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Modelling of a Multi-purpose Commercial Building for Demand Response Analysis

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Abstract

This paper examines the implementation of demand response measures, using an EnergyPlus simulation model, in a multi-purpose commercial building. The simulation model, which has been developed specifically for demand response analysis, is used to assess the effectiveness of different demand response strategies, which were considered for the building. The strategies were examined for a representative zone within the building and evaluate the contribution of the building capacitance and HVAC equipment operation, as mechanisms for shifting the building electrical demand. Associated zone temperature responses and load shifts are also quantified.

1. Introduction

Demand response (DR) is the concept whereby electricity customers participate in different schemes which are operated by utilities or aggregators, to curtail or shift their electrical load. In systems with high RES penetration, the flexibility provided by buildings participating in DR programs can offer additional benefits such as improve system security and decrease electricity prices [1]. Commercial buildings are of considerable interest for the implementation of DR measures. The limited diversity of their heating, ventilation and air conditioning (HVAC) systems, their scheduled occupancy patterns and the existence of a building energy management system (BEMS) highlight their suitability for DR initiatives.

DR strategies are actions taken to change scheduled operations in order to modify the total energy consumption for a defined period in the case of an event. HVAC systems are the largest energy end-use category in both the residential and commercial sector [2], and such systems have more elasticity in demand control due to the building energy storage characteristics [3]. Therefore, building thermal storage capacity can be used to shift energy demand from 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 [4].

Strategies that have been implemented to date focus on zone temperature setpoint adjustment, pre-conditioning of spaces, light dimming and temporary adjustments of different HVAC components. Space pre-cooling is one of the most common load-shifting strategies that is usually implemented in warm and hot climates. Many research teams have investigated its capabilities for peak load reduction and highlight that the implementation of pre-cooling strategies requires careful planning and optimization regarding the duration and the recovery strategies in order to maximize its potential [3,5,6]. Pre-heating and interruption of air-conditioning systems for reductions in peak demand consumption and cost have also been proposed [7]. Fan power modulation has also been used to provide flexible demand in commercial buildings by tracking time varying regulation signals where the supply fan speed of the air handling units (AHUs) is manipulated [8].

Most DR programs to date have been instigated as a mechanism to reduce electrical loads resulting from excess building demands in a constrained supply environment. Algorithms utilised in such DR schemes have mainly focussed on minimizing energy consumption or cost [6,8]. More recently, there is increased interest in the potential of DR as a possible measure to enhance renewable energy sources (RES) penetration. To achieve this goal, more sophisticated algorithms are required that provide additional flexibility to meet utility and aggregator requirements. Such expectations are circumscribed by the need to have knowledge of the magnitude of the load that needs to 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. A control strategy that responds and adjusts the building energy demand profile is necessary to make this concept viable.

From all the above, is clear that formulation of DR strategies is increasingly more critical and requires more comprehensive approaches. In this paper, the development of a DR model and the assessment of two DR strategies...
is described. The two demonstrated DR strategies are zone pre-conditioning and on/off control of the delivery equipment. The main objective of the strategies is to shift and curtail the load respectively.

2. Methodology

EnergyPlus was used to create a DR model of a commercial building, thereby providing a virtual testbed for the current research. The building, the Student Learning Leisure and Sports Facility (SLLS), is located on the campus of University College Dublin and exhibits a strong commercial profile including a wide variability of HVAC systems, space usage and occupancy patterns. Electricity, gas and district heating meet the energy demand of the building, thereby providing a flexible combination of energy vectors for DR analysis. EnergyPlus, in conjunction with SketchUp, was chosen for creating the DR model for the building, as they allow the specification of key building design and operational parameters including: building orientation, building fabric, occupancy loads, HVAC equipment schedules, ventilation rates, as well as indoor control set-points and outdoor weather data. The building was validated against operational data, collected by the BEMS, for the 2014 operational year. The energy management system (EMS) feature in EnergyPlus is used to develop control routines, which are able to overwrite the scheduled operation of the HVAC systems in order to emulate DR strategies.

2.1 Building and model description

The SLLS building, which is used as a sports/entertainment centre, consists of three storeys with total floor area of 11,000 m². It contains a gym, a 50 m x 25 m swimming pool and additional facilities such as offices, meeting rooms, retail units and a cinema. This multi-purpose building was chosen as a representative commercial building on the campus since it contains a number of offices and retail-type facilities which enhance its commercial profile. Additionally, it contains spaces dominated by different loads and occupancy patterns which facilitate the potential to evaluate different DR strategies for different loads. For example, the swimming pool and fitness centre exhibit large occupancy fluctuations on an hour-to-hour basis, while the offices have almost constant occupancy during their operational hours. A BEMS controls and monitors all the primary and ancillary equipment of the building. Gas, electricity and heat are sub-metered in individual HVAC components in fifteen minute intervals. Pressure, humidity, temperature and CO₂ levels are also measured.

