Comparative Analysis of Protocols Used in Measurement and Verification of Energy Performance: Dealing with Practical Issues of Data Availability and Granularity in a UK School Building

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Abstract

Validation of energy models is an important aspect in ascertaining confidence in using these models for applications such as evaluating the scope of Energy Conservation Measures (ECMs). This paper reports of calibration of an energy model of a school building in the UK using various validation methods being used in the industry. During this process the paper looks at design stage performance projections and subsequently various causes of performance gap in the building. It also reflects on practicalities of data collection such as shortcomings in the metering strategies that could be addressed for model calibration.

Introduction

While many energy performance assessments related to new and existing buildings are carried out with uncalibrated simulation models. Measurement and Verification (M&V) protocols provide a framework to validate calibrated energy simulation model so that it is fit for applications like ECM evaluation, optimisation of building system controls and identification of underlying performance gap issues.

During construction of a non-domestic building in the UK, Simplified Building Energy Model (SBEM) or Dynamic Simulation Method (DSM) compliance modes are generally created to assess the energy performance of the building as part of the UK Building regulations compliance, Building Regulations Part L reports at RIBA Construction stages 2, 3 and 4 (RIBA, 2013). While Part L model results are not intended as predictions of energy use but are sometimes mistakenly used as such. CIBSE TM54 provides a more robust framework to overcome this (CIBSE, 2013). For operational stage assessments, there are various approaches practiced for predicting and analysing energy use. Some of the commonly used validation methods are the UK National Calculation Methodology (NCM) adapted for Energy Efficiency Finance (previously known as 'The Green Deal') (BRE, 2012) (Lewry, 2013), ASHAE Guideline 14 (ASHRAE, 2002) or International Performance Measurement and Verification Protocol (IPMVP) calibration method (EVO, 2012), and BS EN 15603 method (BSI, 2008). Based on the application they have their own advantages and limitations.

Demanuele et. al. (2010) used sensitivity analysis with site visits of 15 schools across the UK and found that operational issues with systems and occupant behaviour have a major influence on energy performance. Using post occupancy data and dynamic thermal simulation Burman et. al. (2012) analysed and benchmarked energy performance of a UK school building, focusing on the design and post occupancy stages. The study uncovered the major sources of discrepancy between simulation and actual performance as: design stage assumptions, calculation method limitations (UK NCM) and operational issues ('unknowns' at design stage). Reviewing several studies for UK schools, van Dronkelaar et. al. (2016) suggest the performance gaps in schools are likely due to underspecified assumptions for equipment and occupancy hours.

The aim of this paper is to evaluate a case study UK School Building and assess how design stage calculations carried out for Part L compliance compare to a more robust CIBSE TM54 method. Furthermore, by analysing the various protocols for validation of calibrated energy models, the paper also identifies the intended vs actual performance issues identified in the building. The main objectives of the paper are:

1. To compare the Design Stage predictions for Part L compliance with a CIBSE TM54 model and the actual building performance.
2. To identify the causes of the performance gap in energy and Indoor Environmental Quality (IEQ)
3. To compare various approaches to validation of energy models that are being used in the industry.
4. To explore how practicalities of data collection such as shortcomings in the existing metering strategies could be addressed in the calibration process (e.g. statistical post processing of the available site-level and building-level energy data).

The paper first looks at issues of performance gap in UK schools and calibration and validation of energy models. Then, the case study building's performance gap and its causes are identified and its energy model is validated. The paper concludes with lessons regarding design stage modelling and data required for calibration and model validation, along with reflections on the performance gap and its underlying root causes in the case study.

Background

Performance gap in schools

CarbonBuzz is a collaborative research platform designed to engage the stakeholders to voluntarily provide design energy use and actual energy use side by side to help users close the design and operational energy performance gap in buildings (Kimpian & Chisholm, 2011). It reports an average 114% increase in operational CO_2 emissions compared to design estimations for school buildings. While this provides evidence for energy performance gap, much of the design stage data provided are based on Building Regulations compliance or Energy Performance Certificate (EPC) calculations. This demonstrates the prevalence of interchangeable and contentious use of the outcomes of Building Regulations compliance calculations or EPC calculations as design predictions for buildings (Burman, et al., 2012).

