Using model calibration to develop a measurement and verification framework for managing the energy performance gap in buildings

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Abstract

To deal with the concerns regarding the energy performance gap, detailed operational performance assessment of buildings is necessary to identify and address the root causes of the gap. In this paper, we demonstrate, via a case study of an office building, the use of a new framework based on calibrated energy models to find and validate deviations of actual building performance from its design intentions. The framework separates the effect of (i) operating conditions that are driven by the building's *actual* function and occupancy as compared the design assumptions, and (ii) the effect of technical issues that cause underperformance.

As the identification of issues is based on energy modelling, the process requires use of advanced and well-documented simulation tools. The paper assesses the software tool requirements needed to deliver a calibrated model efficiently. We explore workflows using a new software platform to generate robust calibrated models for operational performance assessments. The paper's findings are a useful guide for building industry professionals to manage the performance gap with appropriate accuracy through a robust methodology in an easy to use workflow.

Keywords: Energy Performance Gap, Model calibration, Measurement and Verification protocols, Performance modelling.

1.0 Introduction

'Performance gap' is a commonly used terminology in the context of building energy consumption and is described as the difference between the actual energy use of the building and the energy use envisaged at the design stage [1], [2]. The key factors that contribute to the performance gap can happen at various stages [3]. While, design stages issues include incorrect design targets, specifications, detailing and modelling inaccuracies; shortcomings in construction practices, poor commissioning, lack of building fine-tuning in early stages of post-occupancy are also observed [4], [5], [6], [7], [8]. Handover and operation stage issues that cause the performance gap include inadequate user training, poor building management and maintenance, occupant behaviour issues and changes of building operating conditions (such as changes in space-time utilisation) [1], [5], [9], [10], [11]. Depending on the baseline selected, the magnitude of the gap varies considerably and as the in-use definition of the performance gap remains vague, sometimes use of an incorrect baseline or change in building use patterns can also be linked to building underperformance.

The aim of this paper is to accurately determine the energy performance gap in the context of measurement and verification (M&V) and to demonstrate a robust M&V protocol to effectively identify root causes of a building's performance gap using calibrated energy simulation models. To address this, the paper first looks at the background of the performance gap, the use of calibrated models in M&V, and the calibration process, including an assessment of simulation software requirements to deliver it. The paper then proposes a framework for M&V for managing performance gap issues. Finally, an application of this framework is provided via a case study building along with conclusions and lessons learnt.

2.0 Background

2.1 Performance calculations, gaps and their causes

To achieve the carbon emissions targets in the UK [12], various schemes have been implemented in the building sector that focus on improving energy efficiency and quantification of performance at the design stage.UK building regulations (Part L) and asset ratings energy performance certificates (EPCs) focus on design stage quantification of energy performance.

Energy performance calculations carried out to comply with Building Regulations in the UK, commonly referred to as 'compliance modelling', are based on default or standardised operating conditions and do not report energy use related to equipment (plug loads). These calculations, developed for performance estimations and comparisons across the building stock, often do not accurately reflect the actual operating conditions of a given building. However, due to the lack of understanding of intentions, limitations and finer details of the calculations used, there is a prevalence of interpreting 'compliance modelling' results as the projected energy use once the building is operational [13]. When these 'compliance modelling' results are compared to the 'actual energy use', the resultant performance gap is generally artificially inflated, leading to a 'perceived gap' [14].

In order to address this, CIBSE TM54 [15] set out a framework for the projection of energy performance of buildings at the design stage. In contrast with 'compliance modelling' this approach is termed as 'performance modelling' [3]. 'Performance modelling' asks the designers to calculate the 'design performance' by tailoring the operating conditions based on the client brief and expected performance of building systems, along with accounting for all energy end-uses. This more realistic calculation can be used as a baseline for a more appropriate performance gap assessment. The resultant gap of the performance modelling results and the actual energy use is a more appropriate quantification of the actual gap.

2.2 Energy model calibration process

Building performance simulation tools, used to calculate thermal loads and resulting energy use, are being improved for better predictive capabilities [16], [17]. While these help to close the actual gap, calibrating simulation models using monitored data can also be used to help understand the underlying performance issues [18]. Calibration can give insights into the operational inefficiencies and pinpoint underlying causes for the performance gap [6]. By reintroducing various design assumptions in a calibrated model, detailed analysis and quantification of the impact of individual causes of the performance gap can be assessed.

