Comparison of Demand Response Performance with an EnergyPlus Model in a Low Energy Campus Building

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ABSTRACT

We have studied a low energy building on a campus of the University of California. It has efficient heating, ventilation, and air conditioning (HVAC) systems, consisting of a dual-fan/dual-duct variable air volume (VAV) system. As a major building on the campus, it was included in two demand response (DR) events in the summers of 2008 and 2009. With chilled water supplied by thermal energy storage in the central plant, cooling fans played a critical role during DR events. In this paper, an EnergyPlus model of the building was developed and calibrated. We compared both whole-building and HVAC fan energy consumption with model predictions to understand why demand savings in 2009 were much lower than in 2008. We also used model simulations of the study building to assess pre-cooling, a strategy that has been shown to improve demand saving and thermal comfort in many types of building. This study indicates a properly calibrated EnergyPlus model can reasonably predict demand savings from DR events and can be useful for designing or optimizing DR strategies.

Introduction

The Merced campus of the University of California (UC Merced) is a unique facility which was designed for high energy efficiency and minimum peak loads (Brown 2002, UC Merced website). In the campus central plant, a two-million-gallon central chilled water thermal energy storage (TES) tank provides chilled water for cooling of all buildings. The tank is charged by electric chillers during the grid demand off-peak hours. This system has successfully shifted peak loads, and achieved significant energy cost savings (Brown 2002) due to differential pricing of electricity by time of day. The central plant provides hot water for heating to each building, as well.

The Classroom and Office Building (COB) is a three-story, approximately 8,385 m^2 (90,253 ft^2) building that functions as instructional and office space for both academic and administrative staff. The building contains approximately 37 classrooms on the first two floors and approximately 100 offices on the second and third floors. The first floor consists of an auditorium, 10 classrooms, two restrooms, and several miscellaneous utility rooms. The second floor contains roughly 25 classrooms, 30 offices, a conference room, two restrooms, and a few miscellaneous utility rooms. The third floor consists of 70 offices, a few conference rooms, and a large open seating plan work area. In COB, a dual fan/dual duct variable air volume (VAV) air distribution system with variable frequency drive (VFD) fans delivers the conditioned air to the building. Much of the building lighting is scheduled, although some areas feature local occupancy or photo sensor controls (Narayanan et al. 2010). The annual electricity usage intensity during the year of July 2007 – June 2008 was 9.03 kWh/ ft^2 (97.2 kWh/m^2), and the peak power was 1.75 W/ ft^2 (18.8W/ m^2) (CIEE 2009).

As a major building on the campus, COB was included in two demand response (DR) events through PG&E’s aggregator-managed portfolio program (PG&E website) in the summers of 2008 and 2009. The first was a three-hour DR event, from 3:00 PM to 6:00 PM, on August 14, 2008; this was a hot day with a maximum outdoor air temperature (OAT) of 40 ºC (104 ºF). The second, two-hour DR event started at 1:00 PM on July 27, 2009. The maximum OAT on this day was 38.3 ºC (101 ºF).

In both events, a pre-programmed global temperature adjustment DR strategy was implemented for the heating, ventilation, and air-conditioning (HVAC) systems. Specifically, temperature cooling setpoints were increased by 2.2 ºC (4 ºF) upon initiation by the energy manager in participating rooms (critical zones were excluded). On event days, the campus energy manager sent notices to building occupants requesting that they turn off unnecessary lights and equipment. At the end of each event, a slow recovery strategy, in which setpoints were returned to normal in several steps, was implemented in order to avoid rebound (Motegi et al. 2007), that is, in order to avoid creating an extraordinary peak at the end of the DR event.

Goals and Objectives

We have previously studied DR on the UC Merced campus and found the demand savings in 2009 were lower than in 2008 (Granderson et al. 2009). The goal of the research presented here was to use an energy simulation tool (EnergyPlus) to quantify the demand savings during a DR event, to assess the potential effectiveness of using a pre-cooling strategy, and to optimize DR strategies on the UC Merced campus. In this paper, an EnergyPlus model was developed for COB and calibrated using the historical energy and building schedule data. Through this model, we:

- Simulated the 15-minute building and end-use demand on DR days to examine how well the model predicts the building load and demand savings.
- Applied different weather conditions to the simulations to investigate how OAT affects building load and demand savings of the DR strategy.
- Quantified demand savings effects on zone temperature changes.
- Investigated demand savings change when longer DR event is scheduled.
- Conducted preliminary analysis to evaluate the potential pre-cooling strategies effects on demand savings.

