Building Performance Evaluation: Balancing Energy and Indoor Environmental Quality in a UK School Building

Abstract

There is a policy-driven focus, at present, on improving the energy performance of buildings. However, energy-related issues alone do not capture the full impact of buildings on occupants and the wider environment. The performance of a building also includes occupant wellbeing and indoor environmental quality (IEQ). Specifically, in schools, IEQ (thermal comfort, indoor air quality, lighting and acoustics) is an important aspect. Additionally, the issue of the 'performance gap', generally focused on energy, also affects IEQ parameters, and needs to be addressed holistically.

This paper reports on a holistic building performance evaluation covering aspects of energy, thermal comfort, indoor air quality, lighting and acoustics. It assesses the performance issues and inter-relationships between energy and IEQ in a recently built school campus in London. Based on the evidence collated from this case study and supplementary literature, the endemic issues and constraints within the construction industry are explored, such as inappropriate design calculations and resistance to new low-carbon technologies. Further, lessons for improved performance in the design, operation and maintenance of schools are highlighted such as factoring in the changing building use trends during design and the significance of optimal operations and maintenance of building systems for better energy and IEQ performance. This study shows that if the building design focus primarily remains on energy, unintended consequence of IEQ underperformance may occur where there are conflicts between energy and IEQ objectives. An integrated approach to building performance can help address this issue.

Keywords: Building Performance Evaluation, Performance Gap, Energy Performance, Indoor Environmental Quality (IEQ), Indoor Air Quality (IAQ)

Practical application: There are often conflicts between energy efficiency and indoor environmental quality (IEQ) objectives in building design and operation. Most building performance evaluations are primarily focused on one set of these performance criteria. This building performance evaluation was done with an integrated energy and IEQ perspective. The study identifies the causes of underperformance in energy and IEQ in a recently built school in London. Some of the key lessons learned from this study provide lessons that are relevant across the industry for the delivery of low-carbon and healthy buildings. These lessons include methods to further strengthen the policy frameworks and design protocols along with overall improvements in the processes followed during design, construction and operation of schools and other non-domestic buildings. The paper can also inform building designers, contractors and facility managers about the ways to reduce the performance gap and achieve energy targets without unintended consequences for indoor environment.

1.0 Introduction

Building performance evaluations and post-occupancy evaluations primarily focus on energy performance. This is in line with the current policy objectives related to energy efficiency and climate change mitigation. However, energy performance alone does not capture the full impact of buildings on occupants and the wider environment; there is recent emerging evidence that relates environmental quality to health and wellbeing [1]. The performance gap, covering built environmental performance parameters along with energy, affects occupant wellbeing and indoor environmental quality (IEQ) [2]. This paper reports on the findings of the building performance evaluation of a newly built and partly refurbished school campus in London.

The aim of this paper is to assess how the case study building is performing against the design intents and industry standards. The paper further identifies the root causes of underperformance in energy and IEQ. A key objective is to link energy to IEQ performance and determine various design and operation stage decisions that have affected the building's performance. The findings are also linked to the endemic issues and constraints within the construction industry and key lessons for improved performance in the design and operation of school buildings are highlighted.

2.0 Background

The performance gap points to the difference between the actual operation of a building against the design intents. There is significant evidence [3] [4] to suggest that buildings underperform post-completion when compared against the anticipated performance during design stages. Various metrics could be used to assess the performance gap in the actual operation of a building, out of which, energy performance is generally the most highlighted and emphasised metric. CarbonBuzz, a research platform where stakeholders voluntarily provide (i) *design* energy use data and (ii) *actual* energy use data of buildings [5], reports an average 48% increase in operational CO_2 emissions compared to design estimates for school buildings. While this provides evidence for energy performance gap, much of the design stage data provided on CarbonBuzz is 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 [6].

Moreover, the gap between actual and expected performance is not limited to energy, it may also be identified for IEQ parameters such as temperature, relative humidity (RH), air quality (pollutants, CO_2), noise and lighting [7], [8], [9] [10]. The relationship of occupant well-being, comfort, and productivity with IEQ in various building types is well established and documented [11], [12], [13]. Specifically, for schools, there is a strong association between key IEQ parameters (temperature, ventilation rates, and indoor CO_2 concentrations) and cognitive performance [14].

In the current trend of sustainable and low energy building design, the ways to achieve high IEQ and building user satisfaction might contradict measures to achieve better energy performance. For example, overheating and air quality (higher levels of certain volatile organic compounds) issues are uncovered in highly insulated and airtight new buildings constructed to higher energy standards [15], [16], [17], [18], [19]. In urban areas, traffic-related external pollutants such as particulate matter and NO_2 are linked to adverse health impacts as well [20], [21]. These have significant implications where energy-efficient strategies such as advanced natural ventilation are adopted and air exchange between the indoor and outdoor environment occurs without any filtration. In such circumstances the use of CO_2 as the only metric used as a proxy for indoor air quality (IAQ) is questionable. While CO_2 levels provide the first indication of exposure to poor air quality, indoor levels of traffic-related pollutants need to be considered separately [12]. A holistic, energy and environmental performance approach is needed to understand the intricate relation between these performance objectives to avoid unintended consequences and address shortcomings in building performance.

3.0 Method

The paper addresses design and operational performance issues, inter-relationships between energy and IEQ and root causes of performance gaps in the context of school buildings, underpinned by findings and observations from a case study building. The case study building is a secondary school and sixth form with academy status, located in inner London, England. The school went under redevelopment in 2014 with the construction of six new buildings (including teaching spaces, sports hall and performance arts and dining hall) and the refurbishment of several existing ones (swimming pool and gymnasium building and assembly hall). The buildings were generally four stories high with a total useful floor area of 21,405 m^2. The project was required to implement on-site renewable energy technologies to meet the local council's planning conditions. To satisfy this, a biomass boiler utilising solely wood pellets and solar thermal collectors were implemented. Figure 1 shows the school building and Figure 2 shows the campus layout.

Figure 1: Case study school; (Left) Entrance – West façade, (Right) Central courtyard.