In a typical calibration process, two data sets are required:

1. Simulation input data which is often based on the design values and the operational assumptions. This is used to calculate the predicted performance.
2. Actual building specifications, operations information and metered data for energy and other environmental parameters from the monitoring of the building.

Then, depending on the objective of the calibration, the most influential parameters affecting the concerned outputs are selected for fine-tuning and are modified until there is a match between the simulation output and metered data. In order to develop calibrated models for diagnosing performance gap issues, a procedural and replicable step by step, evidence-based calibration methodology should be followed [19] [20] [21]. A calibration workflow is shown in Figure 1 and explained in detail in the text below.

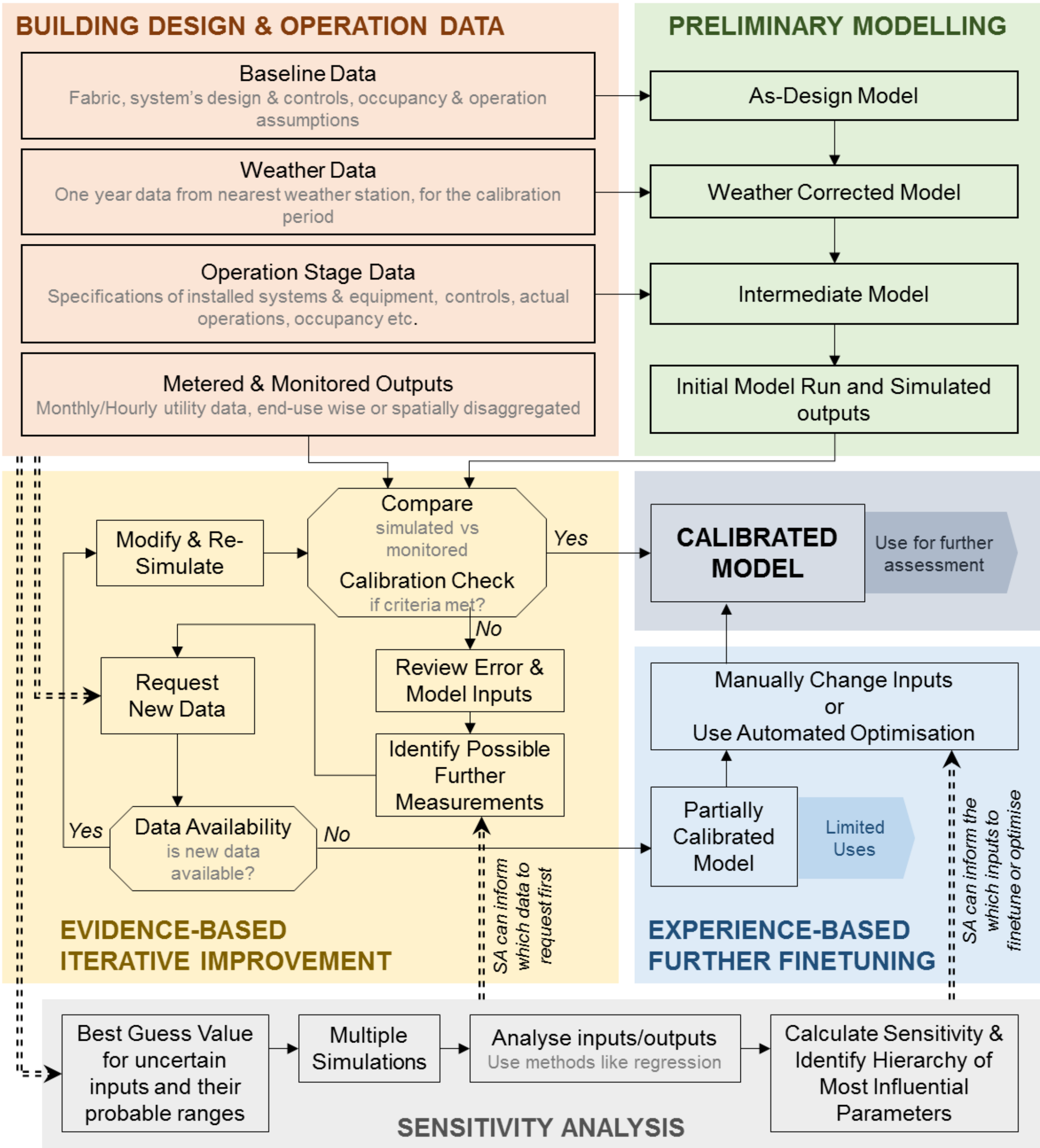


Figure 1: Model calibration workflow

In the first step to develop a calibrated model, an as-designed model is created using all the design stage input parameter values. In the second step, this as-designed model is modified using real weather data and readily accessible information of already identified changes to the building and its operations (collected from the building during audits, post occupancy evaluations, monitoring, metering etc.) to create an intermediate model. In the third step, simulation outputs of the intermediate model are compared against the metered energy use and calibration criteria (e.g. ASHRAE Guideline 14 [22]) checks are made. If the criteria are not met then, in the fourth step, iterative improvements are done by obtaining new operational data from the building until the criteria are met or no further data is available. If no more data is available, then only a 'partially-calibrated' model is possible, based on the empirical evidence. To meet the calibration criteria, further fine-tuning of unmeasured inputs, has to be experience based, done by either user estimation or an automated optimisation processes within user defined parameter values.

Uncertainty analysis (UA) can help to identify the impact of input uncertainty on the outputs and subsequent sensitivity analysis (SA) of simulation outputs can help to identify the most influential simulation input variables. In the calibration process, SA can be used to determine the sequence of input data for iterative changes either at evidence-based or experience-based stages of fine-tuning.

2.3 Simulation tool requirements for model calibration

