PERFORMANCE GAP AND THERMAL MODELLING: A COMPARISON OF SIMULATION RESULTS AND ACTUAL ENERGY PERFORMANCE FOR AN ACADEMY IN NORTH WEST ENGLAND

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ABSTRACT

This paper compares the actual energy performance of a new-built academy with design and compliance stage estimations. The paper then presents the outcomes of a dynamic thermal model developed in accordance with post-occupancy operation of the building. The aim is to use post-occupancy evaluation as an effective tool to reflect on design and compliance simulations and, thereby, identify how the thermal modelling process could be enhanced. An overview of the application of thermal modelling under current building regulations is also provided along with recommendations about how building simulation could be utilised to narrow the design vs. actual energy performance gap.

INTRODUCTION

Overwhelming evidence indicates there is a gap between the design intents and actual performance of new non-domestic buildings. Bordass et al. (2001) reported that design estimates made for the energy performance of sixteen low-energy design buildings were frequently lower than actual consumption. Another study carried out on school buildings revealed that energy performance of 80% of the new-built 'low-energy' schools was worse than the UK median school (Pegg, et al., 2007). CarbonBuzz, a collaborative research platform designed to engage the stakeholders in narrowing the design vs. operational gap, reports an average 114% increase in operational CO_2 emissions compared to design estimations for school buildings (Kimpian and Chisholm, 2011). Some researchers have questioned the ability of designers to estimate building energy performance using thermal modelling (Ahmad and Culp, 2006). They point out the high level of uncertainty and sensitivity associated with the current tools and methods used for building simulation. The variability of modelling results produced by different software packages has also been criticised (Raslan and Davies, 2010). Yet thermal modelling plays a pivotal role under current building regulations and is used extensively to ensure buildings meet the energy efficiency standards and carbon emissions targets set out by national regulations. In England and Wales, thermal modelling is used to demonstrate compliance with Part L of the building regulations. It is also used to produce Energy Performance Certificates (EPC) for buildings which are meant to reflect the as-built energy performance. Uncertainties and limitations associated with thermal modelling account for a significant part of the design vs. operational performance gap. This performance gap hinders the ability of the construction industry to achieve the ambitious carbon emissions targets set out by the new regulations.

This paper investigates the case of a new-built 'low carbon' academy in North West England. Completion and handover of this academy took place in November 2008 and, therefore, its current energy performance is representative of a long term and stable mode of operation.

Actual energy consumption is compared with the design and compliance estimations. The results derived from a new thermal model developed based on post-occupancy information will then be used to reflect on the thermal modelling process and identify improvement opportunities.

CASE STUDY BUILDING

The building is located in North West England on a restricted site and below the flight path of Manchester Airport. Therefore, full mechanical ventilation strategy with heat recovery was adopted for the building to ensure that it meets BB93 acoustic criteria (DfES, 2003).

The total useful floor area is 10,418 m². The building is a four-storey steel frame building comprising lower ground, ground, first, and second floors compliant with Part L 2006. The building's external walls are brick block with cavity. A central atrium space connects different parts of the building and provides opportunities for performance, display, and informal interaction. Classrooms, a sports hall, a dining area, and office spaces are all located around the central atrium. Figure 1 shows typical layout plan of the building. Typical slab-to-slab height is 3.6 m with floor to ceiling height of 2.7 m. The proportion of window areas to the total area of the external envelope is 28%. Figure 2 depicts a 3-D view of the building extracted from its thermal model.

Closed loop ground source heat pumps with vertical boreholes have been installed to satisfy 40% of the heating demand. They also provide cooling to the

ICT enhanced classrooms via active chilled beams. A full back-up heating system in the form of gas-fired condensing boilers has also been installed. Heating terminals vary depending on the activity type in each zone; there are wet radiators in most classrooms, radiant panels in the labs, under-floor heating in the atrium, dining, and other high ceiling spaces, and chilled beams in the ICT enhanced classrooms. The hot water calorifier is served by the low temperature hot water loop via a heat exchanger. Classrooms have been designed with a minimum 2% daylight factor within 6 metres of the building perimeter and artificial lighting is provided by high ballast energy efficient fluorescent fittings. A number of metal halide bulbs have been installed in high ceiling spaces. Automatic daylight and presence detection sensors have also been integrated into the lighting system.