Figure 2: Campus layout

Regular measurements, observations and semi-structured interviews with the facility managers at monthly or bimonthly intervals over a period of one year were used to collect post-occupancy data and information. Metering and monitoring recorded various performance parameters. Electricity and gas use data was recorded for energy while temperature, RH, CO_2 (a proxy for cognitive performance), and particulate matter

($PM_{2.5}$, PM_{10}) were recorded for IEQ. Lighting and acoustic performance of the buildings were also reviewed during typical weeks. Additionally, passive sampling using diffuser tubes was used to determine the concentration level of several volatile organic compounds (VOCs) such as benzene, formaldehyde, and trichloroethylene that, based on previous research [19], may have high concentration levels in low-energy buildings.

Energy use and IEQ performance parameter predictions at the design stage were compared with post-occupancy operations data and the relevant UK and global standards. Subsequently, reasons for performance gap were identified using post occupancy observations and interviews. The root causes for the gap were validated using a calibrated computer model, and potential building specific and industry processes related improvements were identified. The following sections provide further details about building design and monitoring methods.

3.1 Building design characteristics

Envelope: The envelope was made of prefabricated concrete panels, assembled at the site. The building, designed for high energy efficiency, has low fabric U-values (Walls: 0.25 W/m^2K; Windows: 1.6 W/m^2K; Roof: 0.20 W/m^2K; Ground: 0.15 W/m^2K), high airtightness (5 $m^3/hr/m^2$ @ 50Pa) and an emphasis on avoiding thermal bridging. Spaces had large windows for daylighting and were partially operable for natural ventilation and free cooling in summer.

Occupancy: The nominal design stage occupancy was 2250 (2000 pupils and 250 staff). The daily occupancy assumed for students on Mondays was from 8:35am to 2.55pm, Tuesdays to Fridays from 8:35 am to 3:50 pm and on Saturdays the occupied time was from to 9:10 am to 1:00 pm.

Heating, cooling, and domestic hot water (DHW) system: Heating was provided through a centralised plant for the entire campus via a pressurised low-temperature hot water system. A biomass boiler (heating seasonal efficiency: 0.75) for annual DHW demand and two gas-fired boilers (heating seasonal efficiency: 0.84) were installed to provide heat in the building. Variable refrigerant flow systems were installed in rooms with high ICT loads and server rooms (heating/cooling seasonal energy efficiency ratio: 1.47/3.80). There was not any provision for comfort cooling to any other space. Heating and cooling setpoints were 20°C and 23°C respectively.

Mechanical ventilation (MV) system: MV system with heat recovery (efficiency: 0.75) via centralised roof mounted air handling unit (AHU) provided fresh air in the buildings, distributed through wall mounted diffusers/grills. A building management system (BMS) controlled ventilation in the spaces based on the installed CO_2 sensors in each room.

Acoustics and lighting: Appropriate acoustic measures (ceiling baffles) were employed in classrooms to ensure all teaching spaces had adequate speech intelligibility. Besides this, the lighting system was designed to be energy efficient with T5 florescent lamps in classrooms and offices. The rooms were also equipped with daylight and passive infrared (PIR) sensors to provide automated lighting control.

3.2 Data Collection

Design stage information, such as performance targets for energy and standards used for IEQ, were recorded in design documents. The methods used to collect operational data are described below.

Energy: Gas use in the facility, metered at the site level, was recorded in utility bills on a monthly basis. Each new building had its own heat meter which was linked to the BMS system. The mains electricity meter recorded half-hourly electricity use at the site level which was available from utility supplier. At the building level, disaggregated energy use for lights, small power, lifts, server, pumps, and fans could be read through the BMS. Additionally, thermal imaging was used and in-situ U-value measurements were also done to understand the envelope thermal performance and bridging.

Indoor Environment Quality: Temperature, RH, and CO_2 concentrations were monitored in representative zones, covering 5-10% of the floor area with a frequency of at least 10 minutes for one year in accordance with BS EN 15251:2007[1] [22], (measurement accuracies: temperature: ± 0.4 °C, RH: ± 4.5 %, CO_2: ±75 ppm).

A more in-depth investigation was also conducted in four typical locations of the case study school: Library (Ground Floor, West), sample classroom (Building 3 First Floor, North), sample science lab (Building 4 First Floor, East), and external space (within campus close to the main road). The parameters of thermal comfort and various air pollutants such as CO_2, $PM_{2.5}$, PM_{10}, NO_2 were recorded every minute by data loggers and sensors in the monitored spaces (measurement accuracies: CO_2: ± 50 ppm, $PM_{2.5}$: 0.84 coincidence probability at 106 particles/L; PM_{10}: 0.24 coincidence probability at 500 particles/L, NO_2: < ±0.5 ppm). Apart from the active monitoring passive sampling of various VOCs, NO_2 and O_3 was also applied in a typical week during heating and non-heating seasons.

Acoustic measurements of reverberation time (RT) were done in the above mentioned four typical spaces to check for speech intelligibility, as required by BB93 [23]. The RT (T20) was measured in unoccupied condition in accordance with the ISO 3382-2:2008 [24], using the integrated impulse response method; single RT values represent spatial averages (mean of the RT for different source-microphone relative positions). Basic background noise levels measurements with closed windows and in unoccupied condition were also carried out with a binaural recorder conforming to DIN 45631/A1 [25] and DIN 45692 [26] in the "most likely listening position" in each space as per ISO/TS 12913-2:2018 [27]. Left and right channels of the binaural recorder were averaged into a single value.

Lighting illuminance level (lux) measurements, through a lux meter conforming to BS 667:2005 [28], were done in two typical classrooms, Classroom 1 on ground floor facing North-East direction and Classroom 2 on the third floor facing South. Illuminance measurements were taken at desk height at sites equidistant from the nearest luminaires. Light sensors were placed directly above three of the luminaires in each

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[1] The standard, when monitoring was done, has been superseded by BS EN 16798-1:2019 [38]

classroom in the front, middle and back. Sensors were also placed at the windows to measure the daylight.[2]

4.0 Building performance results

4.1 Energy performance

The available design stage projection of energy performance (electricity use and gas) was done as a part of Building Regulations compliance documentation at RIBA Stage 4. The calculation, carried out for the whole facility, reported annual energy use projections for each building separately. Operational stage electricity and gas use data were available from utility bills for four years (2014-2017). Figure 3 shows the comparison against design estimates (for RIBA Stage 4 Report); good practice (25th percentile) and typical (median) benchmarks as per DEC database [29], and CIBSE TM46 benchmark [30].

