The Impact of Control Setpoints on Building Energy Use in Different Weather Conditions

Stephen Treado
Department of Architectural Engineering
Pennsylvania State University
University Park, PA, USA
streado@psu.edu

Xing Liu
Department of Architectural Engineering
Pennsylvania State University
University Park, PA, USA
xul121@psu.edu

***Abstract* - This paper examines the impact of building Heating, Ventilation and Air Conditioning (HVAC) control system setpoints such as temperature and flow rate on total building energy requirements, for a typical system design and operation in four different weather conditions. Through the simulation and the result sensitivity analysis, the range of energy usage and the potential for minimizing building energy requirements by dynamically adjusting setpoints are presented in this paper.**

Keywords-buildings; cooling; control systems; energy; heating; HVAC; simulation; setpoints

I. INTRODUCTION

The increasing demand of air-conditioning and the energy crisis during the last decades have led to a surge of attention and there is no doubt that the improvement of the Heating, Ventilating and Air Conditioning (HVAC) control system is one of the effective solutions to realize sizable energy-saving for the building sector. The aim of HVAC control is to provide a comfortable, safe, healthy and productive environment for occupants using the least energy. Significant energy saving potential exists for building systems during operation with the help of current technology such as intelligent, adaptive or model predictive control. The development of this kind of technology has led to the possibility of the improvement of building operational performance. However, it is difficult to evaluate the potential or effectiveness of the new control strategies without first gaining a better understanding of the range of operating conditions possible for any particular building/HVAC system combination. That is, the amount of energy savings is a function of both the actions of the new control strategy and the fundamental capabilities of the HVAC system. In its most basic form, a building control system can do no more than monitor sensors, apply logic and manipulate actuators. Thus, the main objective of the work described in this paper is to clearly identify and define the space within which the building/HVAC combination is capable of operating in order to enable the determination of both energy saving potential and optimal setpoints and control logic. While this is not specifically an optimization effort, i.e., we are not seeking a single optimal solution since it is understood that setpoints and control logic may need to be adjusted on a dynamic basis, the primary metric utilized, namely total building energy usage, can be considered as an objective function.

The content is organized as follows. Section II reviews the recent studies. Section III presents the models adopted and simulation work. Section IV gives the results and analysis. Lastly, Section V presents the conclusions and possible future work.

II. LITERATURE RIEVEW

Simulation is taken as one of the oldest but very effective tools to engineers in every discipline. Building simulation began in the 1960s and became the hot topic of the 1970s within the energy research community. For nowadays, computer simulation is not only used for the building design stage like sizing and configuration design, but also adopted for system performance analysis more and more widely. Building simulation can be applied to reveal the inter-actions between the building itself and its occupants, HVAC systems, and the outdoor climate This paper is a further improvement to our previous work [1]. A large amount of work has been done to show how important building simulation is in the study of building energy performance [2]. For examples, Li et al. [3] and Pan et al. [4] analyzed and displayed the building energy break-down with calibrated models in 2007 and 2009, respectively; however, more effort is needed to understand how to obtain optimum operating parameters, particularly for building control systems. Simulation does provide a good opportunity to evaluate the dynamic and energy performance of HVAC system control strategy in a convenient and low cost way. The control strategy can also be pre-tuned before being utilized in the real system with the help of simulation. Recent research also showed performing building simulation analysis enabled diagnosis of malfunctioning or incorrectly commissioned equipment within the building and thus also assisted with future commissioning and tuning of the building performance [5].

Future development and application of information technology in the building industry will lead to a completely new building design philosophy and methodology [6]. In 2003, Mathews and Botha [7] conducted simulation with three cases and proved that simulation does indeed have the

TABLE I. REFERENCE CHARACTERISTICS OF EQUIPMENT

Components	Selected parameters values	
Chiller	33 Capacity (hp)	2.75 COP
	44 T_lcw (°F)	85 T_ecf (°F)
	4.24 V_chw (ft^3/min)	4.87 V_cdw (ft^3/min)
Natural Gas Boiler	0.8 Boiler Efficiency	950 Heat Value (Btu/lb)
Variable Volume Fan	4500 Rated Flow rate (ft^3/min)	3 Rated Power (hp)
	0.087 Pressure Rise (psi)	0.7 Fan Efficiency
Variable Speed Pump	2.54 Rated Flow rate (ft^3/min))	2 Rated Power (hp)
	50 Pump head (ft)	0.66 Pump Efficiency

*T-Temperature, V-Flow Rate, lcw-leaving chilled water, ecf-entering condenser fluid, chw-chilled water, cdw-condenser water

TABLE II. DEFAULT PARAMETER VALUE FOR SIMULATION

Variable	Value
Zone Area	S=750 ft^2
Overall Envelope Heat Transfer Rate	U = 0.064 Btu/h-ft^2-°F
Ambient Temperature	T_a = 90 °F (summer condition)
	T_a = 30 °F (winter condition)
Ambient Pressure	P = 1 atm
Zone Air Temperature	T_z = 75 °F (summer condition)
	T_z = 72 °F (winter condition)
Outdoor Air fraction	F_o = 30%
Solar Heat Gain	q_S =1.5 w/ft^2 (summer condition)
	q_S =0.8 w/ft^2 (winter condition)
Lighting Heat Gain	q_l = 1.0 w/ft^2
Equipment Heat Gain	q_e = 1.5 w/ft^2
Occupants Heat Gain	q_o = 1.0 w/ft^2
Ventilation Air Flow rate	M_v = 1.5 cfm/ft^2
Infiltration Air Flow Rate	M_i = 0.1 cfm/ft^2
Heat Exchanger Effectiveness	U_1 = 75%
Energy Recovery Effectiveness	U_2 = 70%

ability to improve the thermal and energy management of building HVAC systems. A lot of work has been done in the field of building energy consumption simulation but more work remains to be done. Traditionally, less attention has been put on buildings operation compared with the design of a system and its construction/installation. What's more, the simulation software has been evolving steadily over recent years. HVAC component and subsystem models are now generally well understood and have been the subject of a number of researches [8]. Simulation has been extended to the use to the building operation process, although it has been traditionally regarded as a design tool.

