Short-Term Reduction of Peak Loads in Commercial Buildings in a Hot and Dry Climate

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2012 by the
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May 2012

ABSTRACT

A major problem faced by electric utilities is the need to meet electric loads during certain times of peak demand. One of the widely adopted and promising programs is demand response (DR) where building owners are encouraged, by way of financial incentives, to reduce their electric loads during a few hours of the day when the electric utility is likely to encounter peak loads. In this thesis, we investigate the effect of various DR measures and their resulting indoor occupant comfort implications, on two prototype commercial buildings in the hot and dry climate of Phoenix, AZ. The focus of this study is commercial buildings during peak hours and peak days. Two types of office buildings are modeled using a detailed building energy simulation program (EnergyPlus V6.0.0): medium size office building (53,600 sq. ft.) and large size office building (498,600 sq. ft.). The two prototype buildings selected are those advocated by the Department of Energy and adopted by ASHRAE in the framework of ongoing work on ASHRAE standard 90.1 which reflect 80% of the commercial buildings in the US. After due diligence, the peak time window is selected to be 12:00-18:00 PM (6 hour window). The days when utility companies require demand reduction mostly fall during hot summer days. Therefore, two days, the summer high-peak (15th July) and the mid-peak (29th June) days are selected to perform our investigations.

The impact of building thermal mass as well as several other measures such as reducing lighting levels, increasing thermostat set points, adjusting supply air temperature, resetting chilled water temperature are studied using the EnergyPlus building energy simulation program. Subsequently the simulation results are summarized in tabular form so as to provide practical guidance and recommendations of which DR measures are appropriate for different levels of DR reductions and the associated percentage values of people dissatisfied (PPD). This type of tabular recommendations is of direct usefulness to the building owners and operators contemplating DR response. The methodology can be extended to other building types and climates as needed.

To my parents and my family!

ACKNOWLEDGMENTS

I would like to take this opportunity to thank all the people who helped me throughout my Master's program and my research. Firstly I want to thank my thesis Chair Prof. T. Agami Reddy for his support and guidance in my research. He has greatly inspired my research by his constructive inputs. I wish to thank my thesis committee members Prof. Harvey Bryan and Prof. Marlin Addison for all their encouragement and support. Thanks to James Erickson for helping me with my questions on EnergyPlus.

I am very grateful to my family and friends for their encouragement and support. Special thanks to my husband Sameer Kibey and my mom and dad, without their support this dream was impossible to achieve. Their love, blessings and support has been constant source of motivation in my pursuit for graduate studies.

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ACRONYMS

ALL	All strategies combined without limiting mass flow rate
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CWTR	Chilled Water Temperature Reset
DOE	Department of Energy
DR	Demand-Response
DX	Direct Expansion
FSEC	Florida Solar Energy Center
HVAC	Heating, Ventilating and Air Conditioning
LBNL	Lawrence Berkeley National Laboratory
LMFR	Limiting Mass Flow Rate
LPD	Lighting Power Density
LPDR	Lighting Power Density Reduction
O&M	Operation and Maintenance
PNNL	Pacific Northwest National Laboratory
SATA	Supply Air Temperature Adjustment
TMY	Typical Meteorological Year
TSS	Thermostat Set-point Setback
VAV	Variable Air Volume

Chapter 1

INTRODUCTION

1.1. Problem Statement

Electric utilities are being increasingly challenged to meet peak loads during summer due to consistent load growth over the years at one end and high cost of installing additional generation power plants on the other. Therefore being able to reduce peak loads which occur for only a few hours during the year is critically important. It must be pointed out that this problem, though similar in some ways, is quite distinct from the other issue of high energy use. Typically energy providers offer incentives to customers to shift their usage to non-peak hours to reduce the peak loads on the grid. In this study, we shall evaluate an alternate strategy of notifying the customers when grid usage is likely to reach its maximum capacity so that customers can voluntarily reduce their consumption. Poor operation and maintenance (O&M) of buildings can result in 10 to 30 percent excess energy use (PNNL, 2011). It is important to work with building owners and operators to improve operation and maintenance practices. This will lead to increased energy efficiency, lower energy costs, longer equipment life, and enhanced occupant satisfaction.

During peak load hours, the ability of the electric utility to meet these peaks is severely compromised resulting in higher costs to most of the demand and/or costly expansion of generation plants. Therefore electric utility providers are extremely interested in reducing the peak electric energy requirement of individual large buildings during peak load hours. On the other hand peak load reduction targets ways to reduce energy use in buildings (which account for about 40% of the nation's energy use (PNNL, 2011)) by drastically improving the energy efficiency of buildings and reducing their environmental footprint.

1.2. Demand Response

Demand response (DR) is the process of managing customer consumption of electricity over a few hours in response to limited power availability so as to improve electrical system reliability and to reduce electricity supply cost (Chen, 2008).

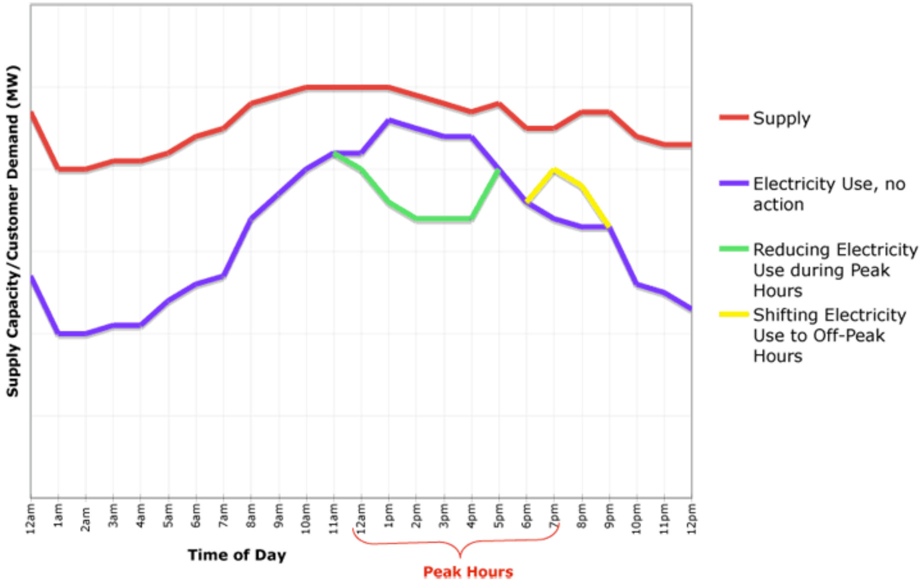

Figure 1.1 Electricity consumption and DR strategies

In demand-*response*, consumers are encouraged to reduce peak electric demand by utilizing demand shifting, shedding or both (Motegi et al. 2007). In demand-*shifting*, shift in demand profile is achieved by consuming electricity at an off-peak time (e.g. shifting the energy usage time from peak afternoon to night time during summer months) to benefit from the time-of-use rates. This can be achieved by precooling i.e. by building thermal mass or thermal energy storage such as ice storage. In demand-shedding, temporary reduction of peak electric demand is necessary to achieve economic savings.

Chapter 2

OBJECTIVE AND SCOPE

In this study we will focus on the peak load energy production issue and identify and evaluate strategies to reduce peak load in commercial buildings during the peak hours in hot and dry climatic conditions like Arizona. We will also study the impact of building thermal mass on demand savings in commercial buildings. The purpose of this research is to identify peak hour energy reduction recommendations on demand-response for different building prototypes. Finally the results will be summarized in tabular form for various simulation scenarios to give practical guidance to building managers and owners.

The focus of this study will be commercial buildings during peak hours. Two types of buildings have been selected and will be modeled using a widely used research tool called EnergyPlus. EnergyPlus is a whole building energy simulation program which is used by architects and engineers to model energy and water use in buildings. It is also used to optimize the building design to use less energy and water (U.S. Department of Energy, 2011). Utility companies often implement DR programs by providing short-term notification (say 3-4 hours) when critical peak periods occur. The strategies used in this thesis will address this requirement from the utility companies. Therefore strategies that are useful for curtailing demand in response to short term notification will be identified and investigated

Expected outcomes from the study:

i. Simulation results will be distilled into a form (tabular) at different reduction levels which building managers and owners could adopt for practical implementation.

ii. We shall define general recommendations on demand-response for different building prototypes.

iii. The study should help the consumers to reduce their utility cost at on-peak hours.

iv. Also these strategies will help energy providers to produce more electricity at increased efficiencies and avoid costly expansion of plants.

Chapter 3

LITERATURE REVIEW AND SUMMARY

3.1. Brief Review

Several studies have tried to address the potential impact of demand-response management systems to resolve peak demand electricity consumption. Many strategies have been proposed to reduce the peak hour by demand on the utility grids. The literature review identified several specific categories of curtailing loads. Of all these categories, literature related to operation and maintenance strategies was of main interest such as, reducing lighting, equipment or HVAC energy.

Yin et al. (2010) at Lawrence and Berkeley National Laboratory, studied the potential impact of building size, thermal mass, climate and DR strategies on demand savings in commercial buildings. They used a precooling strategy to study the impact of building thermal mass and size. The impact of three types of control strategies: linear, step and exponential temperature reset, on the peak demand reduction in a prototypical commercial building was analyzed. Thermal comfort analysis was done to determine the effects of these strategies on the occupancy comfort levels. This research involved buildings with low, medium and high thermal mass. They also studied demand shifting strategy; however they did not investigate any load reduction strategies (Yin et al., 2010).

In a different study by Gu et al. (2011) at Florida Solar Energy Center (FSEC), the impact of most commonly used demand-response control strategies on peak electricity reduction is studied. Their study included small, medium and large size office and retail buildings. Five geographical regions were chosen to study climate specific variations in the results. The effect of several control strategies is studied on different prototype days in one year. The prototype days selected were Summer Peak, Summer Mild, Summer Low, Fall Cool High, Winter Peak, Winter Mild, Winter Low, and Fall Heat High.

Reddy et al. (2004) describe the benefits of multi-building load aggregation and load curtailment measures. The load curtailment measures selected in their study are load reduction measures and not load shifting measures. They studied the lighting and equipment electric density levels reduction, changing the thermostat and cold deck settings and changing the ventilation rates during the occupied hours.

Armstrong et al. (2006) focused mainly on building specific thermal response and estimation of the seasonal benefits of several peak-shifting and night-cooling strategies in the office building.

Newsham et al. (2006) have studied the effects of temperature and lighting ramp downs on the occupants comfort levels. They mention that rapid lighting intensity reductions of up to 20% can remain undetected by occupants. Furthermore, they explain that a slower rate of reduction may enable a higher percentage of reduction.

3.2. General DR strategies

Considerable work has been done by several researchers related to broad demand-response market studies dealing with DR programs. Following are the several broad categories identified:

i. Building automated or manual demand-response: fully automated, semi-manual or manual strategies for reducing building electric demand.
ii. Building mass: strategies based on building thermal mass effect for electric demand reduction.
iii. Reduced lighting levels.
iv. HVAC control strategies.
v. Time-of-use and critical peak pricing structures.
vi. Real time pricing structures.
vii. Intelligent control systems.
viii. Envelope heat transfer: These are methods of reduction in envelope heat transfer through mist spray system or roof cover.
ix. On-site electricity generation.

3.3. Strategies involving Lighting and equipment

The literature review identified several lighting and equipment strategies as follows:

i. Reduction of overhead lighting :Lighting power density reduction
ii. Luminaire/lamp switching

iii. Zone switching
iv. Stepped dimming and continuous dimming
v. Reduction of anti-sweat heaters (supermarket)
vi. Elimination of non-critical equipment
vii. Partial shutdown of critical equipment
viii. Use of backup generators
ix. Use of economizers (in suitable climates) for pre-cooling the building thermal mass

3.4. Strategies involving HVAC

Similarly several HVAC related peak load reduction strategies were identified as follows:

i. Zone/loop set-point reduction
ii. Direct control of fans
iii. Resetting of coil control valves
iv. Global temperature adjustment
v. Passive thermal mass storage
vi. Duct static pressure decrease
vii. Fan variable frequency drive limit
viii. Supply air temperature increase
ix. Fan quantity reduction
x. Cooling valve limit
xi. Chilled water temperature increase

xii. Chiller demand limit

xiii. Chiller quantity reduction

xiv. Rebound avoidance strategies

Chapter 4

METHODOLOGY

4.1. Specifications

Specifications used in this study are based on building type, size, construction type, climate zone, prototype days, system types and peak period selection.

4.1.1. Part 1: Comparison with previous work

The first part of this work is to verify that our EnergyPlus simulation results are consistent with those of other researchers. Such an evaluation is important to lend credibility to the results reported in this thesis. The verification is done by simulating a previously simulated building in a similar research conducted by Florida Solar Energy Center (Gu et al., 2011). The results obtained by our EnergyPlus simulations are then compared with the FSEC results to confirm that we are using the simulation model correctly and using the proper input specifications. This also allowed calibration of the model in EnergyPlus software.

a. For this exercise, the same building specifications as FSEC, i.e. DOE (Department of Energy) reference (Commercial Reference Building Models which complies with ASHRAE Standard 90.1-2004) was selected to run scenario based simulations. A medium size office building with area of 4,982 m^2 and a large size office building with area of 46,320 m^2 were selected.

b. Climate Zone: Phoenix, Arizona (hot and dry). The latest set of TMY3 weather data (DOE, 2011) was used to simulate weather conditions for the chosen location.

c. The prototype days selected by FSEC are listed in the table below.

Table 4.1

Prototype Days selected by FSEC

Prototype Days	High-Peak Summer day	Mid-Peak Summer day
Medium Office building	24th July	18th July
Large Office building	24th July	26th June

d. Peak period: The FSEC study selected cooling peak period to be a 3-hour window between 14:00 PM and 17:00 PM.

e. Simulation software used for this analysis is EnergyPlusV6-0-0. The results of the simulations are discussed in Section 5.

4.1.2. Part 2: Analysis for ASHRAE prototype buildings

In the second part of this thesis, ASHRAE Standard 90.1-2004 prototype building models developed by Pacific Northwest National Laboratory (PNNL) were selected for the simulations, because they reflect buildings covering 80% of the commercial building floor area in the U.S. for new construction. Also these are ASHRAE standard compliant models.

Climate Zone: We have concentrated on one climatic zone in detail in this study i.e. Phoenix, AZ (hot and dry climate). The latest set of weather data (i.e. TMY3) was used to simulate weather conditions for this location.

Prototype days: To reduce time required for yearly simulations, prototype days were selected to represent typical peak working days. As this study only involved AZ climatic conditions, summer peak and summer mid peak are the days when utility grid usage reaches its maximum capacity.

Table 4.2

Prototype peak days in Phoenix, AZ chosen for the study

Peak-Midpeak Date	Month	Day	Time	Load	Temp (^{o}F)	Day Type
5	6	7	17	5112	0	
6	6	1	17	5343	0	
7	6	2	17	5446	106	
21	6	2	17	5106	103	Low-Peak Day
24	6	5	17	5743	110	
27	6	1	17	5224	104	
28	6	2	17	5750	110	
29	6	3	17	5795	108	Mid-Peak Day
30	6	4	17	5986	109	
1	7	5	16	6089	111	
2	7	6	17	6040	112	
8	7	5	18	5966	110	
9	7	6	16	5984	111	
13	7	3	17	5996	108	
14	7	4	17	6140	108	
15	7	5	17	6350	112	High-Peak Day
19	7	2	18	6167	109	
4	8	4	17	5941	109	
5	8	5	17	6053	109	
24	8	3	17	6219	111	

To study demand-response strategies it is very important to take into consideration the utility peak profile and their energy production threshold. Therefore, we acquired actual load data for whole year of a large local electricity provider and then determined the peak days. Based on the utility load data 20 utility peak days were identified in a year and utility high-peak and mid-peak days in a year were chosen accordingly. Table 4.2 shows the electricity consumption for the 20 peak days[1].

As shown in Table 4.3, in this research 15th July is considered to be the high-peak day and 29th June the mid-peak day. It is also clear from the analysis that the days when utility demand reaches its peak would most likely fall into a hot summer day category. Utility peak profile and outdoor dry bulb temperature are directly proportional to each other. The relation between the two is shown in Figure 4.1.

Table 4.3

Peak days selected for this research

Prototype Days	High-Peak Summer day	Mid-Peak Summer day
Medium Office building	15th July	29th June
Large Office building	15th July	29th June

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[1] Due to confidentiality agreement, the name of the Energy Provider and the Load metric cannot be disclosed.

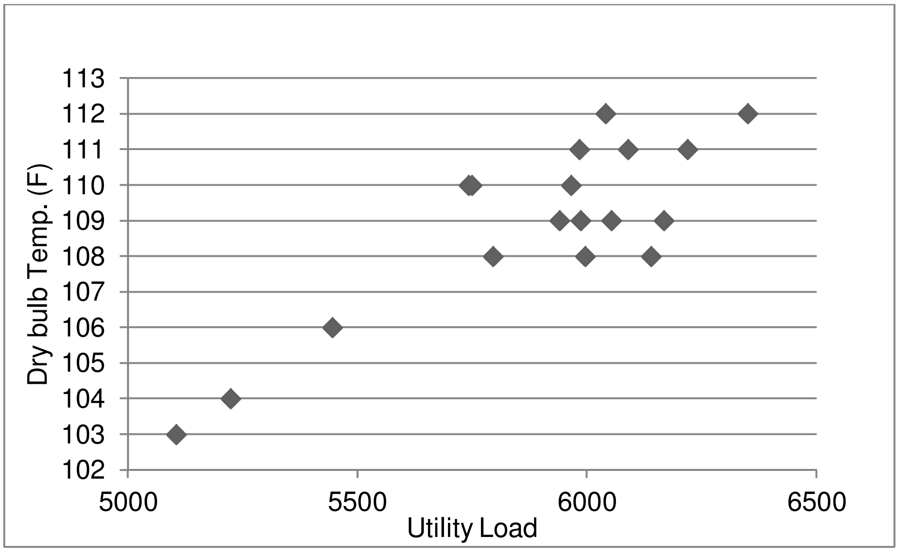

Figure 4.1 Relation between utility load and Dry Bulb temperature for a large utility in Phoenix

<u>Peak period</u>: In Arizona the peak period window in summer is defined to be a 6-hour window between 12:00 PM and 18:00 PM. This is also very clear in the daily utility load analysis as shown in Table 4.4.