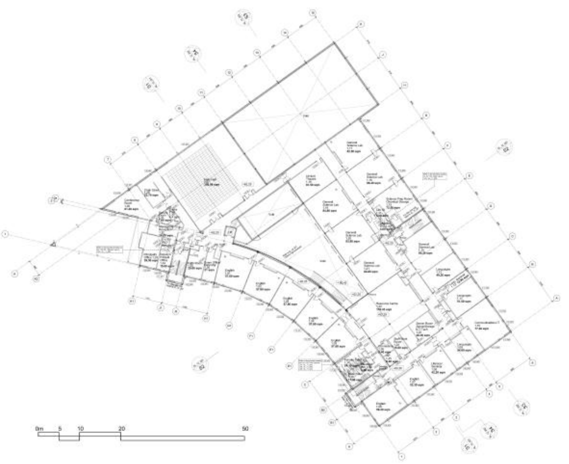

Figure 1 Typical layout plan for the case study building

The building was designed as a 1,150-pupil facility. Normal occupancy hours are 08:30-15:30 with cleaning hours between 07:00-8:30 and 15:30-18:00. During the measurement period, a night school took place on Tuesday and Thursday every week between 18:00 and 21:00. The academy follows the normal England and Wales secondary schools calendar.

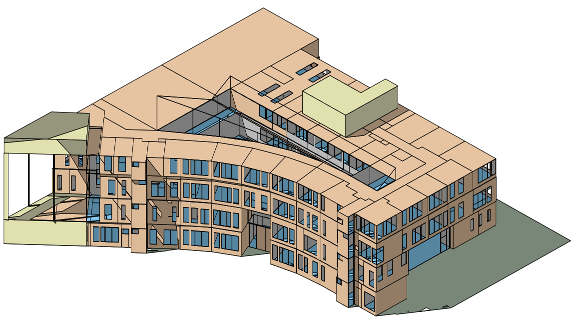

Figure 2 3D view of the case study building (extracted from the thermal model)

The academy was usually closed at weekends but open to facilities' staff on Saturday mornings.

Figure 3 illustrates the Energy Performance Certificate (EPC) issued for the building after completion vs. the existing Display Energy Certificate (DEC). Whilst the asset rating of the building is environmentally acceptable according to the EPC, the actual performance falls short of the design aspirations.

Figure 3 Energy Performance Certificate (B/47) vs. Display Energy Certificate (G/163)

METHODOLOGY

Actual performance: A detailed metering strategy was adopted for the academy that gives a breakdown of all end-uses. The academy has been subject to an on-going post-occupancy evaluation since March 2011. Regular meter readings by the research team provide a detailed picture of all mains and end-uses during the period 31st March 2011-13th February 2012 i.e. 319 days. Linear extrapolation for non-heating fuel was used to establish the whole year's performance. For heating fuel, degree-day analysis was used to derive the consumption for the full 12 months. Total gas and electricity figures have also been compared with utility bills to ensure sub-meters are reconciled with the site gas and electricity intake.

Benchmarking: CIBSE TM46 (2008) provides electricity, fossil fuel, and CO_2 benchmarks for 29 categories of buildings including schools. Whilst the CO_2 benchmark given for school buildings seems to represent the UK median stock (Bruhns et al., 2011), energy benchmarks do not reflect the recent energy performance trends of modern school buildings. Generally, modern school buildings tend to have lower fossil fuel consumption due to higher insulation levels and air tightness. Furthermore, electricity consumption tends to be higher in these buildings due to ever-increasing use of ICT equipment. A recent study by Godoy-Shimizu et al. (2011) provides mean fossil fuel, electricity, and CO2 emissions figures for academies based on the latest information available from Display Energy Certificates. The statistical sample includes 38 academies. The small sample size is partly due to the relatively low number of academies (mostly new-built) with valid DECs. However, these benchmarks are more in line with the experience of this research team from similar post-occupancy studies.