III. SIMULATIONS

The simulations were performed in four different cities. They are: State college, Pennsylvania; Miami, Florida; Phoenix, Arizona and Minneapolis, Minnesota. The weather files used in this paper are typical meteorological year (TMY) format, which are widely adopted in the building energy simulation software nowadays and are obtained from the United States Department of Energy website (2010). A typical meteorological year (TMY) is a collation of selected weather data for a specific location, generated from a data bank much longer than a year in duration. It is specially selected so that it presents the range of weather phenomena for the location in question, while still giving annual averages that are consistent with the long-term averages for the location in question. TMY annual weather data information is known to be used in the EnergyPlus program. As the weather data is given for each hour throughout the year, the simulation is run at intervals of one hour. The four different cities were chosen based on their typical weather patterns. Minneapolis was chosen for its cold and dry climate, State college for its mild climate, Phoenix for its hot and dry climate and Miami for its hot, and humid weather. The detail weather profile for these four cities are not presented here but can be found at the United States Department of Energy website.

The simulations that were conducted consisted primarily of quasi steady state determinations of hourly incremental and total building energy requirements for a range of setpoint combinations and exposed to a summer (cooling) or winter (heating) condition. In essence, a grid was established, which represented a collection of setpoints, and annual building energy performance was determined for each grid point. The setpoints were constrained to maintain proper equipment operating conditions (e.g., temperature, mass flow). The primary objective of the simulations was to quantify the range of possible operating points and the maximum potential savings under different weathers, assuming that the control logic could direct the HVAC system to the optimal operating conditions. HVAC Equipment performance was modeled as described below.

Total building energy was determined utilizing performance characteristics of the each component: the chiller, the cooling tower, the chiller water pump and the supply air fan plus the energy input value related to lighting and other electrical equipment. The evaluation metric is:

$$E_{total} = E_{lighting} + E_{equipment} + E_{chiller} + E_{pump} + E_{fan} \quad (1)$$

where:
E_{total} = total energy power density
$E_{lighting}$ = lighting power density input
$E_{equipment}$ = Equipment power density input
$E_{chiller}$ = chiller power density input
E_{pump} = pump power density input
E_{fan} = fan power density input

The first two terms are specified as follows, according to ASHRAE Standard 90.1 IP [9]:

$E_{lighting}$ =1.0 w/ft^2
$E_{equipment}$ =1.5 w/ft^2

The system schematic is presented in Figure 2. As the diagram shows, one zone of a multiple zone Variable Air Volume (VAV) system with energy recovery ventilator was studied for this simulation analysis. For HVAC component energy consumption analysis, polynomial fits were used with representative coefficients, with the important variables being chilled water supply temperature, coil loads, chilled water flow rate, outdoor air fraction, supply airflow rate, supply air temperature and room temperature [10]. These component mathematical equation models are commonly used in similar applications. For the simulation software, Engineering Equation Solver (EES) [11] was selected because of its built–in high-accuracy thermodynamic and heat transfer parameters and capability for solving design problems in which the effects of one or more parameters must be determined. Previous research work also shows that the simplicity of the models and the use of an equation solver to run the simulation ensure good robustness and full transparency [12]. Then Equation-based simulation models were created through the EES and the equation-based simulation models use generalized solution techniques to solve arbitrarily complex sets of differential and algebraic equation, which is another one of the main advantages of this approach: the easiness of developing and maintaining model. Table I summarizes the model parameters.

To minimize the effect from the building itself on the simulation results, the zone is simplified as much as possible. The case that is used in this simulation is assumed to be an office zone has a dimension of 25ft ×30ft with a 9ft high ceiling and 12ft wall height. An overall envelop thermal transfer rate is given. The U value is assumed to be 0.064 Btu/h-ft^2-°F. The infiltration rate through the exterior walls is set at 0.1cfm/ft^2, which is based on information from [13]. This infiltration occurs 24 hours a day. The ventilation rate is assumed to be 1.5 cfm/ ft^2 which is an assumption for the most energy-intensive scenario. For the lighting and occupants heat gain are all assumed equal to 1w/ft^2, the equipment heat gain is assumed at 1.5w/ft^2. Also, the effectiveness of the energy wheel is assumed to be constant throughout the year while it is not true in real word. It should change with the outdoor temperature and humidity changes throughout the year. For this case, the effectiveness is set at 70% constantly and the effectiveness for the heat exchanger is assumed to be 75%. It is worth mentioning that the system efficiency is more important than the efficiency of individual components, when the energy performance of HVAV system is evaluated.

