A Data-Driven Method for Determining Zone Temperature Trajectories that Minimize Peak Electrical Demand

Kyoung-ho Lee, James E. Braun

Korea Electric Power Research Institute, Korea Electric Power Corporation, Daejeon, 305-380, Korea

140 S. Intramural Drive, School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907-2031, USA

ABSTRACT

Lee and Braun (2007b) developed a simple approach, termed the weighted-averaging (WA) method, that estimates building zone temperature set-point variations that minimize peak cooling demand during critical demand periods. The current paper extends this approach to air conditioning power demand and presents the results of a field evaluation for a small commercial building. The WA method uses data from two or more test days to determine a near-optimal setpoint trajectory for minimizing peak demand during a demand-limiting period. Evaluation of the method was performed over a two-week test period at a small bank building located in Palm Desert, California. The first week of testing was used to collect baseline data for conventional control and data for estimating the optimal setpoint trajectory. The second week of testing was used to evaluate demand reduction for application of trajectories determined using the WA method.

INTRODUCTION

Thermal storage in building thermal mass can be controlled using adjustment of building space setpoint temperatures to reduce peak cooling load and power demand. In conventional night-setup (NS) control, zone setpoint temperature is maintained constant during occupied periods and set up during unoccupied periods. In demand-limiting control, the building is precooled prior to an on-peak period and then setpoints are modulated in a way so that the thermal storage in the building thermal mass is controlled to reduce peak electrical demand.

There have been a number of simulation and experimental studies that have demonstrated significant potential for reducing peak cooling demand using building thermal mass (Braun 1990, Rabl and Norford 1991, Andresen and Brandemuehl 1992, Braun 2003, Morris et al. 1994, Keeney and Braun 1997, Braun et al. 2001, Braun and Lee 2006, Lee and Braun 2006, and Xu and Haves 2006). However, there has been less work on the development of practical control methods for minimizing peak demand. Braun and Lee (2006) found that a simple exponential form for zone temperature setpoint variation during on-peak periods can be effective in reducing peak cooling demand. They used a simulation tool and estimated electrical demand reduction of 1 to 2 W per square foot of floor space for a 4-hour demand-limiting period in small commercial buildings in California climates. However, it is necessary to determine building-specific time constants.

Lee and Braun (2007a) suggested a model-based demand-limiting method that relies on a trained inverse building model. The inverse building model was trained using data from a small test building located in Iowa and the method was validated experimentally at the building. The test results showed 30% reductions in peak cooling loads with setpoint adjustments from 70 to 76°F (21.1 to 24.4°C) for a 5-hour demand-limiting period. The results were consistent with simulation results that were determined for this facility.

Lee and Braun (2007b, 2007c) developed three simplified methods for determining demand-limiting setpoint trajectories using short-term measurements, which are termed the semi-analytical (SA) method, the exponential setpoint equation-based SA (ESA) method, and the weighted-averaging method (WA method). The SA and ESA methods employ simplified inverse building models trained with short-term data and use analytical solutions from the models for the setpoint trajectories. The goal of the ESA method, in fact, was to determine the time constant in the exponential setpoint equation proposed by Braun and Lee (2006).

The WA method exploits an assumption of a locally linear relation between zone temperatures and cooling loads. The method does not utilize a building model and only requires two days of hourly cooling load data for determining setpont trajectories. The methods were evaluated for different buildings using trained inverse building models and simulations. Simulation results showed that the WA method is the most effective among the three simplified methods for peak load reduction and performed nearly as well as optimal demand-limiting control. It also is easiest of the three methods to implement and is applicable to building aggregates.

The current paper extends the WA method to air conditioning power demand and presents the results of a field evaluation for a small commercial building.

WEIGHTED-AVERAGING (WA) METHOD

The original WA method developed and evaluated by Lee and Braun (2007b, 2007c) was presented for use in limiting peak cooling loads. However, it can be applied with minor modifications to limiting peak power associated with air conditioning equipment or the entire building. This section describes the WA method applied to power measurements.

Basic WA Method

Demand-limiting setpoint trajectories are determined using weighted averaging of two different time-varying profiles for power demand determined from different days of testing having two different control strategies for the demand-limiting period (Lee and Braun 2007b). The setpoint trajectory that minimizes the peak power is estimated through a weighted averaging of the two test day results as depicted in Figure 1 (b). The two setpoint trajectories should produce power variations that intersect at some point during the demand-limiting period as shown in Figure 1 (a). An optimal weighting factor is determined by minimizing the peak of the weighted-averaged power demand determined for the two different test sets. The objective function to determine the optimal weighting factor is

$$J = \max_{w^*}\left[wP_{1,k} + (1-w)P_{2,k} \right] = \max_{w^*}\left[P_{w,k} \right] \text{ for the demand-limiting period} \tag{1}$$

where $P_{1,k}$ is the average power for time interval k under control 1, $P_{2,k}$ is the power at time k under control 2, $P_{w,k}$ is the weighted-averaged power at time k, w is the weighting factor, and w^* is the optimal weighting factor. In general, P is average power over an hour or shorter time interval for the air conditioning equipment or the total building electrical usage. In the original method presented by Lee and Braun (2007b, 2007c), the P represents cooling load.

