Improving the Energy Performance Contracting Process using Building Performance Simulation: Lessons Learnt from a Post Occupancy Investigation of a Case Study in the UK

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Abstract

There is a niche trend to use 'Energy Performance Contracts' (EPCs), for new buildings to ensure that minimum energy performance is achieved in practice. Building Performance Simulation (BPS) help to estimate performance and assess risks during design, construction and operational stages. This paper reports on an office building in the UK that has been procured under an EPC. The current performance shows that it will be challenging for the building to achieve the target. Being one of the first new buildings in the UK to be subjected to an EPC, analysis of the design, construction and operation process, provides insights into the specific issues related to building procurement and operation. It is suggested that scenario analysis, accounting for uncertainties and dynamic BPS should be used throughout the procurement process to quantify and manage the risks associated with performance targets. The paper also identifies that if performance targets are not defined comprehensively, there can be unintended consequences that lead to underperformance.

Introduction

Building Performance Simulation (BPS) is used to assess and improve performance throughout a building's life (Design, Construction, Operation, & Retrofit). To address concerns about 'performance gaps' and to realise a minimum level of energy use or CO_2 emissions, some new buildings are subjected to EPCs ('Energy Performance Contracts') (The Carbon Trust, 2011), (Burman, et al., 2012), (Zero Carbon Hub, 2014), (van Dronkelaar, et al., 2016), (Palmer, et al., 2016). In Europe, performance contracting is driven in-part by the Energy Efficiency Directive (EED) and the recast of the Energy Performance of Buildings Directive (EPBD). In the UK, the Display Energy Certificate (DEC) scheme rates a building's operational performance relative to a typical building. DECs use net CO_2 emissions associated with a building's operational energy use as the metric. This standardised system, therefore, may be used as a basis for EPCs.

As buildings under EPCs must meet a quantitative target, an accurate estimate of performance and associated risks is necessary. BPS is the most commonly used method as it can compute, analyse, and optimise the performance and quantify the associated risks.

The Best Practices Guide for Model EPC from the UK (DECC, 2015) identifies various points for consideration when using the contract. One of the key points for consideration is that, with explicit focus on 'energy performance' there is a possible trade-off between energy savings and Indoor Environment Quality (IEQ).

This paper reports on an office building in the UK that has been procured under an EPC to achieve 'DEC A- rating. Analysis of procurement process, comparison of designed and operational performance along with scenario and Sensitivity Analysis (SA) of the building's energy model is done using the evidence collated from the building.

The main objectives of the work are

1. Establish the performance gap in the building.
2. Explain the root causes (technical and process related) of the gap and verify them by BPS and interviews.
3. Identify potential improvements to close the gap.
4. Identify opportunities for improving the EPC process and explore the role of BPS in EPC project delivery.
5. Explore unintended under-performance in IEQ.

The paper first provides a background to the issue of the performance gap, EPCs and performance parameters used in EPCs. Then the as-designed building, its procurement route and technical aspects are defined. Next, the current performance gap is reported and the reasons for the gap (technical and process related) are identified and validated using BPS. Potential improvement opportunities in the process and operations are then identified. Finally, initial findings of IEQ monitoring are presented and analysed.

Methodology

This paper addresses the value of BPS in EPC projects via a case study. Initially, the building's actual performance, assessed by monitoring disaggregated energy use, Indoor Air Quality (IAQ) and thermal comfort, was compared to the as-designed performance. Then, based on information collated from design and construction documentation, building performance evaluations and semi-structured stakeholder interviews, reasons for any identified performance gap were explored. A calibrated energy model was used for scenario and SA to identify and validate the root causes for the gap, also identifying the potential building specific and EPC process related improvements. Comparison of IEQ performance with benchmarks was undertaken to identify any potential unintended underperformance. Figure 1 shows a detailed step-by-step method used to achieve the various objectives in the paper.