Consequently, the energy consumption and carbon emissions of the building have been compared with both TM46 benchmarks and the recent mean values released for academies.

Design & compliance simulations: The researchers did not have access to the original thermal model developed by the M&E service engineers at the design stage. However, the outcomes of that model were available in the format of the compliance stage report (BRUKL report provided to the research team by the design engineers) and EPC calculations (.XML file). In addition, the RIBA Stage D Engineering Report includes the energy performance estimations made at the design stage. Therefore, it was possible to derive energy breakdowns and form a clear picture of design and compliance predictions.

Post-occupancy simulation: A thermal model was then developed based on as-built information and post-occupancy observations to assess the capability of dynamic thermal simulation to estimate actual performance. The program selected for performing post-occupancy simulations was the IES Virtual Environment (VE). An earlier version of the same program was used at design and compliance stages. CIBSE Test Reference Year (TRY) weather file for Manchester was used for the purpose of simulation. The heating energy estimated by the software was weather adjusted based on the latest degree-day information available for the site.

One major difference between the design and compliance simulations and the post-occupancy simulation is that the latter simulation does not involve inverter-driven fans. CO2 levels were logged in four typical types of classrooms with Quest AQ5000 Pro probe (accuracy: ±3% of reading ±50 ppm within the measurement range of 0 to 5000 ppm) over one typical week. It became clear that that the demand control ventilation was not working as intended. Further investigation revealed that the inverters had not been enabled by the Building Management System (BMS). Figure 4 illustrates the variation of CO2 levels within a typical English classroom over one day.

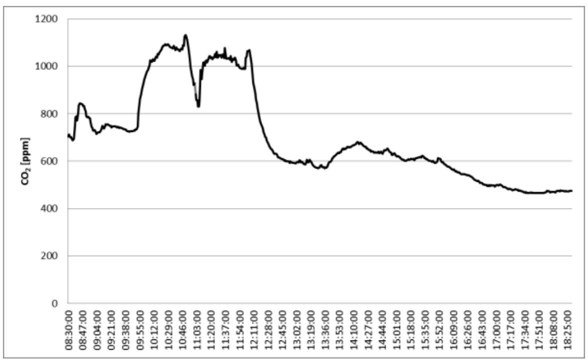

Figure 4 CO_2 level variations in a typical classroom: inverters were not enabled.

Table 1 includes details of the assumptions made for the following simulations:

- 100% heating provided by gas-fired boilers & RIBA stage D information (design stage simulation)
- 60% heating provided by boilers, 40% by GSHP & as-designed information (compliance stage simulation)
- Post-occupancy simulation based on as-built information & post-occupancy evaluation.

Two options had been considered at the design stage: gas-fired boilers only, and GSHP and gas fired boilers. Sub-metered data for the GSHP system revealed that energy consumption of the GSHP over the measurement period was negligible. Therefore, this investigation considered the results of the design option based on 100% gas fired boilers. Similarly, the post-occupancy simulation scenario is based on 100% heating provided by boilers. It is assumed that the GSHP system has only provided limited cooling to the ICT enhanced classrooms via active chilled beams.

Reflection on simulation process: Finally, the assumptions made at the design and compliance stage simulations were reviewed in order to to understand the root causes for the discrepancy between these predictions, post-occupancy simulation, and actual energy performance.

A number of assumptions made in the National Calculation Methodology (NCM) and adopted by the software program are also critically reviewed in light of the actual data collated from the building.

Furthermore, there has been a review of the role of thermal modelling in building regulations, taking into account the lessons learned from this investigation and other research evidence.