Identification of energy performance issues in buildings using calibrated energy modelling, requires a systematic approach and the use of appropriate well-documented simulation tools. Some of the requisites for simulation tools to deliver a calibrated model as per the workflow suggested in Figure 1 are:

1. Handling of raw data from sensors, meters, building management systems, recorded at varying degree of granularity and quality, therefore, often requiring significant processing and cleaning.
2. Comparison of metered data with simulation results as well as use of monitoring data as input values in the simulations.
3. Statistical processing and visualisation of data for identification of trends, patterns and correlations.
4. Use of a well-documented and validated simulation engine, where underlying calculations could be reviewed. Also, the engine should be capable of modifying model inputs and its calculations between the runs, based on monitoring data, if necessary.
5. Integration of modeller's engineering expertise and analytical processes such as uncertainty analysis, sensitivity analysis and parametric optimisation in order to guide the assessments towards most probable issues in a fast and reliable manner.

A simulation toolkit which delivers on all the above points should also be packaged in a procedural and simplified workflow, tailored for industry users within a well-integrated interface. Figure 2 shows how components of a well-integrated operational assessment toolkit can deliver a calibrated model. The 'external data processor' component handles data from the building and processes it either for statistical analysis with simulation data in the 'results visualiser' component or for conversion into simulation input through the 'model input generator' component. The 'Real weather' component develops a bespoke weather file to ensure that the simulation results are calculated with similar external conditions as the monitoring data.

While these components can help to deliver a calibrated model, the other two components, 'uncertainty sensitivity analyser' and 'parametric optimiser', can help in better *understanding* of the building and enhance the modeller's capability to identify and tune the model deviations. The sensitivity analyser can help to uncover the sequence of model inputs to be fine-tuned or to be obtained from the building monitoring to make the calibration more robust. Integrating the sensitivity analyser with parametric optimiser's optimisation algorithms can help in quick identification of likely causes of model deviation, which can then be procedurally verified on site. To support this approach, such a toolkit is being developed which can supplement an existing building performance simulation software.