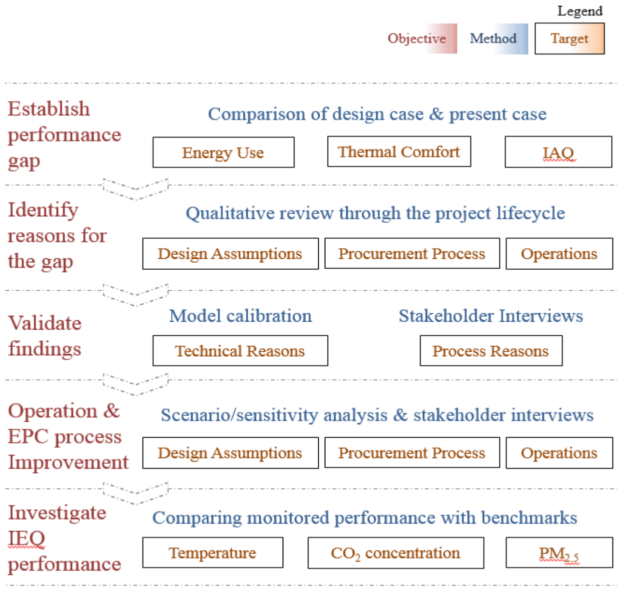


Figure 1: Objectives and methods used

Background

The performance gap and EPC Projects

There is an increasing pressure to address concerns about the energy performance gap that can be more than twice the predicted energy use (Bordass, et al., 2001). While some uncertainty in performance is inevitable, the present discrepancies between the design intents and actual energy use are too wide to be acceptable. To deliver buildings that meet the targeted high performance ambitions through the building lifecycle, there is a need for improved models of building delivery. In the 'performance-contracting' model, building users effectively purchase a working environment with specified comfort boundaries rather than hardware (building and systems) that might – or might not – deliver such an environment (de Wilde, 2014). A report on closing the performance gap highlights the importance of a streamlined approach to build high performance buildings (The Carbon Trust, 2011). The report also emphasises the importance of the involvement of the contractor and designers *after* the handover to fine tune the building and ensure low carbon objectives. Performance contracting integrated within initiative such as Soft Landings (SL) (Way, et al., 2009), which promotes extended involvement of the design and contracting team, helps to ensure that these objectives are met.

While the performance-contacting makes the designers and contractors accountable and a stakeholder in ensuring the operational performance of a building, it raises certain challenges. One of the challenges is to objectively define the targets and the metric to use i.e. ensuring that the metrics are in alignment with the actual intent. Another challenge is the contractual period for ensuring the intended performance is achieved. In such projects, if key sustainability measures that are beneficial in longer term are not safeguarded from the start, some may be value engineered out within the construction process depending on the period of the contractual obligations.

Use of BPS in EPC Projects

BPS usually is used for delivering a project subject to an EPC (RMI, 2004). Performance prediction of buildings relies on many assumptions. Uncertainty and variation in these assumptions is a concerning. As it is possible to use BPS to adjust for operating patterns, weather and other factors, BPS can provide insights to effectively mitigate the key risks and still ensure performance, especially the risks originating from factors beyond their control.

Performance targets in high-performance buildings

Besides energy use or carbon emissions associated with it, the performance gap also applies to parameters such as temperature, relative humidity, air quality (pollutants, CO_2), noise and lighting (Tuohy & Murphy, 2015) (Fabbri & Tronchin, 2015) (Phillips & Levin, 2015). Energy use reduction alone is worthless unless it allows buildings to perform their desired functions; to be healthy, comfortable and productive places to live and work in. There is a direct relation between occupant well-being and comfort and IEQ in buildings (Wyon & Wargocki, 2013) (Chatzidiakou, et al., 2014) (Al Horr, et al., 2016).

Buildings constructed with a low carbon objective under an EPC are intended to achieve a specific energy use and carbon emissions target. However, mostly, this is not the case for IEQ parameters. While, adhering to IEQ performance standards is an essential aspect at the design stage, the actual performance post-construction is not usually contracted in the EPCs. Energy and carbon emissions reductions are the primary, and often the only, objective in high performance buildings (Phillips & Levin, 2015), (Fabbri & Tronchin, 2015).

The ways to achieve high IEQ (temperature, lighting, IAQ, acoustics, etc.) and building user satisfaction objectives might contradict measures to achieve better energy performance. Therefore, if the focus is *only* energy or carbon emissions, this can lead to the unintended consequence of poor IEQ in buildings.

