Implementation of Demand Response Strategies in a Multi-Purpose Commercial Building using a Whole-Building Simulation Model Approach

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Abstract

This paper exploits a whole-building energy simulation approach to develop and evaluate demand response strategies for commercial buildings. The research is motivated by the increasing penetration of renewable energy sources such as wind and solar, which owing to their stochastic nature, means that enhanced integration of demand response measures in buildings is becoming more challenging and complex. Using EnergyPlus, a simulation model of a multi-purpose commercial building was developed and calibrated. Demand response strategies are evaluated for a number of building zones, which utilise different heating, cooling and ventilation equipment. The results show that for events of varying demand response durations, different strategies should be selected for each zone based on their thermal and usage profiles. Overall, a maximum reduction of 14.7% in electrical power demand was recorded when targeting a centralised chiller load, with smaller reductions for other decentralised building loads.

Keywords: commercial buildings, demand response, virtual testbed

1. Introduction

Renewable energy sources (RES) integration in the electricity grid can be enhanced by demand response (DR) programs, in which participants change their electricity usage in response to RES availability or electricity prices [1]. Ireland, for example, is committed to increasing the level of renewable electricity production to 40% by 2020 [2]. In order to achieve this goal, significant work to manage the integration of increasing levels of instantaneous renewable penetration on the island is required [3]. RES power generation, especially solar and wind, largely depends on the time evolution of weather patterns, which are to varying degrees unpredictable, thereby causing potential imbalances between the power supply and demand on the gird [4]. As a way to compensate these imbalances, DR is utilised to provide the necessary flexibility to the grid. Moreover, DR can help to reduce electricity generation from fossil fuels by adjusting the demand to the present availability of fluctuating resources, when and where it is available, so curtailments can be reduced and the overall RES share can be increased [5, 6]. Hence, DR events are increasingly

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likely to occur at times that were not traditionally considered as DR periods and as a result, requirements for electric load reduction from participants can vary significantly.

Among the different demand end use categories, buildings can potentially play a significant role in helping maintain the power supply and demand balance, since they account for almost 50% of the final electricity consumption [7]. Commercial buildings in particular, are capable of providing considerable load reduction and offer a range of options for demand management; thus they are of particular interest for DR implementation [8]. Heating, Ventilation and Air-Conditioning (HVAC) systems are their largest energy end-use category [9], which can also be controlled in order to utilise the building inherent energy storage characteristics and provide demand reduction [10].

As DR is utilised in building as a possible measure to enhance RES penetration, adaptive DR strategies have the capability to provide additional flexibility to meet utility / aggregator requirements. Such expectations are circumscribed by the need to know the magnitude of the load that should be shifted or curtailed, the time at which the response should be activated and the response duration. These three constraints constitute important utility / aggregator requirements. To address this challenge, control strategies capable of responding and adjusting building electricity demand profile is necessary to make the DR concept viable, especially in this changing operational environment. Such control strategies should be capable of controlling shiftable building loads dynamically and deploying these strategies as required without noticeably impacting user comfort.

The current paper focuses on the implementation of DR measures in commercial buildings in order to enhance RES penetration. Research efforts to date have mainly focused on the implementation of pre-defined DR measures for specific DR periods. However, DR events driven by RES availability exhibit unpredictability and therefore utility / aggregator requirements can vary significantly. This increases the complexity over existing DR approaches, as building responses should be triggered by utility / aggregator requirements, as well as factors such as weather conditions and occupancy. In order that buildings are capable of adapting to this changed operating environment, an evaluation of the different DR measures that can be implemented in a case of a DR event is required. The overall aim of the current research is to assess the DR potential of different HVAC components in a building and evaluate the impact of the developed DR strategies on occupant comfort. The main contribution of this paper is the combined evaluation of the potential of various DR strategies to shift / curtail building electric power demand under different utility / aggregator requirements, constrained by occupant comfort. In addition, strategies are evaluated at a zone level, thereby highlighting the significance of the zone thermal and usage profiles to the DR potential.

The paper is organized as follows: Section 2 provides an overview of related work. Section 3 outlines the adopted methodology. Section 4 describes the building and the developed simulation model. Building load analysis is given in Section 5. Section 6 outlines the assessment of the DR strategies and the final section concludes the paper.

2. Background

DR strategies are actions taken to change the scheduled operation of a system / load in order to reduce or increase the total energy consumption in the case of an event. Amongst the most common DR strategies that have been implemented to date are global temperature setpoint adjustment of building zones, which can be combined with space pre-conditioning, light dimming and temporary adjustment of different HVAC components. HVAC-based DR strategies are considered an excellent DR load resource, since they can constitute more than one third of the total building electrical power demand and are usually controlled by a BEMS [11].

One approach, the global temperature adjustment strategy, is based on the modification of the building cooling / heating setpoints for the different zones during the DR event [12]. Yang et al. [13] highlight that raising the cooling setpoint temperature can be applied to both new and existing buildings and provides a significant energy saving potential. Roussac et al. [14] applied two approaches in 33 mechanically ventilated office buildings in Australia. A static control strategy where the temperature setpoints were increased by 1^{o}C above normal for summer conditions and a dynamic approach where the setpoints were adjusted in direct response to variations in ambient conditions during building operational hours. Results indicate a 6% reduction in daily HVAC energy use for the static control strategy, which is slightly less than the 6.3% reduction reported for the dynamic approach. An adaptive comfort temperature model was developed by Mui et al. [15] for office buildings in Hong Kong, where the indoor comfort air temperature setpoints were tracked based on outdoor temperature, achieving a 7% of total energy saving. Sehar et al. [16] proposed an optimal control of building cooling air temperature setpoints which modifies the setpoints on a zone-by-zone basis based on occupant conditions in each zone during a DR event. A maximum peak load saving of 13.8% was achieved when implementing the control during a four-hour DR event in all the building zones for a summer weekday in Virginia.

Space pre-conditioning strategies target to shift the load from peak to off-peak demand hours. Xue and Shengwei [10] investigated the energy storage characteristics of commercial building building thermal mass, by developing an interactive load management strategy of the HVAC systems. A noticeable load shift of 7.67% from office to non-office hours was recorded. Xu [17] investigated the capabilities of different pre-cooling periods and temperature setpoints in two large commercial buildings. HVAC electricity consumption was reduced by up to 25% over a four-hour shed period. Zone pre-heating and interruption of air-conditioning systems in an institutional building in Valencia for one or two hours was investigated in [18]. Pre-heating during unoccupied hours was found to be capable of reducing the morning peak by 30%.

Motegi et al. [12] investigated two different DR strategies targeting directly the fan load in two commercial buildings in California for hourly DR events for a winter day. Initially, 50% of the fans encountered in the first facility were turned off achieving a maximum of 28% load reduction. A fan variable frequency drive (VFD) limit strategy was implemented in the second facility. During normal operation most fans were operated at 100% VFD, whereas during the DR event, the VFD was lowered to 60%, resulting in a 35% reduction on fan power compared to the baseline operation. Hao et al. [19] provided ancillary services to the power grid by manipulating the supply fan speed of air handing units (AHUs) in an institutional building in Florida based on time-varying regulation signal. Results indicate that during an hourly event, a reduction in fan electrical power demand of up to 15% was recorded without a noticeable impact in the building environment.

