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Building model calibration using energy and environmental data

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ABSTRACT

A large number of randomly interacting variables combine to dictate the energy performance of a building. Building energy simulation models attempt to capture these perturbations as accurately as possible. The prediction accuracy of building energy models can now be better examined given the widespread availability of environmental and energy monitoring equipment and reduced data storage costs. In this paper a set of two calibrated environmental sensors together with a weather station are deployed in a 5-storey office building to examine the accuracy of an EnergyPlus virtual building model. Using American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guide 14 indices the model was calibrated to achieve Mean Bias Error (MBE) values within ±5% and Cumulative Variation of Root Mean Square Error (CV(RMSE)) values below 10%. The calibrated EnergyPlus model was able to predict annual hourly space air temperatures with an accuracy of ±1.5 °C for 99.5% and an accuracy of ±1 °C for 93.2% of the time.

1. Introduction

The origins of building energy modelling can be traced back as early as 1920s with the development of response factor method for transient heat flow calculations [1]. The availability of computers in the 60s heralded a new dawn when, especially from early 80s the HVAC companies developed energy models for heating and cooling load calculations [2,3]. This trend accelerated as the 70s oil crises raised building energy standards, leading to greater energy efficiency and modelling methods that continue to this day [4]. Whilst initially a design phase tool, increasingly building energy simulation (BES) models of existing buildings are developed to aid research into model-based controls, optimisation, energy conservation measures (ECM) and financial appraisals [5–7]. The creation, maintenance and updating of virtual building models therefore increasingly require greater levels of accuracy to enable more meaningful studies.

In the last few years the widespread deployment of multifunctional environmental sensors, mandatory sub-metering of building energy consumptions, longitudinal data collection and the internet of things have all led to substantial amounts of building and energy related data being made available. The richness of digital infrastructure output has grown to an extent comparable to biological ecosystems in all their complexity [8]. Within building related applications, the availability of both simulated and measured energy and comfort data gives the issue of model calibration greater potency. Building model calibration is a measure of model accuracy, which despite increasing sophistication still suffers vast under-determined parameter space [9].

The aim of this paper is to conduct an energy calibration using an EnergyPlus model before examining the match between simulated and actual space air temperatures. This two-tiered objective is perused through the following steps:

1 Using an office building as a platform, a first stage energy calibration of the model is performed using 2012 hourly-metered values.
2 Space air temperature is collected for the same period using environmental sensors to enable an assessment of zone temperature prediction accuracy of the calibrated EnergyPlus model.

The calibration process follows ASHRAE guideline 14 recommendations. This guideline was originally developed to quantify energy saving potentials of proposed retrofit schemes, and is among

Abbreviations: AHU, air handling units; BES, building energy simulation; BIM, building information modelling; BWM, Box whisker mean; CV(RMSE), cumulative variation of root mean square error; ECM, energy conservation measures; EPW, EnergyPlus weather (file); HAM, heat, air and moisture (Modelling); HVAC, heating, ventilation, air-conditioning and cooling; MBE, mean bias error; PIR, passive infra-red.

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Fig. 1. The building's heavily glazed front aspect faces +34° from due south.

three current guides that define virtual model acceptance criteria [10–12].

1.1. Case-study building

A modern 5-storey sandstone office inaugurated in 2010 is the platform for the work undertaken here (located 54°58′N, 1°36′W). At north, east, south and west orientations solar control glazing cover 54%, 29%, 87% and 42% of the facades respectively (hence overall the building's external facade is 53% glazed). The south aspect is partially shaded by extruded aluminium brise soleil (Fig. 1).

The building fabric *U*-value exceeded the statutory UK building requirements of the time by an average of 29%. Internally the complex architecture includes two large southerly and westerly voids, two internal atria facilitating displacement ventilation and a blend of cellular and open plan offices over 8365 m^2 of gross area (housing around 500 staff). Thermally induced displacement ventilation and exposed concrete surfaces are among two carbon reduction philosophies that guided the original design (Fig. 2).

A Gill's MetPak Pro weather station combined with a SPN1 pyranometer were mounted on the rooftop of this building (Appendix A) to provide the following outputs (accuracy noted in brackets):

1 Global solar radiation (±5%).
2 Diffused radiation (±5%).
3 Wind speed (±2% at 12 m/s).
4 Wind direction (±3°).
5 Air temperature (±0.1 °C).
6 Relative humidity (± 0.8% at 23 °C).
7 Dew point (±0.15 °C at 23 °C with a dew point of 20 °C).
8 Barometric pressure (±0.5 hpa).

Except for solar radiation, all measurements are instantaneous values sampled at 10-minute intervals. Global and diffused solar components are however 10 min averages which are further rounded to form hourly figures to construct EPW (EnergyPlus weather) files.

1.2. HVAC services

Three equally sized condensing boilers provide a total heating output of 744 kW which are delivered to the zones via a combination of radiators, trench and perimeter heaters, under floor heating and tempered air. Two central air handling units (AHUs) with 2-stage heat recovery facilitate displacement ventilation at a total rate of 11.32 m^3/s with 90% of the supplied volume being recirculated. The design attempted to eradicate any need for refrigerant-driven cooling yet a small degree of back-up cooling capacity is provided first by adiabatic evaporative coils acting directly on the summertime air intake, followed by direct expansion vapour compression coils (which have a relatively small capacity of 100 kW). Because of extensive IT use in the building, power factor correction and surge suppression facilities are incorporated into electrical supply to guarantee a power factor quality of 0.96 at all times. Lighting is operated by presence detection and is equipped with daylight compensation sensors.

Table 1
Comparison of energy benchmarks for existing UK open-plan office buildings (KWh/m^2 of treated floor area).

Category	Case study building	Best practice	Typical
Electricity	137	128	226
Fossil Fuel	51	97	178

1.3. Energy data

Box whisker mean (BWM) plots are used to present 2012 metered energy use of the building (Figs. 3 and 4). This allows quick and efficient communication of many aspects of building energy demand, namely peaks, medians, extreme values (outliers) and seasonal variations [13]. The building has a rather consistent electricity demand throughout the year (Fig. 3) where on average, working-hour electrical loads float at around 180 kWh (with peaks of around 200 kWh) before falling to a base-load of about 50 kWh at night.

Night purge ventilation strategy raises the night time base-load to around 60 kWh in mid and late summer months. Daylight-linked lighting conversely reduces the summer months' electricity demand during office hours.

The building annual heating demand is more variable given that it is a function of climatic conditions. Except in January, loads above 100 kWh fall above the upper quartile range indicating the building's well-insulated fabric (Fig. 4). Building heating requirements are well below CIBSE best practice recommendations (Table 1) [14].

1.4. Software description

EnergyPlus is a first principle based tool and the official building simulation programme of the United States Department of Energy. It is extensively used and examined by the international research community to model heating, cooling, ventilation, lighting and also water consumption using a state-space method (the thermal load of the building is simulated using a heat balance method) [15,16]. Energyplus is primarily a simulation engine (with no interface) and as such DesignBuilder version 3.2.0.067 was used as the graphical interface (front-ending EnergyPlus Version 7.2.0)[17]. Several formatting steps were required to allow weather files to be used in EnergyPlus models, including generating '.stat' files using EnergyPlus weather statistics and conversions program.

2. Literature review

2.1. Modelling limitations

Building models capture an arbitrary and limited part of what essentially is a multiplicity of dynamic (fabric properties and HVAC), stochastic (occupant) and probabilistic (weather) elements, resulting in both inaccuracy [18,19] and uncertainty [9,20]. Software limitations, input parameter and weather data inaccuracy compounded by difficulties in capturing how exactly a building