The zone load is defined as the sum of all kinds of loads, internal and external, sensible and latent, which are needed to be balanced from the indoor zone to keep a comfort environment. In other words, the zone load is actually the sum of heat gains transferred from outer space such as sun, occupant, equipment etc. to the zone air. As a result, there are different types of heat gains, solar, heat transmission through the walls, human, lights, ventilation and infiltration. Depending on the building characteristics, these heat gains are converted to loads after some time delay. The latent load, which is produced when moisture in the air goes from a vapor to a liquid state, is not calculated in this paper but will be discussed in the future work. In order to evaluate the objective function as defined, it is necessary to specify some parameters first (Table II).

$$Q_z = q_s + q_i + q_t + q_o + q_e + q_l \tag{2}$$

where:
q_s = solar load
q_i = infiltration air load
q_t = envelope thermal load
q_o = occupants load
q_e = equipment load
q_l = lighting load

As shown above, for this simulation, the zone load is made up of solar load, lighting load, equipment load, occupants load, infiltration air load and envelope thermal load (heat gains to zone were assumed as positive). The zone heating and cooling loads are met by supplying conditioned air to the zone such that the product of the mass flow rate of the supply air, the specific heat of air and the temperature change of the air from supply (T_s) to return (T_r) are equal to the zone thermal load:

$$q_i = m_i \cdot cp_{air} \cdot (T_z - T_a) \tag{3}$$

$$q_t = UA \cdot (T_z - T_a) \tag{4}$$

Since the heat gain from lighting, equipment occupants and solar was already set up, the load values of infiltration and envelope thermal conduct can be determined from the thermodynamic relationships as described above, the zone load can be figured out for the energy consumption simulation.

$$E_{chiller} = \frac{Q_{avail} \cdot ChillerEIRFTemp \cdot ChillerEIRFPLR}{COP_{ref}} \tag{5}$$

$$E_{pump} = v_{water} \cdot \frac{Pump_{Head}}{Total_{Efficiency}} \tag{6}$$

$$E_{fan} = f_{pl} \cdot m_{design} \cdot \frac{P_{rise}}{e_{tot} \cdot r_{air}} \tag{7}$$

where:
$Q_{avail} = Q_{ref} \times$ ChillerCapFTemp
v_{water} = mass flow rate of chilled/hot water
f_{pl} = air part load factor
m_{design} = fan design flow rate
P_{rise} = fan pressure rise
e_{tot} = fan total efficiency
ρ_{air} = density of air

In the heating situation, the fuel input was calculated with this equation [14]:

$$F_{boiler} = m_{hw} \cdot cp_{water} \cdot \left[\frac{T_{hws} - T_{hwr}}{BE \cdot VHI} \right] \cdot 3600 \quad (8)$$

where:
BE = boiler efficiency
VHI = fuel heat value
m_{hw} = hot water mass flow rate
cp_{water} = specific heat capacity of water
T_{hws} = hot water supply temper
T_{hwr} = hot water return temperature

The operating hours are assumed from 6:00 to 22:00. Fan efficiency is selected as 70% as shown in Table I. For the gas boiler energy consumption, the energy consumed in the form of natural gas is converted to electricity by the unit conversion from BTU/h to KW. The heat rate of natural gas is 1000 BTU/ft^3.

For the cooling and heating coils, cooling/heating and dehumidification/humidification of the incoming fresh air is performed here. The temperature effectiveness in a heating or cooling is governed by the effectiveness relationship. An effectiveness of 75% is assumed as presented previously in Table II. In sum, the effectiveness of all the main components are related to design and operating conditions. When the operating conditions fluctuate near design conditions, the effectiveness change is really small. To simplify analysis, effectiveness for various components is assumed to be constant as discussed in the previous part.

Fan and pump energy is an important factor in the annual energy consumption of an HVAC system. Fan (pump) performance can be characterized by its efficiency, which itself is dependent on operational air-flow rate. Mostly, rated volumetric flow rate, pressure rise and efficiency are available from the manufacturer. But for this research, these numbers are assumed as shown in Table I with reasonable values.

Last thing to notice is that HVAC components such as chiller and pumps are composed of a number of sub-components such as engine, evaporator, compressor, condenser and throttling valve, but these sub-components are not included for this study as in the energy balance equation derived for the simulation, only the inter-connections are of interest.

The setpoints were changed as described in Table III. For the summer condition simulation, five parameters, condenser entering temperature, chilled water supply temperature, chilled water mass flow rate, supply air temperature and flow rate are set as variables. Ten different values are selected for each parameter so there are 50 different scenarios in total. As only hot water supply temperature and mass flow rate, supply air temperature and flow rate were changed in the winter condition, 40 group of total power density resulted from the simulation. But here as the whole year total energy consumption is the object of study, the summer cooling and winter heating will be simulated simultaneously with a condition judgment statement coded in EES. To simply simulation, the heating/cooling is assumed to be enabled immediately when the outdoor air temperature below/above corresponding setpoint temperature. For this simulation, when the outdoor air temperature is greater than 80 °F, the cooling will be on and when the outdoor air temperature is less than 55°F, the heating will be simulated.

IV. RESULTS

The simulation figure depicts the one whole year total power density as a function of different setpoint settings. The total power density consumed in each city is shown in figures below. Each city stands for a typical weather conditions.

