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Investigation of Demand Response Strategies in a Mixed-Used Building

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Abstract

This paper investigates demand response measures, using an EnergyPlus simulation model, developed specifically for demand response analysis, in a mixed-used commercial building. The effectiveness of various building pre-conditioning strategies, which were considered for different durations, immediacy and activation time were assessed using the simulation model. Assessment was carried out for a representative summer day and the contribution of the building capacitance as a mechanism for shifting the building electric power demand was evaluated, recording a maximum load reduction of 6.6% of the baseload.

Keywords - flexible energy demand; demand response; building simulation model;

1. Introduction

Buildings are at the centre of social and economic activity. Along with population growth and an enhancement of building services and comfort levels, building energy demand has risen in the last two decades [1]. They consume about 40% of total final energy requirements in Europe, followed by transport with 33%, industry with 24% and agriculture with 2% [2]. Average energy consumption of commercial buildings in Europe has increased by around 1.5% per year since 1990. This development is characterised by two main trends: a significant increase of gas and electricity use, and a strong decline in the use of solid fuels and oil [3].

Demand response (DR), where consumers shift or curtail their electricity usage in response to financial (or other) incentives, is a measure that could be utilized to increase the penetration of renewable energy resources (RES). DR can help reduce electricity generation from fossil fuels by adjusting the demand to the present availability of fluctuating resources, when and where it is available, so that curtailments can be reduced and the overall RES share can be increased [4].

Commercial buildings are of considerable interest for the implementation of DR measures. Firstly, there is limited diversity in the systems that are used, mainly for heating and cooling. Regardless of the local climate, the size and type of building, they usually need both space conditioning (cooling / heating) and ventilation. For example, even in the UK, where temperate conditions broadly prevail, more than half of new offices are conditioned [1]. Moreover, most of them have a building energy management system (BEMS). Using a BEMS, building operators can monitor and control building systems such as heating, ventilation, air conditioning (HVAC) and lighting [5]. HVAC systems that are linked with the BEMS typically represent around 40% of the total building energy usage, which can reach 70%, if lighting is connected [6]. A BEMS can directly receive signals from the electricity grid without requiring additional metering infrastructure [7]. Commercial buildings operation is usually scheduled according to planned agendas and for a specific number of working day hours, which may vary between weekends and weekdays. All the above constitute points in favour in implementing DR measures in commercial buildings.

DR strategies are actions taken to adjust scheduled operations in order to modify the total energy consumption for a defined period in the case of a DR event. The DR strategies usually target loads derived from the HVAC system, which are the largest energy end-use category in both the residential and commercial sector [1]. HVAC systems exhibit more elasticity in demand control due to the building energy storage characteristics [8]. Therefore, building thermal storage capacity can be used to shift energy demand for a short period up to a number of hours. HVAC based DR strategies for a given building vary based on the type and condition of the building, mechanical equipment and the BEMS [9].

Recently, DR has been utilized as a measure to enhance RES penetration. In order to reach this goal, buildings should be able to provide additional demand flexibility to meet utility and aggregator requirements, which determine the magnitude of the load that needs to be shifted or curtailed, the time at which the response should be activated (immediacy) and the response duration. These three constraints constitute important utility / aggregator requirements. A control strategy that responds and adjusts the appropriate building loads is necessary to make this concept viable.

In this paper, a building energy simulation model is used to investigate the feasibility of a space pre-conditioning DR strategy to meet different utility / aggregator requests. The DR strategy was tested for different durations, immediacy and activation times for a summer weekday. Finally, the strategy was assessed with respect to its modification of the electricity consumption pattern, as well as for occupant comfort.

2. Methodology

A DR virtual testbed was created specifically for the DR analysis using EnergyPlus. The selected building, the Student Learning Leisure and Sports Facility (SLLS), is located on the University College Dublin campus and exhibits a strong commercial profile including a wide variability of HVAC systems, space usage and occupancy patterns. The building model was validated against operational data, collected by the BEMS, for the 2014 operational year. Using the Energy Management System feature in EnergyPlus, different control routines were developed to emulate DR strategies. These routines are able to overwrite the scheduled operation of the HVAC systems.

