

# **CALIBRATION OF A COMMERCIAL BUILDING ENERGY SIMULATION MODEL FOR DEMAND RESPONSE ANALYSIS**

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## **ABSTRACT**

This paper describes the calibration process of an EnergyPlus simulation model, for a multi-purpose commercial building, which has been developed specifically for demand response analysis. Power, gas and air temperature data are collected in fifteen minute intervals as part of the calibration process. Real occupancy data are implemented as well. The results indicate a mean bias error of -1.6% for the annual electricity consumption. Calibration under the scope of demand response at zone and equipment level is also described.

## **INTRODUCTION**

Currently, the electricity sector faces a number of challenges, including, the deployment of renewable energy sources (RES), increasing electric power demand caused by electric vehicles and the electrification of new sectors (e.g., building thermal loads). Ireland, in particular, has committed to an increase in the level of electricity production derived from RES to 40 % by 2020 (SEAI, 2014). In order to achieve the 2020 target, significant work to manage the integration of very high levels of instantaneous renewable penetration on the island is required (EirGrid, 2013). Regulation services and operating reserves are necessary to balance the fluctuations of RES power generation over time. When generation from renewable sources is not available, these services are usually made up by more expensive standby generation units, often fossil fuel units. However, grid operators could utilise the demand side participation as an additional option to ensure balance between supply and demand (Critz et al., 2013). Demand response (DR) is the concept whereby customers participate in schemes, operated by utilities or aggregators, to curtail or shift their electrical load (U.S Department of Energy, 2006).

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 building energy management systems (BEMS) highlight their suitability for DR initiatives. In order for buildings to implement different DR schemes, load control strategies need to be adopted. HVAC systems are the

largest energy end-use category in both the residential and commercial sectors (Perez-Lombard et al., 2008), and such systems have more elasticity in demand control due to the building thermal energy storage characteristics (Xue and Shengwei, 2012). Therefore, the building thermal storage capacity can be used to shift energy demand from a short period, often minutes, up to a number of hours. HVAC-based load control strategies for a given building vary based on the type and purpose of the building, mechanical equipment and the BEMS (Motegi et al., 2007). Zonal air temperature, relative humidity and CO<sub>2</sub> concentration setpoints are the main parameters that can be modified to control the conditioning energy demand of a building.

Building energy models have been widely used for performance analysis in the building industry and to demonstrate compliance for codes and standards. For example, Pan et al. (2006) employed simulation models of two high-rise commercial buildings in Shanghai to analyse their energy usage and calculate the energy savings of possible energy conservation measures. Nevertheless, the use of building energy models can be extended beyond that. They can also be used to optimise design solutions during the design stage or to assist building controls during the building operational phase (Zhao et al., 2014). Thus, significant discrepancies between simulation results and measured data from buildings should be eliminated to add value to the building energy models and extend their usage (Lam et al., 2014). Lam et al. (2014) define building energy model calibration as an approach to modify and adapt the design case model, based on measured data, to generate an updated building energy model that accurately reflects actual building operational performance.

Calibration is usually an iterative, empirical process of adjusting model parameters and comparing the results to measured data. Reddy (2006) classifies calibration methods into three categories: manual iterative, graphical and statistical, and automated methods. All these methods are not mutually exclusive and can be combined. A number of researchers have demonstrated empirical calibration methods (Lam et al., 2014; Pan et al., 2006; Yoon et al., 2003; Raftery et al., 2011; Mustafaraj et al., 2014). Determining the level of calibration that is

required depends on the relative importance of the calibration issue and the availability of data. Different data sources must be assessed in order to be used as simulation inputs. Raftery et al. (2011) propose that the different data sources should be prioritised based on their reliability. The proposed list of recommended sources, in order of importance, is as follows: (1) data measurements; (2) spot or short-term measurements; (3) direct observations; (4) operator and personnel interviews; (5) operation documents; (6) commissioning documents; (7) benchmark studies and best practice guides; (8) standards, specifications and guidelines; (9) design stage information.