RESULTS

Actual performance: Figure 5 demonstrates the breakdown of energy consumption for all end-uses based on sub-metered data.

It is notable that the ground source heat pumps' electricity intake is negligible i.e. 0.4 kWh/m²/yr. This is the result of operational problems experienced with these units. Leakage, malfunctioning pumps, and control issues at the interface between ground source heat pumps and gas-fired boilers meant that the GSHP system was not effectively utilised to condition the building throughout the measurement period. A full back-up system in the form of conventional gas-fired boilers was installed, making it possible to condition the building without ground source heat pumps.

Benchmarking: Figure 6 compares the degree-day adjusted actual CO_2 performance of the building with the UK median school and the new-built academies' mean values. CO_2 conversion factors of 0.19 kg

CO_2/kWh and 0.55 kg CO_2/kWh were used for gas and electricity respectively. Gas consumption of the building is lower than the benchmarks. This could be attributed to the compact geometry of the building, higher than minimum required insulation & air tightness, high efficiency of the heating plant, and effective heat recovery with thermal wheels. Electricity consumption, on the other hand, is even higher than the mean value for new academies. The mechanical ventilation strategy and auxiliary power are the main contributors to this excessive consumption. Lighting is also a significant contributory factor.

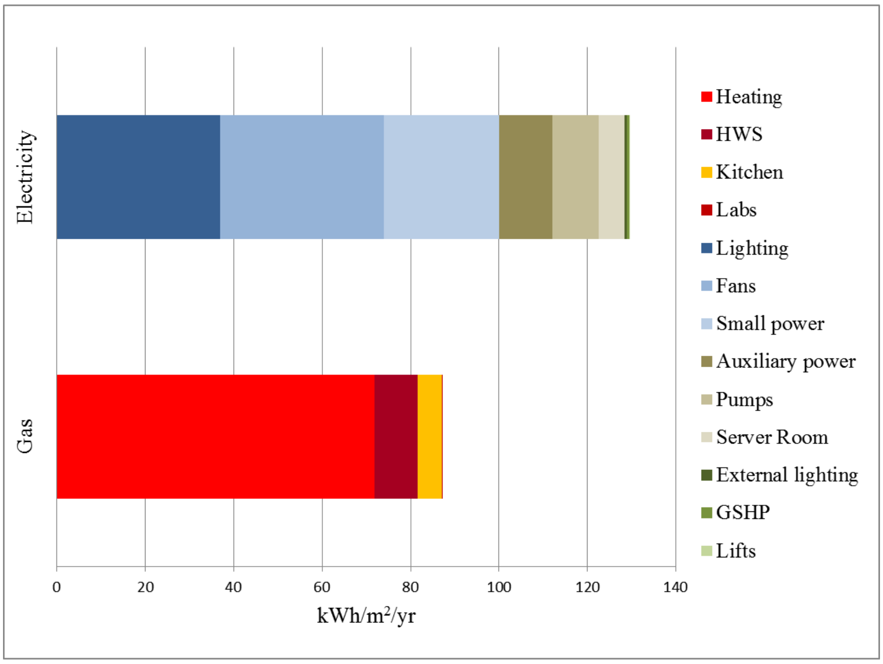

Figure 5 Detail breakdowns of sub-metered gas and electricity consumption for the academy