It is assumed that the power requirement at any time during the demand-limiting period is a locally linear function of the zone temperature. With this assumption, the zone setpoint temperature trajectory that minimizes the peak power is determined using the optimal weighting factor:

$$T_{z,w,k} = w^* T_{z,1,k} + (1-w^*) T_{z,2,k} \text{ for the demand-limiting period} \tag{2}$$

where $T_{z,1,k}$ is the zone setpoint temperature for time interval k with control 1, $T_{z,2,k}$ is the zone setpoint temperature for control 2 at time k, $T_{z,w,k}$ is the optimally weighted-averaged zone setpoint temperature at time k, and w^* is the optimal weighting factor determined by minimizing the cost function in equation (1).

The setpoint trajectory of equation (2) that is obtained from the weighted-averaging is then adjusted using equation (3).

$$T_{z,dl,k} = T_{z,w,k} + \Delta T_{adj,k} \tag{3}$$

$$\Delta T_{adj,k} = \frac{P_{w,k} - P_{w,avg}}{\max\left|P_{w,k} - P_{w,avg}\right|} T_{adj,\max} \tag{4}$$

where $T_{adj,\max}$ is the maximum allowable adjustment temperature for a given hour, and $P_{w,avg}$ is the average of the weighted-averaged power $P_{w,k}$ over the demand-limiting period which is assumed to be the target peak power demand.

Updating WA Method

The setpoint trajectory from the basic WA method can be updated on a daily basis so as to improve the shape of the power profile and respond to changing conditions. The updating process uses the concept of phase cancellation of two functions which are 180 degrees out of phase with each other. If two sets of power data are 180 degrees out of phase, then the optimal weighting factor can be updated perfectly. If a measured profile for the demand-limiting period is not perfectly flat, then the setpoint trajectory is adjusted to obtain a 180 degree out-of-phase load profile for phase cancellation. The updating strategy involves using the setpoint trajectory and measured power profile for the most recent demand-limiting period to estimate a trajectory that would produce a 180 degree out-of-phase profile. This trajectory is then implemented and power profiles are measured. Then, the weighted-averaging approach is applied to the power data from these two days to determine the new updated demand-limiting trajectory. This process can be continually applied for demand-limiting days.

The setpoint trajectory is updated using sequences of two days. First, the basic WA method is applied to determine a setpoint trajectory. On the first day of each updating two-day sequence, the setpoint trajectory is adjusted from the previous days' setpoint trajectory using phase cancellation with a locally linear assumption in a manner very similar to that presented for the basic WA method. The hourly adjustments for phase cancellation are determined on odd days within the updating process as:

$$T^{n}_{z,2,k} = T^{n-1}_{z,1,k} + \Delta T^{n}_{adj,k} \quad (n = 1,3,5,...) \tag{5}$$

hwhere

$$\Delta T^{n}_{adj,k} = \frac{P^{n-1}_{1,k} - P^{n-1}_{1,avg}}{\max\left|P^{n-1}_{1,k} - P^{n-1}_{1,avg}\right|} T^{n}_{adj,\max}\,, \tag{6}$$

$$T^{n}_{adj,\max} = \frac{\max\left\{P^{n-1}_{1,k}\right\} - P^{n-1}_{1,avg}}{\max\left\{P^{0}_{1,k}\right\} - P^{0}_{1,avg}} T_{adj,\max}\,, \tag{7}$$

and where n is an index representing the day after the start of the updating process, $T_{adj,\max}$ is the maximum allowable adjustment temperature (e.g., 1.0°F), and $T^{n}_{adj,\max}$ is a maximum allowable adjustment temperature for the demand-limiting period on the *n*-th day of updating.

The difference between the hourly adjustment scheme of the updating and basic WA methods is that the maximum allowable adjustment, $T^{n}_{adj,\max}$ varies according to the deviation of the hourly and daily average power values. This tends to damp the fluctuations in the setpoint trajectory as the power profile approaches the optimum. The determination of the setpoint trajectory for *n*=1 requires use of the setpoint trajectory determined with the basic WA method, $T^{0}_{z,1,k}$ ($= T_{z,w,k}$ in the basic WA method), and the power profiles that result from implementation of this trajectory, $P^{0}_{z,1,k}$. The power profile from the basic WA method is also used as a normalization factor in determining a maximum temperature adjustment for each hour within the phase cancellation procedure.

On the second day of each updating two-day sequence, the setpoint trajectory is adjusted from the previous days' setpoint trajectory using weighted averaging for the last two demand-limiting days. For each hour within the demand-limiting period on even days within the updating process, the setpoint temperature is determined as a weighted average of the setpoints for the same hour on the previous two demand-limiting days according to

$$T_{z,1,k}^{n} = w_n^* T_{z,1,k}^{n-2} + (1-w_n^*) T_{z,2,k}^{n-1} \qquad (n = 2,4,6,...) \tag{8}$$

where w_n^* is the optimal weighting factor determined for the n-th day of updating by maximizing the following objective function.

$$J_n = \max_{w_n^*} \left[w_n P_{1,k}^{n-2} + (1-w_n) P_{2,k}^{n-1} \right] \qquad (n = 2,4,6,...) \tag{9}$$

The setpoint trajectory can be continually updated using these two-day sequences of phase cancellation and weighted-averaging.