Moreover, energy performance gap alone does not capture the full impact of buildings on occupants and the wider environment. The 'total' performance gap may also impact occupant wellbeing and indoor environmental quality (IEQ) (Shrubsole, et al., 2018). Specifically, for schools, there is a strong association between IEQ (temperature, ventilation rates and indoor CO_2 concentrations) with cognitive performance (Wargocki & Wyon, 2013). Traffic related external pollutants such as Particulate Matter and nitrogen dioxide are linked to adverse health impacts as well. While CO_2 levels provide a first indication of exposure, indoor levels of traffic related pollutants need to be considered separately (Chatzidiakou, et al., 2014).

Performance prediction and validation approaches

Under the Energy Performance of Buildings Directive (EPBD), National Calculation Methodology (NCM) was developed for the UK non-domestic sector to facilitate Simplified and dynamic calculation tools (SBEM and DSM) to be been used for the Building Regulations compliance calculations. These methods calculate energy use under standardised operating conditions comparing the calculated energy performance of a building to the energy performance of notional or reference buildings, depending on the assessment type. Despite the relativist nature of these calculations, these NCM based calculations are sometimes used to project absolute energy performance of buildings (Burman, et al., 2014). One of the biggest drawbacks of using NCM in projecting energy use of a building is that it uses standard inputs for key variables such as the hours of operation and also excludes energy uses such as small power, external lighting, lifts etc. To address this, CIBSE TM54 approach for estimating operational energy use at the design stage accounts for all end uses in the building alongside realistic operating patterns and behaviour (CIBSE, 2013).

In the context of using calibrated energy simulation for evaluating building performance, model validation approaches in various M&V protocols generally focus on quantitative requirement for baseline model and goodness of fit of the simulation model results. Three approaches to thermal calibration are briefly reviewed here.

NCM framework for energy efficiency finance: In this approach (previously known as 'The Green Deal' for non-domestic buildings), a baseline model is developed using Simplified Building Energy Model (SBEM) or Dynamic Simulation Method (DSM) and then the model is updated by changing the standardised operating conditions assumed under the NCM for a closer definition of the building (e.g. occupant density and schedule, equipment gains, temperature set points and ventilation rates). Further, several multipliers are derived to adjust the outcomes of the models to accommodate the effect of building management and maintenance. Finally, actual data on annual consumption per fuel and the reliability of the data are used to calculate a normalisation factor that will be applied to the modelling results (BRE, 2012). The simplicity of methods used in NCM calculations limit the detail and accuracy of estimation of performance of many processes. Also, there is no criteria set for the accuracy of thermal models in relation to actual energy consumption. Moreover, an unbounded and unexplained normalisation factor provides an avenue for having unsubstantiated factors to make the predicted results closer to actual performance (Burman, et al., 2014).

ASHRAE Guideline 14 approach: This Guideline provides detail instructions for Measurement of Energy and Demand Savings in buildings including a whole building calibrated simulation approach (ASHRAE, 2002). It is also in line with the IPMVP Option D: Calibrated Simulation (EVO, 2012). The framework provides step by step method to fine tune the model to reflect the as built status and operating conditions and the criteria to check calibration accuracy either at hourly or at monthly accuracy. Calibration is done over one year of steady mode of operation. The calibration criteria used are based on Coefficient of Variation of the Root Mean Square Error (CVRMSE) and Normalised Mean Bias Error (NMBE). Detail operational information should be collected during site surveys and by measurements to calibrate a thermal model. CVRMSE of <15% and NMBE of <5% must be achieved for monthly calibration. This method provides a criterion to assess the success of calibration. However, if the operation stage information is limited, it is not possible to procedurally evaluate, with high confidence, the value of inputs to progress with calibration. At that stage modeller needs to rely on estimations to meet the criteria.

BS EN 15603 approach: This energy performance of buildings standard includes a procedure for validation of the building calculation models (BSI, 2008). The validation process enables the attainment of a higher level of confidence in the building simulation model and input data, compared to the abovementioned methods, by probabilistically comparing calculated data with actual energy use. The main difference is that the method allows for determining the confidence interval arising from uncertainties for all input data. The input data that cannot be assessed are to be taken from inference rules, national references or standards. Under this procedure, validation is carried out based on annual energy performance. No specific criteria are provided in the standard to define reasonable consistency and, therefore, this should be determined on a case-by-case basis.

Data monitoring and calibration

Minimum level of data needed for any calibration exercise is operational energy use for all fuels, obtained from metering strategy or utility data, for a period of at least one year to have reliable results. More detailed monitored data including disaggregated energy use can further improve the calibration accuracy and confidence in the calibrated simulation. This information can be taken from audits (walkthrough and detailed) and short term and long term disaggregated end use monitored energy data (Reddy & Maor, 2006).

