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A peak-load reduction computing tool sensitive to commercial building environmental preferences

Fakeha Sehar*, Manisa Pipattanasomporn, Saifur Rahman

Virginia Tech-Advanced Research Institute, Arlington, VA 22203, USA

HIGHLIGHTS

- Optimal control of each thermal zone's cooling set points.
- Relationship between peak load savings, internal/external loads and PMV index analyzed.
- Extended DR and slow restoration of zones to normal operation reduces demand rebound.

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ABSTRACT

Demand Response (DR) as an option for electric utility peak load management has gained significant attention in the recent past as it helps to avoid stress conditions and possibly defer or avoid construction of new power generation, transmission and distribution infrastructures. DR in commercial buildings can play a major role in reducing peak load and mitigate network overloading conditions. Small and medium-sized commercial buildings have not historically played much role as a DR resource both due to lack of hardware and software tools and awareness. This paper presents a peak load reduction computing tool for commercial building DR applications. The proposed tool provides optimal control of building's cooling set points with the aim to reduce building's peak load, while maintaining occupant comfort measured by the Predicted Mean Vote (PMV) index. This is unlike other studies which use global cooling set point adjustment resulting in an uneven distribution of occupant satisfaction across the building. The approach is validated by experimentation conducted on a simulated medium-sized office building, which reflects an existing commercial building in Virginia, USA. Research findings indicate that the proposed methodology can effectively reduce the simulated building's peak load and energy consumption during a DR event, while maintaining occupant comfort requirements. The paper also addresses the issue of rebound peaks following a DR event, and offers a means to help avoid this situation.

1. Introduction

Demand Response (DR), as an option for electric utility peak load management, has gained significant attention in the recent past which can decrease both energy and power consumptions [1,2]. Most large commercial buildings (100,000 sq. ft. or more) are equipped with Energy Management Systems (EMS) which provide opportunities for peak load reduction [3,4]. The use of EMS is not widespread in small and medium-sized commercial buildings (<100,000 sq. ft.) [3]. Due to limited availability of DR methods and tools, building owners typically miss building specific DR opportunities [5]. They do not approach DR strategy development systematically and are unable to correctly estimate DR effectiveness [6,7]. The best DR strategies for any building should take into account potential for peak load reduction, electrical energy savings, customer comfort and economics [8]. Overly stringent Heating, Ventilation and Air Conditioning (HVAC)-based DR requirements not only affect occupant comfort and convenience but also create a new peak at off-peak times when DR events end [8]. This new peak also needs to be taken into account for any DR planning. However, building owners usually perform minimal analysis of their load data and adapt DR strategies as described in [8].

In this study, a particular attention is given to the HVAC load. Authors in [9] identify that commercial buildings in the U.S. are usually overcooled and it is a cultural practice to purposely set a low temperature. Authors in [8] discuss HVAC-based DR strategies including global temperature adjustment of zones and systemic adjustments to the air distribution and cooling systems. Findings in [10–12] indicate that among HVAC based DR strategies, global

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* Corresponding author. Tel.: +1 (571) 241 2846; fax: +1 (571) 858 3315.
E-mail address: sehaf0@vt.edu (F. Sehar).

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temperature adjustment of zones, where entire facility cooling set points are raised to some absolute values, best achieves DR goal. Authors in [13] summarize energy savings results from different case studies involving global summer set point temperature increase. However, authors in [14] show that applying global set point changes during peak hours with pre-cooling efforts to a large multi zone commercial building results in poor distribution of HVAC capacity across zones and an uneven distribution of occupant satisfaction across the building. Authors in [14] design a HVAC control strategy to adapt a building's DR on a zone-by-zone basis for planning in advance HVAC operation to balance energy costs, greenhouse gas emissions and occupant thermal comfort.

A recent study indicates that building occupants rank thermal comfort to be of similar importance to visual and acoustic comfort and indoor air quality [15]. Authors in [16] present a review of human thermal comfort in the built environment and identify a gap in thermal comfort studies in relation to interdisciplinary research. Studies [17–19] propose thermostat strategies to understand the trade-off between energy consumption and thermal comfort. Authors in [20] investigate the relationship between building insulation and air conditioning unit supply air temperature to provide better comfort. Authors in [21] identify various factors affecting building thermal comfort and building material to improve it. Authors in [22] investigate energy saving potential of PMV based control in glass façade buildings and suggest careful design of components of glass facade can achieve thermal comfort and energy savings. Authors in [23] control the indoor air velocity to maintain the PMV index within thermal comfort range to achieve energy savings. Authors in [24] perform thermal comfort simulation by integrating building thermal behavior analysis with PMV thermal comfort model to identify appropriate low-energy cooling opportunities which achieve better thermal comfort. Authors in [25] assess summer comfort of a modeled building which depends upon thermal performance of the building envelope with external climate and internal gains and losses which intervene with comfort criteria. Authors in [26] develop a living space thermal-comfort regulator which maintains PMV index within specified limits.

Literature review reveals that an optimal control of each thermal zone's cooling load is needed since all thermal zones do not behave the same, they may not be able to evenly share the DR shed burden. Higher increase in the cooling set points for zones with high solar gains drastically effects occupant thermal comfort. To address the above knowledge gaps the authors propose to design a peak load reduction computing tool for commercial building DR which provides optimal control of each thermal zone's cooling load in a medium-sized office building and an insight into how thermal comfort is related to peak load and energy consumption. The tool maximizes building's economic benefits while being sensitive to occupant needs. Following the DR event, HVAC systems use extra energy to remove the heat gained during reduced service levels of DR event to bring back the system to normal conditions and hence experience rebound. This rebound is investigated and a means to mitigate this impact is suggested.

2. Methodology of the study

The study presents a peak load reduction computing tool for commercial building DR – validated by simulation – and investigates the impact of raising cooling set point schedule for a simulated medium-sized office building during DR event on each thermal zone's PMV index, building peak load and energy consumption. The study has been performed for the summer season when cooling load is high during afternoon hours in an office building. In this study, EnergyPlus, a building energy simulation tool, is used to provide more accurate peak electric load savings. EnergyPlus takes into account factors including weather conditions, building type and condition, HVAC system and DR strategy design which influence HVAC-based DR operation [8].