The building electrical and space conditioning requirements are provided by two combined heat and power (CHP) units (506 kW thermal and 400 kW electrical output), two gas boilers (each 1146 kW) and an air cooled water chiller (865 kW). Moreover, heat is also provided by the campus district heating installation (500 kW). The space conditioning delivery equipment consists of eight AHUs, fan coil units (FCUs), radiators and underfloor heating. The ventilation throughout the building is mechanical.

Based on space usage, conditioning method and occupancy patterns, a detailed simulation model (DR model testbed) consisting of 64 zones was created using floor plans and building data in EnergyPlus and SketchUp. The actual SLLS building and the EnergyPlus model are depicted in Figure 1. All the HVAC equipment and associated performance characteristics were verified against manufacturer documentation and modelled in EnergyPlus. In total, three water loops were created (two for the heating and one for the cooling circuit). Due to the thermally driven nature of the CHP units, two loops (heating and heating recovery) were utilized. The boilers, the CHP units and the heat exchanger were connected together to form the supply side of the heat recovery loop, which supplies a hot water tank on the demand side. This tank is the main component in the supply side of the heating loop, providing hot water to the demand side heating delivery equipment. Regarding the cooling operation, only one loop was introduced, where the chiller and its circulation pump constitute the supply side and the AHU, as well as the FCU cooling coils from the cooling demand side. The swimming pool was modelled using a water tank and a daily schedule at 15 minute intervals, utilizing measured data, to capture its flow rate. The evaporation rate from the pool, incorporated with a schedule, was calculated based on available occupancy data. The heating circuit was modelled to operate continuously as the pool water and the surrounding area are conditioned on a 24-hour basis. However, the plant components were prioritized based on the time of day. The CHP units run only during daytime, whereas the boilers and district heating were used as supplementary units. During night-time, only the boilers and district heating were modeled to operate.
Additionally, internal gains derived from occupants, lights and electric equipment were included in the model. Three sources of data were utilized to create building occupancy schedules. Monitored occupancy hourly data for areas such as the swimming pool and the fitness centre was available for an eight month period in 2013. Operational data for the cinema, debating chamber, drama and meeting rooms were used to represent their operational schedules, whereas ASHRAE occupancy values were used to describe their occupancy [9]. ASHRAE values were also used to describe occupancy in common areas such as corridors, stairs and shops during operation hours [9]. Delivery equipment, lights and electric equipment in every zone are enabled based on occupancy patterns. SLLS operating hours are from 06:00 to 23:00 for weekdays and from 08:00 to 18:00 for weekends and public holidays.

The weather data used in this simulation is the historical weather-file for Dublin provided by the EnergyPlus website [10]. This DR model testbed was comprehensively validated against monitored data archived by the building BEMS for a twelve month period (2014). Using monthly data for total electricity consumption, a mean bias error (MBE) of 2.5% between modelled and measured values was recorded. The same procedure was implemented for the mean air temperature in zones where monitored data was available. Monthly MBE values were also calculated with absolute differences ranging from 0.2°C to 1.5°C.

3. Load Analysis

Gas is the principal heating source for the SLLS building; however electricity consumption also constitutes a significant proportion. In 2014 the total electricity consumption was 2.7 GWh, from which 1.2 GWh was imported from the grid and the rest was provided by the CHP units, which consumed 7.5 GWh of gas. Figure 2(a) illustrates the simulated SLLS electric power demand for four different days; one week and one weekend day from each of summer and winter, representing different seasons and occupancy densities. For both, summer and winter week days, the electrical power demand exhibits two peaks, one at 06:00 when the building starts to operate and one late in the evening, between 16:00 to 18:00. During weekends, the operational hours are reduced, hence electricity consumption is less compared to weekdays.

The main aim of the load analysis is to determine the breakdown of end-use energy consumption. Figure 2(b) depicts the variation in end-use consumption for the four representative days. The simulations conducted for the representative weekdays were utilized as indicators to compare winter and summer days, in terms of both building electric power demand and end-use breakdown. Such a comparison highlights the suitability of different loads for participating in DR. As illustrated in Figure 2(b), the electricity breakdown is similar for the two weekdays (WD and SD) with a difference in total electricity demand of just 6%. The electricity consumption (3.6 MWh for WD and 3.9 MWh for SD) associated with the HVAC systems (cooling equipment, pumps and fans) is almost 50% of the total electricity demand (8 MWh for WD and 7.7 MWh for SD), followed by electrical equipment and lights.
The SLLS electrical equipment consumption, which is observed to be greater than expected (usually 20% in commercial buildings [11]), is 30% due to the electrical systems associated with the swimming pool (such as the water treatment). Pump electricity consumption exhibits greatest difference between winter (1.9 MWh) and summer (1.3 MWh), as during the winter 46 of the 64 zones are conditioned, whereas during the summer only 20 zones are conditioned. Electricity consumption from fans, on the other hand, is almost 16% of the daily electricity demand for both weekdays in winter and summer. Thus, DR strategies that target fan load can potentially be applied regardless of season or time. DR strategies targeting the chiller, however, could be more beneficial during the summer period. Different load magnitudes and time availability is a first indicator of different loads suitability for DR.