In recent times, there has been increased interest in the potential of DR in buildings as a possible measure to enhance RES penetration, specifically wind generation, thereby helping reduce generation curtailment. However, more sophisticated control strategies that respond to utility/aggregator requirements and adjust the building energy demand profile are desirable, in order to make the application of DR in building energy more applicable. Advanced DR strategies should be capable of responding to a number of factors including; the magnitude of the load to be shifted or curtailed, the immediacy of the DR response action and the duration of the DR response. To achieve this goal, different control strategies have to be evaluated for their impact on load shifting and occupant comfort. Thus, a comprehensive building energy model, that reflects the actual building operational performance, is required as a virtual test bed to examine different control strategies. A building energy simulation model built for DR analysis should be able to model building response to aggregator/utility request for electric load curtail/shift in a time range from 15 minutes to several hours (usually 24 hours). For this reason, a DR simulation model requires a more extensive calibration not only for the building electric power demand but also for the zone comfort parameters that are affected by DR strategies. Thus, calibration using 15-minute time step data is required in order for the model to be reliable for DR demonstration.

The current paper demonstrates an empirical calibration of an EnergyPlus model of a multi-purpose building developed specifically for DR analysis. The DR simulation model was initially calibrated using monthly data. Thereafter, a more comprehensive calibration was performed using 15 minute measured data. Daily profiles for electric power demand and zonal variables, for example air temperature, humidity and CO<sub>2</sub> concentration were also generated.

## METHODOLOGY

In this work, EnergyPlus is used as a simulation tool to create a virtual DR test bed, based on a mixed use commercial building. A building with a strong

commercial profile, variability of HVAC systems, space usage and occupancy patterns was chosen as a test platform for investigating the DR capabilities in commercial buildings. This building, the Student Learning Leisure and Sports Facility (SLLS), is located on the UCD campus in Dublin (Ireland).

The building envelope, HVAC systems, occupancy patterns and electrical equipment were modelled in detail using EnergyPlus. The initial SLLS model was created based on the design documentation and operational/commissioning documents. EnergyPlus default and ASHRAE-proposed values were used for building inputs when data were unavailable. Power, gas and temperature data were collected in 15 minute intervals and used for the calibration. The building was simulated and validated against operational data from 2014. The simulation building model was initially calibrated using monthly data.

The final model will be used to evaluate different DR strategies based on their impact on electricity pattern modification and occupant comfort. Hence, data for parameters that affect occupant comfort as zone air temperature, relative humidity and CO<sub>2</sub> concentration were archived in 15 minute intervals and compared with the modelled values.

Two statistical indices are widely used to demonstrate calibration accuracy: the mean bias error (MBE) and the cumulative variation of the root mean squared error (CVRMSE) (Coakley et al., 2014). The MBE is a non-dimensional bias measure between measured and simulated data. Although it captures the mean difference between measured and simulated data points, it is subject to a cancellation effect, where a positive bias compensates a negative bias. In order to overcome this cancellation effect, the CVRMSE index, which determines how well the model fits the data by capturing the offsetting errors between the measured and simulated data, is used (Raftery et al., 2011). The two indexes are calculated using the following formulae:

$$MBE (\%) = \frac{\sum_{i=1}^{N_p} (m_i - s_i)}{\sum_{i=1}^{N_p} (m_i)} \quad (1)$$

$$CVRMSE (\%) = \frac{\sqrt{\sum_{i=1}^{N_p} (m_i - s_i)^2 / N_p}}{\bar{m}} \quad (2)$$

where  $m_i$  and  $s_i$  are the measured and simulated data points, respectively, for each data model instance  $i$ ,  $N_p$  is the number of data time steps ( $N_m=12$  and  $N_h=8760$  for the monthly and hourly data used respectively) and  $\bar{m}$  is the average of the measured monthly or hourly data points where appropriate.

Acceptance criteria set by ASHRAE must be met in order for a model to be considered as ‘calibrated’ (ASHRAE, 2002). These values are 5% for MBE and 15% for CVRMSE for calibration using monthly data, and 10% for MBE and 30% for CVRMSE using hourly data. When hourly data are applied, the

interval is one hour and the period can be defined by the user, often a period of one month is used. All models should be calibrated using monthly data at a minimum, according to the ASHRAE recommendations. This level of calibration is suitable for building energy models that are intended to perform analysis of different energy conservation measures.