Detailed energy use data can be used to create detailed profiles of energy simulation output results and increase confidence in accuracy. However, data quality issues sometimes require statistical post processing to create these profiles. Also, monitoring of some IEQ data streams can provide evidence for detailed building operational profiles. Temperature data can provide evidence of set point temperature being maintained in the spaces. Similarly, CO_2 and $PM_{2.5}$ concentrations can provide details about occupancy patters, ventilation and infiltration rates (Kapalo, 2013), (Parsons, 2014), (Batterman, 2017).

Methodology

The paper assesses the practicality of various model validation approaches used in the UK by applying them when calibrating a case study building.

1. Initially, we develop a design stage model as per CIBSE TM54 protocol and compare the results with the Building Regulations calculation (Part L).
2. Then analyse the building's current energy use and performance deviation factors based on comparison of design stage predictions (Part L and CIBSE TM54) and post occupancy operations data. Post-occupancy data and information were collected by regular measurements, observations and semi-structured interviews with the facility managers at monthly or bimonthly intervals over a period of one year. Disaggregated monthly energy use profiles were created with statistical post processing to fill the gaps in the collected data using trends from site level half hourly energy and IEQ data.
3. Next, using the post-occupancy data along with IEQ (temperature, lighting and CO_2) data from typical zones the simulation model was calibrated by fine-tuning building operational input characteristics.
4. The calibration model was first validated using ASHRAE Guideline 14 / IPMVP protocol.
5. Subsequently, the model was also validated using the BS EN 15603 approach which accounts for uncertainty boundaries of input parameters values.
6. The paper concludes with reflections on design projection of energy performance, the practicality of data collection and compliance with validation methods to generate useful calibrated models.

Case study building

The case study building is a secondary school and sixth form with academy status, located in London, England. The school went under redevelopment in 2014 with six new buildings created and a couple of existing ones being retained. In the paper we focus on one of the new teaching buildings, 'Building 4'(Ground + 3 floors, ~5000 m^2).

The external envelope is made of pre-fabricared concrete panels, assembeled at site. The daily occupancy for students on Mondays is from 8:35am to 2.55pm, Tuesday to Friday it is 8:35am to 3:50pm and on Saturday the occupied time is from to 9:10 am to 13:00 pm. While these are timings for school occupancy, individual spaces within the building are not occupied the whole time. They follow the classroom time tables provided to the authors by the school management.

Figure 1: Case study School Building

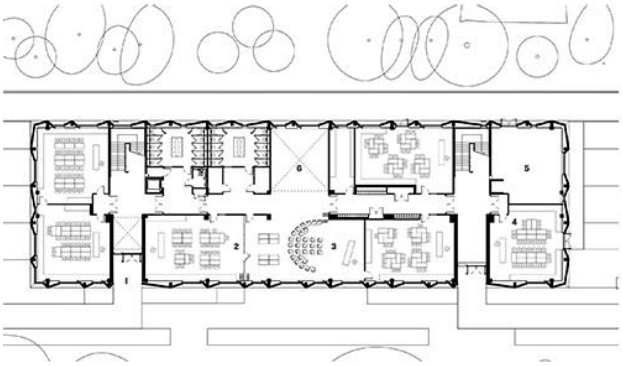


Figure 2: Typical floor plan

Heating is provided through a centralized plant for the entire campus via pressurised low temperature hot water (LTHW) system. There is a biomass boiler (heating seasonal efficiency: 0.75) for annual DHW demand and two gas fired boilers (heating seasonal efficiency: 0.84) to provide remaining heat and as a backup for biomass boiler. Rooms with high ICT and server rooms have Variable Refigerent Flow (VRF) systems that provide both heating and cooling (heating/cooling seasonal efficiency: 1.47/3.80). Comfort cooling is not provided to any other spaces. Mechanical ventilation system is with heat recovery (Heat Recovery Efficiency: 0.75) via centralized roof mounted AHU plant. Wall mounted diffuser/grill are used to distribute the supply air. The ventilation system is controlled via Building Management System (BMS) system based on the installed carbon dioxide sensors in each room.

Gas use in the facility is metered at site level and is recorded in utility bills at periodic levels. Each building has its own heat meter which is linked to the BMS system. The mains electricity meter records half hourly electricity use data at the site level which is available from utility supplier. At the building level, disaggregated energy use for lights, small power, lifts, server, pumps and fans can be read through the BMS.