Chillers constitute a considerable load source that can be utilised in the case of a DR event. Xue et al [20] proposed a DR control strategy targeting chiller loads by limiting chiller water flow rate and / or resetting the space temperature setpoints. HVAC system power demand reductions for a summer day ranged from 32 to 66.5% compared with the normal operation without significant impact on thermal comfort. Cui et al. [21] investigated active and passive cold storage capabilities of a commercial building in Hong Kong. Regarding the passive cold storage, it was observed that when a proportion of operating chillers were shut down for a two-hour period for a summer weekday, it resulted in a 34.5% reduction of the original chiller power consumption. Son et al. [22] proposed a method of day-ahead scheduling and rescheduling on the operation day, for a commercial building with chiller and energy storage system, considering the time-of-use tariffs in Korea.

Building energy simulation models have been widely used for performance analysis, as well as for examination of compliance with codes and standards [23]. Nevertheless, the use of building energy simulation models can be extended to other tasks including optimisation of design solutions during the building design stage or support building control systems during the building operational phase [24]. Moreover, detailed physics-based models have been widely used to demonstrate measures for reducing peak loads due to their ability to simulate complex system behaviour and alternative demand response control strategies [25]. Ma et al. [26], for example, proposed a model predictive control technique to reduce energy consumption and operating costs of building HVAC systems under a time-of-use tariff scheme. Additionally, Yoon et al. [27] developed a dynamic DR strategy, based on an EnergyPlus model, which changes the setpoint temperature to control HVAC loads depending on electricity retail price. For this reason, through the calibration process, significant discrepancies between simulated and measured building data should be eliminated to add value to and ensure reliability of the building energy models and extend their usage [28]. Broadly, calibration techniques can classified as manual or automated, either of which can include the use of analytical tools or mathematical /statistical techniques [29, 30]. Ultimately the comprehensiveness of the model calibration depends on its ultimate usage [31]. In the case of building energy simulation models used to evaluate building DR potential, there is the additional challenge of predicting building response under dynamically changing conditions for time periods as short as 15 minutes. For this reason, DR simulation models require a more extensive calibration. Yin et al. [32], for example, developed a building energy simulation model, calibrated utilising sub-hourly data, to predict building DR behaviour. The model, as in the current work, was also calibrated under DR field tests to ensure accurate DR modelling.

To date, most DR strategies are assessed as a stand-alone measure which is mainly focused on minimizing energy consumption or cost through load profile alterations [17, 19, 11]. However, the increased interest in the potential of DR as a possible measure to enhance RES penetration, requires a control strategy capable of responding and adjusting building energy demand profile to utility / aggregator requirements. These DR events are unpredictable and can be requested at times and for durations that are not traditionally considered as DR periods,thus increasing the complexity of the DR strategies, since buildings participating in DR schemes should be able to provide the required load without compromising occupant comfort. In such a context, the formulation of DR strategies is becoming increasingly challenging and requires more comprehensive approaches in order to meet the expectations of all stakeholders since the events are unscheduled and may last longer than usual. In contrast with previous approaches, where a building response to different DR events is usually pre-programmed, a control strategy which identifies the best strategy from amongst all possible strategies is required. For example, a requirement for high load reduction for a short time period, may initiate more aggressive strategies compared to moderate reductions of longer duration. The current paper addresses this challenge by providing an assessment of the different DR strategies that can be implemented in a building in order to determine their contribution to different utility / aggregator requirements.

3. Methodology

The current study presents the assessment of different DR strategies utilising a building energy simulation model under various DR requests. EnergyPlus is used as a simulation tool to create a virtual DR testbed, based on a mixed-use commercial building. The implementation of DR measures, which have not been evaluated in advance, in an operating building is highly challenging, since unforeseeable effects on equipment operation or occupant comfort could arise during the DR events. Instead, a whole-building simulation model is utilised in the current study to develop targeted DR strategies. The model is further assessed to ensure that it can estimate DR load changes as well as predicting occupant comfort during DR events. Additionally, the building energy simulation model enables a wide permutation of DR strategies to be evaluated in an effective manner that otherwise would require extensive hours of on-site testing and all associated overheads. These strategies were developed using the Energy Management System feature in EnergyPlus in order to overwrite the scheduled operation of the HVAC systems. Figure 1 gives a schematic description of the methodology followed in this paper. The main objective of the followed methodology is that under specific DR requests on a certain day, the model can be used to run a set of different strategies to provide the facility manager with reliable predictions which can be used afterwards to select the strategy which meets the requested demand reduction.

A building with a strong commercial profile, variability of HVAC systems, space usage and occupancy patterns was chosen as a test platform for investigating different DR control strategies. This building, the Student Learning Leisure and Sports Facility (SLLS), is located on the campus of University College of Dublin (Ireland) and is used as a sports / entertainment centre. It consists of three floors with a total floor area of 11,000 m^2 and 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 (cinema) and seminar rooms, radio and student media centre, offices and shops. Additionally, it contains spaces dominated by different load types as well

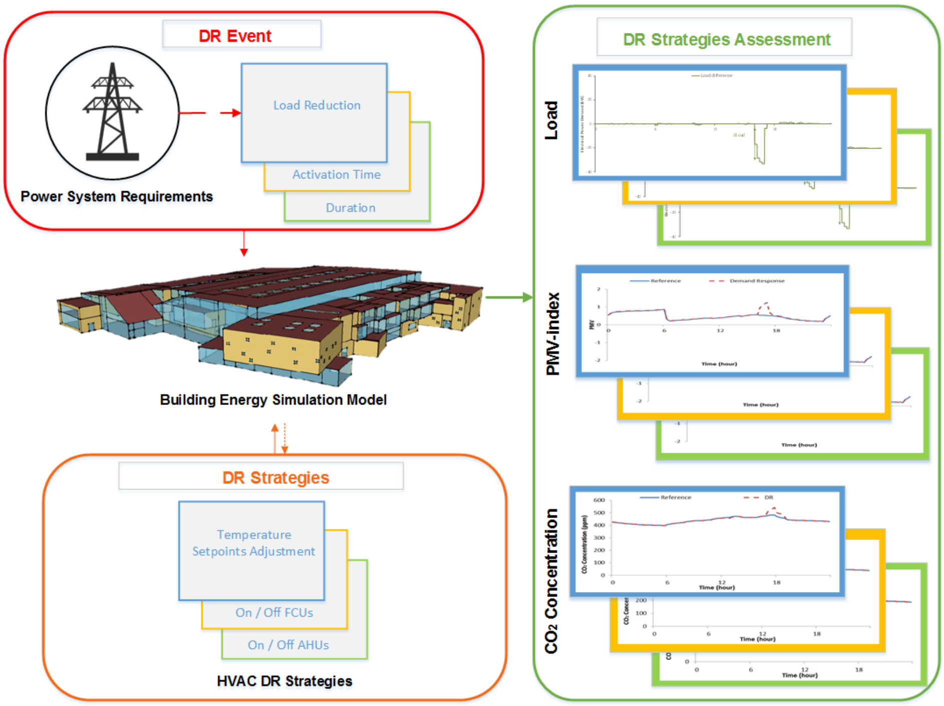

Figure 1: Methodology diagram

as occupancy patterns. The swimming pool and gym occupancy, for example, exhibits large fluctuations at different times of the day, while the offices have almost constant occupancy during their operational hours.

The building electrical and space conditioning requirements are provided by two identical combined heat and power (CHP) units (506 kW thermal and 400 kW electrical output each), two gas boilers (1146 kW each) and an air cooled water chiller (865 kW). Moreover, heat is also provided by a campus district heating installation (500 kW). The space conditioning delivery equipment consists of eight AHUs, thirty-five fan coil units (FCUs), underfloor heating and hydronic radiators heaters. A BEMS controls and monitors all the primary and ancillary equipment of the building. Total electricity and gas consumption are recorded along with sub-meters on individual HVAC components. BEMS data, collected at 15-minute intervals, was utilised to model building operation, as well as for calibration purposes.