Methodology

EnergyPlus Model Development

A model of the COB was created using EnergyPlus version 4.0.0.024. The model was used to make highly resolved energy consumption predictions for demand response events. Figure 1 shows the building surfaces in the COB EnergyPlus model. And Table 1 provides brief descriptions of the major components of the model. The electrical data for two breakers, a dimming control panel and the elevators, were not monitored or simulated during the targeted period which accounts for approximately 15% of the whole building load. Therefore, the whole building power in this study refers to the aggregated lighting, plugs and HVAC electric consumption.

Figure 1. EnergyPlus Model Building Surfaces Representation of COB

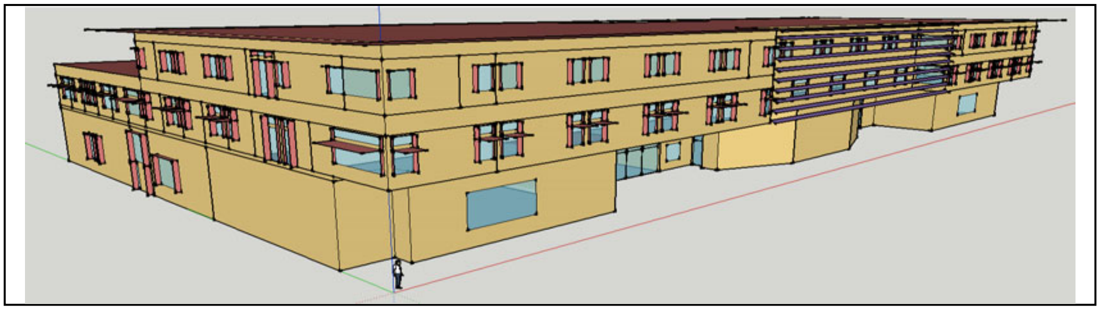


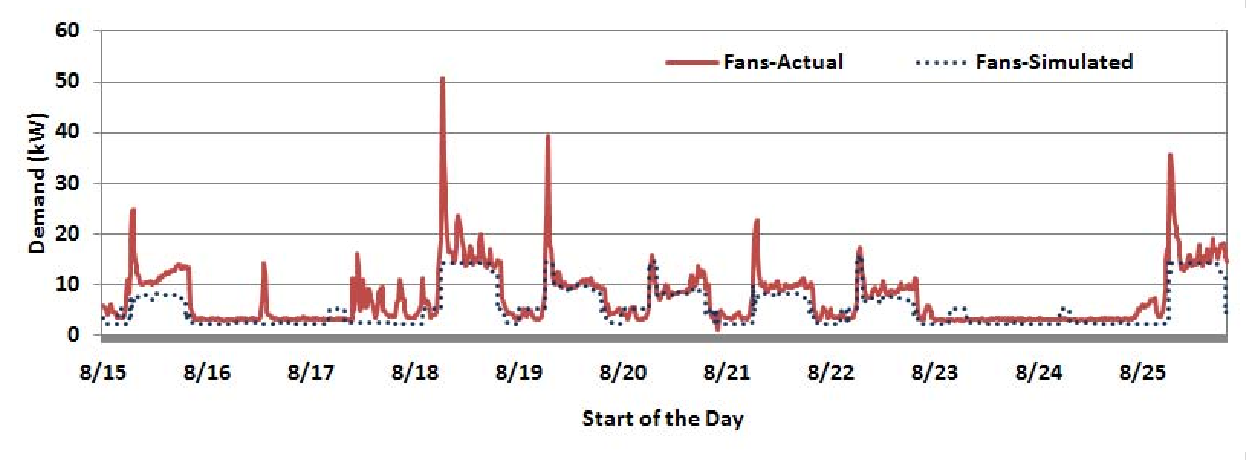
Table 1. COB EnergyPlus Model Summary

Components	Description
Building Surfaces	• Exterior walls: 12” thick concrete with partial curtain wall on northwest and southeast side, a layer of insulation, and an interior layer of gypsum board ; • Interior walls: single layer of gypsum board on each side of layer of sound attenuation blanket; • Windows: Double panel, LoE Tint 6 mm and Clear 6 mm with 13 mm air gap • Overhangs: two foot deep solid horizontal overhangs on the southeast and southwest second floor windows to model three-foot aluminum grating real overhangs for equivalency
Zones	Total 86 zones: 55 of them represent a single room while the remaining are zones in which several adjacent rooms with same type of usage and orientation have been grouped
Internal Mass	Roughly represents the thermal properties of furnishings, paper, books, etc in single room zones; and also represents the internal walls in the aggregated room zones
Infiltration	Zones with an external wall have a nighttime outside air infiltration rate of 0.2 air changes per hour and no infiltration when the HVAC system is operating (VanBronkhorst et al. 1995).
HVAC	Dual-fan, dual-duct, variable air-volume system with economizer; Two cooling fans combined to one single fan (as the current EnergyPlus model requests) with a capacity of 70,000 cfm. Heating supply fan has a capacity of 25,000 cfm. Model uses district heating and cooling to represent the chilled and hot water flows to and from the building.
Internal Loads	Schedules for each of the following three main sources of internal load are represented by the fraction of the load at any given time to fit each weekdays, weekend and holiday room use. • People: Maximum numbers of people in classroom zones based on occupancy figures provided in the architectural drawings. Maximum numbers of people in each office zone were estimated to be two people per office. • Lights: Lighting power in each zone was calculated by summing the rated power of each fixture in each zone as specified in the architectural drawings. • Equipment: Plug-load equipment was specified in units of Watts per square foot for each zone based on the intended use of the space and Title 24 standards.
Weather Data	2008 and 2009 weather data were compiled from several sources to create complete set. Hourly dry-bulb temperature were recorded on roof of COB, wind speed and direction were recorded at campus central plant, and direct normal radiation measured at California Department of Water San Luis Reservoir, located 30 miles southwest of campus. Relative humidity for 2008 was recorded at the Fresno International Airport, and for 2009 was recorded at the Merced Municipal Airport. Wet-bulb temperature was calculated from dry-bulb temperature and relative humidity values.
Output	Electrical consumption by lighting, equipment, and fans disaggregated into categories that corresponded to electric sub-meters in COB. Model predictions were reported at 15-minute intervals.