3. Building Energy Simulation Model

The SLLS building is used as a sports / entertainment centre and consists of three floors with a total floor area of 11,000 m^2. It includes a 50 m x 25 m swimming pool, with related ancillary areas and additional facilities such as a fitness centre with associated aerobics and dance studios, debating chamber, drama theatre, multimedia centre and seminar rooms, newspaper / radio and student media centre, health facilities, offices and shops. Additionally, it contains spaces dominated by different load types and patterns, as well as occupancy patterns. The swimming pool and gym occupancy, for example, exhibit large fluctuations at different times of the day, while the offices have almost constant occupancy during their operational hours. The building operates daily from 06:00 to 23:00, and from 08:00 to 18:00 during the weekends.

Regarding the HVAC equipment, two identical combined heat and power (CHP) units (506 kW thermal and 400 kW electrical output each), two gas boilers (1146 kW each) and the campus district heating installation (500 kW) provide heat in the building. The cooling requirements are met by an air cooled water chiller (865 kW) and a space conditioning delivery system, which consists of eight AHUs, thirty five fan coil units (FCUs), underfloor heating and baseboard heaters. A BEMS controls and monitors all the primary and ancillary equipment of the building. Operational BEMS data has been archived in fifteen minute intervals from September 2012 and utilized as inputs to the building energy model.

The building geometry was created using the 3D modelling software Google SketchUp 8.0. The SLLS building model consists of 63 zones, of which 46 are conditioned and is depicted in Figure 1. The DR model was created in EnergyPlus utilizing building design and operational parameters including: building orientation, building fabric, occupancy loads, HVAC equipment schedules, ventilation rates, as well as indoor control setpoints and outdoor weather data [10].

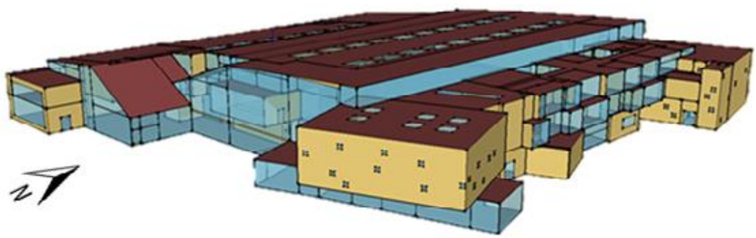

Figure 1: EnergyPlus building model

The weather file used was compiled from 2014 data from the UCD campus weather station. The simulation time-step was set to 15 minutes, so as to produce detailed results that can be validated with the BEMS archived data. Furthermore, this time-step enables building electric loads to be controlled in different time frames from real-time to 24-hour horizons.

The model was comprehensively validated against monitored data archived by the building BEMS for 2014. The mean bias error (MBE) and the cumulative variation of the root mean squared error (CVRMSE) indexes were used as calibration metrics. Acceptance criteria set by ASHRAE must be met in order for a model to be considered as 'calibrated' [11]. These values are +/-5% for MBE and 15% for CVRMSE for calibration using monthly data. The final calibrated model has a monthly MBE value of -1.6% and a monthly CVRMSE value of 10.5%.

4. Demand Response Strategy

The electric power demand of the building and the outdoor air for a representative summer weekday is given in Figure 2. The building electric power demand exhibits a considerable peak at 06:00, when the building starts to operate and two smaller ones at 12:00 and 16:00 which are associated with the building occupancy and the outdoor air temperature.

In order to shift / curtail these peaks and assess the building ability to adapt its electric power demand to RES availability, a zone pre-conditioning strategy was implemented. This strategy is used to maximize the reduction in the electric power demand and minimize the effects on occupant comfort during the event. In this paper, the pre-conditioning period was followed by air temperature setpoint relaxation strategy and was tested using the simulation model for a summer weekday. The combination of pre-cooling and temperature setpoint relaxation results in an increased temperature difference in the zone, in comparison to the case without pre-cooling.

