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Demand Response with Pre-Cooling Study of a Small Commercial Building with Thermal Mass in California

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PREPARED BY:

Primary Author(s):
Sila Kiliccote
Rongxin Yin
Mary Ann Piette
Elliot Nahman
John Goins
Ed Arens

Lawrence Berkeley National Laborator
1 Cyclotron Road
Berkeley, CA 94720

And

University of California at Berkeley
200 California Hall
Berkeley, CA 94720

Contract Number: 500-26-026

Prepared for:

California Energy Commission

David Hungerford
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

Previous field studies demonstrated the effectiveness of demand response (DR) control strategies to reduce the peak demand in large commercial buildings by utilizing the building thermal mass. Meanwhile, the occupancy surveys were conducted to evaluate the impact of various control strategies on the occupancy comfort. However, these field tests were conducted mostly in large commercial buildings with consistent occupancy behavior.

This project provided an opportunity to evaluate the effect of pre-cooling with zone temperature reset strategies to reduce peak demand in a small retail building in warm California climate. The customer comfort surveys were conducted to demonstrate the impact of DR strategies and unique occupancy behavior (short staying time, active state…) on occupancy comfort. Even though the 1-degree F granularity zone temperature setpoints limited the implementation of the exponential temperature setup, the "pre-cooling with step temperature reset" strategy worked well in the field tests. The test results show that the electricity demand during the peak period can be reduced, on average, as much as 44% of whole building power. However, the demand ramp at the beginning of the peak period weakens the effect of DR strategies for reducing the peak demand through the whole peak period. On the occupancy comfort side, based on the results from the comfort survey, the store is normally maintained between 70-72.5°F (21-22.5ºC), and 78% of its patrons feel comfortable.

Keywords: Demand response control strategies, building thermal mass, occupancy behavior, small commercial building, occupancy comfort,

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EXECUTIVE SUMMARY

Introduction

In previous studies, large commercial buildings were tested to evaluate the effectiveness of building thermal mass and various control strategies for reducing the peak demand, all with relatively small impacts on occupant comfort.

Project Purpose

This project aimed to evaluate the potential of pre-cooling as a DR strategy to reduce peak demand in small commercial buildings, and to study occupancy comfort in non-office buildings.

Project Results

A small commercial business was used to study the effect of the pre-cooling and DR control strategies for reducing the peak demand in a small retail building with heavy thermal mass. Impacts of control strategies were evaluated from the thermal energy side and occupancy comfort side.

- The demand profile predicted from the initial building model can better match the field test results, while underestimate the potential of the peak demand savings for the field-tested control strategy.
- Pre-cooling and DR control strategies worked well in the small retail building and were able to reduce the peak demand of the whole building significantly (20%-55%).
- There was no big rebound for the demand profile during the peak period on all the field test days.

Project Benefits

For this small retail facility, the field test results showed that pre-cooling a building with significant thermal mass during warm weather conditions improved potential peak demand savings during DR events. It also identified several uncertainties related to occupant behavior related to the DR response.

CHAPTER 1:
Background and Overview

Pre-cooling generally works as follows: the building is pre-cooled at night or early morning at moderately low zone temperature setpoints (68°F-70°F) and then the zone temperature setpoints are raised within the comfort zone (below 78°F) during peak electricity demand periods. The cooled building thermal mass and higher zone temperature setpoints lead to the reduction of on-peak cooling loads for the heating, ventilation, and air-conditioning (HVAC) systems.

The potential for using building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory and field studies. Optimal dynamic building control strategies were studied in a representative room in a large office building, the peak cooling load was reduced by as much as 40% (Morris et al, 1994). Keeney and Braun (1997) developed a building control strategy and conducted an experiment in a large office building. It was found that the pre-cooling strategy could limit the peak cooling load to 75% of the cooling capacity. Xu et al. (2004) demonstrated the potential for reducing peak electricity demand in moderate-mass commercial buildings by modifying the control of the HVAC systems. The field test results showed the chiller power was reduced by 80-100% during the peak period without causing thermal discomfort. A series of field tests in two commercial buildings in Northern California were conducted to investigate the effects of various pre-cooling and demand shed strategies. The cooling loads were reduced by 25-50% in peak hours for various control strategies. Xu et al. (2005) conducted a series of simulations and strategy analyses by using EnergyPlus to evaluate various demand response strategies. The initial models were revised and the parameters were adjusted to ensure the hourly simulation profiles matched the measured data.

In 2006, with the support from the California Energy Commission's PIER Demand Response Research Center, the Demand Response Quick Assessment Tool (DRQAT) was developed to predict demand reduction, operating cost savings, and occupant comfort impacts associated with using building thermal mass. Based on the EnergyPlus prototypical models, this tool allows users to specify a relatively small number of important parameters in order to determine a quick assessment for various building control strategies.

In 2008, the pre-cooling tests were conducted in eleven commercial buildings in the Tri-City Corporate center (Yin et al, 2010). The pre-cooling strategies were optimized with the assistance of DRQAT. For all tested buildings, the electrical demand during the peak period was reduced by 15-30% on DR event day. Meanwhile, the demand shed predicted by DRQAT matched well with the measured data on the DR event days.

With respect to the DR study in small commercial buildings, both of research and experimental test of demand response using building thermal mass have been done in previous studies. 30% reductions in peak cooling loads were achieved through demand-limiting strategies of precooling and afternoon setpoint adjustment (Lee et al, 2006; Braun et al, 2006). However,

comfort level changes associated with the DR control strategy hasn't been well investigated, in particular for short-stay customers in some small commercial buildings such as retail stores.

Project Objective

In previous studies, large commercial buildings were tested to evaluate the effectiveness of building thermal mass and various control strategies for reducing the peak demand, all with relatively small impacts on occupant comfort. The objective of this project is to evaluate the potential of pre-cooling as a DR strategy to reduce peak demand in small commercial buildings, and to study occupancy comfort in non-office buildings. It provides an opportunity to evaluate the impact of DR control strategies on the occupancy comfort where the occupants' behavior is unique (short staying time, active state…).

Chapter 1 provides an introduction with previous studies review, the background and the objectives of this research. Chapter 2 summarizes the methodologies used in this project. Chapter 3 outlines field test results that include load-shedding and thermal comfort surveys in a small size retail building with large thermal mass. Chapter 4 provides conclusions and recommendations for future work.

CHAPTER 2: Methodology

DR Optimization and Field Test

As a first step, the building energy manager completed a site survey. The purpose of the survey is to collect the basic building information that can be used to develop a building simulation model. Based on the collected information, an initial building model was developed with the assistance of DRQAT. For the initial model, the densities and schedules of occupancy, lighting and plug loads were derived from the benchmark prototypical retail building. Then proposed pre-cooling and DR control strategies were simulated to calculate the peak demand savings. Finally, an optimal control strategy was developed to be field tested in the building.

The control system in this building allows the operators to, for example, turn on or turn off the HVAC system and setup the zone temperature setpoints manually. Meanwhile, the zone temperature setpoints can only be adjusted in 1 degree increment. During the study period, the operator setup the proposed pre-cooling and DR control strategies and sent the energy and temperature data to Lawrence Berkeley National Laboratory (LBNL) and the Center for Built Environment (CBE).

Customer Comfort Survey

DR strategies strive to achieve a different objective than daily buildings operations. While daily building operations are designed to maximize occupant comfort while minimizing energy consumption, DR strategies strive to minimize peak demand on limited number of days in limited number of hours to find a detectable but at the same time acceptable comfort level for the occupants (Newsham 2008). In order to study and gage the effectiveness of the demand shifting strategies, CBE installed a free-standing, touch-screen kiosk system to survey customers in the store.

This survey kiosk is a full computer system with a touch screen interface, allowing researchers to gather a more complete picture of the occupants, their environments, and comfort level. The computer itself is a Windows based machine running a survey developed in Flash. The Flash authoring environment was chosen for its design flexibility and the relative ease to create a visually appealing user interface that would catch people's attention in the busy, colorful atmosphere of the Cost Plus World Market Store.

Figure 1: Image of Kiosk in the Store

The survey questions ask the customers to rate their comfort level at the time they take the survey, their comfort when they entered the store, their soak time (time spent in the store), and what clothing they were wearing, in order to assess the respondents clothing insulation value (Clo)[1]. The survey did not include a question about the respondent's metabolic activity/rate (Met), since this might confuse the respondent and make the survey too long. Because they are all customers shopping, Met can be assumed to be easy walking on level ground—2.0 met.

The comfort scale employed for the survey is a combination comfort-sensation scale as was used with the previous polling stations. Although customers are able to touch anywhere on the scale, there were prompts along the scale creating a 5-point scale:

- Too Warm! It Bothers Me
- Warm, but it doesn't bother me
- Just Right
- Cool, but it doesn't bother me
- Too Cold, it Bothers Me

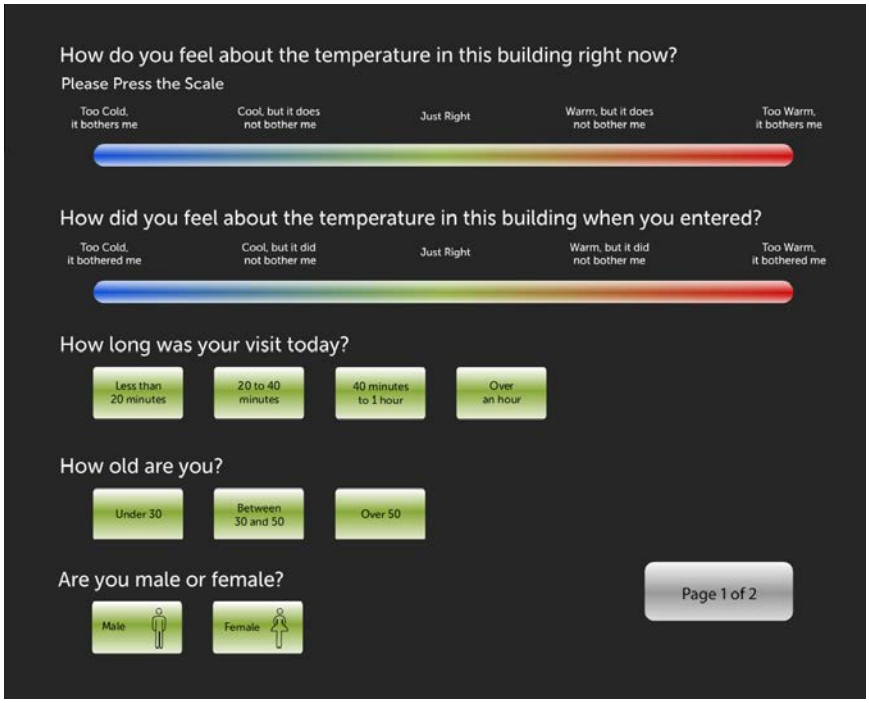
This comfort scale allows us to simultaneously ask the user their thermal comfort which taking into account their thermal sensation of the space. Traditionally in thermal comfort surveys, only a sensation scale would be used, inquiring about the respondents' perceptions of a space and