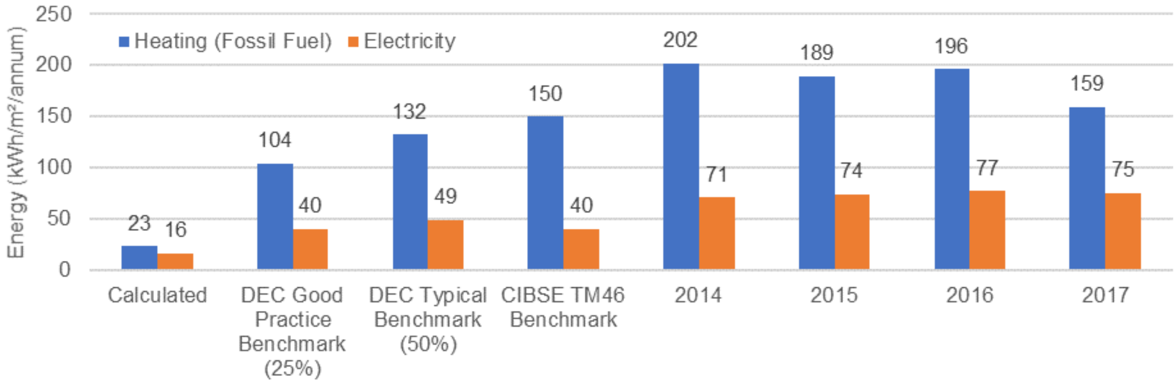

Figure 3 Comparison of actual gas and electricity use of school compared against design estimates and industry benchmarks (kWh/m^2/annum)

It is seen that heating energy use is significantly higher than benchmark buildings – especially for a new build school. Electricity use is also slightly more than benchmark buildings. However, both heating and electricity use are strikingly much higher than the design estimates. As per the latest display energy certificate, the operational rating of the school is currently DEC-F.

Analysing high-resolution building level data helped in identifying specific issues dealing with design, operations, and management. Disaggregated annual operational energy use of individual buildings (heating demand, lighting, equipment, auxiliaries, server and lifts) was available from the BMS readings taken over a period of one year. Data and operational performance for one building on the campus were analysed using a calibrated building performance model[3] [31] developed with DesignBuilder software [32]. The model helped in validating many deviations from the design intent which were probable causes of the performance gap. These deviations were observed on-site visits, noted during interviews with the facility managers and uncovered in IEQ data trends.

[2] Detailed daylight results have not been analysed for this paper as the intention was to assess the IEQ in the context of its impact and inter-relation with energy, which is covered by artificial lighting.
[3] Performance assessment analysis using model calibration for this building has been published in detail in another paper [31].

4.2 IEQ performance

4.2.1 Thermal comfort

The building maintained comfortable indoor temperature and RH in most spaces during both heating and non-heating seasons. Indoor temperatures in the monitored spaces were kept around 20°C and 23°C during heating and non-heating seasons respectively. RH was between 40%-55%. Figure 4 and Figure 5 show internal and external temperature and RH ranges of three representative building spaces[4].

Figure 6 shows time series of indoor temperatures during the heating season. It is observed that during occupied times the indoor temperatures in all sampled rooms were maintained above 23°C. Also, during holidays, the temperatures were recorded much above the outdoor levels for the lab and the library, whereas the classroom temperature profile was similar to the external measurements.

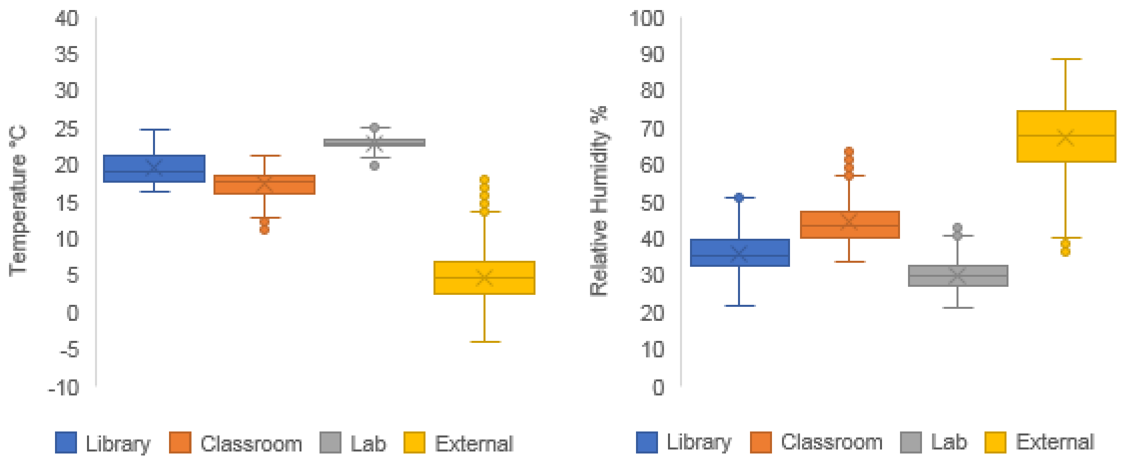

Figure 4 Box and whisker plots showing the spread of Temperature and RH during heating season (All hours in Feb 2018)