In this paper, MBE and CVRMSE indexes were used for the calibration process, even though there are no acceptance criteria for calibrating using 15 minute data. For the part of the calibration process that was carried out using hourly and monthly data, ASHRAE acceptance criteria were followed.

## **BUILDING DESCRIPTION**

The SLLS building, depicted in Figure 1, used as a sports/entertainment centre, consists of three floors with a total floor area of 11,000 m<sup>2</sup>. Included in the SLLS is a 50 m x 25 m swimming pool, with related ancillary areas including a wellness suite, fitness centre, aerobics and dance studios, debating chamber, drama theatre, multimedia and seminar rooms, newspaper/radio and TV media centre, health facilities, offices, shops and cafe space. The SLLS contains numerous zones subject to different loads and occupancy patterns. The swimming pool and gym, for example, exhibit large fluctuations in occupancy at different times of the day, while the offices have almost constant occupancy during their operational hours.



*Figure 1: SLLS building*

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

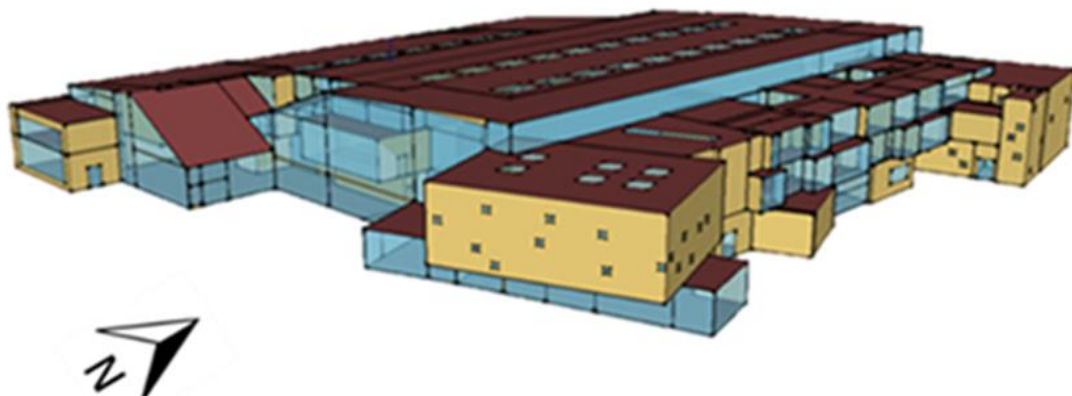
(865 kW). Moreover, heat is also provided by the campus district heating installation (500 kW). The space conditioning delivery equipment consists of eight air handling units (AHUs), fan coil units (FCUs), underfloor heating and baseboard heaters. Ventilation throughout the building is mechanical. The boilers, CHP units and district heating system are connected via individual pumps to a primary heating circuit, thereby constituting the supply heating circuit. Seven secondary heating circuits are provided with hot water by the primary circuit. These circuits cover the needs of the low temperature hot water calorifiers, the pool water heat exchangers, the AHU heating coils, the FCU heating coils, the underfloor heating circuit, the radiators and the trench heaters. The air-cooled chiller with its individual pump constitutes the chilled primary circuit, which provides chilled water to all AHU and FCU cooling coils.

A BEMS controls and monitors all the primary and ancillary HVAC equipment in the building. The BEMS facilitates the planning of targeted DR strategies using the electricity/energy breakdown of the building. Operational BEMS data has been recorded in 15 minute intervals from September 2012 onwards. Total electricity and gas consumption are monitored and there are sub-meters on individual HVAC components (i.e., boilers, CHP units, and the chiller). Pressure, humidity, air temperature and CO<sub>2</sub> levels are measured at different points of the HVAC systems. In addition, air temperature, relative humidity and CO<sub>2</sub> concentration are measured at zone level.