Display Energy Certificate

A Display Energy Certificate (DEC) is an operational rating used in the UK that identifies the actual energy performance of a building and compares this against a benchmark building of the same type. The operational rating is a comparative numerical indicator of the actual annual CO_2 emissions associated with the building's energy use.[1] The rating, from 0 to 150+ is on a A to G scale (band of 25 points each). A band is the best rating and G band is the worst. A building which has the same emissions as the benchmark building will have a rating of 100 (lower end of band D) and a building that resulted in twice the typical CO_2 emissions would have an operational rating of 200 (band G of 150+). If the building has on-site energy generation from renewable sources, the emissions reduction achieved due to any export of such

[1] *Emissions factor for each fuel is provided by UK government in a Central Information Point (CIP) database.*

energy is deducted from the building's carbon emissions. If the building is a net energy generator, it would still be given an operational rating of zero. DEC- A rating means that the building's carbon emissions are 75% less than a typical building of the same type in the UK.

Case Study Building

The office building (~6500 m^2) used as the case study is in CIBSE weather region 5 (Nov'15- Oct'16 Degree days: Cooling =300; Heating = 1499). It was designed to achieve a DEC-A rating by the second year of operation. This section explains the as-designed building. As per the design stage documents provided by the design team[2] details about the building fabric, occupancy and technical cum operational parameters of building services are listed in the Table 1, Table 2 and Table 3 respectively.

Procurement process

To ensure that the project teams are responsible for the operational performance of the building, it was built under an EPC and followed a Design & Build (D&B)[3] procurement route. Initially, a conceptual design was developed for the tender stage. The main contractor was then appointed to develop a detailed design and execute as per the concept, while ensuring the energy performance targets are met. While the contractor and their appointed designers developed the detailed design, the concept design team was always engaged to review the process.

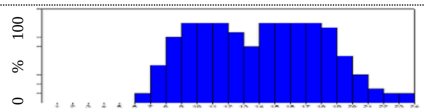
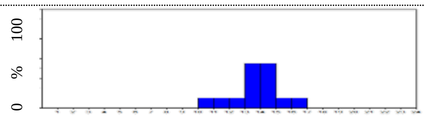
Architectural Design

The fabric is highly insulated and the architectural design promotes passive design. Narrow floor plates, connected by atriums and cut-outs, create an interconnected and open environment, have deep natural light penetration and enhance natural ventilation by creating a stack effect.

Table 1: Fabric Details

Walls	U-Value = 0.15 W/m^{2}K
Windows	U-Value = 1.4 W/m^{2}K, SHGC = 0.4 (North -0.7), VLT = 0.69
Roofs	U-Value = 0.15 W/m^{2}K

Table 2: Occupancy details

General Office - Weekdays (24 hrs)	
Meeting Rooms- Weekdays (24 hrs)	
Weekends	Nil

HVAC Systems Design

The building is primarily naturally ventilated and cooling is only provided for meeting rooms by chilled beams. Trench heaters heat all offices and meeting rooms. There is underfloor radiant heating in circulation and common areas. Toilets and other enclosed occupied spaces have dedicated mechanical exhausts.

Heating is primarily provided by heat pumps that can produce simultaneous heating and cooling and is distributed to the building via heating and cooling buffer vessels[4]. The heat pumps are also designed to satisfy the cooling needs of the IT server room. But, the heat pumps only operate if there is a heating demand in the building. If there is no heating demand, then a free cooling chiller[5] satisfies cooling needs, via a chilled water buffer vessel. The amount of heat produced by the heat pumps is insufficient for the building heat load when the external temperature is low and/or the building is unoccupied. When additional heat is needed, it is provided by modular condensing gas fired boilers which are designed to meet the peak loads and give full back-up. When working in heat transfer mode, the heat pumps have a maximum combined Coefficient of Performance (COP) (40% cooling / 60% heating) of 6.5. The Energy Efficiency Ratio (cooling mode, full load) is 2.75 and Heating COP (full load) is 2.31. The boiler seasonal efficiency is 95.6%.

There are two heating loops, one constant temperature loop that runs at a fixed flow temperature of 45°C and other a weather compensated variable temperature loop running at a maximum of 65°C during boost time.

Natural ventilation, by means of vents controlled via Building Management System (BMS), is based on CO_2 concentration and temperature. A night-cooling strategy is specified to keep the open plan offices cool in summer. Manually openable vents and windows are also provided.