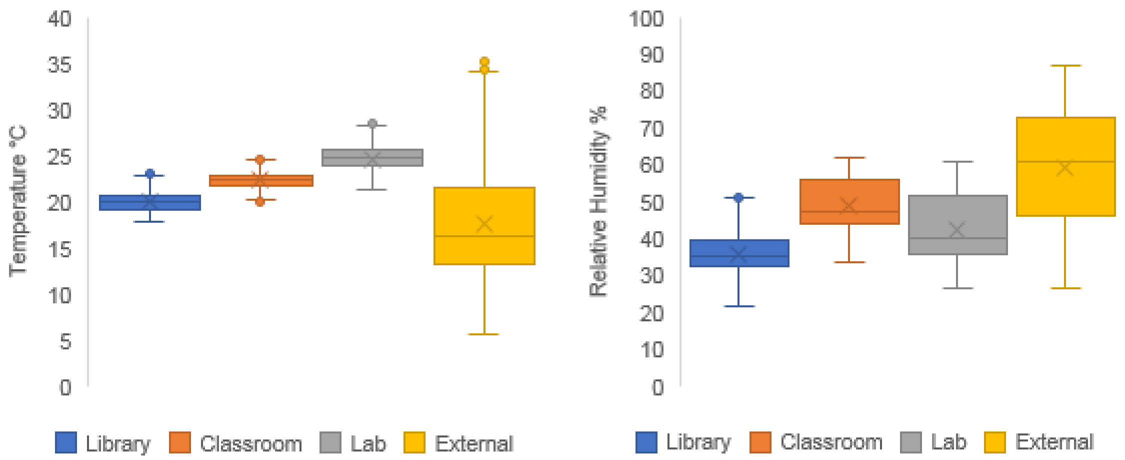

Figure 5 Box and whisker plots showing the spread of Temperature and RH during non-heating season (All hours in May 2018)

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[4] Box and whisker plots in the paper show Interquartile ranges and outliers.

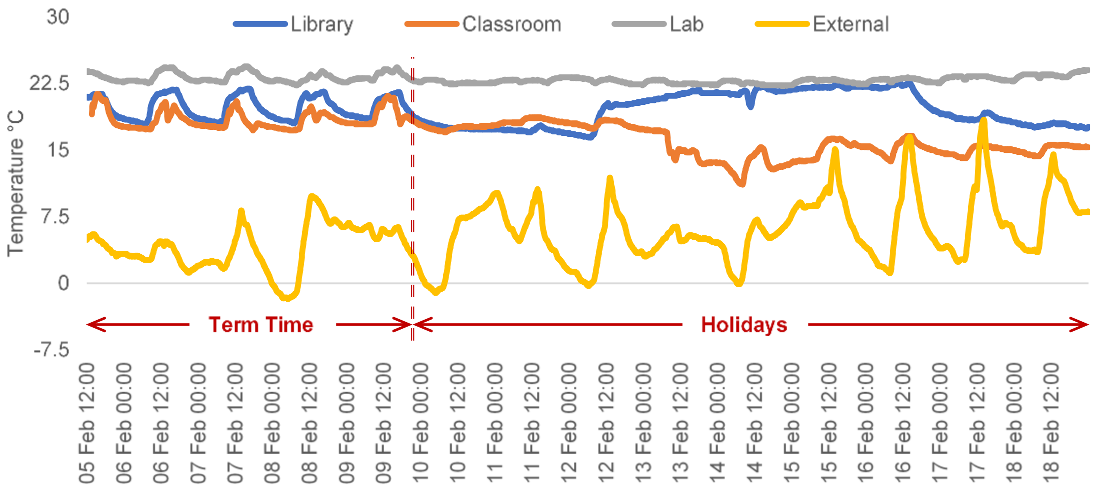

Figure 6 Temperature variations during term time and holidays in the heating season

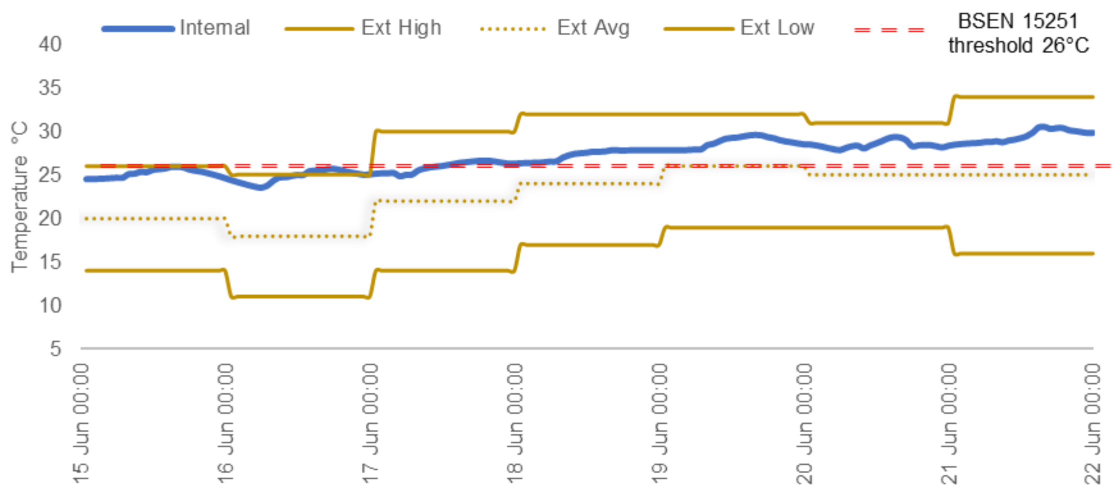

Figure 7 Indoor monitored temperatures in a classroom during a hot summer week

During the non-heating season, while most of the spaces did not suffer from overheating, rooms on the south façade, lacking solar controls (blinds/shades) had high heat gains. They were susceptible to overheating risks in 'hot' summers. Figure 7 shows indoor temperatures in a south facing classroom on the second floor during a hot spell in the month of June. To evaluate the overheating risk of mechanically ventilated buildings, a threshold 26°C is specified by BS EN 15251[5] [33], which was seen to be exceeded as external temperatures remained high. However, for all sampled spaces the BB101:2006 [34] overheating criteria, which was the basis of the design was met. The temperatures of the samples spaces were within the hours of exceedance limits, daily weighted exceedance limits and upper limit temperature. This, suggests that while the current overheating risk is not high for longer periods of time, in the context of changing climate and increasing temperatures, the building will need to adapt by using strategies such as night purge ventilation.