<u>Building type</u>: In order to study the impact of DR strategies on different HVAC system types, medium and large office building were selected. A medium size office building with area of 53,600 sq. ft. (4,982 m^2) and a large size (46,320 m^2) office building with area of 498,600 sq. ft. were selected. The detailed description and the construction details are provided in Appendix A and Appendix B.

Table 4.4

Utility load for high-peak day in Arizona, showing the peak period window

YR	MO	Date	Day	Hour	Total Utility Load	Temp (°F)
2010	7	15	5	1	4209	99
2010	7	15	5	2	3937	98
2010	7	15	5	3	3756	96
2010	7	15	5	4	3625	95
2010	7	15	5	5	3592	95
2010	7	15	5	6	3615	94
2010	7	15	5	7	3713	95
2010	7	15	5	8	3970	98
2010	7	15	5	9	4315	101
2010	7	15	5	10	4701	102
2010	7	15	5	11	5109	104
2010	7	15	5	12	5450	105
2010	7	15	5	13	5801	107
2010	7	15	5	14	6015	109
2010	7	15	5	15	6223	111
2010	7	15	5	16	6313	112
2010	7	15	5	17	6350	112
2010	7	15	5	18	6295	112
2010	7	15	5	19	6130	111
2010	7	15	5	20	5908	110
2010	7	15	5	21	5818	106
2010	7	15	5	22	5502	103
2010	7	15	5	23	5055	103
2010	7	15	5	24	4657	102

Construction type: To study how different thermal mass in a buildings are likely to affect DR strategies, two different construction types in commercial buildings were selected. The initial selection of light weight construction is obtained from prototype building model. It consists of sheathing, fiber insulation and ½” gypsum insulation. The mass wall constructions consist of 1” stucco, 8” concrete block, fiber insulation and ½” gypsum drywall. The variation in thermal mass also included variation in slab thickness. The slab thickness selection was based on a previous ASHRAE study (Henze et al., 2007).

Following construction types are selected for this study:

i. Heavy weight construction (Mass wall)

ii. Light weight construction (Steel frame)

Table 4.5

Construction type details

Construction Type	Slab thickness	Wall type
Light weight construction	0.33 ft.	Steel frame
Heavy weight construction	0.5 ft.	Mass wall

Simulation software: EnergyPlusV6-0-0 was chosen as the software for simulations as the prototype building models were already available in EnergyPlus.

Building Occupancy: The following table 4.6 and 4.7 show the occupancy in each zone for medium and large office building.

Table 4.6

Medium office occupancy

Zone	No. of Occupants
Core	161
Zone 1	33
Zone 2	21
Zone 3	33
Zone 4	21
Total	268

Table 4.7

Large office occupancy

Zone	No. of Occupants
Core	1791
Zone 1	216
Zone 2	139
Zone 3	216
Zone 4	139
Total	2500

4.2. Modeling Methodology/Approach

To reduce the time required for the simulations, the run period is reduced from a yearlong simulation to 10 days. As only peak hour energy consumption is of interest, the simulations were restricted to nine consecutive days prior to the specific day of interest. So the simulations consist of only 10 consecutive days of simulation for all the prototype days. The data for the 10th day (last day) of the simulation was used for the final analysis. Compared to the yearly simulation this methodology drastically reduced the time required to complete the simulations. The latest weather file (TMY3) is used for all the prototype days for Phoenix, AZ. Controlled strategies will be modeled separately to determine the individual impact each strategy has on reducing building peak demand. To achieve the highest possible peak demand reduction different control strategies must be combined. Since there are many combinations it is not possible to simulate cases with all possible combinations. Therefore all the best performing strategies were modeled on top of each other (cascaded) to determine the overall combined effect. Multiple variations of that function were investigated. The savings for combinations of control strategies cannot be calculated by adding the results of the individual strategies. Therefore, the result of both combined and individual strategies were studied.

Finally thermal comfort analysis was conducted for all the control strategies. Two types of occupant comfort measures were studied:

i. Predicted Mean Vote (PMV) predicts the mean response of a larger group of people according to the ASHRAE thermal sensation scale as shown in the table below (ASHRAE Standard 55, EngineeringToolbox.com).

Table 4.8

ASHRAE Thermal Sensation Scale for PMV

+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

ii. Predicted Percentage Dissatisfied (PPD) is a quantitative measure of the thermal comfort of a group of people at a particular thermal environment.

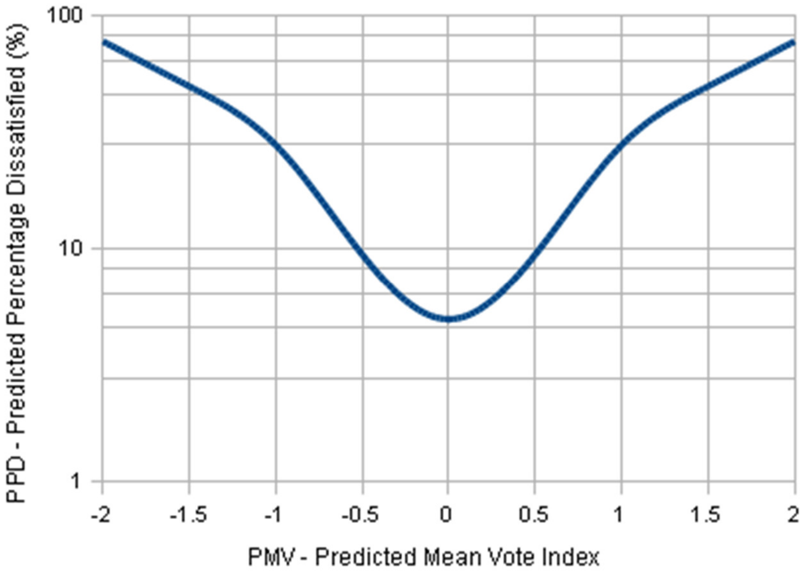

Figure 4.2 PPD to PMV relation

As PMV moves away from zero in either the positive or negative direction, PPD increases indicating that a higher percentage of people will be dissatisfied.

Chapter 5

COMPARISON WITH FSEC DATA

The first part of this thesis is validation of the results generated by simulations done in EnergyPlus. To validate results generated in EnergyPlus, buildings previously simulated in a similar research conducted by Florida Solar Energy Center are used. Medium and large size Department of Energy reference office buildings are modeled.

Table 5.1

Building specifications for validation with FSEC data

Building Type	Medium Office	Large Office
Area (m^2)	4982	46320
HVAC	VAV	VAV
Cooling Type	DX	Chilled water
Heating Type	Gas furnace	Hot water
Fan control	Variable	Variable

The comparison was done for Phoenix, AZ geographical region. The peaks are mainly observed in summer months therefore summer peak and mid-peak days are selected for study.

5.1. Medium office

Lighting power density reduction and thermostat set-point setback are the two DR strategies used for the medium office. For both the strategies, hourly stepped reduction pattern was studied for 12:00-17:00 peak hour window. In lighting power density 10% reduction (LPDR) per hour for 3 hours is observed, which gives a total of 30% reduction. This results in 5-6% energy reduction for peak hours whereas FSEC found 8-9% reduction. In thermostat set-point setback (TSS) we selected 3.3 ^{0}C (total) reductions for 3 hours in stepped pattern. It saved 18-20% energy whereas FSEC found 18-22%. Combining both the strategies gave 22.5-24% energy reduction for which FSEC found 26-28% reduction. The results are plotted in Figures 5.1 and 5.2.

Table 5.2

Percent reductions in electricity consumption for Medium office building

DR Strategies	Our Results		FSEC results	
	07/24(Peak)	07/18(Mid-Peak)	07/24(Peak)	07/18(Mid-Peak)
LPD reduction	5.0	5.5	8.5	9
Thermostat set-point setback	20.0	17.6	22	18
Combined control strategies	24.0	22.2	28	26

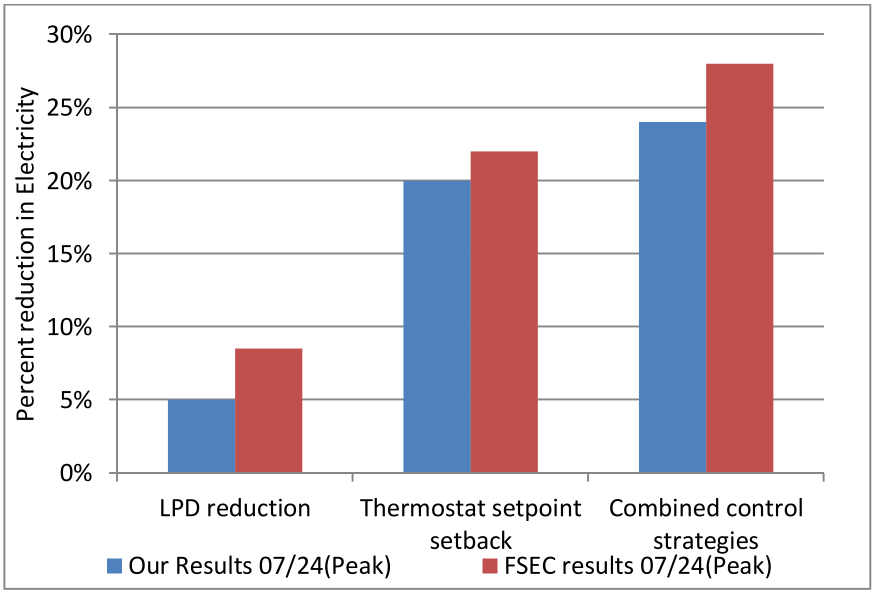

Figure 5.1 Percent reductions in electricity consumption for Medium office building: High-Peak day

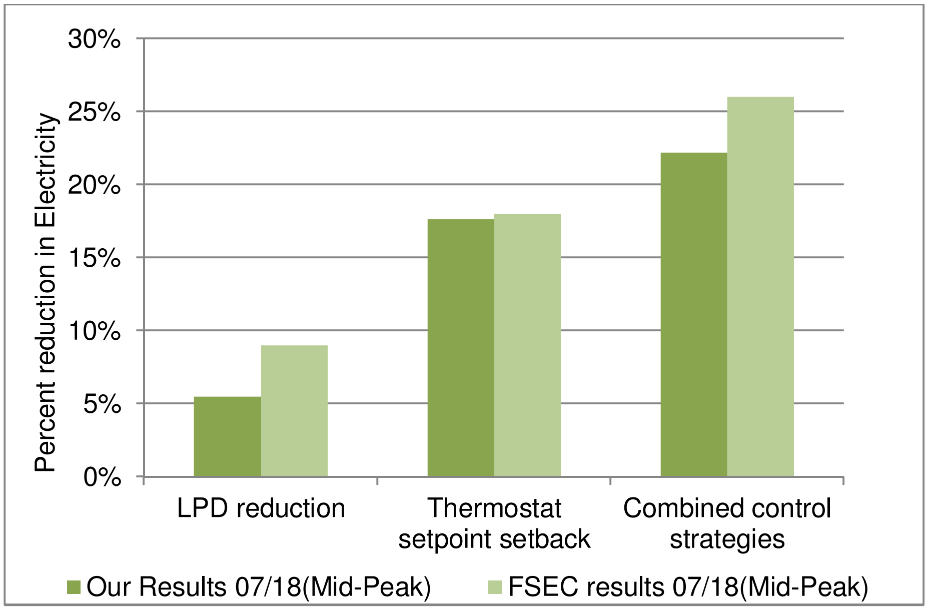

Figure 5.2 Percent reductions in electricity consumption for Medium office building: Mid-Peak day

5.2. Large Office

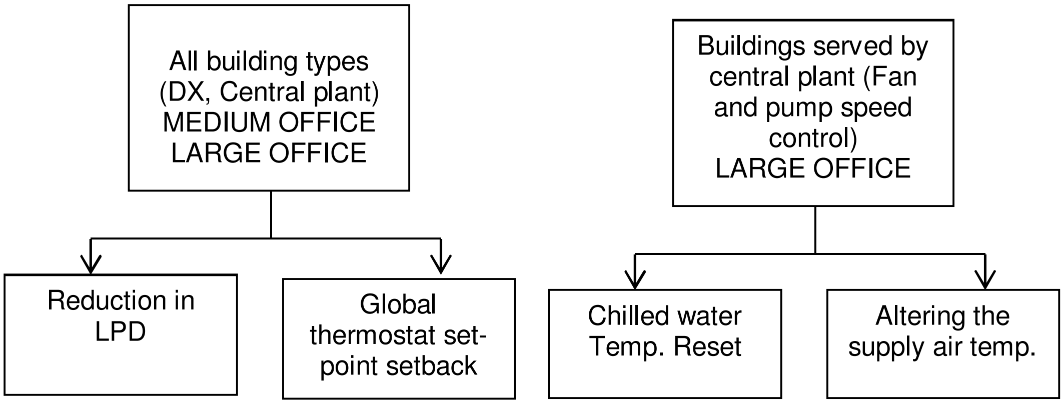

Figure 5.3 Possible strategies to consider according to the system type

The DR strategies for large office building can be quite complex and require investigation. Figure 5.3 shows the feasible DR strategies for the type of HVAC system in medium and large office building. In total, seven demand reduction strategies have been identified for large office building and will be studied further. The percentage reductions are summarized in the table 5.3 and visually in figure 5.4 and figure 5.5.

Table 5.3

Percent reductions in electricity consumption for Large office building (VAV)

Demand-Response Strategies	Our Results		FSEC results	
	07/24(Peak)	06/26(Mid-Peak)	07/24(Peak)	06/26(Mid-Peak)
LPD reduction	5.22%	5.18%	10.30%	10.50%
Thermostat Set-point Setback (TSS)	7.50%	7.00%	10.50%	9.80%
Supply Air Temperature Adjustment (SATA)	-4.87%	-4.29%	-5%	-4%
SAT adjustment+ limiting mass flow rate	5.00%	3.50%	4.50%	3%
Chilled Water temperature reset	0.84%	-0.34%	2%	1%
CWT reset+ limiting mass flow rate	10.36%	9.22%	14.00%	7.50%
Combined control strategies	20.19%	20.50%	25.00%	23.50%

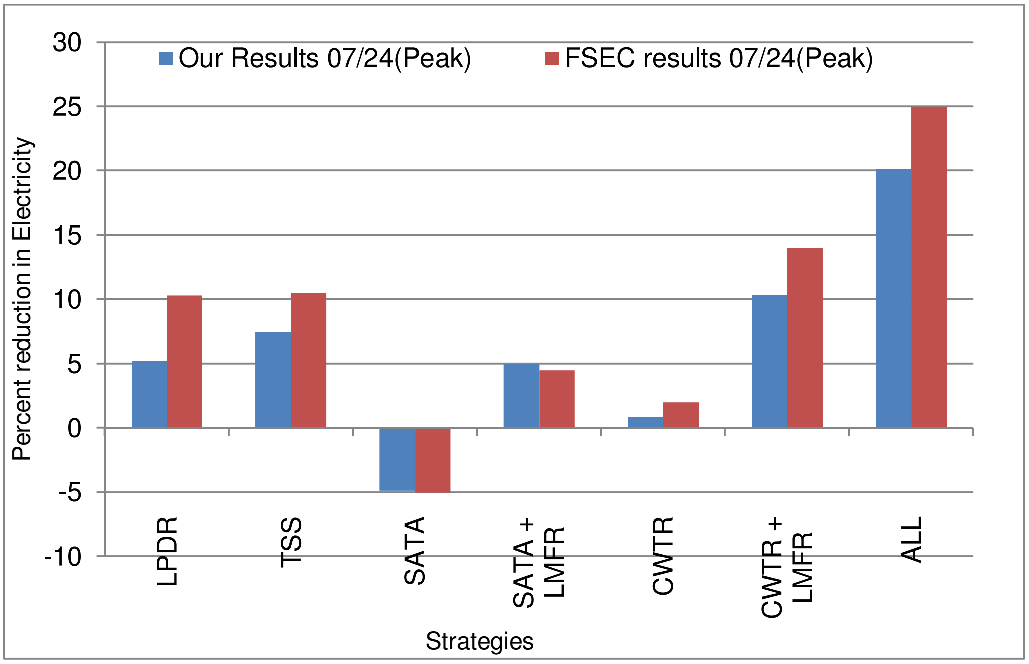

Figure 5.4 Percent reductions in electricity consumption for Large office building (VAV): High-Peak day