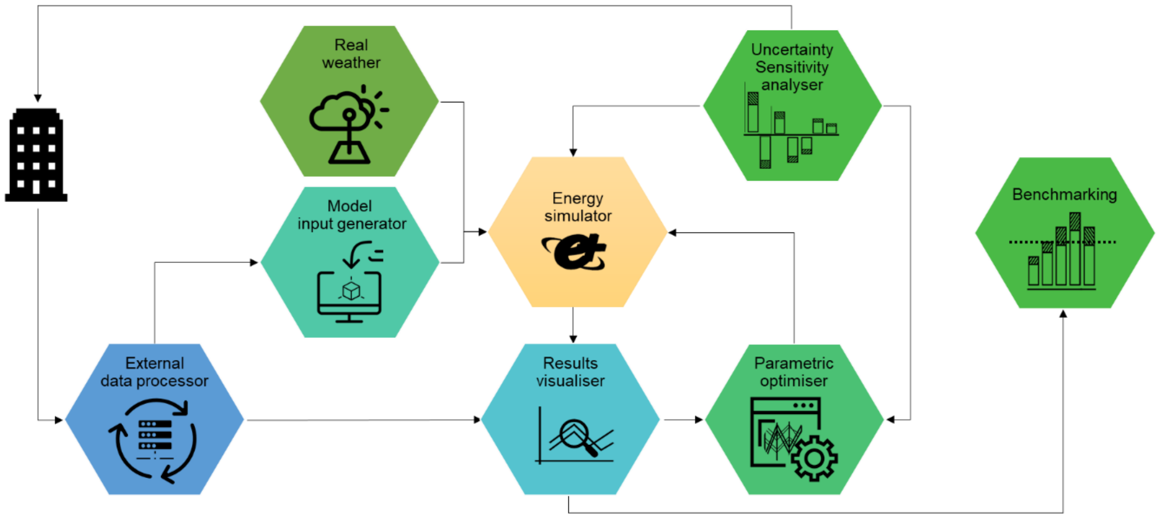


Figure 2: Components and workflow of a calibration toolkit

2.4 M&V protocols

M&V is the process in which planning, measuring, collecting, and analysing of data is undertaken for verifying and reporting a building's performance. In the context of using calibrated energy simulation in M&V, protocols such as ASHRAE Guideline 14 [22] and IPMVP [23] provide guidance on model validation approaches. These approaches generally focus on quantitative statistical requirements and goodness of fit of the simulation results with the actual simulation. They do not aim to provide a framework on how to create a reasonable simulation model or on how to calibrate it or on how to verify the performance issues.

While the 'performance modelling' guidance as per CIBSE TM54 [15] can help in better baseline model creation, it is primarily focused on the building's design stage. Problems during construction and operation stages, such as technical issues arising from poor workmanship and maintenance or issues arising from change in building operations and usage over time can contribute to underperformance but are not necessarily reflected in the model that is created using TM54.

In addition to potential discrepancies between actual operating conditions and design assumptions, during the building operation stage, performance evaluations often uncover several technical issues with building services and operations that are causes of the performance gap. However, in the absence of a robust M&V framework, it is not certain that the technical issues uncovered in a building reflect all or most of the key causes of the performance gap. It is likely that one or two key issues are identified during investigations whilst other potential issues are not uncovered. A robust energy performance M&V framework for operational stage in a building therefore must be able to identify and separate two key categories:

1. Deviations of operating conditions from design assumptions that are primarily driven by the building's function and its actual occupancy,

2. Technical issues in the building systems and their operations and maintenance that cause a performance gap between design intent and actual operation.

3.0 Method

To address the two key categories defined above effectively and comprehensively, a new modelling M&V framework to define the energy performance gap with reasonable accuracy is presented in Figure 3, which is based on the following principles:

1. Use of a systematic method of data collection to identify various discrepancies.
2. Use of a calibrated simulation model with actual operation to ensure that the uncovered issues can explain the actual performance with reasonable accuracy.
3. Through the calibration process, two sets of simulation model input data relating to the discrepancies in building performance should be identified and separated:

   3.1. Actual operating conditions required for the building to perform its functions,

   3.2. Technical issues related to construction, systems, commissioning, control, etc.
4. Once the computer model of the building is calibrated, a new performance baseline can be defined that reflects actual operating conditions (adjusted for 3.1 above) but assumes that the original design intents are met (technical issues identified in 3.2 above are corrected in the model and reverted to their design intents).
5. The technical energy performance gap is the difference between the measured value and the new baseline defined in point 4. It needs to be reduced to improve the building's operational performance.