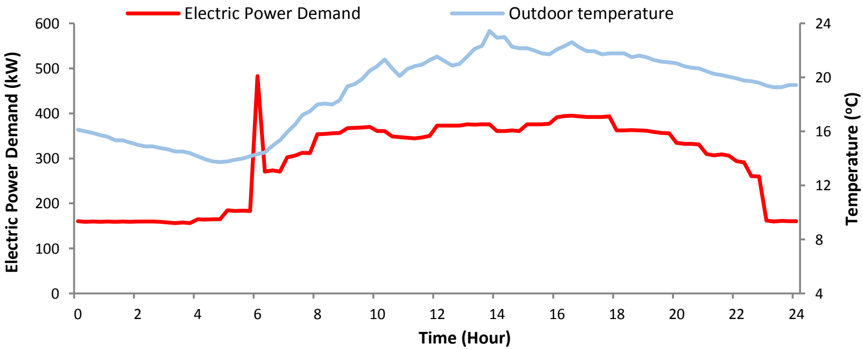

Figure 2: SLLS electric power demand and outdoor air temperature on test day

The information for the DR event is assumed to be available two or four hours in advance, denoting short and moderate pre-conditioning periods of two and four hours, respectively. Throughout this period the air temperature cooling setpoints were decreased by 2 ^{o}C from their scheduled values, so as not to exceed the occupant comfort limits, as pre-conditioning in some cases took place during the building operational hours. The pre-conditioning period was followed by two and four hour duration events. During the events, the air temperature setpoint relaxation strategy, where the cooling air temperature setpoints were increased according to ASHRAE allowed rates for operative temperature drift [12], was activated. These values, given in Table 1, were used to form the strategy for the SLLS building, as all the zones under consideration are conditioned exclusively by air systems. For example, the setpoint temperature was set 1.1 ^{o}C higher than the scheduled value for the first fifteen minutes and 1.7 ^{o}C higher for the next fifteen minutes (16-30 min). During the summer period only 20 of the 46 zones are conditioned, of which 14 require cooling and are conditioned either by FCUs or by a combination of FCUs and AHUs. The strategy was implemented in these 14 zones which include five office zones, two shops, a meeting room, a fitness centre and the associated studios, drama theatre, debating chamber and radio studio. Finally, the strategy was tested at three times of day: morning (09:00), midday (12:00) and early afternoon (16:00).

Table 1: ASHRAE acceptable limits on temperature drift [12]

Time Period	0.25 h	0.5 h	1 h	2 h	4 h
Maximum Operative Temperature Change (^{o}C)	1.1	1.7	2.2	2.8	3.3

Commercial and industrial buildings in Ireland can be part of a Demand Side Unit (DSU), which reduces its demand when instructed by the utility in cases where grid is under pressure or RES penetration is low [13]. DSUs that are available for demand reduction are eligible for capacity payments. A campus which contains a number of buildings with different uses and profiles is considered as a stand-alone DSU. Thus, electricity tariffs are not taken into account as driver for the DR events, since the building under investigation is part of a DSU.

5. Results

The difference in electric power demand between the reference case (Figure 2) and each of the four DR events starting at 09:00, 12:00 and 14:00 are given in Figures 3, 4 and 5, respectively. Positive values indicate a load increase and negative values indicate a load reduction.

As displayed in Figures 3, 4 and 5, pre-cooling of the zones results in an additional electric power demand, which highly depends on the time of the day that pre-cooling takes place. For example, as shown in Figure 3, in the two first hours (05:00 to 07:00) of the four-hour pre-cooling period, the increase in the power demand is considerably high. This increase in power demand is caused by starting up the HVAC systems (chiller, pumps and fans) which are normally not operating at this time. For the following two hours (07:00 to 09:00) the increase in power demand is lower, as it is derived only from the 2 ^{o}C temperature decrease of the cooling temperature setpoints. Moreover, comparing the same pre-cooling periods for two or four hours when the event starts at 12:00 and at 16:00 (Figures 4 and 5), it appears that pre-conditioning later in the day when the cooling system already operates and outdoor temperatures are lower, results in a lower power demand increase.