As per the design stage documents provided by the design team details about the building fabric and technical cum operational parameters of building services are listed in the Table 1.

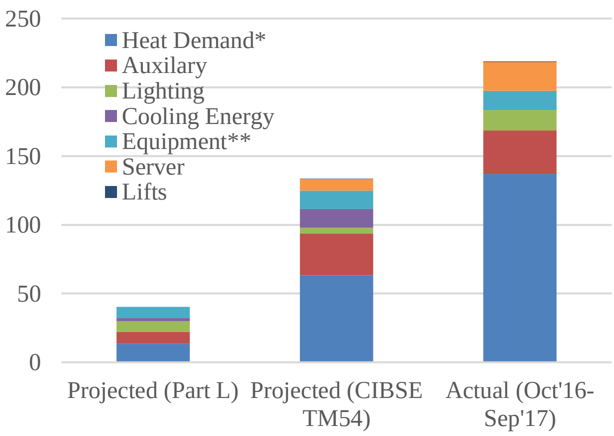
Table 1: Building 4- Fabric, operations and load details

Fabric Element	**Details**
Walls	U-Value = 0.25 W/m²K
Windows	U-Value = 1.60 W/m²K, G value = 0.26, VLT = 0.49
Roofs	U-Value = 0.20 W/m²K
Airtightness	5 m³/hr/m² @ 50Pa
End Use	**Details**
Heating	Set point: 20°C; Set back: 15°C (3 hours preheating)
Cooling	Set point: 23 °C
Mech. Vent. with HR	Rate: 5 l/s/person to 12 l/s/person (CO_2 control); SPF: 1.8W/l/s; HR eff: 0.75
Int. Lighting	Loads: 12 W/m² – daylight integrated;
Small Power	Classroom Load: 20 W/m² Offices Load: 10 W/m² ICT Areas Load: 50 W/m²

Building performance

Design stage and operational energy projections

The design stage projection of energy performance was done as a part of Part L Building regulations compliance documentation at RIBA Stage 3. The calculation, carried out for the whole facility, reported annual energy use projections for each building separately. Figure 2 compares the Projected (Part L), Projected (CIBSE TM54) and Actual Energy used for Building 4.



*Heat demand used instead of heating energy; **Equipment includes cooling and heating energy use of VRF system in some zones.

Figure 3: Comparison of projected (Part L), projected (CIBSE TM54) and actual energy use of Building 4

Disaggregated annual operational energy use of Building 4 (Heating Demand, Lighting, Equipment, Auxiliaries, Server and Lifts) was available from the BMS readings taken over a period of one year (October 2016 to September 2017). Heat demand from a heat meter was recorded by BMS instead of the building's heating energy use as there is one central boiler for the entire facility. Also, the three spaces (ICT classrooms and server room) which have cooling and heating provided by VRF systems had their conditioning energy use accounted for in the small power energy.

There is a significant underestimation of energy use in the design stage Part L calculations. The major reason for it is that these calculations primarily aimed at benchmarking use NCM default power densities for pumps and some of the key energy use areas such as equipment, server and lift are not included in the total projections. Moreover, the occupancy and operational profile of the building is also calculated based on NCM defaults which, in real scenarios, can be significantly different. NCM profiles assume all system are shut down during half-term breaks and school holidays. The methodology proposed in CIBSE TM54 provides an approach for estimating operational energy use at the design stage, accounting for all end uses in the building alongside realistic operating patterns and behaviours.

Based on CIBSE TM54 methodology, the design stage projections of energy use for Building 4 were recalculated. While CIBSE TM54 calculation result is not very close to actual energy use, it is significantly better than Part L calculations. Based on observed occupancy patterns and loads, a closer estimation of actual energy use is possible by this method. The remaining gap is predominantly caused by technical issues which are explored in the next sections. At design stage, to account for variations in design and operation of the building, CIBSE TM54 also recommends developing scenarios based on estimated variability of various inputs to inform the design team about realistic best, worst and most likely energy use patterns.