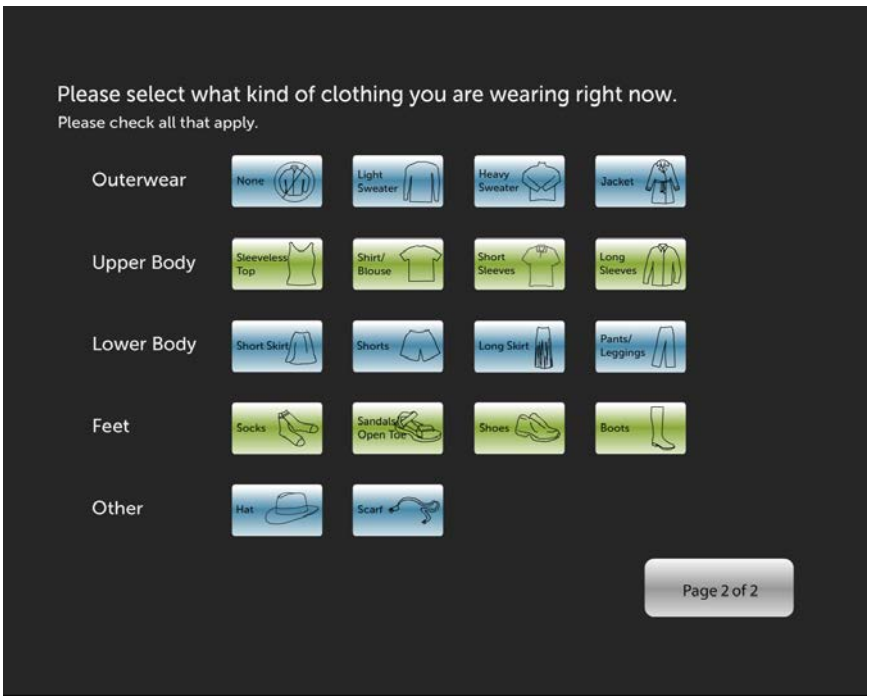
---

[1] [1] Clothing insulation may be expressed in clo units. The clo has the same dimensions (and roughtly the same magnitude) as the R value used to describe insulation used in residential and commercial construction. One clo is the amount of thermal resistance necessary to maintain thermal comfort for a sitting-resting subject in a normally ventilated room (air movement 20 ft/min or 10 cm/sec) at a temperature of 70°F (21.1°C) and a RH<50%. Clo units range from 0 (naked body) to 4 (Eskimo clothing with fur pants, coat, hood, etc.) with typical summer clothing ~ 0.6 clo and typical winter clothing ~ 1 clo.

the respondents' comfort assumed to be in the neutral range of that sensation scale. Alternatively, two separate scales could be used to gather the two variables. It should be noted that a neutral environment does not necessarily provide a comfortable environment. Combining these two scales into one not only shortens the length of the survey, avoids potential confusing on the part of the respondent, and ensures that we are gathering accurate comfort data. If both scales were used, a lot of text explaining the difference would be necessary to ensure the validity of the responses. The combined comfort-sensation scale is far more intuitive for a lay audience.

Figure 2: Screen Shots from the Kiosk


How do you feel about the temperature in this building right now?
Please Press the Scale
Too Cold, it bothers me
Cool, but it does not bother me
Just Right
Warm, but it does not bother me
Too Warm, it bothers me
How did you feel about the temperature in this building when you entered?
Too Cold, it bothered me
Cool, but it did not bother me
Just Right
Warm, but it did not bother me
Too Warm, it bothered me
How long was your visit today?
Less than 20 minutes
20 to 40 minutes
40 minutes to 1 hour
Over an hour
How old are you?
Under 30
Between 30 and 50
Over 50
Are you male or female?
Male
Female
Page 1 of 2


Please select what kind of clothing you are wearing right now.
Please check all that apply.
Outerwear
None
Light Sweater
Heavy Sweater
Jacket
Upper Body
Sleeveless Top
Shirt/ Blouse
Short Sleeves
Long Sleeves
Lower Body
Short Skirt
Shorts
Long Skirt
Pants/ Leggings
Feet
Socks
Sandals/ Open Toe
Shoes
Boots
Other
Hat
Scarf
Page 2 of 2

The kiosk included sensors to locally measure the air temperature and humidity. A USB temperature/humidity sensor was attached to the kiosk computer and logged the indoor environmental conditions constantly. When a customer submitted a survey response, their dataset is appended with a timestamp and temperature/humidity stamp. This allows researchers to correlate the respondent's responses with the environmental conditions present at the kiosk when they were taking the survey, as well as examine temperature/humidity trends I the store over time.

The kiosk computer was also connected to the internet via a 3G network wireless modem. This allowed researchers to remotely monitor the system and examine survey responses while the survey was still underway.

The kiosk was installed on September 9, 2009 around 12pm and ran until November 7, 2009 around 12pm. During that time period, there were a number of system outages due to unforeseen software conflicts between the wireless modem and the survey engine. This plagued the first half of the survey until the wireless modem was removed, disabling the remote login capabilities.

The kiosk was installed away from the front entrance of the store as to encourage a more typical residency period among the respondents. It was located on the opposite side of the checkouts from the front entrance along the store's secondary main aisle.

The survey itself was a self-administered survey and the respondents were self-selecting In order to notify occupants about the survey, signs were displayed requesting their participation. The signs read: "Help save energy in California. Take UC Berkeley's 1 minute survey." Additionally, occupants were told about the survey by store personnel while at the checkout. Being a self-selecting sample, the sample not being representative of the population is possibility.

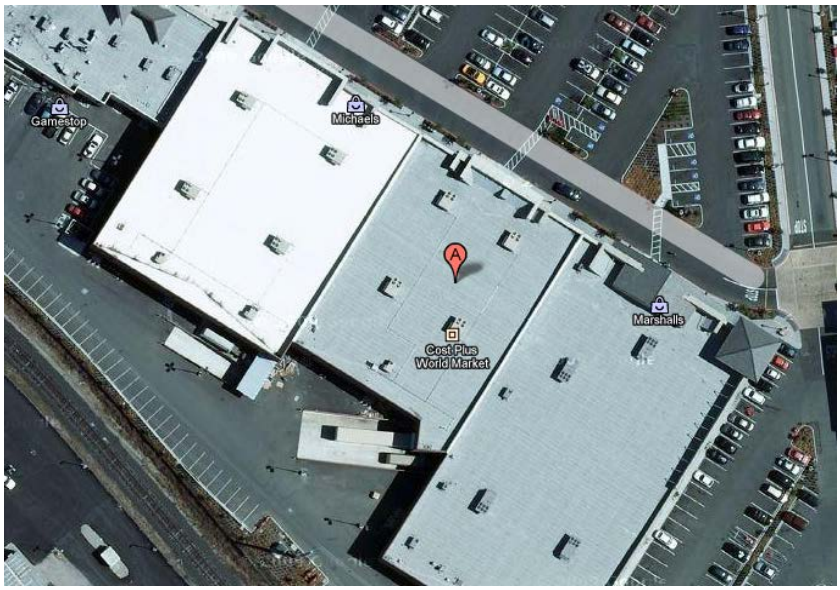
CHAPTER 3: Results

Test Site Description

The test site, Cost Plus World Market (CPWM) is a 18,894-square-foot typical retail building in t San Jose, California (**Figure** 3). CPWM, which mainly sell home furnishings and living room furniture, is a high mass rectangle building. The window-to-wall ratio on the north side is nearly 100%, and there is no window on other sides.

The typical operating hours of the building is 3:50-22:15, 6:50-22:15, 7:50-20:15 on weekdays, Saturday and Sunday, respectively. The store has five roof-top units. Two of the units serve the front sales area and each are 15-ton units. Two units that serve the rear of the sales area are 13-ton units. The remaining 6-ton unit serves the office area in the back. During normal operations, HVAC (Heating, ventilation and air-conditioning) system starts from 4 a.m. when employees come to work, and the normal zone temperature setpoint is around 73 °F.

Figure 3: Test Site – CPWM (Cost Plus World Market), San Jose, California



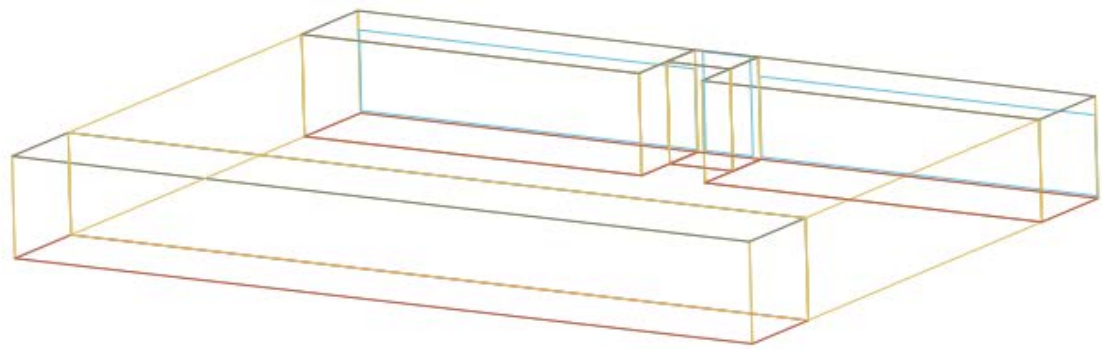
Proposed Pre-Cooling and DR Control Strategies

Demand Response Quick Assessment Tool (DRQAT) was used to optimize the pre-cooling and DR control strategies in this building. This tool is based on EnergyPlus simulations of prototypical retail building and HVAC equipment. Based on the previous experience of DR tests, two control strategies ("pre-cooling with step temperature reset" and "pre-cooling with exponential temperature reset") were proposed to be analyzed by using DRQAT. Through the comparison of peak demand savings, an optimal pre-cooling and DR control strategy is implemented in the building.

Model Descriptions

As shown in Figure 4, the building was divided into five zones – Front retail, point of sale, entry, core retail and back retail. The west-side wall and east-side wall are adjacent to other buildings. In order to simulate the actual building, it was assumed that there was no heat transfer between adjacent walls and these two exterior walls in the building model were modified to be heat insulated.