[5] The standard, valid when monitoring was done, has been superseded by BS EN 16798-1:2019 [38]

4.2.2 CO_2 concentrations

As buildings are mechanically ventilated in this school most spaces had an adequate fresh air supply during occupancy hours. The daily averaged value of 1500 ppm, recommended by BB101:2006, was the basis of the design [34]. Figure 8 shows that CO_2 levels during the heating and non-heating season in the monitored space were always under 1500 ppm except for the classroom where the CO_2 sensor for ventilation control was faulty.

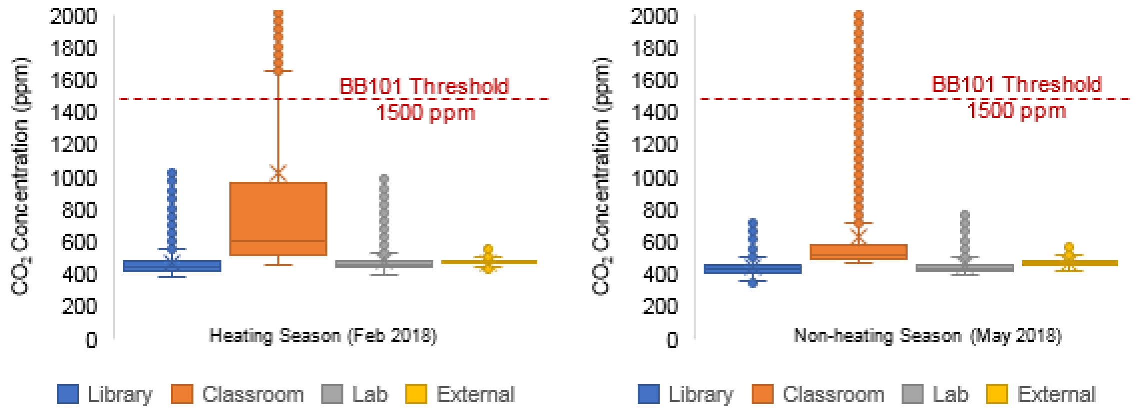

Figure 8 Indoor monitored CO_2 concentrations for all hours in Feb and May 2018

4.2.3 Particulate Matter

Being mechanically ventilated, the buildings have good airtightness and the fresh air intake was controlled and filtered. $PM_{2.5}$ and PM_{10} concentrations in the monitored spaces were always below external values and significantly below the WHO 24-hour mean threshold of 25 μg/m^3 and 50 μg/m^3 for $PM_{2.5}$ and PM_{10} respectively (Figure 9).

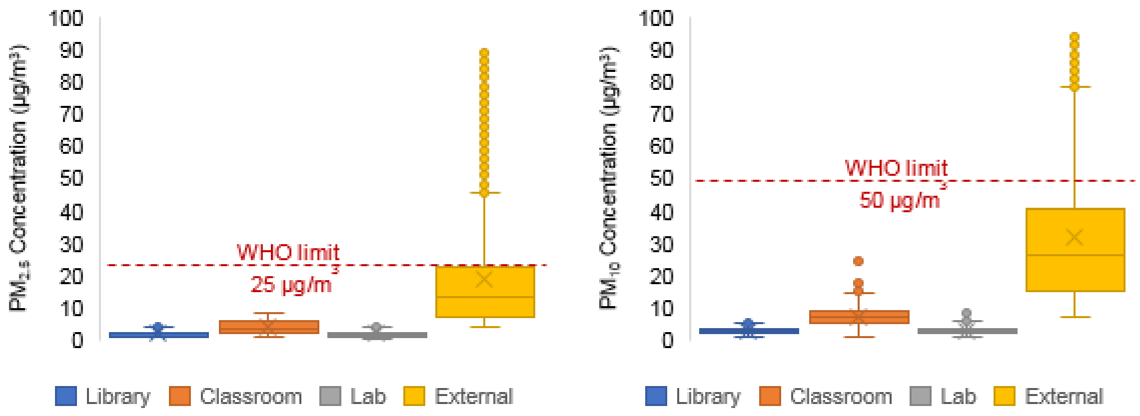

Figure 9 Daily mean PM_{25} and PM_{10} concentrations during heating season (All hours in Feb 2018)

4.2.4 VOCs, NO_2 and O_3

These pollutants were measured through passive sampling. Results (Table 1 and Table 2) show that most pollutants were below the best practice exposure limit values [35], except for benzene, formaldehyde and NO_2. The comparison with outdoor concentration levels suggests that the exceedance of benzene limits can be attributed to outdoor sources, mainly traffic. The increased levels of NO_2 in the lab, compared to other rooms, was only observed in passive sampling and could be because of particular chemical exposure. Longitudinal monitoring of NO_2 in the school and comparing indoor to outdoor concentration trends and levels did not reveal any serious issue with NO_2 concentrations in the school.

Table 1 Indoor and outdoor concentrations of VOCs (μg/m³) and other pollutants measured with diffusing sampling during the heating season.

	Lab (μg/m³)	Classroom (μg/m³)	Library (μg/m³)	Outside (μg/m³)	Limit *[35]* (μg/m³)
Benzene	**<1.90***	**2.50**	**2.10**	**2.60**	0.20
Toluene	<1.60*	3.50	1.60	1.70	250.00
Trichloroethylene	<0.90*	<0.90*	<0.90*	<0.90*	2.00
Tetrachloroethylene	<1.10*	<1.10*	<1.10*	<1.10*	100.00
Styrene	<1.00*	3.60	<1.00*	<1.00*	30.00
Naphthalene	<0.80*	1.00	<0.80*	<0.80*	2.00
Formaldehyde	<0.13*	<0.13*	<0.13*	1.10	9.00
NO_2	**42.94**	23.49	24.55	**48.61**	40.00
O_3	14.25	5.10	5.18	57.76	100.00
*Indicates the recorded value was lower than the measurement Limit of Detection (LoD)					

Table 2 Indoor and outdoor concentrations of VOCs (μg/m³) and other pollutants measured with diffusing sampling during the non-heating season