Application to Building Aggregates

The WA method can be adapted to determine a single setpoint trajectory to minimize peak demand of aggregated building power. Demand-limiting control for building aggregates is treated as an optimization problem for determining a single setpoint trajectory that minimizes the peak demand of aggregated total cooling demands while maintaining zone temperatures within the comfort temperature range for all of the buildings. The problem involves minimization of the following cost function:

$$J = \max \left\{ \sum_{i=1}^{N_b} P_{b,i,k} \right\} \text{ for the demand-limiting period} \tag{10}$$

with respect to $T_{z,k}$ subject to $T_{z,i} \le T_{z,k} \le T_{z,f}$ and $0 \le \dot{Q}_{b,i,k} \le \dot{Q}_{cool,\max,i}$ where $P_{b,i,k}$ and $\dot{Q}_{b,i,k}$ are the power and cooling load requirements for the i-th building at time k, $\dot{Q}_{cool,\max,i}$ is capacity of the cooling equipment for the i-th building and N_b is the number of buildings. If individual building power requirements are locally linear with zone temperature, then the sum of power requirements is also a linear function of zone temperature. Based on the assumption of linearity, the weighted averaging can be applied to building aggregates. The optimal weighting factor in this application is determined by minimizing the peak of the weight-averaged cooling loads for building aggregates. The optimization problem is a minimization problem with the following objective function:

$$J = \max_{w^*} \left\{ w \sum_{i=1}^{N_b} P_{1,i,k} + (1-w) \sum_{i=1}^{N_b} P_{2,i,k} \right\} \quad \text{for the demand-limiting period} \tag{11}$$

where $P_{1,i,k}$ is the power requirement of the i-th building for time interval k under control 1 and $P_{2,i,k}$ is the power for i-th building at time k under control 2. With the linearity assumption, the zone temperature trajectory that minimizes the aggregated peak power is determined by:

$$T_{z,w,k} = w^* T_{z,1,k} + (1-w^*) T_{z,2,k} \text{ for the demand-limiting period} \tag{12}$$

where $T_{z,1,k}$ is the zone setpoint temperature for time interval k with control 1, $T_{z,2,k}$ is the setpoint temperature for control 2 at time k, $T_{z,w,k}$ is the optimal zone setpoint temperature at time k, and w^* is the optimal weighting factor determined by minimizing the cost function in equation (6). The weighted-averaged setpoint trajectory $T_{z,w,k}$ can be adjusted using equations (3) and (4). The same method for the updating of the setpoint trajectory used for the individual building approach can be used for application to building aggregates.

REVIEW OF PREVIOUS CASE STUDIES

Lee and Braun (2007c) evaluated the performance of the WA method applied to peak cooling load reduction for three different buildings in different climates. In order to allow a thorough comparison with both conventional and optimal control, data from the sites were used to train detailed inverse models that were then used to evaluate performance of the simplified demand-limiting approaches. The three buildings were representative of small, medium, and large commercial facilities and include midwest and west coast climates.

The basic WA method gave more than 90% of the peak load reduction associated with optimal control for all three buildings with a six-hour afternoon demand-limiting period. Compared to conventional control, the peak cooling loads were reduced by from 30 to 50% depending on the building and time of year. In absolute terms, the peak cooling load reductions were between about 2 and 3 W per square foot of floor area. The results for the basic WA method were relatively insensitive to the choice of summer days used for training as long as the days were relatively clear (i.e., not sensitive to ambient temperature effects). Furthermore, relatively little benefit was realized from applying the updating scheme.

Lee and Braun (2007c) also used the inverse models to evaluate application of the WA method to a set of aggregated buildings derived from combinations of the three building types. The WA method was applied to determine a single setpoint trajectory for all of the buildings using the aggregated cooling load data. Results for peak cooling load during the demand-limiting period were compared with the minimum possible aggregated peak determined using optimization applied to all of the individual buildings. The basic WA method for building aggregates captured about 85% of the maximum possible demand reduction compared to optimal control.

APPLICATION TO PEAK AC POWER REDUCTION IN A SMALL COMMERCIAL BUILDING

The goal of the work described in this paper was to apply the WA building to power measurements and evaluate demand reduction potential for a small commercial building. Based on the previous case studies of Lee and Braun (2007c), only the basic WA method was utilized.

Description of Test Building and Data Measurement

A number of different sites were considered for the field study. The goal was to find a building in a hot climate that was typical of small commercial facilities in terms of size, construction, and occupancy. In addition, it was necessary that the thermostats be a wire-to-wire compatible retrofit for new pageable thermostats.

The building selected was a small single tenant bank located in Palm Desert, CA and is shown in Figure 2. The interior of the building was representative of a traditionally designed bank, including a typical teller arrangement and side areas for account representatives. The building construction is summarized in Table 1 and the building schedules and internal gains are described in Table 2.

The occupied areas within the building employed 10 rooftop air conditioning units, each having separate thermostats. The units were retrofit with communicating thermostats that allowed global temperature setpoints to be sent remotely. The power requirements for these units were monitored with data recorders installed specifically for the testing. The data loggers were set to record average kW demand at 15-minute intervals. Clocks on the loggers were synchronized to the NIST (National Institute of Standards and Technology) clock available on the web. The air conditioning power was measured separately using hand-held instruments, to validate the logger data. Total air conditioning power was determined during post processing as the sum of the individual recorded data channels.