Figure 4: 3D View of Simulation Model Developed in DRQAT

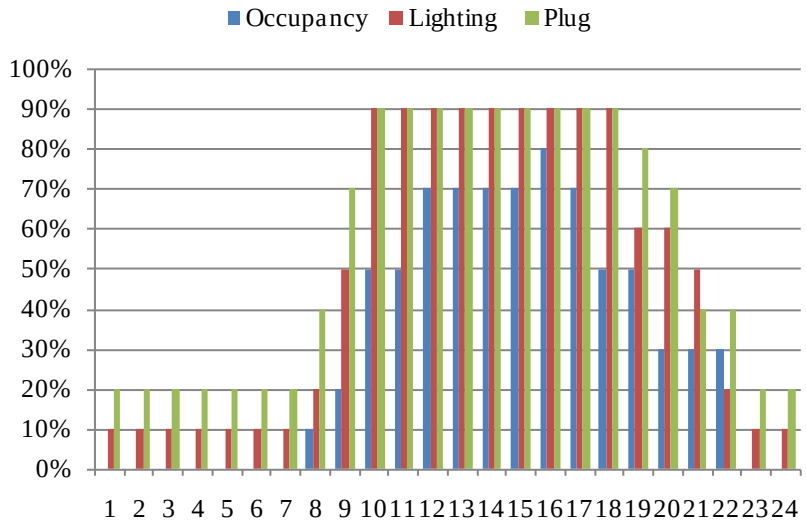


Building constructions of the initial simulation model met the requirements of the corresponding vintage of California's Energy Efficiency Standards for Residential and Non Residential buildings (Title 24, CEC 2005), as well as the occupancy, lighting and plug intensities. As shown in Table 1, ANSI/ASHRAE Standard 62.1-2007 gives estimated maximum occupancy density of 50 ft^2 per person for retail area and 200 ft^2 per person for entry area. The lighting and plug densities vary with the primary function for each zone as shown in Table 1. Figure 5 shows the schedules of occupancy, lighting and plug load for the initial model, which were obtained from the commercial buildings benchmark models (Torcellini et al, 2005).

Table 1: Building Internal Loads for Initial Simulation Model

Primary Function	Occupancy (ft^2/Person)	Lighting (W/ft^2)	Plug (W/ft^2)
Front Retail	50	1.7	0.3
Point of Sale	50	1.7	2.0
Entry	200	1.1	0.0
Core Retail	50	1.7	0.3
Back	50	0.8	0.75

Figure 5: Schedules of Internal Loads (Occupancy, lighting and plug)



Simulation Results of Various Strategies

Figures 6 and 7 show the proposed pre-cooling and DR strategies: "pre-cooling with exponential temp reset" and "pre-cooling with steps temp reset", respectively. The initial assumption was that this site would participate in the Peak Day Pricing rate with PG&E. According to this rate, on upto 15 days in between May and October, between 2 pm and 6 pm, there will be a $0.90/kWh increase in the price of electricity.

For the pre-cooling strategy, 10 am to 2 pm were selected as the pre-cooling period. During this period, the zone temperature setpoints, normally at 73°F was reduced by 1°F at 10 am. From 11 am to 2 pm, the zone temperature setpoints were reduced to 71°F.During the DR period, from 2 pm to 6 pm, the setpoints were raised exponentially to 77°F. After 6 pm, before the system was shut off, the setpoints were rolled back to normal setpoints (73°F). The second strategy was termed as "pre-cooling with steps temperature reset". While the pre-cooling period was operated the same as the first strategy, the temperature setpoints were raised up by two steps rather than exponentially in the afternoon period. The setpoints were raised to 76°F from 2 pm to 4 pm. At 4 pm, the zone temperature setpoints were reset to 77°F and remained there until 6 pm. After 6pm, the setpoints were reset to normal setpoint (73°F) until the HVAC system was turned off at the end of the day.

Figure 6: Proposed Pre-Cooling with Exponential Temp Reset

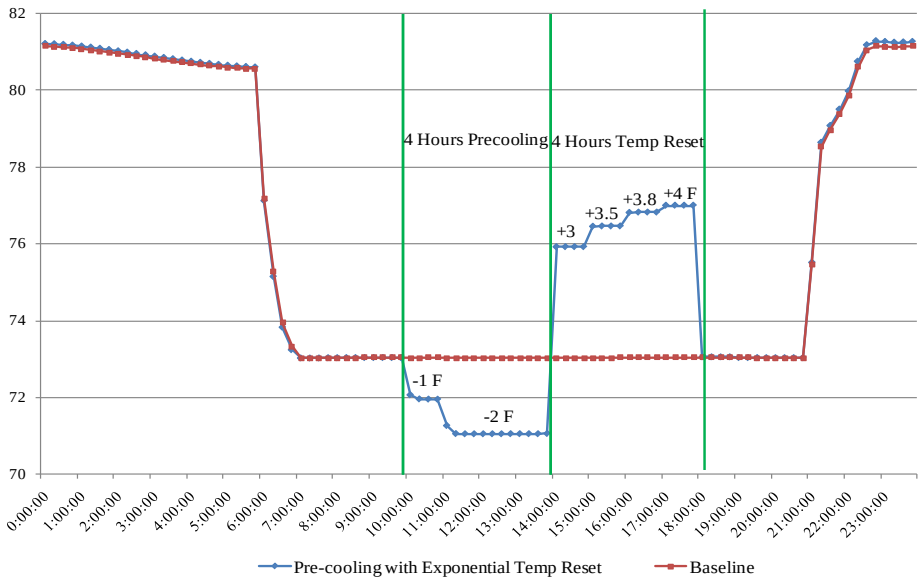
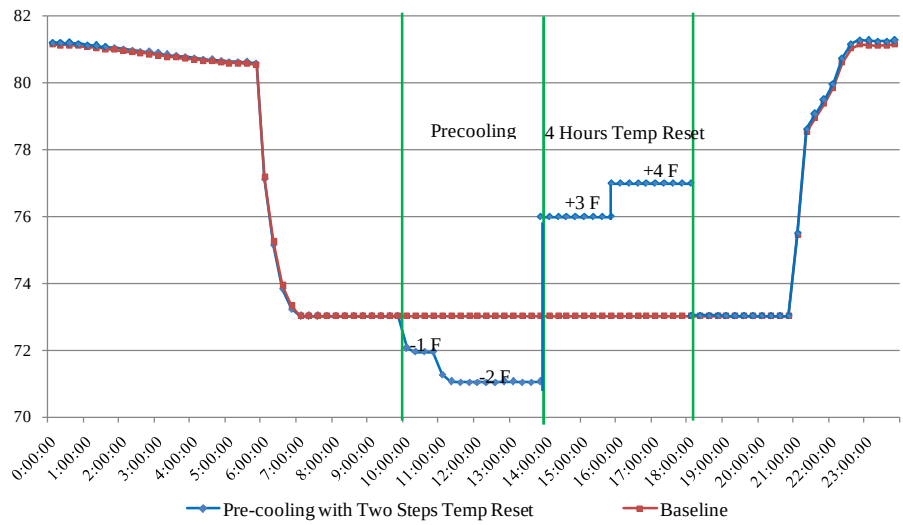


Figure 7: Proposed Pre-Cooling with Steps Temp Reset



Proposed pre-cooling and DR strategies were simulated in the initial simulation model. Figure 8 and Figure 9 show the simulation results of the whole building power for the baseline model and DR models. The two DR strategies have identical load profiles during the pre-cooling period. During the peak period, the peak demand power were almost same for it can be clearly seen that "pre-cooling with exponential temp reset" strategy achieved flatter load profiles than "pre-cooling with steps temp reset" strategy. The characteristic of the load profile is influenced by the actual building operation and the outside weather conditions.

Figure 8: Simulation Results of "Pre-Cooling with Exponential Temp Reset"

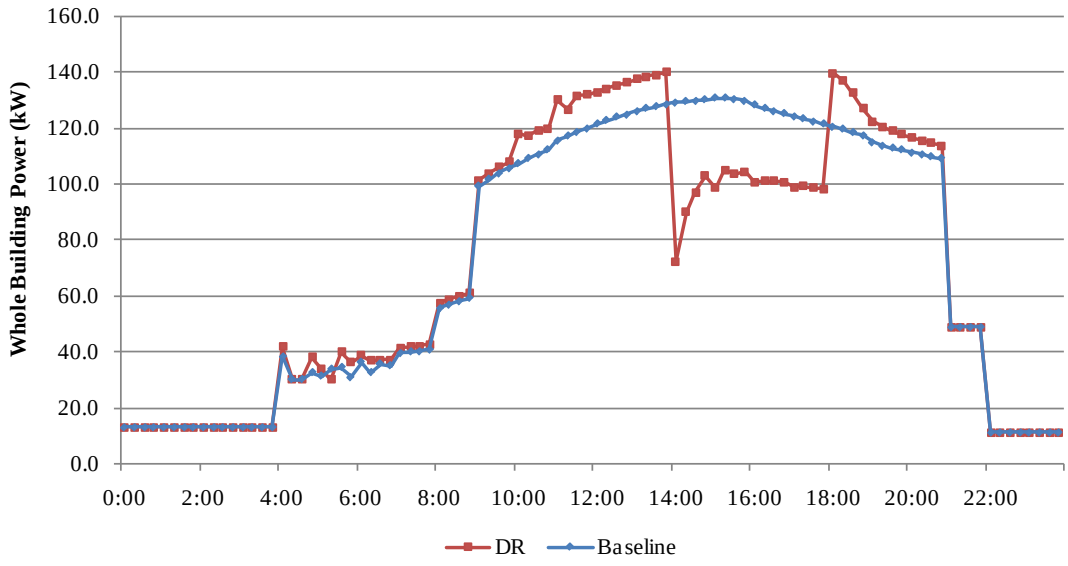
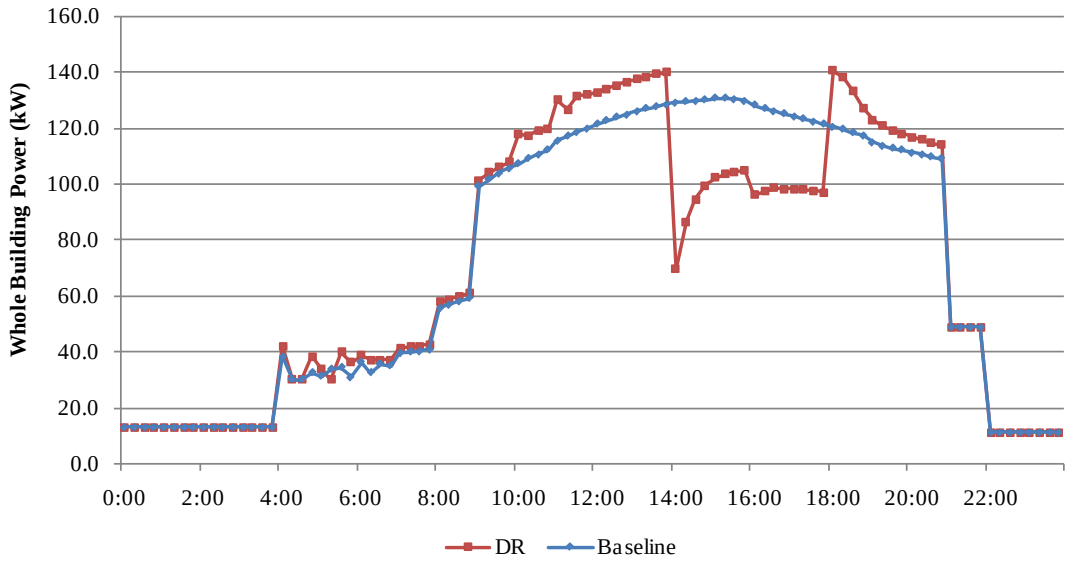