EnergyPlus Model Calibration

Internal load schedules were tuned to fit model predictions to sub-meter measurements of electrical consumption by lighting, equipment, and HVAC supply fans for the demand response periods. The calibration criteria used in this study are based on the ASHRAE Guideline 14 (ASHRAE 2002). Statistical mean bias error (MBE) and coefficient of variation of the root mean squared error (CV(RMSE)) (Yin et al. 2010) were used to evaluate the accuracy of the model. Because use of the COB varies considerably throughout the year, we used a time period during which the building would most likely be used similarly. The model was calibrated for 2008 based on the period of August 15 to 25, which is during summer break when classrooms are not fully scheduled. We assumed regular occupancy and internal load schedules for offices. Occupancy and internal load schedules for classrooms for each weekday were created and adjusted according to the UC Merced class schedules. The COB was operated at 23.3 °C (74 °F) during morning catch-up and occupied hours. However, cooling setpoints for some zones were adjusted. During calibration, the zone cooling setpoint for each individual zone was matched to the actual zone setting. After calibration, the MBE for the building's two lighting breakers and two plug breakers were -1% and -4%, respectively. Fan energy consumption was fit to the DR period in this study by reducing the cooling fan efficiency to 0.43. The MBE of the building's fan breaker is slightly high at -21% (see Figure 2). The actual fan catch-up demand is much higher than predicted by the model, which combines the two cooling supply fans to just one as required by the current EnergyPlus version. During the operation hours of 8:00 AM to 8:00 PM, the MBE is reduced to 15%. The cooling load is approximately 10% over the actual cooling load. The MBE and CV(RMSE) for the whole building demand during this period are 1% and 1.4%, respectively.

Figure 2. Actual Fan Demand vs. Simulated Demand during the Calibration Period



Simulation Scenarios

Using the calibrated model, we proposed twenty-two simulation scenarios for the DR event day (see Table 2) to examine the following four hypotheses:

- Hypothesis 1: building load and demand savings are reduced when OATs decrease.

- Hypothesis 2: demand savings are non-linearly correlated with zone temperature increases.
- Hypothesis 3: hourly average demand savings may be reduced when a longer DR event is scheduled.

In addition, the hypothesis that pre-cooling strategies increase the magnitude of demand savings is explored.

Scenarios 1 and 2 model cases for which no DR strategies were used on the DR event day; these scenarios yield baselines for other scenarios that implement DR strategies. We conducted two simulations for each strategy in scenarios 3 - 22 by using weather data from 2008 and 2009 to investigate hypothesis 1, which tests the weather effect on building load and demand savings when the building internal load is fixed. Scenarios 3 - 6 examine hypothesis 2, simulating the DR strategies of global temperature adjustment (GTA). Among them, Scenario 5 is the actual building operation case on the 2008 DR event day. Numerous recent studies (Xu et al. 2004; Xu and Haves 2005; Xu 2006) show that pre-cooling can increase demand saving and maintain occupant comfort. Scenarios 7 - 12 examine hypothesis 3, simulating DR strategies of combined pre-cooling with GTA. The Pacific Gas and Electric Company (PG&E) proposed a four-hour DR program, and the current participants on time-of-use (TOU) rates will be defaulted on this program. Scenarios 13 - 22 examine hypothesis 4, simulating demand savings of different DR strategies in a four-hour DR event.