2.1. Predicted Mean Vote (PMV)

Cooling energy conditions the indoor environment to thermal comfort range. Thermal comfort is satisfaction with the thermal environment. Thermal comfort is affected by environmental factors including air temperature, mean radiant temperature, relative humidity, air speed and two personal factors including activity and clothing. In 1972, Fanger proposed a PMV model that takes into account all the above factors and can be applied to air conditioned buildings to determine the occupant thermal comfort [23]. Fanger model assumes that the person is thermally at steady state with his environment. The model is based on energy analysis that takes into account all modes of energy loss from the body. It was developed with human subjects in climate chambers exposed to well control environments. The PMV model has been validated in various field studies including the ASHRAE's worldwide research in buildings with HVAC systems situated in cold, temperate and warm climates and during both summer and winter [27]. PMV is calculated using the following relations [23,28].

$$\begin{aligned} PMV = {} & (0.303 * e^{-0.036M} + 0.028) \\ & \times \Big\{ (M - W) - 3.05 * 10^{-3} [5733 - 6.99(M - W) P_a] \\ & - 0.42[(M - W) - 58.15] - 1.7 * 10^{-5} M (5867 - P_a) \\ & - 0.0014M(34 - t_a) - 3.96 * 10^{-8} F_{cl} [(t_{cl} + 273)^4 \\ & - (t_{mr} + 273)^4] - F_{cl} h_c (t_{cl} - t_a) \Big\} \end{aligned} \tag{1}$$

where

$$\begin{aligned} t_{cl} = {} & 35.7 - 0.028(M - W) \\ & - I_{cl} \Big\{ 3.96 * 10^{-8} F_{cl} [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - F_{cl} h_c (t_{cl} - t_a) \Big\} \end{aligned} \tag{2}$$

$$h_c = \begin{matrix} 2.38(t_{cl} - t_a)^{0.25} \textit{ for } 2.38(t_{cl} - t_a)^{0.25} > 12.1(v_{ar})^{\frac{1}{2}} \\ 12.1(v_{ar})^{\frac{1}{2}} \textit{ for } 2.38(t_{cl} - t_a)^{0.25} < 12.1(v_{ar})^{\frac{1}{2}} \end{matrix} \tag{3}$$

$$F_{cl} = \begin{matrix} 1.00 + 1.290 * I_{cl} \textit{ for } I_{cl} < 0.078\ \mathrm{m^2\ {}^\circ C\ W^{-1}} \\ 1.05 + 0.645 * I_{cl} \textit{ for } I_{cl} > 0.078\ \mathrm{m^2\ {}^\circ C\ W^{-1}} \end{matrix} \tag{4}$$

$$V_{ar} = v_a + 0.005 \left(\frac{M}{A_{DU}} - 58.15 \right) \tag{5}$$

where t_a – Air temperature (°C), t_{mr} – Mean radiant temperature (°C), v_{ar} – Relative air velocity with respect to human body (m/s), p_a – Partial water vapor pressure (N/m^2)), t_{cl} – Surface temperature of clothing (°C), h_c – Convective heat transfer coefficient (w/m^2 °C), I_{cl} – Thermal resistance of clothing (clo), F_{cl} – Ratio of man surface area while clothed to that of nude(dimension less), A_{DU} – Dubious area (m^2), V_a – Air velocity (m/s), M – Metabolic rate (met), W – External work (w/m^2).

When PMV is zero, thermal comfort is maintained; +1, +2 and +3 indicate slightly warm, warm and hot conditions respectively, while −1, −2 and −3 present slightly cool, cool and cold conditions respectively. Comfortable range for PMV considered as a condition for air conditioning is between −0.5 and +0.5 [27].

EnergyPlus can handle PMV calculations, considering activity and clothing schedules based on time of day together with thermostats for the zones. In this study, an HVAC system conditions the space based on comfort not just temperature. Internal gains from occupants, light, equipment, infiltration and ventilation that affect thermal zones are also taken into account. In addition, the radiative effect of surfaces is taken into account and inside surface temperatures are generated without which thermal comfort calculations are not possible [29].

2.2. Building simulation tool used for the study

EnergyPlus – a building energy simulation program – version 8.1 has been used for modeling and simulation; details of which are available in [30,31]. EnergyPlus uses three basic components including a simulation manager, a heat and mass balance simulation module, and a building systems simulation module to calculate the heating and cooling loads needed to maintain thermal control set points, energy consumption and other parameters visualizing actual building performance based on user's description of building envelope, mechanical systems, location, weather and other inputs [32].

The optimal control algorithm to be discussed in Section 2.4 has been designed with EnergyPlus EMS module. The EMS uses a simple programming language, EnergyPlus Runtime Language (Erl), to specify control algorithms based on IF-THEN-ELSE statements and other logic structures described in [33]. The core of EMS module is the EMS Manager which co-ordinates activities of EMS objects like sensors and actuators with the overall EnergyPlus simulation. The EMS works by polling a set of sensors and retrieves data about external environmental conditions, internal building conditions, HVAC and other equipment conditions. Sensor data becomes input variable for EMS control algorithms. Remote actuators are controlled to make changes to system operations once the EMS passes judgment. The concept is to emulate, inside EnergyPlus, the same type of controls that can be implemented with digital EMS in real buildings. EnergyPlus EMS can turn on or off the lights, change zone thermostat set points and other actions thereby affecting building operation.

2.3. Simulated medium-sized office building model and input assumptions

This section summarizes the simulated medium-sized office building model used as a basis to develop the proposed peak load reduction computing tool for commercial building DR. The simulated medium-sized office building model is based on Department of Energy (DOE) medium-sized reference office building model, available in [34] and reflects medium-sized office buildings found in Virginia/Maryland area and is of post-1980 construction.

Input assumptions about climate conditions, building envelope characteristics, building operating characteristics, internal and external loads for developing the simulated medium-sized office building model in EnergyPlus are discussed below:

- *Climate data* – The weather data used is of Ronald Reagan Washington National airport available from [6]. Fig. 1 shows the outdoor air dry-bulb temperature for a summer day used in this study. From noon to around 6 pm outside air temperature is greater than 30 °C.
- *Building envelope* – The simulated medium-sized office building for this study is a 53,600 ft^2 (4980 m^2) three-story building. It is rectangular shaped, 164 ft. by 109 ft. The envelope constructions include steel-framed walls, flat roof with insulation above the deck and slab-on-grade floors. The windows have a height of 4 ft and are distributed evenly in continuous ribbons around the perimeter of the building. Fig. 2 shows the axonometric view of the simulated medium-sized office building used in this study.

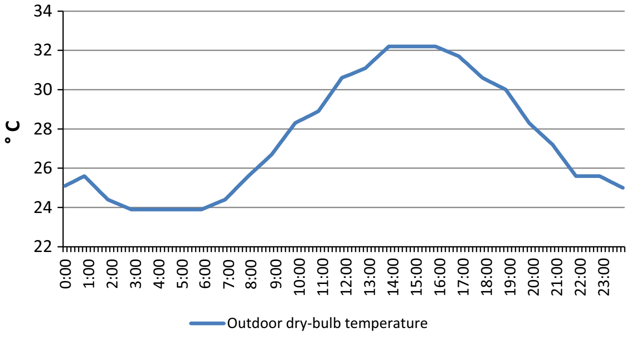

Fig. 1. Outdoor dry-bulb temperature for a summer day used in this study.

