OPTIMIZATION OF SUPPLY AIR TEMPERATURE RESET SCHEDULE FOR SINGLE DUCT VAV SYSTEMS

A Thesis

by

WENSHU FAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	W. Dan Turner
Committee Members,	David E. Claridge
	Jeff S. Haberl
Head of Department,	Dennis O'Neal

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ABSTRACT

Optimization of Supply Air Temperature Reset Schedule for Single Duct VAV
Systems. (December 2008)
Wenshu Fan, B.E., Tongji University, Shanghai, China
Chair of Advisory Committee: Dr. W. Dan Turner

In a single duct variable air volume (SDVAV) system, the supply air temperature is usually set as a constant value. Since this constant setpoint is selected to satisfy the maximum cooling load conditions, significant reheat will occur once the airflow reaches the minimum and the heating load increases. Resetting the supply air temperature (SAT) higher during the heating season can reduce the reheat. However, air flow will increase when the SAT is higher which consume extra fan power. Therefore, to minimize the total operating cost of a SDVAV system, the supply air temperature is typically reset based on outside air temperature (OAT) with a linear reset schedule. However, the linear reset schedule is often determined based on the engineer's experience and it may not represent the optimal reset schedule for each building.

This thesis documents a study to determine the optimized supply air temperature reset schedule for SDVAV systems and analyzes the influencing factors under different operation scenarios. The study was divided into five main sections. The first section introduces the research background and objective. Literature review is documented after the introduction. The third section describes the methodology used in this study and the fourth section develops an in-depth discussion and analysis of the impact of the key influencing factors: minimum air flow ratio; ratio of exterior zone area to total floor area (i.e., exterior area ratio); internal load and the prices of the electricity; the cooling and the heating energy. The simulation results using EnergyPlus Version 2.1.0 for various operation scenarios are investigated in this section. The last section is a conclusion of the whole study.

The optimized supply air temperature can be set with respect to the OAT. The study found that instead of a simple linear relationship, the optimal reset schedule has several distinctive segments. Moreover, it is found that the optimal supply air temperature reset schedule should be modified with the change of operation conditions (e.g., different minimum flow ratios and internal loads). Minimum air flow ratio has a significant impact on energy consumption in a SDVAV system. Exterior area ratio determines zone load distribution and will change system load indirectly. For buildings with small internal load, a more aggressive supply air temperature reset tactic can be implemented. In addition, the cost of electricity, cooling and heating energy can determine which end use energy (i.e., reheat energy and fan power) should take the priority.

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I would also like to acknowledge the cooperation and support of the ESL staff especially Chen Xu, Qiang Chen and Cory Toole for their time in providing information about the building being simulated in the research.

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NOMENCLATURE

OAT	Outside air temperature
SAT	Supply air temperature
RMSE	Root mean square error
MBE	Mean bias error

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1. INTRODUCTION

Single duct VAV (SDVAV) systems are popular air-handling systems installed in commercial buildings around the world. In many cases, the supply air temperature (SAT) of a SDVAV system is set at a constant value or implemented with an experiential linear reset reschedule. According to the existing research, the potential to save cost on SDVAV systems can be achieved by a fine-tuned SAT reset schedule. As a result, it is necessary to study the optimization of the SAT of SDVAV systems. This section is an introduction of the research background and objectives.

1.1 Research Background

Statistically, in the United States, around one-third of the energy is consumed in building operations (DOE 2008). Half of the building energy consumption is consumed by heating, ventilating and air conditioning (HVAC) systems (DOE 2008). The air-handling unit is one of the major end user of HVAC systems. As a result, more and more attention is being focused on the minimization of energy consumption in AHU systems. Since the SDVAV system with terminal reheat boxes is a common system installed in commercial buildings, it is significant to find the optimal operation sequence for SDVAV systems. The objective of this research is to find the optimal reset schedule for the SAT. Figure 1-1 shows a typical diagram of a SDVAV unit with reheat terminal boxes. The SAT for a SDVAV system is usually set as a constant value. Since this constant setpoint is selected to satisfy the maximum cooling load conditions, significant reheat can occur when the airflow reaches the minimum and heating is required. To minimize this simultaneous cooling and heating, the SAT can be increased when the

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This thesis follows the style of *ASHRAE Transactions*.

building loads do not require maximum cooling. By looking at temperature and humidity in various zones, the SAT can be reset to a higher value, up to the mixed air temperature, for example 70°F. This will minimize the amount of simultaneous heating and cooling. However, energy conservation cannot occur at the expense of comfort and improper reset of the SAT may introduce humidity problems.

In addition, when the SAT increases, more air flow is required in order to meet the cooling load, which will increase the electricity consumed by the supply air fan. On the other hand, if the SAT decreases, more cooling and reheating energy is likely to be consumed although fan power may be reduced. Moreover, the minimum total cooling and heating energy consumption does not necessarily mean minimum total energy costs, balance of the electricity cost of fan power should also be considered. Therefore, the total cost of the HAVC system operation (i.e., cooling, heating and fan electricity) should all be taken into consideration when optimization strategies are developed. Buildings with reheat provided by heat reclamation and renewable energy need special consideration and they are not the subject of this study.

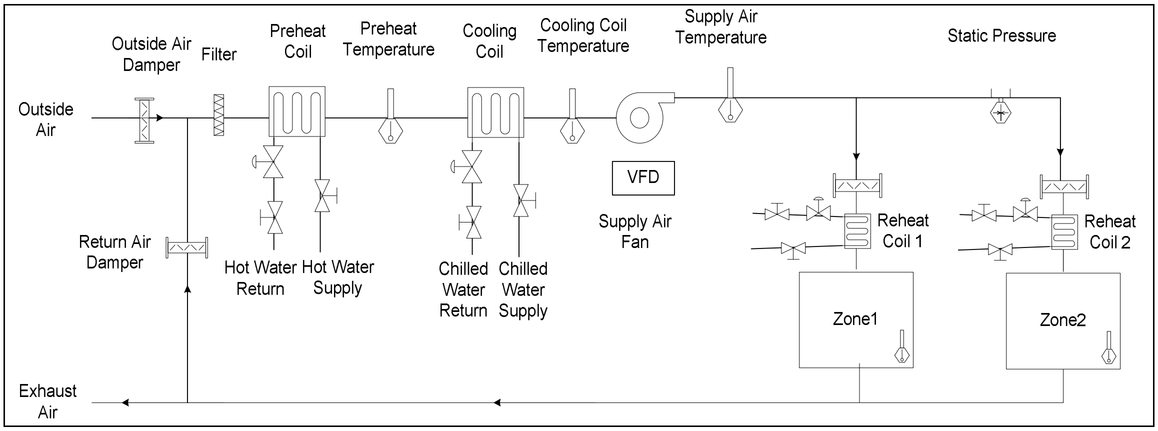

Figure 1-1 Diagram of SDVAV with Terminal Reheat Boxes

1.2 Research Objectives

The main objectives for this research can be divided into two parts. The first is to determine the most cost effective reset schedule for SAT in a SDVAV system under each weather bin, which is different from the traditional linear function of resetting the SAT based on the outside air temperature (OAT). The second objective is to determine the impact of different operational conditions on the optimal SAT. The relationship among SAT reset with four major influencing factors, which are the minimum air flow ratio, the ratio of exterior zone area to the total floor area, the internal load level as well as the energy prices is discussed.

To accomplish the first objective, a detailed simulation was carried out step by step to obtain a SAT curve with respect to the OAT. This optimal SAT may have several transient positions in different ranges of the OAT. A detailed analysis was then developed for each OAT range. To accomplish the second research objective, four major influencing parameters were changed in this research, which are the minimum air flow ratio, the exterior area ratio, the internal loads and the energy prices.

To analyze the first parameter, the terminal box minimum air flow ratio was analyzed. When the minimum air flow is high, more reheat may be needed, resulting in simultaneous heating and cooling. Conversely, if the minimum air flow rate is low, the SAT can stay low without too much reheat.

To analyze the second parameter, the ratio between exterior area and total floor area was analyzed. In this analysis, it was found that the loads for the interior area were relatively stable throughout the year. However, the loads vary greatly with the ambient conditions for the exterior area, which experience maximum cooling loads in the summer and maximum heating loads in the winter. Hence, in the heating season, depending on the ratio of exterior zone area to the total floor area, a low SAT may result in significant reheat for the exterior zones.

To analyze the third influencing factor for the SAT reset schedule, the internal load was analyzed. If the internal load is low, a higher SAT will definitely help to minimize cooling and heating energy usage, but for areas with relatively high internal load, smaller modification should be implemented to the SAT reset schedule to meet the cooling requirements.

Last but not least, when it comes to the most cost efficient operation, it is essential to take the ratio between electricity, cooling and heating costs into consideration. To analyze this, the total energy consumption cost (i.e., thermal energy and fan power) was analyzed as a function of the energy prices, and the reset schedule adjusted as the electricity, cooling and heating costs changed.

2. LITERATURE REVIEW

This section gives an overview of the major topics affecting the study of SAT reset. This review shows that most research can be divided in three major groups: theoretical analysis, case-study results and simulation models.

This literature review covers the following areas: theory and analyses of optimizing SAT; case studies of energy saved by resetting SAT; simulation results supporting optimal SAT. Published literature from the above-mentioned areas was acquired from the following conferences, journals and magazines: *ASHRAE Handbook; ASHRAE Journal; ASHRAE Transactions; ASHRAE HVAC&R Research; Energy and Buildings; Applied Energy; Energy Conversion and Management Journal; the Proceedings of Engineering Indoor Environment Conferences; the Proceedings of the International Conference for Enhanced Building Operations (ICEBO) and the Proceedings of the Improving Building Systems in Hot and Humid Climates*. In addition to the above, past theses and dissertations from Texas A&M University relating to this research have also been cited.

2.1 Theoretical Analyses of Optimizing SAT

A theoretical analysis of the optimization of SAT has a wide application that shows positive results that a fine-tuned SAT reset schedule can save energy when it is a function of the OAT. Nevertheless, it has often been limited to simplified ideal conditions in the literatures, which are hard to implement in the real operating conditions. Moreover, some variables are difficult to obtain which make it unrealistic for real cases.

To obtain a reasonable SAT reset schedule, one needs to consider the heat transfer characteristics of a system and perform an overall energy balance. In the previous literature, the results are usually presented in the form of formulas which can be generally applied (Engdahl and Svensson 2003, Liu et al. 2002, Engdahl and Johansson 2004). Engdahl and Svensson (2003) showed the theory of an optimal SAT in regards to energy use and analyzed the energy savings potential when applying the optimal temperature to a 100% outside air VAV system in a northern European climate. Liu et al. (2002) published a guideline of SAT reset schedule in the Continuous Commissioning® (CC®)[1] Guidebook and provided some case studies as support for the necessity of a SAT reset schedule. Later, in a separate study, Engdahl and Johansson (2005) created a function for the SAT in four case groups. Their results show that SAT should be determined by a relationship of the OAT and the SAT after the fan and reheat coil, when consideration of heat recovery is included.

2.2 Case-study Supporting Optimal SAT

Besides theoretical investigations, another method to obtain a well-tuned SAT reset is to take a real building as the research object and collect building energy consumption data with different SAT settings. In the previous literatures, several case studies have shown energy savings ranging from 11% to 30% with various systems and operational scenarios. Generally, results obtained by case studies are considered as the most reliable because the data reflect measured consumption. However, the conclusion is usually limited to a specific system or operational condition. In one study, Norford et al. (1986) proved that by changing the SAT, the energy consumption was reduced by 10% in the winter and between 11 and 21% during summer conditions in a commercial building. In another study, Zheng and Zaheer-Uddin (1996) saved 20% energy use in

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[1] Continuous Commissioning® and CC® are registered trademarks of Texas Engineering Experiments Station., Texas A&M University.

Montreal Quebec, Canada, by resetting the SAT and also increased the usage of outdoor air during specific conditions.

All of these citations use real data collection to arrive at a convincing conclusion that significant energy can be saved by resetting the SAT. The amount of energy savings in these previous studies can be considered as a reference benchmark for the results of this research.

2.3 Simulation Results Supporting Optimal SAT

Simulation programs are widely used for research purposes attributing to their powerful capabilities and flexibility. Simulation tools include detailed whole building simulations, such as EnergyPlus (DOE 2007a), DOE-2.1e (LBNL 2002), BLAST (BSO 1993); detailed system simulations, such as HVACSIM+ (Clark and May 1985); and simplified models, such as ASEAM (Fleming 1983) and AirModel (Liu et al. 1997). Many studies have been based on the results using calibrated simulation models. Wei et al. (1998) introduced "Calibration Signature" method to fine-tune a simulation model. For a given system type and climate, the graph of this difference has a characteristic shape that depends on the reason for the difference. It has been used for diagnostics and the prediction of the savings to be expected from commissioning projects. Bensouda (2004) extended this method in his thesis for use in the climates typified by Pasadena, Sacramento, and Oakland, California; and for four major system types: SDVAV, single-duct constant-volume, dual-duct variable-air-volume and dual-duct constant-volume. Song (2006) developed a new percentile analysis to the previous signature method. Haberl and Bou-Saada (1998) have used a combined analysis of the root mean square error (RMSE), the Coefficient of Variance of RMSE (CV(RMSE)) and the mean bias error (MBE) (Kreider and Haberl 1994) as a better judge of the goodness of fit of the model to the measured data. These two variables are used for calibration in this research. A simulation with a small RMSE, but with a significant MBE, might indicate an error in simulation inputs. A simulation with a large RMSE but a small MBE might have no errors in simulation inputs, but building performance may reflect some other un-modeled behavior (such as occupant behavior) that is difficult to simulate, or it may have significant input errors (Ahmad 2003).

Considering the development of simulation software, the previous researches related to SAT reset schedules were relatively limited and stay in a preliminary stage. Most researchers are focused on a specific operation (e.g., 100% outside air unit). A few papers contained some discussion for different operational scenarios, but usually are short of a systematic investigation. In many studies, the traditional reset strategy is still based on a linear relationship between outside air and SAT. Although this approach is an improvement over a fixed SAT, it can be improved. Ke and Mumma (1997) used BLAST to simulate the effect on ventilation when changing SAT in a fan powered VAV system (FPVAV). The climate data was from Harrisburg, PA, USA. Nevertheless, they only discussed one operation condition and did not attempt further investigations. Wei et al. (2000) showed results for an optimal SAT for a SDVAV system in weather file of College Station, TX using AirModel program. He also investigated several influencing operational factors. However, his research contained only preliminary results and needed further investigation to reach general conclusions.

The U.S. Department of Energy (DOE) (2007a, 2007b, 2007c, 2007d) released EnergyPlus Version 2.1.0., a very powerful and flexible simulation software program. By using this program, it is possible to develop a systematic investigation of resetting the SAT to maximize the savings in SDVAV systems. As a result, the current research is significant because it is an analysis of the optimum SAT under each OAT for various operating conditions for a hot and humid climate.

3. METHODOLOGY

This section is intended to describe the method used in this study to obtain the optimal SAT reset schedule. To simulate the SDVAV system in a case-study building, the EnergyPlus Version 2.1.0 program was used as the main simulation program. As a first step in the analysis, a calibrated simulation model was developed for the case-study building. After the simulation program was adequately calibrated, selected input settings were changed to obtain the most cost efficient SAT reset schedule. In this thesis, the major research results are shown and explained. The detailed research procedures are documented in the internal technical report (ESL-ITR-08-10-01).

3.1 Building Information

3.1.1 Introduction

The case-study building applied in this research was designed and built specifically to meet the needs of leading-edge transportation research, located in the Texas A&M University Research Park adjacent to the main Texas A&M University campus. The building is a three story structure housing offices and laboratories with 59,520 ft² of floor area. The building was constructed with concrete floors and supporting columns with concrete block walls with 14% of total wall area containing single pane windows and a flat concrete roof.

The heating and cooling system consists of three (3) SDVAV systems with terminal reheat boxes serving the conditioned spaces on the three floors. The supply air fan modulates the fan speed based on the static pressure setpoint. The cooling valve in the main cooling coil modulates to maintain SAT at the setpoint. Dampers and heating valves in the terminal reheat boxes adjust the air flow and heating energy to meet the room cooling or heating load.