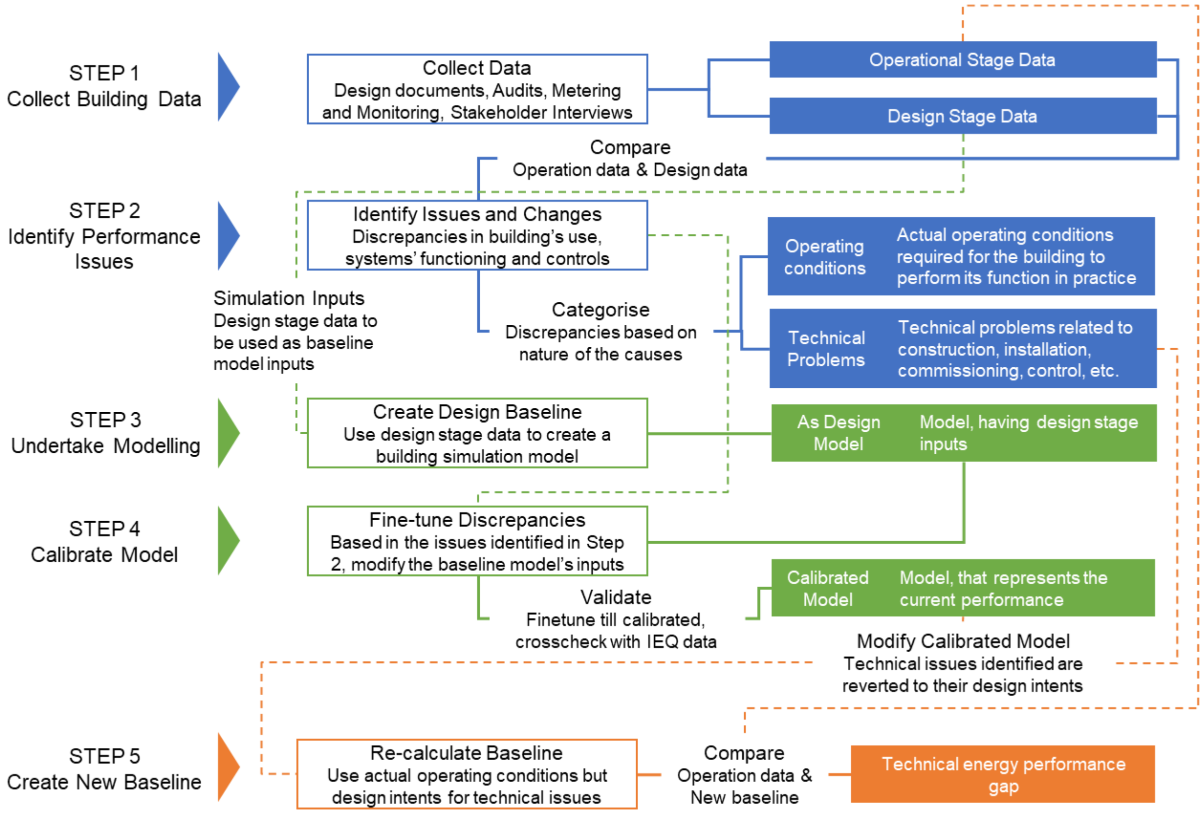


Figure 3: A new calibration-based M&V framework to identify performance issues

4.0 Case study application

The four storey case study office building (~6500 m^2) is located in South-West England. The building, which has open plan offices and meeting rooms, is designed to high energy efficiency standards.

4.1: Step 1: Design vs actual performance

Details about the building fabric, occupancy and technical / operational parameters of building services were collected for the design stage through design documentation and for the operation stage data during regular site-visits.

Envelope design: U-values: Walls - 0.15 W/m^{2}K; Windows - 1.4 W/m^{2}K; Roof - 0.15 W/m^{2}K; Ground - 0.15 W/m^{2}K; and airtightness: 5 m^3/hr/m^2 @ 50Pa.
Occupancy: The nominal design stage occupancy was 455 persons with a weekday operation schedule from 0700 to 1900 hrs, having diversity and some out of hours use. Weekends were assumed to be unoccupied.
Heating, Cooling, and domestic hot water (DHW) system: Heating is provided through heat pumps (designed to use rejected heat from the servers) with gas-fired boilers for additional need and as a backup. Under-floor heating and perimeter trench heaters provide heating to internal spaces. The heat pumps meet the cooling requirements for the server room and meeting rooms. If there is no heating demand, a free cooling chiller satisfies the chilled water requirements. Design stage assumed heating and cooling setpoints were 19°C and 23°C respectively.
Ventilation system: Natural only, supplied by automatic vents controlled based on CO_2 levels and temperature. Manually operable vents are also provided.
Lighting: Background lighting (LED) and task lighting (CFL) scheme; Controls included passive infra-red and daylight sensors.
Metering and Monitoring: Separate meters were present for all systems and end-uses to record the disaggregated energy use in high resolution.

The actual performance from Nov 2015 to Oct 2016, when compared to design data (Figure 4) shows that the building was not, operating at design intended levels.