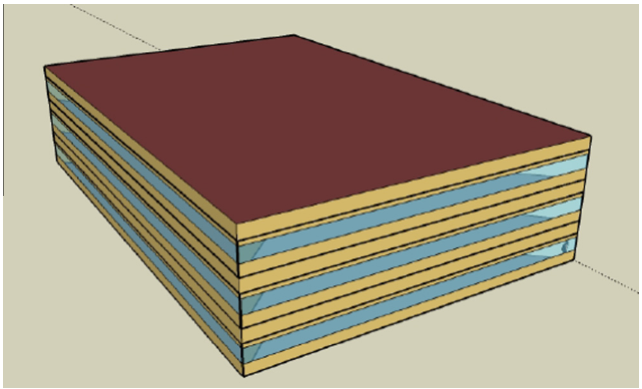

Fig. 2. Axonometric view of simulated medium-sized office building used in this study [35].

- *Building operation and HVAC load* – The occupancy, lighting, HVAC and electric equipment schedules on a typical weekday used in this study are shown in Fig. 3. The simulated building follows typical occupancy patterns for office building with peak occupancy between 8 am to 5 pm on weekdays and a decrease during lunch time between 12 pm to 1 pm. Each floor's HVAC system, a package rooftop variable air volume system, starts earlier before occupants arrive to bring the space to desired temperature. For a summer weekday from 6 am to 10 pm the normal operating cooling set point is 24 °C. During off-hours set back strategy is applied and the cooling temperature set point is 26.7 °C. The simulated building has five thermal zones, four perimeter zones and one core zone, on each floor. Each perimeter zone extends from exterior wall inward for 15 ft.

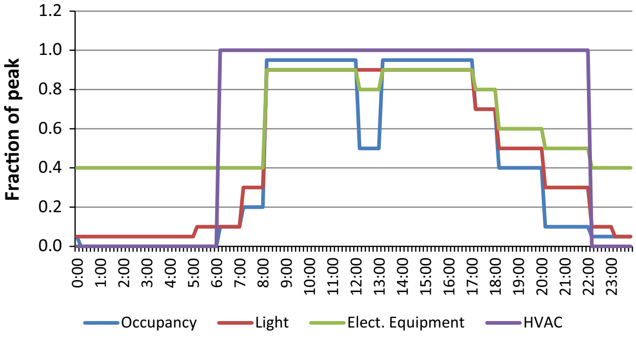

Fig. 3. Simulated medium-sized office building typical weekday schedule used in this study.

- *Occupants, lighting and equipment* – Occupant density is 5 persons per 1000 ft^2 of gross floor area. Ambient electric lighting power density for the entire simulated building is 1.6 W/ft^2. Office buildings have plug loads, such as office equipment, refrigerators, coffee makers, beverage and vending machines. The electric plug load density is 0.75 W/ft^2 [35] which is distributed throughout the simulated building. For the mid floor, as more tenants are considered, this leads to higher number of office equipment and plug load density than other floors. Table 1 shows the plug load density for different zones and floors of the simulated medium-sized office building under study. The simulated medium-sized office building has two elevators, each with 20hp hydraulic motor. These elevators are modeled as an internal zone load. Heat gain from these elevators is added to the bottom floor core zone.

2.4. Algorithm for optimal comfort control of cooling system

Typically a DR event on a weekday can be at any time between 1 pm to 7 pm during summer [36,37]. The DR event selected for this analysis starts from 2 pm to 5 pm. To study the demand rebound affect, duration of simulation studies is extended to 7 pm. By 7 pm occupants have mostly left the simulated building and only 40% remain. Fig. 4 shows the flowchart for the designed algorithm.

The flowchart is explained as follows:

- The EMS module and its zone temperature control actuators are activated and override normal building operation upon start of DR event.
- At each time step the EMS sensors retrieve the PMV index and cooling set points of each zone on all floors. This data is mapped to EMS variables to be used in control algorithms specified in the EMS program.
- At the beginning of each time step the EMS Program Calling Manager calls the EMS program, which contains instruction blocks of Erl code, to adjust each zone's cooling set points. During DR event, 2–7 pm, the normal cooling set point is 24 °C, which is set as the lower limit and each zone's cooling set points are raised above 24 °C repeatedly until a value is obtained at which the PMV index remains lower than +0.5 and maximum peak load savings can be achieved. Once judgment has been made as per the Erl program instructions, EMS zone temperature control actuators adjust, i.e., increase or decrease, the thermostat cooling set points for all zones as per Eq. (6). It is a schedule-based control since the building's normal operating cooling set point schedule is considered. The "SET" instruction performs control actions on the object to which it is mapped, here zone temperature control actuators. As soon as the DR event finishes the cooling set points are brought back to their normal operating values by setting the temperature control actuators for each zone to "Null". Null is a special structure that stops the actuator from overriding control.

$$\begin{aligned}&\text{SET Zone cooling set point actuator value}\\&\quad = \text{normal operating cooling set point schedule} + \text{offset}\end{aligned} \tag{6}$$

Table 1
Plug load density for the simulated medium-sized office building used in this study.

	Plug load power density watts/square feet		
	Bottom floor	Mid floor	Top floor
Core zone	0.16	0.22	0.16
Perimeter zone 1	0.79	1.73	0.79
Perimeter zone 2	2.66	1.44	2.66
Perimeter zone 3	1.28	2.22	1.28
Perimeter zone 4	1.37	2.22	1.37
Average density for each floor	0.67	0.91	0.67
Average density for the entire building	0.75		

3. Simulation results and discussions

Simulations are performed for a summer day. Note that the façade design for the three floors of the simulated medium-sized office building is same; the main climatic element, solar radiation, affects the building occupant thermal comfort as it includes the amount of heat transferred to the building. The simulated medium-sized office building's north axis is specified to true North. The 4-perimeter zones on all floors are exposed to external environment as they have exterior walls and windows, while the core zones on all floors are not directly exposed to external environment. For each of the three floors, zone 1 faces south, zone 2 faces east, zone 3 faces north and zone 4 faces west. In the morning hours, the east facing zone 2 experiences more sunlight as the sun rises north of due east. In the afternoon hours, the west facing zone 4 experiences more sunlight since the sun sets south of due west.

Internal loads also impact the cooling energy use. Since the number of electrical plug loads is different for the zones on each floor, hence the increase in cooling energy is more for zones with higher electrical plug load density. The bottom floor core zone requires additional cooling energy since the elevators are modeled as an internal load for this zone.

3.1. PMV index without EMS

The normal operating cooling set point from 6 am to 10 pm is 24 °C in all zones on all three floors. The PMV index during this time is mostly negative for all zones, as illustrated in Figs. 5–7 which show the PMV index without EMS for all zones on the bottom, mid and top floors, respectively. For zone 4 on the mid and top floors the PMV index gets positive during the evening hours (i.e., 4–5 pm). The PMV index starts to decrease for all zones after 5 pm due to decrease in simulated building's occupancy. From 10 pm to 6 am the normal operating cooling set point is increased to 26.7 °C which makes the PMV index positive, especially for mid and top floor zones but not too high since there are no occupants in the simulated building and the internal building load is less.