The EnergyPlus Version 2.1.0 simulation software program used in this research requires extensive information about the building in order to create a simulation model. For this purpose, the following resources were used to determine the building envelope characteristics and system configurations. The architectural and mechanical drawings of the case-study building were obtained from the facilities office on the Texas A&M campus, who is responsible for the construction records of all the building and facilities associated with the Texas A&M University System. System information about this building was obtained from the commissioning engineers of the Energy Systems Laboratory (ESL) of Texas A&M University. This information included the type and number of air- handlers, design airflow etc.

3.1.2 Data Information and Data Acquisition

The primary emphasis of this research is on determining the optimal SAT reset schedule for SDVAV air-handling systems using the EnergyPlus Version 2.1.0 program. EnergyPlus Version 2.1.0 is an innovative simulation software program that uses a nodal connection methodology to connect all the components installed in the building instead of a fixed schematic method as used in the conventional simulation programs such as DOE-2 and BLAST. Therefore, it is more complicated to set up the original model and correct the errors and warnings. In addition, more detailed information such as pipe and duct geometry information are required for the input file. Such information was obtained from as-built drawings and from the commissioning engineers, including the definition of the nodes and branch lists, setting-up the air and water loops for the HVAC objects and filling-in the detailed equipment and component information for HVAC systems.

The thermal parameters and construction details for the envelope were obtained from the as-built drawings, which remain the same for all the cases simulated.

3.1.3 Introduction to the EnergyPlus Program

3.1.3.1 Background

This research depends on the results of simulations obtained from EnergyPlus (Version 2.1.0). This section illustrates the general information of this simulation software. EnergyPlus has its roots in both the BLAST and DOE–2 programs.

BLAST (Building Loads Analysis and System Thermodynamics) is a set of programs for predicting heating and cooling energy consumption in buildings and analyzing energy costs using the Heat Balance Loads Calculator. It has been supported by the Department of Defense (DOD), and has its origins in the NBSLD program developed at the US National Bureau of Standards (now NIST) in the late 1960s.

DOE-2 is a public-domain computer program for building energy analysis, which has been developed and maintained by the Lawrence Berkeley National Laboratory (LBNL). It is supported by the Department of Energy (DOE), and has its origins in the Post Office Program written in the late 1960s for the US Post Office.

The need for two separate government supported programs has been questioned for many years, and discussions of the possible merger of the two programs began in May 1994 with a DOD sponsored conference in Illinois. This is the original motivation of the idea of EnergyPlus. Like its parent programs, EnergyPlus is an energy analysis and thermal load simulating program. Based on a user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., EnergyPlus calculates the heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would. Many of the simulation characteristics have been inherited from the legacy programs of BLAST and DOE–2 such as heat balance based solution.

One of the benefits of the structural improvements over the legacy programs that used the fixed-schematic structure is that EnergyPlus is object-oriented and modular in nature. This results in a well-organized, module framework that facilitates adding features and links to other programs, which was difficult to accomplish with DOE-2 and BLAST.

3.1.3.2 Specific Characteristics of EnergyPlus

The "Modularity" characteristic of EnergyPlus makes it easier for other developers to quickly add other component simulation modules. This means that it will be significantly easier to establish links to other programming elements, such as SPARK, Pollution Models and Airflow Network. Since initially the EnergyPlus code will contain a significant number of existing modules, there will be many places within the HVAC code where natural links to new programming elements can be established. In addition to these more natural links in the HVAC section of the code, EnergyPlus will also have other more fluid links in areas such as the heat balance that will allow for interaction where the modules might be more complex or less component based. The following diagram depicts how other programs have already been linked to EnergyPlus and a big picture view of how future work can impact the program. Figure 3-1 shows the structure of EnergyPlus.

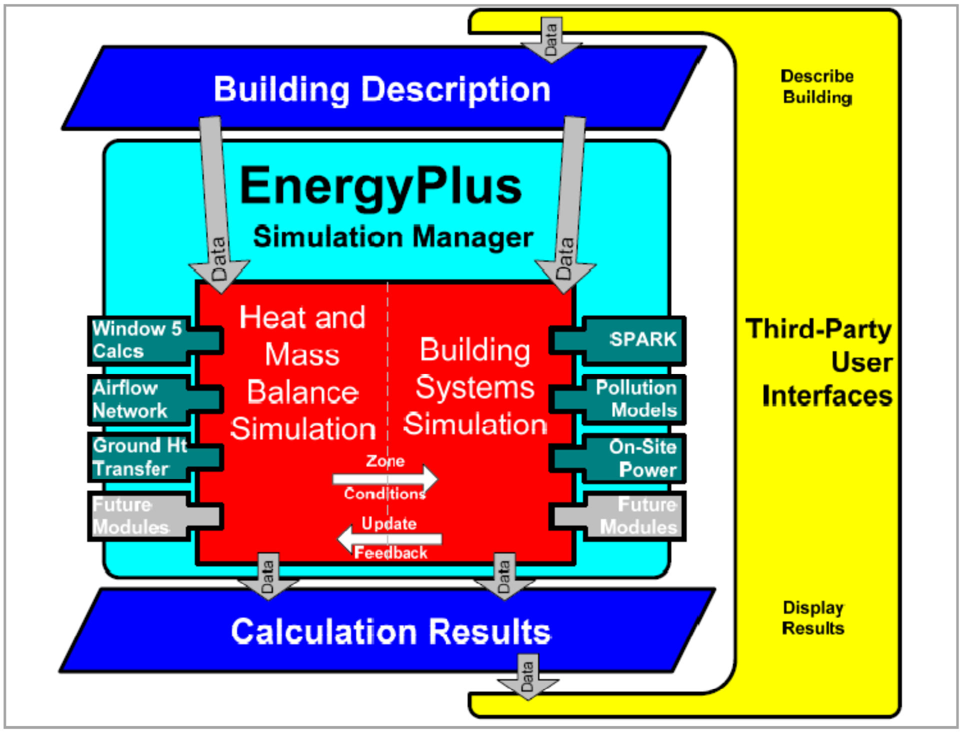


Figure 3-1: EnergyPlus-Simulation Structure (DOE, 2007b)

3.1.3.3 Input of Loads, Systems, and Plants

Compared to its parent program, one of the strong points of EnergyPlus is the integration of all aspects of the simulation—loads, systems, and plants. Based on a research version of the BLAST program called IBLAST, the system and plant output is allowed to directly impact the building thermal response rather than calculating all loads first, then simulating systems and plants. After defining the nodes and branches properly, users can customize their systems and plants by configuring and connecting all of the equipments and components. Figure 3-2 shows a basic overview of the integration of these important elements of a building energy simulation.

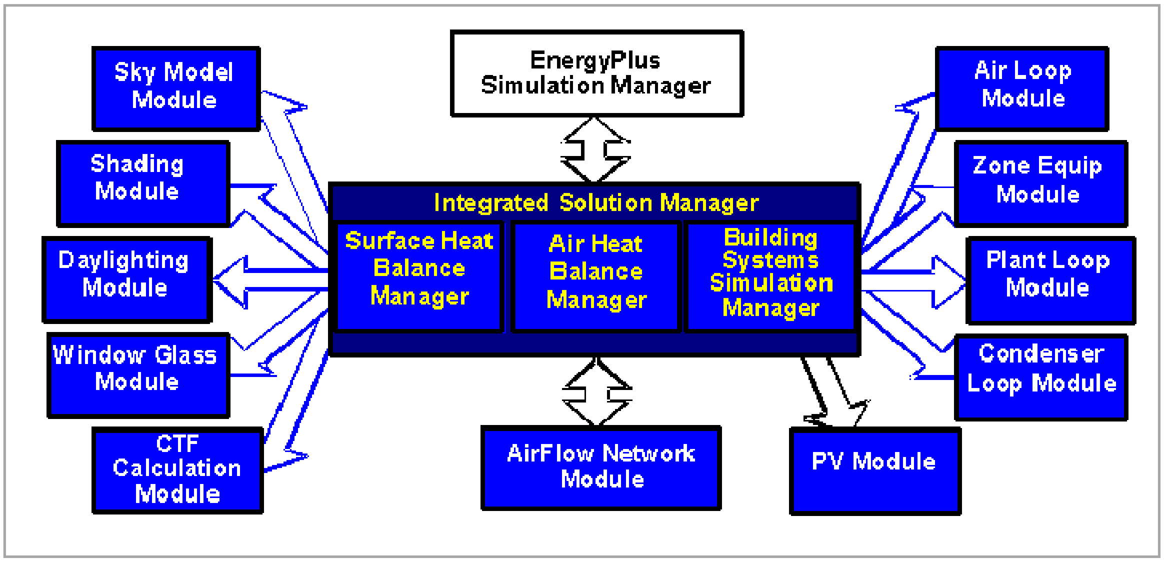


Figure 3-2: EnergyPlus Internal Elements (DOE, 2007b)

A module developer is someone who is going to add to the simulation capabilities of EnergyPlus. A module is a Fortran 90/95 programming construct that can be used in various ways. In EnergyPlus, its primary use is to segment a rather large program into smaller, more manageable pieces. Each module is a separate package of source code stored on a separate file. The entire collection of modules, when compiled and linked, forms the executable code of EnergyPlus.

The “Surface Heat Balance Manager” is driven to calculate the heat transferring through the building envelop. It includes “Sky Model Module”, “Shading Module”, “Daylighting Module”, “Window Glass Module” and “CTF Calculation Module”. “Sky Module” is designed to calculate the sky radiation. In EnergyPlus, the calculation of diffuse solar radiation from the sky incident on an exterior surface takes into account the anisotropic radiance distribution of the sky. “Shading Module” is designed for shading and sunlit area calculations. When assessing heat gains in buildings due to solar radiation, it is necessary to know how much of each part of the building is shaded and how much is in direct sunlight. “Daylighting Module”, in conjunction with the thermal analysis, determines the energy impact of daylighting strategies based on analysis of daylight availability, site conditions, window management in response to solar gain and glare, and various lighting control strategies. “Window Glass Module” is considered to be composed of four components: glazing, frame, divider and shading device.

The “Air Heat Balance Manager” is driven to solve the heat balance problems in the air flow in the building. It includes “AirFlow Network Module”. It includes five segments: infiltration, ventilation, mixing, cross mixing and earth tube.

The “Building Systems Simulation Manager” is developed for HVAC systems applied in the building. It includes “AirLoop Module”, “Zone Equip Module”, “Plant Loop Module”, “Condenser Loop Module” and “PV Module”. “AirLoop Module” is developed to calculate the mass and heat transfer in the primary air loop (i.e., representing the supply side of the loop). “Zone Equip Module” is developed to calculate the mass and heat transfer in the zone equipment (e.g., terminal VAV box). “Plant Loop Module” and “Condenser Loop Module” are developed to calculate the heat and mass transfer between the energy demand side and the plant side. Typically, the central plant interacts with the systems via a fluid loop between the plant components and heat exchangers, called either heating or cooling coils.

In the EnergyPlus input file, detailed information of HVAC systems is required. Zone load information includes number of people, lighting and equipment intensity. System information includes configuration of air loop and water loop. During this configuration, nodes and branches should be carefully connected to complete the loops for both air and water. Moreover, detailed information of coils, pumps, connecters, splitters, mixers and controllers should also be configured.

3.1.3.4 Output Files of EnergyPlus

This section is intended to give a brief introduction for the various output files produced by EnergyPlus. The two scripts that are distributed with EnergyPlus are: EPL-Run.bat (which is used by the EP-Launch program) and RunEPlus.bat (which can be used from the command line). The RunEPlus batch file can also be used to string together several runs such as usually termed “batch processing”. In renaming the files created by the program or its post-processing program(s), usually the file extension will be retained. For output purposes, the most important files to understand are the eplusout.eso, eplusout.mtr and eplusout.err files. The first two are manipulated with the ReadVarsESO post processing program. The latter will contain any critical errors that were encountered during the run.

3.1.4 Description of the Simulation Model

The calibrated model was created to represent the initial system of the building being simulated. For this model, load information, zoning and system operation schedules were created to represent the current operating conditions. The envelope materials data and their U-values were provided by the facility office. Figure 3-3 is the picture of the case-study building and the model created by the simulation software DesignBuilder V1.0 (DesignBuilder Software Ltd. 2007)

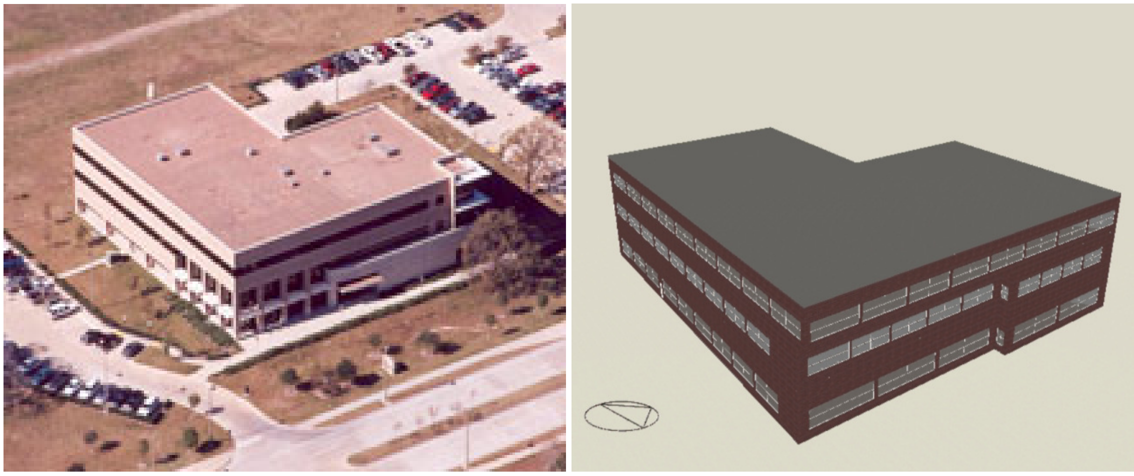


Figure 3-3: Simulation Model

To simplify the research while still achieving the research objective, only one terminal reheat box was assigned to each zone. In the actual case-study building, each zone has several boxes. To calibrate the model, 2006 hourly weather data for College Station, Texas was used and the simulation results were compared against the measured energy use. Coefficient of variance of the root mean square error CV(RMSE) for whole building electricity, chilled water consumption and hot water consumption as well as the mean bias errors (MBE) was used as an overall indicator to fine-tuned the simulation to an acceptable level.

3.1.5 Location and Weather File

The simulated building is located in the research park of Texas A&M University, College Station, Texas (30.61°N, 96.32°W). Real weather files for College Station, Texas were used for calibration. According to ASHRAE definition, it is located in a hot and humid area. The average daily outdoor dry bulb temperature of 2006 ranges from 34°F to 88°F and relative humidity is from 34% RH to 94% RH. The annual average temperature is 60.8°F and the annual average relative humidity is 65% RH. Figure 3-4 is daily average OAT and outdoor humidity ratio for College Station in 2006.