Table 2. Simulation Scenario Summary

Scenario[1] 2008/2009	**DR Strategy**	**DR Duration**	**Temperature Setting**	
			Pre DR	**During DR**
1/2	-	15:00-18:00	Normal CLSP[2]	Normal CLSP
3/4	GTA	15:00-18:00	Normal CLSP	Normal CLSP + 1.1 °C
5/6	GTA	15:00-18:00	Normal CLSP	Normal CLSP + 2.2 °C
7/8	Pre-cooling, GTA	15:00-18:00	Normal CLSP - 1.1 °C, two hours	Normal CLSP + 2.2 °C
9/10	Pre-cooling, GTA	15:00-18:00	Normal CLSP - 1.1 °C, three hours	Normal CLSP + 2.2 °C
11/12	Pre-cooling, GTA	15:00-18:00	Normal CLSP - 1.1 °C, four hours	Normal CLSP + 2.2 °C
13/14	GTA	14:00-18:00	Normal CLSP	Normal CLSP + 2.2 °C
15/16	GTA	14:00-18:00	Normal CLSP	Normal CLSP + 1.1°C, first two hours, + 2.2°C, second two hours
17/18	Pre-cooling, GTA	14:00-18:00	Normal CLSP - 1.1 °C, two hours	Normal CLSP + 2.2 °C
19/20	Pre-cooling, GTA	14:00-18:00	Normal CLSP - 1.1 °C, three hours	Normal CLSP + 2.2 °C
21/22	Pre-cooling, GTA	14:00-18:00	Normal CLSP - 1.1 °C, four hours	Normal CLSP + 2.2 °C

[1] Weather data for 2008 and 2009 used odd and even numbered scenarios, respectively.
[2] CLSP: Cooling setpoint

Results

Whole Building Demand and DR Savings

Demand savings correspond to the difference between the measured (or simulated DR) data and the simulated load profile when a DR strategy is not employed. Figure 3 shows the actual whole building power (WBP, as indicated in the previous session, it is the aggregated of lighting, plug and HVAC loads), simulated demand in the absence of DR strategy (i.e., the baseline), and the simulated demand using the strategy of a GTA 2.2 ºC (4 ºF) increase from 15:00 – 18:00 and assuming 2008 weather conditions. Comparing measured data to the simulated baseline, the average three-hour demand saving is about 11 kW, accounting for 13% of whole building power. The result is close to the evaluation result (14%) by OAT regression (where the relationship between OAT and building power consumption is established by regression) with a morning adjustment baseline (Han et al. 2008) in our previous research. Comparing the simulated demand of the DR strategy to the baseline, the averaged demand saving is about 8 kW, approximately 10%. The measured saving is bigger than the simulated strategy of a GTA 2.2 ºC (4 ºF), possibly because of a lighting and plug demand savings contribution.