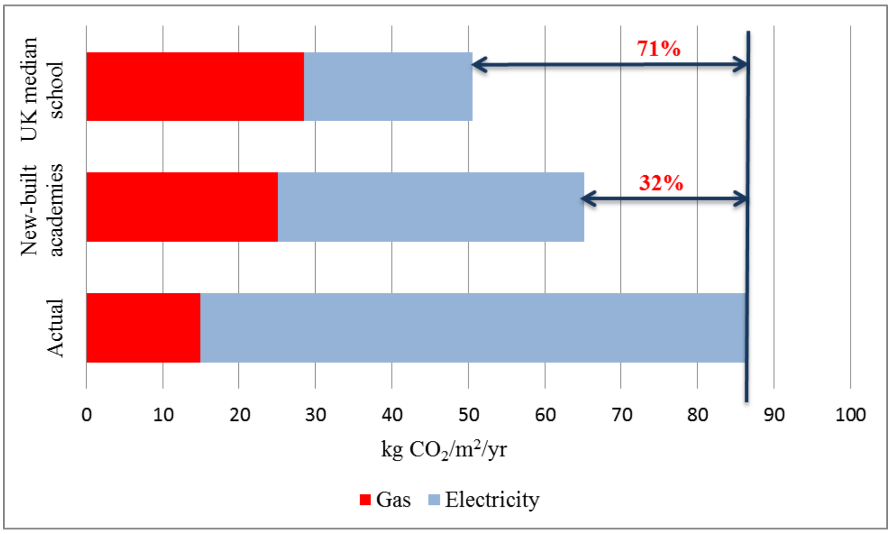

Figure 6 CO_2 performance of the academy vs. Benchmarks

Predictions vs. post-occupancy simulation: Table 2 provides the energy breakdowns derived from the simulations included in the scope of this investigation.

Figure 7 illustrates the breakdown of the CO_2 emissions associated with each scenario.