Building electricity consumption analysis, based on simulated data, was conducted to determine the building energy usage breakdown and seasonality of the different HVAC system loads. Based on this analysis, the main electricity consumption end-uses were determined and targeted DR strategies, which modify the operation schedules under the utility / aggregator requirements, were built using the energy management system (EMS) feature in EnergyPlus [33].

As DR is increasingly being utilised to enhance the penetration of RES on the grid, DR events can occur at times that are not typically considered for DR events (winter evening periods for example in Ireland). Furthermore, load reductions could be required over longer periods than those currently found in the literature, which range typically from one to two hours. In the current paper, three different DR scenarios were created and utilised to initiate the DR strategies under evaluation. Namely, the event durations are specified either as one, two or four-hour events, representing short, medium or long duration events, respectively. The strategies were tested for a weekday in summer in all the building zones which require air-conditioning, except for the swimming pool area and associated changing rooms since they are not a common feature of a typical commercial building. The DR events commenced at noon when the building exhibits its highest occupancy level, which is the most critical time for maintaining occupant comfort. In order to establish an electricity demand baseline, a simulation was run without DR activation. This baseline was used to compare the different DR strategies based on their impact on the electricity demand profiles as well as occupant comfort.

4. Model Description

The building geometry was created using the 3D modelling software Google SketchUp 8.0. The SLLS building model, depicted in Figure 2, consists of 63 zones, of which 46 are conditioned [34]. Data inputs required for EnergyPlus, were gathered from construction and manufacturer specifications, in conjunction with standard property data from the ASHRAE-2005 dataset [35].

Internal heat gains related to occupant activity, lights and electrical equipment were included in the EnergyPlus building model. Occupancy schedules were developed and integrated into the model utilising three different sources of data: monitored occupancy data, operational schedules and ASHRAE datasets [36]. The lighting operational schedules were determined from manufacturer data, whereas electric equipment schedules were taken from ASHRAE datasets [37].

A constant air infiltration rate of 5 $m^3m^{-2}hr^{-1}$ at 50 Pa was set for all perimeter zones, based on data acquired from the specifications of the building design report. This value is in accordance with the Irish regulations for acceptable limits of air infiltration rates for energy efficient dwellings [38]. The ventilation required for all zones that are not mechanically ventilated was estimated based on the ASHRAE indoor air quality (IAQ) guide [36].

The SLLS building operates from 06:00 to 23:00 on weekdays and from 08:00 to 18:00 on weekend days. The weather file used was compiled from 2014 measured weather data from the UCD campus weather station. A simulation time-step of 15 minutes was defined in order to produce detailed results that can be validated against the BEMS archived data. Furthermore, this time-step enables building electric loads to be controlled over different time frames from real-time to 24-hour horizons.

A challenge for building energy simulation models is to predict building behaviour under dynamic conditions such as DR events [32]. A building energy simulation model built for DR analysis should be able to model building response to aggregator / utility requests for electric load curtail / shift in a time range from 15 minutes to several hours (up to 24 hours). For this reason, it requires a more extensive calibration not only for the building electricity power demand but also for the zone comfort parameters that are affected by DR strategies [39]. Thus, calibration using

15-minute time-step data is required in order for the model to be reliable for DR analysis. An empirical calibration of the SLLS building energy simulation model utilising archived data by the building BEMS for 2014 was conducted. Building total electricity demand and zonal parameters such as air temperature and relative humidity were calibrated using data measured on a 15-minute basis [39]. The mean bias error (MBE) and the coefficient of 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 [40]. 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% [39].

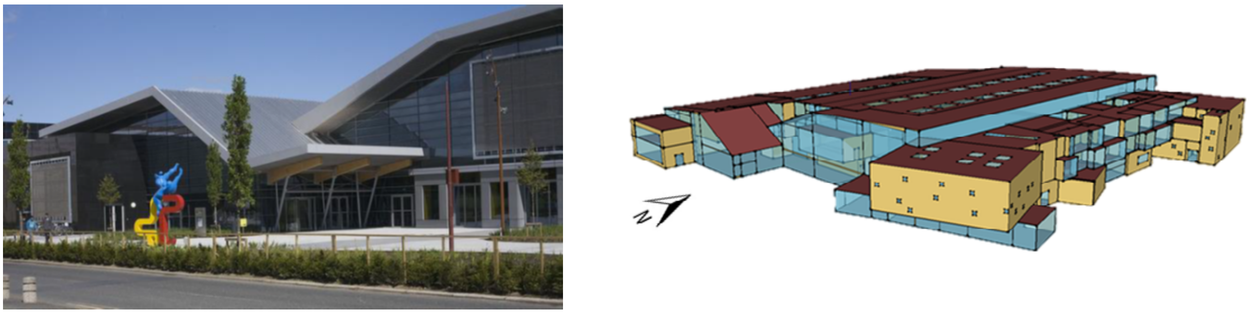

Figure 2: EnergyPlus building model of the Student Learning Leisure and Sports Facility (SLLS)

5. Load Analysis

Natural gas is the principal heating source for the SLLS building; however, electricity consumption is significant as well. In 2014 the total electricity consumption was 2.7 GWh, of which 1.2 GWh was imported from the grid and the remaining 1.5 GWh was provided by CHP units, which consumed 7.5 GWh of gas.

The main aim of the load analysis is to categorise end-use energy consumption. Two average profiles, one for the winter and one for the summer weekdays were created and utilised as indicators to compare winter and summer days, in terms of both the building electrical power demand and end-use breakdown. Such a comparison highlights the suitability of different loads for participating in DR at different times. An average winter weekday electricity consumption profile, based on 15-minute intervals, was created using simulated data from all winter weekdays (from 1st of October to 31st of March) as shown in Figure 3. For example, the 01:00 to 01:15 time interval was obtained by averaging the 01:00 to 01:15 time intervals for all the weekdays over the winter period. The advantage of using average instead of daily profiles is that it mitigates against fluctuations that could occur over a single day due to extreme weather conditions, non-predictive occupancy variations or equipment breakdown. The total electricity consumption profile is composed of pumps, fans, a chiller, lights, electrical equipment and other loads. The electricity consumption of each end use category was also calculated in the same way. The same process was followed in order to create an average summer weekday electricity consumption profile. These two profiles were utilised not only to compare the

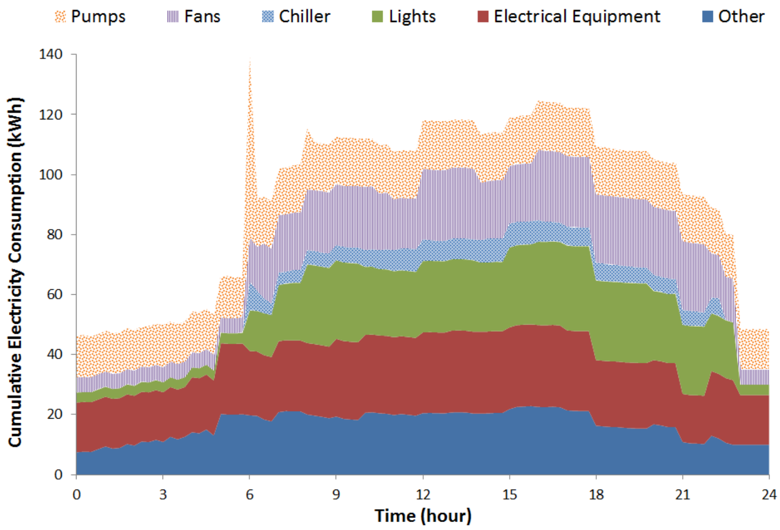

Figure 3: Cumulative electricity consumption profile for the average winter weekday in 15-minute intervals

electrical power demand for the two seasons, but also to examine the different load availability for participating in a DR event.