Setpoint Schedules

Figure 3 depicts the baseline and demand-reduction strategies that were tested. The baseline was conventional night-setup (NS) control where the setpoint was constant at 72ºF (22.2ºC) during occupancy and set up to 85ºF (29.4^{o}C) for the unoccupied period. The occupied period was from 6 am in the morning to 7 pm in the evening. The demand-reduction strategies involved precooling at 70 F from 6 am to 12 pm and then adjusting the setpoints from 70 F (21.1ºC) to 78 F (25.6ºC) during a demand-limiting period from 12 to 6 pm. The setpoint temperature was then set up to 85ºF (29.4^{o}C) after the end of occupancy.

Preliminary precooling tests included a ‘linear-rise (LR)” and a ‘step-up (SU)’ strategy with precooling. Data from these tests were used with the WA method to estimate demand-limiting (DL) setpoint trajectories that would minimize peak demand.

The testing was performed over two weeks. Table 3 shows the setpoint schedule used for the first week of testing from October 9 to 13, 2006. October 9, 10, and 13 were controlled using night-setup control for the baseline and October 11 and 12 were for used for obtaining the preliminary test data to provide input data for the WA method to determine demand-limiting setpoints.

Table 4 shows the setpoint schedule applied for the second week of testing from October 23 to 27 and includes one day with NS control and four days with DL control. For the first two days of DL control, October 24 and 25, the setpoint trajectory from the weighted-averaging step described in equation (2) in the WA method was used whereas the adjusted setpoint trajectory determined using equations (3) and (4) was employed for the last two days of October 26 and 27. A value of 1.0°F (0.6°C) was used for the maximum allowable adjustment. The setpoint trajectories determined with the WA method could not be precisely implemented because the thermostat only allows integer numbers for setpoint values and the time interval between setpoint changes was restricted to 15 minutes. Therefore, the trajectories implemented on October 24 and 25 bound the trajectory determined with equation (2). Similarly, the trajectories implemented on October 26 and 27 bound the trajectory determined with equations (3) and (4). Figure 4 graphically displays the demand-limiting setpoint trajectories with and without adjustment of the setpoint trajectory in the WA method.

Peak Demand Reduction

Figure 5 shows comparisons of outdoor temperature and total air conditioner power for three days from the first week of testing where the NS, LR and SU strategies were implemented and weather conditions were similar. Outdoor temperature data were available from a local weather station near Palm Desert. The shaded region in Figure 5 indicates the demand-limiting period from 12 to 6 pm. There is a dramatic peak in the air conditioning power at the beginning of the morning due to the return from night set up. The LR and SU strategies have somewhat higher morning power consumption than the NS strategy due to a lower setpoint temperature. The afternoon power profiles are very sensitive to the shape of the zone temperature variation. Neither a LR strategy (10/11) nor a SU strategy (10/12) resulted in very good profiles from the viewpoint of minimizing peak power. The LR strategy produced high power requirements at the beginning of the demand-limiting period and low power at the end. Conversely, the SU strategy resulted in very little power consumption at the beginning and a peak near the end of the demand-limiting period. These results are very consistent with results presented by Lee and Braun (2006a) for prototypical small commercial buildings. Peak air conditioning power and savings for these comparable days are given in Table 5 along with maximum outdoor temperatures and average sky cloud cover information. Average cloud cover data for Palm Desert were available from the National Weather Service.

Figure 6 shows comparisons of outdoor temperature and total air conditioner power for two days where the NS and DL strategies were implemented and weather conditions were similar. The DL resulted in a power profile that was relatively flat with very significant demand reduction compared to NS control. Peak air conditioner power and savings for the two days are given in Table 6 along with maximum outdoor temperature and average cloud cover. Peak power reduction during the demand-limiting period was much greater than for the results of implementing the LR and SU controls.

The weather conditions for the other three days where DL strategies were tested (10/24, 10/25, and 10/27) were fairly similar to the baseline NS test day of October 19 as shown in Figure 7. Comparisons between measured air conditioner power profiles for these three DL test days and the NS test day are presented in Figures 8, 9, and 10. Table 7 gives the peak air conditioner power and savings along with the maximum outdoor temperature and average cloud cover information. Significant peak power reductions during the demand-limiting period are shown for the three days with DL control compared to the baseline with NS control. The power profiles were not as flat as for the results in Figure 6. This may be due to limited precision in adjustments of setpoint temperatures that was possible for these thermostats. Also, there are relatively large fluctuations in power due to on/off cycling of the units. These fluctuations could be reduced leading to greater demand savings if the control of the multiple rooftop units were coordinated.

Figure 11 presents the percent peak air conditioner power reductions for the different demand reduction strategies that were tested. Demand-limiting control with setpoint trajectories determined with the WA method gave much better demand reduction than the simple LR and SU strategies. The average peak air conditioner power reduction for the four test days with DL control was 31.6% as compared with the baseline. The average peak power savings for the four DL test days was 9.1 kW or 0.76 W/ft^2 (8.18 W/m^2).