Regarding the power demand reduction, it is greater for longer duration events, as illustrated in Figures 3 to 5. The power demand reduction is also affected by the time of the event, as the differences in zone occupancy and external temperatures influence the rate of the air temperature increase in the zone. Moreover, the pre-conditioning duration does not considerably affect the electric power demand reduction during the event. In [13]all cases, the reduction in electricity consumption is almost the same when comparing events of same duration and start time but with different pre-conditioning duration. Demand spikes (rebound), following the event, are caused by the immediate increase of the cooling load. The highest rebound demand of 6.22 kW for a 15 minute period was recorded for the four-hour duration event starting at 16:00 (Figure 5).

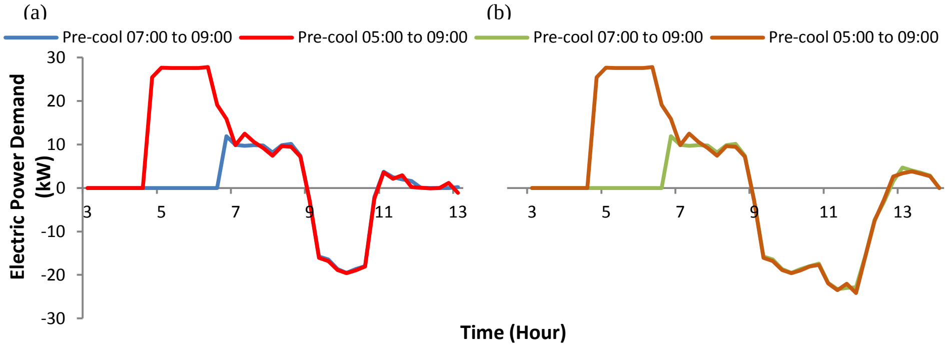

Figure 3: DR load when the DR events take place: (a) from 09:00 to 11:00 and (b) from 09:00 to 13:00

Apart from the changes in electric power demand, building electricity consumption during the pre-cooling and the DR event periods, are also concerned. During the pre-cooling period, a maximum increase of 302.1 kWh is recorded when the pre-cooling takes place from 05:00 to 09:00. Whereas, the lowest increase in electricity consumption of 14.6 kWh, is recorded for the two hours of pre-cooling from 14:00 to 16:00. During the DR event periods, the highest electricity reductions for the two and four-hour events are 113.8 kWh and 246.8 kWh, respectively.

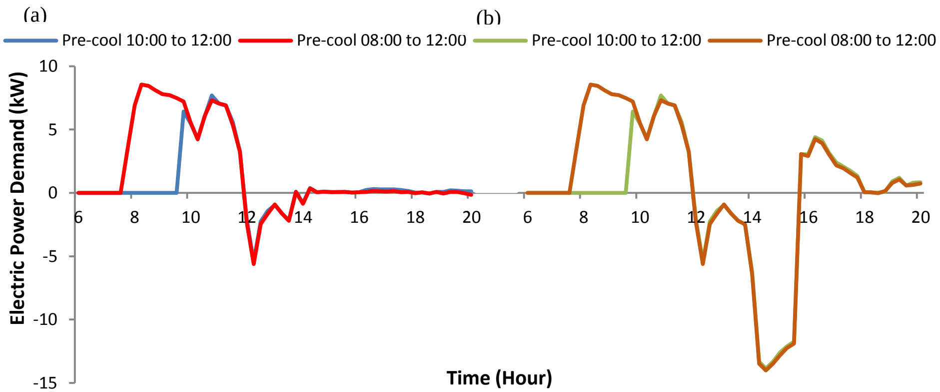

Figure 4: DR load when the DR events take place: (a) from 12:00 to 14:00 and (b) from 12:00 to 16:00