The average winter electricity consumption profile is depicted in Figure 3. The total consumption, 8.9 MWh,estimated by adding the electricity consumption from the different electricity end-use categories. The profile exhibits two well-defined peaks, one early in the morning (06:00), when the building starts to operate, and one in the evening (from 16:00 to 18:00), correlated with the higher evening occupancy level in the fitness centre and pool zones. The morning peak is caused by the operation of water circulation pumps associated with the underfloor heating system which exhibits an increased heat demand at start up. Comparing the two peaks, the first one lasts for just 15 minutes but reaches the highest electricity consumption over the average winter weekday, namely 139 kWh. On the other hand, the evening peak lasts for two hours, with an estimated average electricity consumption of 123 kWh. The chiller, pumps and fans, which account for almost 40% of the total electricity consumption, are the HVAC end-use loads that could be controlled to provide DR.

The average summer electricity consumption profile and end-use breakdown are given in Figure 4. Two peaks in electricity consumption occur at the same time as for the winter profile (at 06:00 in the morning and from 16:00 to 18:00 in the evening). However, the morning peak is lower than the corresponding winter peak (123 kWh for the summer peak versus 139 kWh in winter), as less HVAC systems are initiated in the summer, since fewer zones need to be conditioned. Regarding the evening peak, which also lasts for 2 hours, the demand is slightly higher (average of 125 kWh) compared with the winter evening peak. The total electricity consumption for the summer day is 9.2 MWh.

Comparing the two profiles, the daily electricity consumption is 2% higher for the summer weekday due to the increase in chiller electric power demand. Chiller and pump electricity consumption exhibit the greatest difference between the winter and summer weekdays. During the winter period, 46 out of the 64 zones are conditioned (heated

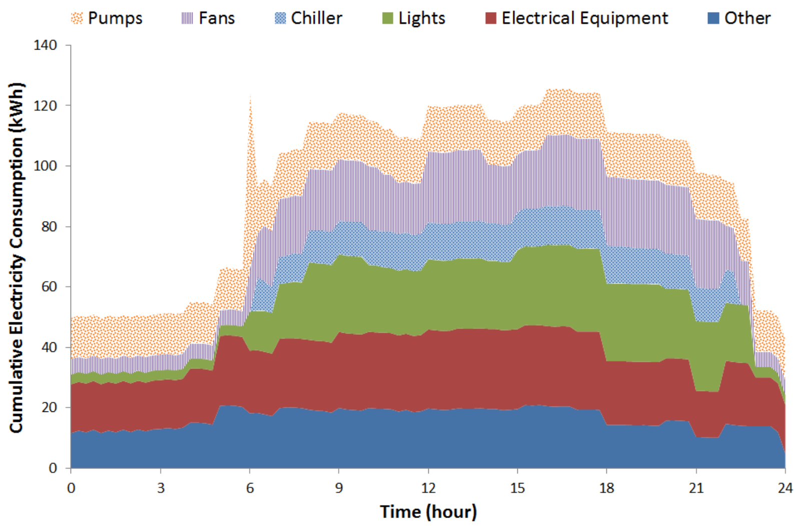

Figure 4: Cumulative electricity consumption profile for the average summer weekday in 15-minute intervals

or cooled by baseboard heaters, FCUs or AHUs), whereas during the summer period only 19 zones are conditioned (cooled by FCUs or AHUs). Thus, pump electricity consumption is reduced by 7% in summer. Moreover, during the summer period, all the conditioned zones of the building, except the pool zone and the changing rooms, mainly require cooling. For this reason, chiller electricity consumption is increased by almost 45% in summer compared to winter, when just few of the conditioned zones require cooling.

The two profiles indicate that there is a considerable DR potential capable of being derived from controllable HVAC loads. For example, electricity consumption from fans is almost 16% of the daily electricity consumption on weekdays, both in winter and summer. Thus, DR strategies that target fan load can potentially be applied regardless of the season or time of day. On the other hand, DR strategies targeting the chiller could be more beneficial during the summer period, as its electricity consumption in 45% higher during summer and accounts almost 10% of the daily electricity consumption. The daily electricity consumption of different HVAC systems and their maximum electric demand power for both seasons are given in Table 1. In order to estimate the actual potential of the building for participating in a DR event, DR strategies targeting this load should be tested under different requirements.

DR actions targeting the HVAC system affect thermal comfort and air quality; thus occupant comfort assessment records changes on these values. Acceptable occupant comfort values for the PMV-index lie between -1 (slightly cool) and +1 (slightly warm), since it is impossible to satisfy everyone in a large group sharing a collective climate [41]. Regarding the air quality, the threshold value for the CO_2 concentration in a zone is 1000 parts per million (ppm) [36]. All the DR strategies implemented in a building should maintain occupant comfort and air quality within acceptable limits. In this way, the overall building DR potential is constrained by occupant comfort.

Table 1: HVAC Systems Electricity Consumption Summary Table

	Winter day		Summer day	
End-use	Daily Electricity Consumption (kWh)	Maximum Power Demand (kW)	Daily Electricity Consumption (kWh)	Maximum Power Demand (kW)
Fans	1562	94	1549	94
Pumps	1512	160	1447	220
Chiller	389	38	761	51

6. Demand Response Strategies Evaluation

In the following sections, the tested DR strategies, which target the HVAC system loads, are described. These strategies are the chilled water temperature (CWT) increase control for the chiller, the on / off and supply air flow rate control targeting the fan load, and finally the increase of the zone air temperature setpoint for all the conditioned zones.

6.1. Chiller

The CWT increase control results in the rise of the chiller COP during a DR event, as it performs better at higher water temperatures. The main advantage of this strategy is that energy savings can be achieved without a significant impact on occupant comfort, so long as the delivery equipment can maintain the supply air temperature setpoints.

In this strategy, the CWT setpoint, which was set at 6^{o}C for normal operation, was increased to 12^{o}C (upper operational temperature limit) during the event. In order to avoid unwanted demand spikes (rebound) caused by an increase of cooling load after the DR event, rebound avoidance techniques, such as a gradual restoration of the CWT setpoint, complement the strategy [12]. After each event, a two-hour recovery period was used in order to linearly decrease the CWT to 6^{o}C. In the case of a one-hour event, a one-hour recovery period was implemented.