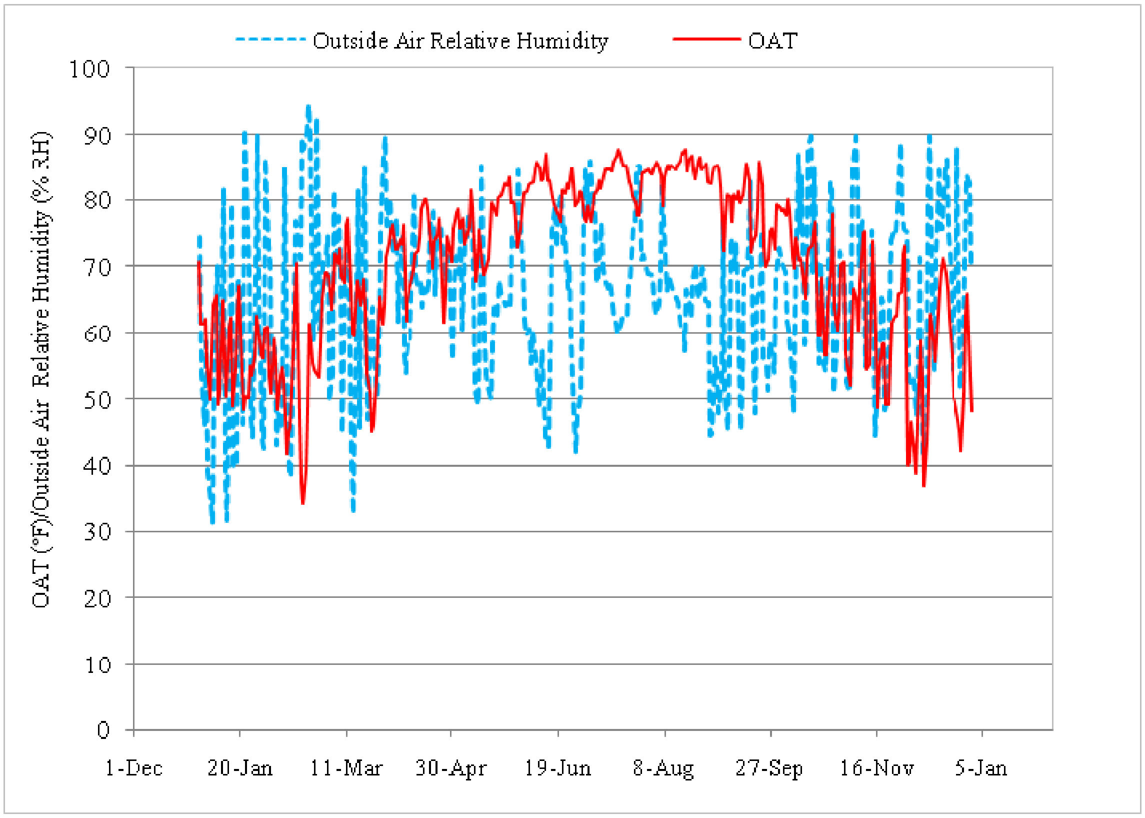


Figure 3-4: OAT and Outdoor Relative Humidity for College Station 2006

3.1.6 Zone Loads

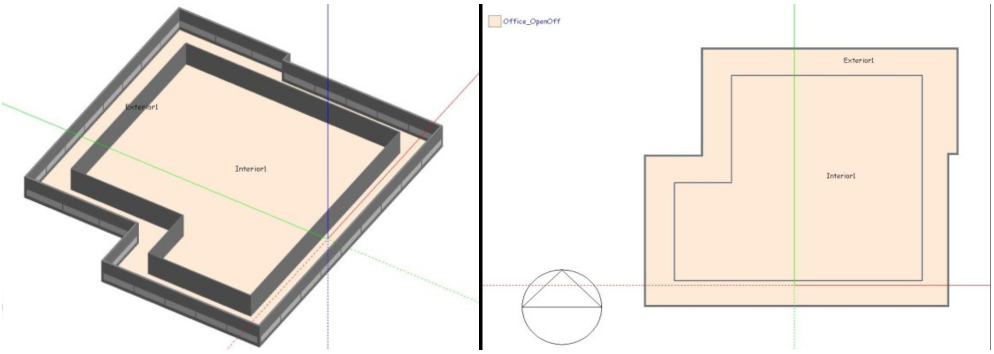
3.1.6.1 Building Envelope Information

The external envelope of the building is constructed of concrete walls, glass walls and single-panel glass windows. The internal walls separate the conditioned zones into exterior areas and interior areas.

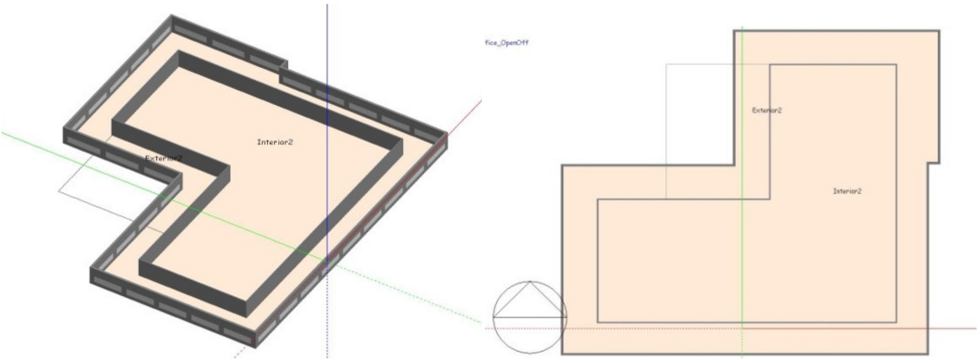
There are two types of exterior walls. One is an opaque wall and the other is glass block. The opaque wall is made up of 4-inch brick, 3-inch polystyrene, 4-inch concrete block as well as ½ inch gypsum paste. The overall U-value of the exterior wall is 0.062 Btu/ ft^2·F°·h. The glass block has a U-value of 0.89 Btu/ ft^2·F°·h. For the interior walls, a ¾ inch gypsum board was assigned with an R-value of 0.67 ft^2·F°·h/Btu. The drop ceilings are acoustic tiles with an R-value of 3.7 ft^2·F°·h/Btu. Roof construction is combined with ½ inch roof gravel, ⅜ inch built-up roofing, polyurethane insulation and ¾ inch wood. The U-value of roof is 0.05 Btu/ ft^2·F°·h. The floor construction is 6-inch lightweight concrete with a U-value of 0.05 Btu/ ft^2·F°·h. The glass for the windows is single-pane, tinted, with a U-value of 1.09 Btu/ ft^2·F°·h. The ratio between windows to external walls of this building is 14%.

3.1.6.2 Zoning

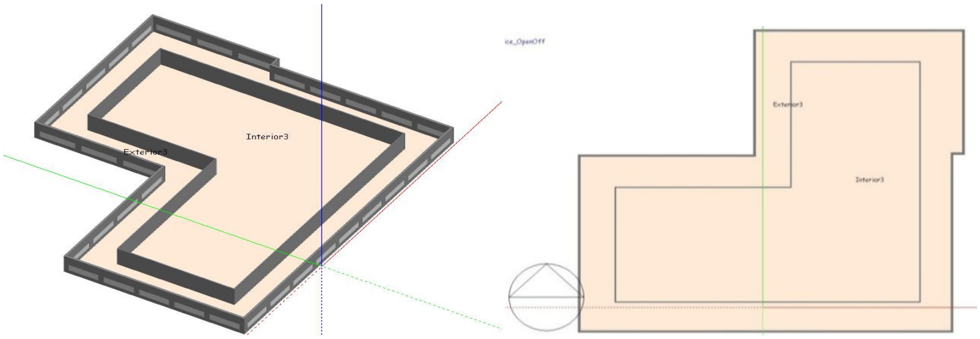
All of the floors are divided into two zones (i.e., exterior and interior). The interior zone is defined as a barrier 15 ft away from the exterior wall in each direction. Figure 3-5 shows the detailed zoning plan for each floor. The spaces between the internal walls and external walls are defined as exterior areas.



(a) First Floor



(b) Second Floor



(c) Third Floor

Figure 3-5: Building Zoning

3.1.6.3 Schedules

In the loads portion of the input file, the schedules for occupancy, equipment, and lighting are configured. Table 3-1 states the detailed information for the zone load.

Table 3-1 Internal Load Settings

	Exterior1	Interior1	Exterior2	Interior2	Exterior3	Interior3
Area(ft^2)	8,550	13,120	8,550	10,375	8,550	10,375
People	102	111	63	33	59	90
Lighting(W)	18,500	28,567	18,500	24,000	4,360	4,621
Equipment(W)	13,282	21,000	13,282	21,000	2,613	4,533
Lighting(W/ft^2)	2.16	2.18	2.16	2.31	0.51	0.45
Equipment(W/ft^2)	1.55	1.60	1.55	2.02	0.31	0.44

a) Occupancy: According to the information given by the commissioning engineers, the office hours for this building are between 8:00 am and 5:00 pm. For the weekends, the occupancy is 50% of the maximum between 8:00 am to 5:00 pm, while it is 5% from 6:00 pm to 8:00 am. Figure 3-6 shows hourly schedule of occupancy for weekdays and weekends.

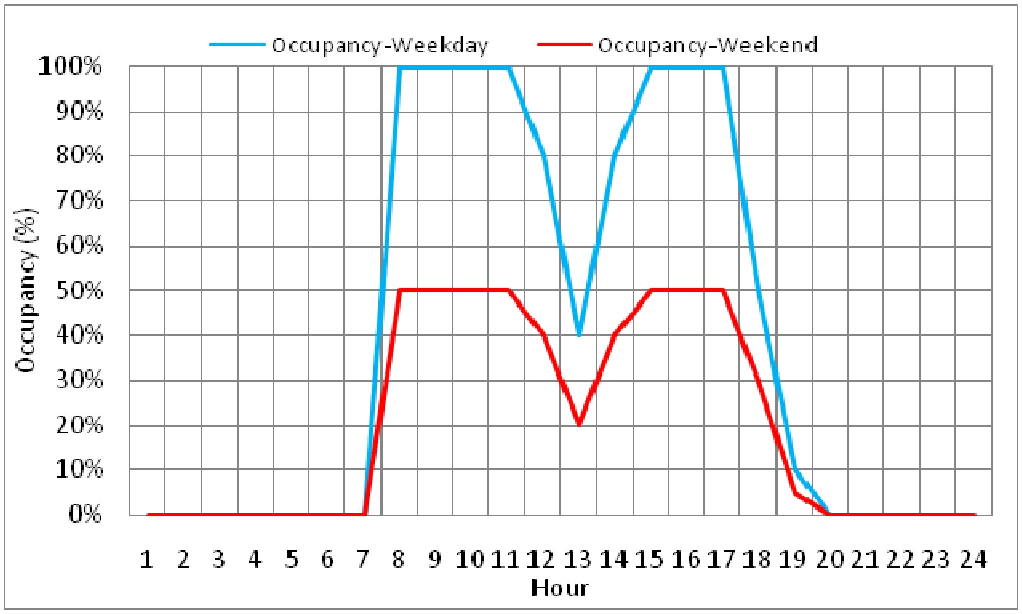


Figure 3-6: Hourly Occupancy Schedule

b) Lighting: The lighting level varies from 80% to 100% of the lighting load defined in the space conditions, between 8:00 am to 6:00 pm during the weekdays and 50 % during the weekends. The lighting load was reduced to 5% during the night time hours. Figure 3-7 shows the hourly lighting schedule for weekday and weekends.

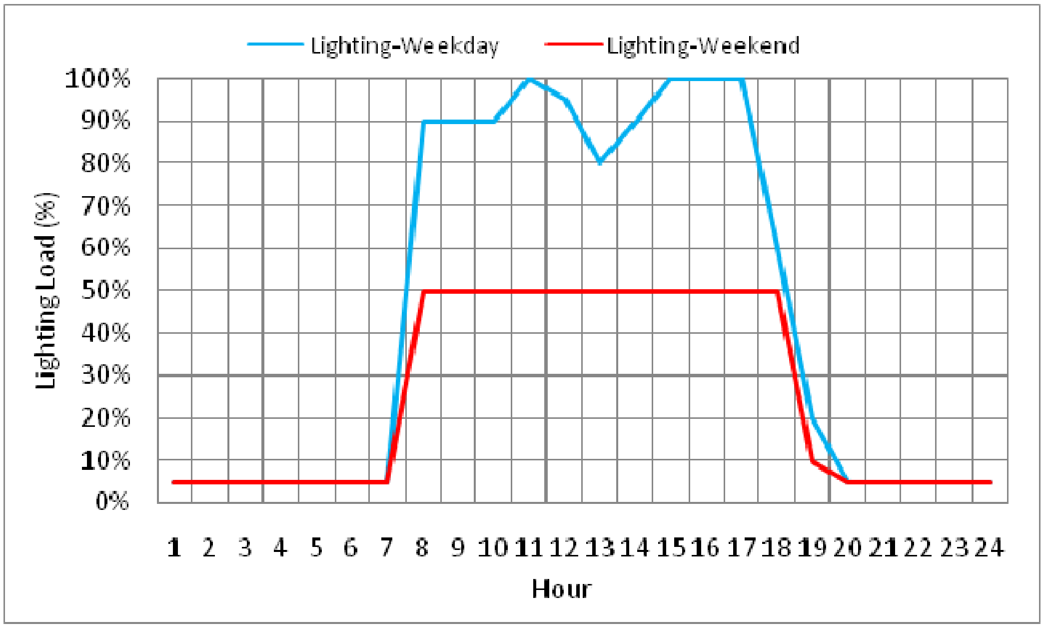


Figure 3-7: Hourly Lighting Schedule

c) Equipment: The Equipment load varied from 50% to 100% of the full load defined in the space conditions, between 8:00 am to 9:00 pm. For the remainder of the time it was assumed to be at 50%. On weekends, the equipment load remained at 50% during daytime and 30% during the evening hours. Figure 3-8 shows the hourly equipment schedule for weekday and weekends.

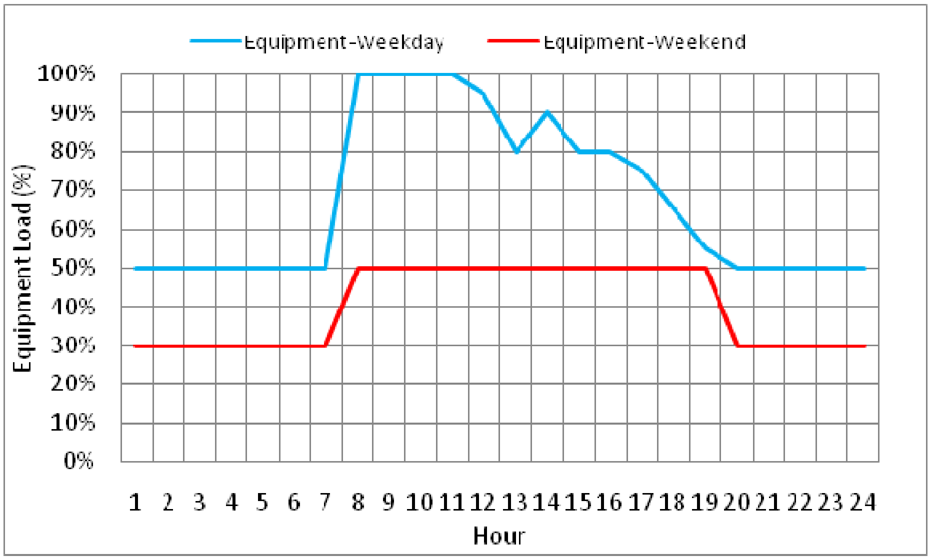


Figure 3-8: Hourly Equipment Schedule

3.1.7 HVAC System

There are three (3) SDVAV air-handling units serving the building. In all three units, the outside air is mixed with the return air and is then cooled down through the cooling coil to the SAT setpoint and reheated, if necessary, at the terminal box to maintain the zone temperature setpoint. The diagram of a typical SDVAV unit with terminal reheat boxes is shown in Figure 3-9.

In this system, the preheat coil warms the mixed air to the preheat setpoint to protect the cooling coil from freezing. Chilled and hot water is provided by the campus central plant. In this simulation, purchased chilled water and hot water were used to account for the heating and cooling loads. No chillers or boilers were simulated. This configuration was chosen to match the measured chilled and hot water from the physical plant.