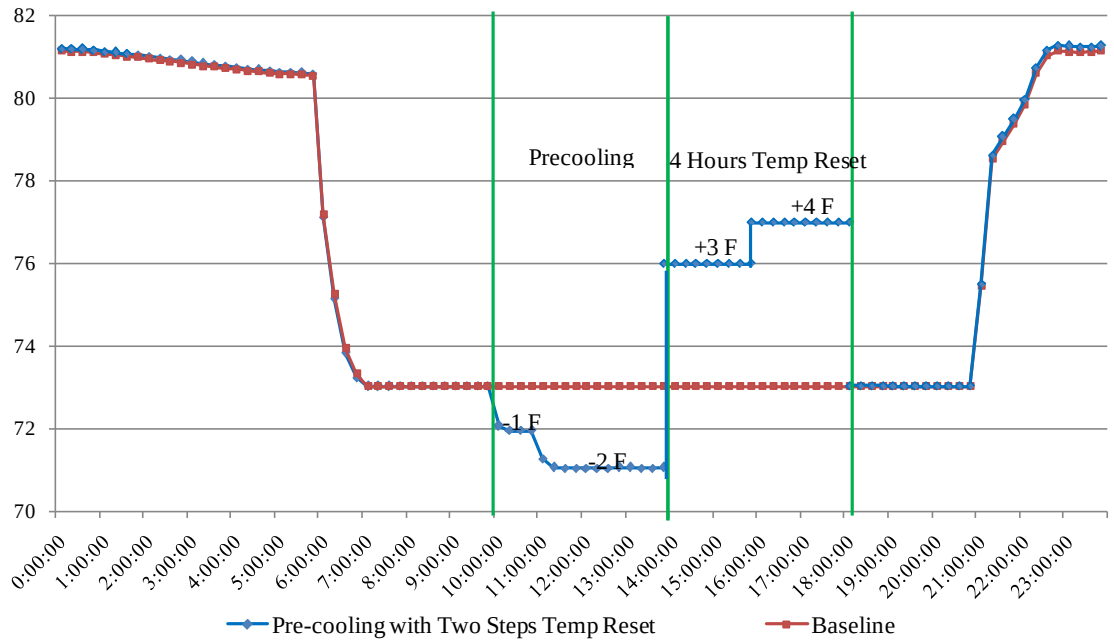
Figure 9: Simulation Results of "Pre-Cooling with Steps Temp Reset"



Field Tested Strategies

"Pre-cooling with exponential temp reset" strategy was proposed to be implemented in the building due flatter load profile. However, the zone temperature setpoints can only be adjusted manually and in 1 degree increments. Therefore, "pre-cooling with steps temp reset" (Figure 10) was field tested instead of "pre-cooling with exponential temp reset".

Figure 10: Field Tested Demand Response Strategy



Field Test Data Analysis

Baseline Model

Previous research recommended a weather regression baseline model without adjustments for morning load variations to estimate the demand saving from implementing the DR strategies (Coughlin, Piette et al, 2008). With respect to this baseline model, the whole building power baseline is estimated using a regression model that assumes that whole building power is linearly correlated with outside air temperature.

Pre-cooling Test 1 – 9/11/2009

The first pre-cooling test was conducted on 9/11/2009, when the outside air temperature was around 90 °F. The results in Figure 11 show that the whole building demand power was reduced by 21.2% on average during the DR period compared to baseline model. At the beginning of the D period, the whole building demand decreased suddenly with the adjustment of the zone temperature setpoints. This is transient savings due to fans and compressors shutting off. As the zone temperatures start to increase, the system adjusts to the new setpoints by operating in reduced capacity and reaches a steady state period. Table 2 presents the summary results of DR test on 9/11/2009. The peak demand power was reduce by 30 kW.

Figure 11: Pre-Cooling and DR Test at CPWM on 9/11/2009

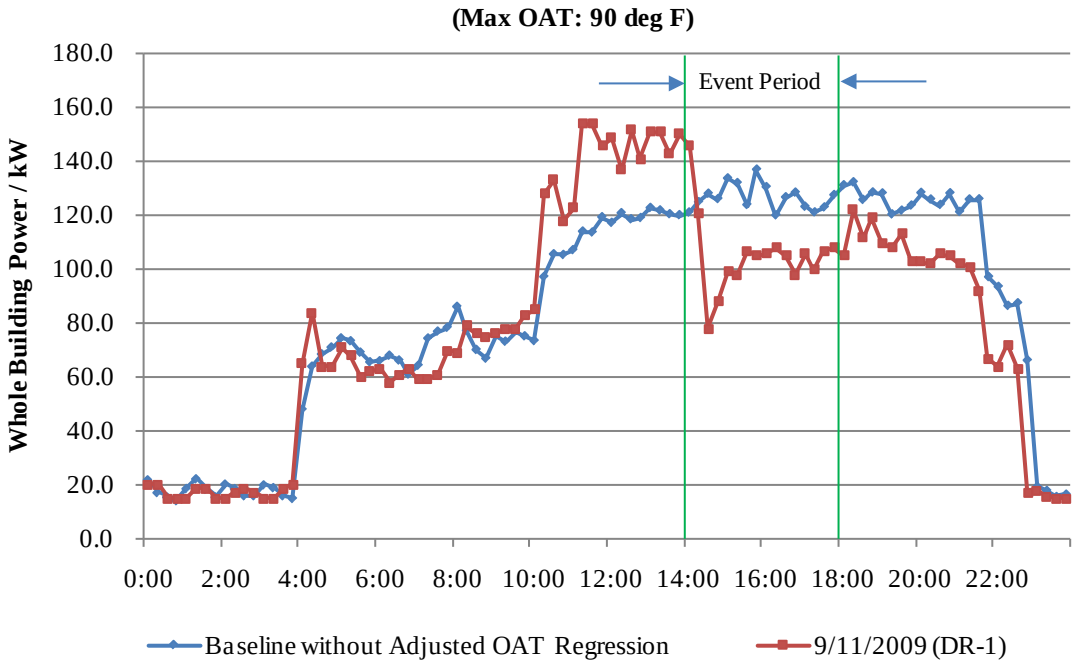


Table 2: DR Field Test Results on 9/11/2009

Hourly Interval	kW		W/sq ft		WBP%	
	Max	Ave	Max	Ave	Max	Ave
14:00 – 15:00	50.1	31.7	2.65	1.68	37.4%	24.7%
15:00 – 16:00	34.0	26.8	1.80	1.42	24.8%	20.5%
16:00 – 17:00	30.5	20.4	1.61	1.08	23.7%	16.3%
17:00 – 18:00	26.2	20.7	1.39	1.10	20.0%	16.5%

Pre-cooling Test 2 – 9/21/2009

The results of tests on September 21, 2009 (Figure 12) showed that the DR control strategy worked effectively in reducing peak demand during the peak period. The peak demand of the whole building was reduced by 37.7% on average during the DR period. After 6 pm, the operator reset the zone temperature to the normal setpoints and then decreased the zone temperature setpoints to 77 °F until the HVAC system was shut down. The rebound after the event is due to the adjustments of zone temperatures. As presented in Table 3, the peak demand was reduced by an average 50 kW over four hours, 37.7% of the peak demand.

Figure 12: Pre-Cooling and DR Test at CPWM on 9/21/2009

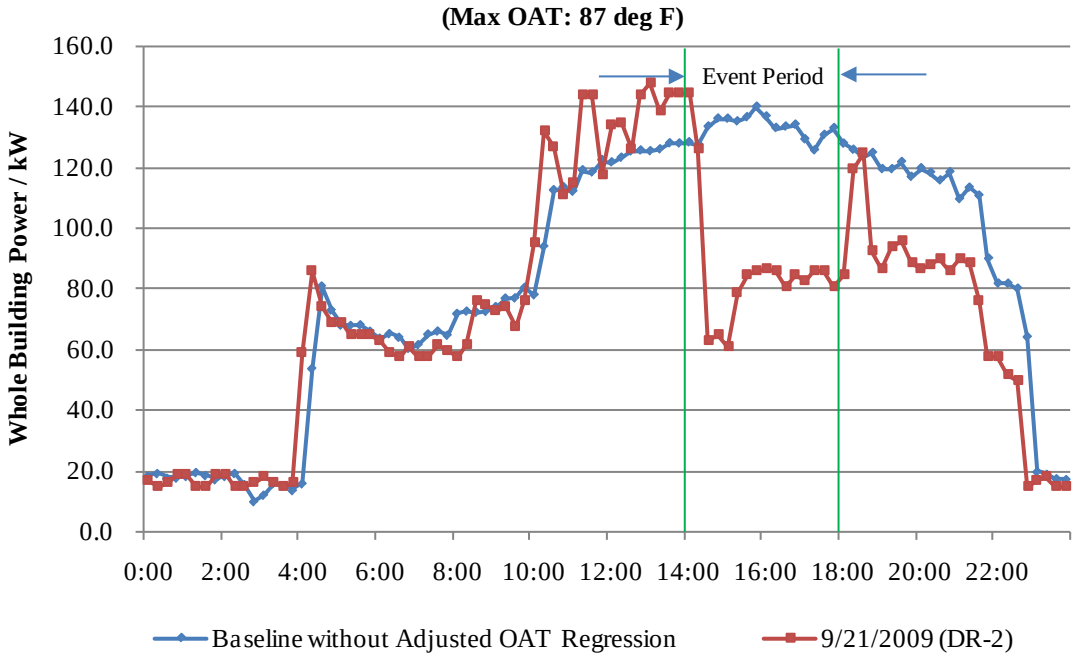


Table 3: DR Field Test Results on 9/21/2009

Hourly Interval	kW		W/sq ft		WBP%	
	Max	Ave	Max	Ave	Max	Ave
14:00 – 15:00	75.0	54.5	3.97	2.89	55.1%	40.9%
15:00 – 16:00	56.2	52.9	2.97	2.80	40.1%	38.6%
16:00 – 17:00	52.4	48.7	2.78	2.58	39.1%	36.8%
17:00 – 18:00	52.0	44.8	2.75	2.37	39.1%	34.6%

Pre-cooling Test 3 – 9/23/2009

For the third pre-cooling test on 9/23/2009, the DR strategy worked well during the peak period and following hours. After 3 p.m., the whole building demand power was reduced as much as 49.9% in average. Compared to previous field tests, the building operator kept the zone temperature setpoints until HVAC system turned off. The maximum demand savings reached to 3.92 W/sq ft.

Table 4 presents the summary field test results on 9/23/2009. Leave alone the demand ramp, the peak demand was reduced by 57 kW. Different from the second field test, the demand profile kept flat after the peak period.

