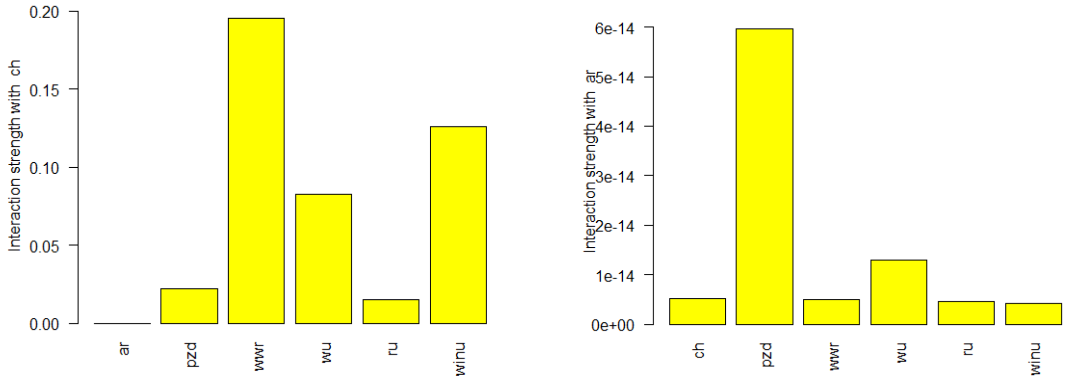



*Figure 80: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Albuquerque – Displacement Ventilation*

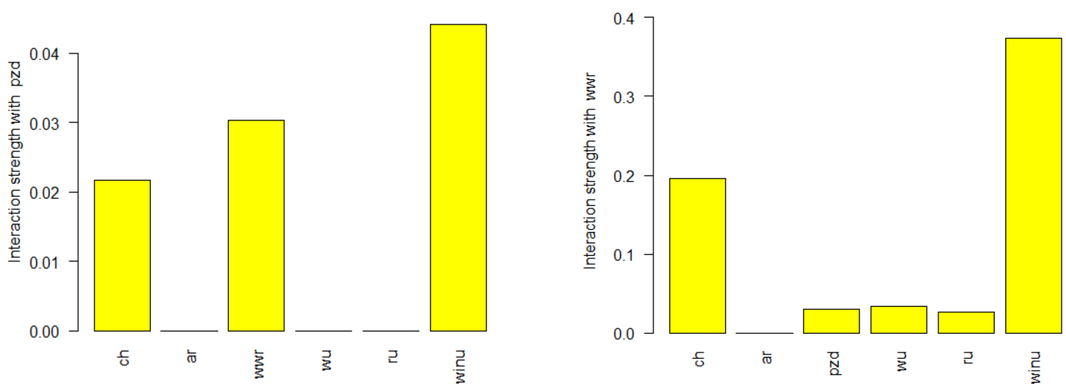



*Figure 81: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Albuquerque – Displacement Ventilation*

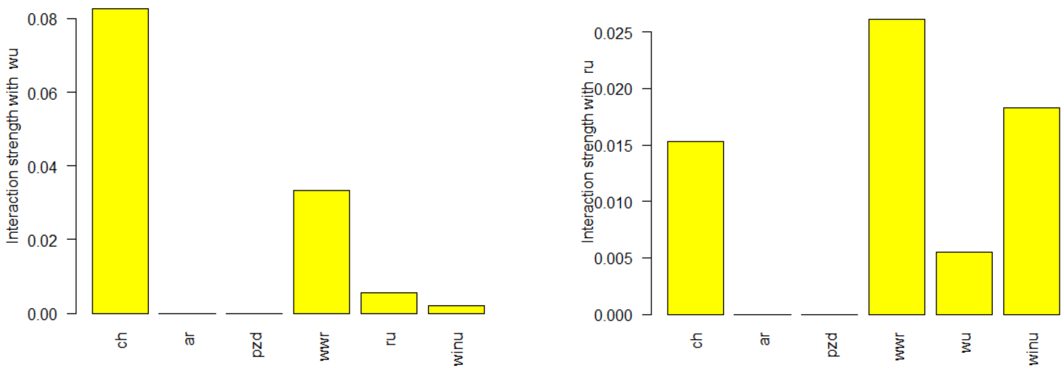



*Figure 82: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Albuquerque – Displacement Ventilation*

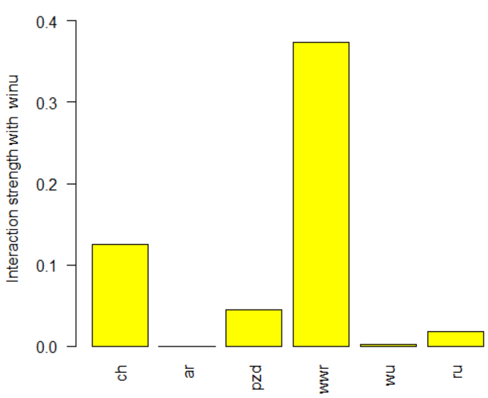



*Figure 83: RuleFit Method - Interaction Strengths with 'WinU' for Albuquerque – Displacement Ventilation*