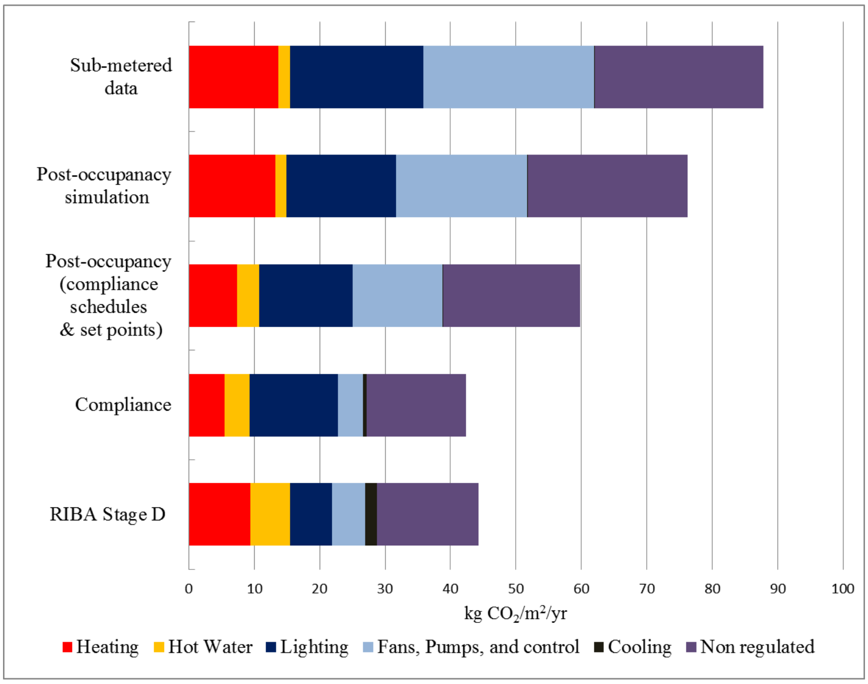

Figure 7 Breakdowns of CO_2 *emissions for each scenario vs. actual data*

DISCUSSION

Compliance calculations carried out in accordance with the National Calculation Methodology are used to demonstrate that criterion 1 of Part L of the England and Wales building regulations is met. The basis of these calculations is a comparison between annual CO_2 performance of an actual building with that of a notional building to ensure the CO2 emissions of the actual building are not greater than the notional building. The notional building possesses the minimum acceptable specification. This specification is revised with every new version of the Approved Document Part L to set out increasingly stringent targets and, thereby, further reduce the CO2 emissions of national building stock. Consequently, in practice, the emphasis of compliance thermal modelling is on the *relative* performance of buildings and not on the absolute energy or carbon performance. Schedules of operation, set points, HVAC system supply rates, and auxiliary consumption associated with pumps, are among the items that users have very little control over them. These are mainly estimated based on building and system type in the calculation engine. Moreover, the calculations exclude some energy end-uses that constitute a sizable portion of total energy. Notably, equipment loads are only taken into account to estimate the cooling loads and are excluded from the overall building performance (CLG, 2011). On the other hand, as there is not yet a nationwide legal requirement to predict the absolute and total performance, this simplified and relativist approach to building energy performance is often the only source of information available prior to occupancy. Scarce resources exacerbated by the current economic climate often means clients are reluctant to pay anything above what is required to meet regulatory requirements. Energy Performance Certificates produced for buildings based on this approach are being compared with, often, poorer Display Energy Certificates that reflect the actual energy performance. There is yet no mechanism in place to link the so-called design and compliance stage estimations, derived from compliance calculations, with actual performance. These issues raise the question of whether the ambitious energy performance targets set out in the building regulations can be achieved in practice.

An overview of the case study building's characteristics and the simulation outcomes summarised in Table 2 uncovers the following three major sources of discrepancy between simulations and actual performance.

- Design stage assumptions
- NCM limitations
- Operational issues ('unknowns' at design stage)

Design stage assumptions: A number of assumptions made at the design and compliance stage contribute to the energy performance gap. It was assumed that the specific fan power of the mechanical ventilation system would be no greater than 2.5 W/L/s. In practice, specific fan powers may change radically due to changes in ductwork installation by contractors, number of bends, fans' curve characteristics, dirty filters, replacing fans, etc. The authors have carried out post-occupancy evaluations on a number of mechanically ventilated school buildings and the SFPs were frequently higher than the design assumptions often by a factor of two. For example, the ductwork aspect ratio for a number of air handling units in the case study building has been changed from the design values of 1.6/1 & 2/1 to 4/1 due to spatial constraints. This will increase the pressure drop substantially. Furthermore, it should be noted that the SFP of 4.02 W/L/s used for post-occupancy simulation is based on the commissioning results. It is realistic to assume the actual SFP will be even higher than the commissioning stage due to higher pressure drop across dirty filters. To a certain extent, these could have been anticipated and allowed for at the design stage. It also appears that the lighting density assumed at the design stage (given per 100 lux) is more appropriate for classrooms and the installed lighting density in corridors and common areas is much higher. Furthermore, the benefit attributed to daylight sensors is often compromised when teachers use internal blinds to use projectors or to avoid overheating and glare.

NCM limitations: The NCM profiles assume classroom set point of 20 °C. The heating set point in the case study building is 21°C and the rather long hot water loop index run along with less than optimal control valves mean that internal temperatures could easily reach 23-24°C in winter. Furthermore, the set point is often changed in a number of zones as requested by building occupants. None of these factors could be allowed for in compliance simulations contrary to design and post-occupancy simulations.

The NCM profiles overestimate the hot water consumption for the case study building. It appears that the domestic hot water consumption assumed for changing rooms is 59.8L per person for every occupied hour. This is much higher than the actual usage.

One of the major root causes for the energy performance gap is the fact that the pumps' auxiliary power could not be modelled for compliance purposes and NCM default values based on HVAC system type must be used instead. In the case study building, this amounts to approximately 9.3 kWh/m²/yr error in estimating the actual energy usage of pumps, whereas a simple back of envelope calculation based on the pumps' ratings would yield a result close to the sub-metered data.

Finally, schedules of operation and mechanical ventilation supply rates are fixed for compliance calculations. Adjusting these factors in the post-occupancy simulation gives very close results to the metered data.