	Lab (μg/m³)	Classroom (μg/m³)	Library (μg/m³)	Outside (μg/m³)	Limit *[35]* (μg/m³)
Benzene	**<1.90***	**<1.90***	**<1.90***	**2.60**	0.20
Toluene	<1.60*	2.20	<1.60*	1.70	250.00
Trichloroethylene	<0.90*	<0.90*	<0.90*	<0.90*	2.00
Tetrachloroethylene	<1.10*	<1.10*	<1.10*	<1.10*	100.00
Styrene	<1.00*	4.20	<1.00*	1.20	30.00
Naphthalene	<0.80*	<0.80*	<0.80*	<0.80*	2.00
Formaldehyde	5.10	1.33	**12.94**	1.80	9.00
NO_2	17.31	13.02	11.26	20.38	40.00
O_3	31.39	6.07	4.58	72.15	100.00
*Indicates the recorded value was lower than the measurement Limit of Detection (LoD)					

4.2.5 Acoustics

Noise level measurement results ($L_{Aeq\text{-}5min}$) for the sample spaces were as follows: Library: 50.1 dB; Classroom: 42.7 dB; Lab: 33.1 dB; and Common Space: 47.5 dB. The background noise levels show that the spaces were relatively quiet, thus more emphasis was put on the RT as a proxy for the acoustic quality of the spaces.

The RT values, in Figure 10, show that in the middle frequencies (500-1000 Hz), values typically ranged between 0.6-0.9s for the classroom, 0.9-1.2s for the library, and 0.5-0.8s for the science lab. These are within BB93 requirement of average value being ≤ 0.8s for classroom and lab, and ≤ 1.0 in library. The common space, however, with exposed thermal mass and no acoustic tiles, stands out due to high RT values (BB93 requirement of 0.8-1.2s) with a peak value of more than 2.0s in the 500-1000Hz frequencies. This points to the significance of measures such as acoustic rafters or tiles to ensure acoustic criteria will be met where exposed thermal mass is part of the environmental strategy of a building.

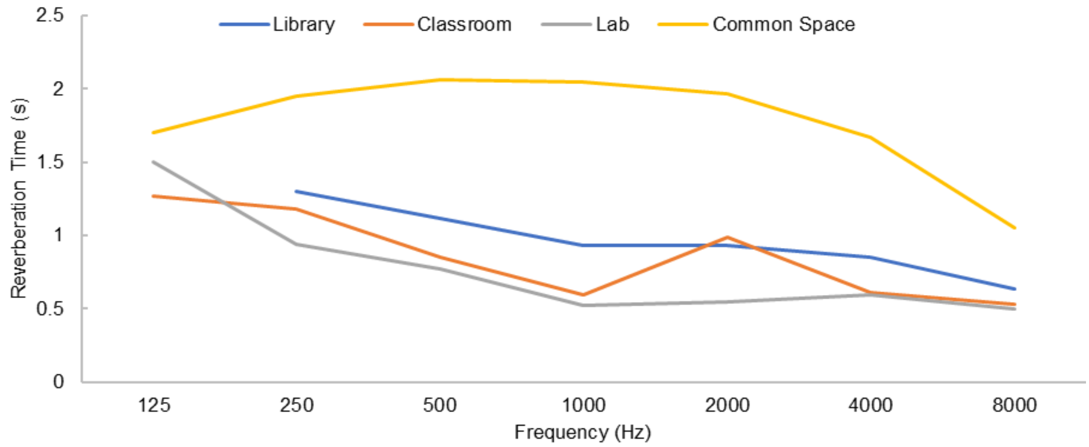

Figure 10 Reverberation time as a function of frequency for the four investigated spaces

4.2.6 Lighting

Both classrooms assessed were fitted out with appropriate lighting equipment that was capable of providing enough light for activities and had separate controls for the row of luminaires near the windows and for those in the rest of the space.

The provision of large windows provided good daylight but during the early stages of post-occupancy a few spaces lacked blinds. This led to glare issues, which were reported in discussions with the occupants and building managers. While this was recognised and rectified, in Classroom 1 blinds were still missing from eastern windows. Furthermore, day-linking of the luminaires was not appropriate in either classroom. While in Classroom 1 the automatic controls were never configured, in Classroom 2 luminaires near to the window were very dim. Figure 11 shows that luminaires near the window (back left luminaire) were set up incorrectly and five minutes after being switched on, dim to around 7% regardless of the amount of daylight. Figure 11 also shows that the PIR sensor was not effective as the other room luminaires (mid right luminaire) were constantly on most of the day. These findings point to the commissioning issues related to automated lighting control.

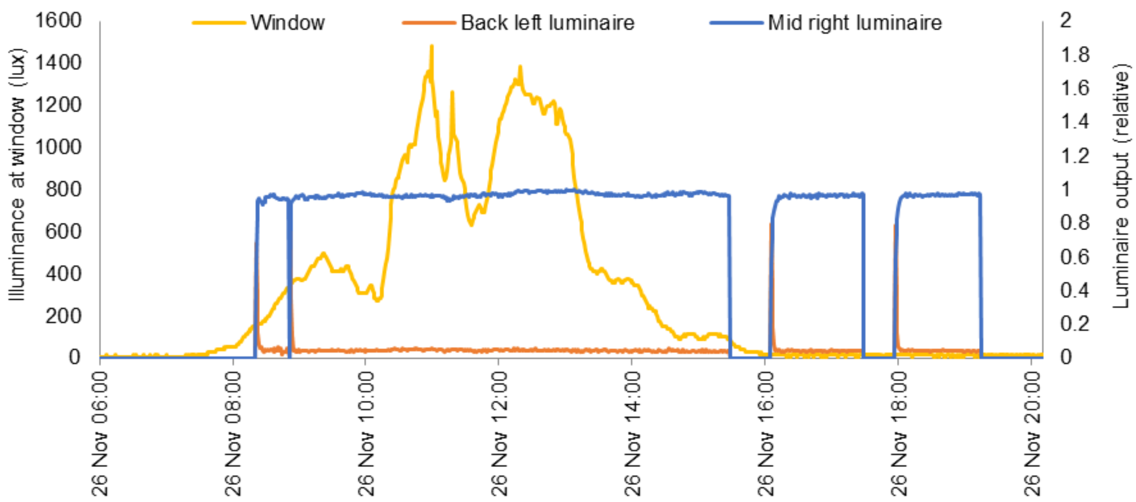

Figure 11 Failure of automated lighting control, Classroom 2

5.0 Performance analysis, root causes, and potential solutions

5.1 Energy

The higher than intended energy use for both gas and electricity was partially due to some technical issues with building systems, but the main reason was suboptimal operations and their maintenance. Some of the identified deviations are listed below.