Two DR strategies targeting to shift / curtail the peak load are evaluated. A pre-conditioning strategy which shifts the morning peak (06:00 hrs) to an earlier period is evaluated. An on/off control strategy for the delivery equipment (especially fans that count almost 16% of the daily building power demand) is implemented to curtail the evening peak load.

4. DR Strategy case study

Building electric loads participating in DR programs can be divided based on their control time frame to the following categories: long-term (one-year ahead), medium-term (24 hours horizon), short-term (1 hour) and dispatchable (controlled in real time) [12]. The two DR strategies under examination are implemented in one of the SLLS zones, the fitness centre, for a summer weekday. The pre-conditioning strategy represents a medium-term control, while the on/off control strategy represents a short-term control.

The fitness centre occupies 8% of the conditioned building area and is conditioned by a combination of FCUs and an AHU that supplies fresh outdoor air. The fact that the operation hours for the fitness centre are from 06:00 to 23:00 makes this zone beneficial for the implementation of the pre-conditioning DR strategy. Moreover, the usage of FCUs for the conditioning of the zone is ideal for the assessment of the on/off control strategy, at any time during the day and between 16:00 to 18:00 in particular. The first step is to examine the application of the strategies during summer time. During the summer, the cooling setpoint is set at 21 °C. In the pre-conditioning strategy, pre-cooling takes place between 03:00 and 06:00 (unoccupied period) with a setpoint temperature of 18 °C. Between 06:00 and 12:00 the cooling set-point is set at 22 °C and afterwards returns to its scheduled value (21 °C). In the on/off strategy, the FCUs are turned off between 16:00 and 17:00. A simulation based on normal building operation represents the reference case.

The results of the application of the two strategies are depicted in Figure 3. The baseline zone temperature is described by Tref when there is no DR action, whereas TDR describes the zone temperature when a DR action is applied. The corresponding difference in building electrical load (Δload) is also depicted, where positive values indicate a load increase and negative a load reduction. As displayed in Figure 3(a), pre-cooling of the zone to 18 °C between 03:00 to 06:00 results in an additional electrical consumption of 104 kWh, which provides a corresponding reduction of 87 kWh between 06:00 and 12:00, when the zone set-point is relaxed to 22 °C. During 03:00 to 06:00, the chiller and the FCUs of the fitness centre zone are activated to enable the pre-cooling. A reduction of 28 kWh of the building total electrical consumption, which is 353 kWh for the reference case, is observed when the FCUs are turned off for one hour, as given in Figure 3(b). As this interruption takes place in the mid to late afternoon, where high external temperatures often prevail, the zone mean air temperature is observed to increase from 21 °C to 24 °C, which is likely to exceed the zone thermal comfort conditions.
Thermal comfort is assessed using the 7-point predicted mean vote (PMV) index of the Fanger thermal comfort model [13]. Figure 4 depicts the PMV-index values in the Fitness Centre for the reference and the two DR scenarios. In general, acceptable PMV-index values lie in between -1 (slightly cool) and +1 (slightly warm), since it is impossible to satisfy all persons in a large group sharing a collective climate [13]. As it is illustrated, pre-conditioning keeps the PMV-index values within the acceptable limits, whereas the on/off strategy results in a peak PMV-index value of 1.25.

figure 4: PMV values in the fitness center for pre-conditioning and delivery equipment DR strategies for a summer weekday

Comparing the two DR strategies from the perspective of the associated impact on the electrical load reduction, it can be seen that on/off control strategy is capable of a greater reduction in the total building response (28 kWh per hour compared to the pre-conditioning strategy, which exhibits 24 kWh for the first hour and 12 kWh, in average, for the following five hours). However, it also has a greater impact on the zone mean air temperature and occupant comfort. These changes should be taken into account before the final formulation of the building response on utility / aggregator requirements. From the above, it is clear that the demand load shifting or reduction has considerable potential in commercial buildings similar to the SLLS building.

5. Conclusions

The described model can be considered as a virtual testbed for analysis of DR strategies in a mixed use commercial building. It comprehensively models the building behavior discriminating between zone loads, zone occupancy patterns and associated HVAC system loads. Thus, the model is capable of investigating the DR suitability of a variety of HVAC systems found in commercial buildings. A building load analysis using electrical power demand profile and end-use breakdown was conducted to determine load availability for participating in DR. Based on this analysis, two different DR strategies targeting building thermal capacitance and HVAC equipment load shedding were implemented for a single zone. The simulation results indicate promising potential for implementing DR, with an 8% (28 kWh reduction from a 353kWh baseload) electrical load reduction achieved by turning off the delivery equipment for one hour. Nevertheless, DR measures using electrical load also cause considerable change in zone mean air temperature. Future work includes primarily the application of the strategies during winter time, as well as the investigation of more sophisticated DR strategies before formulating flexible responses that can be applied to commercial buildings to different DR requests.

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