Figures 3, 4, 5, and 6 illustrate the annual power density for four different weather cases from highest to the lowest for the year around. The different colors present the breakdown of the electricity usage. As we can see, HVAC system (including chiller, cooling tower pump, chiller water pump and supply air fan) is the biggest electric consumer in the model, which accounts for around 60% of total energy consumption, while both lighting and equipment account for around 15% of the total power consumption, respectively. According to Table IV, the maximum annual power density can reach 36.121kwh/sf-year at Miami when the chilled/hot water flow rate at the biggest value and a small supply air flow rate can decrease the energy consumption to 26.712kwh/sf-year at state college. Please note the annual power density is high compared to typical office buildings' numbers due to the high ventilation air flow rate setting in the simulation. The simulation is operated in this way to reflect the possible situation using the most energy.

Figure 7 is the simulated building energy usage breakdown in the four weather conditions. The percentage of the total power that is required by HVAC system to ventilate and condition (fans, pumps, chillers and boilers) is 67% in Minneapolis, 71% in Miami, 68% in Phoenix and 63% in state college. Among the HVAC system energy consumption itself, chiller and boiler is the largest power consumer while the pump consumes the least energy.

To sum up, the energy performance of this particular building/HVAC system combination was evaluated for typical scenarios in order to illustrate the methodology and the energy saving potential of dynamic setpoint manipulation. While the magnitude of the potential energy savings would be expected to vary for different buildings and locations, the methodology would still be applicable and useful provided the proper information was available to accurately model the HVAC system and its components. The methodology could also be used to evaluate the effectiveness of advanced control strategies by comparing

TABLE III. CASE DESCRIPTION FOR THE TWO CONDITIONS

Cases(summer)	Simulation Description
1 (10 numbers)	Increase condenser entering temperature (50-60 °F)
2 (10 numbers)	Increase chilled water flow rate (0.4-0.7 lbm/s)
3 (10 numbers)	Increase chilled water supply temperature (45-55 °F)
4 (10 numbers)	Increase supply air flow rate (500-700 cfm)
5 (10 numbers)	Increase supply air temperature (60-65 °F)

Cases(winter)	Simulation Description
1 (10 numbers)	Increase hot water supply temperature (185-195 °F)
2 (10 numbers)	Increase hot water supply flow rate (0.4-0.7 lbm/s)
3 (10 numbers)	Increase supply air flow rate (500-700 cfm)
4 (10 numbers)	Increase supply air temperature (85-95 °F)

TABLE IV. COMPARISON OF POWER DENSITY IN DIFFERENT SCENARIOS

City	Annual Power Density maximum (Kwh/sf-year)	Annual Power Density minimum (Kwh/sf-year)	Potential Energy Saving (Kwh/sf-year)	Saving Percentage
Minneapolis	34.689	31.723	2.966	8.55%
Phoenix	33.423	31.645	1.778	5.32%
Miami	36.121	35.340	0.781	2.16%
State College	28.644	26.712	1.932	6.75%

TABLE V. RESULT STATISTICAL ANALYSIS

City	Mean Value of Annual Power Density	Standard deviation of Annual Power Density minimum
Minneapolis	32.65	0.45
Phoenix	32.37	0.29
Miami	35.61	0.11
State College	27.63	0.34

TABLE VI. SENSITIVITY ANALYSIS RESULTS FOR: (A) MILD, (B) COOL AND DRY, (C) HOT AND DRY AND (D) HOT AND HUMID WEATHER CONDITION

Parameters	SC(A)	SC(B)	SC(C)	SC(D)
Supply air flow rate	0.51	0.47	0.54	0.38
Chilled/hot water supply flow	0.49	0.51	0.68	0.26
Supply air temperature	0.011	0.73	0.89	0.41
Condenser entering temperature	0.0037	0.012	0.015	0.13
Chilled/hot water supply temperature	0.0021	0.045	0.0092	0.084

the energy savings predicted or realized by those methods to the maximum potential savings identified using the approach described here.

To gain a deeper understanding of the simulation results, statistical analysis was carried out showing the cumulative percent of the total data population described at each yearly energy density value, working from smallest to largest. The distribution of the data is close to a normal cumulative distribution, which agrees with previous assumption that most total energy consumption for buildings has a normal distribution. It can be seen that the considered cases show a significant energy usage difference between the best and worst cases. Thus, there should be a significant savings potential, which can be potentially achieved by adjusting the HVAC system setpoints.

Another thing should be noticed is that the standard deviation and mean numbers for these four conditions as presented in Table V. The mean number stands for the average energy usage during a whole year. So, based on the results, Miami (hot and humid weather) has the largest average power density while state college (mild weather) has the smallest one. Perhaps the difference on the running time of chillers may contribute to such an outcome.

In statistics and probability theory, the standard deviation shows how much variation or dispersion from the average exists. A low standard deviation indicates that the data points tend to be very close to the mean; a high standard deviation indicates that the data points are spread out over a large range of values. So for here, a larger standard deviation means the energy usage is relatively unstable when changing the setpoints, but at the same time it also indicates a larger saving potential. Minneapolis has the biggest standard deviation which is consistent with the results in Table IV. And Miami has a relatively stable data so it is likely in the hot and humid weather condition, changing system setpoints will not bring a significant fluctuation in the energy usage per to this study.

To evaluate the effects of these key parameters on the energy performance in different climate conditions, sensitivity analysis was generated. Sensitivity Analysis (SA) is defined as the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input [15], which provides a good opportunity of giving a hierarchical rating to a large number of energy model inputs based on their relative importance to building energy consumption.