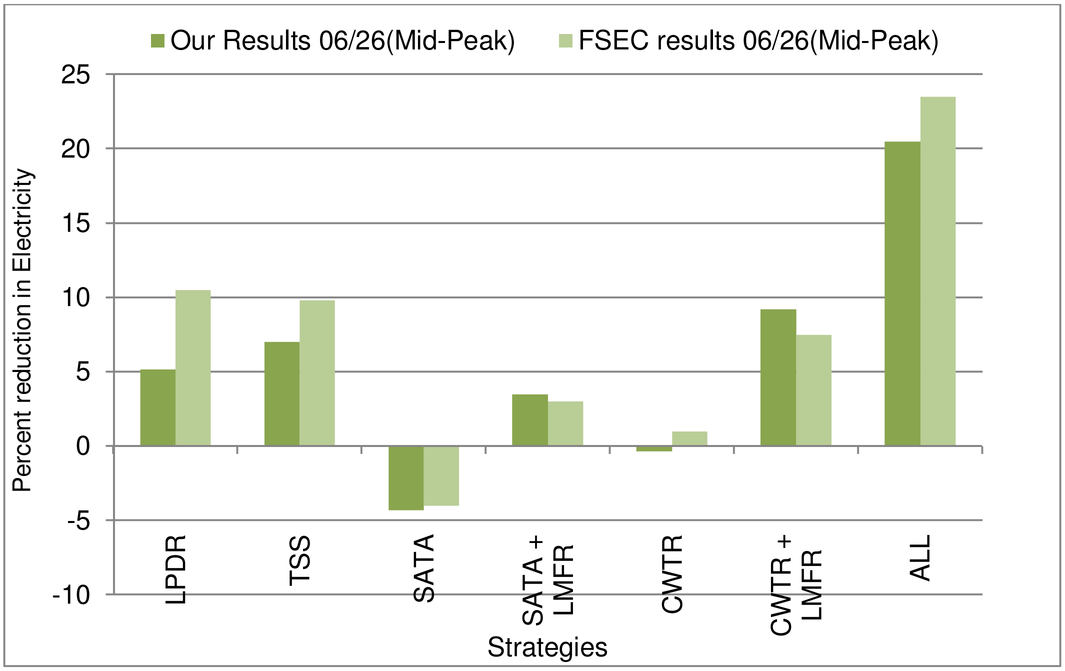

Figure 5.5 Percent reductions in electricity consumption for Large office building (VAV): Mid-Peak day

5.3. Remarks

As seen in the Figures 5.1, 5.2, 5.4 and 5.5, difference of about 2-4% are observed in some of the strategies compared to FSEC results. The potential causes for these differences are as follows:

a. For the first part of the thesis, version 1.3_5.0 of DOE reference building model was used which was updated in September 27, 2010 whereas there are three versions prior to this. FSEC study may have used a different version.

b. As stated in the FSEC's report, they revised the envelope constructions to meet the project requirements. The final construction is not specified in their final report and so could not be exactly replicated.

c. Our simulations were done for Wednesday, while FSEC may have considered a different day in their simulation (not specified in their report).

To investigate further the last possibility and to look at the effect of different working days in the same week, simulations of only the TSS strategy in medium office building was performed for all the working days over one week. As noted form table 5.4 the results were very consistent which eliminated the last possibility stated above. See Table 5.4.

Table 5.4

Medium Office building: Percent of energy savings on all the different working days in one week

	Mon	Tue	Wed	Thu	Fri
Base Design(J)	$2.69X10^9$	$2.68X10^9$	$2.68X10^9$	$2.68X10^9$	$2.68X10^9$
TSS (J)	$22X10^9$	$22X10^9$	$22X10^9$	$22X10^9$	$22X10^9$
Percent Savings (%)	19.83	19.79	19.78	19.78	19.78
Starting day	Sat	Sun	Mon	Tue	Wed

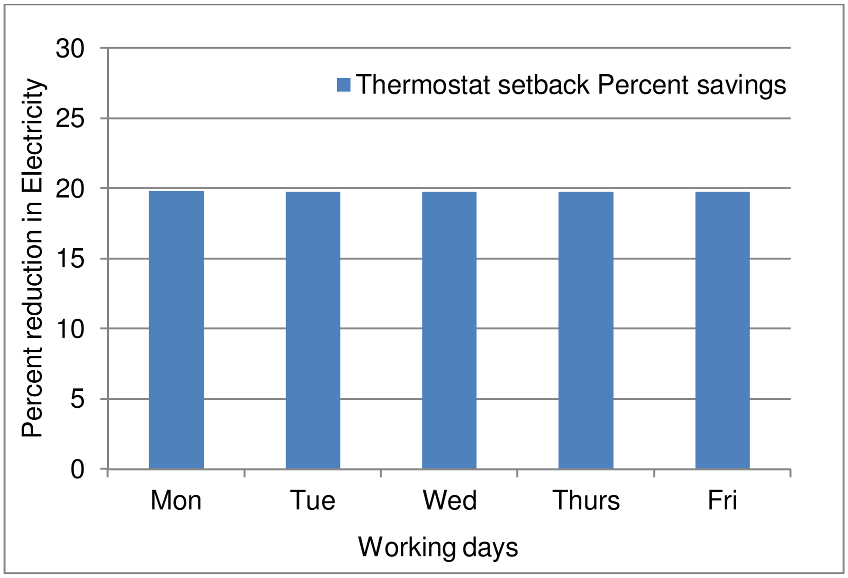

Figure 5.6 Percent of energy savings on all the different working days in one week.

5.4. Analysis

Our simulations regarding energy reduction trend are consistent as compared to the FSEC results for the DOE reference buildings. This validated (partially) our EnergyPlus simulation analysis approach, and hence the results of the second part of this thesis can be stated and analyzed with a certain amount of credibility and confidence.

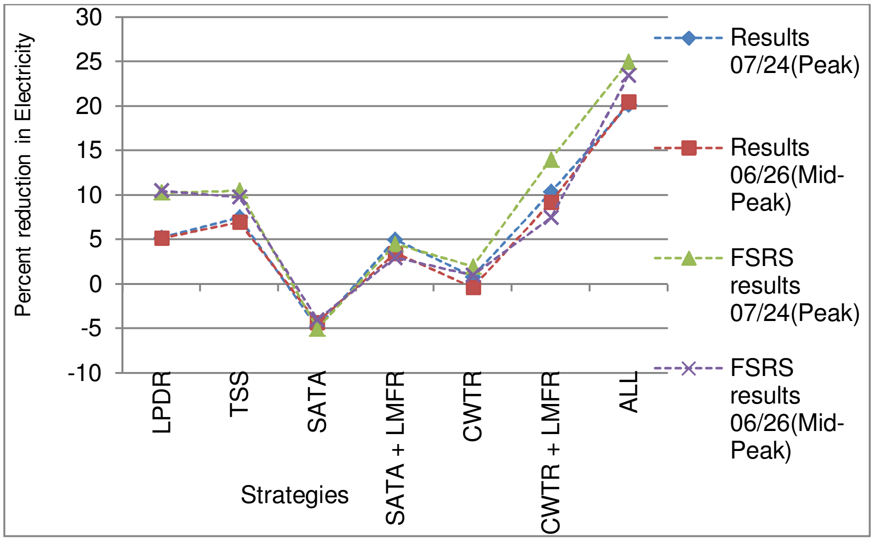

Figure 5.7 Trend in the results validating the correctness of the simulations

Chapter 6

BUILDING SIMULATION AND ANALYSIS

This section presents the DR strategies evaluated, their simulations and analysis of these results. In all the simulations, percent reduction is calculated as the ratio of difference of energy use during the intervals defined as peak demand hours between the base case and that with the DR strategy implemented.

6.1. Medium office building

6.1.1. Experiment 1: Lighting power density reduction

In this experiment LPD was reduced from 90% to 70% for the high-peak day and mid-peak day peak hour window (12:00-18:00 pm). Initially 10% reduction in lighting power (90% LPD) was evaluated. Similar experiments were run for 30% reduction in stepped pattern for 6 hours peak period window (i.e. 4.29% reduction each hour). In this study it was assumed that 30% LPD reduction would be possible without impacting occupants' productivity.

Result and Analysis:

As expected, savings increased as the LPD reduction increased from 10% to 30%. For the high-peak day, LPD of 90% provided a saving of 2% compared to the base model. Similarly an energy demand reduction of 3-4% was found with stepped 30% LPD reduction, whereas for the mid-peak day more savings i.e. 4-5% were found. It is also observed that with

LPD reduction strategy the cooling energy, fan energy and pump energy also reduced by small amount in addition to the lighting energy. This indicates that the control strategy of lighting power density is effective for peak demand reduction. Highest energy savings were achieved in summer mid peak or low-peak day and not summer high-peak day.

6.1.2. Experiment 2: Thermostat set-point setback

In this experiment, zone thermostat temperature was set back for the peak hour window. A maximum of 3.5 ^{0}C set-back temperature from the baseline thermostat temperature is investigated in stepped pattern (Gu et al, 2011). The 3.5 ^{0}C zone thermostat temperature increase is divided over 6 hour peak period window increasing only 0.5 ^{0}C per hour.

<u>Result and Analysis:</u>

On high-peak day, thermostat set-point setback strategy gave very impressive results. 23% savings were found on high-peak day and 15% on mid-peak day. This strategy gave cooling as well as fan and pump energy savings. From the results, thermostat set-point setback strategy gives very impressive savings for buildings served with variable air volume system. The best performance is reached in summer high-peak day and not mid-peak day. It is also true that thermostat set-point setback strategy will have less of an impact on buildings served by constant air volume system because they will respond to zone increased temperature by reducing the cold deck air flow rate but in turn will increase the hot deck air flow rate increasing the heating energy.

Table 6.1

Percent reductions in electricity consumption for Medium office building (light construction)

No.	Demand-Response Strategies	Results	
		07/15(high-Peak day)	06/29(Mid-Peak day)
1	LPD reduction	3.19	4.38
2	Thermostat set-point setback	22.51	14.15
3	Combined control strategies	25.26	17.85

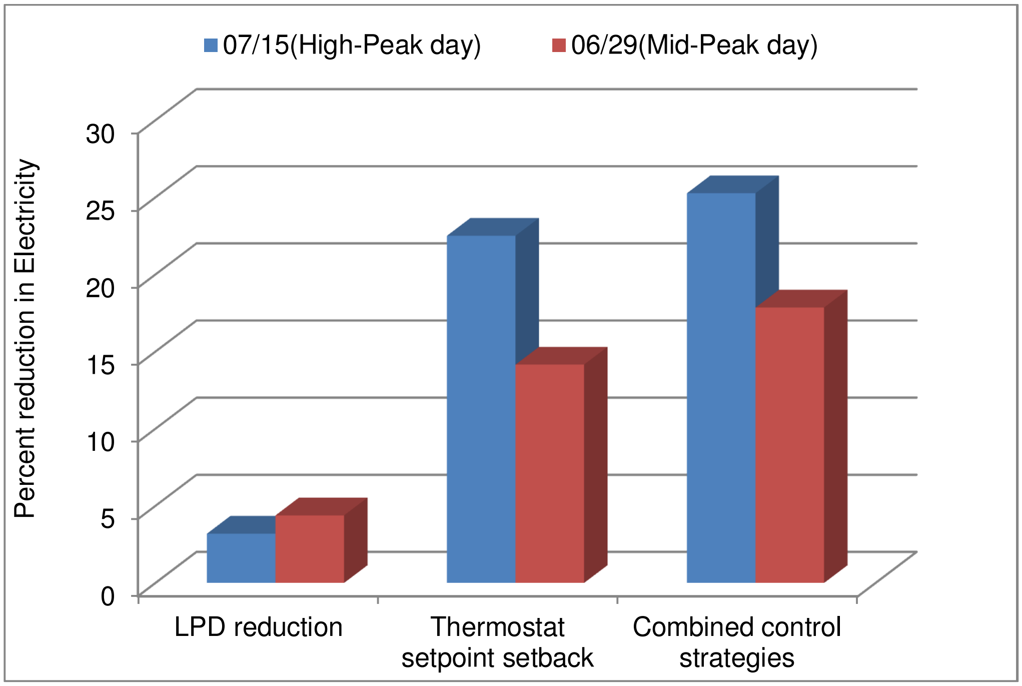

Figure 6.1 Percent reductions in electricity consumption for Medium office building: light construction

6.1.3. Experiment 3: All strategies combined

To achieve highest possible peak demand reduction it is essential to combine all the best performing control strategies and study the cascaded effect of all the individual strategies together. Therefore the combined effect of 30% LPD reduction with thermostat set-point temperature setback was evaluated.

<u>Result and Analysis:</u>

All the combined strategies together gave 26% energy savings on peak summer day whereas 18% peak demand reduction was found for mid-peak summer day. From Figure 6.1 it can be seen that the highest savings are achieved on summer high-peak day compared to summer mid-peak day.

6.2. Large office building

Control strategies for large office building were quite involved and complex and required investigation of many different demand reduction strategies compared to the relatively simpler ones for medium office building. Lighting power density reduction (LPDR), thermostat set-point setback (TSS), supply air temperature adjustment (SATA) and chilled water temperature reset (CWTR) are the base strategies which were evaluated on the large office building.

Table 6.2

Percent reductions in electricity consumption for Large office building (VAV)

No.	Demand-Response Strategies	FROM 12:00 to 18:00		FROM 13:00 to 17:00	
		07/15(Peak)	06/29(Mid-Peak)	07/15(Peak)	06/29(Mid-Peak)
1	LPDR	4.85	1.99	5.00	2.05
2	TSS	18.30	7.25	23.05	10.42
3	SATA	-8.20	-10.26	-8.53	-10.29
4	SATA + LMFR	2.34	-3.07	5.84	1.56
5	CWTR	-3.67	-5.12	0.19	-0.39
6	CWTR + LMFR	7.31	2.27	10.47	6.04
7	ALL	9.41	8.19	12.36	16.41
8	TSS + LPDR	21.96	11.24	27.21	14.83
9	TSS + SATA	16.49	7.18	21.17	12.23
10	TSS + CWTR	8.78	4.96	13.10	8.84
11	LPDR + SATA	5.79	0.48	9.87	5.95
12	LPDR + CWTR	4.85	5.96	5.00	10.22
11	SATA + TSS + LPDR	21.22	9.80	26.87	14.81
12	ALL + LMFR	25.20	18.00	28.00	26.50

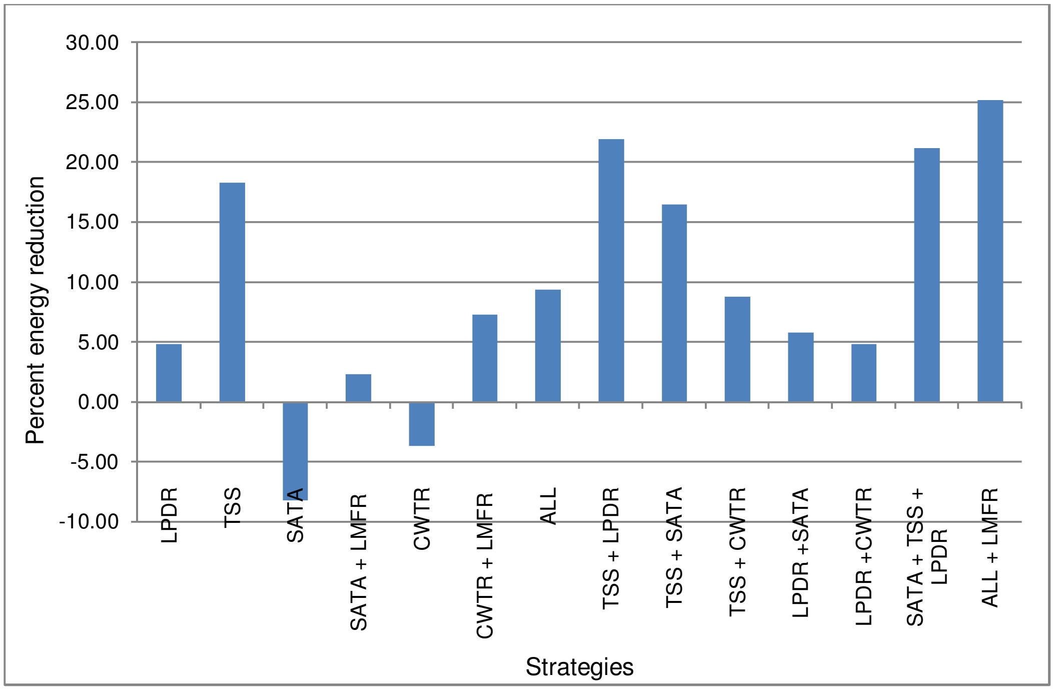

Figure 6.2 Percent reductions in electricity consumption for Large office building (VAV) on High-Peak day

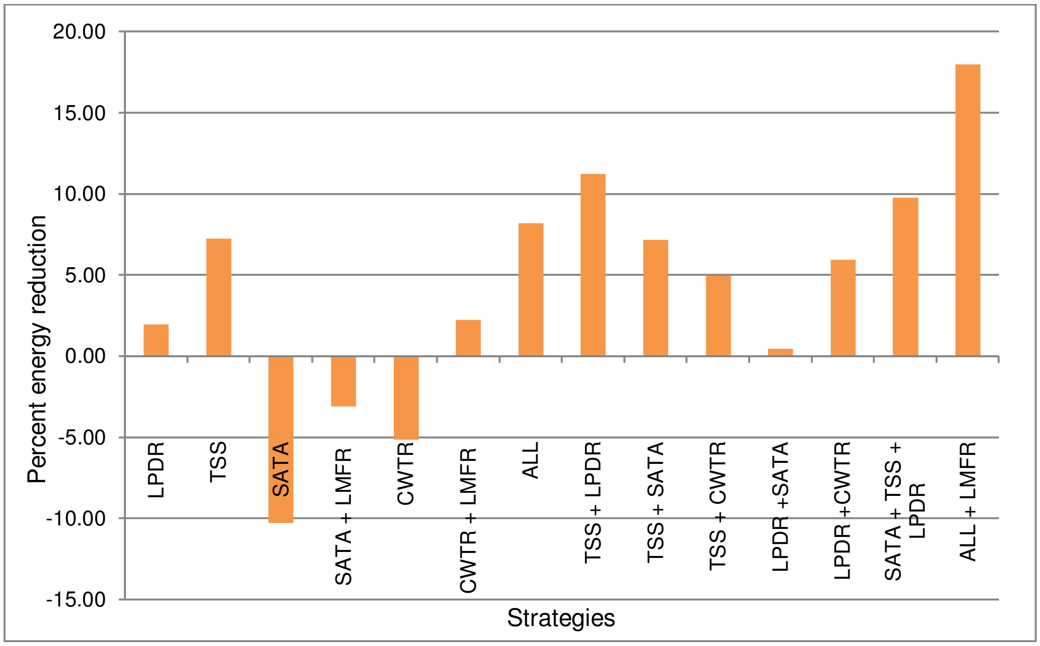

Figure 6.3 Percent reductions in electricity consumption for Large office building (VAV) on Mid-Peak day

6.2.1. Experiment 1: Lighting power density reduction

Base case simulation was done to determine a reference point for all the other simulations. Lighting power density reduction strategies from 10% to 30% were simulated. In this case LPD reduction was done from 12:00 to 17:00 PM only as the base LPD at 18:00 PM is more stringent compared to the simulation strategy.