Figure 13: Pre-Cooling and DR Test at CPWM on 9/23/2009

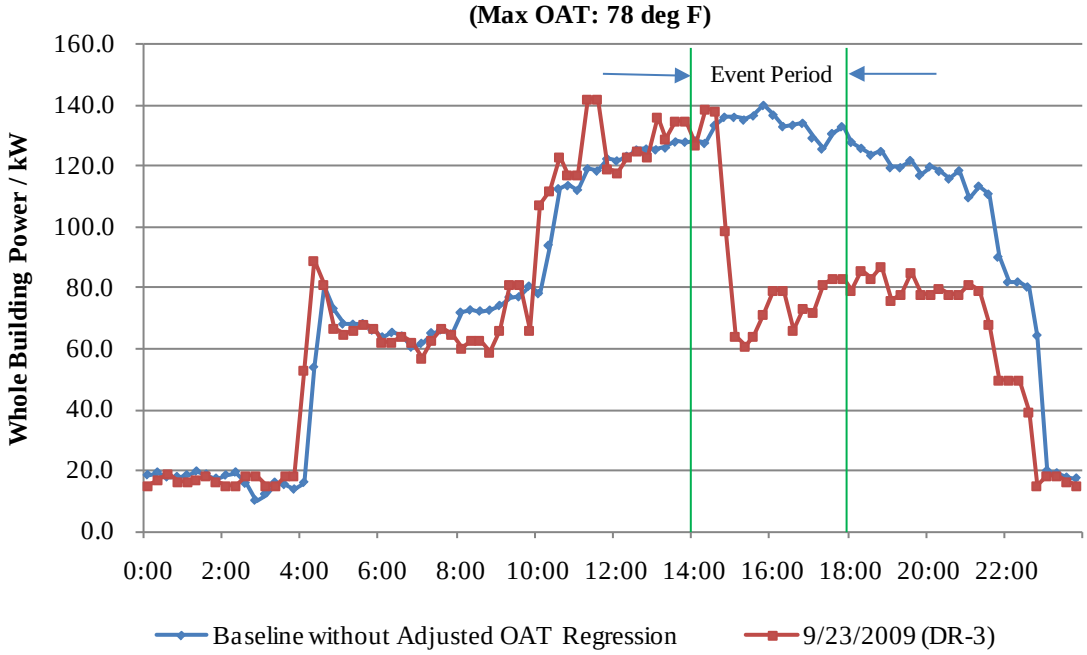


Table 4: DR Field Test Results on 9/23/2009

Hourly Interval	kW		W/sq ft		WBP%	
	Max	Ave	Max	Ave	Max	Ave
14:00 – 15:00	72.0	23.3	3.81	1.23	52.9%	17.5%
15:00 – 16:00	74.2	68.4	3.92	3.62	53.0%	49.9%
16:00 – 17:00	67.4	60.0	3.57	3.17	50.3%	45.3%
17:00 – 18:00	50.0	47.8	2.64	2.53	37.6%	37.0%

Economic Analysis

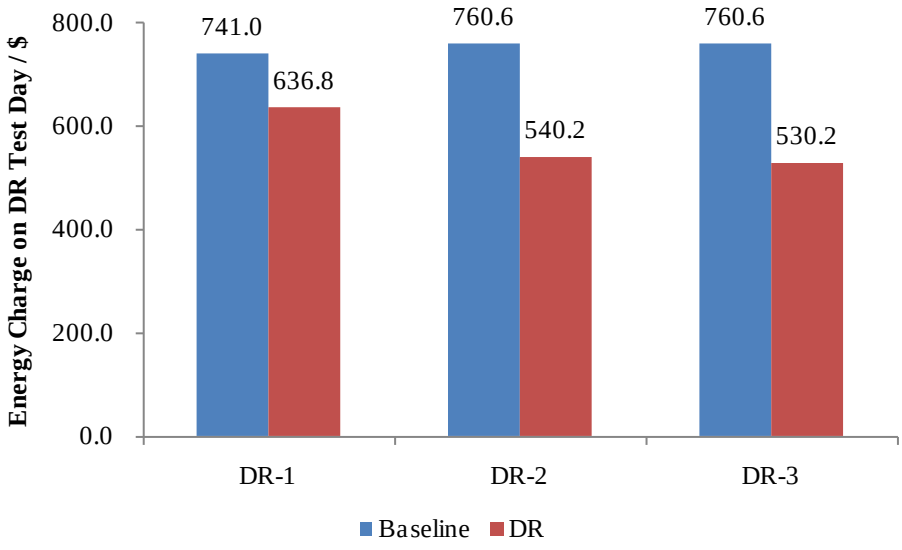
Based on peak demand power and locations, Pacific Gas and Electric Company (PG&E)'s rate schedule A10S – TOU/PDP is used for small-size commercial customers with registered demand equal or below 200 kW. Peak Day Pricing (PDP) is a new rate plan proposed by PG&E to improve the reliability of the electrical grid and reduce greenhouse gas emissions. Under PDP, the design basis for rates is 12 PDP calls per year. PDP event days are generally triggered by high temperature. Table 5 presents the summer TOU (Time-of-Use) and PDP rate programs for small commercial customers.

Table 5: Summer Rate Programs for Small Commercial Customers

Rate Schedule	Energy Charge ($/per kWh)			Demand Charge ($/kW)	PDP Adder ($/per KWh)
	On-Peak	Mid-Peak	Off-Peak		Peak Days
A10S TOU	0.16628	0.14370	0.13026	11.32	-
A10S PDP	0.15573	0.13315	0.11971	9.78	0.90
PG&E: Peak hours (12 p.m. to 6 p.m.), off-peak hours (9:30 p.m. to 8:30 a.m.)					

Figure 14 shows the comparison of energy charge between the DR test days with pre-cooling and baseline days. The daily energy charge savings ranged from 14.0% to 30.3%, which is a result of the peak demand savings. In this building, demand charges are calculated based on the monthly maximum demand power during on-peak period. If the building runs this optimal DR strategy all through the summer period, the demand charge can be reduced by as much as 40%, around $557.5 per month.

Figure 14: Energy Charge on Pre-cooling and DR Test Days and Baseline Days



Comfort Survey Results

There were a number of unique characteristics of this comfort survey. First, the soak time of the respondents was relatively short. Second, the number of responses collected on a given day was small, averaging about 5 per day, but, due to the length of the survey, a large number of responses were collected (218 responses).

The survey asked respondents, "How long was your visit today?" with the possible answers: "< 20 minutes", "20 to 40 minutes", "40 minutes to 1 hour", and "Over an hour". The most typical response was "< 20 minutes" (109 responses) followed by "20 to 40 minutes" (68 responses)(Figure 2).

Due to the small number of responses collected during the demand response days (10 responses), it is not possible to make any meaningful statistical comparisons between the test days and baseline days. However, the collective responses from both test days and non-tests days can be pooled to generate a statistically significant dataset.

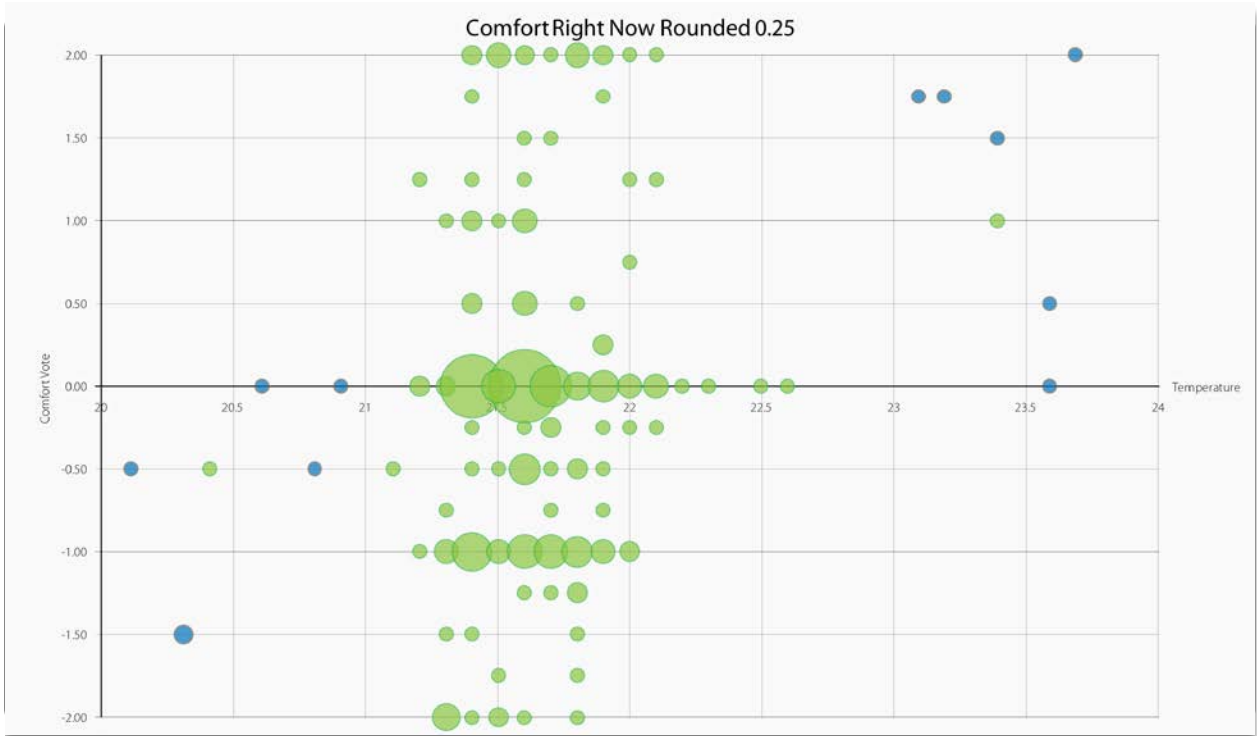
Goal

The goal of this analysis is to examine the results from the survey and determine the efficacy of the store to provide comfort at different temperature ranges.

Visual Analysis of the Data

Results of the survey show a high degree of variability in the comfort responses at any given indoor temperature (Figure 15). The survey responses correspond to the five-point scale: +2: "Too Hot, It Bothers Me", +1: "Warm, but it does not bother me", 0: "Just Right", -1: "Cool, but it does not bother me", and -2: "Too Cold, it bothers me". The green data points represent results from non-test days and the blue dots represent responses from demand response test days.