Figure 3. Actual and Simulated Building Demand

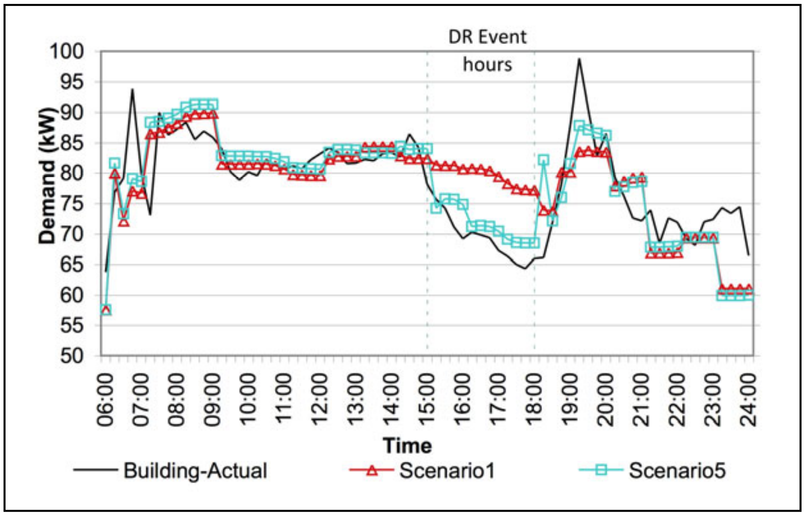


Figure 4. Effects of Different DR Strategies

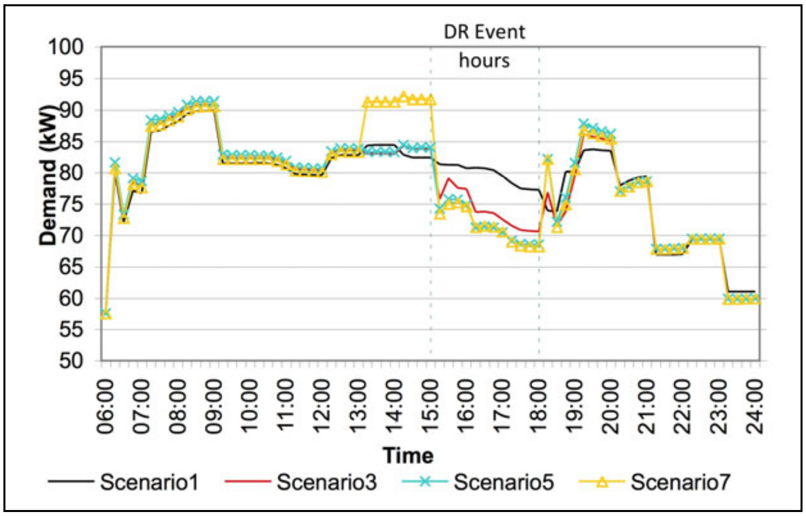


Figure 4 shows the simulated WBP profiles using different DR strategies at the 2008 weather conditions. With a 1.1 ºC (2 ºF) GTA increase, a 6 kW (i.e., 7%), demand saving can be achieved. Compared to the first 1.1 ºC (2 ºF) GTA increase, each additional 1.1 ºC (2 ºF) increase will provide less demand savings. Simulation results show that the pre-cooling strategy has only a very slight effect on demand savings, possibly because of the low building thermal mass. Table 2 summarizes average demand savings for all proposed DR strategies.

For same building internal load, demand savings tend to be less in cooler weather conditions. On August 14, the maximum temperature in 2008 was 40 ºC (104 ºF), whereas in 2009 this value was 32 ºC (90 ºF). Figure 5 shows demand savings for combined pre-cooling and a GTA of 2.2 ºC (4 ºF) under both 2008 and 2009 weather conditions. Demand savings under the 2008 conditions were 11%, and dropped to 9% under the 2009 conditions. Demand savings for other strategies show the same trend (see table 3). Simulations also show the hourly average demand savings with the same DR strategy will reduce in a longer DR event.

Figure 5. Building Demand Under Different Weather Conditions

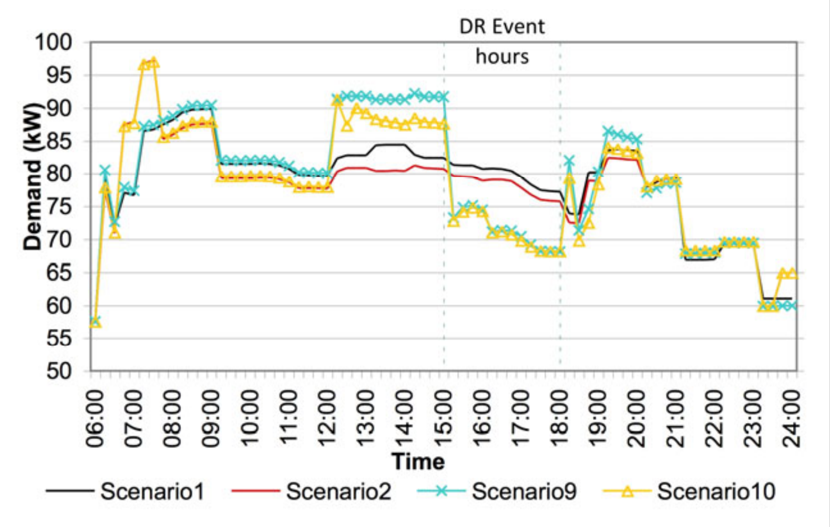
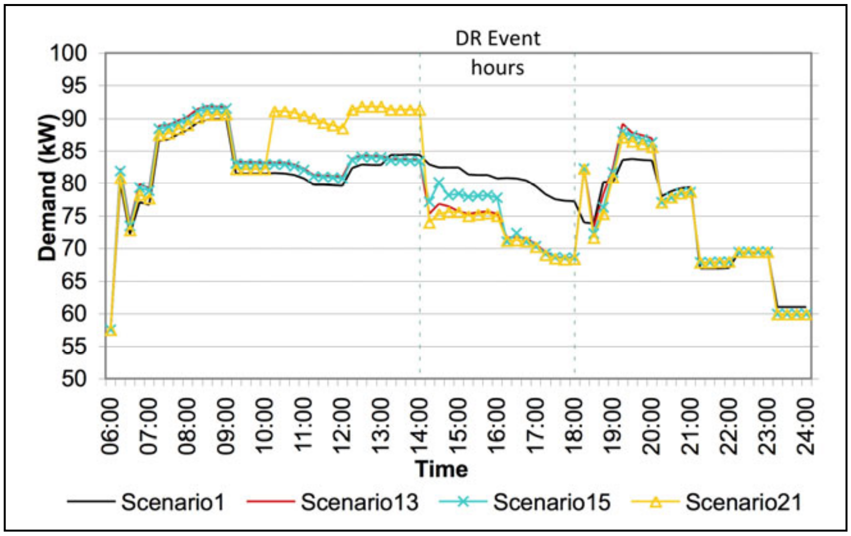