Occupancy: During term time, the school was considered occupied during the day, but all the individual spaces were not occupied for the whole time. They followed the classroom timetables provided. During term breaks the school was not completely shut; extra-curricular activities and events take place, especially during the summer holidays. This was seen in the school's half-hourly load profiles. More realistic calculations should be undertaken for performance estimations and baseline identification at the design stage. This is important because occupancy patterns affect the building servicing strategy, and any significant changes to occupancy patters need corresponding modifications and improvements to servicing strategy. This has been further discussed in sections below.

Operational inefficiencies Lights in the circulation areas, computers in ICT rooms, heating system and MV systems were operational even after the end of the classes. During out-of-hours and half-term breaks, when there is very low occupancy, mechanical ventilation and heating are provided to multiple zones. The supply fan during unoccupied times was operating at 30% to 40% of its nominal speed, a necessity for operational fans due to reduction of cooling capacity in the motor at lower speeds. However, turning the system off outside core hours and relying on operable windows for fresh air could save a significant amount of energy especially during non-heating season. Additionally, the heating system maintains an elevated temperature in the range of 22-23°C or higher in the winter season, which is more than the intended setpoint temperatures of 20°C (Figure 6).

HVAC system equipment: The Specific Fan Power in AHU specification sheets was 66% high than the values used in the design stage estimations of 1.8 W/l/s.

Thermal performance of the envelope: The results of in-situ U-value measurements in one section of the external envelope showed that the values were much higher than design calculations. Measured U-values were in the range of 0.72-0.78 W/m^{2}K, significantly higher than the design value of 0.25 W/m^{2}K. This suggests that construction issues related to poor insulation and thermal bypasses can partly explain the increased heating energy use.

Along with the above factors, another reason for a poor DEC rating was that low carbon strategy of using biomass as the primary heating fuel was not followed. A biomass boiler was installed to provide more than 50% of the total heating demand (including DHW) with the intent of decarbonising energy use, a measure recommended by the local council. However, the biomass boiler was never used, and heating was provided using gas-fired boilers, due to practical and logistic issues of using biomass as fuel. Finally, some of the performance issues can also be attributed to the fact the actual energy use also includes the two possibly underperforming existing buildings that were refurbished.

5.2 IEQ

Thermal Comfort: Temperature and RH monitoring graphs show that heating system operation and pre-conditioning of fresh air from MV system were appropriate. Also, there is a high level of airtightness in the buildings (design airtightness: 5 $m^3/hr/m^2$ @ 50 Pa) as the sampled zones are able to retain heat and temperatures overnight during the heating season (see term time temperatures in Figure 6). However, temperatures measured in some of the south facing zones pointed to the risk of overheating in summer. These issues were exacerbated by the airtight envelope and inadequate number of operable windows in the classrooms. Figure 7 shows the increased indoor temperatures on hot summer days in the classroom as the MV system was not operational in one building due to maintenance issues and windows were not able to provide enough fresh air. In these situations, night purge ventilation could be used a strategy to mitigate overheating risks during hot spells.

Air Quality: Fresh air availability in indoor spaces was generally good with low levels of CO_2 concentrations except in the building with the malfunctioning MV system (Figure 8). The MV system effectively controlled the ingress of micro particles (Figure 9). However, Benzene and NO_2 concentrations (Table 1 and Table 2) suggest that there might be a need for additional measures such as activated carbon filters to protect building users against other outdoor sources of pollution in urban environments. Low levels of VOCs indicate appropriate indoor finishes and material selection.

Acoustics: The acoustic underperformance of the building was conflicting with the exposed thermal mass requirements. As seen in Figure 12, classrooms, stairwells and common spaces, all have exposed concrete ceiling for exploiting the use of thermal mass for better thermal comfort and energy efficiency. However, this leads to a conflict with acoustics because of longer reverberation times (as seen in Figure 10) and noise transmittance through the structure. While acoustic measures were taken in study spaces, baffling in the stairwells and exposed ceilings and acoustic breaks in construction assemblies can be used to avoid noise issues and its transmission between the spaces as reported by building occupants.

Lighting: Glare prevention is particularly important in schools. Excessive glare hinders teaching as interactive screens, projectors and whiteboards become difficult to read. Glare also has adverse health effect for students suffering from migraines [36]. Blinds, while reducing some natural light, are an easy solution to avoid glare. Regarding the artificial lighting, the problems with automated lighting controls (as seen in Figure 11) were likely due to poor commissioning; the daylight sensor in Classroom 2 had incorrect configuration of the photocell, the PIR sensor also had a long time-off setting.

5.3 Balancing other energy and IEQ requirements

It is a challenge for designers to balance the energy efficiency and the IEQ performance due to potential conflicts between these performance objectives. Besides the conflicts noted earlier, another key determinant of the performance gap is the complexity and disaggregation of building controls. The building services control strategy in this building was not responsive enough to partial demand during out-of-hours use. This results in unoccupied spaces being heated during transitional occupancy times, leading to excessive energy use (see Figure 6 – holiday time). The zoning arrangements of environmental sensors and the building’s control strategy could also benefit from refining and fine-tuning. One space controlling the temperature in other teaching spaces was observed in the monitoring.

The issue with automated lighting sensors in the classroom affected both energy and IEQ. While the unnecessary dimming of some of the lights led to dark areas and uniformity issues, the longer time-off settings of PIR meant that lights remained on for longer than necessary. Generally, provision of operable windows for natural ventilation and comfort cooling in summer needs to address outdoor noise ingress issues. However, it also needs to be integrated within lighting comfort requirements. While the outdoor noise was not a major issue in the school, use of roll-up blinds for glare prevention was. As internal blinds conflict with airflow from open windows because of rattling an integrated design solution for the façade balancing all requirements is required.