When mentioned the method of sensitivity analysis, [16] documents three SA Techniques: Differential Sensitivity Analysis (DSA), Monte Carlo Analysis (MCA) and Stochastic Sensitivity Analysis (SSA), the DSA is most commonly used due to its simplicity and easy-to-understand. For this research, the DSA method is picked to assess the relative influences of selected inputs on the energy consumption.

The sensitivity coefficient presented below is defined as the percentage change of the output divided by the percentage change of the input. Figure 1 provides a more vivid picture of the proposed procedure.

Figure 1. Total Power Density for Winter Condition

The equations used for the sensitivity analysis are shown as below:

$$SensitivityCoeffecient(SC) = \left|\frac{\Delta O}{\Delta I}\right| \quad (9)$$

where:

$$\Delta O = \frac{O_{pert} - O_{base}}{O_{base}} \quad (10)$$

$$\Delta I = \frac{I_{pert} - I_{base}}{I_{base} - I_{\min}} \quad (11)$$

These two terms are the changes of the ouput and input relative to the base model and input, respectively. O_{base} and I_{base} are the base model output and input, respectively. O_{pert}, I_{pert} and I_{min} are the perturbed model output, input and potential minimum value of input, respectively.

In this paper, the interested simulation outputs include whole building annual electricity (lighting, etc.) and boiler gas energy uses, as well as the chiller, the pump and the fan energy uses. And these outputs are connected to certain input parameters. So, to sum up here, for both the cooling and heating conditions, there are five interested input variables, they are condenser entering temperature, chilled/hot water supply temperature, chilled/hot water supply flow rate, supply air flow rate and supply air temperature. Then, the range of each parameter was determined according to the actual building operation situation. But here the range is set as shown in Table III. Perturb one parameter at a time while keeping other parameters constant, the sensitivity coefficient can be calculated based on the simulated output.

So, based on the sensitivity-analysis method described in previous, and pre the simulation results for these four different climates, the sensitivity coefficient (SC) that determined by their relative importance to the annual whole building energy use for the four different climates is demonstrated as in Table VI.

According to the data shown in the previous page, with regards to the mild weather, the supply air flow rate has the largest sensitivity coefficient, which means minimizing the supply air flow rate is shown to be the most effective measure to save the energy usage. On the opposite, chilled/hot water temperature has the smallest value, which indicates the variation on the chilled/hot water temperature settings will have the least influence on the power consumption. While for the rest three outdoor conditions, the supply air setpoint temperature is in the driving position.

V. CONCLUSIONS AND FUTURE WORK

A methodology was developed and demonstrated for determining the impact of HVAC control system setpoints on the total building energy requirements for a typical combination of HVAC system in four different outdoor environment situations in order to quantify the maximum potential energy savings due to dynamic setpoint adjustment. The analysis reveals that a large potential of energy reduction exists in the building. Whole building energy saving from fine tuning HVAC system can be significant in certain condition. According to the simulation result, the energy saving potential through possible optimum control is substantial and more noticeable in winter season. The potential saving can be as high as 8.55% and as low as 2.16% for cold and dry climate and hot and humid climate, respectively, when comparing the best performance with the worst one. Sensitivity analysis shows different control system setpoints provide different degree of energy savings. Minimizing the supply air flow rate is shown to be the most effective measure to save electricity usage in mild weather, while a too high or too low supply air temperature may lead to overwhelm other settings effects on power consumption in other three weather conditions. The results suggest that control strategies that are capable of dynamically adjusting setpoints in response to environmental and occupant conditions can potentially save a substantial amount of energy as compared to fixed setpoints.

What's more, the use of the engineering equation solver computer program to perform simulations on a conditioned zone with various collections of setpoints in four different cities which stand for four different outdoor environments further proofs of the possibility and usability of equation-based simulation methods.

However, there are still some investigations needed. For the future work, the following recommendations are made for future work:

- The number of setpoints studied is limited and the more detailed model could be studied.
- Latent load should be considered in the future work.
- The results should be conducted with cross comparison with other software output.
- More comprehensive climate regions should be further extended and investigated.
- Sensitivity analysis might consider the simultaneous variation of parameters and interaction term.
- The energy recovery system efficiency could include the effects from outdoor air temperature and humidity. Perform an energy consumption simulation with variable effectiveness values of energy recovery system to see the effect of changing effectiveness due to outdoor temperature and humidity on the result.