CONCLUSIONS

This paper demonstrated a method for determining a trajectory of zone temperature setpoints that minimizes peak power demand during a specified time period. The paper also demonstrated that small commercial buildings can be good candidates for utilization of this type of demand-limiting strategy. The demand-limiting (DL) strategy was tested in a small building in Palm Desert, California and resulted in greater than a 30% reduction in peak air conditioner power requirement for a 6-hour demand-limiting.

The test utilized ten air conditioners with their own individual thermostats. The peak power reduction associated with control of building thermal mass could be sensitive to the number of air conditioners and stages of capacity control at the site. The power consumption associated with air conditioning has larger short-term fluctuations when there are fewer capacity steps due to compressor cycling. Power fluctuations due to on/off cycling of single-stage equipment were evident in the data. Smaller fluctuations would be expected for a larger building with more air conditioners or if each of the units had multiple stages of control. Furthermore, lower peak power could be achieved if the run times of the air conditioners were coordinated.

Comfort evaluations for customers were performed both prior to and during the tests. The comfort survey illustrated a highly variable response to the indoor environment on base days as well as test days and no adverse effects of the DL strategies could be determined. The high variability might be characteristic of buildings such as banks that have a relatively short customer occupancy time. In future studies of buildings that have relatively short customer occupancy time, it would be useful to collect data from employees rather than customers, as the employee response to thermal sensation over an extended period of time will better describe the affect of the thermal profile generated by the DL strategy.

NOMENCLATURE

DL = demand-limiting control
J = objective function
LR = linear-rise setpoint control
N = number
NS = night-setup control
P = air-conditioner power
$\dot{Q}$ = cooling load
SU = step-up setpoint control
T = temperature
w = weighing factor

Superscripts

* = optimal
n = n^{th} day of updating

Subcripts

adj = adjusted
avg = averaged
b = building
$cool$ = cooling
dl = demand-limiting control
f = final
i = initial

k = time step
$\max$ = maximum
n = n^{th} day of updating
w = weight-averaged
z = zone
1 = control 1
2 = control 2

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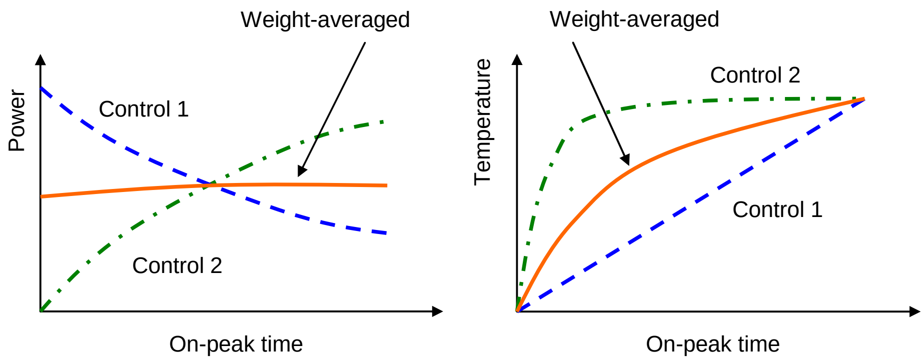


(a) *(b)*

Figure 1. Schematic illustration of WA method. (a) power and (b) zone temperature.

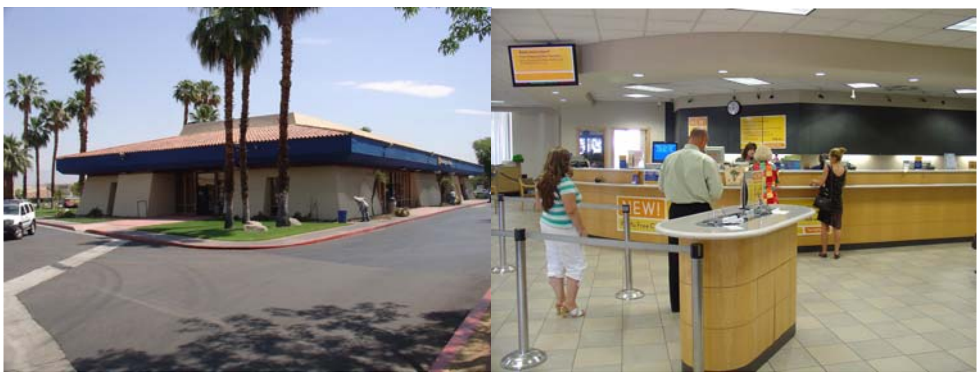
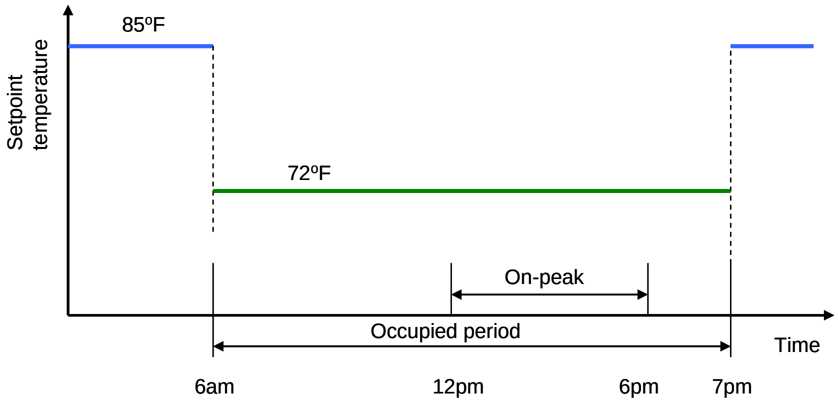
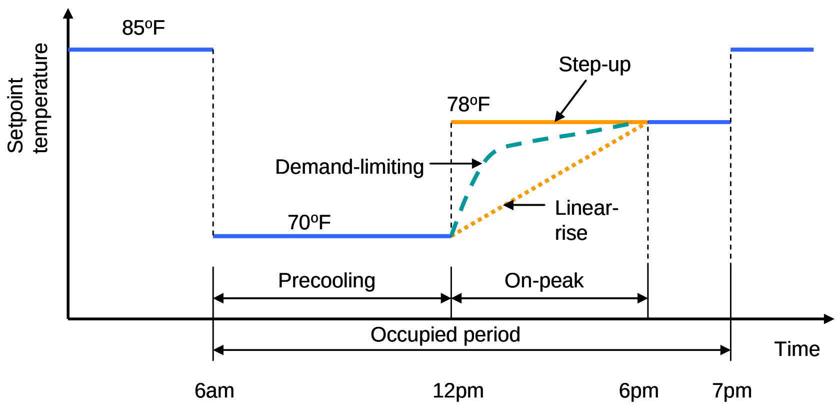