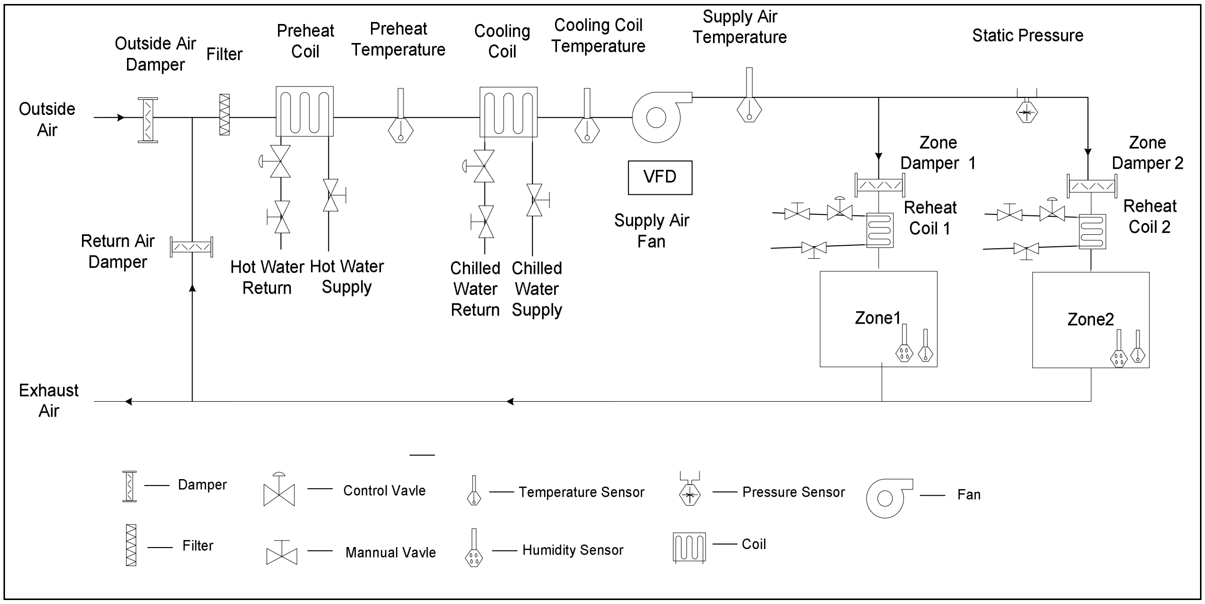


Figure 3-9: Diagram of SDVAV with Terminal Reheat

3.1.7.1 HVAC System Operation Description

In the system control objects, the preheat temperature is set at 45°F. There is a linear reset schedule for the SAT implemented to the three units under the existing operation. Figure 3-10 illustrates the current reset schedule for the SAT. When the outside air is above 60°F, the SAT is set to a constant number as 55°F. The SAT can be raised to a higher temperature when the cooling load decreases as the OAT drops. When the OAT is below 40°F, the SAT is fixed to 65°F. When the ambient temperature is between 60°F and 40°F, the SAT increases from 55°F to 65°F linearly.

The minimum outside air control method was a proportional minimum, which means it will be kept at a constant ratio with respect to the total flow rate. The cooling design flow method was set as “flow/system”, which means the program will use the user input flow rate as the system flow rate instead of the program calculated design value. Due to the specific requirement for the laboratories in the simulated building, the units are scheduled to operate 24/7. As a result, the fan schedule was set to always be on in the system operation schedule. The economizer is only enabled in the modified model but was disabled in the calibration model to better match the existing operating strategy. Table 3-2 shows the input parameters of the operation condition of the main air-handling units. The system design data, fan and pump information were obtained from the mechanical drawings. The operational parameters were provided by the commissioning engineers at the ESL.

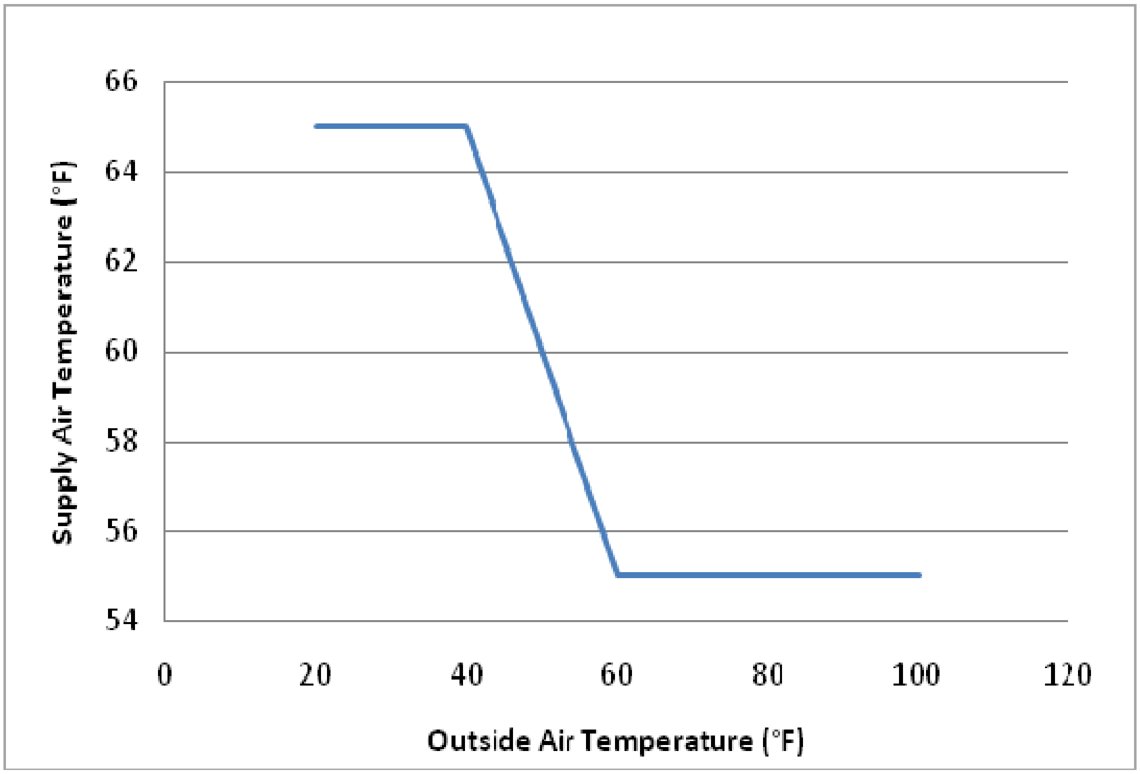


Figure 3-10: Current Implemented SAT Reset Schedule

Table 3-2: System Setting Parameters

Item	Unit	AHU1	AHU2	AHU3
Serving Floor Area	ft^2	21,670	18,925	18,925
Design Flow Rate	cfm	22,050	21,610	20,160
Design Min OA Flow Rate	cfm	3,950	2,070	1,900
OA flow method		Proportional Minimum		
Min Flow Ratio		0.15	0.15	0.15
Preheat Set Point	°F	45	45	45
Precool design humidity ratio	lb-H$_2$O/lb-air	0.008	0.008	0.008
Cooling Design Setpoint	°F	55	55	55
Cooling design air flow method		flow/system		
Economizer		No Economizer		
Fan Type		Simple: Variable Volume		
Fan Delta Pressure	in H$_2$O	4.5	4.15	4.05
Fan Total Efficiency		0.7	0.7	0.7
Fan Schedule		Weekday: Always On / Weekend: 6:00-22:00		

3.1.7.2 Zone Equipment Operation Description

In EnergyPlus, the user must define equipment for each zone; including terminal reheat boxes, heating coils, air distribution units, thermostats as well as humidity sensors if humidity control is required. In addition, the zone control strategy can also be customized. Table 3-3 summarized the input control parameters for terminal reheat boxes used in the simulation. The outside air flow rate, maximum design flow rate and minimum flow rate were kept the same as the design value. The design value matches the measured data according to the commissioning engineers at the ESL. The zone thermostat control method was a dual setpoint with a deadband. Both the heating and cooling setpoints can be scheduled for any given time period. The cooling setpoint is 74°F during occupied hours and 79°F during unoccupied hours. The heating setpoint is 70°F during occupied hours and 61°F during unoccupied hours. The operation schedule and zone temperature setpoint information was provided by the commissioning engineers at the ESL.

Table 3-3: Load Ratio Schedule

	Unit	Exterior1	Interior1	Exterior2	Interior2	Exterior3	Interior3
OA Flow Rate	cfm	1,778	2,172	1,040	1,030	950	950
Min cfm Ratio		0.15	0.15	0.15	0.15	0.15	0.15
Zone Max Relative Humidity	%RH	No Humidity Control Implemented					
Zone Cooling Setpoint(Occ)	°F	74	74	74	74	74	74
Zone Cooling Setpoint(Unocc)	°F	79	79	79	79	79	79
Zone Heating Setpoint(Occ)	°F	70	70	70	70	70	70
Zone Heating Setpoint(Unocc)	°F	61	61	61	61	61	61
Zone Thermostat Control Method		Dual Setpoint with Deadband					

3.1.7.3 Plant Operation Description

The chilled water and hot water of the simulated case-study building are provided by the campus central plant. There is one chilled water pump and one hot water pump in the building to provide enough pressure for the building. Hence, in EnergyPlus purchased energy system was configured in the simulation input file. The heating and cooling systems were set to always be available during the year. The hot water supply temperature setpoint was set to 160°F, and the chilled water supply temperature was set at 43°F.

3.2 Simulation Output Analysis and Calibration

3.2.1 Need for Calibration

Historically, the inputs for energy simulations of commercial buildings have been based on design data. The experience of the researchers and engineers who have performed hundreds of energy simulations indicates that differences of 50% or more between simulation results based on design data and measured consumption are not unusual. These errors are not thought to be due to errors in the simulation software itself, but to errors in the input assumptions for a particular building, due to misunderstanding of the building's design or to the differences between design and as-built conditions or operations. Consequently, many organizations and individuals have developed procedures to adjust the inputs used to "calibrate" a simulation so the simulated results more closely match measured consumption.

For commercial buildings, the variables of interest are chilled water (CHW) and hot water (HW) usage and the whole building electricity (WBE). For a building that is being supplied chilled water and hot water, these three variables can often satisfy the purposes of calibration.

3.2.2 Calibration Method and Calibration Result

In this thesis, the approach to calibrated simulation is based on the previous work by the Energy Systems Laboratory (ESL) for several years in different applications. The method is based on a unique graphical representation of the difference between the simulated and measured performance of a building, referred to as a "Calibration Signature". For a given system type and climate, a graph of this difference has a characteristic shape that depends on the reason for the difference. Calibration signatures have been used for diagnostics and prediction of the savings from commissioning projects. The process is efficient enough that it has been used to predict savings from commissioning measures in dozens of buildings in a variety of contracted commissioning jobs. There are several metrics used in evaluating whether or not a simulation is sufficiently calibrated, or in comparing two possible calibration adjustments. Three parameters (i.e. MBE, RSME, CV(RSME)) are used to evaluate the simulation results.

3.2.2.1 Mean Bias Error (MBE)

The mean bias error (MBE) is a measure of the sum of errors in a non-dimensional format. The total difference between the two sets of data for each hour or day is then divided by the total number of data points minus the number of regression variables. This will give the mean bias or the mean of the residuals. This value divided by the mean of the model will give the MBE in percentage form. Mathematically it is given by:

$$MBE= \frac{\sum(E_{sim}-E_{mea})}{n\times E_{mea,ave}} \times 100\% \qquad \textbf{3-1}$$

where *n* is the number of data points. With the MBE, positive and negative errors cancel each other out, so the MBE is an overall measure of how biased the data is. The MBE is also a good indicator of how much error would be introduced into annual energy consumption estimates, since positive and negative daily errors are cancelled out.

3.2.2.2 Root Mean Square Error (RMSE)

Root Mean Square Error is defined as:

$$RMSE = \sqrt{\frac{\sum (E_{sim} - E_{mea})^2}{n-2}} \quad \mathbf{3\text{-}2}$$

where *n* is the number of data points. The RMSE is a good measure of the overall magnitude of the errors. It reflects the size of the errors and the amount of scatter, but does not reflect any overall bias in the data.

A simulation with a small RMSE, but with a significant MBE, might indicate an error in simulation inputs. A simulation with a large RMSE but a small MBE might have no errors in simulation inputs, but building performance may reflect some other un-modeled behavior (such as occupant behavior) that is difficult to simulate, or it may have significant input errors.

3.2.2.3 Coefficient of Variance of Root Mean Square Error CV(RMSE)

The coefficient of variation of the root mean square error (CV(RMSE)) is essentially the non-dimensional form of the RMSE. It is obtained by dividing the RMSE by the mean of the data set, which is being used as the benchmark. It is given by

$$\mathrm{CV}(RMSE) = \frac{RMSE}{E_{mea.\mathrm{ave}}} \quad \mathbf{3\text{-}3}$$

This value depicts how well the simulation model fits the measured data. The main aim of calibrating a simulation model is to lower this value. The CV(RMSE) and MBE have been used extensively in the calibration process of building energy simulation models. For the purpose of better calibrating a simulation model to the measured data, the use of hourly CV(RMSE) and MBE can be justified. The reason is that in using daily or monthly percentage differences, the dissimilarities between the model and the actual conditions are overlooked, because over longer periods these changes tend to balance out. So it cannot be said with certainty that the resulting model is a true depiction of the building operations. Nevertheless, daily data is used in this research for calibration limited to the lack of hourly data.

3.2.2.4 Simulation Calibration Result

Figure 3-11 to Figure 3-13 are the results of the model calibration for electricity, chilled water and hot water consumption respectively. In Figure 3-11, it is noticed that the whole building electricity (WBE) consumption of this case-study building increases slightly when the OAT is below 50ºF. However, since the course for this increase remains unknown, the simulation was not adjusted to account for this. In Figure 3-12 and Figure 3-13, it is found that the simulated data and the measured data matched quite well. The data of weekday and weekend are separated for both measured and simulated chilled water and hot water consumptions.