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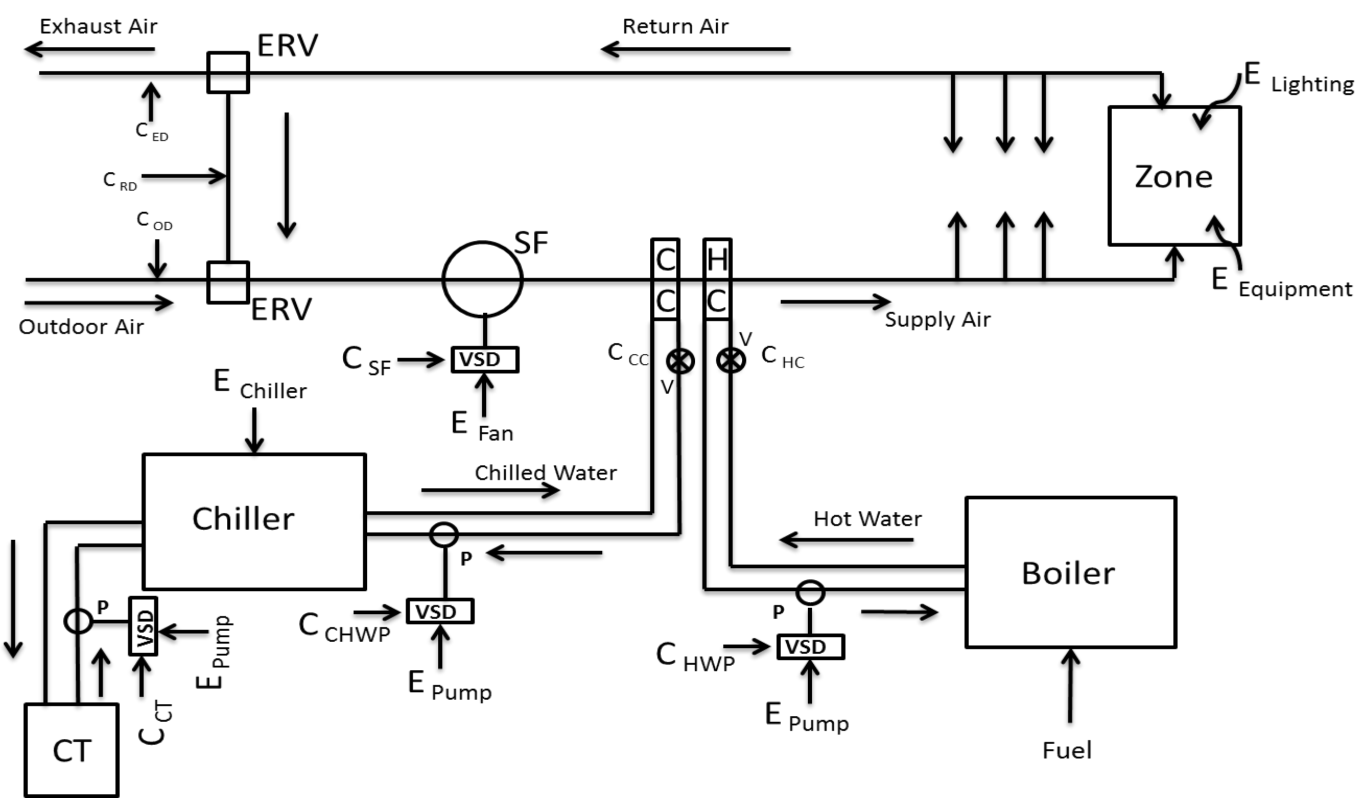

Nomenclature

ERV	Energy Recovery Ventilator
SF	Supply Fan
CC	Cooling Coil
HC	Heating Coil
VSD	Varied Speed Driver
P	Pump
V	Valve

Control Point Lists

C_{ED}	Exhaust Air Damper
C_{RD}	Return Air Damper
C_{OA}	Outdoor Air Damper
C_{SF}	Supply Fan Driver
C_{CC}	Cooling Coil Valve
C_{HC}	Heating Coil Valve
C_{CT}	Cooling Tower Pump
C_{CHWP}	Chilled Water Pump
C_{HWP}	Hot Water Pump