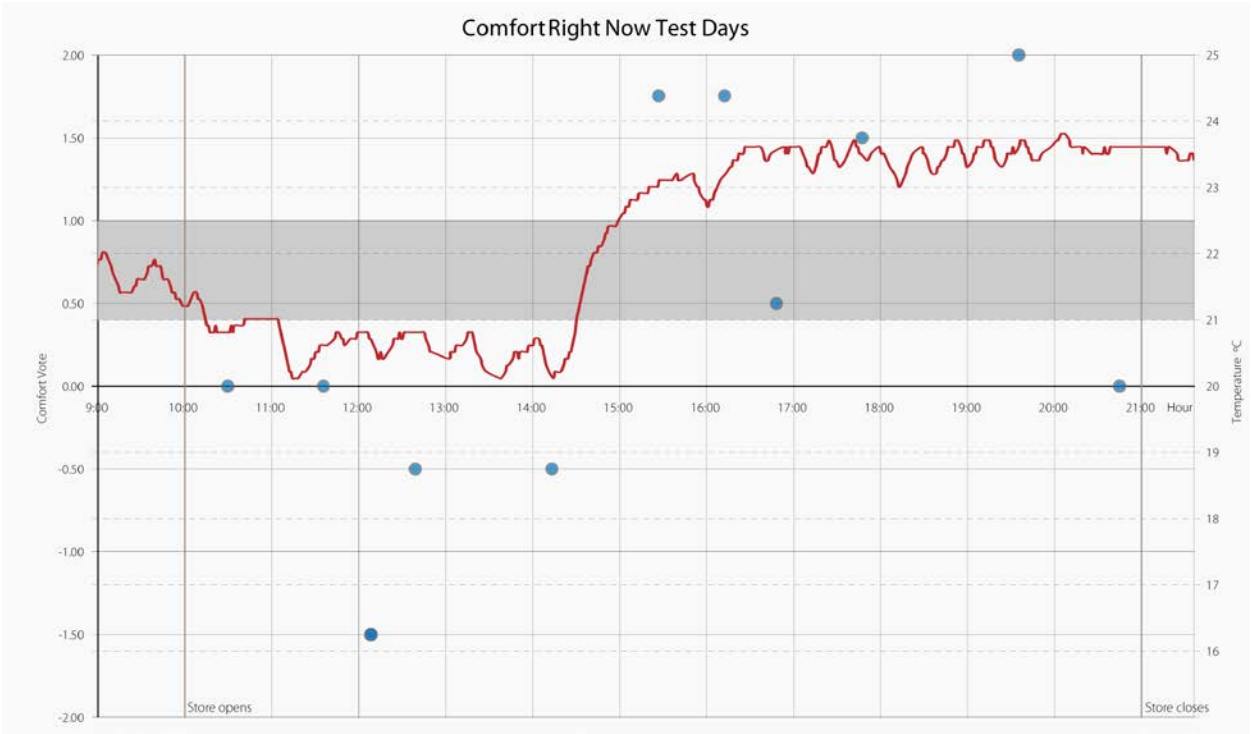
Figure 15: Comfort Right Now Scatter Plot



The responses from the demand response test days all fall outside the normal operating range of the store. Figure 16 illustrates all the test day responses with respect to the time of the day

and shows the interior temperature curve as measured by the survey kiosk on the test day, 23 September 2009; the store's normal operating range is also highlighted. As can be seen on this graph, the pre-cooling and coasting strategy afforded the store a very brief period of passing through its normal range and accounts for why all responses fall outside of this range.

Figure 16: Test Days' Responses and Temperature during a Day



Respondent reported Clo values had a great variability, from 0.22 clo to 1.8 clo, as can be seen in Figure 17. As clothing levels obviously have an effect on a respondent's perception of the thermal environment, comfort/sensation responses were normalize to 0.5 clo as shown in Figure 04. ASHRAE Fundamentals section 8.12 states that comfort zones move 0.6K for each 0.1 change in clo. Based on this and ASHRAE 55-2004 comfort model, comfort/sensation responses were normalized with the following equation: Comfort Vote – (1.1 * (0.2 to 0.5) clo + 1.1 * (0.5 to 0.7) clo + 0.9 *(0.7 to 0.9) clo +0.7 * (0.9 to 1.1) clo +0.6 * (1.1 to 1.3) clo+0.5 * (1.3 to 1.8) clo)

Figure 17: Clo Values Breakdown

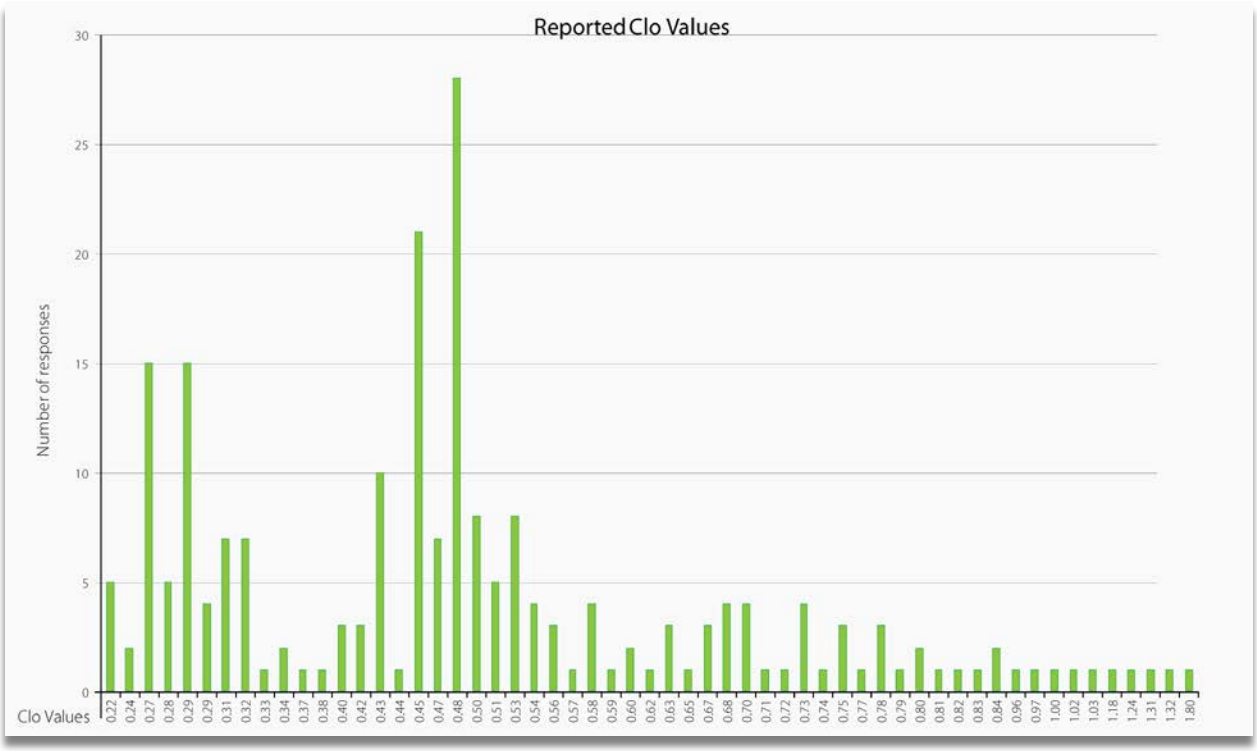
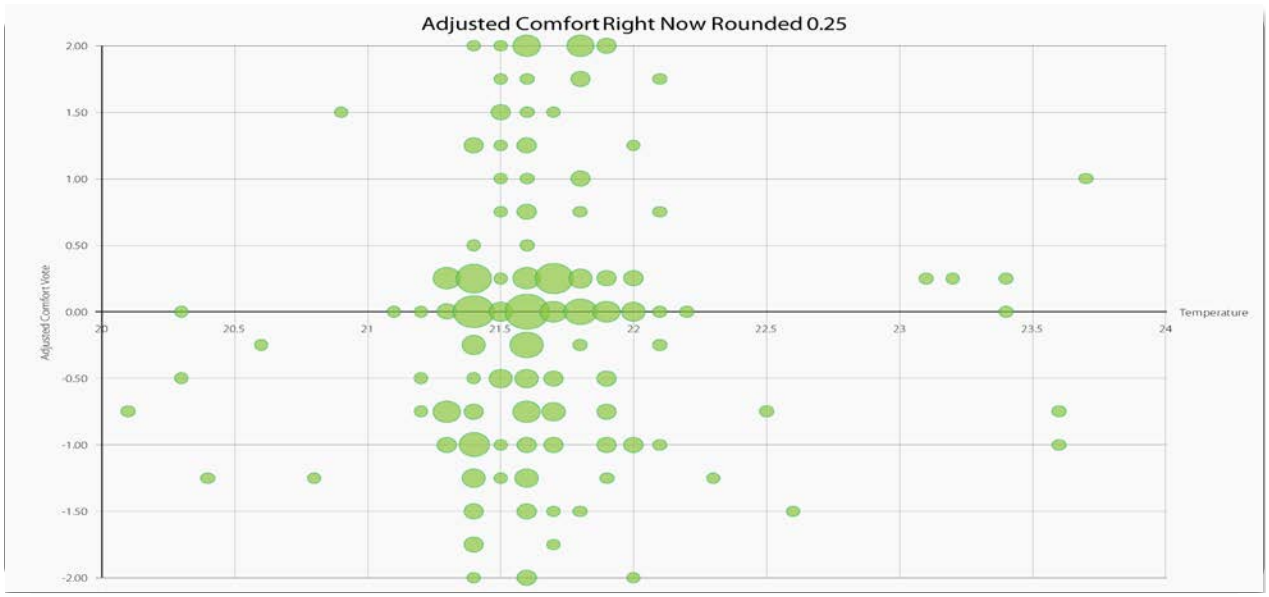


Figure 18: Adjusted Comfort Right Now Scatter Plot



To help identify the general trend in the comfort sensation data, averages for different temperature rangers were calculated. Figure 18 shows the data with a spline average at the 0.1°C level, 0.5°C level, and 1.0°C level. As can be seen, the smaller the temperature range, the more variability there is in the average due to the relatively small number of responses for each temperature, particularly at the extremes of the data. With the 1.0°C spline, these variations get

smoothed out and illustrate the general trend of increased responses of warm sensation with increased temperatures.