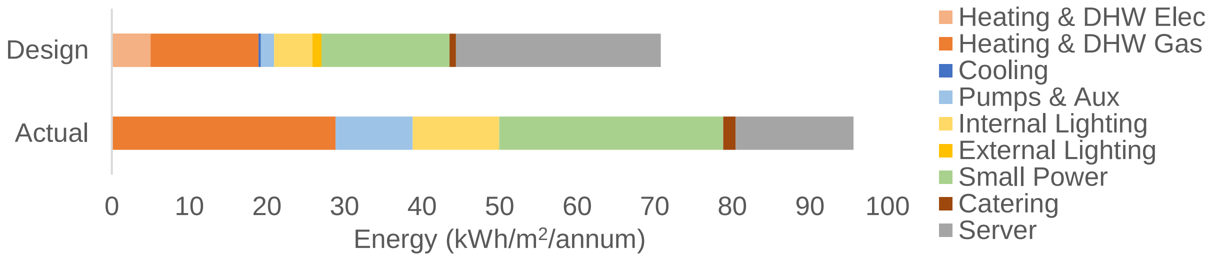


Figure 4: Comparison of building design and actual energy performance

4.2: Step 2: Performance gap issues

To investigate the performance gap causes, first the existing documentation was analysed and then specific potential reasons for deviations from design assumptions were catalogued through walkthrough audits, analysing meter data, and semi-structured interviews with facility manages and occupants. The performance gap issues identified were categorised into issues related to operating conditions and technical issues.

The main changes in operating conditions identified were:

1. The total occupancy of the building was about 25-30% higher and there were extended operation hours along with some weekend use of the building.
2. To manage the occupant comfort needs, heating set-point was maintained at about 21-22°C, higher than the design intent.
3. Departmental structure of the occupant organisation limited the scope of hot-desking and use of 'kill-switches' to shut off systems in unoccupied areas of the building during out-of-hours use.

The main technical issues identified in the building were:

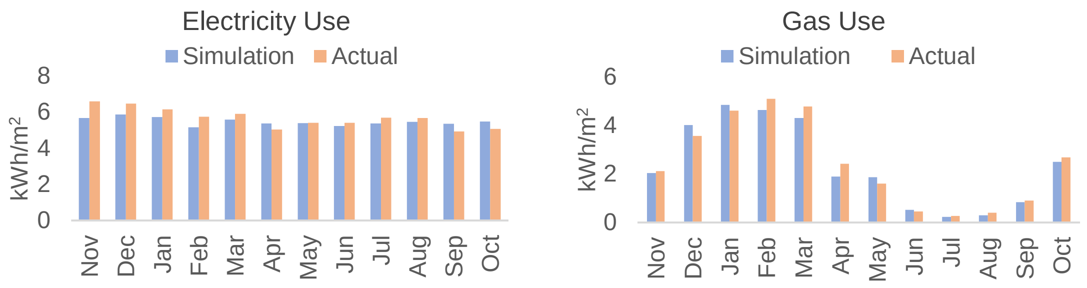
1. Technical issues with heat exchangers and the flow rates specification caused the heat pumps to malfunction.
2. Heating terminals sizing was not consistent with the low temperature heating flow required for energy efficient operation of the heating system.
3. Server loads were overestimated in design calculations. These had an adverse impact on heating efficiency as there was significantly less free heat available for the heat pumps.
4. Some of the ventilation control sensor malfunctioned and required a subsequent modification to the control strategy to overcome the system shortcomings.
5. Parasitic loads were identified when the building was unoccupied.

4.3: Step 3 and Step 4: Energy Modelling and Model Calibration

Using the workflow defined in Figure 1, a streamlined software toolkit was used which revolves around the 'DesignBuilder' software, an interface for EnergyPlus, along with spreadsheets to deliver the calibrated model. The simulation results of the baseline model and subsequent iterations were created in DesignBuilder and compared to the actual metered data, processed through spreadsheets, in the 'DesignBuilder Results Viewer' for compliance with ASHRAE Guideline 14 criteria. During the calibration process, sensitivity analysis and uncertainty analysis tools in DesignBuilder were also used to identify the most likely performance deviation factors and to check if their variation was able to account for the total performance gap. Figure 5 shows the calibrated results meeting the ASHRAE Guideline 14 monthly criteria (i.e. CVRMSE < 15% and NMBE < ±5%), which validate that the performance issues identified were able to account for most of the gap in building energy use. Further validation of the calibrated model was done against temperature data from a few zones. Figure 6 shows that the simulated and trends of zone temperatures closely follow the actual measurements, except during the weekends where there is a dip in simulated temperatures. However, these do return close to the measured values over the longer period. More fine tuning of the calibrated model could be done at this high resolution (hourly) to match these deviations but in the context of monthly calibration for assessing causes of the performance gap the current accuracy is deemed sufficient.