## **DR SIMULATION MODEL**

### **Envelope and zones**

The building geometry, which is depicted in Figure 2, was created using the 3D modelling software Google SketchUp 8.0. The SLLS building model consists of 63 zones, of which 46 are conditioned. The model was built on a zone-by-zone basis from AutoCAD plans for building floors and sections. The criteria used to separate the thermal zones were: function of the space, its position relative to the exterior, measured data available, and the method used for conditioning the zone (Raftery et al., 2011).



*Figure 2: SLLS EnergyPlus model*

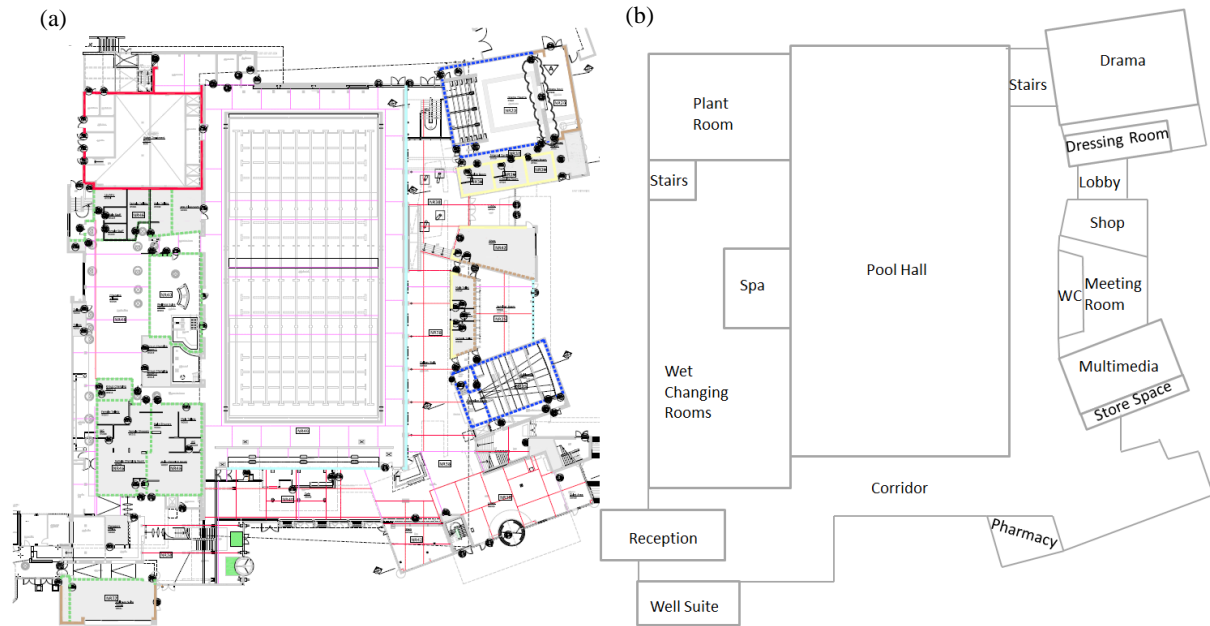


Figure 3: Ground floor plan (a) and modelled thermal zones (b)

All of the different HVAC equipment units were modelled in EnergyPlus. Additionally, different occupancy and activity profiles were assigned to each zone enabling a sensitivity analysis to be carried out. Figure 3 depicts the ground floor plan and the defined thermal zones. Based on the as-built AutoCAD drawings, all the different construction elements used in the SLLS building were characterised. The different material properties, required by EnergyPlus, were gathered from manufacturer specifications. When such information was unavailable, properties from the ASHRAE-2005 material dataset were used.

### Heating, Cooling and Ventilation Systems

The modelling of the HVAC systems proved to be challenging, not only for the way that different components should be modelled but also in the way that they should be linked together in order to create heating/cooling loops that allow the model to operate as close as possible to actual system operation. Initially, all equipment and associated performance characteristics were verified against manufacturer documentation. In cases where information was missing, data from similar equipment was used.

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 created. 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 and the FCU

cooling coils form the demand side. A schematic representation of the three loops, generated in EnergyPlus, is given in Figure 4.

The swimming pool was modelled using a water tank. A schedule to model the evaporation process from the pool was incorporated in the model and the evaporation rate was calculated based on available occupancy data (Costa et al., 2011).