Figure 19: Comfort Right Now Scatter Plot with Means

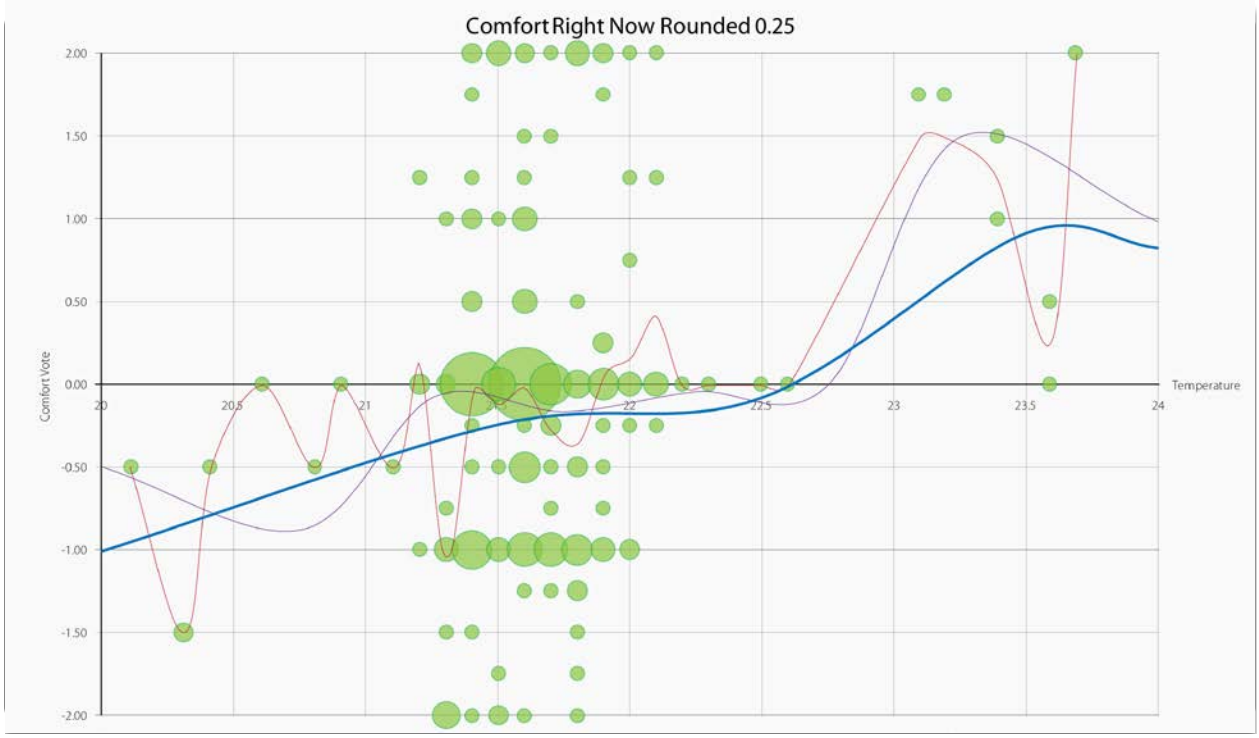
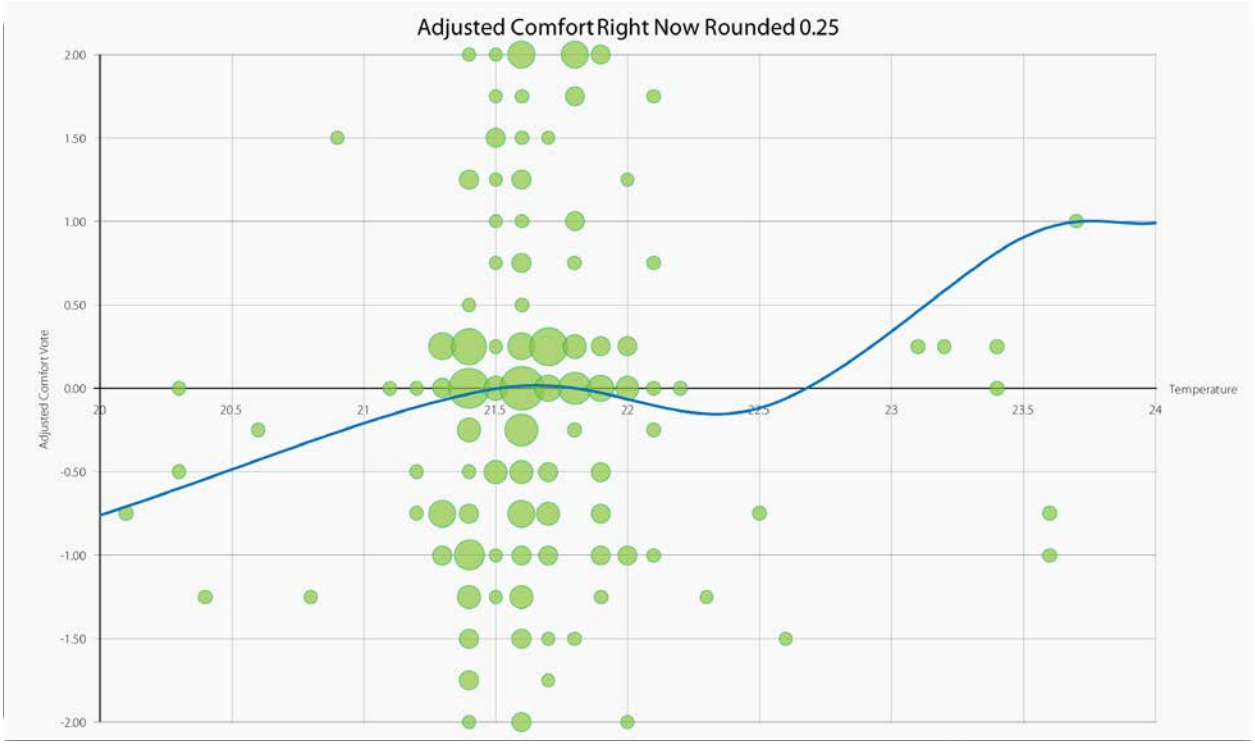


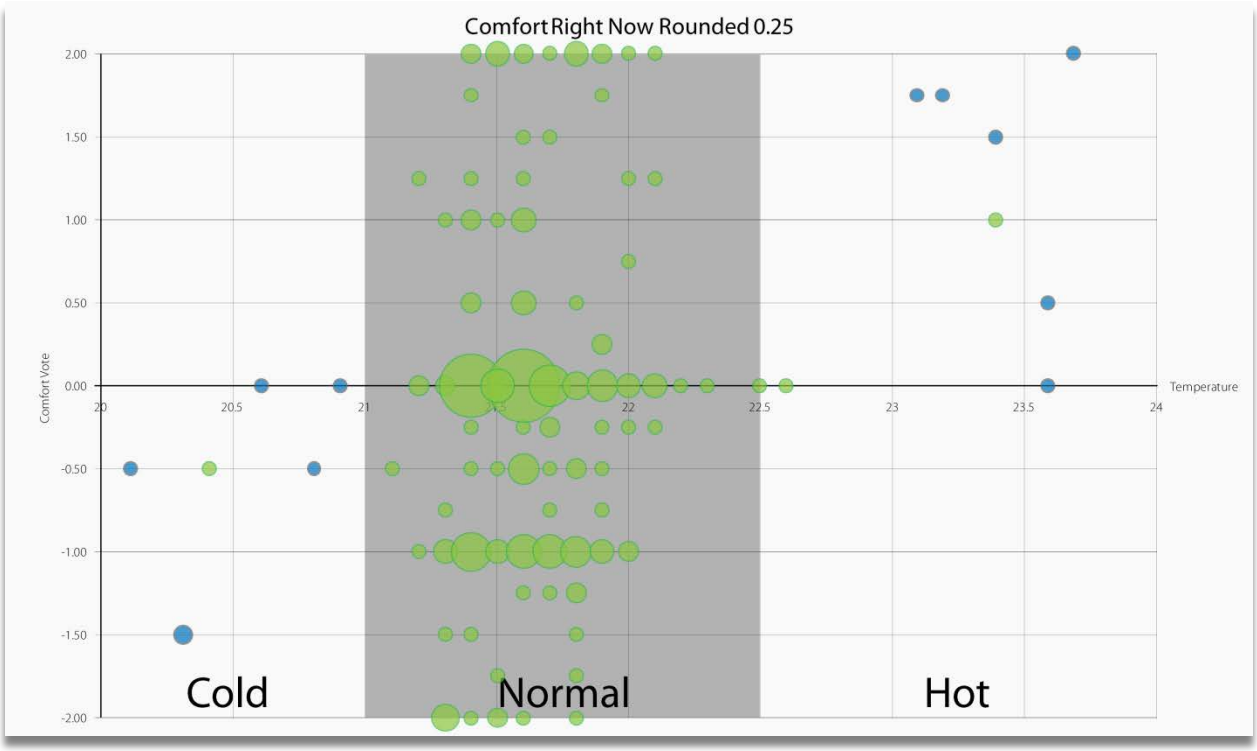
Figure 20: Adjusted Comfort Right Now Scatter Plot with Means



Looking at the PPD, where we define dissatisfied as a vote greater than ±1, we see that in the raw data, the store is providing 78% satisfaction and 22% dissatisfied, almost at the 80/20 ratio to which most buildings are designed. Of those dissatisfied, 9% are too cold and 13 % too hot. After adapting the responses for clo, the population percentages change to 72% satisfied and 28% dissatisfied, with the dissatisfied breaking up into 13% too cold and 15% too hot. This decrease in the number of satisfied patrons suggest that people in general are either dressing appropriately for the store conditions prior to entering the store, or adapting their clo levels in response to store conditions. In retrospect, it is regrettable we did not inquire if the respondent had altered their clo level while in the store to increase their comfort; this would have allowed us to determine if people adapt their clothing levels in response to store conditions or if the store patrons' clo level is determined by other factors. Looking at clo versus outdoor temperatures, clo appeared to be fairly consistent regardless of outdoor conditions.

Further examination of the store comfort results show that, for the un-weighted comfort votes, 56% of respondents are quite comfortable with responses between -0.5 – +0.5. Adjusting for clo, this percentage drops to only 50%. Meanwhile, the number of respondents whom are very cold and uncomfortable, -1.5 or less, is 5% for both un-weighted and adjusted votes. Those whom were too hot and uncomfortable, +1.5 or greater, were 9% for un-weighted responses and 10% for adjusted. All together, this means that 14% of the respondents were very uncomfortable in the store and, adjusting for their clo level would result in 15% being very uncomfortable.

Figure 21: Comfort Right Now graph with temperature zones mapped



To determine whether or not these trends are significant Student's T-test comparisons were calculated for the comfort responses with regards to the temperature ranges found in the store. Based on the data, the store's normal operating temperature range is defined at 21°–22.5º. T-test comparisons of the ranges below and above this "normal" range were conducted with the following results:

Table 6: Un-Weighted and Adjusted Comfort Responses

Un-Weighted Comfort Responses			
Comparison	**T Value**	**Two-Tail**	**One-Tail**
normal vs cold	1.45	0.147	0.0736
normal vs hot	3.68	0.0003	0.0001
normal & hot vs cold	1.54	0.125	0.062
normal & cold vs hot	3.54	0.0005	0.0002
Adjusted Comfort Responses			
Comparison	**T Value**	**Two-Tail**	**One-Tail**
normal vs cold	1.08	0.283	0.141
normal vs hot	3.01	0.0029	0.0015
normal & hot vs cold	1.16	0.246	0.123
normal & cold vs hot	2.53	0.012	0.006

These results suggest that there are statistically significant differences in the level of comfort provided in the store for these different temperature ranges.

For the un-weighted dataset, we see not only a very large difference between the responses for the hotter range and the normal range with a confidence level of 99.97%, but with the result that the hot range results are in fact on average higher than averages for the normal range with a 99.99% confidence level. When the dataset is adjusted for clo, we see similar trends, but with slightly decreased confidence, 99.7% confidence that the two ranges result in different comfort means and a 99.85% confidence that the hot range is on average higher than the normal range.

For the cold range, we see more variation in the dataset and this is illustrated in the results from the statistical tests. In the un-weighted dataset, we find that we are only 85% confident that the difference in comfort between the cold temperature range and the normal temperature range are not random, but we are 92.5% confident that the cold temperature range results in a lower comfort mean than the normal range. The adjusted dataset shows an even weaker statistic: we can only say with a 72% confidence level that the differences between comfort responses in the cold range are different than the normal range.