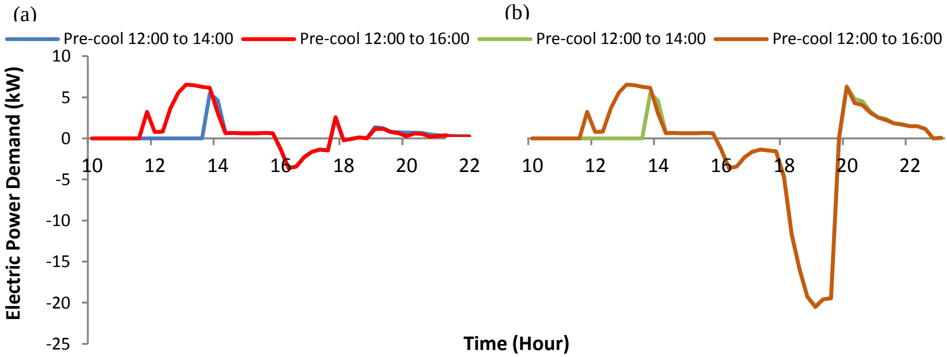

Figure 5: DR load when the DR events take place: (a) form 16:00 to 18:00 and (b) from 16:00 to 20:00

The increase in building electricity consumption during the pre-conditioning period, the decrease in electricity consumption throughout the event duration, the maximum recorded increase and decrease in power demand and the reduction / increase ratio for all the tested cases are given in Table 2. Regarding the reduction / increase ratio values higher than one indicate that the building overall electricity consumption was decreased with the implementation of the DR strategy and vice versa. When the duration of the event is equal or greater than the duration of the pre-conditioning strategy, the result is usually lower electricity consumption (two hours of pre-conditioning followed by a four-hour setpoint relaxation period). Otherwise, the electricity consumption is always greater than the reference case.

Table 2: Pre-conditioning Strategy Results

Pre-cooling duration	Event duration	DR event start time	Electricity Increase (kWh)	Maximum Demand Increase (kW)	Electriciy Reduction (kWh)	Maximum Demand Reduction (kW)	Reduction / Increase Ratio
2	2	9	86.7	11.9	112	19.5	1.3
		12	52.7	7.7	16.6	5.4	0.3
		16	14.6	5.5	15.1	3.6	1
	4	9	86.7	11.9	244.5	23.3	2.8
		12	52.7	7.7	101.6	13.9	1.9
		16	14.6	6.3	127.5	20.4	8.7
4	2	9	302.1	27.8	113.8	19.6	0.4
		12	111.4	8.6	17.5	5.6	0.2
		16	47	6.5	15.1	3.6	0.3
	4	9	302.1	27.8	246.8	24.2	0.8
		12	111.4	8.6	103.6	14	0.9
		16	47	6.5	127.9	20.5	2.7

The strategy was planned such that the temperature change both during the pre-conditioning period as well as during the temperature setpoint relaxation during the DR events ensured thermal comfort between -1 and 1, at all times [14]. Figure 6 gives the PMV index values for a representative office zone in the SLLS building that operates daily from 06:00 to 23:00. In the reference case the cooling air temperature setpoint is set at 25 ^{o}C, resulting in a PMV-index value of -0.5 throughout its operational hours. The three cases shown are where the longest pre-conditioning period is followed by the four-hour setpoint relaxation period for the three different times of the day. It can be seen that, in all three cases, the PMV-index values are less than the +/- 1 threshold values. During the pre-conditioning periods, the PMV-index values are close to their lower limits and during the event they gradually increases towards to the upper limit. In this way, the air temperature in the zones at the start of the event are lower than usual, thus there is a greater potential for load savings.