Result and Analysis:

As expected, savings increased as the LPD reduction increased from 10% to 30%. This strategy gave 5-6% energy reduction for the summer high-peak day and 2-3% energy reduction for the summer mid-peak day. Studying the output file in detail it is observed that with LPD reduction strategy cooling energy, fan energy and pump energy also reduced by a small amount in addition to the lighting energy. Therefore Lighting power density reduction strategy gives significant results on summer high-peak and mid-peak days.

6.2.2. Experiment 2: Thermostat set-point setback

Similar to thermostat set-point setback strategy for medium office building, zone temperature was increased by 3.5 ^{0}C during 6 hours peak window from the base case temperature. This is done by an increase of 0.5^{0}F/hour on base case thermostat temperature over 6 hours in a stepped pattern.

Result and Analysis:

Very impressive savings of 19% were achieved in peak summer day by the thermostat set-point setback strategy and 8% reduction in building peak demand for mid-peak summer day. This strategy gave cooling as well as fan and pump energy savings. Hence the thermostat set-point setback strategy seems to be one of the best choices of strategies for commercial buildings for hot and dry climatic conditions in Arizona.

6.2.3. Experiment 3: Supply air temperature adjustment

Strategies like supply air temperature adjustment and chilled water reset are only possible for buildings served with central plants. The expected outcome was to reduce the coil load hence decreasing the load on the central plant. In this strategy, supply air temperature set-point was increased to reduce cooling loads. Similar to thermostat set-point setback strategy, maximum supply air temperature was increased by 5 ^{0}C over 7 peak hour window, resulting in 0.71 ^{0}C per hour increase in the base case supply air temperature.

Result and Analysis:

Implementing this strategy resulted in a penalty of 8% in high-peak summer day and 10% during mid-peak summer day. After studying the energy consumption in detail it is observed that very minor electricity saving in cooling energy is achieved by adjusting supply air to a higher temperature, but the fan speed increased considerably for those peak hours, resulting in increase in building total energy use. Even though the supply air temperature was increased, the system attempted to meet the zone thermostat request, so it increased airflow resulting in higher fan speed as the supply temperature got warmer until it reached its design flow rate limits. Therefore supply air temperature adjustment might not be a feasible strategy by itself.

6.2.4. Experiment 4: Supply air temperature adjustment limiting fan mass flow rate

In this simulation supply fan flow rate (mass flow rate m^3/s) was held constant at the values (fan speed) found just prior to the start of the peak demand window. This was done to restrict the excess fan energy.

Result and Analysis:

Restricting fan mass flow rate resulted in 3% energy savings for summer high-peak day where as it gave very minimal to no savings during mid-peak summer day. Therefore supply air temperature adjustment is not very effective strategy for buildings served by VAV system.

6.2.5. Experiment 5: Chilled water temperature reset

In this experiment chilled water temperature was reset to reduce the chiller load finally resulting in total building energy reduction for peak hour. The chilled water temperature was increased by a total of 5 ^{0}C in stepped pattern over the 6 hour peak demand window.

Result and Analysis:

As expected, after using chilled water reset strategy, minor electricity savings in cooling energy were received but chilled water pump and fan energy increased for the peak period. Penalties of 3.5% and 5% were seen over high-peak and mid-peak day respectively (energy consumption increased compared to the base case).

6.2.6. Experiment 6: Chilled water temperature reset limiting pump and fan mass flow rate

In this experiment pump mass flow rate (pump speed) was held constant to the pump speed found just prior to the start of the peak demand window. This was done to restrict the excess pump energy due to chilled water temperature reset. But because the pump speed was restricted the fan speed increased thereby resulting in fan flow rate restriction as well.

Result and Analysis:

On summer high-peak day, 8% saving was obtained by the chilled water temperature reset strategy limiting pump and fan mass flow rates. Compared to high-peak day savings mid-peak day savings are not very significant (2.5%). Therefore chilled water temperature reset is an effective strategy.

After simulating all the strategies individually, they were then simulated on top of each other (cascaded). Many such different combinations were evaluated. Finally, only combinations which gave promising results are documented in this section.

6.2.7. Experiment 7: Thermostat set-point setback + lighting power density reduction

By combining these two strategies, 22% savings were obtained on summer high-peak day and 12% savings were found on summer mid-peak day. Therefore this combination of strategy is advisable.

6.2.8. Experiment 8: Thermostat set-point setback + supply air temperature adjustment

These two strategies together reduced total energy by 17% compared to base case during high-peak day, and by 7% during mid-peak day. This indicates that the combined strategy gives small penalty on the savings bound by thermostat set-point setback alone. This is due to the fact that even though the cooling and fan energy reduced, the pump energy increased. The pump worked harder to meet the same load.

6.2.9. Experiment 9: Thermostat set-point setback + Chilled water temperature reset

In this combination the savings obtained by the thermostat set-point setback were attenuated because of chilled water temperature reset. 9% and 5% savings were achieved during summer high-peak day and mid-peak day respectively.

6.2.10. Experiment 10: Lighting power density reduction + Supply air temperature adjustment

The combined strategy gave 6% saving during summer high-peak day whereas on the mid-peak day, negligible savings of 0.5% were found. Therefore this strategy should be considered only for high-peak day.

6.2.11. Experiment 11: Lighting power density reduction + Chilled water temperature reset

In this combination 5% during high-peak and 6% savings were observed during mid-peak day. For mid-peak day compared to the individual strategies the combined savings were higher. Therefore it should be considered for mid-peak summer day.

6.2.12. Experiment 12: Thermostat set-point setback + supply air temperature adjustment + Lighting power density reduction

Very impressive saving of 22% were found by combining all the strategies during summer high-peak day and 10% during mid-peak day. It is observed that supply air temperature adjustment did not contribute much to the energy savings.

6.2.13. Experiment 13: All strategies combined +limiting fan and pump mass flow rate

Finally all the strategies were combined i.e. lighting power density reduction + Thermostat set-point setback + Supply air temperature adjustment limiting fan mass flow rate + Chilled water temperature reset limiting mass flow rate in one strategy. All the strategies together gave remarkable results: saving 25% energy during high-peak summer day and 18% energy during mid-peak summer day.

It is also observed that the first and last hour in the peak window give less savings compared to the hours in the middle of the window. So the percent energy saving for the middle hours except the first and the last hour is higher. The utility companies and the building manager should keep this in mind with respect to the peak demand window selection. Percent energy savings in electricity consumption for different peak windows for high-peak day and mid-peak day is shown in Figure 6.4 and Figure 6.5.

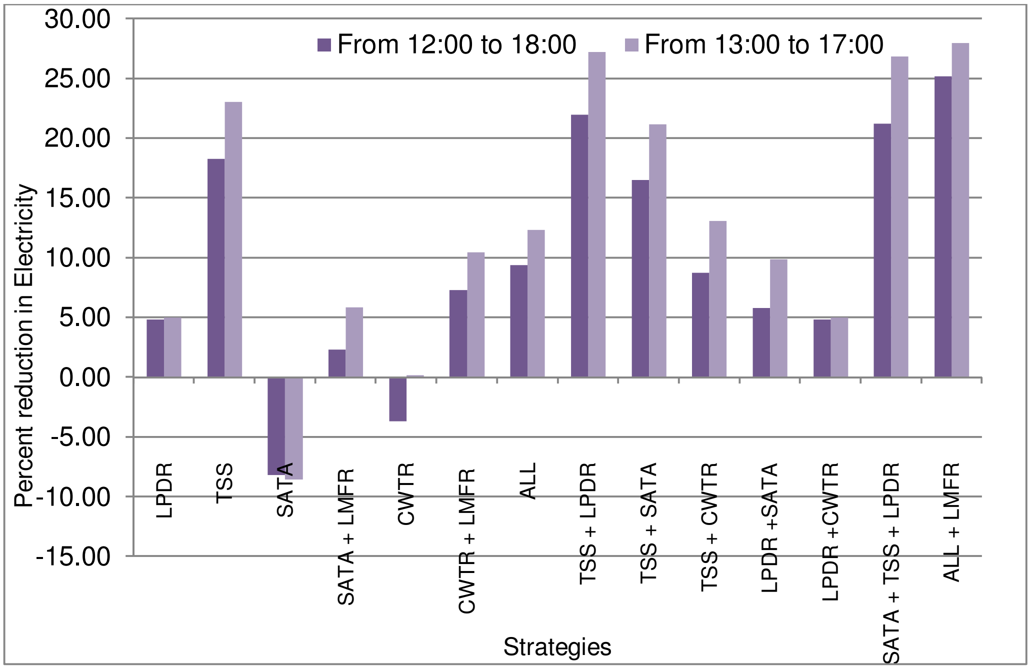

Figure 6.4 Comparison between percent reductions in electricity consumption for different peak windows during the high-peak day

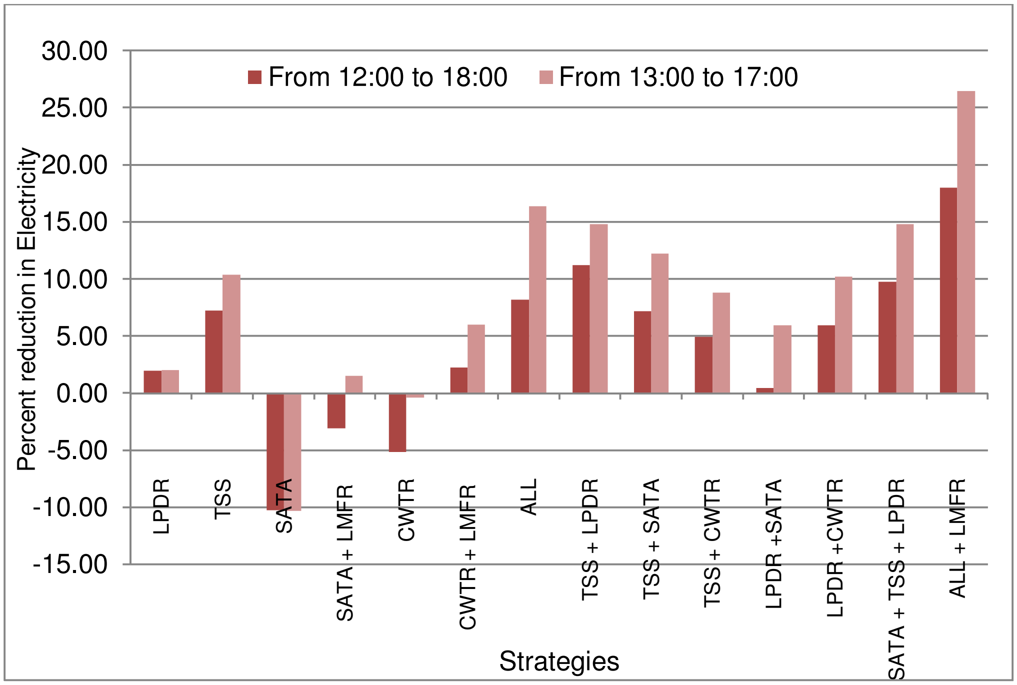

Figure 6.5 Comparison between percent reductions in electricity consumption for different peak windows during the mid-peak day

It is clear from the above graphs that during the peak period window of 12:00 to 18:00 most energy was saved during the hours from 13:00 to 17:00 hours.

Chapter 7

THERMAL MASS EFFECT ON DEMAND RESPONSE STRATEGIES

A separate study was conducted to examine the impact of thermal mass on buildings peak demand reduction. Two types of building construction were chosen to represent heavy and light thermal mass buildings. The study was conducted on the medium office prototype building model. The model was simulated by changing its construction from light to heavy.

Table 7.1

Comparison of light and heavy construction: percentage reduction in electricity consumption for Medium office building

No.	Demand-Response Strategies	Light	Heavy	Light	Heavy
		07/15 (Peak)	07/15 (Peak)	06/29 (Mid-Peak)	06/29 (Mid-Peak)
1	LPD reduction	3.19	3.39	4.38	4.40
2	Thermostat set-point setback	22.51	22.01	14.15	14.31
3	Combined control strategies	25.26	24.83	17.85	17.96

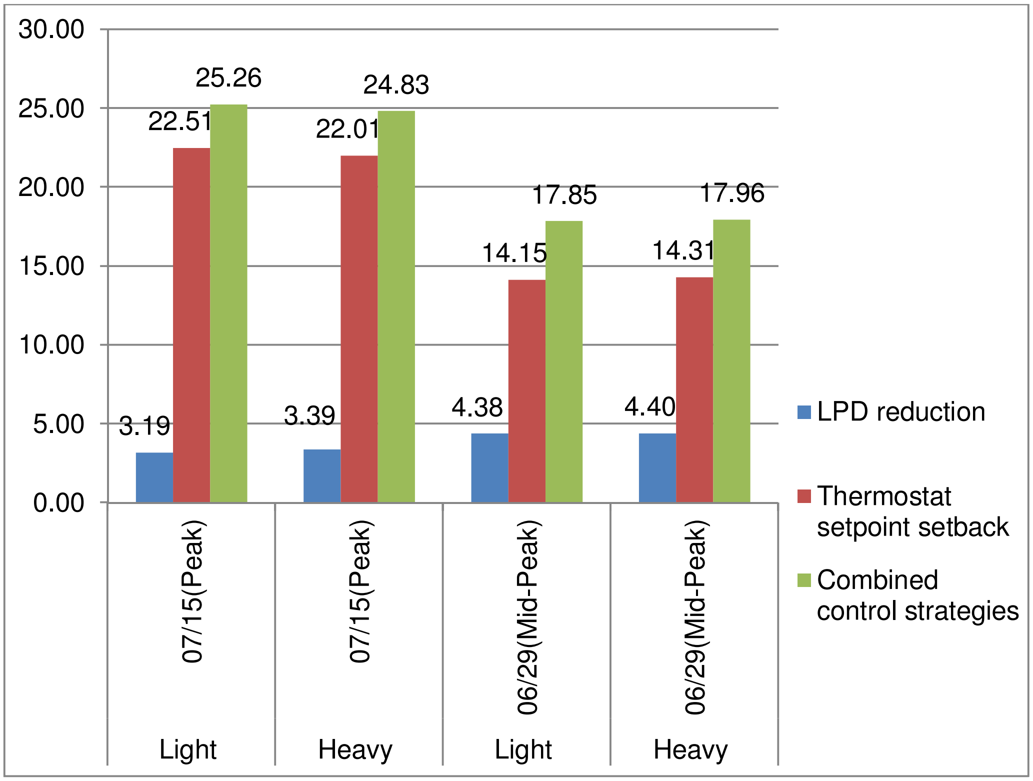

Figure 7.1 Comparison of light and heavy construction: Percent reductions in electricity consumption for Medium office building

Simulation results showed that the difference between the percent peak demand reductions offered by different thermal masses is negligible for the buildings selected for this study. It was assumed that utility peak period notification will occur only few hours in advance and insufficient time was available to precondition the building. Therefore the impact of thermal mass was very insignificant. The difference in percent reductions between the two constructions was less than 0.5-1%. Compared to the percent reductions gained from the various other strategies, this is very small.

Large and medium buildings are core dominant, therefore the same experiment was run on small office building to see if the thermal mass made any difference on perimeter dominant building. Surprisingly not much change was seen in the percent reductions of small office building as well.

Conclusion: The impact of thermal mass on peak demand reduction need not be considered for demand shading strategies for commercial buildings in Arizona.

Chapter 8

THERMAL COMFORT ANALYSIS

It is very important to perform thermal comfort analysis to study the impact of demand-response strategies on the occupants' comfort level before recommending DR strategies. Thermal comfort analysis for high-peak summer day is presented here as discomfort is likely to be more severe in the summer months. The Fanger comfort model is used in this study to describe occupants' thermal comfort (Fanger, 1970). ASHRAE Standard 55 lists the predicted mean vote (PMV) comfort range to be in between -0.5 to 0.5 where 0 is neutral, -0.5 is on the cooler side and 0.5 is on the warmer side.