Operational issues: The fact that the GSHP system was out of operation for most of the time during measurement period or the demand control ventilation had not been enabled could not have been anticipated in design and compliance stage simulations. However, given the heating capacity of the installed GSHP system, it appears that the design team assumed GSHP would be the lead heating system at full capacity at all times. Perhaps, it was realistic to allow for the operational learning curve associated with low or zero carbon technologies and explore a number of what-if scenarios based on the percentage availability of the GSHP system. The necessity to get a Pass result at the compliance stage and the deterministic nature of the existing energy performance evaluation framework effectively discourages designers to explore these possibilities and widens the design vs. operational gap.

Finally, as there is no requirement to validate actual energy performance in reference to design estimations, the fact that inverters were not enabled went unnoticed for a long time. A more realistic simulation approach along with a feedback loop between operation and design could have resulted in lower energy consumption and greater consistency between design aspirations and operational outcomes.

CONCLUSIONS

The post-occupancy simulation clearly demonstrates that, if correct and up to date information is used, the dynamic simulation method can yield realistic results and reflect the actual energy performance with reasonable accuracy. The NCM assumptions related to auxiliary power do not produce accurate results and it is preferable to model all HVAC pumps to achieve outcomes that are more realistic. However, it should be noted that thermal modelling is often used to demonstrate compliance with the building regulations and, therefore, the NCM methodology will be adopted. Limitations of the NCM methodology will compromise the ability of the dynamic simulation approach to predict energy performance accurately.

The deterministic (pass/fail based on fixed total CO_2 emissions) and relativist (actual vs. notional) nature of the approach adopted by the building regulations means that designers are not encouraged to think about practicalities of the adopted strategies and what-if scenarios in their energy performance calculations. If a Low or Zero Carbon (LZC) system has a back-up system installed, this means the designers have factored in the operational issues and learning curve associated with this technology. It is, therefore, reasonable to expect a relation between the size of the back-up system and the availability of the LZC system in building simulation. Yet there is no requirement to consider this in compliance calculations. A confidence band depending on the availability of LZC technology could be worked out by building simulation to assess the corresponding energy implications. The same risk assessment approach could be adopted for different energy conservation features. The case study building would have benefited from a similar approach to demand control ventilation.

The non-regulated energy end-uses constitute 35% of the total electricity consumption and 6% of the gas consumption in the case study building. Whilst some of this equipment is subject to bespoke energy efficiency standards and requirements, building specific control features such as automated control and power down management could radically reduce the energy consumption. Given the proportion of these end-uses' energy consumption, it seems reasonable to regulate them under building performance evaluation frameworks and policies.

Finally, post-occupancy simulation afforded the authors the benefit of hindsight in approaching the actual performance. This luxury is not available to designers. Two main factors could help narrow the gap between design predictions and actual performance:

- Improving the calculation/simulation methodology
- Feedback loop between operation and design

It would be reasonable to move toward probabilistic and comprehensive modelling approaches to assess the risk of different design strategies and include all energy end-uses to predict energy performance with accuracy. This approach must be reinforced by creating a feedback loop between operation and design so that design teams and contractors get involved in fine tuning buildings post-occupancy and ensure actual energy performance is within reasonable limits of design predictions.

The fragmented nature of the supply side of the UK construction industry (Cooper, 2001) and the fifty-year history of post-occupancy evaluation indicate that this could only be achieved if supported and enforced by appropriate policies and regulations. If the UK construction industry is to meet the ambitious energy performance targets set out by the government, the operational gap between building design and actual operation must be narrowed. This investigation revealed that, under an integrated design-operation energy performance framework and subject to some improvements in calculation methodologies, building simulation could yield accurate predictions and play a vital role in narrowing this operational gap.