Figure 2. Test Building



(a)



(b)

***Figure 3**. Setpoint control strategies: (a) baseline night-setup (NS) control and (b) demand-limiting (DL) control strategies*

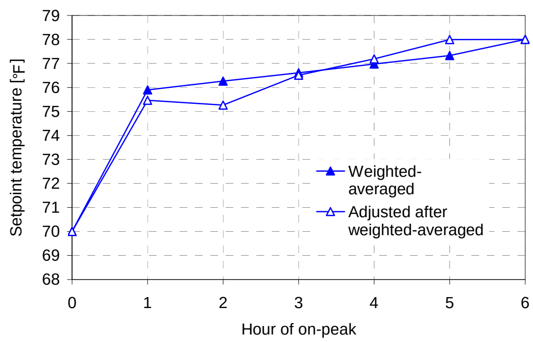


***Figure 4**. Demand-limiting setpoint trajectories determined by WA method.*

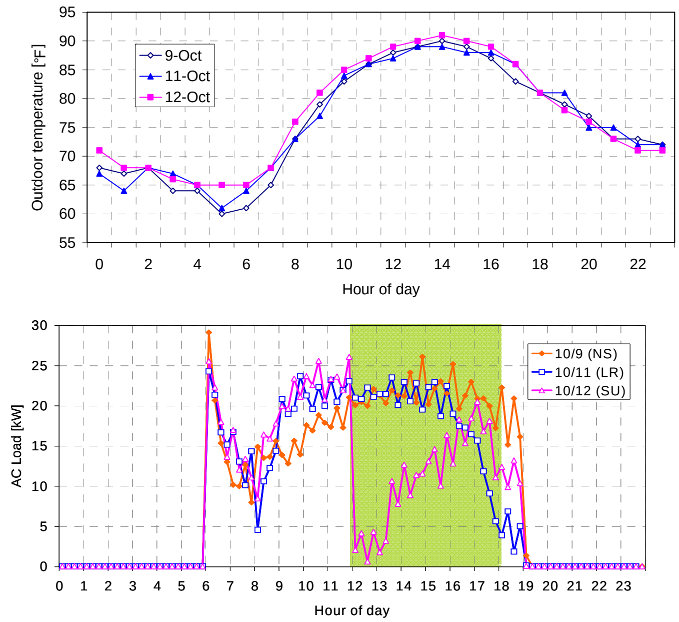


Figure 5. *Ambient temperature and total air conditioning power for night setup (NS), linear rise (LR), and step up (SU) control strategies with comparable weather*

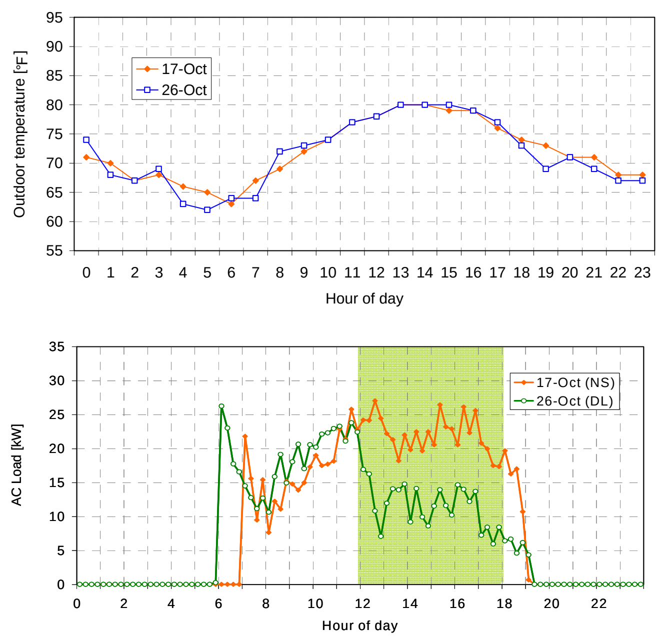


Figure 6. *Ambient temperature and total air conditioning power for night setup (NS) and demand-limiting (DL) control strategies with comparable weather*