8.1. Medium Office

8.1.1. Results of PMV analysis

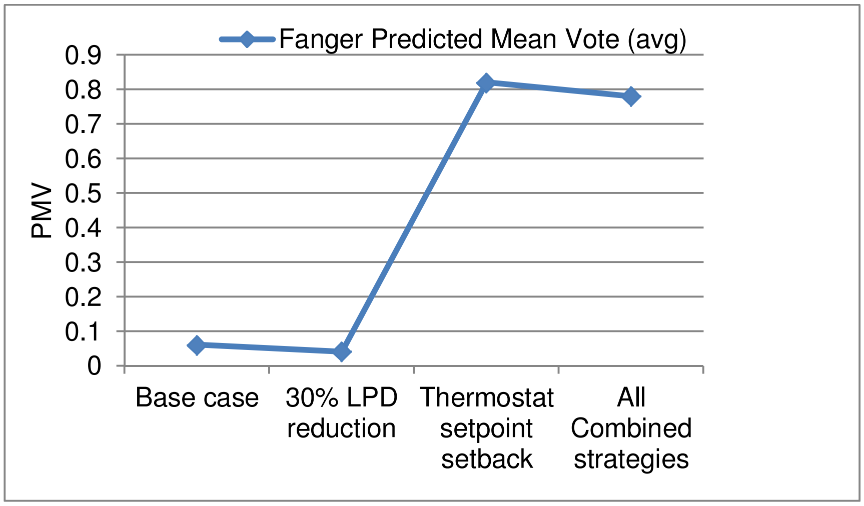

Figure 8.1 Fanger predicted mean vote (average of all zones) for the simulated medium office

For medium office building, PMV for the base case is 0.06. This is very close to neutral perception. Comparing the base line with all the other control strategies shows increase in the PMV value towards the warm comfort region in the range of 0.04 to 0.8. Since these values do not exceed the slightly warm comfort criteria (1= slightly warm) it is assumed that the strategies selected for this study are feasible when implemented as Demand-Response strategies.

8.1.2. Result of PPD analysis

To study the thermal comfort in detail, Predicted Percent Dissatisfied (PPD) analysis is done for the middle floor. In Medium office building for the base case we observed values of PPD in the range of 5-10%.

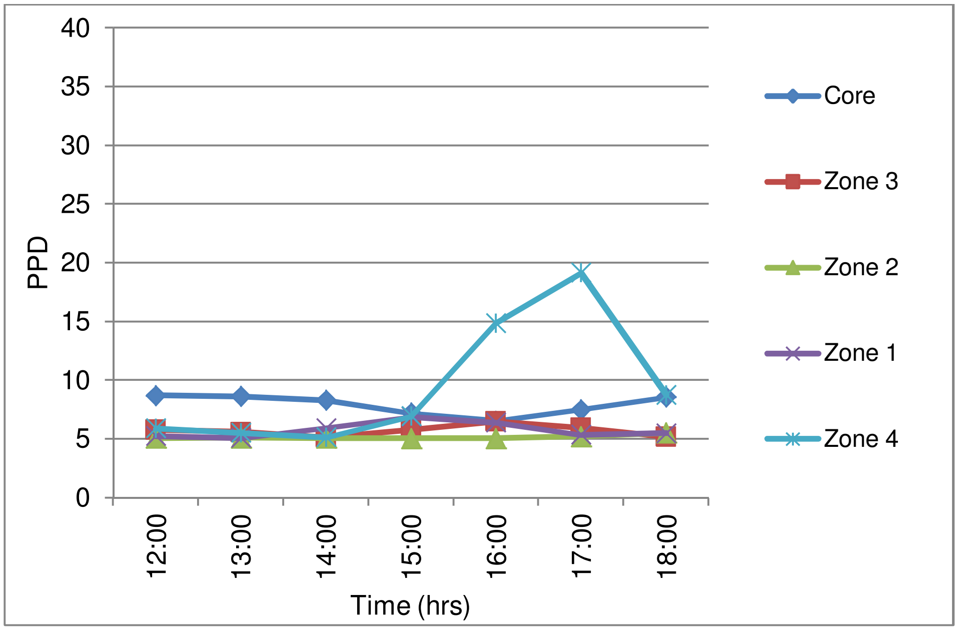

Figure 8.2 Fanger predicted percentage dissatisfied during peak period window for medium office for Base case for high-peak day.

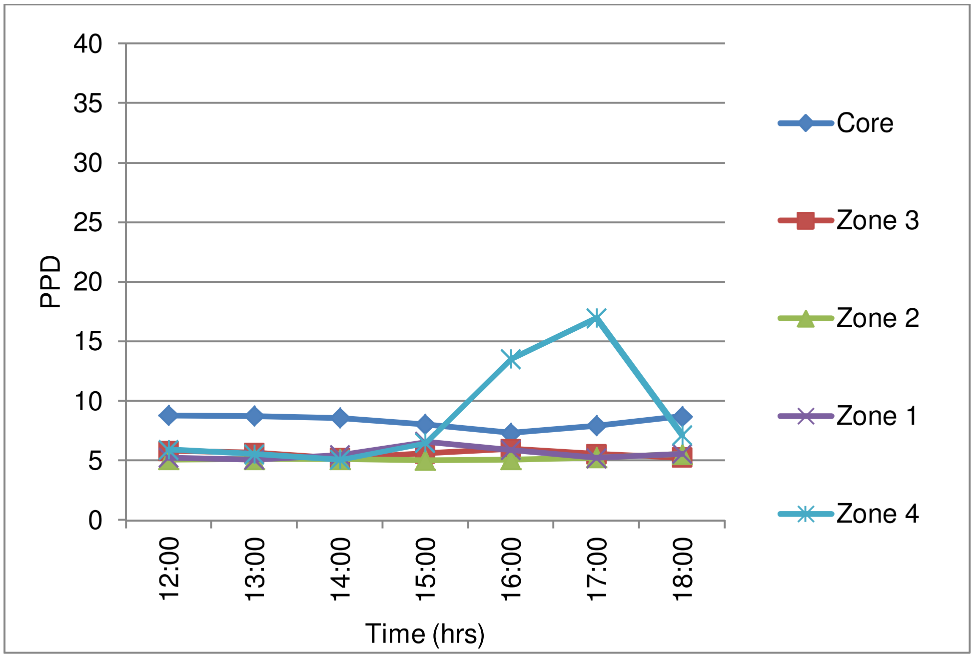

Figure 8.3 Fanger predicted percentage dissatisfied during peak period window for medium office for lighting power density reduction strategy for high-peak day.

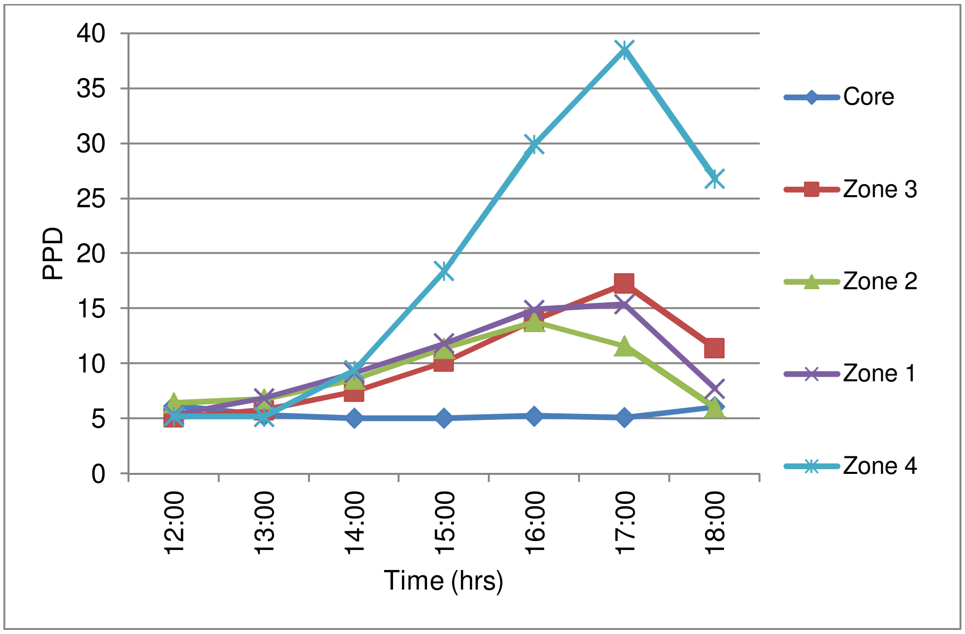

Figure 8.4 Fanger predicted percentage dissatisfied during peak period window for medium office for thermostat set-point setback strategy for high-peak day.

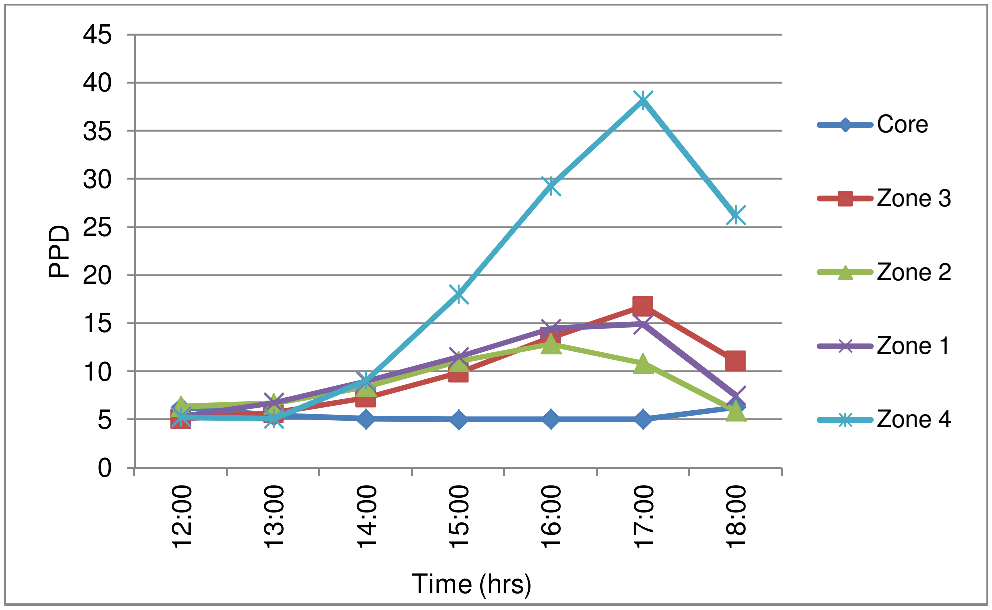

Figure 8.5 Fanger predicted percentage dissatisfied during peak period window for medium office for all the combined strategies for high-peak day.

From the graphs it is clear that the PPD for all the control strategies is in the range of 5-15% except one zone facing west side. Therefore from the PMV and PPD analysis it is clear that the strategies selected in this study are reasonable as DR strategies for medium office building.

8.2. Large Office

8.2.1. Result of PMV analysis

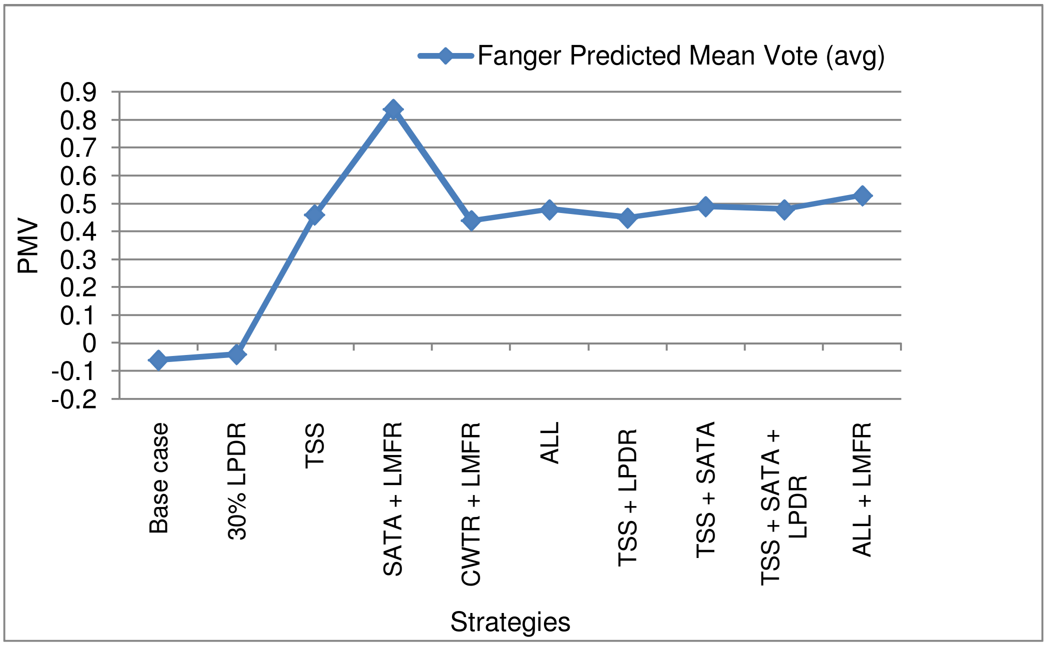

Figure 8.6 Fanger predicted mean vote (average of all the zones) for large office

In large office building, average PMV for the base case is -0.07. This is slightly cool but very close to neutral perception. Comparison of the base case with all the other control strategies shows an increase in the PMV value towards the warm comfort region in the range of 0 to 0.6 except for the supply air temperature adjustment strategy whose PMV= 0.85 (slightly warmer). Since these values do not exceed the slightly warm comfort criteria (1= slightly warm) it is assumed that the strategies selected for this study are feasible when implemented as Demand-Response strategies.

8.2.2. Result of PPD analysis

To study the thermal comfort more in detail Predicted Percent Dissatisfied (PPD) analysis is conducted. The large office building is 12 storied high and core dominant. Except for top and base floors all the 10 middle floors have similar exposure to the exterior and consist of 80% of the floor area; therefore for the detailed thermal comfort analysis only the middle floor is selected.

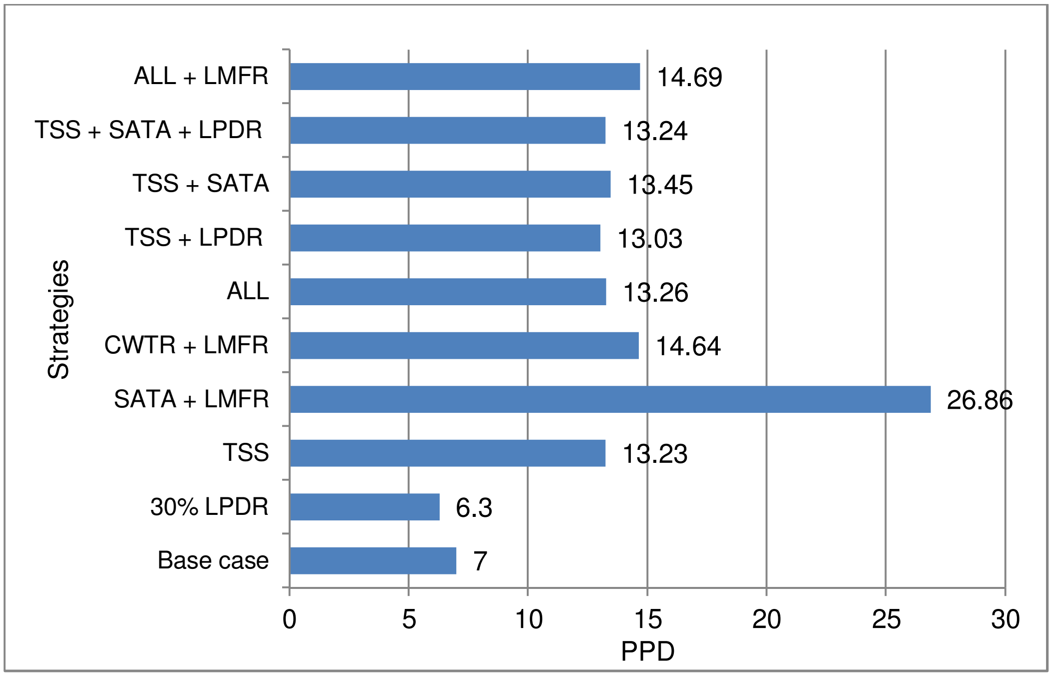

Figure 8.7 Fanger predicted percentage dissatisfied (average of all the zones) during peak period window for large office.

For Large office building, the base case has Predicted Percentage Dissatisfied value in the range of 5-12% for all the zones of the middle floor. The Lighting power density reduction has a very similar PPD range compared to base case. Therefore, from Figures 8.8 and 8.9, it is clear that occupancy comfort is not compromised by the lighting power density reduction strategy.