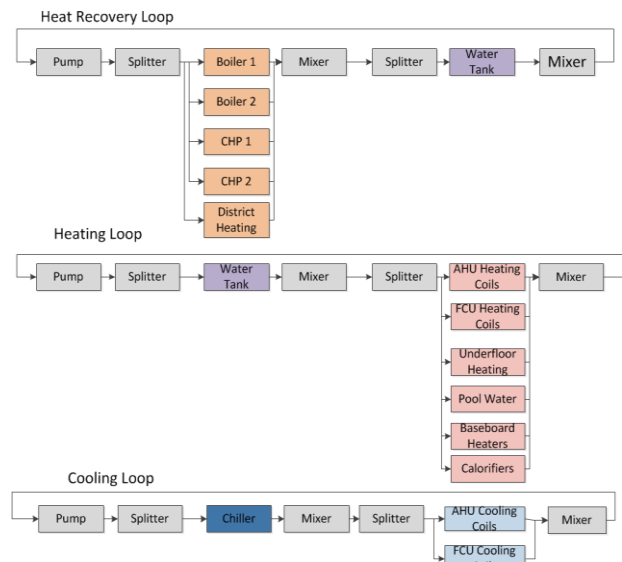


Figure 4: Schematic representation of the HVAC loops

### Internal Gains

Internal gains caused by people, lights and electrical equipment were included in the model. Occupancy data are the most difficult to be estimated. Initially, ASHRAE occupancy values were assigned to each zone (ASHRAE Standard 62.1, 2007).

Electricity is monitored in the SLLS building, not only as a total value, but also on the distribution boards for some of the zones. As the electricity

consumption recorded from the distribution boards combined lighting and electric equipment consumption, they could not be utilised as inputs to the model. The lighting level and operational hours were determined from manufacturer literature. Electric equipment power consumption and schedules for the different zones were taken from ASHRAE datasets (ASHRAE 90.1, 2004).

### Operation Schemes

In order for the model to be a realistic representation of the building, schedules regarding plant operation and ventilation were utilised. The heating plant loop operates continuously, as the pool water and surrounding area are conditioned on a 24-hour basis. However, depending on the time of day and season, the plant equipment is prioritised differently resulting in three different plant operation scenarios:

- Winter day: both CHP units are operating; district heating system and boilers are used complementarily.
- Summer day: both CHP units are operating, exporting surplus electricity to the grid and dumping heat to the atmosphere as necessary.
- Night: CHP units are not running as it is cheaper to buy electricity from the grid, so boilers or district heating are operating to provide heat.

The chiller and chilled water supply loop operate on a daily basis from 06.00 to 23.00. Initially, the heating set point for all the zones was 21 °C, while the cooling set point set was 25 °C.

### Infiltration Rate and Outdoor Air Flow Rate

Infiltration rates are important concerning the overall thermal energy consumption for the building. A default infiltration rate of 5 m<sup>3</sup>/m<sup>2</sup>/hr at 50 Pa was set (on the basis of design data) to all perimeter zones and it was held constant with time. The ventilation rate required for all zones that are not mechanically ventilated were estimated based on the ASHRAE indoor air quality guide (ASHRAE Standard 62.1, 2007).

### Weather Data

The weather data used in the simulation for a one year period is the typical weatherfile and the Design Conditions Design Day Data for Dublin provided by the EnergyPlus website (EnergyPlus, 2015). The design day object describes the parameters for the software to create the 24-hour weather profile that is often used for sizing equipment or load calculations. However, since manufacturer data were used in most of the inputs, sizing was used only for a limited number of equipment components where these data were missing.

The simulation time-step was defined as 15 minutes to produce detailed results that can be compared with the BEMS archived data. Furthermore, under the scope of DR, building electric loads are grouped based on their control time frame. These time frames range from real-time control to 24-hour horizons. For

this reason, a time step of at least 15 minutes is required to examine the controllability and prioritization of building electric loads in the case of a DR event.