Table 3. Summary of Building Average Demand Savings

Scenario	Average demand savings, 2008			Scenario	Average demand savings, 2009		
	kW	W/m^2 (W/ft^2)	WBP%		kW	W/m^2 (W/ft^2)	WBP%
3	5.8	0.69 (0.064)	7.3%	4	5.1	0.61 (0.056)	6.5%
5	8.1	0.96 (0.090)	10.2%	6	6.7	0.80 (0.074)	8.6%
7	8.3	0.99 (0.092)	10.4%	8	7.0	0.84 (0.078)	9.0%
9	8.4	1.00 (0.093)	10.6%	10	7.0	0.84 (0.078)	9.0%
11	8.5	1.01 (0.094)	10.6%	12	7.0	0.84 (0.078)	9.0%
13	7.8	0.93 (0.087)	9.9%	14	6.5	0.78 (0.072)	8.4%
15	7.1	0.85 (0.079)	8.9%	16	5.8	0.69 (0.064)	7.5%
17	8.0	0.96 (0.089)	10.1%	18	6.7	0.80 (0.074)	8.6%
19	8.1	0.97 (0.090)	10.2%	20	6.7	0.80 (0.074)	8.6%
21	8.2	0.98 (0.091)	10.3%	22	6.8	0.81 (0.075)	8.7%

Figure 6 shows demand savings for four-hour DR events. The average demand saving from a one-step GTA of 2.2 ºC (4 ºF) was 10%, i.e., the same as during a three-hour event. The saving from the two step 1.1 by 1.1 ºC (2 ºF) increase strategy was slightly lower at 9%. The longer pre-cooling hours last, the greater the increase in demand savings, although this effect is slight. These preliminary results need field confirmation and future investigation.

Figure 6. Building Demand Savings at a Four-Hour DR Event



Supply Fans DR Savings

Using chilled water supplied from the central plant TES, the supply fan is the major executor of DR strategy. Fan demand directly reflects temperature settings for zone cooling. Table 4 summarizes fan average demand savings for all proposed DR strategies. Comparing actual fan power to the simulated baseline in Scenario 1 (see Figure 7), the three-hour average demand saving is about 9 kW, accounting for 66% of fan power. The simulated fan demand saving for the strategy with a GTA of 2.2 ºC (4 ºF) is 6 kW, or 48%.

Table 4. Summary of Fan Average Demand Savings

Scenario	Average demand savings, 2008			Scenario	Average demand savings, 2009		
	kW	W/m^2 (W/ft^2)	WBP%		kW	W/m^2 (W/ft^2)	WBP%
3	4.1	0.48 (0.045)	30.8%	4	3.3	0.40 (0.037)	28.9%
5	6.4	0.76 (0.070)	48.3%	6	4.9	0.59 (0.055)	42.9%
7	6.6	0.78 (0.073)	49.9%	8	5.3	0.63 (0.058)	45.8%
9	6.7	0.80 (0.074)	50.7%	10	5.3	0.63 (0.059)	45.9%
11	6.7	0.80 (0.075)	51.1%	12	5.3	0.63 (0.059)	46.0%
13	6.1	0.73 (0.068)	46.5%	14	4.8	0.57 (0.053)	41.6%
15	5.4	0.64 (0.059)	41.1%	16	4.1	0.49 (0.045)	35.6%
17	6.3	0.75 (0.070)	48.0%	18	4.9	0.59 (0.055)	42.9%
19	6.4	0.76 (0.071)	48.7%	20	5.0	0.59 (0.055)	43.1%
21	6.5	0.77 (0.072)	49.1%	22	5.1	0.60 (0.056)	43.9%