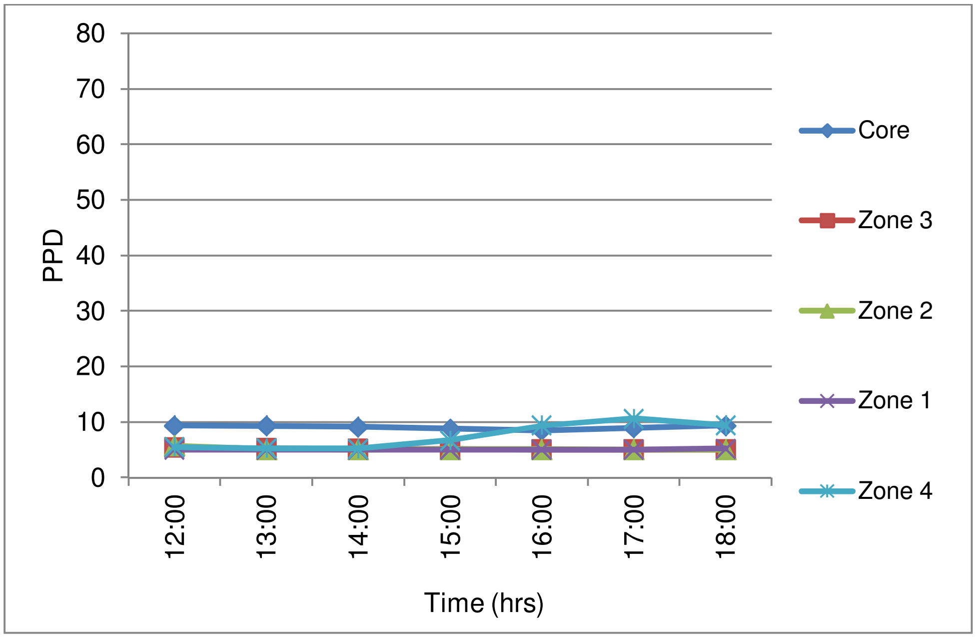

Figure 8.8 Fanger predicted percentage dissatisfied during peak period window for large office for Base case for high-peak day.

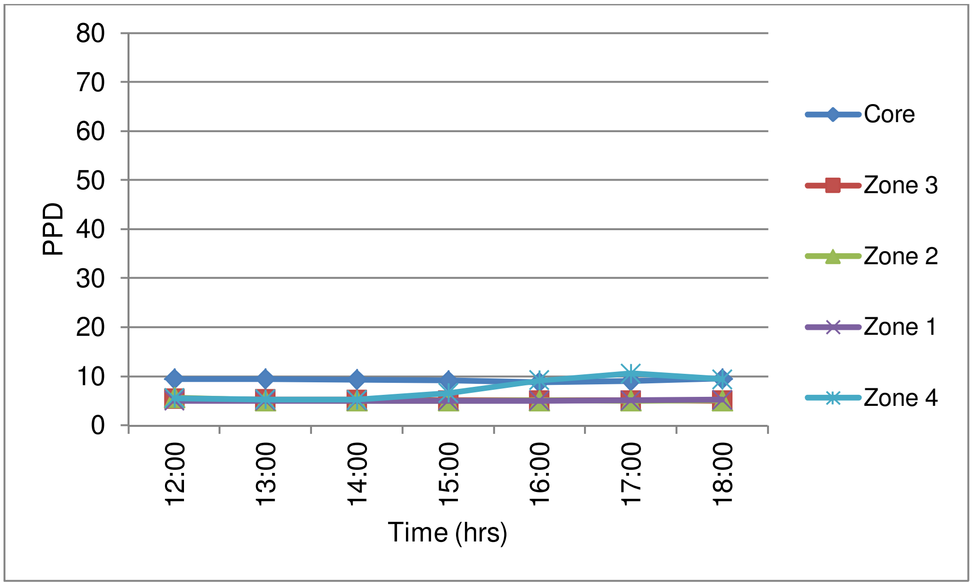

Figure 8.9 Fanger predicted percentage dissatisfied during peak period window for large office for lighting power density reduction strategy for high-peak day.

The PPD for thermostat set-point setback is in the range of 5-20% for all the middle zones during 6 hours peak window except for zone facing west side. For this zone, the PPD increases to 45% for 2-3 hours.

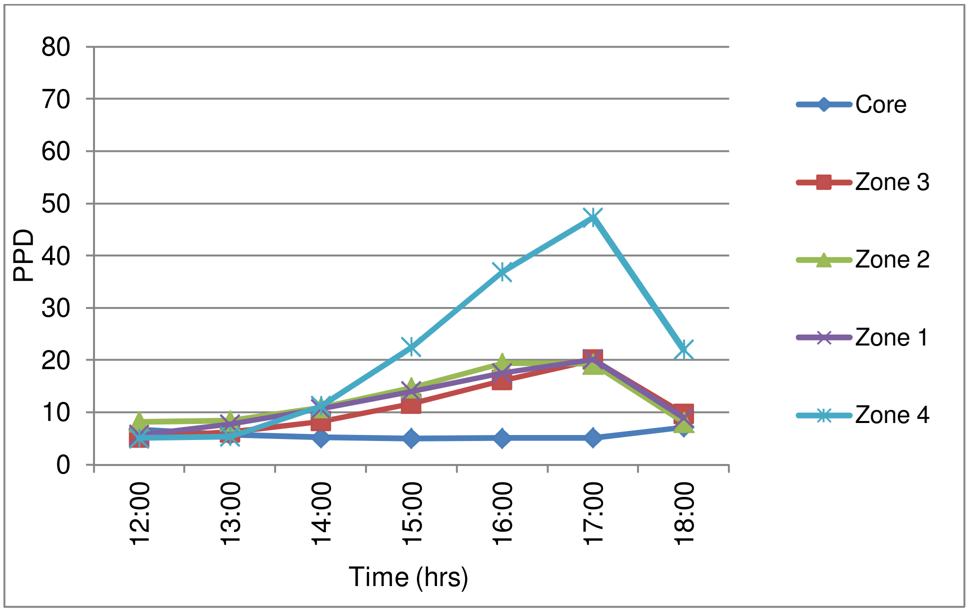

Figure 8.10 Fanger predicted percentage dissatisfied during peak period window for large office for thermostat set-point setback strategy for high-peak day.

With the supply air temperature adjustment strategy the PPD increased. It resulted in a PPD range of 25-40%. The west zone reached to the maximum of 60-80% PPD for the later hours in the peak period window. Therefore, from Figure 8.11 looking at the occupants' discomfort level it is clear that adjusting supply air temperature to higher temperature individually is not an advisable strategy.

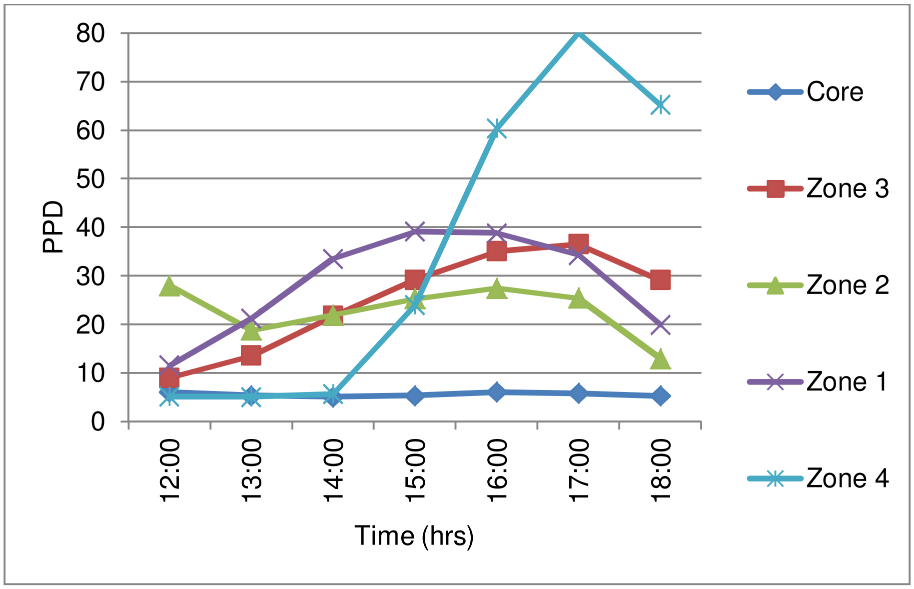

Figure 8.11 Fanger predicted percentage dissatisfied during peak period window for large office for supply air temperature adjustment strategy for high-peak day.

Similarly the PPD increased to a range of 25-33% by implementing chilled water temperature reset strategy for two zones. And as expected for the west zone it increased to 50-70% for 2-3 hours.

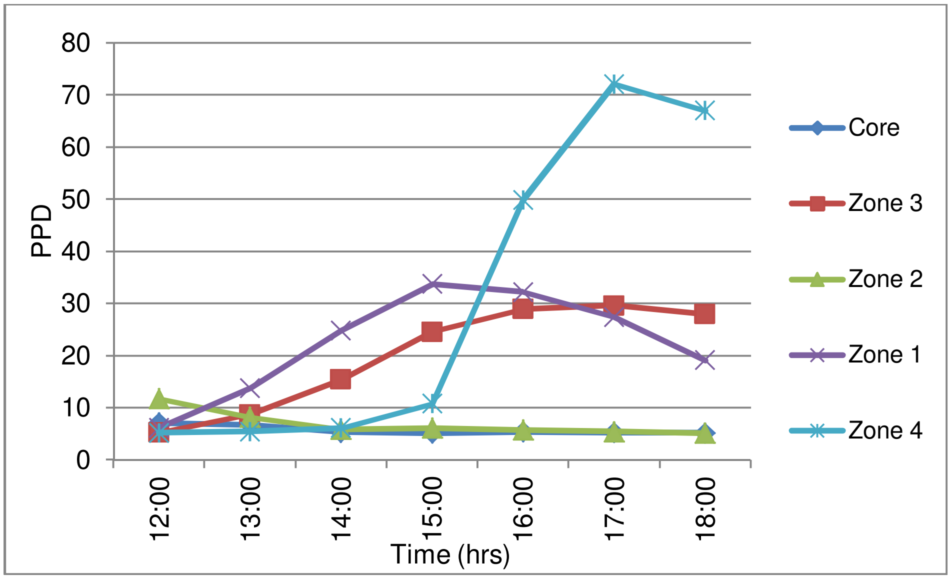

Figure 8.12 Fanger predicted percentage dissatisfied during peak period window for large office for chilled water temperature reset strategy for high-peak day.

Compared to the individual strategies, strategies in combination showed some promising thermal comfort results. The PPD and the PMV ranges reduced when the strategies were combined. The thermostat set-point combined with lighting power density reduction resulted in PPD value in the range of 10-20% except one zone. Therefore, alternate DR strategies are recommended.

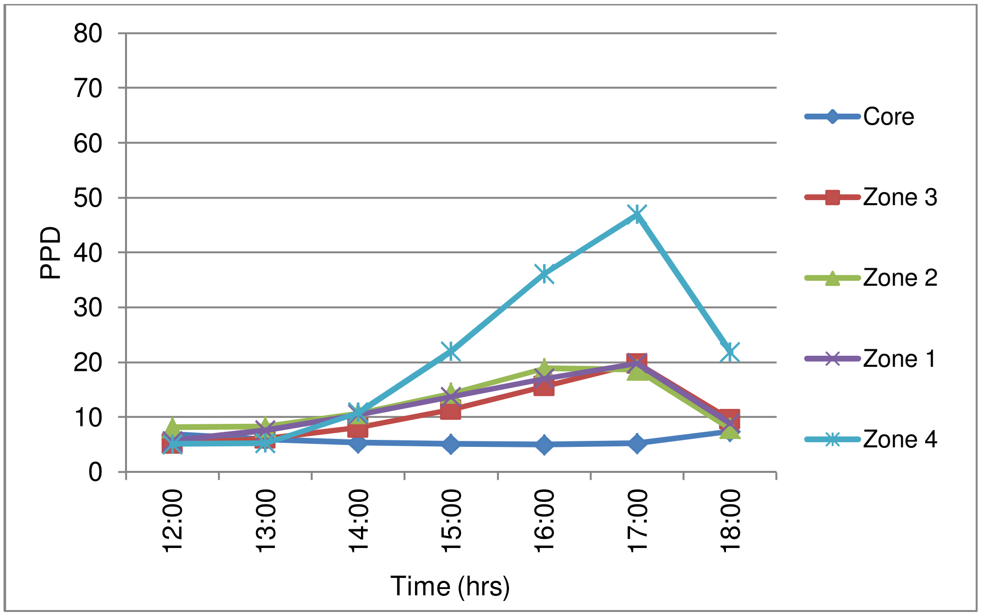

Figure 8.13 Fanger predicted percentage dissatisfied during peak period window for large office for thermostat set-point setback + lighting power density reduction strategies for high-peak day.

Thermostat set-point setback combined with supply air temperature adjustment increased the PPD value to 10-38%. Similarly thermostat set-point setback combined with chilled water temperature combined with chilled water temperature reset increased it to 10-28%.

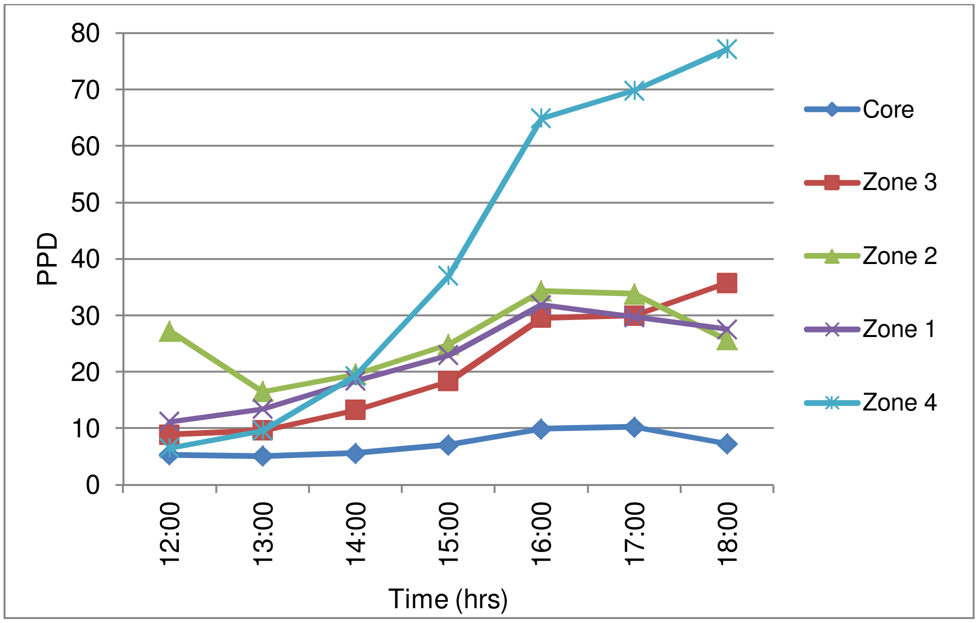

Figure 8.14 Fanger predicted percentage dissatisfied during peak period window for large office for thermostat set-point setback + supply air temperature adjustment strategies for high-peak day.

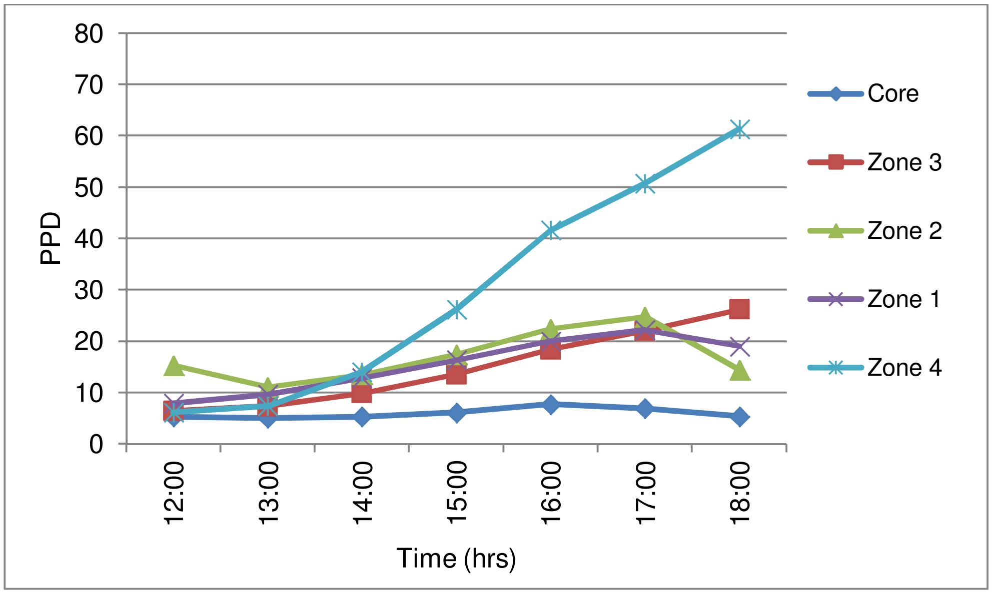

Figure 8.15 Fanger predicted percentage dissatisfied during peak period window for large office for thermostat set-point setback + chilled water temperature reset strategies for high-peak day.

Strategies combined with Supply air temperature adjustment were observed to have higher PPD values as observed in Figure 8.16 where supply air temperature is combined with lighting power density reduction and the PPD values are in the range of 10-38%.