Figure 5 depicts the difference in the building electric demand for each DR event for the building operating hours

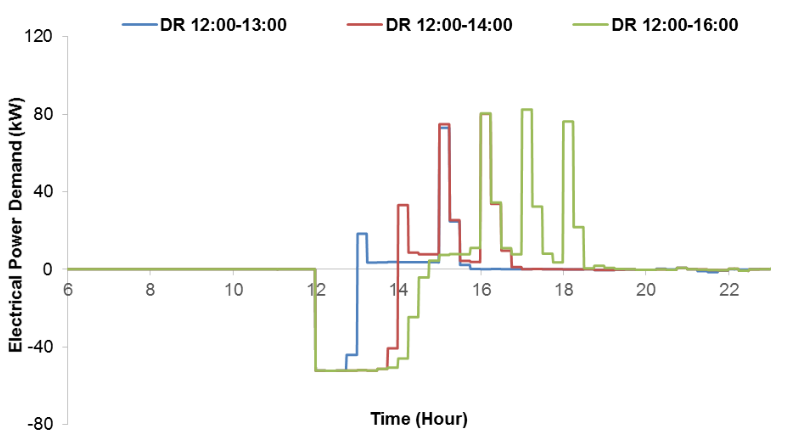

Figure 5: Difference in building electric load demand for the CWT strategy

(from 06:00 to 23:00 hrs). All demand values are referenced with respect to the baseline case. Positive values indicate a load increase, and negative values a load reduction - relative to baseline (370 kW, on average, during the events). As indicated in Figure 5, the strategy is capable of significant load reduction (maximum load reduction of 52.4 kW over the duration of the DR event). The total energy reduction was 50.2, 101.4 and 113 kWh for the one, two and four-hour events, respectively. After the DR event, there are significant rebound peaks (maximum load increase up to 82.4 kW), which increase with the duration of the event. In particular, after the event, the increase in building electricity consumption was 35.9, 72.5 and 90 kWh for the one, two and four-hour events, respectively. Although the rebound effects are significant, the overall energy consumption of the building is reduced when implementing the DR strategy. Nevertheless, when the strategy is applied for four hours, it is only capable of a load reduction for a limited period of time (2.5 hours), as shown in Figure 5. Over the time period of 2.5 hours, even though the CWT was set at 12^{o}C, the chiller electric power demand was greater compared to the reference case resulting in an increase in the total building electric power demand. This explains the fact that the electricity reduction for the four-hour event is just 11.6 kWh greater than the reduction for the two-hour event. The ratio between the electricity reduction and the electricity increase during the rebound effect for the one, two and four-hour events is 1.4, 1.4 and 1.2 respectively. Ratio values greater than 1 indicate that the overall decrease in electricity consumption during the event is greater than the increase in electricity consumption calculated during the rebound period, and thus the overall electricity consumption is reduced. Regarding occupant comfort, as assessed in the zones which are conditioned, little differences were recorded between the reference case and the three DR events, for both the mean air temperature and the PMV-index values (to within 0.1^{o}C and ?, respectively).

6.2. *Delivery Equipment (terminal units)*

In the SLLS building, three different types of fans are encountered. All the FCU fans are on / off fans which are cycled on and off to meet the heating or cooling demand. The AHUs are either constant air volume (CAV) units which operate continuously based on a time schedule or variable air volume (VAV) units which vary the air flow rate to meet the demand. A summary of the AHU systems and associated HVAC systems is given in Table 2. The delivery equipment on / off DR strategy was tested on the FCU fans, while the supply air flow rate control strategy was tested on the VAV fans.

6.2.1. *On / Off Fans*

The delivery equipment on / off control strategy was tested on the FCUs supplying air to the fitness centre. The associated fan nominal electrical capacity is 19 kW, thereby constituting a considerable DR load. The fitness centre, which normally operates from 06:00 to 23:00 on weekdays, represents 8% of the conditioned building area and uses a combination of FCUs and an AHU. During the DR events, the AHU damper position was locked in order to avoid the AHU compensating for the cooling load arising from FCUs unavailability.

The corresponding variation in building electrical load for each event is illustrated in Figure 6, indicating a significant reduction by turning off the delivery equipment. In particular, the building total electricity reduction was of 20.5, 36.2 and 94.8 kWh for the one, two and four-hour events, respectively. The zone air temperature for each event and for the reference case (Tref) are also shown in Figure 6. There was no rebound effect in any of the three cases, as within fifteen minutes the system is capable of reaching the same air temperature in the zone as the reference case.

As the FCUs interruption takes place at midday, when higher external temperatures occur, the zone mean air temperature is seen to increase from 20 ^{o}C to 22.4 ^{o}C for the four-hour event. This maximum temperature increase of 2.4 ^{o}C does not violate occupant comfort as the PMV-index at this time reaches a maximum value of 0.88, which is still below the threshold value of 1. The CO_2 concentration level in the zone remain the same, as the AHU continues to provide adequate ventilation.

Table 2: AHUs description

AHU No.	Terminal Units	Conditioned Zone	Additional HVAC Systems
AHU 1&2	CAV	Pool	None
AHU 3	CAV	Changing rooms	Underfloor Heating
AHU 4	VAV	Fitness centre & associated studios	FCUs
AHU 5	VAV	Cinema	FCUs
AHU 6	VAV	Seminar room	None
AHU 7	VAV	Drama Theatre	FCUs
AHU 8	VAV	Debating Chamber	None

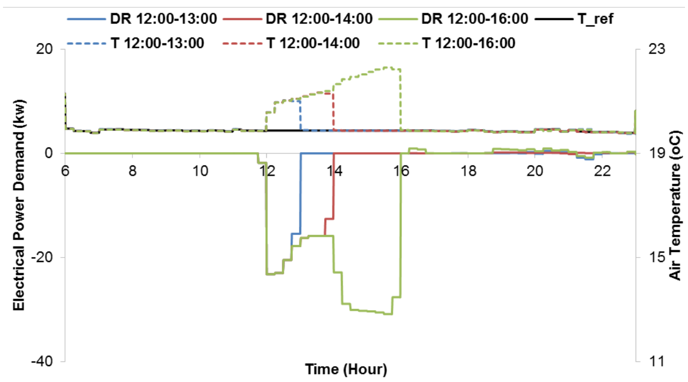

Figure 6: Difference in building electric load demand and mean air temperature for the fitness centre zone for the on / off fan control strategy

A fitness centre, with a reasonably high fan capacity, is not a common feature in typical commercial buildings. For this reason, the on / off control strategy was also implemented in another group of zones (two meeting rooms, three offices, one radio station studio and two retail units) that are more germane of commercial building and are conditioned exclusively by FCUs. Space air conditioning and ventilation for these zones are provided by FCUs with nominal electrical fan capacity of 6.5 kW, in total. The FCUs were divided into two groups, which were in turn turned on / off in 30-minute intervals, in order to reduce the impact on the zone air temperature and therefore occupant comfort.

Figure 7 presents the variation in building electrical load for each of the three cases. As shown, the maximum electric power demand reduction recorded in one time interval was 3.4 kW, which is low compared with the total building electrical power demand of 350 kW. However, this reduction is likely to be proportionally larger in smaller office buildings, where office zones conditioned by FCUs would represent a larger portion of building floor area. In the SLLS building, this group of zones only represents 3% (234 m^2) of the total floor area. The electricity consumption was decreased by 3.1, 6.2 and 12.4 kWh for the one, two and four-hour events, respectively. As the zones were partially conditioned throughout the duration of the events, rebound effects are negligible, as seen in Figure 7.