Figure 7. Actual and Simulated Fan Demand

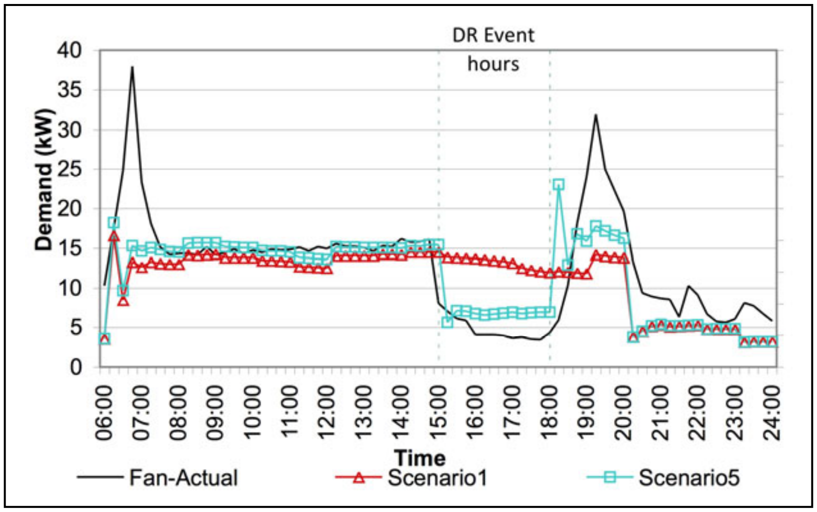


Figure 8. Fan Demand Saving From Different Strategies

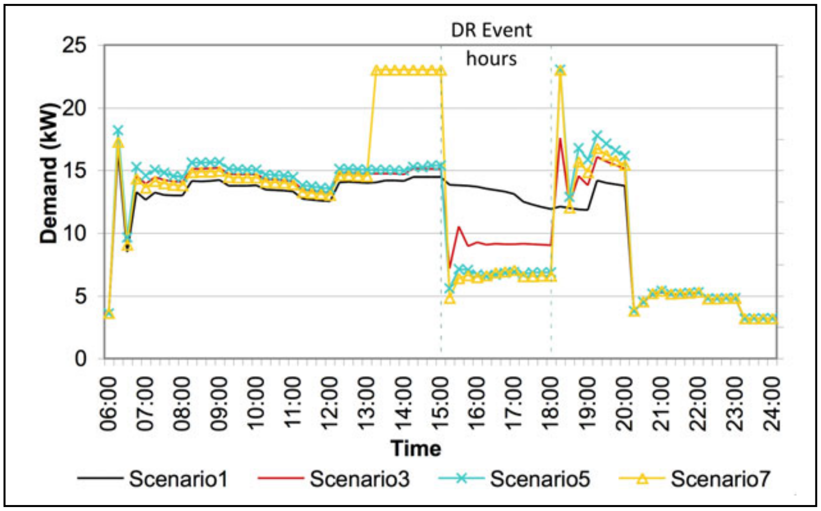
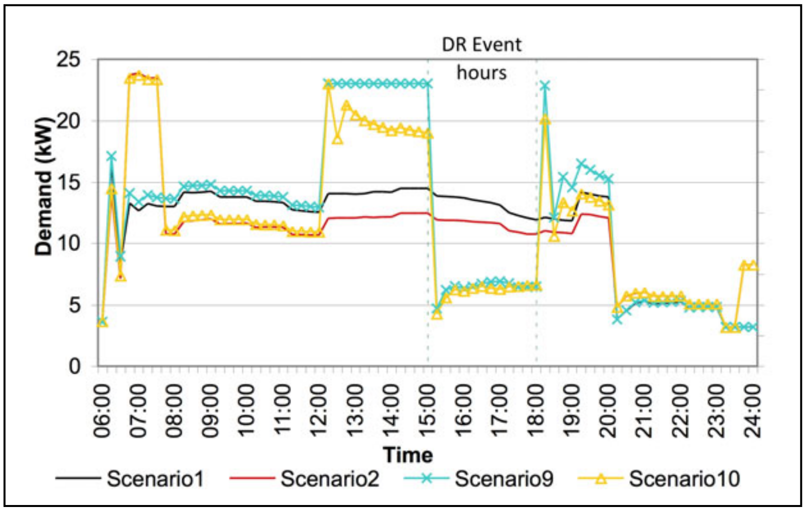


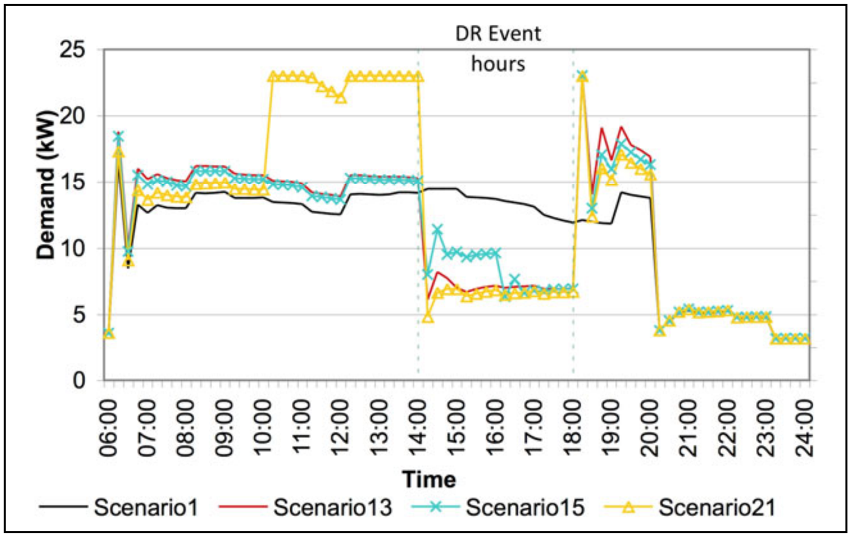
Figure 9. Fan Demand Saving at Different Weather Conditions