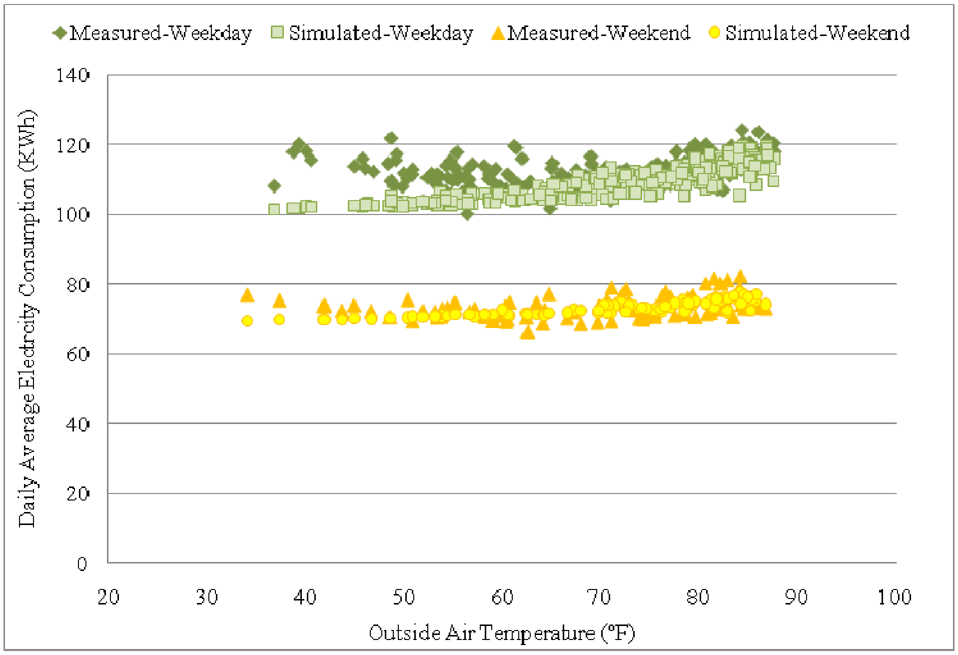


Figure 3-11: WBE Consumption Calibration

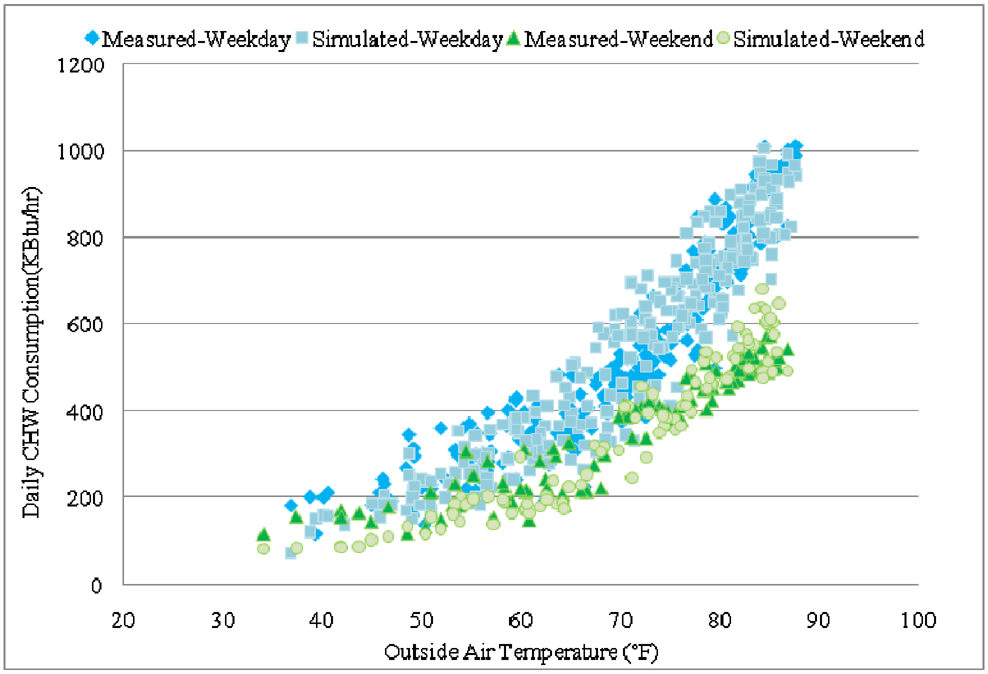


Figure 3-12: Chilled Water Consumption Calibration

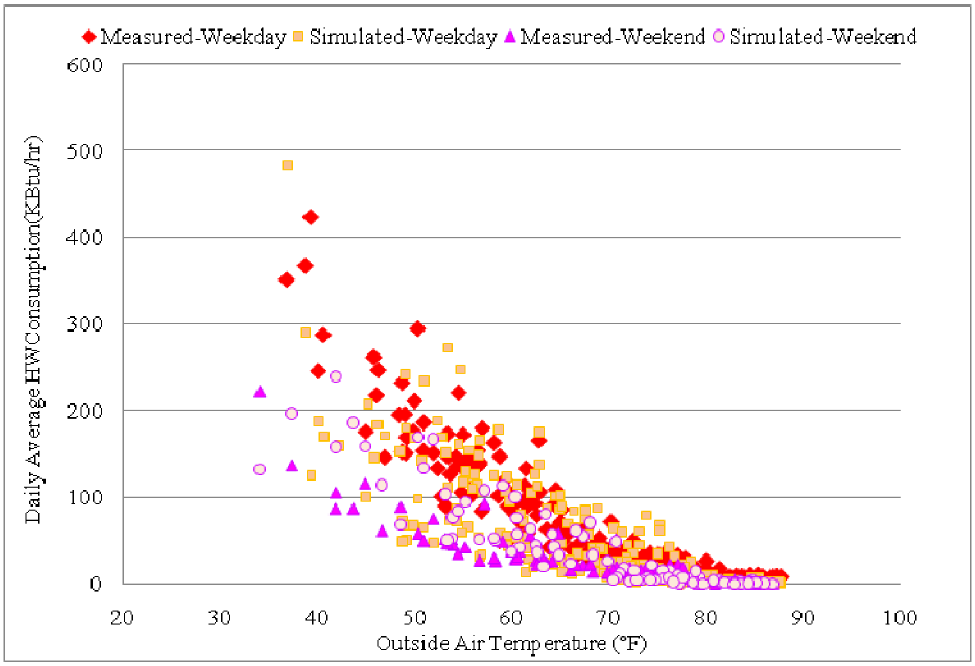


Figure 3-13: Hot Water Consumption Calibration

The only change in the input file from the design configuration was the minimum air flow ratio. In the calibrated simulation, the minimum air flow ratio was adjusted to 15% to match the measured conditions. In the remaining of this thesis, a value of 30% was assigned. Table 3-4 shows the results of calibration.

Table 3-4: Summary of Calibration Results

	Measured Energy Use	Simulated Energy Use	CV(RMSE)%	MBE%
WBE	94kWh	98kWh	9.54	1.84
CHW	378KBtu/hr	376KBtu/hr	5.71	-0.24
HW	88KBtu/hr	62KBtu/hr	41.60	-4.53

3.3 Optimized SAT Reset Schedule

This section contains the methodology and results from the simulation including the optimized SAT reset schedule. An example is provided in the first section to demonstrate the method of how to simulate the most cost effective SAT schedule.

3.3.1 Optimal SAT Reset and Cost Comparison

The traditional reset schedule is typically implemented as a linear function with respect to the OAT. Figure 3-14 shows the current as well as the optimal reset schedule for the simulated building.

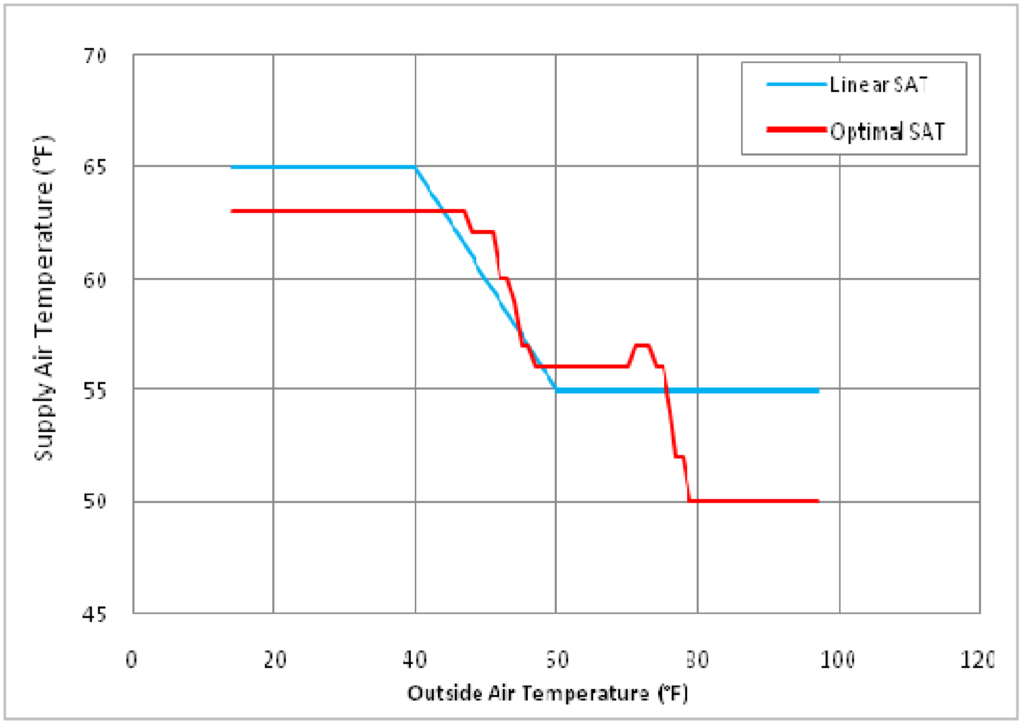


Figure 3-14: Comparison of Linear and Optimal SAT Reset Schedules

Figure 3-15 and Figure 3-16 show the comparison of energy consumption and costs among the optimal SAT reset schedule, the linear SAT reset schedule and non-reset SAT schedule. Table 3-5 shows details of the fan electricity, cooling and heating costs for three SAT reset schedules. Compared with the conventional linear reset schedule, the optimized reset schedule can save electricity, cooling and heating consumption by 18.59%, 3.44% and 2.47% respectively while the total costs can be reduced by 6.23% on an annual basis. If the optimal supply air temperature reset schedule is compared with a constant supply air temperature setpoint of 55 °F, these savings will reach 11.80%, 3.84% and 34.78% for electricity, cooling and heating respectively including an 8.44% total cost savings.

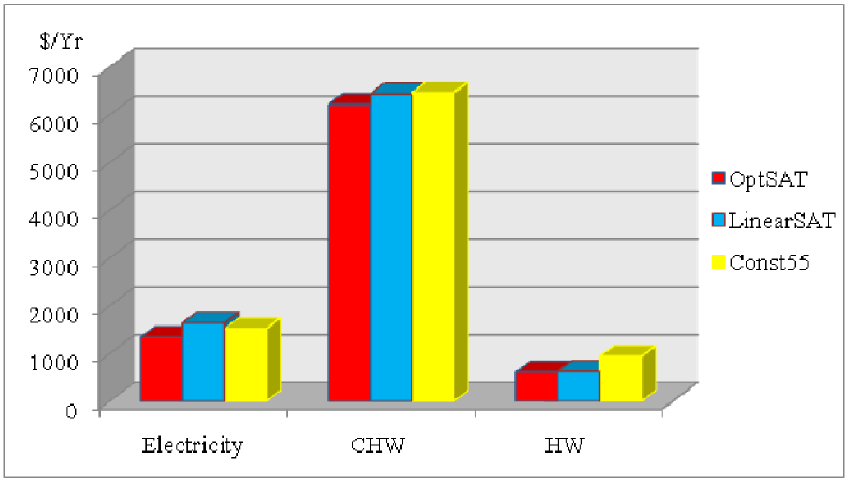


Figure 3-15: Annual Energy Consumption Comparison

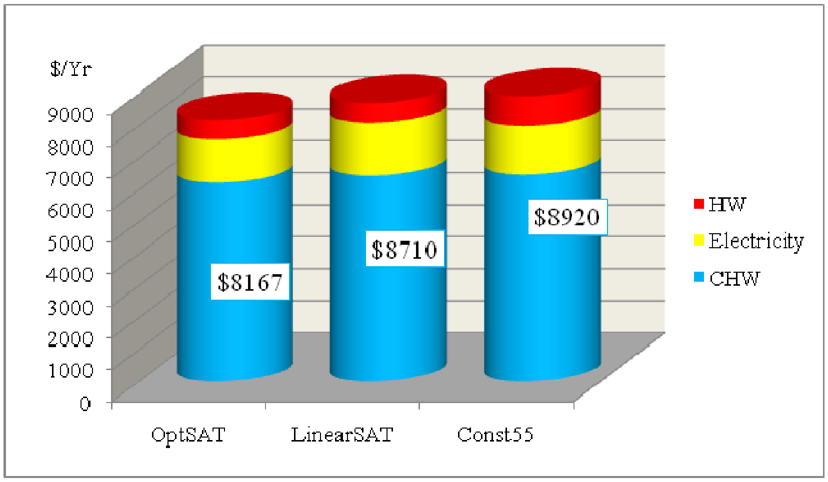


Figure 3-16: Comparison of Annual Total Cost

Table 3-5: Cost Comparison for Three SAT Schedules

	Energy Consumption			Savings (%)	
	Opt SAT	LinearSAT	Const55	OptSAT vs LinearSAT	OptSAT vs Const55
Fan Electricity	$1,339.71	$1,645.73	$1,518.96	18.59	11.80
CHW	$6,217.45	$6,438.95	$6,465.93	3.44	3.84
HW	$610.31	$625.74	$935.53	2.47	34.76
Total Cost	$8,167.47	$8,710.42	$8,920.42	6.23	8.44

3.3.2 Typical Optimal SAT Reset Schedule

To facilitate the discussion of an example simulation, a typical optimal supply air temperature is divided into five zones. Ten critical temperatures are also defined. Table 3-6 shows the definition of those ten critical temperatures. Figure 3-17 shows the typical optimal supply air temperature reset schedule.

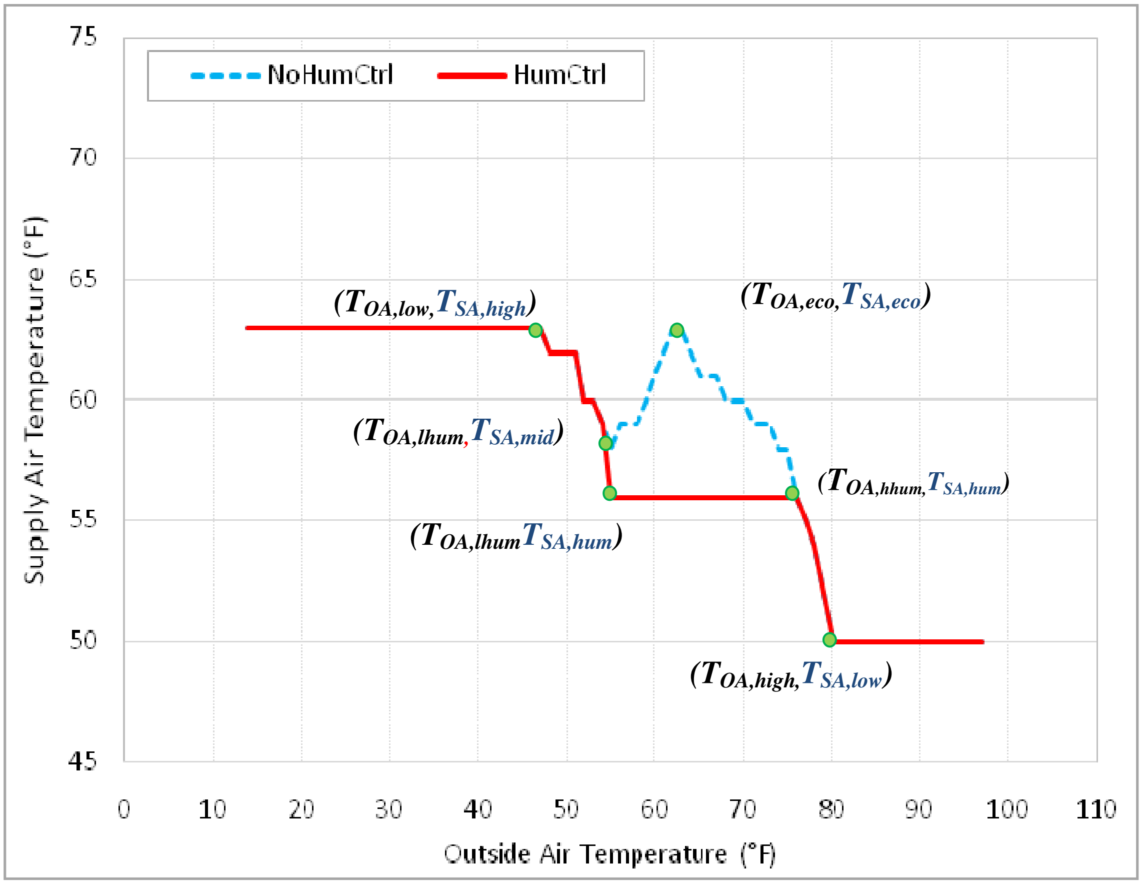


Figure 3-17: Optimized Supply Air Temperature with and without Humidity Control

For a typical optimized supply air temperature with humidity control, five zones are defined and analyzed in the rest of this research.

- Zone 1: $T_{OA} \le T_{OA,low}$
- Zone 2: $T_{OA,low} < T_{OA} \le T_{OA,lhum}$

- Zone 3: $T_{OA,lhum} < T_{OA} \leq T_{OA,hhum}$
- Zone 4: $T_{OA,hhum} < T_{OA} \leq T_{OA,high}$
- Zone 5: $T_{OA} > T_{OA,high}$

Table 3-6: List of Critical Temperatures

Name	Definition	Name	Definition
$T_{OA,low}$	Outside air temperature at which a constant high supply air temperature can be implemented.	$T_{SA,high}$	Supply air temperature high limit.
$T_{OA,lhum}$	Outside air temperature at which outdoor humidity becomes high. The optimal supply air temperature begins to be override to a low value for humidity control.	$T_{SA,mid}$	Supply air temperature when outdoor humidity is high and optimal supply air temperature begins to be override to a low value.
$T_{OA,lhum}$	Same as above.	$T_{SA,hum}$	A constant supply air temperature to assure the humidity level in the conditioned space is below 65%RH.
$T_{OA,hhum}$	Outside air temperature at which supply air temperature can be increased from $T_{SA,hum}$.	$T_{SA,hum}$	Same as above.
$T_{OA,eco}$	Outside air temperature at which economizer is enabled.	$T_{SA,eco}$	Supply air temperature when economizer is enabled.
$T_{OA,high}$	Outside air temperature at which cooling energy consumption is significant and heating load is negligible.	$T_{SA,low}$	Supply air temperature when the cooling load is at its peak and air with constant low temperature can be sent into conditioned space.

3.3.2.1 Zone 1: $T_{OA} \leq T_{OA,low}$

When OAT is lower than a certain temperature ($T_{OA,low}$), the heating load is significant in the exterior area and the supply air temperature can be set at the high limit ($T_{SA,high}$) to minimize the reheat consumption in the terminal boxes. Meanwhile, interior area still needs cooling. As a result, the SAT should still be kept at a certain level to remove the heat gain in the interior area. In this research the high limit is set at 65°F, because if the supply air temperature is above this value, it is unable to remove zone cooling load.