4.4 Step 5: Operational baseline and the associated performance gap

Changing the technical issues identified in section 4.2 back to their design intents, a new operational baseline was generated. Figure 7, described in detail in the discussion section, shows the various energy calculations and related performance gaps observed in the case study building. These form the basis of the new calculations



CVRMSE = 8.0%; NMBE = -3.7%   CVRMSE =12.5%; NMBE = -3.3%

Figure 5: Calibrated electricity and gas use (November 2015 to October 2016)

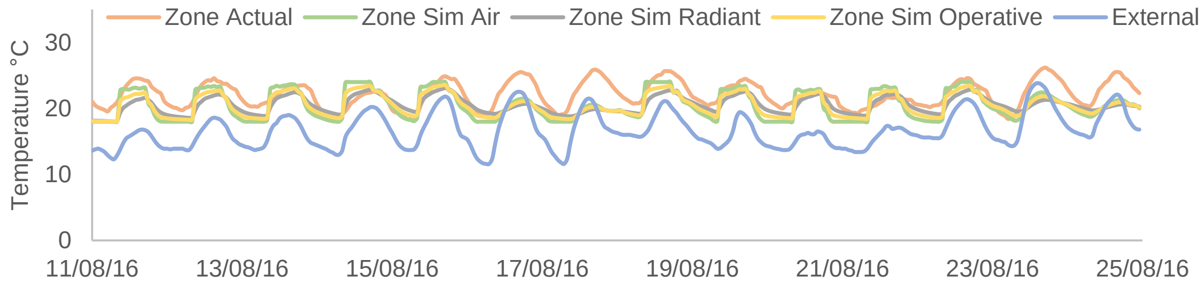


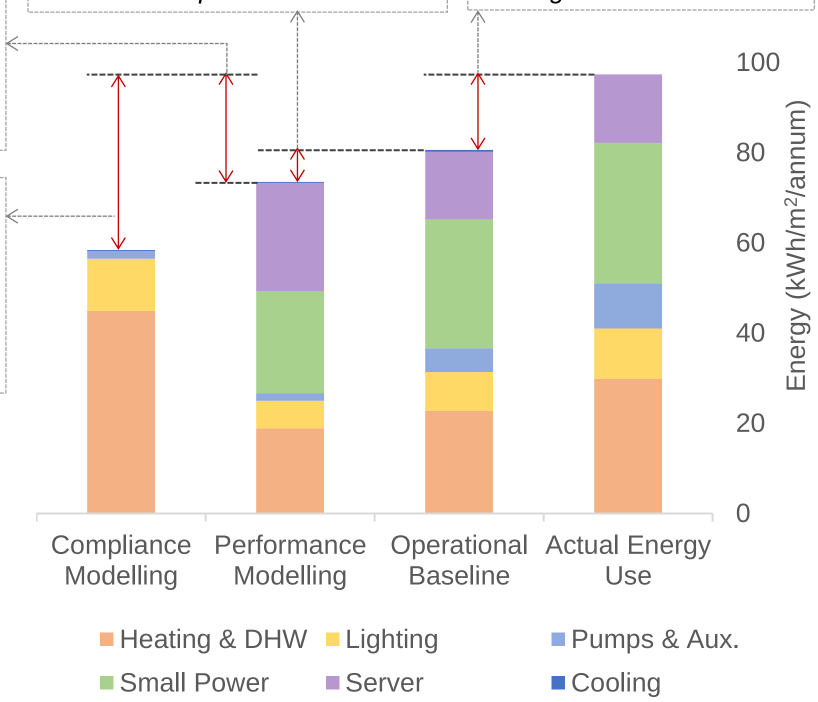
Figure 6: Hourly simulated and measured temperature profiles for typical days

Actual gap*: Gap between the performance modelling results done at design stage and the actual energy use which can be due to operational changes in building's usage and due to systems related technical and maintenance issues.*

Gap due to the ***changes in operational requirements*** *such as modification to occupancy numbers and patterns*

Gap due to the ***technical issues*** *identified with building systems and their running.*