Demand savings for several different scenarios under the 2008 weather conditions are shown in Figure 8. Simulated fan demand saving from the strategy with a GTA of 1.1 ºC (2 ºF) is 4 kW, or about 31%. Exploratory analysis showed that a greater number of pre-cooling hours is associated with bigger demand savings, although the magnitude of this effect is slight. In Figure 8, only one pre-cooling scenario is shown. Figure 9 compares demand savings from the same pre-cooling strategy under different weather conditions. Under the lower temperature conditions of 2009, fan demand savings dropped to 46% relative to 51% in 2008 conditions.

Figure 10 illustrates fan demand savings from the strategies using a GTA of 1.1 ºC (2 ºF), 2.2 ºC (4 ºF), and pre-cooling with a 2.2 ºC (4 ºF) adjustment over a four-hour DR event. The savings from those strategies are 41%, 46%, and 49%, respectively. The exploratory pre-cooling strategy tends to reduce fan power consumption after the DR event ends, possibly because the discharge of thermal mass from pre-cooling reduces the magnitude of zone temperature increase during DR.

Figure 10. Fan Demand Saving at a Four-Hour DR Event



Discussion

Through a well-calibrated EnergyPlus model, building operation based on the actual 2008 DR event day was simulated. The EnergyPlus model predicted DR savings fairly well (The average difference between predicted DR load and actual load is within 4%). Through the model, we found that OAT_regression baseline in our previous study (Granderson et al. 2009) overestimated one of the lighting breakers demand savings during the event; OAT_regression with morning adjustment baseline predicts demand savings more accurately.

Through simulations under different weather conditions, we found that the building DR capability in response to the same strategy can vary. As expected, under the lower temperature conditions, building heat gain from outdoor is smaller and less conditioned air flow is needed. For COB, fan power reduce reflects this cooling load reduction. For a site with rooftop or chiller installed, the demand saving reduction would be greater because of the reduced cooling load.

Through the EnergyPlus model, two factors underlying demand saving reductions in 2009 were clarified. One, lighting demand savings in 2008 were over-estimated by the previous study (Granderson et al. 2009). Two, lower OAT weather conditions in 2009 substantially influenced demand savings.

The preliminary analysis on pre-cooling strategies provided some insight into the benefits. However, the existing modeling of the thermal mass needs further review to better understand opportunities for the pre-cooling strategies. This work needs to consider the TES charging and whole campus cooling loads.

Conclusions and Future Work

A detailed EnergyPlus model of COB was developed. The model was calibrated based on the end-use breakers and the aggregated lighting, plugs and HVAC electric consumption during August 15 to 25 for 2008. Using the calibrated model, twenty-two simulation scenarios were conducted. The findings can be summarized as follows:

- EnergyPlus model is proven to be useful to predict GTA demand savings for DR events and to design or optimize DR strategies.
- Model calibration for a university is schedule driven because of variable occupancy during semesters and academic breaks.
- A well-calibrated model can better predict whole building demand and DR demand savings.
- For a building using TES, fans of AHUs are the major executors of the HVAC DR strategy. A well-calibrated model can accurately predict fan power and fan demand savings.
- For same building internal load, demand savings tend to be smaller in cooler weather.
- Compared to the first 1.1 ºC (2 ºF) GTA increase, each additional 1.1 ºC (2 ºF) increase will provide less demand savings.
- Simulation shows the hourly average demand savings will reduce in a longer DR event.
- The modeled exploratory pre-cooling analyses provided some insight into the benefits of these strategies. However, more research and validation is necessary in the future.

For future research, we must separate quantitatively the two cooling supply fans in the EnergyPlus model, so that fan catch-up demand can better be matched to actual building operation. We need to add the missing dimming control panel and elevators in the model, so that the whole building power can be simulated in the future. In this study, we don’t fully understand how the EnergyPlus model is handling the internal thermal mass and temperature changes with the zone setpoint change. The benefits of the pre-cooling strategies need further research. The simulated cooling load in this study is approximately 10% over the actual cooling load in the COB. A calibrated model for the summer semester 2009 DR event will corroborate findings in this study.

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