Figure 2. System Schematic

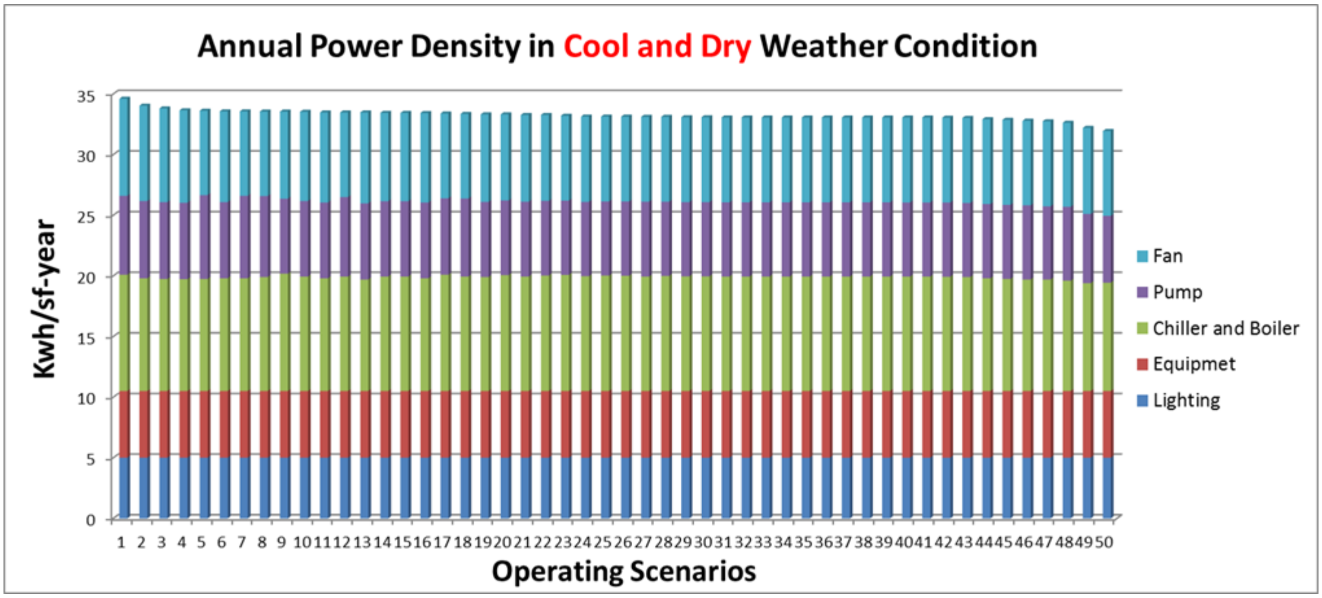

Figure 3. Annual Power Density in Minneapolis

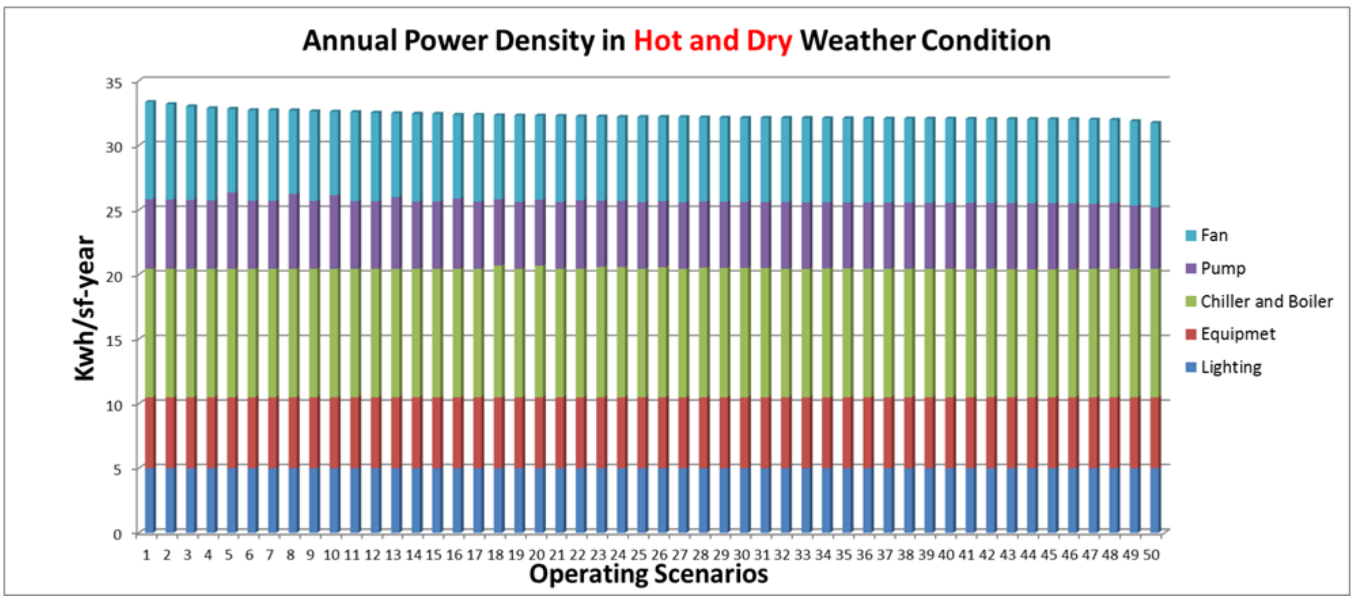

Figure 4. Annual Power Density in Phoenix

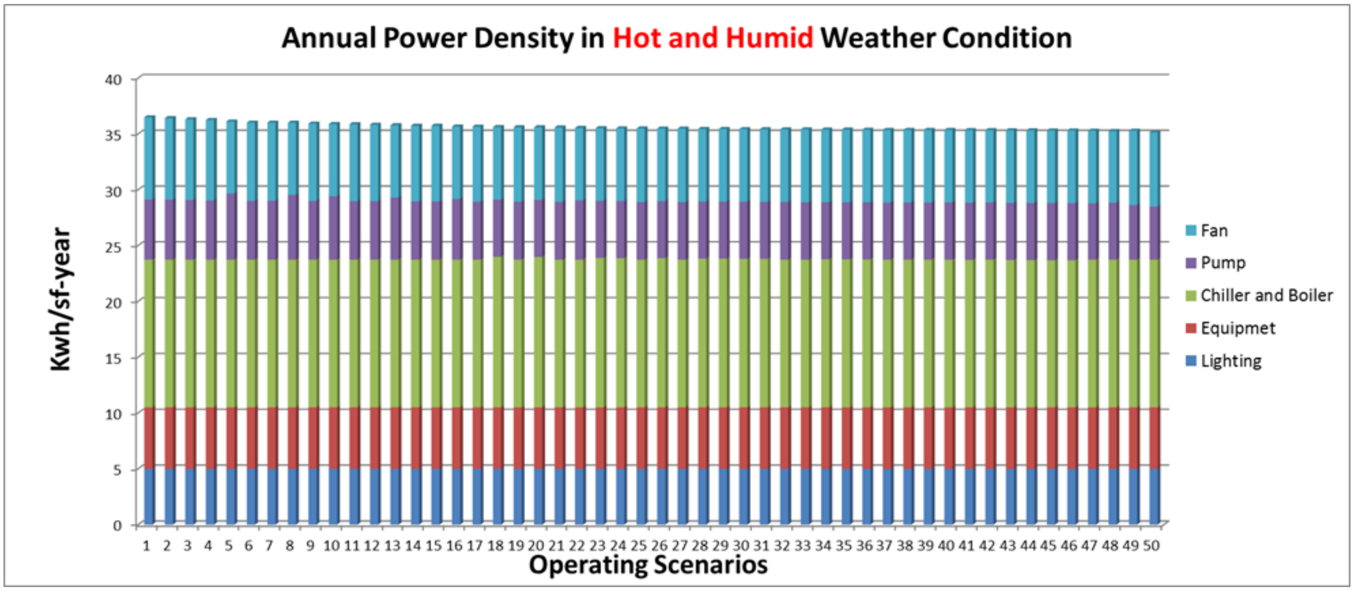