It is observed that during the early hours, from 8 am onwards the PMV index starts increasing for zone 2, facing east, on all floors and starts to decrease after 12 pm. This is due to sunrise which provides direct sunlight to the east zones. PMV index during this time is higher, especially for zone 2 on mid and top floors than for the bottom floor. This is due to the fact that mid and top floors receive more sunlight than the bottom floor.

Similarly, during the afternoon hours, from 3 pm onwards, the sun starts to set in the west, the PMV index starts increasing, and gets positive for the west facing zone 4 on mid and top floors. Zone 4 PMV index reaches its highest at around 4:30 pm and then starts decreasing since the sun is setting. After 5:30 pm PMV index for zone 4 becomes negative since simulated building's occupancy has decreased. Again PMV index is more positive for top and mid floors zone 4 than the bottom floor zone 4 as they receive more sunlight.

Zones 1 and 3 on all floors face south and north respectively. South zones receive plenty of early morning and afternoon sun

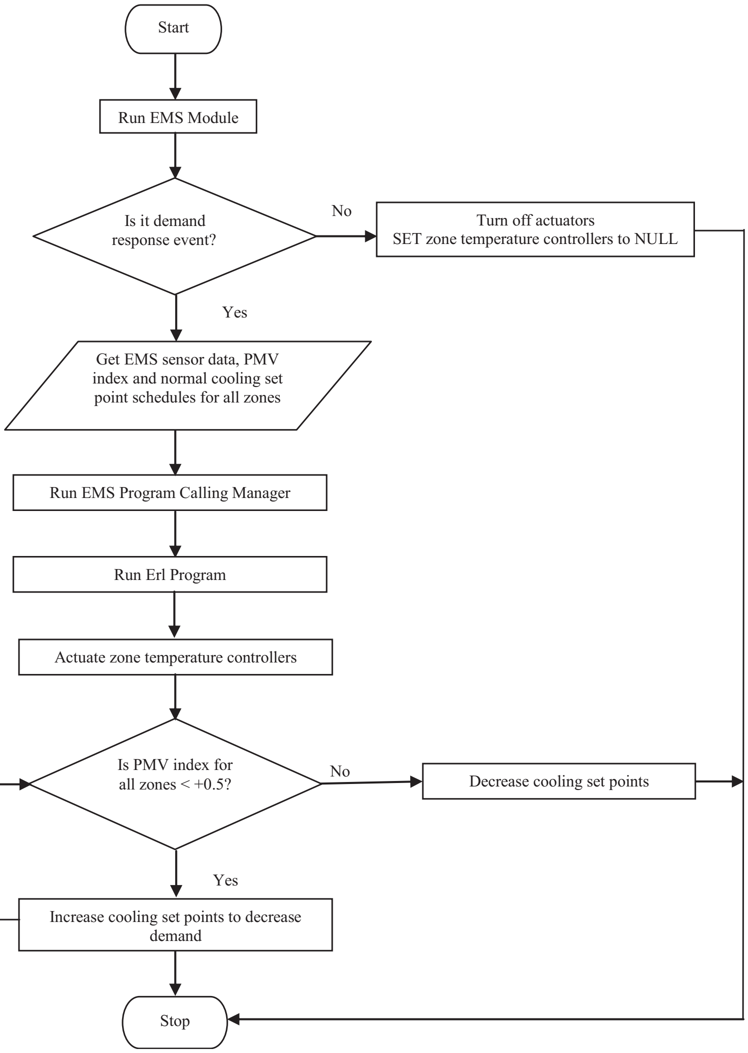

Fig. 4. Algorithm to control thermal zone's cooling set points for optimal comfort and peak load savings.

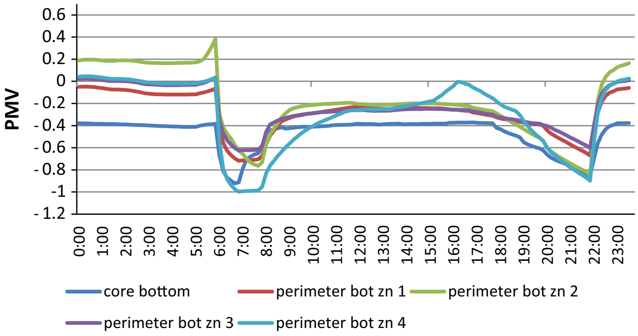

Fig. 5. Bottom floor PMV index without EMS for a summer day.

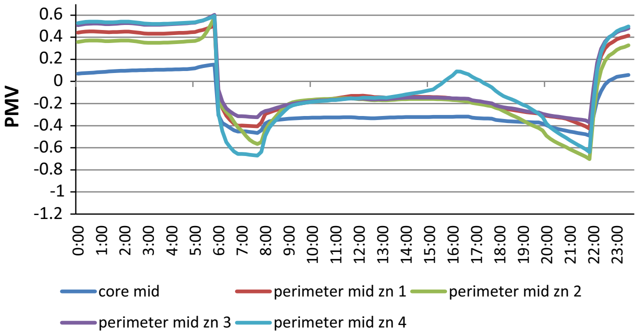

Fig. 6. Mid floor PMV index without EMS for a summer day.

while the north zones receive afternoon sun. For these zones the PMV index remains negative but there is a slight increase in the afternoon hours from around 12 pm to 4 pm when the sun is at its peak and external temperatures are high.

For the core zones on all floors the PMV index remains low and negative. The core zones are protected against external environmental conditions. These zones have mostly the internal loads due to occupants, lighting and electric equipment.

It is also noted that the PMV index for all zones on mid floor, except zone 2, is slightly higher than top floor's respective zones. This is because these mid floor zones have higher plug load densities leading to higher internal loads.

3.2. PMV index with EMS

It is assumed that DR event occurs between 2 pm and 7 pm. Figs. 8–22 show the PMV index and cooling set point temperatures

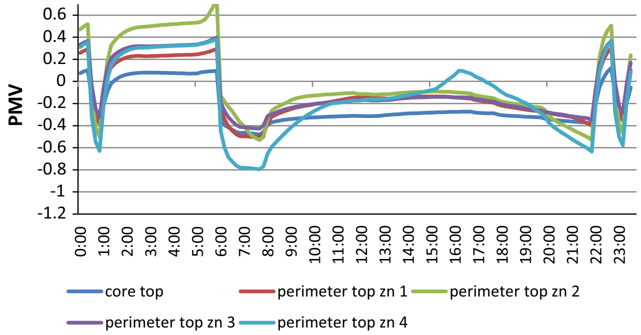

Fig. 7. Top floor PMV index without EMS for a summer day.