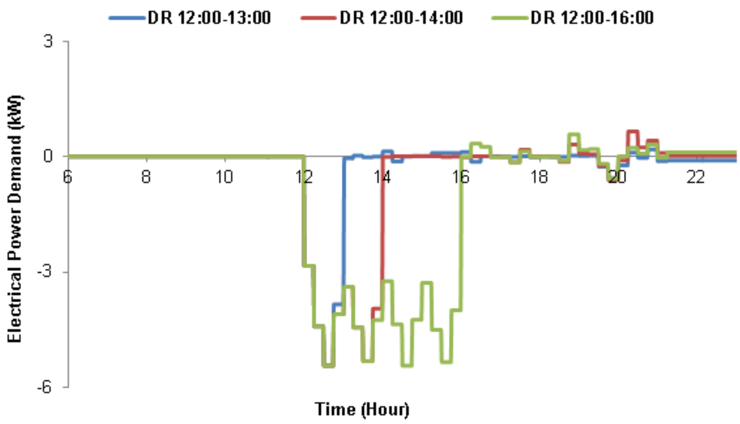

Figure 7: Difference in building electric load demand for the offices FCUs on / off control strategy

Table 3 gives the maximum values recorded for the zone mean air temperature, PMV-index value and CO_2 concentration level for all zones. D1, D2 and D4 denote for one, two and four-hour events, respectively. Values in bold text indicate that threshold limits were exceeded. The highest mean air temperature is recorded for the pharmacy, which located on the ground floor. The pharmacy has external windows for three of its four walls. As a result, it has the highest level of solar heat gains in comparison with the other zones tested, which contributes to the high temperature difference. For example, at 12:00 the solar radiation transmitted to the pharmacy through its windows is 14 kW, whereas for the shop, which is also located on the ground floor but has only one external window, this value is 1 kW. The variation in the maximum temperature difference between the reference case and the DR events for the rest of the zones is mainly due to the various internal heat gains.

The CO_2 concentration levels estimated for the reception, shop and pharmacy are the lowest because these zones experience air mixing with the main corridor during their operational hours. The remainder of the zones experienced higher CO_2 concentration levels than for the reception, shop and pharmacy, as the FCUs were used for ventilation purposes (fresh air is provided in particular zones based on CO_2 sensor readings) and an interruption to their operation results in limiting the provision of fresh outdoor air. However, out of the eight zones concerned with such DR events,

Table 3: Maximum recorded values for the mean air temperature, CO_2 concentration levels and PMV-index values for the offices FCUs on / off control strategy throughout the DR events

	Air Temperature (^oC)			CO_2 Concentration (ppm)			PMV-index		
Zone	D1	D2	D4	D1	D2	D4	D1	D2	D4
Meeting 1	27.8	28.0	28.0	916.8	**1042.9**	**1196.2**	0.8	0.8	0.8
Meeting 2	26.8	27.0	27.0	625.9	731.2	823.6	0.5	0.5	0.5
Reception	25.4	25.5	25.5	253.7	305.1	366.2	-0.1	-0.1	-0.1
Shop	25.4	25.6	25.6	583.2	589.2	618.7	0.0	0.1	0.1
Pharmacy	27.7	27.7	28.8	511.7	529.2	562.6	**1.1**	**1.2**	**1.7**
Newspaper Office	24.3	24.3	24.3	677.2	731.9	806.0	-0.4	-0.4	-0.3
Library	27.8	27.8	27.8	**1057.3**	**1111.1**	**1214.6**	0.8	0.8	0.9
Radio	25.2	25.3	25.5	713.1	717.7	730.1	0.1	0.2	0.2

only two exhibit CO_2 concentration levels higher than the threshold value of 1000 ppm.

6.2.2. Supply Air Flow Rate Control

Supply air flow rate reduction is a strategy that can be implemented in VAV systems by controlling the fan air flow rate. By reducing the average air flow rate, ventilation systems equipped with VAV fans can operate below their maximum air flow rate, and thus at lower electrical power demand.

In the SLLS building, the AHUs 4 to 8 (see Table 2), are equipped with VAV fans using 100% of outdoor air. During the DR event, the supply air volume of each fan was set to 80% of the nominal pre-event value to ensure that no significant increase in CO_2 concentration levels would occur in any zone. The main advantage of this strategy is that it avoids a significant alteration in occupant comfort, as the zones remain conditioned. As a result, the DR potential is limited. This strategy was implemented in all zones served by these AHUs.

Figure 8 shows the variation in the total building electrical demand for each of the three events and the reference case. As shown, the strategy is capable of providing a maximum load reduction of 5.3 kW in one time-step from 12:00 to 14:00 and of 3.5 kW from 14:00 to 16:00, by reducing fan power. The load reduction is lower from 14:00 to 16:00 because of the HVAC systems operation. Fitness centre occupancy is at its peak from 12:00 to 14:00 resulting in a higher air flow rate from the AHU at this time, in comparison with the air flow rate from 14:00 to 16:00 for the reference case. Consequently, the fan electrical demand is higher during the period from 12:00 to 14:00. During DR events, the air flow rate is maintained at 80% of the nominal pre-event value regardless of the occupancy and demand. Thus, the difference between the reference case and the DR events varies with time of day. The energy reduction was 4.6, 9.8 and 16.4 kWh for the one, two and four-hour events respectively, whereas the rebound effect was negligible in all cases, as the zones were conditioned throughout the events.

Table 4 gives the maximum vales recorded for the zone mean air temperature and CO_2 concentration level for all

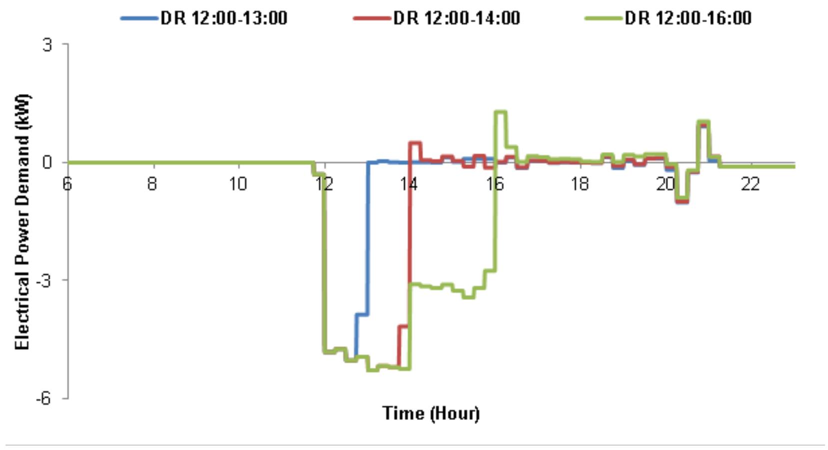

Figure 8: Difference in building electric load demand for the supply air flow rate decrease strategy

Table 4: Maximum recorded values for the mean air temperature and CO_2 concentration levels for the supply air flow rate decrease strategy

	Air Temperature (^oC)			CO_2 Concentration (ppm)		
Zone	D1	D2	D4	D1	D2	D4
Fitness centre	20.3	20.4	20.4	490.5	508.5	508.7
Seminar room	22.3	22.5	22.5	494.1	496.0	496.1
Drama theatre	22.9	22.9	22.9	565.7	568.4	568.7
Multimedia centre	23.2	23.3	23.3	587.5	599.3	705.3
Debating Chamber	25.3	25.8	27.4	848.2	**1024.1**	**1591.9**

zones. The debating chamber and seminar room are the only zones conditioned exclusively by AHUs. The highest mean air temperature was recorded in the debating chamber and the temperature increase during the event is the highest compared with the other zones. Namely, when no DR measure was applied, the temperature in the zone was 25 ^oC and increased by up to 2.4 ^oC during the four-hour event. On the other hand, the mean air temperature exhibits almost no change for zones that are conditioned by a combination of FCUs and AHUs. During such a DR event, FCUs operation was identical to that for the reference case, in order to ensure that they would not cover the excess load.