3.3.2.2 Zone 2: $T_{OA,low} < T_{OA} \leq T_{OA,lhum}$

In this zone, the space heating requirement is decreasing with the increase in the OAT. As a result, the cost efficient supply air temperature is decreasing when the ambient temperature increases. In this range of OAT, the economizer is enabled, which means free cooling is being used and the mechanical cooling is reduced. In addition, outdoor air is relatively dry. In this zone, the optimized SAT reset is the same for both humidity control and non-humidity control situation.

The SAT is supposed to decrease from $T_{SA,high}$ when the OAT is $T_{OA,low}$ to $T_{SA,mid}$ or when the OAT is $T_{OA,lhum}$. In addition, the $T_{OA,low}$ and the $T_{OA,lhum}$ are dependent on several factors: building location, weather conditions, minimum air flow rate, etc.

3.3.2.3 Zone 3: $T_{OA,lhum} < T_{OA} \leq T_{OA,hhum}$

In this zone, the outside air is very humid and the SAT should be lowered to control the humidity at the cost of simultaneous heating and cooling. The supply air temperature is set as low as is needed to control the relative humidity in the conditioned spaces and as high as possible to minimize over-cooling. The $T_{OA,lhum}$ and the $T_{OA,hhum}$ are the two points where the optimal supply air temperature resets for humidity and non-humidity control meet. $T_{OA,lhum}$ is the critical temperature where supply air temperature should be lowered to dehumidify the mixed air while on the opposite side, $T_{OA,hhum}$ is where the most cost efficient SAT is low enough to control the humidity. Both the $T_{OA,lhum}$ and the $T_{OA,hhum}$ are related to location and weather conditions. In this particular case, $T_{OA,lhum}$ is 55ºF while $T_{OA,hhum}$ is 74ºF. $T_{SA,mid}$ and $T_{SA,hum}$ are different for different operation conditions which will be discussed later.

3.3.2.4 Zone 4: $T_{OA,hhum}<T_{OA}\leq T_{OA,high}$

In this zone, the optimal SAT declines from $T_{SA,hum}$ to $T_{SA,low}$ while the OAT increases from $T_{OA,hhum}$ to $T_{OA,high}$. During this period, the cooling load is climbing swiftly with the rise of the OAT while the heating load is neglected. The optimized SAT decreases as long as overcooling is avoided and it is low enough to control the humidity below 65 %RH in the conditioned space. Both the $T_{OA,hhum}$ and the $T_{OA,high}$ are affected by weather conditions and operation scenarios.

3.3.2.5 Zone 5: $T_{OA}>T_{OA,high}$

When the OAT is above a specific temperature ($T_{OA,high}$), the zone cooling load is dominant and no heating is called from the conditioned zones. As a result, the SAT can be lowered to a constant value where no over-cooling will occur. In this research, this low temperature is defined as $T_{SA,low}$, and cut off at 50°F which is the limit established by the capacity of chillers. Both the $T_{OA,high}$ and the $T_{SA,low}$ change with varying operation conditions.

4. DIFFERENT OPERATING CONDITIONS

4.1 Influence of Minimum Flow Ratio

This section analyzes the changes of the optimal SAT reset driven by changing minimum air flow ratio. To analyze this, the minimum flow ratio has been changed from 15% to 30%, 50% and 100% while all the other input parameters were kept the same. Notice that at the 100% minimum air flow ratio, the system cooperates as a constant volume unit. Figure 4-1 shows the four temperature curves of the four different minimum flow ratios when the internal peak load is around 4.0W/ft^2, exterior area account for 42% of the total floor area and cooling price was \$5.5/MMBtu while heating cost was \$12.82/MMBtu.

The results show that a proper minimum flow should be applied in a SDVAV system. It should be high enough to meet ventilation requirement and low enough to prevent over-cooling and reheat. A high minimum flow is likely to produce extra cooling or heating energy. For example, when the outside air is 75°F, a 15% air flow at 55°F can exactly remove the cooling load from the space. However, if the minimum flow is set at 30%, 15% extra cooling energy is going to be sent to the zone which results in 15% over-cooling as well as a 15% reheat. In this case, if the SAT is increased to a higher value, for instance, 57°F, overcooling can be avoided. As a result, the SAT reset should be higher for a higher minimum flow setpoint if other operation parameters are kept the same.

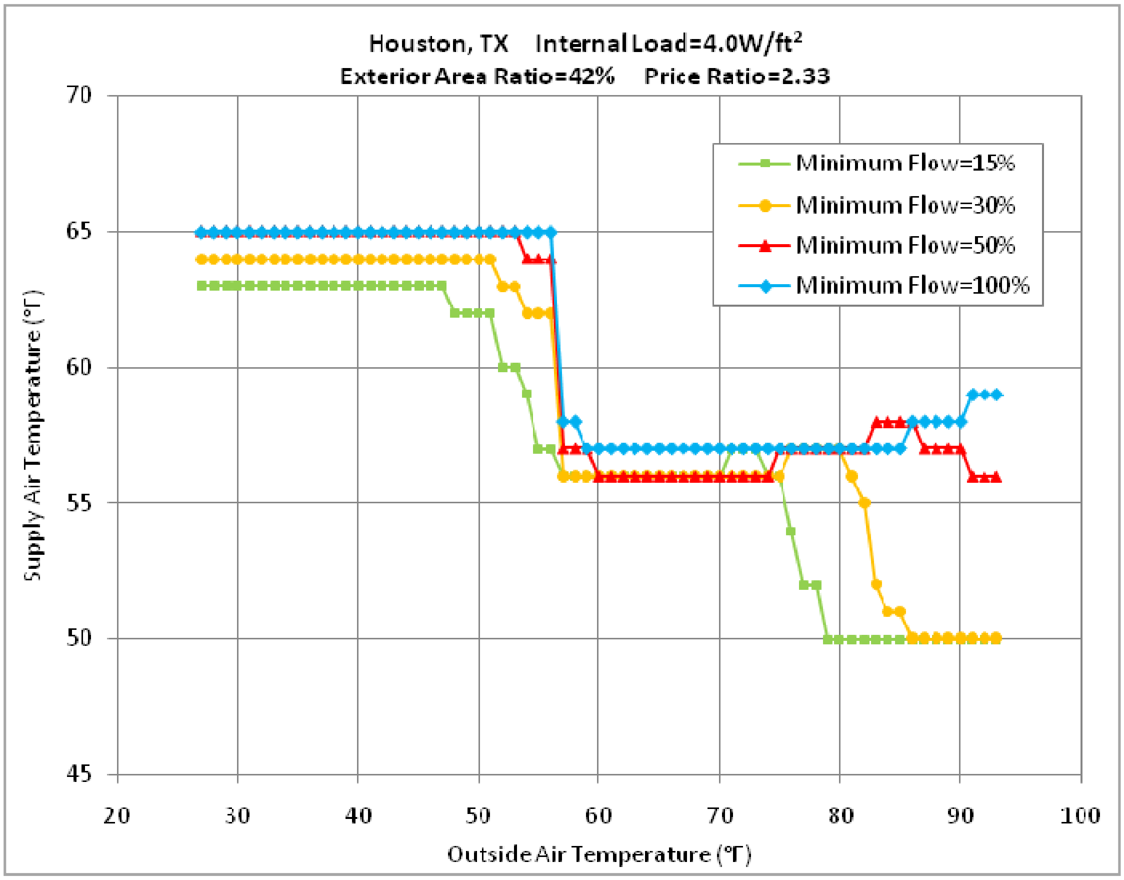


Figure 4-1: SAT Reset Schedules for Different Minimum Flow Ratios

4.2 Influence of Exterior Zone Area Ratio

The cooling and heating loads for the exterior zone vary significantly during the year depending on outside conditions. They call for a large amount of cooling in the summer and heating in the winter. Meanwhile, the load for the interior zone remains quite stable year round, requiring cooling to fulfill the zone thermal comfort requirements. Different zoning methods may result in different load distributions and different optimized control strategies. Hence, it is necessary to evaluate the impact of the zone loads on the SAT reset. Figure 4-2 and Figure 4-3 show system cooling and heating loads with different exterior zone area ratios. In this research, the exterior zone area ratio was defined as the ratio of exterior zone area to the total floor area. It was adjusted from 0% to 22%, 42% and 100% in steps where 100% exterior zone area ratio equals to one single zone for the entire floor. The results show that both the cooling and heating loads for the system are lower for a larger exterior zone area ratio. The only exception is that when the OAT is higher than the zone setpoint temperature. During this condition, the cooling load is lower for the interior zone than the exterior zone. The reason is that for the unit serving the exterior zone, the cooling load in the exterior zone is influenced by the heat transfer through the building envelope. When the OAT is lower than the setpoint temperature, the internal heat gain by the occupants, equipment and lights compensate the heat loss through the envelope which results in a lower heating load in the exterior zone. As a result, for large exterior zones, more internal heat gain can contribute to counteract the heat loss from the envelope, which results in less heating load in the exterior zone. Since the internal load in the exterior zone are counteracted by the heat loss through the envelope when the OAT is less than the setpoint temperature, the cooling loads will be reduced in the interior zone. Here, minimum flow is 30%, internal load is 4.0 W/ft^2 and the heating/cooling energy price ratio is 2.33. Figure 4-4 shows the results of the different SAT reset schedules for different exterior zone area ratios. The result shows that the larger the exterior zone area is, the higher SAT should be set in the heating season and lower SAT in the cooling season. For example, if it is an exterior area only unit, $T_{SA,high}$ can be up to 65°F while $T_{SA,high}$ is only 62°F for an interior area only unit. The reason is that the heating load takes priority in the exterior zone area while in the interior zone area only a cooling load exists. When the OAT is below 28°F, the large variations for the system loads shown in Figure 4-4 is due to the solar radiation and small number of hours for these OAT bins in Houston.

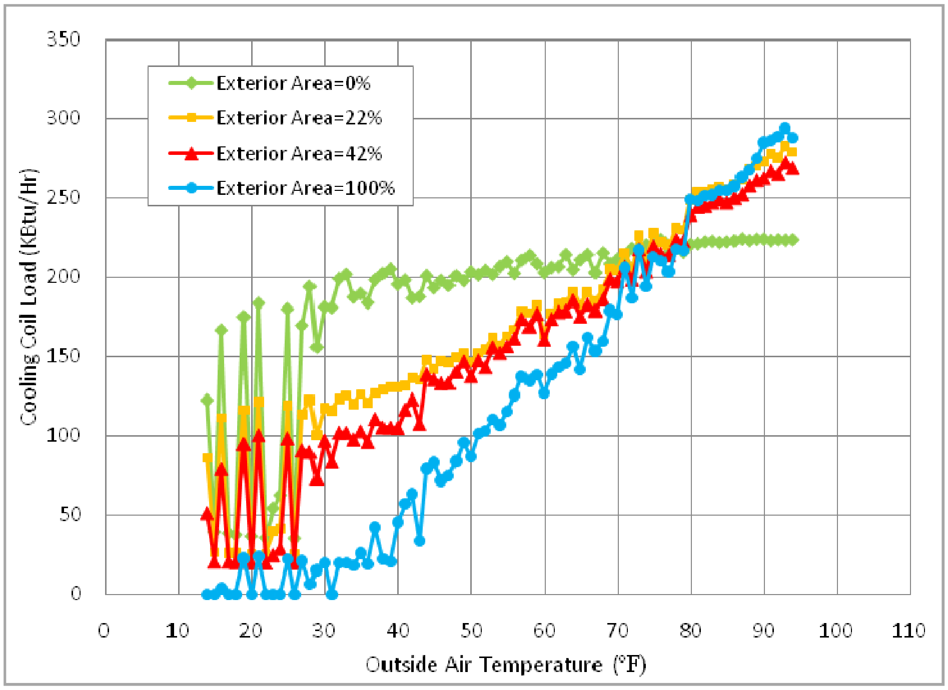


Figure 4-2: System Cooling Loads for Different Exterior Zone Area Ratios

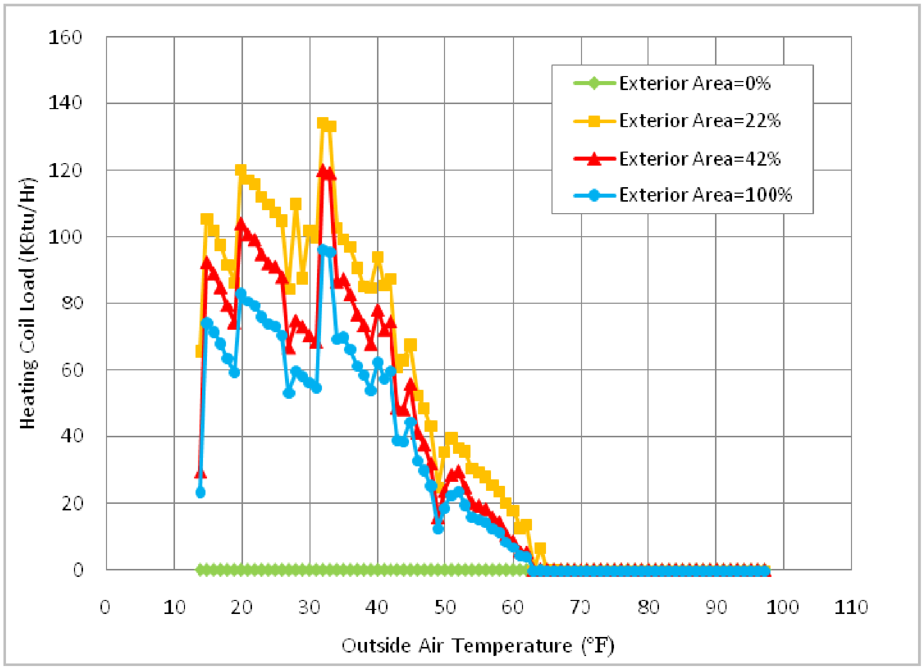


Figure 4-3: System Heating Loads for Different Exterior Zone Area Ratios

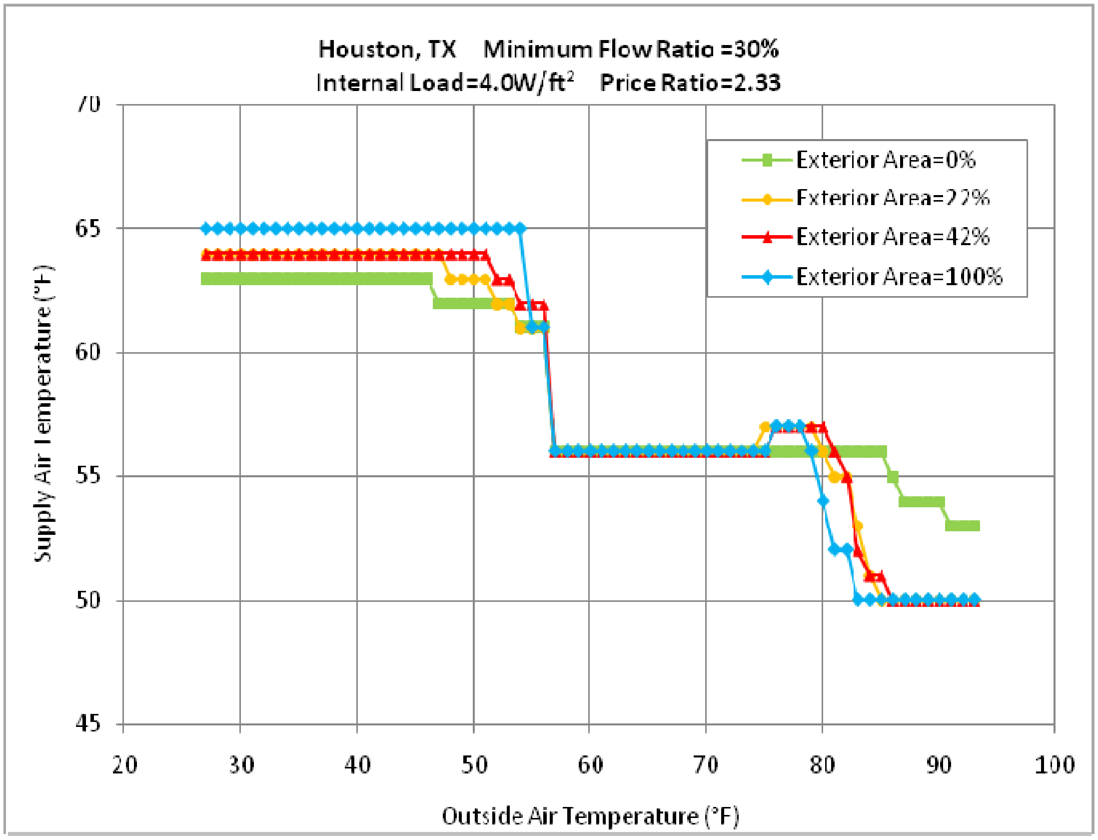


Figure 4-4: SAT Reset Schedules for Different Exterior Zone Area Ratios

4.3 Influence of Internal Load

In this section, the impact of the internal loads will be discussed. Similar to the previous analysis, all the other operation conditions were kept the same. Only the internal load was increased from 3.5 W/ft^2 to 4.0 W/ft^2 and 4.5 W/ft^2.