## MODEL CALIBRATION

### Internal Gains

Monitored occupancy hourly data for areas such as the swimming pool and the gym was available for an eight month period in 2013. Based on this data, representative occupancy profiles for weekdays and weekends were created and used to update the initial occupancy schedules. Operational data for the cinema, debating chamber, drama and meeting rooms were also used to represent the operational schedules, whereas ASHRAE occupancy values were used to describe their occupancy (ASHRAE Standard 62.1, 2007). Figure 5 depicts the occupancy of the swimming pool area, and the lighting and electric equipment schedules as a fraction of the peak value for weekdays. The swimming pool occupancy schedule was created based on measured data and the peak occupancy is 70 people. Lighting and electric equipment peak power density values are 12 W/m<sup>2</sup> and 10 W/m<sup>2</sup> respectively.

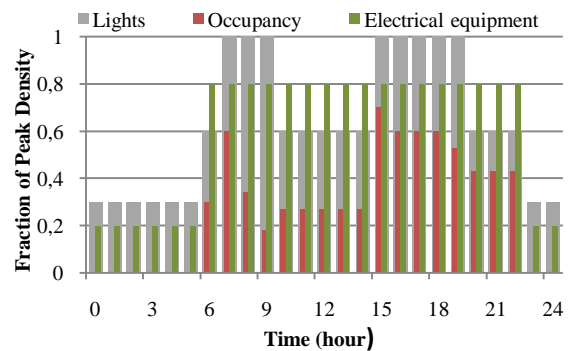


Figure 5: Occupancy, lighting and electric equipment weekday schedules for the swimming pool area

Table 1 lists the building input peak densities for lighting as well as for electric equipment based on the different types of zones. The percentage of the building total space for each type of activity is also given in Table 1.

### Non-HVAC systems

Electricity consumption data for 2014 were used to create daily electricity demand profiles for the non-HVAC systems. Elevators, exterior lights, pool water treatment and motor control cubicles electrical power demand profiles were created based on measured data and assigned to the model. Moreover, a radiant fraction also attributed to this equipment enhancing the internal heat gains. Values of similar equipment from EnergyPlus example files were used.

As already mentioned, two water tank objects were used to model the calorifiers, which cover the building hot water needs, and the pool water demand. The initial constant schedule was updated by two



daily schedules at 15 minute intervals, utilising the available data, to model the water flow rate of the tanks.

Table 1: Building model characteristics

	Percentage of total building floor space (%)	Lighting power density [W/m <sup>2</sup> ]	Electric equipment power density [W/m <sup>2</sup> ]
Pool	23	16	2
Fitness & Auxiliary Spaces	21	12	10
Offices & Meeting Rooms	11	12	10
Drama	4	15	8
Debating Ch.	3	11	5
Retail Units	2	16	14
Multimedia	1	11	2
Auxiliary	34	5	4

### Weather data

Weather data from the campus weather station were used to update the weather file. Using the Weather Statistics and Conversions software of EnergyPlus, the initial weather file was converted to an editable file. The archived data for outdoor air temperature, wind speed and direction, global solar radiation and relative humidity were used to update the historical data with measured values for 2014.

## RESULTS

### Electricity and gas consumption

In 2014, the total electricity consumption of the SLLS building 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 6 illustrates the simulated results for the DR model and the measured values for electricity consumption on a monthly basis for 2014. The final calibrated model has a monthly MBE value of -1.6% and a monthly CVRMSE value of 10.5%. Both values are below the threshold values prescribed by ASHRAE (ASHRAE, 2002).

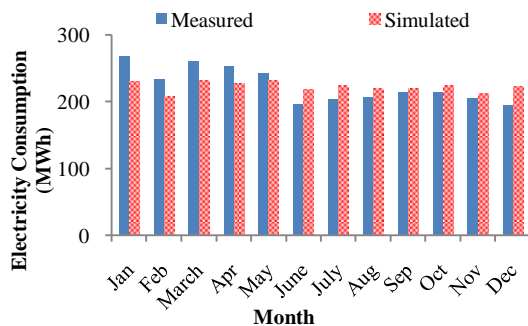


Figure 6: Monthly measured and simulated electricity consumption for 2014

MBE and CVRMSE monthly values for the measured and simulated annual gas consumption were -3% and 20% respectively.