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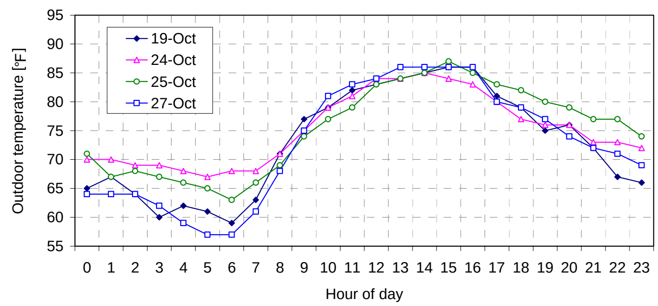

Figure 7*. Measured outdoor temperatures for October 19, 24, 25, and 27*

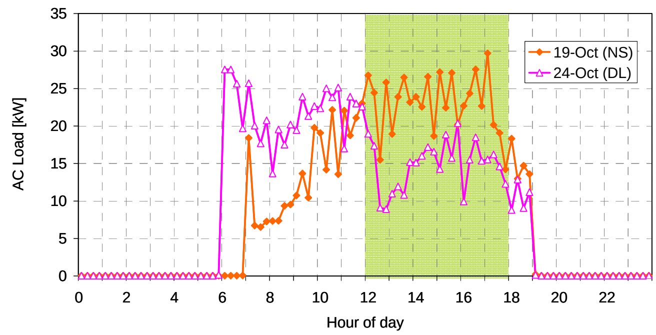

Figure 8. *Total air conditioning power for NS strategy on October 19 and DL control on October 24*

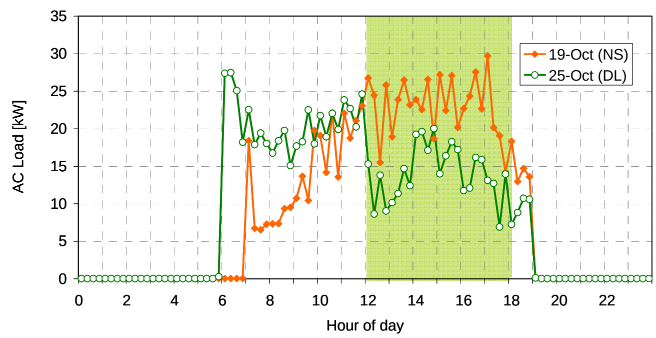

Figure 9*. Total air conditioning power for NS strategy on October 19 and DL control on October 25*

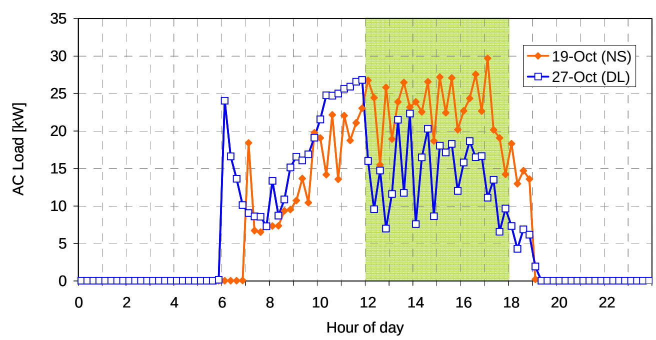

Figure 10. *Total air conditioning power for NS strategy on October 19 and DL control on October 27*

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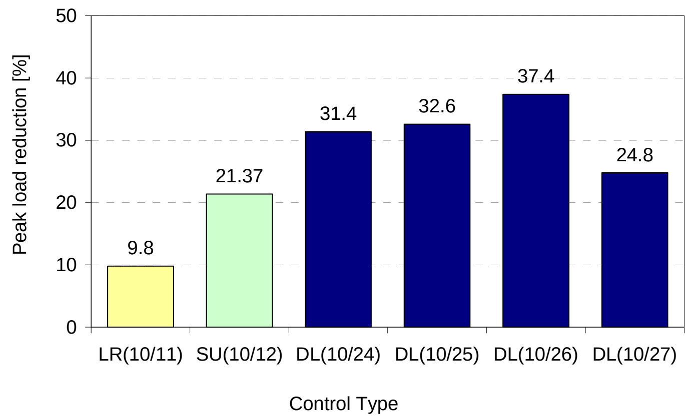

Figure 11. *Comparison of peak load reductions with different cooling setpoint controls of LR, SU, and DL controls*

Table 1 Building Geometry and Construction

	Value/Description
Total floor area (ft^2)	12,000 ($1115m^2$)
Number of stories	One
Percentage of exterior walls that are windows (%)	36
Description of exterior wall materials and thicknesses	Stucco over wood framing. 6in (0.15m) thick
Description of windows	Single pane tinted
Description of floor construction and treatments (e.g., 4in concrete, carpeted)	4in(0.10m) concrete with ceramic tile and carpet
Description of internal walls and other thermal mass	5/8 drywall over wood framing

Table 2 Building Schedules and Internal Gain

	Value/Description
Start of Occupancy	8:00 am.
End of Occupancy	7:00 pm.
Start of On-Peak Period	12:00 pm
End of On-Peak Period	6:00 pm
Lighting (W/ft^2)	1.25 ($13.45W/m^2$)
Number of computers	30
Number of people	25