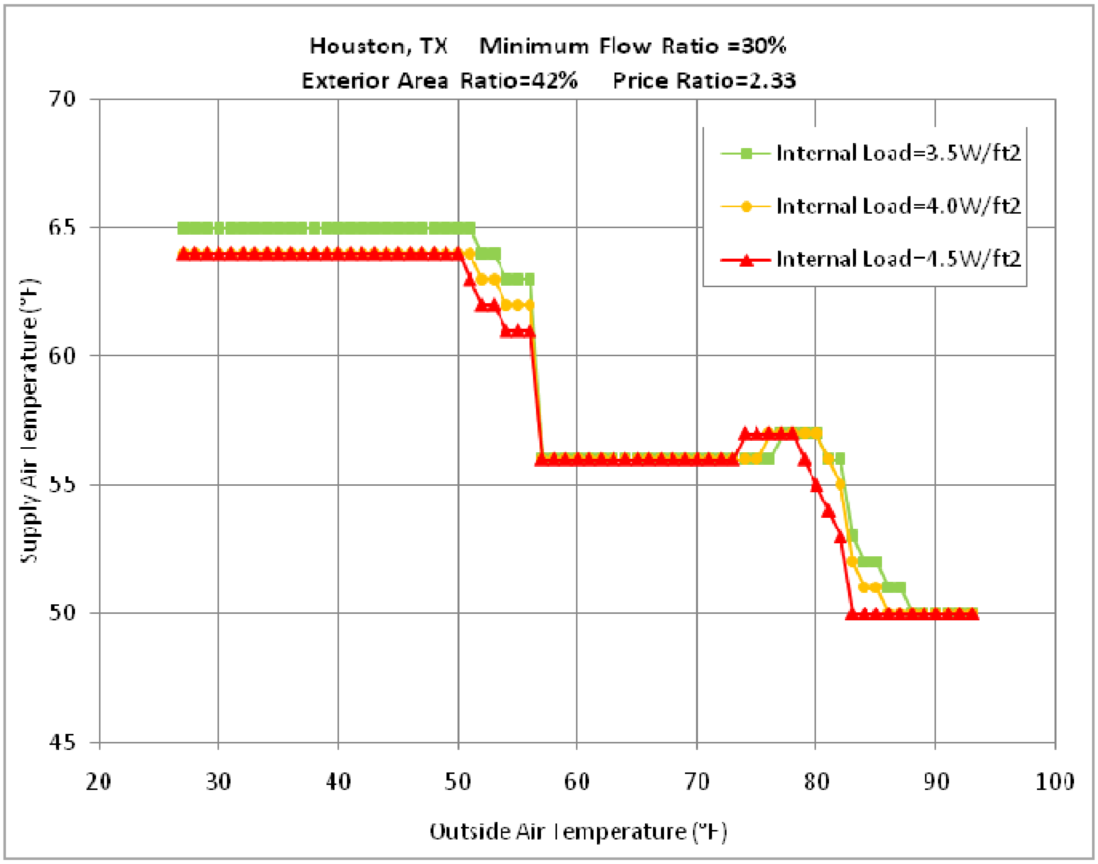


Figure 4-5: SAT Reset Schedules for Different Internal Loads

Figure 4-5 shows the three SAT curves for the three internal load intensities when the exterior zone area ratio was set to 42%, minimum flow ratio was 30% of the total flow and heating/cooling price ratio was 2.33. From the results, it is reasonable to conclude that a higher internal load should result in a lower SAT. In this specific case, the optimized SAT was lowered by 1°F when the internal load increased by 0.5 W/ft². This would indicate that when the internal load increases, the SAT should be decreased due to the additional cooling load.

4.4 Influence of EnergyPrices

The energy price is another important factor in determining the optimized SAT reset. The price ratio is defined as:

$$\text{Price Ratio} = \frac{\text{Heating Energy Cost(\$/MMBtu)}}{\text{Cooling Energy Cost(\$/MMBtu)}} \qquad \textbf{4-1}$$

In this study, three price ratios were investigated including 1.17, 2.33 and 3.50. Figure 4-6 shows the different SAT reset schedules for the different price ratios. The results show that the higher the price ratio is, the higher the SAT should be set in the heating season. If the price for hot water goes up, the cost on the heating side should take priority reset because more money can be saved if the SAT is increased and less heating energy is consumed. On the contrary, if the gas price or the heating energy price decreases, electricity should take priority for cost efficiency which indicates a lower SAT. Notice that there is no difference for the three SAT reset schedules when the OAT is above $T_{OA,lhum}$. When the OAT ranges from $T_{OA,lhum}$ and $T_{OA,hhum}$, the SAT should be lowered to control the space humidity and when the OAT is above $T_{OA,hhum}$, no heating is required for the system. As a result, the heating price has no impact on the SAT reset schedule when the OAT is above $T_{OA,lhum}$.

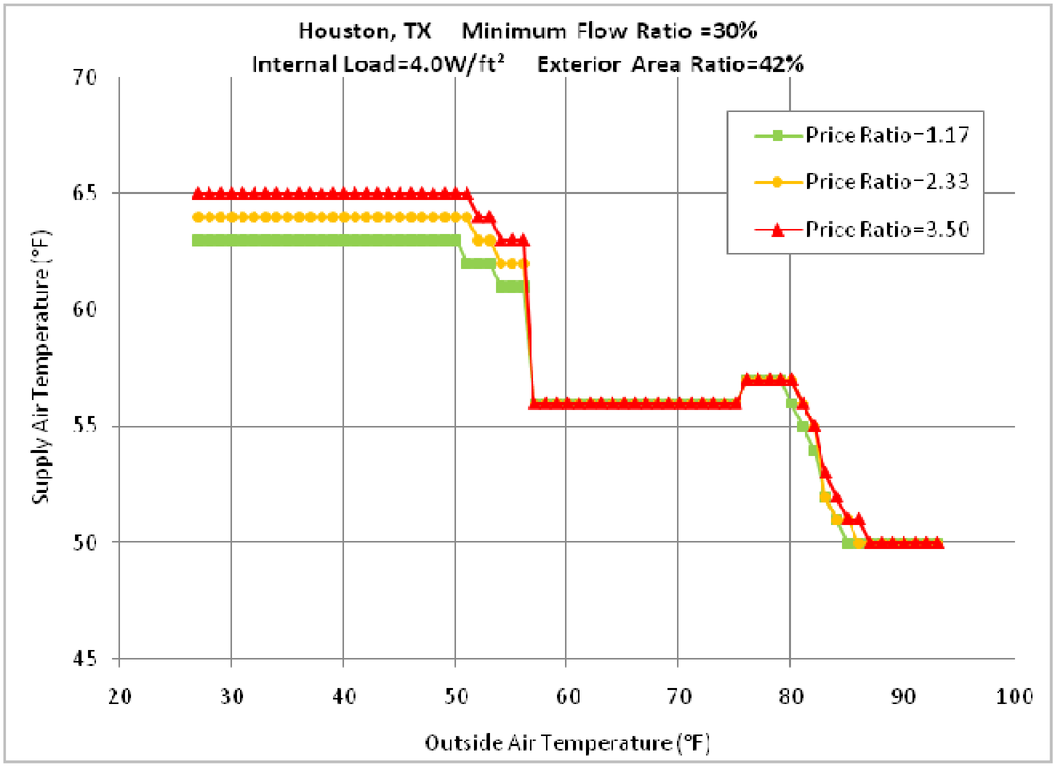


Figure 4-6: SAT Reset Schedules for Different Price Ratios

5. CONCLUSIONS

Determining the optimal SAT is a complex process which is influenced by various factors, such as weather condition, minimum air flow rate, exterior area ratio, internal load and utility price. A guideline for determination of a cost efficient SAT for single duct VAV units is drawn in this research. Furthermore, a brief introduction on how to adjust SAT reset schedule with different operation scenarios is presented.

5.1 Five Zones for SAT Reset Schedule

The most cost efficient optimal SAT can be divided into five zones with respect to ambient temperature. To simplify the discussion, some critical temperatures are defined in this research as shown in Figure 5-1 and the detailed definition can be found in the former sections.

- Zone 1: $T_{OA} \leq T_{OA,low}$
- Zone 2: $T_{OA,low} < T_{OA} \leq T_{OA,lhum}$
- Zone 3: $T_{OA,lhum} < T_{OA} \leq T_{OA,hhum}$
- Zone 4: $T_{OA,hhum} < T_{OA} \leq T_{OA,high}$
- Zone 5: $T_{OA} > T_{OA,high}$

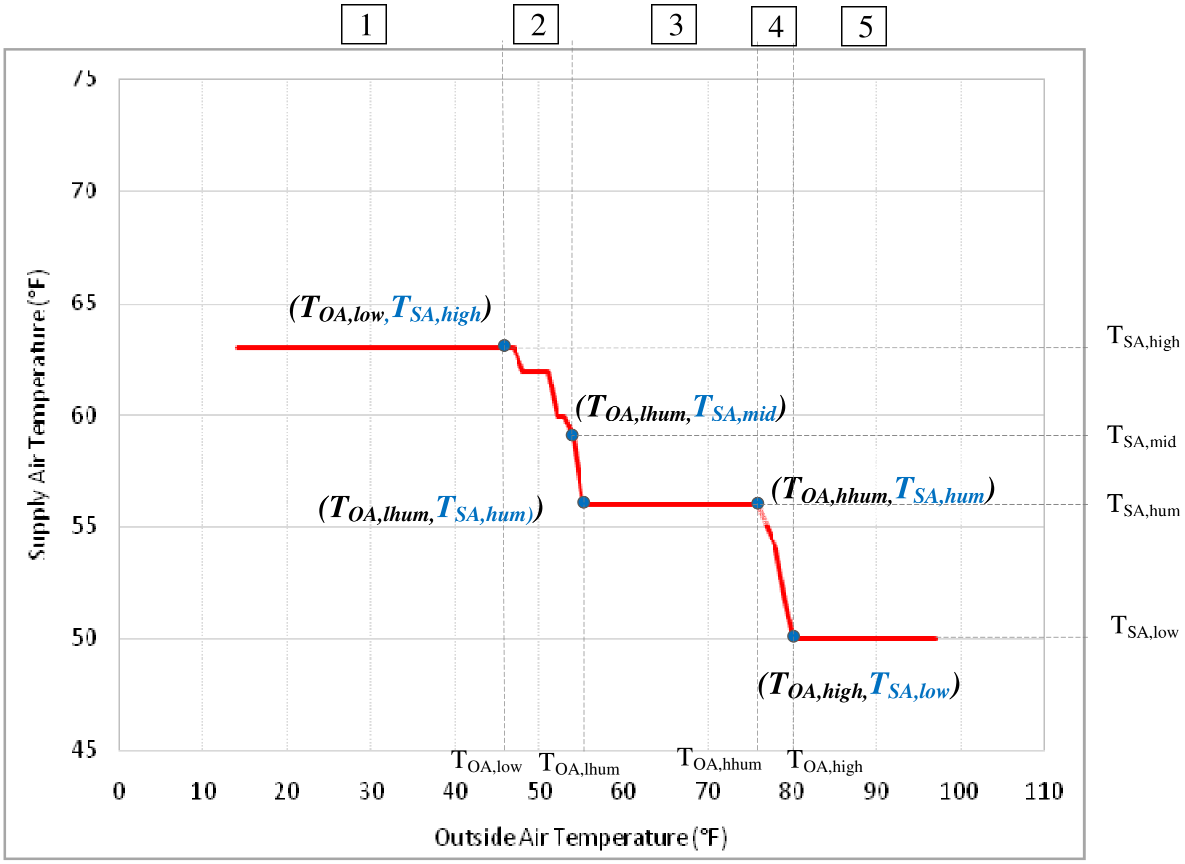


Figure 5-1: Typical Optimized SAT

5.1.1 Zone One: $T_{OA} \leq T_{OA,low}$

In the first zone, when the OAT is equals to or below $T_{OA,low}$, the zone cooling load is very small and significant heating energy is required. Therefore, the SAT can be set as a constant value, $T_{SA,high}$.

5.1.2 Zone Two: $T_{OA,low} < T_{OA} \leq T_{OA,lhum}$

In the second zone, when the OAT is above $T_{OA,low}$ and equals to or below $T_{OA,lhum}$, the zone heating load is decreasing and the SAT should decrease from $T_{SA,high}$ to $T_{SA,hum}$ while the OAT increases from $T_{OA,low}$ to $T_{OA,lhum}$.

5.1.3 Zone Three: $T_{OA,lhum} < T_{OA} \le T_{OA,hhum}$

When the OAT ranges from $T_{OA,lhum}$ and $T_{OA,hhum}$ and outdoor humidity level is high, the SAT is required to be kept at a low value, $T_{SA,hum}$, even at the cost of extra energy consumption in the form of reheat energy to maintain zone humidity ratio below 65 %RH.

5.1.4 Zone Four: $T_{OA,hhum} < T_{OA} \le T_{OA,high}$

When the OAT continues to increase, the cooling load increases rapidly and the SAT should decrease so that less fan power is consumed in the air-handling unit. In other words, when the OAT increases from $T_{OA,hhum}$ to $T_{OA,high}$, the SAT should decrease from $T_{SA,hum}$ to $T_{SA,low}$. Note that depending on different building conditions, if minimum air flow ratio is high above a certain level, $T_{OA,high}$ may become an infinitive large number and SAT should keep at $T_{SA,hum}$ to control zone humidity.

5.1.5 Zone Five: $T_{OA} > T_{OA,high}$

The last zone indicates an area where the cooling load is very large and the SAT can be set at a constant low value, $T_{SA,low}$.

5.2 Influence of Different Operating Conditions

Four key influencing operation parameters have been analyzed in this study and Table 5-1 summarizes the guidelines of the adjustment of the optimized SAT reset schedule, including:

1) A high minimum flow ratio indicates a high SAT for both the heating and cooling mode.
2) A high exterior area zone ratio results in a high SAT in the heating mode and a low SAT in the cooling mode.

3) A high internal load should have a low SAT in both the heating and cooling seasons.
4) A high electricity cost implies a low SAT while a high heating price implies a high SAT setpoint.

Table 5-1: Adjustment of Critical Temperatures for Various Conditions

	Minimum Flow↑	Exterior Area↑	Internal Load↑	Price Ratio↑
$T_{OA,low}$	↑	↑	↓	↑
$T_{SA,high}$	↑	↑	↓	↑
$T_{OA,lhum}$	–	–	–	–
$T_{SA,mid}$	↑	–	↓	↑
$T_{OA,hhum}$	↑	↓	↓	–
$T_{SA,hum}$	–	–	–	–
$T_{OA,high}$	↑	↓	↓	–
$T_{SA,low}$	↑	↓	↓	–

5.3 Recommendations for Further Research

The optimization of the SAT is a complex issue that is related to many factors. Unfortunately, it is difficult to discuss and analyze all the influencing factors in a single analysis. This research has provided a weather bin method for optimizing the SAT. Moreover, four major influencing factors (minimum flow ratio; exterior area zone ratio; internal load and energy prices) have been individually investigated. Nevertheless, further research for some other variables could be developed. To name a few, five considerations were carried out below as suggestions.

5.3.1 Installed Plant Equipment

In this research, the purchased chilled water and hot water were used to meet the building cooling and heating requirement. As a result, a constant chiller and boiler efficiency was assumed while in a real case the chiller efficiency will be higher in the cold season and the boiler efficiency will be higher in the hot season. In addition, the electricity consumed by the chillers, boilers, cooling towers and pumps should also be considered in the calculation of the total cost when determining the optimal SAT reset schedule.