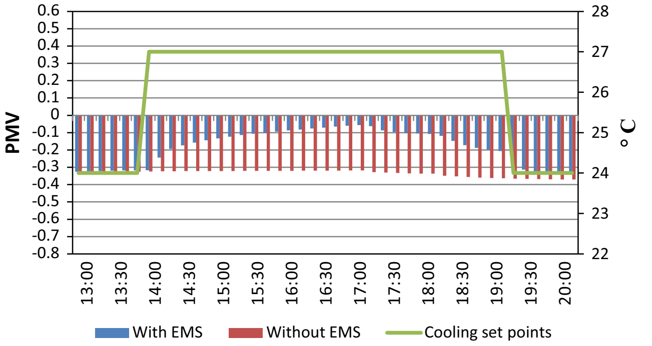

Fig. 9. Mid floor core zone cooling set points and PMV index with and without EMS for a summer day.

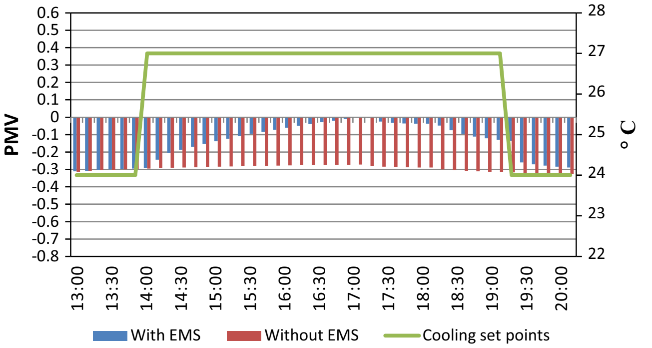

Fig. 10. Top floor core zone cooling set points and PMV index with and without EMS for a summer day.

for the DR duration from 2 pm to 7 pm. During the DR event the cooling set points are actuated by the EMS. The cooling set points for all zones are increased to achieve maximum peak load savings. As the cooling set points increase the PMV index starts increasing due to less conditioning. Not every zone behaves the same, thus the cooling set points are optimally adjusted in each zone to achieve maximum peak load savings and maintain thermal comfort. The PMV index is not allowed to increase beyond +0.5.

Solar heat gain through building envelope contributes significantly to sensible cooling load and increases space temperature. Other factors influencing sensible cooling load are occupants, electric equipment, lights, ventilation and infiltration. Number of occupants, lighting densities, ventilation and infiltration rates is same for all zones except for the plug load density which varies slightly. It is the external heat gain through solar radiation which varies for all zones, and hence it controls each zone's sensible cooling load. It is observed from simulation results that the PMV index, peak load and energy savings for zones with less solar radiation – less sensible cooling load – remain unaffected beyond 27 °C. The sensible cooling rate – cooling delivered by HVAC – is unchanged for temperature offset greater than 3 °C due to almost constant sensible cooling load. Maximum peak load and energy savings, discussed in later sections, are obtained with an upper limit of 3 °C temperature offset from the original 24 °C cooling set point.

Figs. 8–10 show the PMV index and cooling set points during the DR event for the core zones on all three floors. It is observed that throughout the DR event the core zone's cooling set points can be maintained at 27 °C, while the PMV index remains below +0.5. Since the core zones are not directly influenced by external environment they are much more comfortable and provide an opportunity to increase their cooling set points up to 27 °C and achieve maximum peak load savings. For the bottom floor core zone, increasing cooling set point to 27 °C which reduces conditioning, the PMV index gets positive, from around 4:20 pm to 6 pm, as shown in Fig. 8, due to additional heat gain from the elevators. Hence higher internal load for the bottom floor core zone, unlike the mid and top floor core zones, increases its PMV index at increased cooling set point. After 6 pm when the elevators stop operating due to decrease in occupancy, PMV index goes much negative as there is no more additional heat gain from the elevators.

Figs. 11–13 show the PMV index and cooling set points during the DR event for zone 1 on all three floors. For zone 1 on the bottom and top floors, cooling set point of 27 °C can be maintained. For the mid floor cooling set points fluctuate between 27 °C and 26 °C due to higher plug load density. The top floor receives more sunlight than mid or bottom floor, it is able to maintain 27 °C cooling set point but with higher PMV index.

Figs. 14–16 show the PMV index and cooling set points during the DR event for zone 2 on all three floors. It can be seen that a constant cooling set point of 27 °C can be maintained to achieve

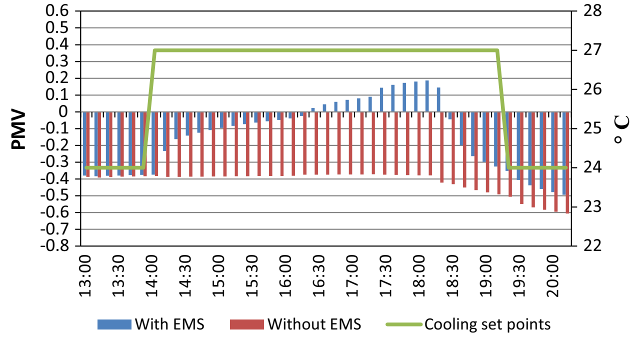

Fig. 8. Bottom floor core zone cooling set points and PMV index with and without EMS for a summer day.

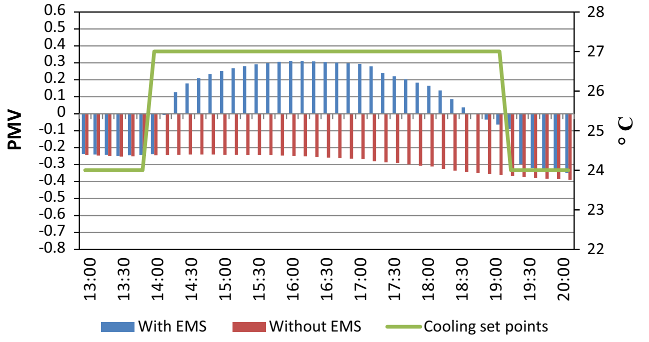

Fig. 11. Bottom floor perimeter zone 1 cooling set points and PMV index with and without EMS for a summer day.

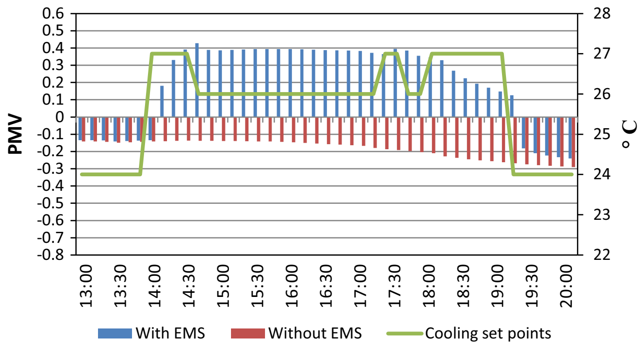

Fig. 12. Mid floor perimeter zone 1 cooling set points and PMV index with and without EMS for a summer day.

maximum peak load savings and thermal comfort. Zone 2 has an east facing window, during the DR event this side does not face the direct sunlight and hence remains comfortable with high indoor cooling set points. The PMV index is higher for the top floor zone 2 as it receives more sunlight and also has a high plug load density. The PMV index for bottom and mid floor's zone 2 is comparable, although mid floor zone 2 receives more sunlight but plug load density is higher for the bottom floor zone 2.