Building's monthly operational energy performance

Obtaining disaggregated, regular and high granularity data for any building can be a very challenging task. While logistics of extensive monitoring is always a factor, practical issues during sites visit such as access, regularity and data quality are also encountered. For this school building, all data for Building 4 was not available directly. While disaggregated electricity use data for Building 4 was available from BMS system, it could only be recorded during site visits which happened at varying time intervals. Site visit readings were taken every one or two months, throughout the year. The high granularity electricity use data was available at half hourly intervals from the utility supplier, which was at the facility level with no disaggregation. In order to create monthly energy use profiles for Building 4, trends for facility level half hour electricity use data was used to proportionally redistribute Building 4's energy use data recovered from the BMS system. This way the BMS readings were appropriately distributed as per weekdays, weekends, term times and holidays. This method assumed that the whole facility's energy use trends are similar.

Heating energy use, being supplied by gas fired boilers, did not have high granularity use profiles. Utility supplier data at facility level was available at irregular intervals spanning one to two months and Building 4's heating use, recoded by a heat meter during site visits was also at varying time intervals. Therefore, to create a heating demand profile for the building at monthly level, the heat demand recoded between site visits was proportionally distributed based on daily heating degree days and further, redistributed for weekdays, weekends, term times and holidays (using the trends from electricity use data). Figure 4 shows Building 4's monthly electricity use and heat demand profile.

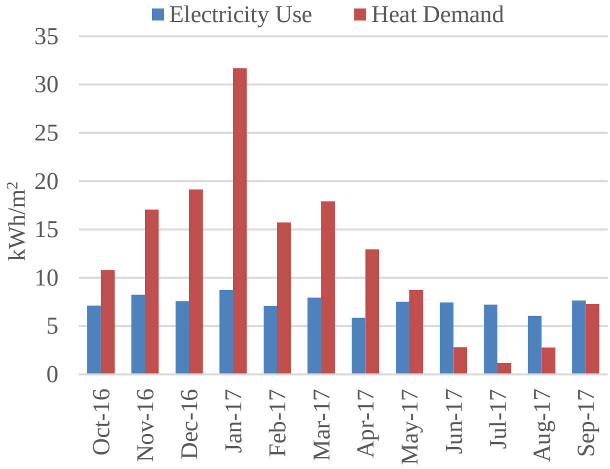


Figure 4: Actual electricity use and heat demand of Building 4

Building's operational IEQ performance

Among various IEQ parameters being monitored in the building, initial findings regarding thermal comfort and air quality show underperformance in some zones. To evaluate the overheating risk of mechanically ventilated buildings, a threshold 26°C is specified by BS EN 15251. While most of the spaces do not suffer from overheating, rooms on the south façade, lacking solar controls (blinds/shades) suffered from high heat gains and overheating problem in those spaces can be regarded as severe. Figure 5 shows indoor temperatures in a south facing room on the second floor during a hot spell in month of June.

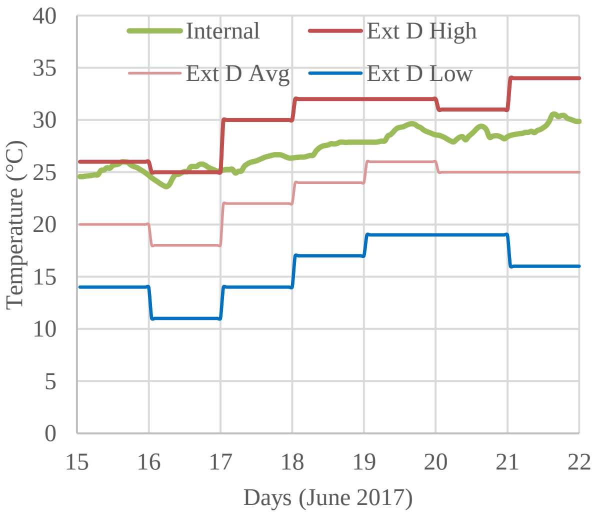


Figure 5: Indoor monitored temperatures in a classroom during a hot summer week

As the building is mainly mechanically ventilated based on CO_2 control, most of the spaces in the building had adequate fresh air being supplied to the building during occupancy hours. However, it was noticed that in one of the other building (Building 3, it is identical to building 4 in terms of design and services) a malfunctioning supply fan led to indoor CO_2 concentrations in access of 1500ppm throughout the day in regularly occupied spaces. Also, there were increased indoor $PM_{2.5}$ concentrations observed in those spaces because of ingress of polluted external air through the windows.

Deviation from design intent

Post occupancy site visit observations, interview with the facility managers and analysis of IEQ data revealed many deviations from the design stage intent which are probable causes of performance gap.