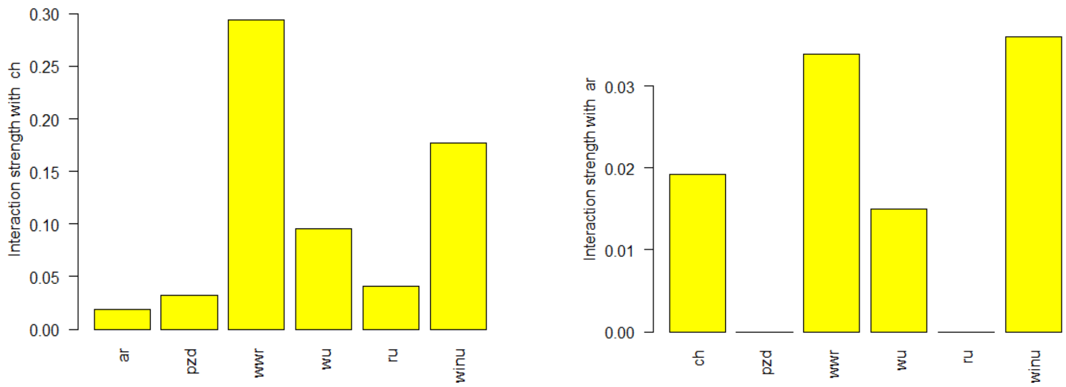



*Figure 84: RuleFit Method - Interaction Strengths with 'CH' and 'AR' for Albuquerque – DOAS + Radiant Cooling*

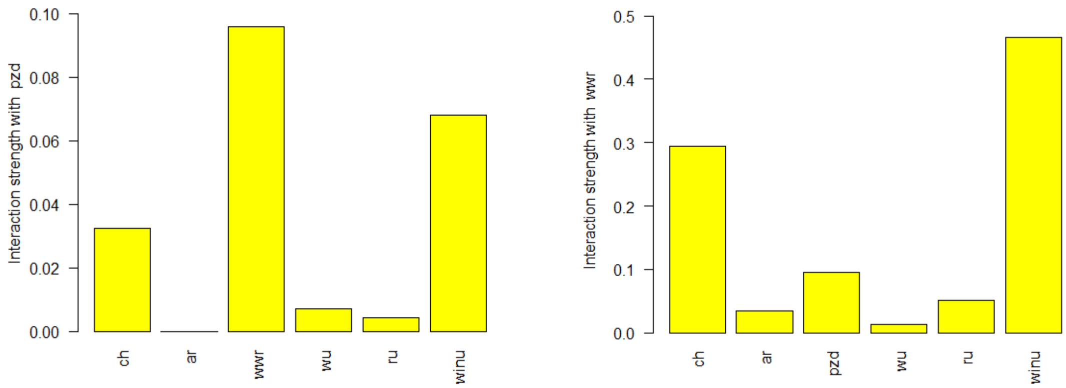



*Figure 85: RuleFit Method - Interaction Strengths with 'PZD' and 'WWR' for Albuquerque – DOAS + Radiant Cooling*

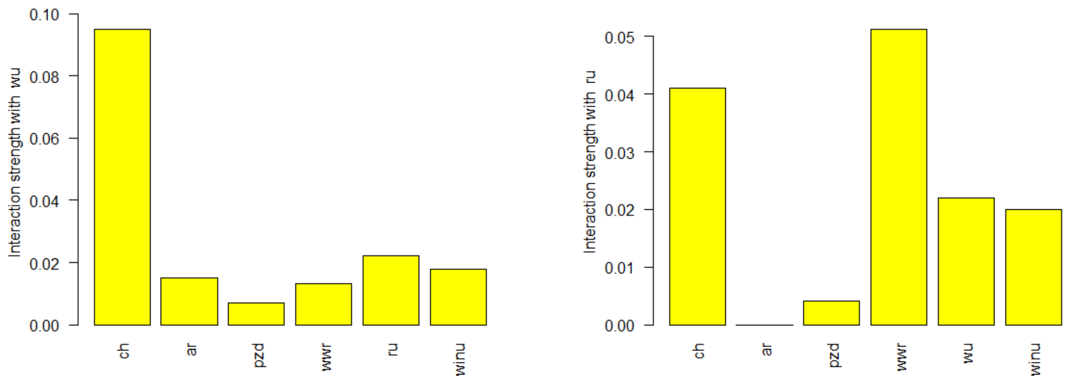



*Figure 86: RuleFit Method - Interaction Strengths with 'WU' and 'RU' for Albuquerque – DOAS + Radiant Cooling*

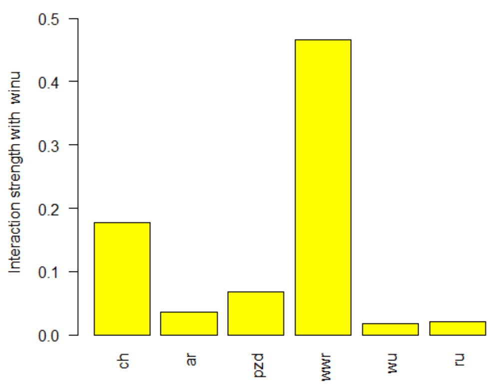



*Figure 87: RuleFit Method - Interaction Strengths with 'WWR' for Albuquerque – DOAS + Radiant Cooling*

The scales for y-axis is different as discussed earlier. These figures demonstrate that the parameter 'WWR' has very high interaction with 'WinU' and 'CH' which is as expected.