Figs. 17–19 show the PMV index and cooling set points during the DR event for zone 3 on all three floors. For zone 3 on the bottom and top floors, a constant cooling set point of 27 °C can maintain thermal comfort throughout the DR duration. For zone 3 on the mid floor, a constant 27 °C cooling set point cannot be maintained due to higher plug load density. The top floor receives more sunlight than mid or bottom floor, hence it has a higher PMV index at 27 °C cooling set point.

Figs. 20–22 show the PMV index and cooling set points during the DR event for zone 4 on all three floors. For zone 4 on all floors, till 3:30 pm, 27 °C cooling set point can be maintained. After this time it is observed that by raising the cooling set points to 25 °C, 1 °C higher than the normal operating temperature of 24 °C, the PMV index increases rapidly. During this time, for zone 4 on all floors 25 °C cooling set point is maintained to achieve maximum peak load savings and occupant thermal comfort. Rapidly fluctuating cooling set points are able to maintain thermal comfort but cause the cooling system's demand to fluctuate unevenly and as a result the cooling system's peak demand increases. Since, zone 4 is the west facing zone, during the later afternoon hours this zone gets more heat transferred from sunlight to the indoor environment. Due to higher plug load density mid floor's zone 4 PMV index is comparable to top floor's zone 4 although top floor receives more sunlight.

3.3. Energy and peak load savings

Two durations for the DR have been investigated to evaluate peak load and energy savings potentials. One DR event is from 2 pm to 5 pm and other from 2 pm to 7 pm.

Figs. 23 and 24 show peak load savings achieved for the simulated building and its HVAC system with EMS respectively. By optimally raising the cooling set points in all zones using the proposed strategy, cooling energy consumption and peak load can be reduced. It is observed that more peak load and energy savings can be achieved during the afternoon hours, from 2 pm to around 5 pm, since during this time the outdoor temperatures are higher and cooling contributes significantly to building load. During the evening hours as the outdoor environment gets cooler, raising the indoor cooling set points and having less conditioning does not achieve much savings as compared to the afternoon hour's savings.

Tables 2 and 3 present the peak load values and savings with the proposed optimal cooling set point control and with global cooling set point control respectively. Although global cooling set point adjustment achieves more peak load savings but occupant comfort is adversely affected. Fig. 25 shows as an example PMV index for perimeter zones on mid floor with global temperature adjustment.

For DR duration from 2 pm to 5 pm, when DR event ends, instantly HVAC load increases from 79 kW to 136.22 kW, representing an increase of 72.42% if all zone's cooling set points are abruptly brought back to normal operation. This exceeds the original HVAC peak load at 4:30 pm without EMS by roughly 29 kW. At the end of DR event from 2 pm to 5 pm, if all zone's cooling set points are slowly brought back to normal operation within an hour it is observed that HVAC load increases from 89.30 kW to 118.23 kW around 6 pm, representing an increase of only 32.39%. For DR duration from 2 pm to 7 pm, when DR event ends, instantly HVAC load increases from 64.27 kW to 87.36 kW, representing an increase of 35.92%. This indicates that demand rebound is reduced when DR event ends later in a day when both the building's internal and external loads have reduced. From Fig. 23 it can be seen that HVAC electric demand rebound has little effect on building's electric demand.

Figs. 26–28 show peak load savings for each floor's air conditioning system. It is observed that the top floor's air conditioning system, which receives most sunlight, has higher peak load than other floors with and without EMS. Top floor's demand rebound at the end of DR event is also higher than other floors. At the end of DR event from 2 pm to 5 pm, demand rebound is less if all the zone's cooling set points are slowly brought back to normal operation within an hour instead of abruptly switching them.

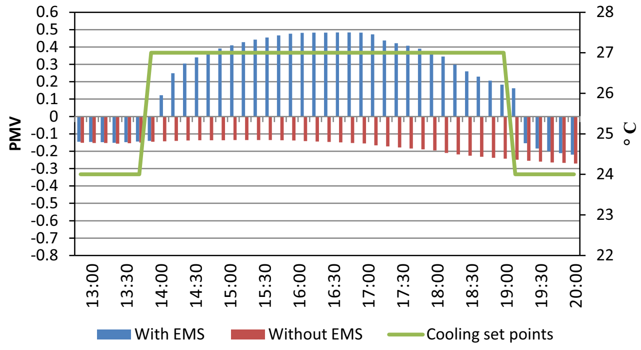

Fig. 13. Top floor perimeter zone 1 cooling set points and PMV index with and without EMS for a summer day.

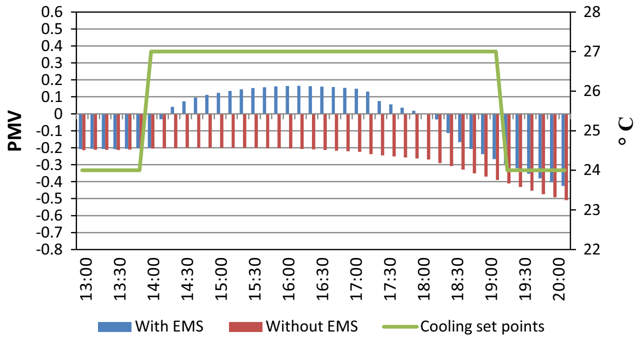

Fig. 14. Bottom floor perimeter zone 2 cooling set points and PMV index with and without EMS for a summer day.

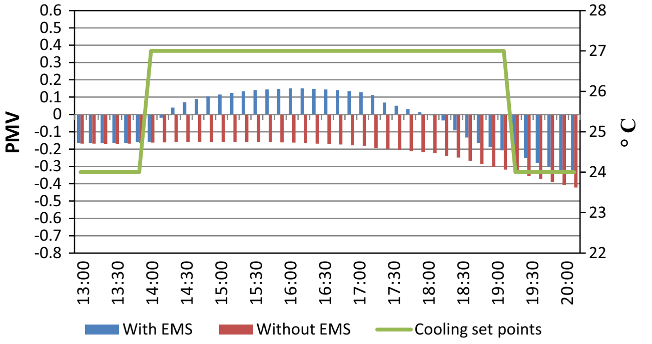

Fig. 15. Mid floor perimeter zone 2 cooling set points and PMV index with and without EMS for a summer day.

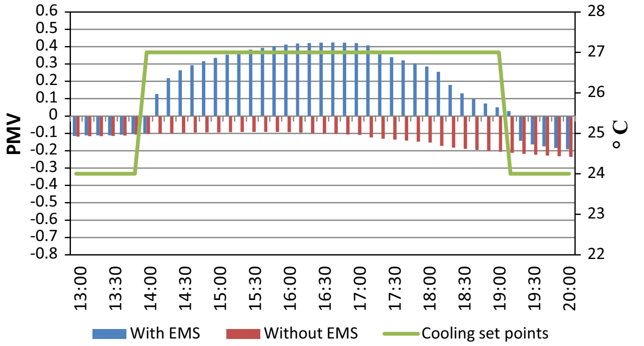

Fig. 16. Top floor perimeter zone 2 cooling set points and PMV index with and without EMS for a summer day.