5.3.2 Different Zone Temperature Setpoint

There are many operation parameters that may influence the reset strategy of the SAT. In this research, four major factors were being discussed while the zone temperature setpoints were locked at one constant value. Therefore, it might be desirable to find out what other adjustments to the SAT should be made if the zone temperature setpoint is changed.

5.3.3 Different Envelope Construction

Characteristics of the building envelope will significantly affect the exterior area cooling and heating load. Both the cooling load and heating load will vary significantly for a well-insulated building versus a poorly-insulated building. Sets of optimal SAT resets can be developed for varying envelope insulating levels using a similar method introduced in this research.

5.3.4 Scenarios for a System without an Economizer

An economizer is a sound method to save energy that uses free cooling when the OAT is below a certain point. However, many SDVAV systems are unable or not suitable to use an economizer. Therefore, it is worth analyzing the conditions for systems where the economizer is disabled year-round.

5.3.5 Different Occupancy Schedule

Building and occupancy schedules have a large influence on energy consumptions. Some buildings have regular office hours while some special spaces like hospitals and data centers need to be served year-round. As a result, both the zone load and humidity level varying significantly for different schedules.

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APPENDIX A

CASE-STUDY BUILDING ENVELOPE INFORMATION

A.1 External Walls

A.2 Flat Floor

A.3 Ground Floor

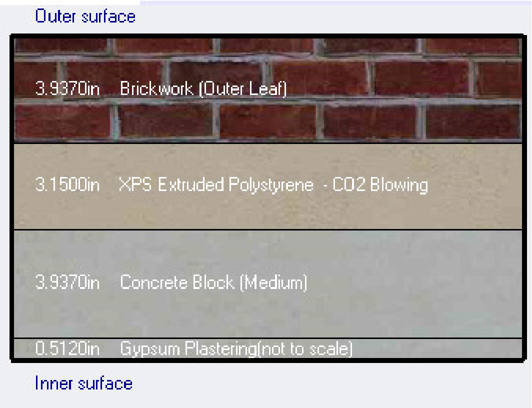
A.4 Ceiling Tiles

A.5 Internal Walls

A.6 Windows

Appendix A has documented all the materials information of the case-study building being simulated in this research.

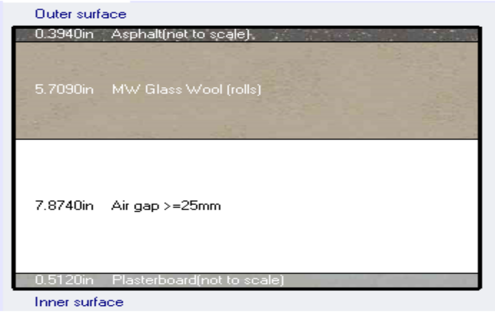
A.1 External Walls



Layers	Thickness(in)
Brickwork(Out leaf)	3.937
XPS extruded Polystyrene	3.150
Concrete Block(Medium)	3.937
Gypsum Pastering(Inner layer)	0.512

Inner Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	0.379
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.976
	Surface resistance(ft2-F-hr/Btu)	0.739
Outer Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	3.499
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.903
	Surface resistance(ft2-F-hr/Btu)	0.227
No Bridging	U-Value surface to surface(Btu/h-ft2-F)	0.065
	R-Value(ft2-F-hr/Btu)	16.310
	U-Value(ft2-F-hr/Btu)	0.061
With Bridging	Upper resistance limit(ft2-F-hr/Btu)	16.312
	Lower resistance limit(ft2-F-hr/Btu)	16.312
	U-Value surface to surface(Btu/h-ft2-F)	0.065
	R-Value(ft2-F-hr/Btu)	16.312
	U-Value(ft2-F-hr/Btu)	0.061

A.2 Flat Roof



Layers	**Thickness(in)**
Asphalt(Out layer)	0.394
MW Glass Wool(rools)	5.709
Air Gap>=25mm	7.874
Plasterboard(Innermost layer)	0.512

Inner Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	0.379
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.976
	Surface resistance(ft2-F-hr/Btu)	0.739
Outer Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	3.499
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.903
	Surface resistance(ft2-F-hr/Btu)	0.227
No Bridging	U-Value surface to surface(Btu/h-ft2-F)	0.065
	R-Value(ft2-F-hr/Btu)	16.310
	U-Value(ft2-F-hr/Btu)	0.061
With Bridging	Upper resistance limit(ft2-F-hr/Btu)	16.312
	Lower resistance limit(ft2-F-hr/Btu)	16.312
	U-Value surface to surface(Btu/h-ft2-F)	0.065
	R-Value(ft2-F-hr/Btu)	16.312
	U-Value(Btu/h-ft2-F)	0.061

A.3 Ground Floor

Layers	Thickness(in)
UF Foam(Out layer)	3.425
Cast Concrete(rolls)	3.937
Screed	2.756
Wooden Flooring(Inner layer)	1.181

Inner Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	0.060
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.976
	Surface resistance(ft2-F-hr/Btu)	0.966
Outer Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	3.427
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.976
	Surface resistance(ft2-F-hr/Btu)	0.227
No Bridging	U-Value surface to surface(Btu/h-ft2-F)	0.067
	R-Value(ft2-F-hr/Btu)	16.234
	U-Value(ft2-F-hr/Btu)	0.062
With Bridging	Upper resistance limit(ft2-F-hr/Btu)	18.088
	Lower resistance limit(ft2-F-hr/Btu)	18.088
	U-Value surface to surface(Btu/h-ft2-F)	0.067
	R-Value(ft2-F-hr/Btu)	16.234
	U-Value(Btu/h-ft2-F)	0.062

A.4 Ceiling Tiles

Layers	Thickness(in)
Ceiling Tiles	0.394

Inner Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	0.785
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.976
	Surface resistance(ft2-F-hr/Btu)	0.568
Outer Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	3.427
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.976
	Surface resistance(ft2-F-hr/Btu)	0.227
No Bridging	U-Value surface to surface(Btu/h-ft2-F)	0.986
	R-Value(ft2-F-hr/Btu)	1.810
	U-Value(ft2-F-hr/Btu)	0.553
With Bridging	Upper resistance limit(ft2-F-hr/Btu)	1.811
	Lower resistance limit(ft2-F-hr/Btu)	1.811
	U-Value surface to surface(Btu/h-ft2-F)	0.986
	R-Value(ft2-F-hr/Btu)	1.811
	U-Value(Btu/h-ft2-F)	0.553

A.5 Internal Walls

Layers	Thickness(in)
Cast Concrete	3.937

Inner Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	0.379
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.976
	Surface resistance(ft2-F-hr/Btu)	0.739
Outer Surface	Convective heat transfer coefficient(Btu/h-ft2-F)	3.499
	Radiative heat transfer coefficient(Btu/h-ft2-F)	0.903
	Surface resistance(ft2-F-hr/Btu)	0.227
No Bridging	U-Value surface to surface(Btu/h-ft2-F)	2.466
	R-Value(ft2-F-hr/Btu)	1.372
	U-Value(ft2-F-hr/Btu)	0.729
With Bridging	Upper resistance limit(ft2-F-hr/Btu)	1.372
	Lower resistance limit(ft2-F-hr/Btu)	1.372
	U-Value surface to surface(Btu/h-ft2-F)	2.466
	R-Value(ft2-F-hr/Btu)	1.372
	U-Value(Btu/h-ft2-F)	0.729

A.6 Windows

General	Bronze 6mm	Absorptive
Outer Surface	Thickness(in)	0.2362205
	Conductivity(Btu/h-ft2-F)	6.24133
Solar Properties	Solar Transmittance	0.48200
	Outside solar reflectance	0.05400
	Inside solar reflectance	0.05400
Visible Properties	Visible transmittance	0.53400
	Outside Visible reflectance	0.05700
	Inside Visible reflectance	0.05700
Infra-Red Properties	Infra red transmittance	0.0000
	Outside Infra red reflectance(emissivity)	0.8400
	Inside Infra Red reflectance(emissivity)	0.8400

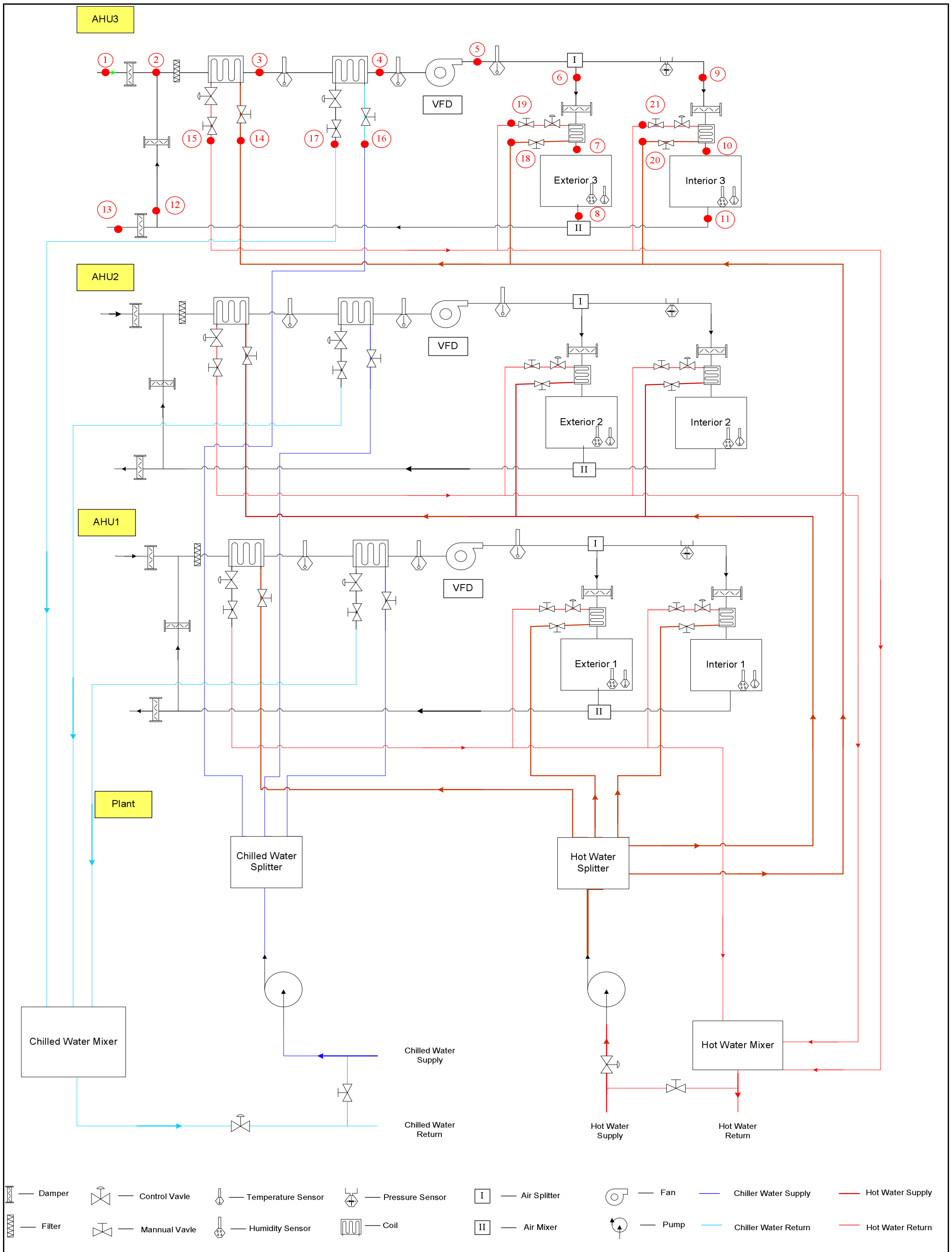
APPENDIX B

ENERGYPLUS INPUT AND OUTPUT FILES INFORMATION

B.1 HVAC System Diagram of EnergyPlus Input File
B.2 EnergyPlus Standard Output Files

Appendix B has documented EnergyPlus input and output files information of the case-study building in this research.

B.1 HVAC System Diagram of Case-study Building



Node List:
1. Outside Air Node; 2. Mixed Air Node; 3. Preheat Air Node; 4. Cooling Air Node; 5. Fan Outlet Node; 6. Zone1 Air Inlet Node; 7. Zone1 Air Node;
8. Zone1 Return Air Node; 9. Zone2 Air Inlet Node; 10. Zone2 Air Node; 11. Zone2 Return Air Node; 12. Air Loop Return Air Node; 13. Exhaust Air Node;
14. Preheat Coil Inlet Node; 15. Preheat Coil Outlet Node; 16. Cooling Coil Inlet Node; 17. Cooling Coil Outlet Node; 18. Reheat Coil1 Inlet Node
19. Reheat Coil1 Outlet Node; 20. Reheat Coil2 Inlet Node; 21. Reheat Coil2 Inlet Node

B.2 EnergyPlus Standard Output Files

Output File Name	Description	EP-Launch File Name
eplusout.audit	Echo of input, includes both IDD echo and IDF echo – may have errors shown in context with IDD or IDF statement	<filename>.audit (without echoing IDD unless errors in IDD).
eplusout.bnd	This file contains details about the nodes and branches. Useful in determining if all your nodes are connected correctly. May be used to diagram the network/ nodes of the HVAC system.	<filename>.bnd
eplusout.dbg	From Debug Output object – may be useful to support to help track down problems	<filename>.dbg
eplusout.dxf	DXF (fro Report,Surfaces,DXF;)	<filename>.dxf
eplusout.eio	Contains several standard and optional "report" elements. CSV format – may be read directly into spreadsheet program for better formatting.	<filename>.eio
eplusout.end	A one line summary of success or failure (useful for Interface programs)	Not saved in the standard EPL-Run script file.
eplusout.epmidf	Output from EPMacro program – contains the idf created from the input imf file	<filename>.epmidf
eplusout.epmdet	Output from EPMacro program – the audit/details of the EPMacro processing	<filename>.epmdet
eplusout.err	Error file – contains very important information from running the program.	<filename>.err
eplusout.eso	Standard Output File (contains results from both Report Variable and Report Meter objects).	<filename>.eso
eplusout.log	Log of items that appear in the command file output from the run.	<filename>.log
eplusout.mtd	Meter details report – what variables are on what meters and vice versa	<filename>.mtd
eplusout.mtr	Similar to .eso but only has Report Meter outputs.	<filename>.mtr
eplusout.rdd	Report Variable names that are applicable to the current simulation	<filename>.rdd
eplusout.mdd	Report Meter names that are applicable to the current simulation	<filename>.mdd
eplusout.shd	Surface shadowing combinations report	<filename>.shd
eplusout.sln	Similar to DXF output but less structuresd. Results of Report Surface, Lines object.	<filename>.sln

B.2 EnergyPlus Standard Output Files-Continued

Output File Name	Description	EP-Launch File Name
eplusssz.<ext>	Results from the System Sizing object. This file is "spreadsheet" ready. Different extensions (csv, tab, and txt) denote different "separators" in the file.	<filename>Ssz.<ext>
epluszsz.<ext>	Results from the Zone Sizing object. This file is "spreadsheet" ready. Different extensions (csv, tab, and txt) denote different "separators" in the file.	<filename>Zsz.<ext>
eplusmap.<ext>	Daylighting intensity "map" output. Different extensions (csv, tab, and txt) denote different "separators" in the file.	<filename>Map.<ext>
eplusscreen.csv	Window screen transmittance (direct and reflected) "map" output.	<filename>Screen.csv
eplustbl.<ext>	Results of Report Table and Economics requests. Different extensions (csv, tab, and txt) denote different "separators" in the file.	<filename>Table.<ext>
eplusout.svg	Results from the HVAC-Diagram application. SVG is a Scalable Vector Graphics file for which several viewers can be found.	<filename>.svg
eplusout.sci	File of cost information	<filename>.sci
eplusout.delightin	File produced during Delight simulations – descriptive of EnergyPlus inputs into Delight inputs.	<filename>.delightin
eplusout.delightdfdmp	File produced during DElight simulations – basic results from DElight simulation.	<filename>.delightdfdmp
eplusout.delighteldmp	File produced during DElight simulations – includes any warning or error messages from DElight	<filename>.delighteldmp
eplusout.sparklog	File produced during DElight simulations – timestep results from the simulation	<filename>Spark.log
eplusout.wrl	File produced during simulations of SPARK component models – includes statistics as well as any warning or error message from the SPARK link.	<filename>.wrl

VITA

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