ACKNOWLEDGEMENT

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Table 1Assumptions made for the case study building simulations

Building element	**RIBA Stage D simulation**	**Compliance simulation**	**Post-occupancy simulation**
Heating	100% heating provided by gas fired condensing boilers. Heating terminals include wet radiators (normal classrooms), radiant panels (labs), and under-floor heating in areas with high ceiling (e.g. atrium and academy's hall).	60% of heating load provided by condensing boilers, 40% by the ground source heat pumps. Heating terminals the same as Stage D except active chilled beams served by the GSHP for ICT enhanced areas and a number of office areas	100% heating provided by gas fired boilers. Seasonal gross efficiency in condensing mode: 95.2% Seasonal gross efficiency in non-condensing mode: 88%
Ventilation	Full mechanical ventilation with heat recovery (thermal wheels) and demand control ventilation. Specific Fan Power (SFP) of 2.5 W/L/s.	The same as Stage D	All airflows based on as-built drawings, overall system SFP of 4.02 W/L/s in accordance with commissioning results, no demand control ventilation enabled.
Air conditioning	Split DX units provide cooling to ICT enhanced rooms and a number of office spaces.	Active chilled beams served by GSHP. DX split units for the server room.	The same as compliance stage, GSHP COP: 5.2, Server room DX units Energy Efficiency Ratio: 3.27.
Hot water	Hot water calorifier served by the low temperature hot water loop through a plate heat exchanger.	The same as Stage D	The same as Stage D (assumed). Hot water tank capacity: 2000 litre with 0.0026 kWh/L/day loss.
Lighting	Minimum installed capacity of 3 W/m^2 per 100 lux. Automatic daylight sensing with an average daylight factor of 2% within 6m of the building perimeter, and presence detection sensors.	The same as Stage D	All lighting wattages based on as-built drawings; average lighting density is 12.2 W/m^2. Similar control features.
External envelope	The building fabric properties were assumed to meet the maximum allowable U values by the approved document Part L 2006.	The same as Stage D	External wall U value: 0.28 W/m^2°K, Windows: 1.8 Roof: 0.15 External floor: 0.25
Air tightness	10 m^3/h/m^2 @ 50 Pa	9.2 m^3/h/m^2 @ 50 Pa (pressure tested)	9.2 m^3/h/m^2 @ 50 Pa
Non-regulated loads under current building regulations	Assumptions made for small power, catering equipment, and other miscellaneous end-uses.	Small power in accordance with NCM only for estimating cooling loads. Other non-regulated loads excluded.	All based on as-built drawings and post-occupancy observations.

Table 2 Energy breakdowns derived from the simulations vs. sub-metered data

<table>
<tr><th>End-use (kWh/m^2/yr)</th><th colspan="2">RIBA Stage D simulation</th><th>Compliance simulation (40% GSHP, 60% gas boilers)</th><th>Post-occupancy simulation (same operation schedules & set points as compliance stage)</th><th>Post-occupancy simulation (actual operation schedules & set points)</th><th>Metered data</th></tr>
<tr><td>Heating</td><td colspan="2">49.51</td><td>16.47</td><td>39.00</td><td>69.89</td><td>71.81</td></tr>
<tr><td>Hot Water</td><td colspan="2">32.1</td><td>19.94</td><td>17.8</td><td>8.90</td><td>9.77</td></tr>
<tr><td>Lighting</td><td colspan="2">11.5</td><td>24.54</td><td>25.97</td><td>30.36</td><td>37</td></tr>
<tr><td>Fans, pumps, and control</td><td colspan="2">9.2</td><td>6.97</td><td>24.99</td><td>36.49</td><td>47.33</td></tr>
<tr><td>Cooling</td><td colspan="2">3.4</td><td>1.00</td><td>0.12</td><td>0.19</td><td>0.4</td></tr>
<tr><td rowspan="3">Reported non-regulated (including small power)</td><td>Equipment (elec.)</td><td>18.5</td><td rowspan="3">27.68</td><td rowspan="3">Reconciled with schedule-adjusted metered data within 5%</td><td rowspan="3">Reconciled with metered data within 5%</td><td rowspan="3">5.59 (gas), 44.83 (electricity)</td></tr>
<tr><td>Catering (elec.)</td><td>7.2</td></tr>
<tr><td>Catering (gas)</td><td>7.0</td></tr>
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