6.0 Discussion

Current regulations focus on meeting the *compliance* requirements and do not sufficiently ensure that the design intents translate into *actual* performance. This school's energy consumption is higher than the typical benchmarks, with the gas energy use significantly higher than expected. This is due to the combination of extended hours of operation, operational inefficiencies, and maintenance issues. Moreover, the biomass boiler, although installed, has never been put into function. Consequently, the operational DEC rating of the school is currently F. IEQ performance in terms of thermal comfort and IAQ is generally within acceptable levels except overheating during very hot summer spells in some classrooms and exposure to pollutants that cannot be controlled with particle filters (F type). While there were some design-related acoustic issues in common areas, lighting controls sensors had major problems with their commissioning. Findings in this building performance assessment are case specific but they do project some larger industry-wide issues. In this section, these factors are looked at in a broader context.

6.1 Delinking regulatory compliance calculations and design projections

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 or equivalent protocols, accounting for all end users in the building alongside realistic operating patterns and occupant behaviour [5].

6.2 Flexible designs for the changing trends of building use

Buildings continually evolve in the way they are used, and this leads to a difference in the perception of how a building operates to what is the reality. These days it is common for school buildings to have partial occupancy during half-term breaks and they are also occupied after normal operating hours for extracurricular activities. Even during term times, some spaces were not fully occupied throughout the day. As building uses become more flexible, optimum space-time utilisation is a cost-effective way of saving energy. Strategies such as demand-controlled ventilation should be used effectively. Moreover, hydraulic isolation of heating/cooling zones that are not occupied would ensure that large areas are not unnecessarily conditioned in these buildings.

6.3 Safeguarding low-carbon technologies

A biomass boiler was installed in the school to meet the CO_2 emissions criterion of Part L of the Building Regulations and the local council's intention to use and promote low carbon technologies in the borough. However, this system was not operational post-handover, due to logistic limitations of running it and disagreements between the school management and the council. This meant that the expected CO_2 emissions of this building were significantly higher than what was assumed on the completion of the building. At the policy level, steps are required for not only enabling smooth integration of new technologies with conventional practices but also safeguarding them and encourage their use.

6.4 Enhanced stakeholder engagements

The issues observed in acoustic and lighting performance, easily rectifiable, were linked either with design stage oversights or poor commissioning. It is common that after the handover, engagement of design and construction team with the building is minimal. This means that most focus is on delivery and system functionality rather than performance. Shortcomings in commissioning and qualitative design issues subsequently identified largely remain unaddressed. Enhanced engagement within all stakeholders along with accountability of people delivering the building is necessary to ensure that the building performs as expected both an energy and IEQ fronts. Soft Landings [37], and performance contracting approaches can be used as frameworks to achieve it.

6.5 Improvements in managing of building operations

Most of the energy performance gaps were due to sub-optimal operation and maintenance issues related to building systems. This was partly due to a coarse and centralised system design (one control and sensor for many zones) and lack of user-friendly BMS controls to manage it. A more streamlined building operation and management strategy envisaged in design and incorporated at handover would enable a building to operate reasonably close to what is assumed at the design stage.

6.6 Ventilation strategies in urban areas

A natural ventilation strategy may not be suitable for dense urban environments where external air can be more polluted than indoor air. MV systems provide the necessary controls and create more airtight envelopes. The industry's main metric for assessment of IAQ is currently CO_2 concentrations. Most existing control strategies for ventilation systems also use this metric. In mechanically ventilated buildings filtration is used to provide a level of protection against outdoor sources of pollution such as micro-particles. While, this was not an issue in the case study building, however, some traffic-related pollutants (such as benzene, NO_2) are not mechanically filtered and advanced activated carbon filters or other measures are required to enact chemical filtration.

Additionally, advanced control strategies that consider the balance between requirement for fresh air and protection from outdoor sources of pollution could provide a healthier environment and at the same time save energy in both mechanically and naturally ventilated buildings that rely on automated ventilation. Provision of natural ventilation through operable windows or vents, when specified, should consider interdependent aspects of acoustic and visual comfort requirements.

6.7 Design reliance to mitigate the future climate risks

Current building design and operation strategy catering to today's climatic conditions shows indications of overheating risks in hot summer spells in certain zones. In the context of future climate, where we expect warmer spells, this risk can become significant. The future performance can be tested using future climate data in building performance simulations.

In this building, the current building systems (with no mechanical cooling) would be able to provide comfortable environments until they are required to be refurbished or replaced at the end of their life. Modifications to environmental strategy to cater to a changing climate can be undertaken then. However, at this stage, the building design itself could be made resilient and adaptable so as to avoid major disruptions during retrofits. Passive solutions such as integrated shading design, energy efficient strategies such as night purge ventilation and low energy technology such as circulation fans could be adopted or planned for future retrofits.

7.0 Conclusions

This study identified several lessons that can potentially be used to inform and improve current building design practices. The findings regarding performance issues might be specific to the case study, especially the technical issues regarding building systems. However, the significance of optimal operations and maintenance of building systems for better energy and IEQ performance has applicability for other schools in general.

Summarising the discussion in the previous section, firstly, at the design stage it is important to predict energy use accounting for all end uses and probable variabilities that might occur during operations. The changing trend of schools' occupancy patterns in general, beyond regular school hours and term times, needs to be considered when estimating performance. Factoring resilience in design, in the context of climate change, safeguards the performance of the building over its entire lifecycle.

Addressing energy and IEQ performance holistically is important so as to ensure that energy efficiency is not achieved at the expense of IEQ and other aspects of building performance. For example, ventilation strategies should be balanced with acoustic comfort requirements and external pollution in dense urban environments need to be addressed for both naturally and mechanically ventilated buildings.

At the policy and regulatory level, robust safeguards, such as measurement and verification of building and system performance in the first few years, are needed to ensure the installed low or zero carbon strategies and technologies will be used in practice. This can be supplemented by a Soft Landings [37] or performance contracting approach, in which the designers, contractors and building managers are accountable and a stakeholder in ensuring the operational performance of the building. The purview of performance contracting should account for specific requirements for both energy and IEQ (Environment and Energy Performance Contracting).

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