Occupancy: Occupancy in classrooms in schools during term time is as per class timetables. It is observed that all spaces are not occupied throughout the day. Any given space is occupied only 60-70% of full working day. Therefore, this variability in occupancy and subsequent operation profile for internal loads need to be accounted for. During term breaks the school is not completely shut; there are extra-curricular activities and events that take place, especially during the summer holidays. As per half hourly load profiles, the site level day time electrical demand during holidays reached around 100kW when the baseload was 50kW. This was verified by onsite observations. Monitored CO_2 data of some typical spaces also showed small spikes during term breaks showing low level occupancy beyond normal hours of use.

Equipment and lighting operations: It was seen during site-visits that lights in the circulation areas were switched on even after the end of the classes. Also, many computers were found to be 'on' when the computer rooms were not occupied. These provide anecdotal evidence of suboptimal operation.

HVAC system equipment: Biomass boiler was designed and installed to provide maximum 50% of the total DHW demand with the intent of decarbonizing energy use, as a policy measure by local council. However, the boiler was never used by the facility managers, citing practical and logistic issues of using biomass as fuel. The Specific Fan Power in AHU specification sheets was 66% high than the values used in design stage estimations.

Set point temperatures: Indoor temperatures monitored in some sample spaces showed that during the winter season the indoor temperatures maintained throughout the day were in the range of 21-22 °C and sometimes a little higher. Also, the temperatures were often observed at these levels during unoccupied times and term breaks as well. The building is sufficiently air-tight and has high performance fabric. It is observed that heating system is operational during unoccupied periods and maintains elevated temperature; the pre-heated air from the mechanical ventilation system also increases the indoor temperatures. This can be seen in Figure 6 which shows indoor temperature and CO_2 concentrations on a typical winters day (External maximum and minimum temperature = 9°C and 4°C).

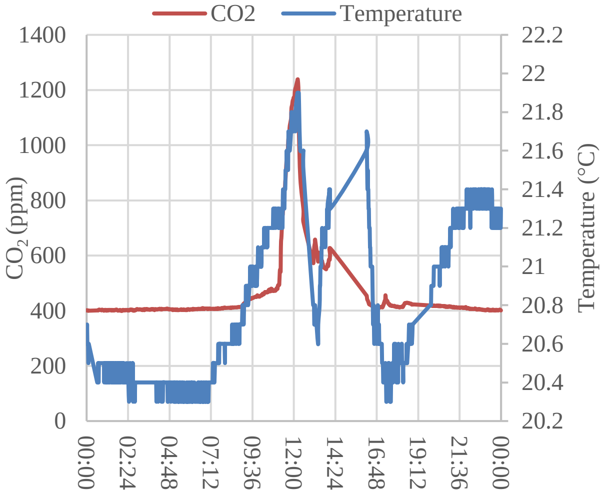


Figure 6: Indoor monitored temperatures and CO_2 in a classroom during a typical winter day

HVAC system operation: The design intent of boiler being turned on three hours before the classrooms were occupied until the end of classes, was not happening at the building. During the site visits, it was noticed that the system was on even after the end of the classes. Moreover, the indoor monitored temperature data (Figure 6) shows that building heating system and mechanical ventilation systems are functional during unoccupied hours as well both during term time and during holidays. Conditioned fresh air is provided in the building by a centralized air handling unit. During out-of-hours and half-term breaks, when there is very low occupancy, the fresh air and heating is served to multiple zones. Moreover, the supply fan during unoccupied times is operating at 30% to 40% of its nominal speed (based on BMS observations).

Calibrated model validation

To understand and validate the performance gap findings, a calibrated model was created in DesignBuilder Software which is an interface to EnergyPlus. The monthly calibration was validated as per ASHRAE Guideline 14 criteria. ASHARE Guideline 14 monthly calibration criteria is CV(RMSE) <15% and NMBE<±5%. To calibrate the simulation model for Building 4, changes to some of the design stage inputs were known, such as occupancy patterns during term times as per school timetables and changes to equipment and lighting loads. However, some inputs could not be estimated precisely, such as set-point temperatures, occupancy during off term times and suboptimal out of hours operation of lighting equipment and ventilation systems. The uncertainty in these inputs arise because their deviations were either based on spot observations or trends observed from short term secondary data. Central estimates of these deviations were used to create an ASHRAE Guideline 14 validated model. Figure 7 and 8 show calibrated electricity use and heat demand for Building 4 respectively. The calibrated model result had a CV(RMSE) and NMBE of 4.6% and 1.9% for electricity use and a CV(RMSE) and NMBE of 5.6% and -2.6% for heat demand.