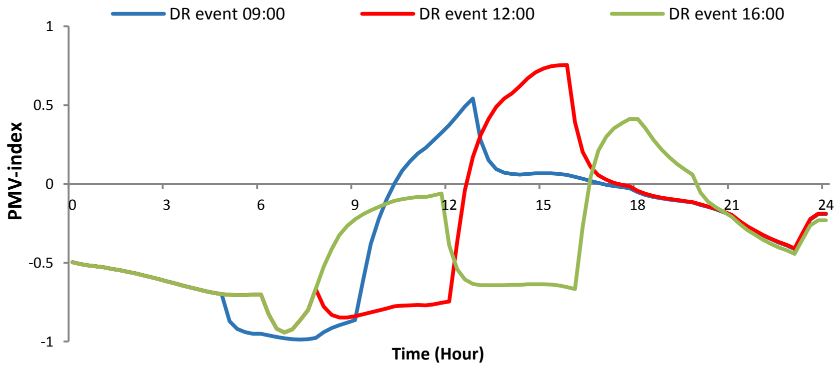

Figure 6: PMV-index values for an office zone for the four pre-conditioning period followed by a four hour air temperature setpoint relaxation period

The zone air temperatures when the DR events commence are lower than the reference case (because of pre-conditioning). So fans should either shut off (on/off fans) or operate with decreased air flow rates (VAV fans) for a period, until they reach the new higher air temperature setpoints during the events. This results in slightly higher CO_2 concentration levels in the zones. Namely, the highest increase of 27 ppm was recorded in the seminar room, reaching its maximum concentration value of 496 ppm during the four hour event starting a 12:00. The results indicate that the CO_2 concentration levels in all zones are below the threshold value of 1000 parts per million (ppm) [15].

From all the cases examined, it is clear that the zone pre-conditioning strategies can be implemented without affecting occupant comfort. Table 3 summarises the reduction in electricity consumption for each of the events compared to the reference case. The reduction in electricity consumption is expressed as a percentage of the reference case consumption.

Table 3: Average reduction in electricity consumption

Pre-conditioning duration (h)	Event duration (h)	Commencement time	DR event start time		
			09:00	12:00	16:00
2	2	1	-3.6%	-1.0 %	-1.0%
		2	-5.1%	-1.0%	-1.0%
	4	1	-3.6%	-1.0 %	-1.0%
		2	-5.1%	-1.0%	-1.0%
		3	-6.5%	-3.2%	-3.5%
		4	-2.5%	-3.3%	-5.5%
4	2	1	-3.7%	-1.2%	-1.2%
		2	-5.2%	-1.1%	-1.1%
	4	1	-3.7%	-1.2%	-1.2%
		2	-5.2%	-1.1%	-1.1%
		3	-6.6%	-3.3%	-3.6%
		4	-2.5%	-3.3%	-5.5%

The results indicate that there is considerable potential for load savings for all the different inputs for the strategy under investigation. Namely, the electricity reduction with respect to the base case during the air temperature setpoint relaxation strategy reaches a maximum of 6.6% when the strategy is implemented at 09:00, a maximum of 3.3% when the strategy starts at 12:00 and 5.6% when it starts at 16:00. In all cases, the maximum reduction is recorder for the four-hour events. When the event starts later in the day (12:00 or 16:00), when outdoor air temperature is higher, the load reduction is lower. The pre-conditioning duration seems to have a small impact on the electricity reduction. The two-hour pre-cooling period is proven to be adequate in this case. Finally, it is noticed that the event duration should be equal to or greater than the duration of the pre-conditioning strategy in order to result in lower overall electricity consumption.

6. Conclusions

A building energy simulation model was used to investigate the effectiveness of zone pre-conditioning followed by a zone air temperature setpoint modification strategy to shift / curtail building electric load. The results indicate that the strategy could provide a maximum reduction in electricity consumption of 6.6%, with reference to the baseload, even though it was applied 14 out of 46 zones. It is clear that the strategy requires a careful planning (especially for the pre-conditioning duration) to achieve the maximum potential, as its implementation at different times gives different results. The strategy was implemented in a number of zones with different occupancy patterns and activity profiles, and its impact on occupant thermal comfort and CO_2 concentration levels in these zones was assessed. The strategy is capable of maintaining both thermal comfort and CO_2 concentration level with acceptable thresholds. Future work includes the investigation of combining the pre-conditioning strategy with the on/off control of the delivery equipment to examine the effects on load reduction and occupant comfort.

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