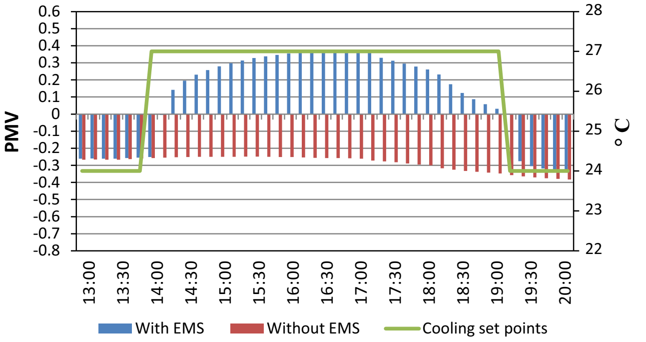

Fig. 17. Bottom floor perimeter zone 3 cooling set points and PMV index with and without EMS for a summer day.

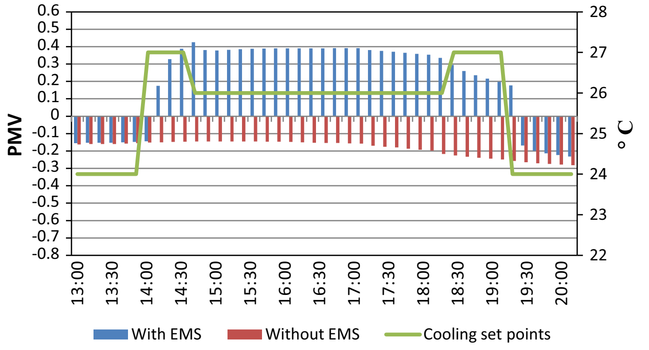

Fig. 18. Mid floor perimeter zone 3 cooling set points and PMV index with and without EMS for a summer day.

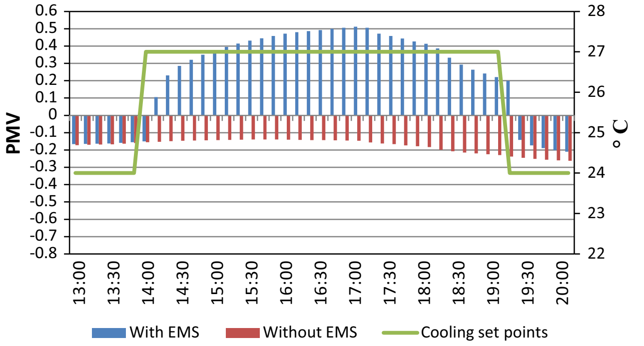

Fig. 19. Top floor perimeter zone 3 cooling set points and PMV index with and without EMS for a summer day.

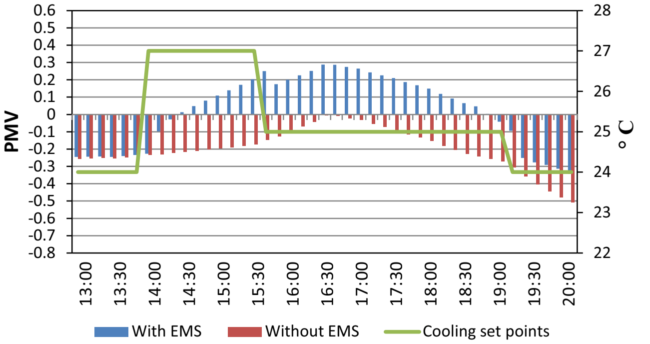

Fig. 20. Bottom floor perimeter zone 4 cooling set points and PMV index with and without EMS for a summer day.

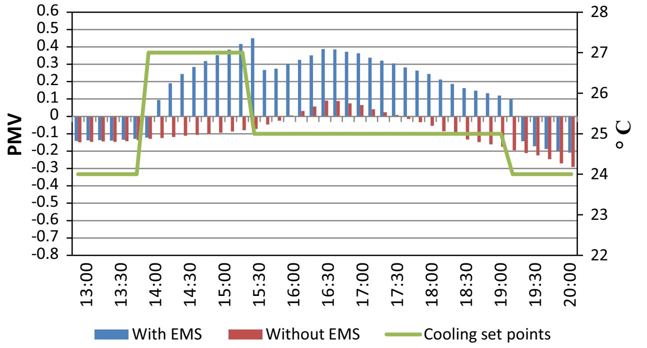

Fig. 21. Mid floor perimeter zone 4 cooling set points and PMV index with and without EMS for a summer day.

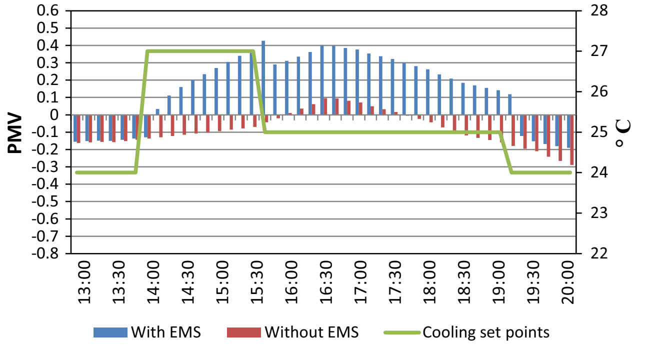

Fig. 22. Top floor perimeter zone 4 cooling set points and PMV index with and without EMS for a summer day.

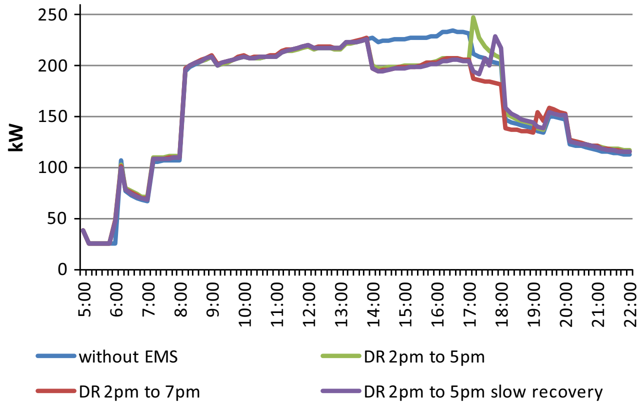

Fig. 23. Simulated building peak load with and without EMS for a summer day.