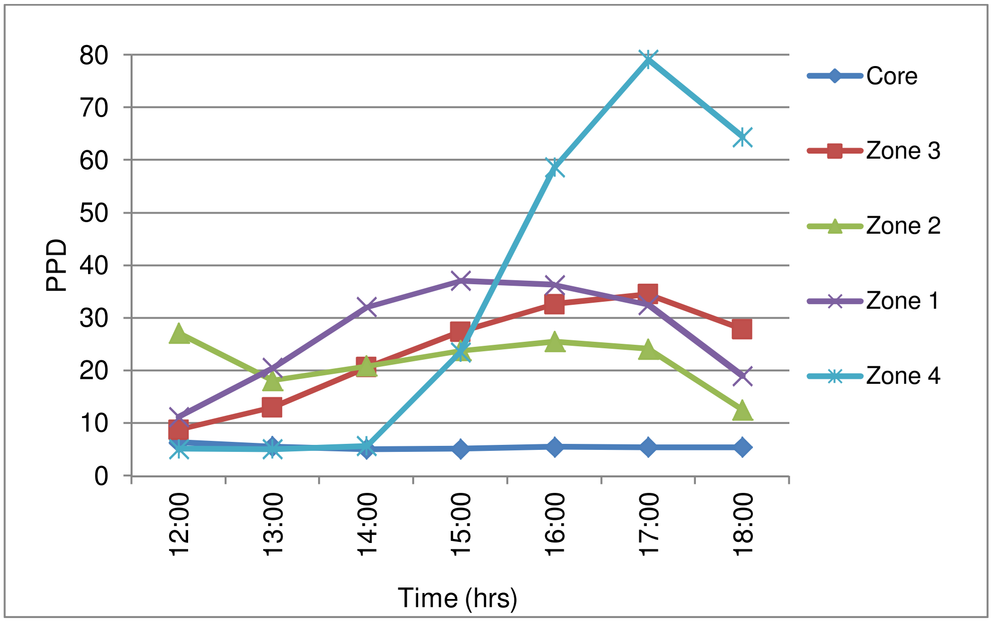

Figure 8.16 Fanger predicted percentage dissatisfied during peak period window for large office for supply air temperature adjustment + lighting power density reduction strategies for high-peak day.

On the other hand Chilled water temperature combined with lighting power density has lower discomfort with the PPD ranging from 20-28%.

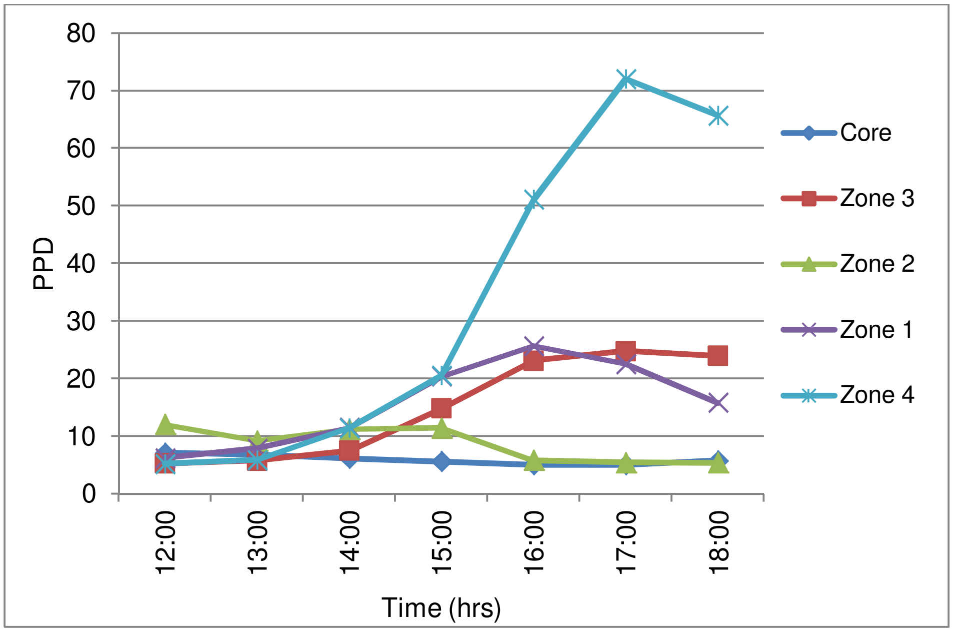

Figure 8.17 Fanger predicted percentage dissatisfied during peak period window for large office for chilled water temperature reset + lighting power density reduction strategies for high-peak day.

Thermostat set-point setback combined with lighting power density and supply air temperature adjustment reduced the percent of dissatisfied occupants to 10-20% except zone 4 where the PPD range is higher (10-47%).

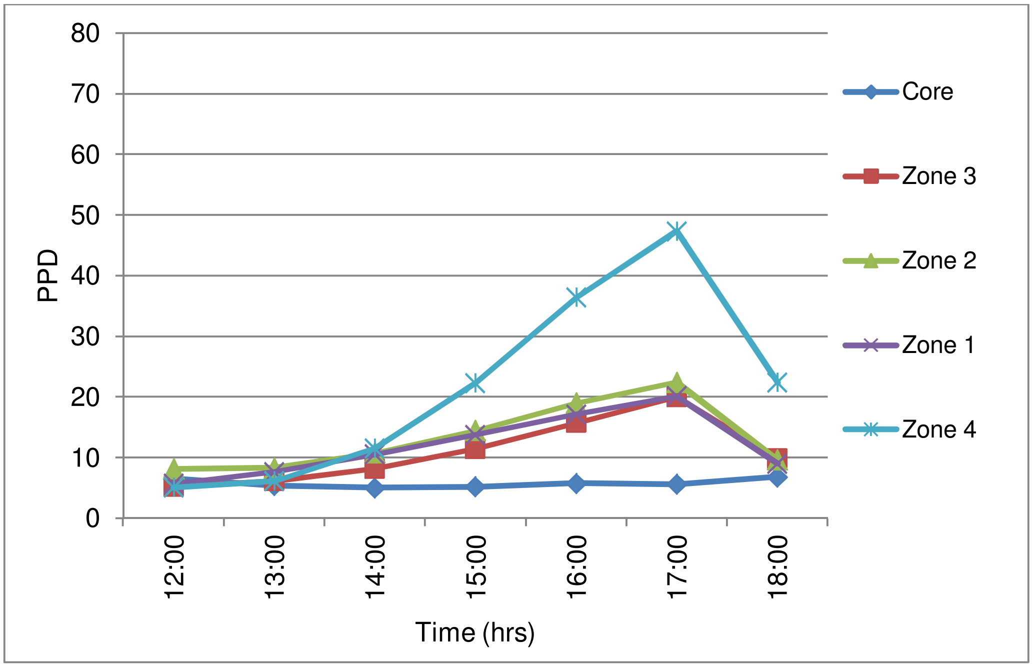

Figure 8.18 Fanger predicted percentage dissatisfied during peak period window for large office for supply air temperature adjustment + thermostat set-point setback + lighting power density reduction strategies for high-peak day.

Finally, for all the strategies combined together without restricting the fan and pump mass flow rate and with restricting mass flow rate, the PPD range is 10-20% except for the zone 4 where it was 10-47% and 10-56% respectively.

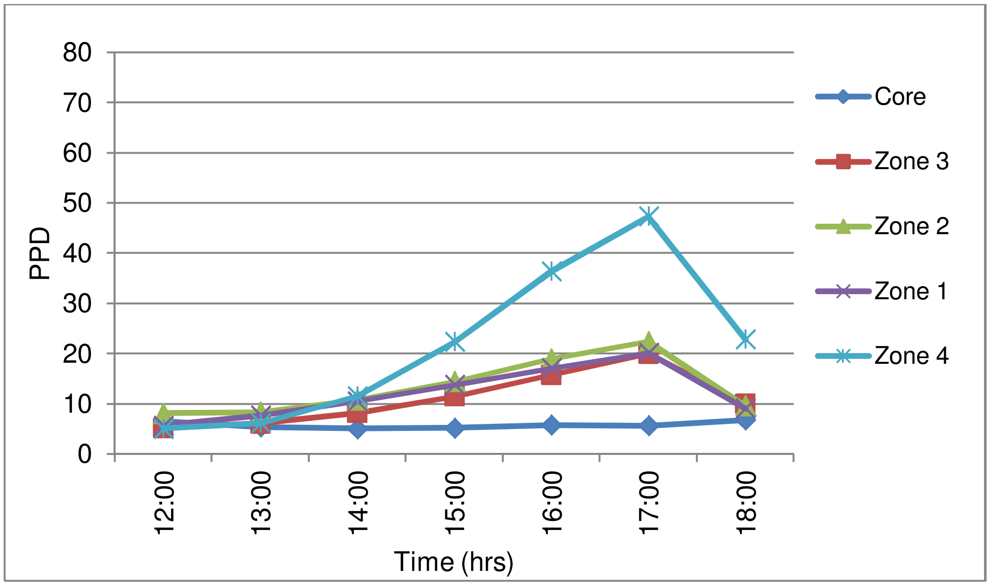

Figure 8.19 Fanger predicted percentage dissatisfied during peak period window for large office for all the combined strategies without restricting the fan and pump mass flow rate for high-peak day.

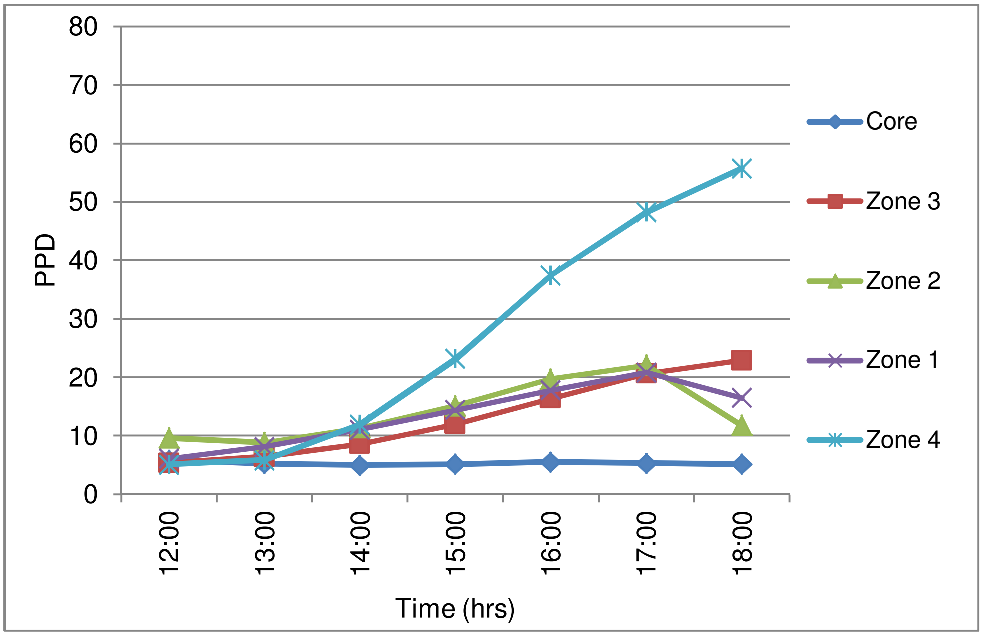

Figure 8.20 Fanger predicted percentage dissatisfied during peak period window for large office for all the combined strategies with restricting the fan and pump mass flow rate for high-peak day.

Chapter 9

SUMMARY AND RECOMMENDATIONS

This study investigated DR strategies used to reduce peak demand consumption during fixed time window near on-peak period in commercial buildings in hot and dry climates like Arizona. This study limited itself to evaluating DR strategies applicable under the case of short time notification by the energy provider. Therefore the focus of this study is on demand shedding only during the peak period window. The selected fixed time window is from 12:00 to 18:00 PM. For this study summer peak (15th July) and summer mid peak (29th June) were selected for evaluating the effect of various DR strategies on a DOE prototypes for medium size office building and large size office building.

The main DR strategies investigated are Lighting power density reduction, thermostat set-point setback, supply air temperature adjustment and chilled water temperature reset. Effect of these strategies was investigated individually first and later all the different combinations of these strategies were studied. Strategies like lighting power density and thermostat set-point setback were applied on both the building types. But strategies like supply air temperature adjustment and chilled water temperature reset were possible to buildings served with central plant only. The last two strategies were quite complex as they involved fans and pumps as well.

For this study ASHRAE 90.1 prototype building models developed by Pacific Northwest National Laboratory (PNNL) in support of DOE's Building Energy Codes Program were selected. These models cover 80% of the commercial building floor area in the U.S. for new construction. The prototype building models were simulated in EnergyPlus program to do the energy analysis of the DR strategies.

To study the thermal mass impact on the DR strategies two different constructions were experimented. Finally thermal comfort analysis of all the strategies was conducted to study the occupants discomfort level due to these DR strategies.

Based on the study, following are the recommendations to the building owners and operators:

i. DR management is very effective process to reduce peak hour energy consumption for fixed time window. It can give up to 25% savings in large office buildings served with VAV system and in medium office building served with packaged air conditioning unit.

ii. Thermostat set-point setback strategy gave highest energy savings compared to all individual strategies. It saved up to 18% in large office and up to 23% in medium office building. But it also had more thermal discomfort levels in occupants compared to the lighting power density reduction strategy.

iii. Lighting power density reduction strategy is effective strategy to meet the peak demand energy reduction requirements. Lighting power density reduction varied from 90%, 80% to 70% and as the percent of LPD reduced the energy savings increased linearly. Lighting power density has no impact on the occupants' thermal comfort levels. It surely has impact on the occupants' visual comfort but visual comfort analysis is not supported by EnergyPlus, so no data could be collected on that.

iv. Supply air temperature adjustment and chilled water temperature reset strategies used individually gave penalty and the total energy consumption increased as the fan and pump flow rate increased.

v. If fan speed is held constant supply air temperature adjustment strategy gives small savings. But at the same time with this strategy the occupants discomfort level reaches its peak. Therefore this strategy is not recommended to be used separately.

vi. Chilled water temperature holding fan and pump flow rate (speed) constant gives good savings and the discomfort levels are smaller compared to the supply air temperature adjustment strategy.

vii. It is observed that a single control strategy did not provide maximum savings. Whereas various combinations of these strategies gave impressive savings.

viii. All the strategies combined together saved maximum energy.

ix. The study showed that impact of thermal mass on peak demand reduction is not very significant therefore it need not be considered.

x. Assuming that the control strategies will have adverse impact on the occupants comfort levels thermal comfort analysis of all the strategies was done. From the analysis it is clear that strategies like supply air temperature adjustment and chilled water temperature reset have highest discomfort levels but the discomfort levels reduce if these strategies are combined with thermostat set-point setback.

xi. From the thermal comfort analysis for DR strategies it is observed that discomfort levels in the zone facing west were always higher compared to other zones therefore it is recommended that if the particular strategy is selected alternate arrangements (e.g. permanent or temporary shades, blinds etc.) should be done for the particular zone facing west direction.

xii. Following are the results for medium (packaged roof top unit) and large office (VAV) buildings for high-peak day in tabular format:

Table 9.1

Recommendations for building owners and operators for Medium office building for high-peak day

Percentage of reduction expected	Strategies	Fanger Predicted Percentage Dissatisfied (PPD): Range	Exception zone (alternate arrangements required)
2-5%	LPDR 10%, LPDR 20%	5-8%	None
	LPDR 30%,	5-8%	None
20-25%	TSS	5-15%	zone4: 5-36%
25-30%	ALL	5-15%	zone4: 5-35%

Table 9.2

Recommendations for building owners and operators for large office (VAV) building for high-peak day

Percentage of reduction expected	Strategies	Fanger Predicted Percentage Dissatisfied (PPD): Range	Exception zone (alternate arrangements required)
2-5%	LPDR 10%, LPDR 20%	5-12%	None
	SATA + LMFR	5-40%	zone4: 5-80%
5-10%	LPDR 30%,	5-12%	None
	LPDR+CWTR	5-25%	zone4: 5-72%
	LPDR+SATA	5-36%	zone4: 5-78%
	TSSR+CWTR	5-23%	zone4: 5-62%
	CWTR+ LMFR	5-32%	zone4: 5-72%
10-15%	ALL	5-22%	zone4: 5-47%
15-20%	TSSR+SATA	5-33%	zone4: 5-75%
	TSSR	5-20%	zone4: 5-45%
20-25%	SATA+TSSR+LPDR	5-22%	zone4: 5-47%
	TSSR+LPDR	5-20%	zone4: 5-45%
25-30%	ALL + LMFR	5-23%	zone4: 5-56%

Chapter 10

CONCLUSIONS AND FUTURE WORK

i. More energy savings were received on summer high-peak day compared to summer mid-peak day.

ii. Higher percent reductions were observed for medium size office building compared to large size office building.

iii. Thermostat set-point setback is seen to be the best strategy among all other individual strategies. When all strategies are combined, the highest energy savings are obtained.

iv. Supply air temperature adjustment and chilled water temperature reset strategies should not be performed individually without holding the fan and pump flow rate constant.

v. Supply air temperature adjustment strategy gives minimal energy savings and has the highest occupants' discomfort level.

vi. Lighting power density gives reasonable savings and there are no occupants' discomfort levels observed. No visual comfort analysis can be performed in EnergyPlus so that data is not available.

vii. This study is performed for medium office building with packaged air conditioning unit and large office with VAV system. For buildings with same configuration, the results from this study can be directly applied. But for buildings with different systems, size and location, similar study should be conducted to derive the results.

viii. The study is focused on summer months since the location was chosen as Arizona, which is a hot and dry place. For winter months, similar study will have to be done to come up with the effective strategies.

ix. This study can be extended as follows:

   a. Most of the existing buildings are constructed before year 1999-2000 therefore similar analysis should be performed on old building specifications.
   b. Passive strategies like operable windows, blinds and drapes should be investigated.
   c. Visual comfort analysis to evaluate the visual discomfort levels for the lighting power density reduction strategy should be done. We have seen that thermal comfort analysis plays an important role. But it is also crucial to do visual comfort analysis.
   d. Different strategies like use of evaporative cooling, shutting lights in the perimeter zones should be investigated.
   e. Similar study should be performed on different building types, sizes, and weather locations.