Regarding the CO_2 concentration levels, the debating chamber is the only zone in which the concentration level exceeded the threshold value of 1000 ppm, due to the fact that during the DR event the damper position was locked based on the air flow rate recorded just before the event. During the four-hour event, for example, the air flow rate value was maintained at 0.7 kg/s (80% of the pre-event value), whereas in the reference case from 15:00 to 16:00, it reached 2 kg/s. That corresponds in a 65% reduction in the air flow rate during the event, which is higher than the desired 20% reduction. As a zone, the debating chamber experiences high occupancy variation throughout the four hour event, varying from 150 occupants from 12:00 to 14:00, to 210 occupants after 14:00, resulting in higher cooling and ventilation requirements. On the other hand, in zones such as the seminar room, minor variation in occupancy are recorded, thus almost constant conditioning demand occurs throughout the events.

6.3. *Air Temperature Setpoint Adjustment*

The operative temperature drift rate allowed, set out by ASHRAE [42], are given in Table 5. These values were used in the model, as all zones under consideration are conditioned exclusively by air systems, to form the temperature setpoint adjustment strategy for the SLLS building. 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). The strategy was tested in all the conditioned zones of the building, except for the pool and the changing rooms.

The difference in total building electric power demand for each event is given in Figure 9. It is clear that longer duration events enable a greater load reduction, as the setpoints are allowed to increase / decrease further. The electricity consumption was decreased by 5.6, 14.0 and 57.0 kWh during the one, two and four-hour events, respectively. Rebound consumption was 1.6, 1.2 and 4.4 kWh for the one, two and four-hour events, respectively.

Table 6 shows the maximum values recorded throughout the events for the PMV-index and the CO_2 concentration level in the different zones and for each event. For the zones conditioned by both FCUs and AHUs for ventilation purposes (fitness centre, multimedia and drama theatre), there is almost no difference in the CO_2 concentration levels. For the zones that are conditioned and ventilated only by VAV AHUs (seminar room and debating chamber), the fans limit the air flow rate in order to meet the setpoints. As they use 100% of outdoor air, significant changes in CO_2 concentration level are observed. For the remaining zones, conditioned only by FCUs, variations in the CO_2 concentration are insignificant. This can be attributed to the FCU fans which operate in an on/off mode at a constant speed, thereby providing a fixed air flow rate when the unit is operational. The maximum PMV-index values were recorded for the debating chamber and pharmacy during the four-hour event but without exceeding the threshold value.

Table 5: ASHRAE acceptable limits on temperature drift [42]

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

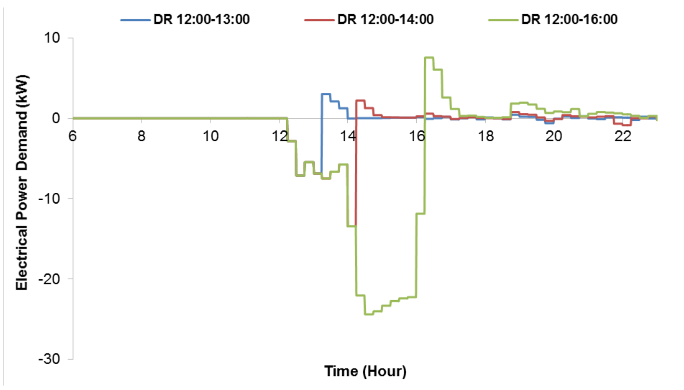

Figure 9: Difference in building electric load demand for the air temperature setpoint adjustment strategy

Although the tested strategy has a significant impact on the power demand reduction, it does not necessarily maximize the building DR potential associated with the air temperature setpoints. Therefore the strategy was modified and tested to determine its maximum potential. The heating / cooling air temperature setpoints that keep the PMV-index values within the acceptable limits (-1,+1) were estimated for the different zones, using the EnergyPlus model. For example, in the summer period, a maximum cooling setpoint of 28^{o}C was used for the office zones, whereas for the fitness centre, 25^{o}C was used as higher levels of physical activity were occurring. For this strategy, the cooling setpoints for all zones were set to their limit value immediately following the start of the DR events and regardless of their duration.

Table 6: Maximum recorded values for the PMV-index and CO_2 concentration levels for each zone under the air temperature setpoint adjustment strategy

	PMV-index			CO_2 Concentration (ppm)		
Zone	D1	D2	D4	D1	D2	D4
Fitness Centre	0.7	0.8	0.9	461.5	471.6	471.6
Multimedia	-0.1	0.1	0.2	591.3	597.4	701.7
Drama Theatre	-0.5	-0.5	-0.5	548.4	548.4	548.7
Seminar	-0.7	-0.7	-0.6	492.8	495.5	495.6
Debating Chamber	0.3	0.6	1.0	595.3	637.2	701.7
Meeting 1	0.2	0.4	0.5	722.4	770.3	786.0
Meeting 2	0.2	0.4	0.5	579.4	653.2	693.2
Reception	-0.3	-0.2	0.0	687.2	691.1	722.9
Shop	0.1	0.2	0.3	597.3	607.5	615.7
Pharmacy	0.6	0.8	1.0	498.0	506.4	516.0
Newspaper office	-0.3	-0.2	-0.1	645.7	674.3	692.7
Library	0.6	0.7	0.8	765.9	768.8	768.9
Radio	-0.2	-0.1	0.1	624.0	624.0	629.8

The variation in total building electrical demand for each of the three events is given in Figure 10. The total building electricity reduction was 14.1, 27.3 and 76 kWh for the one, two and four-hour events, respectively. The total building electricity reduction is 3.1, 2.1 and 1.4 times greater compared with the corresponding electricity reduction for the one, two and four-hour events when following the ASHRAE recommendations. The difference is higher for the shorter duration events because the allowed temperature drifts are higher in this case.

The maximum values recorded for the PMV-index and CO_2 concentration levels are given in Table 7. In this case the PMV-index reached its threshold value in the fitness centre as well. Comparing these values with those in Table 6, they are higher, especially for the one-hour event because of the higher cooling temperature setpoints. Another noticeable point is that these maximum values vary significantly. For example, the maximum value for the PMV-index during the four-hour event in the library is 0.9, whereas in the seminar room this value is -0.6. This is associated with the internal and external heat gains of each zone that affect the temperature increase rate in the zone. Moreover, it is related with the zone cooling temperature setpoint. In some zones, the setpoints were scheduled closer to the upper and in others closer to the lower limit of thermal comfort. Consequently, zones for which the cooling setpoint was already close to the upper thermal comfort temperature, and which exhibit a high level of internal heat gains, are capable of reaching this temperature setpoint within the hour event period. Regarding the maximum values for the CO_2 concentration levels are broadly similar with the maximum values recorded for the ASHRAE strategy.

7. Discussion

Building HVAC systems constitute a flexible load that can be utilised for DR requirements. The assessment of the capabilities of different DR strategies targeting these systems, in order to provide load reduction, reveals their potential to be implemented in DR events depending on the requirements for load curtailment and duration. Table 8 summarizes the strategies in order to compare their performance. For each strategy, the percentage reduction in electricity consumption (kWh) is compared with the reference case when no DR action was applied.