Perceived Gap: *Misinterpreting compliance modelling results as predicted performance adds to the deviation calculated in actual gap leading to an inflated 'perceived' gap.*



Compliance Modelling*: The calculations done for regulatory compliance, for benchmarking across the building sector, don't factor in building specific operations and don't report all energy end-uses.*

Performance Modelling*: Design stage calculations, using building specific inputs and accounting for all end uses for a realistic design prediction (as per CIBSE TM54 or equivalent protocols).*

Operational Baseline: *A new baseline calculated during operation stage, from a model which reflects actual operating conditions (such as modified occupancy patters) but still has the original technical design intents.*

Actual Energy Use*: Metered performance of the building to which the energy simulation model is calibrated.*

Figure 7: Performance calculations and associated gaps in the case study

5.0 Discussion

5.1 Performance gap issue categorisation

It is important to appropriately define the performance gap based on the underlying issues. Figure 7 shows that the misinterpretation of compliance modelling results can lead to inflation of the actual gap, which is quite prevalent in the UK industry. In this case study the designers were aware of the perceived gap issue and undertook detailed performance modelling using realistic operational conditions in the building. Now, within the actual gap, quantification of the impact of performance gap causes, separately categorised for operational changes and technical issue, enables a more appropriate performance gap assessment. The operational changes after occupancy happen in each building as the occupants get used to their regular functioning over time, sometimes to the extent of change of use of some of the spaces. The gap in this case study due to operational changes is masked a little by the designer's overestimation of server load, but can be seen in increased heating, lighting and small power energy uses. This increase however is expected in baseline energy use and should not be categorised as a performance gap per se. During operational stages, the performance gap which should be assessed and addressed is the gap due to technical issues. This gap provides immediate insights into what are the key technical problems in the building that can and should be corrected in order to ensure that the building runs at its optimal level.

5.2 Need for calibrated simulation based M&V protocol

Integrating calibrated simulation as an investigative tool and validation measure for post occupancy evaluation processes in a M&V protocol provides three clear benefits:

1. **Identification of major issues**: Conventional post occupancy evaluations for identifying causes of underperformance, which do not undertake calibrated simulation, could miss some of the causes. Using a calibration assisted procedure incorporating all input uncertainty can validate whether, through the initial assessment, all the major issues have been identified or if more detailed site investigation is necessary.
2. **Operational baseline creation**: As discussed in the section 5.1 above, a new operational baseline is necessary to separate the technical causes of performance. This process is only possible, when a validated calibration model is created as it is possible in the calibrated model to revert all the technical issues identified, back to their design intent.
3. **Enhanced assessment and analysis**: Due to the use of simulation models UA and SA can also help in speeding up identification of causes of the performance gap by providing the hierarchy of most influential parameters. This is especially useful in the cases when initial assessments could not account for all the deviation. Using simulation, quantification of impact of individual issues and correction measures could be done, exploring the various 'what if' scenarios.

A procedural workflow for calibration, through an integrated simulation software toolkit, is essential for practical industry application of model calibration, especially in the performance gap evaluation context. The calibration procedure explained in Figure 1, can go beyond current industry practices by incorporating analytical techniques such as UA and SA and cross validation through dependent variable checks such as zone temperatures.

6.0 Conclusions

The work highlights many useful lessons that can potentially be used to inform and improve current industry practices for operational stage performance analysis. The paper demonstrates the application and usefulness of integrating energy simulation as an investigative tool and validation measure for post occupancy evaluation processes in the context of identification of the performance gap issues. This new M&V framework, moves the post occupancy evaluation, done for operational optimisations or ongoing/retro commissioning or retrofit assessments, to a more robust and procedural setup. The ability of the framework to identify all the key potential issues and separate the technical ones from discrepancies driven by change of use, enables a more appropriate assessment of the performance gap and provides immediate insights into what needs to be corrected in the building.

While the new M&V framework is intuitive the case study provides an example template for practitioners to emulate in their performance evaluations. The example gives a detailed guidance and explanation of how simulation tools can be used procedurally to undertake robust energy modelling and model calibration. Therefore, due to the immediate relevance of the findings of this paper in industry applications, the framework and the workflow presented in this paper also form a part of an upcoming CIBSE Technical Memorandum which focuses on undertaking robust and holistic operational performance assessments. This software toolkit, which enables practical application of this framework, is also being developed using DesignBuilder Software, a’s graphical user interface for EnergyPlus.

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