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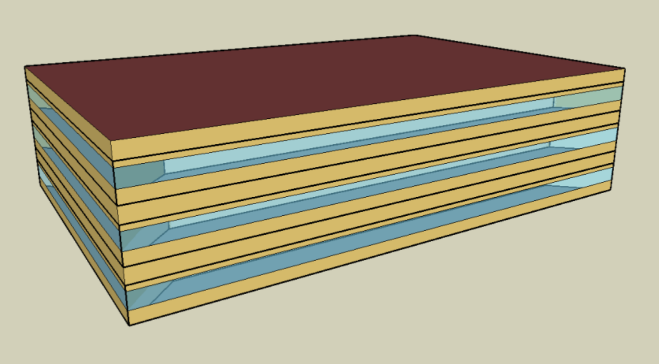
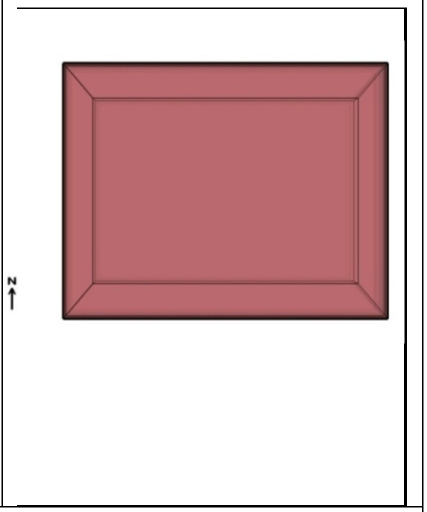
APPENDIX A

DESCRIPTION OF MEDIUM OFFICE BUILDING PROTOTYPE ANALYZED

ASHRAE 90.1 Prototype Building Modeling Specifications

	Item	Descriptions		
Program				
	Vintage	NEW CONSTRUCTION		
	Location (Representing 8 Climate Zones)	Zone 1A: Miami (very hot, humid) Zone 1B: Riyadh, Saudi Arabia (very hot, dry) Zone 2A: Houston (hot, humid) Zone 2B: Phoenix (hot, dry) Zone 3A: Memphis (warm, humid) Zone 3B: El Paso (warm, dry) Zone 3C: San Francisco (warm, marine)	Zone 4A: Baltimore (mild, humid) Zone 4B: Albuquerque (mild, dry) Zone 4C: Salem (mild, marine) Zone 5A: Chicago (cold, humid) Zone 5B: Boise (cold, dry) Zone 5C: Vancouver, BC (cold, marine)	Zone 6A: Burlington (cold, humid) Zone 6B: Helena (cold, dry) Zone 7: Duluth (very cold) Zone 8: Fairbanks (subarctic)
	Available fuel types	gas, electricity		
	Building Type (Principal Building Function)	OFFICE		
	Building Prototype	Medium Office		
Form				
	Total Floor Area (sq feet)	53,600 (163.8 ft x 109.2 ft)		
	Building shape			
	Aspect Ratio	1.5		

	Number of Floors	3		
	Window Fraction (Window-to-Wall Ratio)	33% (Window Dimensions: 163.8 ft x 4.29 ft on the long side of facade 109.2 ft x 4.29 ft on the short side of the façade)		
	Window Locations	even distribution among all four sides		
	Shading Geometry	none		
	Azimuth	non-directional		
	Thermal Zoning	Perimeter zone depth: 15 ft. Each floor has four perimeter zones and one core zone. Percentages of floor area: Perimeter 40%, Core 60%		
	Floor to floor height (feet)	13		
	Floor to ceiling height (feet)	9 (4 ft above-ceiling plenum)		
	Glazing sill height (feet)	3.35 ft (top of the window is 7.64 ft high with 4.29 ft high glass)		
Architecture				
	Exterior walls			
	Construction	Steel-Frame Walls (2X4 16IN OC) 0.4 in. Stucco+5/8 in. gypsum board + wall Insulation+5/8 in.		

	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	ASHRAE 90.1 Requirements Nonresidential; Walls, Above-Grade, Steel-Framed
	Dimensions	based on floor area and aspect ratio
	Tilts and orientations	vertical
	Roof	
	Construction	Built-up Roof: Roof membrane +Roof insulation+ metal decking
	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	ASHRAE 90.1 Requirements Nonresidential; Roofs, Insulation entirely above deck
	Dimensions	based on floor area and aspect ratio
	Tilts and orientations	horizontal
	Window	
	Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio
	Glass-Type and frame	Hypothetical window with the exact U-factor and SHGC shown below
	U-factor (Btu / h * ft^2 * °F)	ASHRAE 90.1 Requirements Nonresidential; Vertical Glazing, 31.1-40%, U_fixed
	SHGC (all)	
	Visible transmittance	Hypothetical window with the exact U-factor and SHGC shown above
	Operable area	0
	Skylight	
	Dimensions	Not Modeled
	Glass-Type and frame	NA
	U-factor (Btu / h * ft^2 * °F)	
	SHGC (all)	
	Visible transmittance	
	Foundation	
	Foundation Type	Slab-on-grade floors (unheated)
	Construction	8" concrete slab poured directly on to the earth

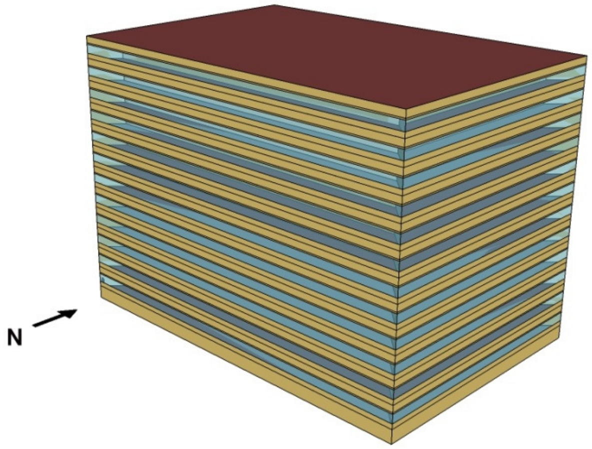
	Thermal properties for ground level floor U-factor (Btu / h * ft2 * °F) and/or R-value (h * ft2 * °F / Btu)	ASHRAE 90.1 Requirements Nonresidential; Slab-on-Grade Floors, unheated
	Thermal properties for basement walls	NA
	Dimensions	based on floor area and aspect ratio
	Interior Partitions	
	Construction	2 x 4 uninsulated stud wall
	Dimensions	based on floor plan and floor-to-floor height
	Internal Mass	6 inches standard wood (16.6 lb/ft^2)
	Air Barrier System	
	Infiltration	Peak: 0.2016 cfm/sf of above grade exterior wall surface area (when fans turn off) Off Peak: 25% of peak infiltration rate (when fans turn on)
HVAC		
	System Type	
	Heating type	Gas furnace inside the packaged air conditioning unit
	Cooling type	Packaged air conditioning unit
	Distribution and terminal units	VAV terminal box with damper and electric reheating coil Zone control type: minimum supply air at 30% of the zone design peak supply air.
	HVAC Sizing	
	Air Conditioning	autosized to design day
	Heating	autosized to design day
	HVAC Efficiency	
	Air Conditioning	Various by climate location and design cooling capacity ASHRAE 90.1 Requirements Minimum equipment efficiency for Air Conditioners and Condensing Units
	Heating	Various by climate location and design heating capacity ASHRAE 90.1 Requirements Minimum equipment efficiency for Warm Air Furnaces
	HVAC Control	
	Thermostat Setpoint	75°F Cooling/70°F Heating

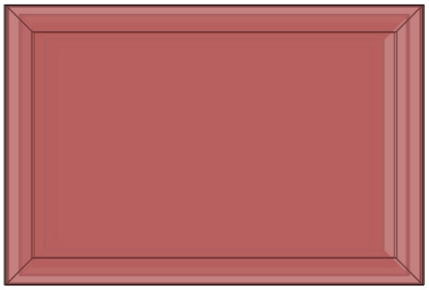
	Thermostat Setback	80°F Cooling/60°F Heating
	Supply air temperature	Maximum 104F, Minimum 55F
	Chilled water supply temperatures	NA
	Hot water supply temperatures	NA
	Economizers	Various by climate location and cooling capacity Control type: differential dry bulb
	Ventilation	ASHRAE Ventilation Standard 62.1 See under Outdoor Air.
	Demand Control Ventilation	ASHRAE 90.1 Requirements
	Energy Recovery	ASHRAE 90.1 Requirements
	Supply Fan	
	Fan schedules	See under Schedules
	Supply Fan Total Efficiency (%)	60% to 62% depending on the fan motor size
	Supply Fan Pressure Drop	Various depending on the fan supply air cfm
	Pump	
	Pump Type	NA
	Rated Pump Head	NA
	Pump Power	autosized
	Cooling Tower	
	Cooling Tower Type	NA
	Cooling Tower Efficiency	NA
	Service Water Heating	
	SWH type	Storage Tank
	Fuel type	Natural Gas
	Thermal efficiency (%)	ASHRAE 90.1 Requirements Water Heating Equipment, Gas storage water heaters, >75,000 Btu/h input
	Tank Volume (gal)	260
	Water temperature setpoint	120F
	Water	See under Schedules

	consumption	
Internal Loads & Schedules		
	Lighting	
	Average power density (W/ft^2)	ASHRAE 90.1 Lighting Power Densities Using the Building Area Method
	Schedule	See under Schedules
	Daylighting Controls	ASHRAE 90.1 Requirements
	Occupancy Sensors	ASHRAE 90.1 Requirements
Plug load		
	Average power density (W/ft^2)	See under Zone Summary
	Schedule	See under Schedules
Occupancy		
	Average people	See under Zone Summary
	Schedule	See under Schedules
Misc.		
	Elevator	
	Quantity	2
	Motor type	hydraulic
	Peak Motor Power (W/elevator)	16,055
	Heat Gain to Building	Interior
	Peak Fan/lights Power (W/elevator)	161.9
	Motor and fan/lights Schedules	See under Schedules
	Exterior Lighting	
	Peak Power (W)	14,385
	Schedule	See under Schedules

APPENDIX B

DESCRIPTION OF LARGE OFFICE BUILDING PROTOTYPE ANALYZED

<table>
<tr><td colspan="5">ASHRAE 90.1 Prototype Building Modeling Specifications</td></tr>
<tr><td></td><td>Item</td><td colspan="3">Description</td></tr>
<tr><td colspan="5">Program</td></tr>
<tr><td></td><td>Vintage</td><td colspan="3">NEW CONSTRUCTION</td></tr>
<tr><td></td><td>Location (Representing All 17 Climate Zones)</td><td>Zone 1A: Miami (very hot, humid)
Zone 1B: Riyadh, Saudi Arabia (very hot, dry)
Zone 2A: Houston (hot, humid)
Zone 2B: Phoenix (hot, dry)
Zone 3A: Memphis (warm, humid)
Zone 3B: El Paso (warm, dry)
Zone 3C: San Francisco (warm,marine)</td><td>Zone 4A: Baltimore (mild, humid)
Zone 4B: Albuquerque (mild, dry)
Zone 4C: Salem (mild, marine)
Zone 5A: Chicago (cold, humid)
Zone 5B: Boise (cold, dry)
Zone 5C: Vancouver, BC (cold, marine)</td><td>Zone 6A: Burlington (cold, humid)
Zone 6B: Helena (cold, dry)
Zone 7: Duluth (very cold)
Zone 8: Fairbanks (subarctic)</td></tr>
<tr><td></td><td>Available fuel types</td><td colspan="3">gas, electricity</td></tr>
<tr><td></td><td>Building Type (Principal Building Function)</td><td colspan="3">OFFICE</td></tr>
<tr><td></td><td>Building Prototype</td><td colspan="3">LARGE OFFICE</td></tr>
<tr><td colspan="5">Form</td></tr>
<tr><td></td><td>Total Floor Area (sq feet)</td><td colspan="3">498,600
(240 ft x 160 ft)</td></tr>
<tr><td></td><td>Building shape</td><td colspan="3"> </td></tr>
</table>

	Aspect Ratio	1.5
	Number of Floors	12 (plus basement)
	Window Fraction (Window-to-Wall Ratio)	40% of above-grade gross walls 37.5% of gross walls (including the below-grade walls)
	Window Locations	even distribution among all four sides
	Shading Geometry	none
	Azimuth	non-directional
	Thermal Zoning	
		Perimeter zone depth: 15 ft. Each floor has four perimeter zones and one core zone. Percentages of floor area: Perimeter 33%, Core 67%
	Floor to floor height (feet)	13
	Floor to ceiling height (feet)	9
	Glazing sill height (feet)	3 ft
Architecture		
	Exterior walls	
	Construction	Mass (pre-cast concrete panel): 8 in. Heavy-Weight Concrete + Wall Insulation + 0.5 in. gypsum board
	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	ASHRAE 90.1 Requirements Nonresidential; Walls, Above-Grade, Steel-Framed
	Dimensions	based on floor area and aspect ratio
	Tilts and orientations	vertical
	Roof	
	Construction	Built-up Roof: Roof membrane+Roof insulation+metal decking

	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	ASHRAE 90.1 Requirements Nonresidential; Roofs, Insulation entirely above deck
	Dimensions	based on floor area and aspect ratio
	Tilts and orientations	horizontal
	Window	
	Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio
	Glass-Type and frame	Hypothetical window with the U-factor and SHGC shown below
	U-factor (Btu / h * ft^2 * °F)	ASHRAE 90.1 Requirements Nonresidential
	SHGC (all)	
	Visible transmittance	Hypothetical window with the exact U-factor and SHGC shown above
	Operable area	0%
	Skylight	
	Dimensions	Not Modeled
	Glass-Type and frame	NA
	U-factor (Btu / h * ft^2 * °F)	
	SHGC (all)	
	Visible transmittance	
	Foundation	
	Foundation Type	Basement (unconditioned)
	Construction	8" concrete wall; 6" concrete slab, 140 lbs heavy-weight aggregate
	Thermal properties for ground level floor U-factor (Btu / h * ft2 * °F) and/or R-value (h * ft2 * °F / Btu)	ASHRAE 90.1 Requirements Nonresidential; Floors, Mass
	Thermal properties for basement walls	No insulation
	Dimensions	based on floor area and aspect ratio
	Interior Partitions	
	Construction	2 x 4 uninsulated stud wall
	Dimensions	based on floor plan and floor-to-floor height
	Internal Mass	6 inches standard wood (16.6 lb/ft^2)

	Air Barrier System			
	Infiltration	Peak: 0.2016 cfm/sf of above grade exterior wall surface area (when fans turn off) Off Peak: 25% of peak infiltration rate (when fans turn on)		
HVAC				
	System Type			
	Heating type	Gas boiler		
	Cooling type	Two water-cooled centrifugal chillers		
	Distribution and terminal units	VAV terminal box with damper and hot-water reheating coil Zone control type: minimum supply air at 30% of the zone design peak supply air.		
	HVAC Sizing			
	Air Conditioning	autosized to design day		
	Heating	autosized to design day		
	HVAC Efficiency			
	Air Conditioning	Varies by climate locations based on cooling capacity		
	Heating	Varies by climate locations based on heating capacity		
	HVAC Control			
	Thermostat Setpoint	75°F Cooling/70°F Heating		
	Thermostat Setback	85°F Cooling/60°F Heating		
	Supply air temperature	Maximum 110F, Minimum 52F		
	Chilled water supply temperatures	44 F		
	Hot water supply temperatures	180 F		
	Economizers	Air-side economizer only in all the zones except: 1a, 1b, 2a, 3a, and 4a.		
	Ventilation	See under Outdoor Air		
	Demand Control Ventilation	No		
	Energy Recovery	No		
	Supply Fan			
	Fan schedules	See under Schedules		
	Supply Fan Total Efficiency (%)	60% to 62% depending on the fan motor size		

	Supply Fan Pressure Drop	Various depending on the fan supply air cfm
	Pump	
	Pump Type	CHW and HW: variable speed; CW: constant speed
	Rated Pump Head	CHW: 56 ft HW and CW: 60 ft
	Pump Power	autosized
	Cooling Tower	
	Cooling Tower Type	open cooling tower with two-speed fans
	Cooling Tower Power	autosized
	Service Water Heating	
	SWH type	Storage Tank
	Fuel type	Natural Gas
	Thermal efficiency (%)	80%
	Tank Volume (gal)	260
	Water temperature setpoint	180 F
	Water consumption	See under Schedules
Internal Loads & Schedules		
	Lighting	
	Average power density (W/ft^2)	ASHRAE 90.1 Lighting Power Densities Using the Building-Area Method
	Schedule	See under Schedules
	Daylighting Controls	No
	Occupancy Sensors	No
	Plug load	
	Average power density (W/ft^2)	See under Zone Summary
	Schedule	See under Schedules
	Occupancy	
	Average people	See under Zone Summary

	Schedule	See under Schedules		
Misc.				
	Elevator			
	Quantity		12	
	Motor type		traction	
	Peak Motor Power Watts per elevator		20370	
	Heat Gain to Building		Exterior	
	Peak Fan/lights Power Watts per elevator		161.9	
	Motor and fan/lights Schedules		See under Schedules	
	Exterior Lighting			
	Peak Power	60,216 watts		
	Schedule	Astronomical Clock		