From a DR perspective, even more important than the total electricity consumption is that the simulated electrical demand profile follows the same pattern as the real building. The highest electricity consumption in 2014 was on the 20<sup>th</sup> of January, a winter weekday (WD), whereas the lowest was on the 13<sup>th</sup> of July, a summer weekend day (SE). Utilising measured and simulated data in 15 minute intervals, electrical power demand profiles were created for these two days. The profiles are depicted in Figure 7. Regarding the high load winter weekday, the higher discrepancies between the model and simulated values occur during the morning from 07:00 to 07:30 and in the evening from 17:00 to 18:00. The morning spike in the measured data is caused by the start of the different heating system circulation pumps. Whereas, the evening difference is associated with the end of the delivery equipment operation which is occupant dependent. For the profiles created for the low summer weekend, the greatest differences are detected during the unoccupied night time hours. Figure 7 shows the difference in weekday and weekend electric power demand profiles.

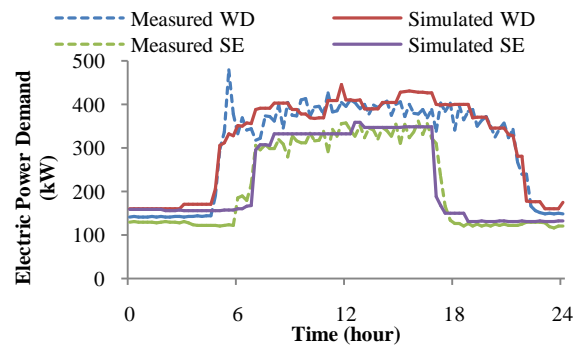


Figure 7: Measured and simulated electrical power demand for a winter day and a summer weekend

Figure 8 depicts the measured and simulated data for lighting and electrical equipment electricity consumption for an office zone which was sub-metered separately based on 15 minute intervals. The office zone operates from 07:00 to 22:00 on weekdays, and from 10:00 to 18:00 during the weekends. The results indicate that the simulated load matches the measured load behaviour with MBE of 1.8 % and CVRMSE of 25 %.

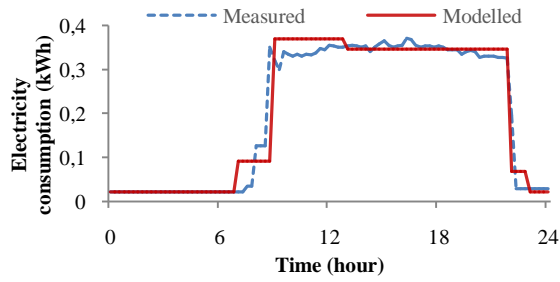


Figure 8: Office zone lights and electrical equipment electricity consumption

Data for lighting electricity demand was derived from design specifications prior to construction. The lighting load was given as a value per square meter for each zone and the SLLS lighting systems consumption was estimated to be about 54 kWh/m<sup>2</sup>/annum. The monthly MBE value for the lighting systems is 5.5 % as the simulated value for 2014 is 57 kWh/m<sup>2</sup>.

### Zonal Parameters

The fitness centre zone, which operates from 06:00 to 23:00 daily, is conditioned by a combination of FCUs and a variable air volume AHU. The zone air temperature set point is constant at 21°C during its operation. Figure 9 depicts the air temperature in the fitness centre for one weekday in February. Two other data series are also displayed. The first is the simulated air temperature data of the pre-calibrated model for the same day and the second is the air temperature values of the calibrated model. The MBE and CVRME indexes, calculated for February using 15 minute intervals data, are 11% and 13%, respectively for the pre-calibrated model. These values were achieved using measured occupancy data and air temperature set-points.