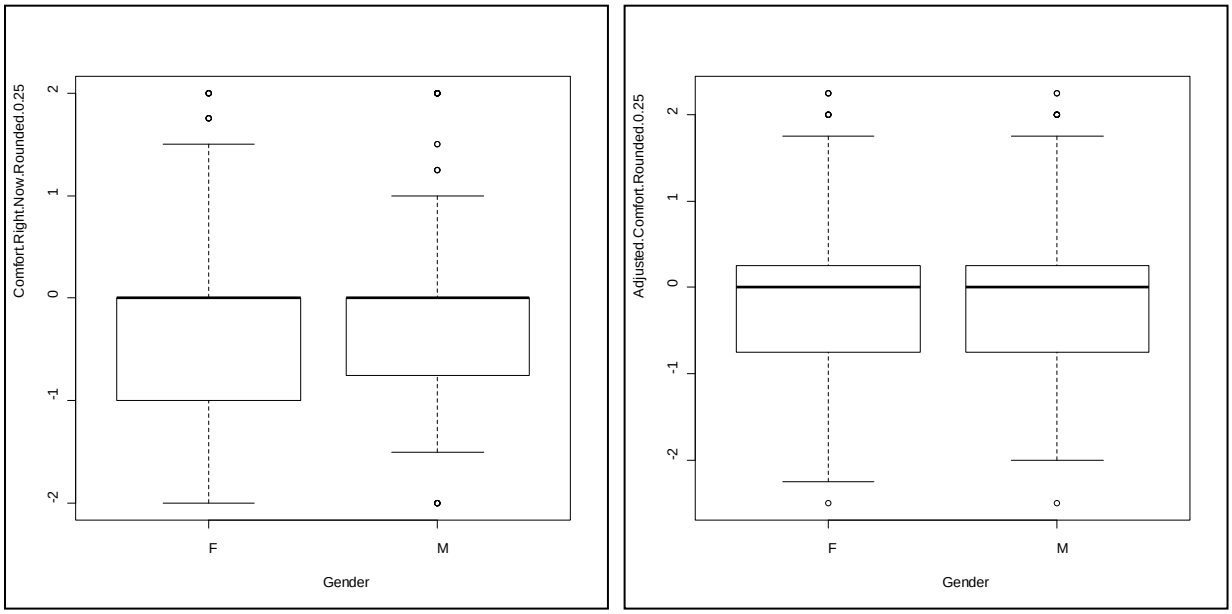
As a result of these two sets of statistical comparisons, it is concluded that when the temperature swings above the normal range found in the store, comfort can be expected to decrease and occupants will be warm to too hot. However, with this dataset, we cannot conclusively speak about the comfort level of occupants when the temperature swings below the normal range.

Examining comfort responses by groups

Other variables collected by the survey include gender, age, and the soak time of the respondents. Examining these distinctions offers some interesting findings regarding the level of comfort the store is providing to these different groups.

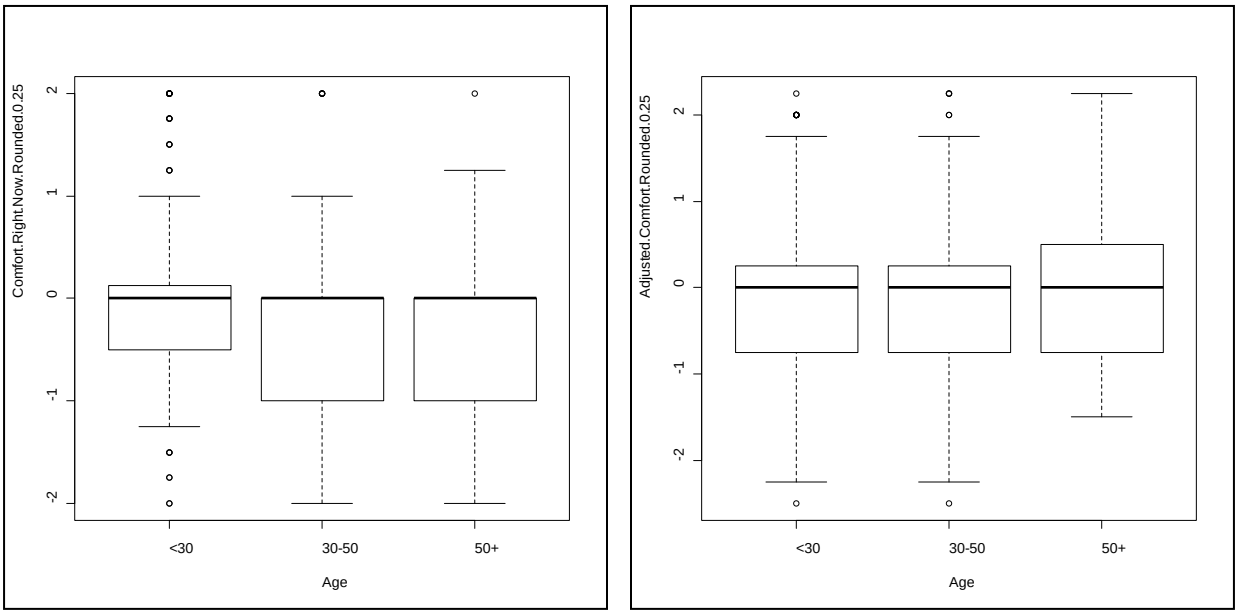
Beginning with box plots of comfort responses by gender, the dataset includes 108 responses by women and 109 responses by men. We see that the medians of these two groups are represented by the dark horizontal line. The box around the median represents the inner quartile range—totaling 50% of the votes in each category. The whiskers extend to the upper and lower range of the data, with the dots representing outlier points beyond. The median comfort responses for the two groups are quite similar, but the range for the inner quartiles is a bit lower for women than for men. Also the range overall for women is greater than for men. However, if the data is adjusted for clothing, the box plots for the two groups fall more in line with one another. Median responses, quartile ranges, and overall ranges were quite similar for the two groups implying that the reason for the variation between the two groups in the raw data is a result of the insulative values differences between men's and women's clothing.

Figure 22: Box plots of Comfort and Adjusted Comfort by Gender



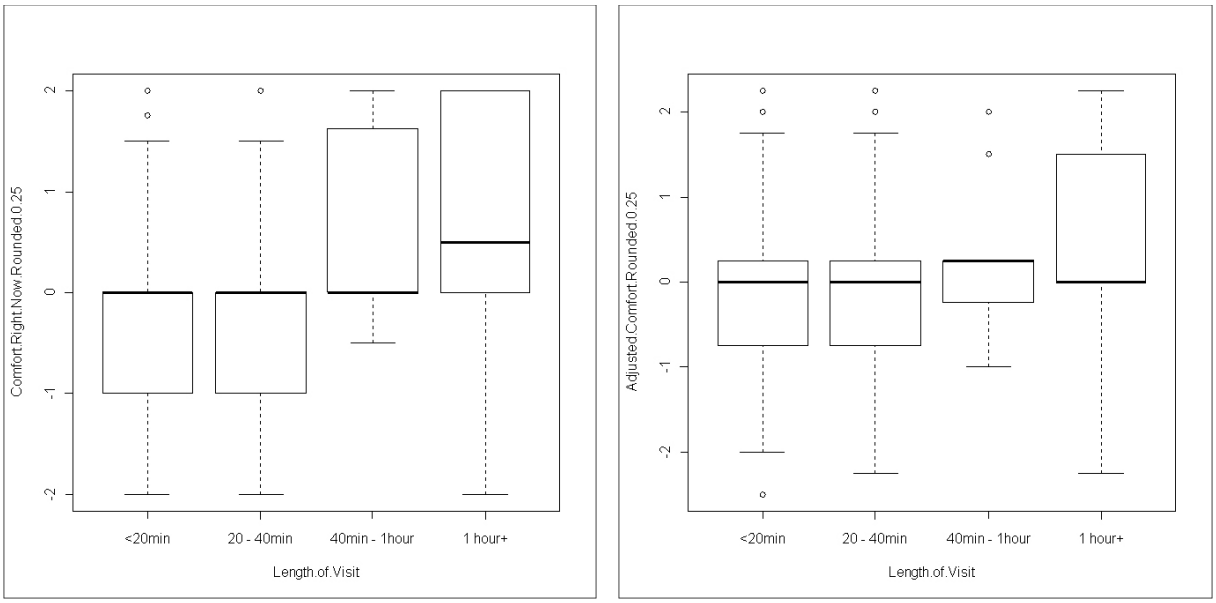
Similarly with the different age groups ("under 30": 127 responses, "30 to 50": 67 responses, and "over 50": 23 responses) the box plot shows that while median comfort responses are similar across the age groups, quartile ranges and overall ranges vary, though age groups "30 to 50" and "over 50" are quite similar. The difference between the "under 30" group and the other two groups is significant, with a confidence level of 94.5% that this difference is not random. However, adjusting for clo, this confidence completely disappears with the three groups more or less in line.

Figure 23: Box Plots of Comfort and Adjusted Comfort by Age



Finally, examining the soak time for the respondents ("under 20 minutes": 109 responses, "20 to 40 minutes": 68 responses, "40 minutes to 1 hour": 12 responses, and "over 1 hour": 28 responses) we see that the comfort responses for those in the store "under 20 minutes" and "20 to 40 minutes" are quite similar and those in the store "40 minutes to 1 hour" and "over 1 hour" are also quite similar. But dramatic differences between those in the store less than 40 minutes and those in the store over 40 minutes exist. Comparing these two groups, Student's t-test results in near 100% confidence the two groups experience the store environment differently and that those in the store under 40 minutes are generally cooler than those in the store longer. Adjusting for clo values, there is quite a dramatic change in the ranges for the "40 minutes to 1 hour" group, but only modest changes for the other three. Statistically, the difference between the two groups still existed with a 92.3% confidence level.

Figure 24: Box Plot of Comfort and Adjusted Comfort by Soak Time



CHAPTER 4: Conclusions and Recommendations for Future

Conclusions

This project studied the effect of the pre-cooling and DR control strategies for reducing the peak demand in a small retail building with heavy thermal mass. The impact of control strategies was evaluated from the thermal energy side and occupancy comfort side.

- The demand profile predicted from the initial building model can better match the field test results, while underestimate the potential of the peak demand savings for the field-tested control strategy.

- Pre-cooling and DR control strategies worked well in the small retail building and were able to reduce the peak demand of the whole building significantly (20%-55%).
- Note that there was no big rebound for the demand profile during the peak period on all the field test days.

On the occupancy comfort side, based on the results from the comfort survey, the store is normally maintained between 21-22.5º C, and 78% of its patrons feel comfortable. When the temperature rises above the warm end of this temperature range, we can say with a high degree of certainty that discomfort due to a warm sensation will occur. When temperatures drop below the cool end of the normal range, occupant sensations appear to follow suit, but a larger dataset would be needed to confirm or refute this hypothesis. Occupants spending more time in the store (e.g., over 40 minutes) tend to be warmer and more uncomfortable at all temperatures than those in the store for shorter periods of time (e.g., less than 40 minutes). We cannot determine whether occupants alter or adjust their clothing level for store conditions, or otherwise choose their clothing ahead of time based on the conditions they expect to find in the store because we did not have a question for this in the survey. But on average, occupants seem to dress appropriately for store conditions.

Recommendations

For this small commercial building, the field test results have shown the potential peak demand savings of DR control strategies with pre-cooling in warm weather condition. It also identifies several uncertainties that should be resolved for the future studies in small commercial buildings. The following work is proposed:

- **Start the demand control strategy half hour before the peak period.** This reduced the demand charges by avoiding high demand transient at the beginning of the DR period. Therefore, it is recommended that the demand control strategy starts at least a half hour before the peak period in the future studies.
- **Conduct survey on the change of occupants' clothing.** The survey results provided the occupants' clothing when they were in the store, while didn't indicate any change of clothing related to the choice of demand response strategies. For the future work, the survey of the change of occupants' clothing can help us better understand their response to the store's selected DR strategies.

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