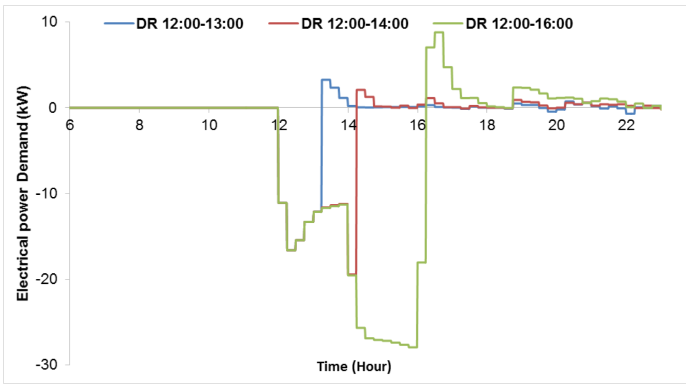

Figure 10: Difference in building electric load demand for the maximum air temperature setpoint adjustment strategy

The results indicate that the CWT increase strategy provides the greatest reduction, up to 14.2% of the electricity consumption, although it is able to provide load reductions up to 2.5 hours. Fan load was targeted through on / off control and supply air flow rate control strategies, which were applied to a number of zones that account for 20% of the building total floor area. Combining the two strategies together, they can provide up to 9.9% electricity reduction. FCU on / off control was applied to small group of eight zones which represent 3% of the building total floor area and their fan total nominal capacity is 6.2 kW. The strategy results in 3.4 kW load reduction, corresponding to an 1.1% reduction in the total building electricity consumption. Assuming the strategy is applied to a 10% of the building floor area with similar fan power density per square meter, it can potentially provide a 30 kW reduction in the electrical power demand, thus delivering a considerable DR potential. Regarding the decrease of the air flow rate strategy, it requires careful planning when it is implemented in zones with high occupancy variation during the DR event,

Table 7: Maximum variations in PMV-index values and CO_2 concentration levels for each zone under the maximum air temperature setpoint adjustment strategy

	PMV			CO_2 Concentration		
Zone	D1	D2	D4	D1	D2	D4
Fitness Centre	0.8	0.8	1.0	465.2	471.6	471.6
Multimedia	0.1	0.2	0.3	595.7	636.7	701.7
Drama Theatre	-0.5	-0.5	-0.5	548.4	548.6	548.7
Seminar	-0.7	-0.7	-0.6	492.8	495.5	495.6
Debating Chamber	0.3	0.7	1.0	906.1.4	**1549.7**	**2039.6**
Meeting 1	0.4	0.4	0.5	695.5	761.2	783.1
Meeting 2	0.5	0.8	0.9	678.7	688.3	725.7
Reception	-0.2	-0.2	0.0	681.7	691.3	725.7
Shop	0.2	0.5	0.6	598.7	608.1	617.5
Pharmacy	0.6	0.9	1.0	499.7	507.1	516.2
Newspaper office	-0.3	-0.2	-0.1	645.5	674.2	692.6
Library	0.7	0.8	0.9	766.5	769.7	769.0
Radio	0.7	0.8	0.9	619.4	619.4	619.4

otherwise it can result in poor IAQ during the event. In general, zones where space conditioning and ventilation needs are covered from the same equipment, IAQ is more likely to be violated. Another interesting point is the comparison between the two cases for the air temperature setpoint adjustment strategy. The electricity reduction is much higher for the one-hour event (or during the first hour of longer events) for the maximum air temperature setpoint adjustment, as the temperature in the zones is allowed to increase further during the first hour.

The detailed investigation of the DR strategies in the different thermal zones, reveals that zones exhibit different occupant comfort levels for the same applied DR measures; hence based on their thermal and usage characteristics different DR strategies should be chosen. For example, in zones with high heat gains, such as the pharmacy, the temperature adjustment strategy is preferable since temperature increase is controlled and occupant comfort is ensured. On the other hand, in some zones, fan on / off control and temperature setpoint adjustment strategy, both result in PMV-index values lower than the threshold limits. Thus, fan on /off control is preferred as it provides greater load reduction. Moreover, occupancy proves to be essential for the implementation of DR measures in a zone, since in zones with high occupancy values is far more challenging to maintain occupant comfort in the case of an event. Therefore expected occupancy could act as an indicator for zone participation / exclusion in the case of a DR event, especially for buildings similar to SLLS, with a wide variety of zones. For example, in the debating chamber zone, after the second hour of the four-hour event, the CO_2 concentration levels in the zone exceed the threshold limit of 1000 ppm, as the occupancy in the zone considerably increases. For this reason, the AHU operation could be restored

Table 8: Percentage of average reduction in electricity consumption for the implemented DR strategies (%)

Event Duration (hours)	Period under Investigation	CWT increase	FCUs off Fitness Centre	FCUs off Office Zones	VAV flow rate decrease	Air temperature setpoint adjustment	Maximum Air temperature setpoint adjustment
1	12:00-13:00	-13.6	-5.5	-1.1	-1.3	-1.0	-4.0
2	12:00-13:00	-14.2	-5.5	1.1	-1.3	-1.0	-4.0
	13:00-14:00	-13.3	-4.0	-1.1	-1.3	-1.8	-3.0
4	12:00-13:00	-14.2	-5.5	-1.1	-1.3	-1.0	-4.0
	13:00-14:00	-13.3	-4.3	-1.1	-1.3	-1.8	-3.0
	14:00-15:00	-5.0	-7.8	-1.1	-0.9	-5.8	-7.0
	15:00-16:00	2.1	-7.9	-1.1	-0.9	-5.9	-7.0

to ensure acceptable IAQ into the zone. On the other hand, the air flow rate of the AHU serving the seminar zone could be further increased to cover the decrease in the DR load, provided that CO_2 concentration levels in the zone are well below the limit.

The presented results were obtained utilising a comprehensively calibrated energy simulation model, developed using high resolution data (15 minute) from the building BEMS. The usage of fifteen minute data for the calibration process enables validation of the building energy simulation model in order to capture building behaviour under transient conditions. However, in order to enhance the usage of the proposed approach, the model results could also be validated against data archived from DR field tests. In the case where field tests cannot be carried out, the validation could also be accomplished using short-term on-site measurements for periods which are similar in nature to DR events, such as unexpected shut down of equipment or unscheduled changes in building operation. Nevertheless, calibrating building energy models with limited field measurements (as in the case of the DR events) can lead to an under-determined system, wherein multiple solutions exist that produce good overall agreement with measurement [43]. For this reason, the calibration of the building energy simulation model can be performed using other calibration techniques, such as Bayesian calibration [44], which can address this issue by considering parameter uncertainties of model parameters in the form of prior probability distributions.

8. Conclusions

This paper presented a combined evaluation of the capabilities of different DR strategies to maintain thermal comfort while simultaneously meeting utility / aggregator requirements regarding the immediacy and the duration of the load reduction. Demand response events were considered to be driven by RES availability and thus occurred at times which are not commonly considered as DR periods. An energy simulation model of a multi-purpose building was utilised as a virtual test environment to assess the developed DR strategies targeting building HVAC loads. Using this multi-zone environment, the DR measures were tested in zones exhibiting different usage and occupancy patterns.

Different effects on occupant comfort in the zones were observed, revealing the importance of zone thermal behaviour. In contrast with previous research, where the same DR strategies were often applied in all zones, the results indicate that zones thermal and usage profiles should be considered before a DR strategy is implemented in a specific zone, resulting in different strategies being applied in different zones. Regarding the electrical power demand reduction, the chilled water temperature control strategy provides the largest reduction, providing up to 14.2% of the baseload. Delivery equipment on / off control constitutes also a significant DR load, but it requires careful planning to ensure occupant comfort in zones is maintained, especially where considerable heat gains occur. Moreover, it was observed that longer duration demand response events are more likely to disrupt occupant comfort. In addition, load reduction was observed to be highly affected by the time of day at which the strategy is implemented, this is especially true for air temperature setpoint adjustment. Finally, the results show that even for temperate climate conditions, as exhibited in Ireland, there is a considerable DR potential in the commercial building sector, which can be utilised to provide additional flexibility to electricity end-use demand profiles, thereby enhancing improved RES integration.

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