Figure 5. Annual Power Density in Miami

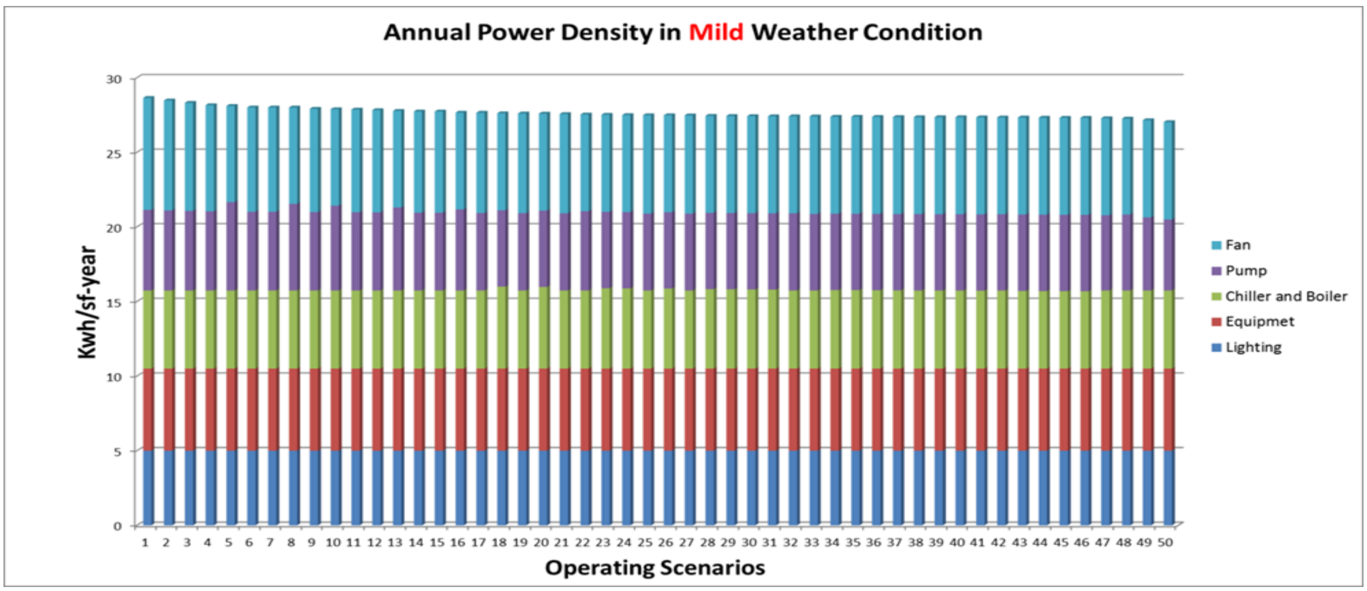

Figure 6. Annual Power Density in State College

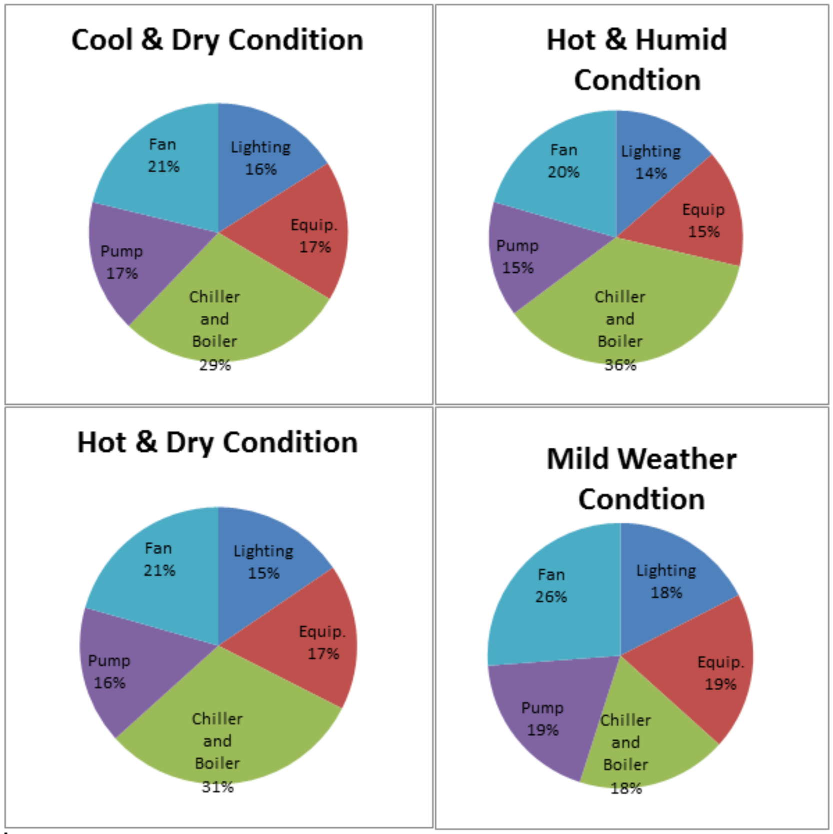

Figure 7. Breakdown of Power Use