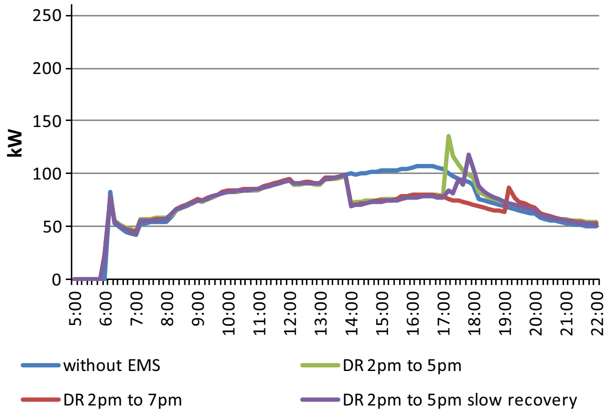

Fig. 24. Simulated building's HVAC peak load with and without EMS for a summer day.

Table 2
Peak load values for simulated building and HVAC without EMS, with optimal and global cooling set point control for a summer day.

	Peak load values during DR event 2–7 pm	
	Building (kW)	HVAC (kW)
Without EMS	234.15	107.7
With EMS, optimal cooling set point control	207.07	80.19
Global cooling set point control	201.64	74.76

Table 3
Peak load savings for simulated building and HVAC with optimal and global cooling set point control for a summer day.

	% Peak load savings during DR event 2–7 pm	
	Building	HVAC
With EMS, optimal cooling set point control	11.56	25.54
Global cooling set point control	13.88	30.58

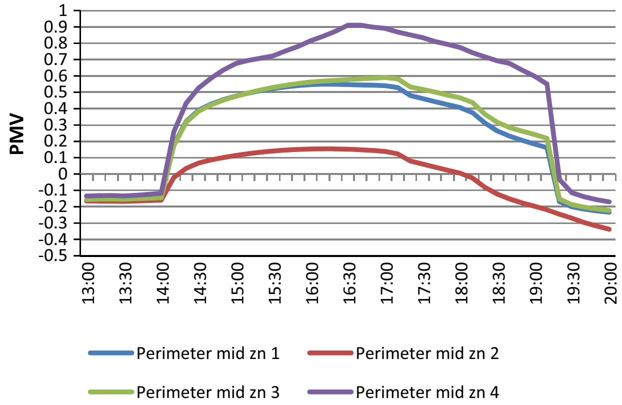

Fig. 25. Mid floor perimeter zones PMV index with global cooling set point control for a summer day.

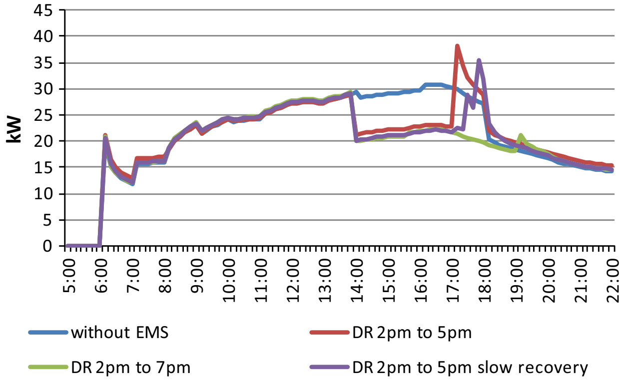

Fig. 26. Bottom floor cooling system peak load with and without EMS for a summer day.

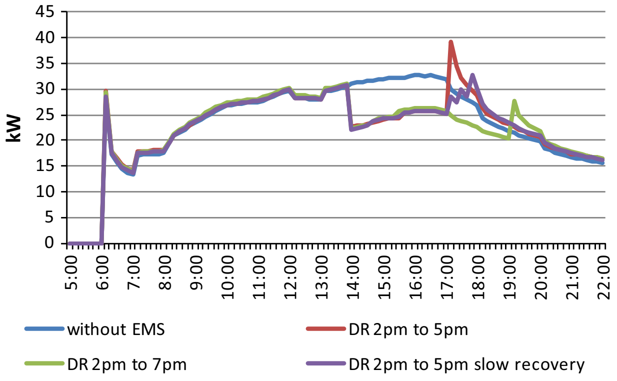

Fig. 27. Mid floor cooling system peak load with and without EMS for a summer day.

Table 4 shows the energy consumption for the entire day, a summer day, without EMS and for the two DR durations with EMS. Extended DR event achieves more energy savings.

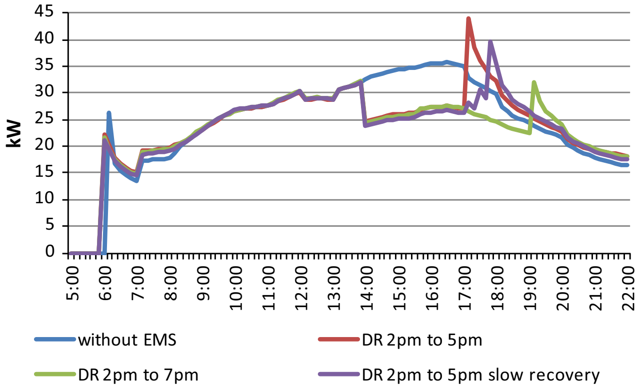

Fig. 28. Top floor cooling system peak load with and without EMS for a summer day.

Table 4
Energy consumption of simulated building and HVAC with and without EMS for a summer day.

	Energy consumption (GJ)	
	Building	HVAC
Without EMS	11.46	4.61
DR 2–5 pm	11.34	4.49
DR 2–5 pm slow recovery	11.31	4.46
DR 2–7 pm	11.24	4.40

4. Conclusions

Thermal zones do not behave the same; hence a global temperature adjustment will result in poor distribution of HVAC capacity across zones and an uneven distribution of occupant satisfaction across the building. The peak load reduction computing tool for commercial building DR developed in this study optimally controls cooling set points of each thermal zone in a simulated medium-sized office building while maintaining occupant thermal comfort and achieves optimized peak load savings. The PMV index is used to provide direction for DR savings and achieving thermal comfort. The proposed tool can be used by building owners and utilities to correctly estimate DR effectiveness and potential benefits. Simulation results from using the proposed tool in a simulated medium-sized office building model show that a maximum affective temperature offset of 3 °C in cooling set point achieves maximum savings and maintains thermal comfort. The study also provides an understanding of how thermal comfort is related to peak load and energy consumption and its interaction with internal loads and external environment. The results show that the PMV index increases more for zones with higher internal loads at increased cooling set points. For the west facing zones, it is observed that from late afternoon onwards, PMV index increases rapidly even with 1 °C rise in cooling set point as these zones are exposed to direct sunlight. Hence the designed strategy works successfully and has a large potential field of application. The research provides an understanding between cooling temperature set points and PMV index. Demand rebound reduces when DR duration is extended to hours when both the building's internal and external loads have reduced or if the zone's cooling set points are slowly brought back to normal operation at the end of DR event. This study can also benefit researchers in academia and industry as it demonstrates how an EMS can be developed and integrated with EnergyPlus for analyzing peak load and energy consumption in buildings taking into account comfort perspective. This is unlike other studies which estimate building's load profiles from data samples.

Acknowledgement

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