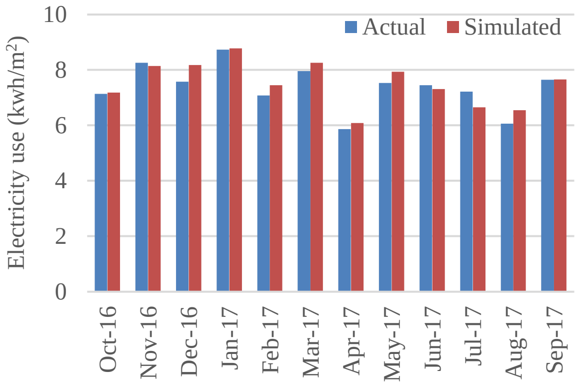


Figure 7: Simulated vs actual monthly electricity use of Building 4

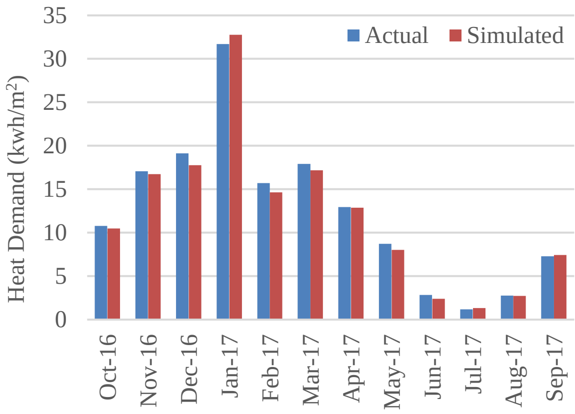


Figure 8: Simulated vs actual monthly heat demand of Building 4

For the uncertain input parameters (set-point temperatures, occupancy during off term times and suboptimal out of hours operation of lighting equipment and ventilation systems), there is a lack of direct regularly monitored value throughout the calibration period. Therefore, as their deviations from design intent is based on spot observations and secondary data trends. Realistically, there can be numerous possible permutations which can create a validated ASHRAE Guideline 14 model. For example, the gap in heating demand can be closed by increasing either indoor set point temperatures (observed by IEQ measurements of some typical zones) or mechanical ventilation supply (based on BMS observations during site visits) or both. Therefore, based on limited data, even when ASHRAE Guideline 14 are met, it is not possible to deterministically identify the exact deviations in both these areas.

A probabilistic approach is more suitable to represent these calibration results. BS EN 15603 provides a probabilistic approach in which the uncertainty on inputs is included to provide a probabilistic annual energy use result. Similar to that, in monthly calibration, the observed deviations inputs can be factored in using probable upper and lower values to create monthly energy use range. This result can be presented with confidence bands without deterministically calculating the exact values for unknown input areas. This methodology is applied to the partially calibrated model.

For each of the uncertain deviation inputs, a value range is defined to create the best and worst scenarios. Table 2 lists the deviation areas observed and their range of values. Figure 9 and 10 show the calibrated simulation results with uncertainty. The bars indicate the maximum and minimum range in which monthly energy use would lie in due to the variability in the input. The actual energy use in that month is marked by the dot. This diagram suggests that the actual value of these inputs lie somewhere in between. More monitoring evidence is required to further narrow down these ranges.

Table 2: Deviation areas and its ranges

Input area	Range	Remarks
Heating set point	20°C to 23°C	Temperatures observed in some typical spaces
Occupancy Sat and in term breaks	Nil to 20%	On site observations and CO_2 data
Common area lighting	Off to 100% (occupied hrs)	On site observations
MV Supply during unoccupied times	0.2 to 0.5	On site observations from BMS data

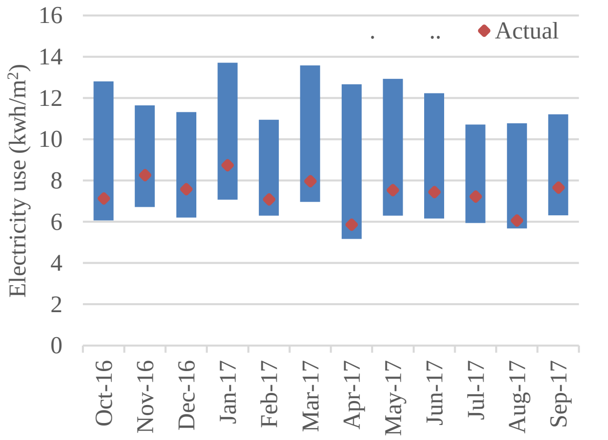


Figure 9: Probabilistically simulated vs actual monthly electricity use of Building 4