Table 3 Actual cooling setpoint schedules during the first week for baseline testing

	1st day (10/9)	2nd day (10/10)	3rd day (10/11)	4th day (10/12)	5th day (10/13)
Setting 1 (Time/Temp)	8:00 am 72ºF(22.2ºC)	8:00 am 72ºF(22.2ºC)	6:00 am 70ºF(21.1ºC)	6:00 am 70ºF(21.1ºC)	6:00 am 72ºF(22.2ºC)
Setting 2 (Time/Temp)	7:00 pm 85ºF(29.4ºC)	7:00 pm 85ºF(29.4ºC)	12:00 pm 71ºF(21.7ºC)	12:00 pm 78ºF(25.6ºC)	7:00 pm 85ºF(29.4ºC)
Setting 3 (Time/Temp)			12:45 pm 72ºF(22.2ºC)	7:00 pm 85ºF(29.4ºC)	
Setting 4 (Time/Temp)			1:45 pm 73ºF(22.8ºC)		
Setting 5 (Time/Temp)			2:30 pm 74ºF(23.3ºC)		
Setting 6 (Time/Temp)			3:30 pm 75ºF(23.9ºC)		
Setting 7 (Time/Temp)			4:15 pm 76ºF(24.4ºC)		
Setting 8 (Time/Temp)			5:00 pm 77ºF(25.0ºC)		
Setting 9 (Time/Temp)			5:30 pm 78ºF(25.6ºC)		

Table 4 Actual cooling setpoint schedules during the second week for demand-limiting test

	1st day (10/23)	2nd day (10/24)	3rd day (10/25)	4th day (10/26)	5th day (10/27)
Setting 1 (Time/Temp)	º6:00 am 72ºF(22.2ºC)	6:00 am 70ºF(21.1ºC)	6:00 am 70ºF(21.1ºC)	6:00 am 70ºF(21.1ºC)	6:00 am 70ºF(21.1ºC)
Setting 2 (Time/Temp)	7:00 pm 85ºF(29.4ºC)	12:00 pm 71ºF(21.7ºC)	12:00 pm 71ºF(21.7ºC)	12:00 pm 71ºF(21.7ºC)	12:00 pm 71ºF(21.7ºC)
Setting 3 (Time/Temp)		12:15 pm 72ºF(22.2ºC)	No change	12:15 pm 72ºF(22.2ºC)	No change
Setting 4 (Time/Temp)		No change	12:15 pm 73ºF(22.8ºC)	continued	12:15 pm 73ºF(22.8ºC)
Setting 5 (Time/Temp)		12:30 pm 74ºF(23.3ºC)	12:30 pm 74ºF(23.3ºC)	12:30 pm 74ºF(23.3ºC)	12:30 pm 74ºF(23.3ºC)
Setting 6 (Time/Temp)		12:45 pm 75ºF(23.9ºC)	No change	12:45 pm 75ºF(23.9ºC)	12:45 pm 75ºF(23.9ºC)
Setting 7 (Time/Temp)		1:00 pm 76ºF(24.4ºC)	12:45 pm 76ºF(24.4ºC)	2:00 pm 76ºF(24.4ºC)	2:00 pm 76ºF(24.4ºC)
Setting 8 (Time/Temp)		1:15 pm 77ºF(25.0ºC)	1:15 pm 77ºF(25.0ºC)	2:45 pm 77ºF(25.0ºC)	2:45 pm 77ºF(25.0ºC)
Setting 9 (Time/Temp)		4:00 pm 78ºF(25.6ºC)	4:00 pm 78ºF(25.6ºC)	3:45 pm 78ºF(25.6ºC)	3:45 pm 78ºF(25.6ºC)
Setting 10 (Time/Temp)		7:00 pm 85ºF(29.4ºC)	7:00 pm 85ºF(29.4ºC)	7:00 pm 85ºF(29.4ºC)	7:00 pm 85ºF(29.4ºC)

Table 5 Peak air conditioning powers for October 9, 11, and 12

Date	$T_{out,max}$ [ºF]	Average sky cover	Control strategy	Peak power [kW]	Power savings [kW]
10/9	90(32.2ºC)	0	NS	26.10	-
10/11	89(31.7ºC)	0.1	LR	23.53	2.57
10/12	91(32.8ºC)	0.1	SU	20.52	5.58

Table 6 Peak air conditioning powers for October 9, 11, and 12

Date	$T_{out,max}$ [ºF]	Average sky cover	Control strategy	Peak power [kW]	Power savings [kW]
10/17	80(26.7ºC)	0.2	NS	27.04	-
10/26	80(26.7ºC)	0.0	DL	16.94	10.10

Table 7 Peak air conditioning powers for October 19, 24, 25, and 27

Date	$T_{out,max}$ [ºF]	Average sky cover	Control strategy	Peak power [kW]	Power savings [kW]
10/19	85(29.4ºC)	0.0	NS	29.70	-
10/24	85(29.4ºC)	0.2	DL	20.38	9.32
10/25	86(30.6ºC)	0.2	DL	20.03	9.67
10/27	87(30.6ºC)	0.0	DL	22.34	7.36

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