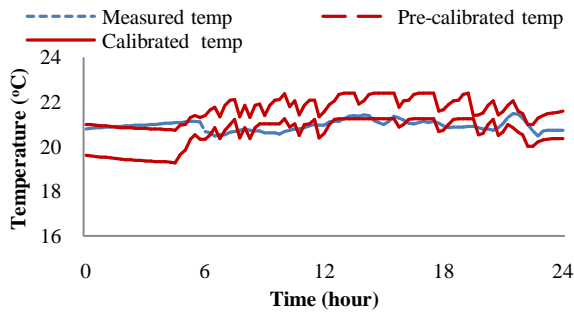


Figure 9: Improvement of the simulated air temperature with calibration against measured data for a winter weekday in fitness centre

However, for the pre-calibrated model lighting schedule, lights were operating at 100% of their power all the time causing high internal heat gains and zone overheating. This schedule was replaced by a more realistic one where light operation is in line with the zone occupancy, resulting in simulated zone air temperatures more closely matching the measured values for the occupied hours. Values of 6% for the MBE and of 10% for the CVRME were obtained for the calibrated model.

In the SLLS building, relative humidity is measured in the swimming pool area and is regulated between 40% and 60%. The pool area is conditioned in a 24-hour basis by an AHU consisting of a heat exchanger, a heating coil and a constant air volume fan. The minimum outdoor air ratio for the AHU is set at 30% outdoor air. The measured and simulated relative humidity values, using 15 minute intervals data for a winter day, are presented in Figure 10. Relative humidity exhibits two peaks, one in the morning (07:00 to 09:00) and one during the afternoon and early evening (15:00 to 19:00). These peaks are due to the higher occupancy levels of the zone at these periods (as illustrated in Figure 4). Relative humidity in the swimming pool zone has a MBE of -1% and a CVRME of 11.9 %. The zone air temperature (the zone air temperature set-point is at 30°C) for the same day is also plotted in Figure 10.

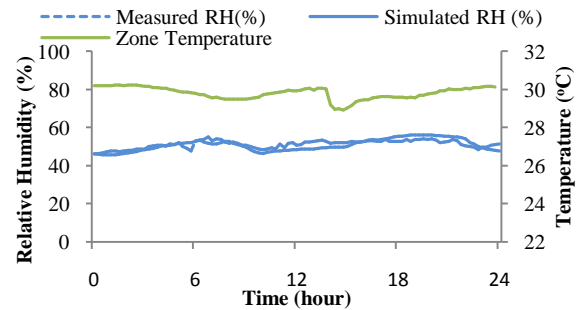


Figure 10: Air temperature, measured and simulated relative humidity in pool area in a winter day

Figure 11 depicts the CO<sub>2</sub> concentration in the multimedia centre and the zone occupancy as a fraction of the maximum value (86 occupants). The measured and simulated values are displayed for one winter weekday in January.

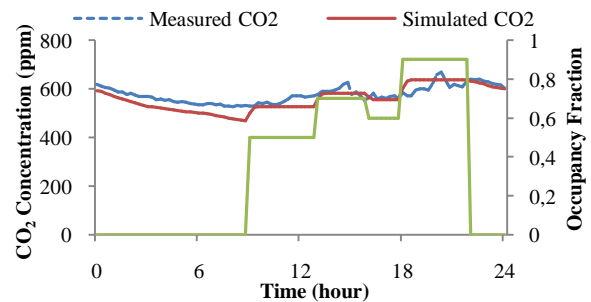


Figure 11: Measured and simulated CO<sub>2</sub> concentration for a winter weekday in multimedia centre

The HVAC systems conditioning the zone operate with 100% outdoor air. The CO<sub>2</sub> concentration in the zone is dependent on the zone occupancy level, as shown in Figure 11. The MBE and the CVRME, also calculated using 15 minute data, are -5% and 15% respectively.

### CONCLUSIONS

This paper discusses the challenges and issues associated with the calibration of a building energy simulation model that has been created specifically

for DR analysis. The paper focuses on the calibration of the electricity demand and zonal parameters using high resolution measured data. Challenges associated with the calibration using 15 minute data and the suitability of the calibration standards for such a detailed calibration are evaluated. MBE and CVRMSE indexes were used to denote the calibration results. The monthly MBE and CVRMSE indexes are -1.6 % and 10.5 % respectively. Electricity demand profiles, both on a building and zonal level, were created using 15 minute measured and simulated data, so that the model is suitable for DR sensitivity analysis. Future work includes the development of an optimization-based approach to calibrate the building energy model using the measured data.

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