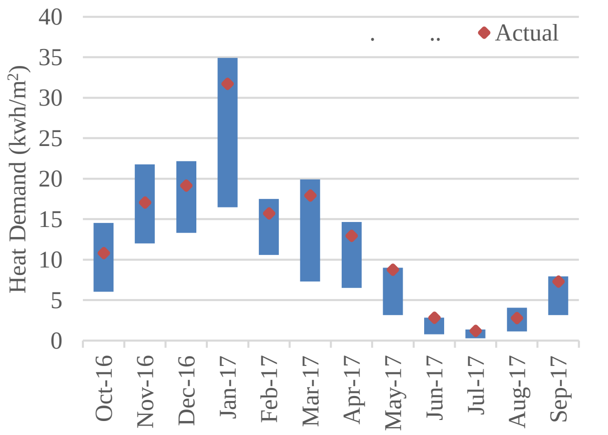


Figure 10: Probabilistically simulated vs actual monthly heat demand use of Building 4

Discussion

Design projections of energy performance: Building Regulation compliance models use simplified calculations intended to ensure that minimum regulatory requirements are met and to benchmark energy use for entire building stock. Using these results as a projection of energy use of a building is not appropriate as it generally leads to significant underestimation. The approach for estimating operational energy use at the design stage should be as per CIBSE TM54 guidelines, accounting for all end uses in the building alongside realistic operating patterns and occupant behaviour.

The case for 'total' performance: Most of the energy performance gaps were due to suboptimal operation and irregular maintenance of building systems. This was partly due a centralised system design and lack of user-friendly BMS controls to manage it. Besides this, procurement/handover stage issues such as using less efficient fans, more small power equipment, and not using biomass boilers also contributed to the gap. There were also some IEQ issues observed in Building 4 relating to summer time overheating. In Building 3, poor indoor air quality was observed due to malfunctioning mechanical ventilation system. To deliver a high level of 'total' performance, IEQ needs to be addressed simultaneously with energy.

Data availability and granularity: Calibration of any building requires detailed, regular and granular data about the building performance and operations. However due to practical reasons such information is not always available. In such cases secondary data analysis (e.g. in this case using facility level granular data to infer trends) and IEQ data, along with site visit observations and interviews can help in identifying the appropriate values for both creating end use profiles and estimating building operational settings.

Validation of these calibrated models: ASHARE Guideline 14 criteria accommodate uncertainty in model predictions. But as the criteria are represented as statistical indices, they fail to capture that multiple solutions may exist that do not necessarily reflect the real performance. A modified BS EN 15603 approach, while not necessarily improving on calibration quality, provides a way to determine the confidence levels in the validated model. However, it should be noted that BS EN 15603 method requires significantly more monitored and observed data to obtain appropriate range of variation and longer computational time to model all scenarios. A model could be validated by ASHRAE Guideline 14 criteria with much less input and computation time, and therefore this might be a more practical option for the industry.

Conclusion

The work highlights many useful lessons that can potentially be used to project energy simulation results at design stage and validate a calibrated operational stage simulation results. The findings regarding the deviation from design intent might be specific to the case study, specially the technical issues regarding building systems, but the larger issue of optimal operations and maintenance of building systems for better energy and IEQ has applicability for other schools in general. The changing trend of schools' occupancy patterns in general, beyond regular school hours and term times needs to be considered when estimating performance.

At design stage it is important to project energy use accounting for all end uses and probable variabilities that might occur during operations. For calibrating an operational stage model statistical post processing of secondary data sources can help in overcoming shortcoming in directly monitored data. Validation of energy use predictions of simulation models by probabilistic methods is more appropriate, but requires more data and computational effort compared to using deterministic statistical indices. Lastly, when assessing performance gap issues, addressing Energy & IEQ performance gaps is important so as to move towards an assessment of 'total' performance and to ensure that energy efficiency is not achieved at the expense of IEQ and other aspects of building performance.

Future work

Further extension to this method is a BS EN 15603 cum ASHRAE Guideline 14 method in which multiple simulation runs are done while probabilistically varying input ranges and the results of all scenarios which meet the ASHRAE Guideline 14 criteria are presented in box and whisker plots.

Acknowledgements

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