Lighting and Electrical Systems Design

The building, designed to be largely daylit, uses low energy artificial lights. In open plan office areas, general background lighting is provided to defined circulation routes with additional free standing up/downlighters for the desks. Lights are dimmable and are controlled by Passive Infra-Red (PIR) and daylight sensors.

The building has low energy equipment and thin client computers. There is a constant server load in addition to other loads including catering, lifts, actuators, CCTV, etc.

Metering strategy and On-Site Energy Generation

There are separate meters for all systems and end uses to record the disaggregated energy use in high resolution. Separate meters are provided for heating, cooling, hot water, lighting, small power, servers (electrical and cooling), pumps, vents, lifts and PV generation. All uses are broken down per floor and per zone except where the total end use is less than 0.5 kW. The meters are designed to be integrated to a BMS systems.

The building has a rooftop Photovoltaic installation of 210 kWp with an area of approximately 1000 m^2.

[2] *To maintain anonymity of the stakeholders, details that could identify the building have been withheld.*

[3] *A procurement route where the main contractor is appointed to the design and the construction following an initial concept design. It is opposed to a traditional contract where consultants make the design and then the contractor is appointed to construct (Design-Bid-Build).*

[4] *Buffer vessels are storage tanks that act as an interface between the primary and secondary sides of heating/cooling systems.*

[5] *Free cooling chiller cools a building by using outside air directly when outside air is at a lower temperature than indoor air, instead of mechanical cooling following a refrigeration cycle.*

Table 3: Building Services Operations and loads detail

End Use	Details
Heating	Operation: 07:00 to 20:00 (warmup at 06:00); Set point: 19°C; Set back: 12°C
Cooling	Operation: 10:00 to 17:00; Set point: 23 °C
Pump + Aux; Mech. Vent.	Load: 0.5 W/m^2 (Pumps: 2.5 kW; Fans: 0.7 kW) Operation: 09:00 - 19:00
Int. Lighting	Loads: 5 W/m^2 – daylight integrated; Operation: 4 hours per day
Server Elec.	Loads: Peak 29 kW; Standby 15 kW Operation: Peak: 09:00-19:00 Mon-Fri
Small Power	Load: 10 W/m^2; Operation follows occupancy
Miscellaneous	Load: 10 W/m^2; Operation follows occupancy

Performance targets

As noted the building is designed to achieve a DEC-A rating and net annual emissions[6] of 16.22 kgCO_2/m^2. To achieve a DEC-A, the building's emissions need to be 75% less than the DEC typical office, the DEC typical office's net annual emissions are 75.12 kgCO_2/m^2. Thus, annual emissions need to be less than 18.78 kgCO_2/m^2.

To achieve acceptable indoor environment BSEN 15251:2007 (BSI, 2007) along with Part L (DCLG, 2013) and Part F (DCLG, 2010) of UK Building Regulations were followed. These provide design stage overheating, ventilation, lighting and acoustic targets. However, there is no evidence of *specific* operational IEQ performance objective in the design & construction documents.

Measures to ensure performance

To ensure a DEC-A rating and to aid a smooth transition from design to construction, a risk matrix was created at the concept stage. The main risks identified were value engineering, controls' optimisation, user behaviour and small power loads. Technical compliance parameters for mechanical and electrical systems were also pre-defined at concept design stage, to be followed during detailed design development. Measures such as the SL framework, a robust metering strategy and creating Change Champions for the operational stage were identified to mitigate deviations. Post-construction contractor involvement was ensured to address operational issues within the SL framework, which allows for building fine tuning and after care activities for up to three years.

Building Energy Performance

Building's predicted vs operational performance

The actual performance from November 2015 to October 2016, two years after building handover and following initial fine-tuning, although encouraging, shows that the building was not, at that point, operating at a DEC-A level. The contractor and the Facilities Management (FM) are still working to optimise the performance under the SL framework. Table 4 and Table 5 show the designed and actual performance in terms of energy use and carbon emissions respectively. Figure 2 and Figure 3 show monthly gas and electricity use respectively. The design projections are from the design documents and actual use is based on meter readings collected by the contractor.

Table 4 shows that there are discrepancies in designed and actual performance for almost all end uses. A big variation is seen in the gas used for heating. The design stage heat demand estimate for heating and hot water was 28.7 kWh/m^2. As the heat pumps were designed to use rejected heat from the servers to heat the building, the effective energy use estimated was 18.9 kWh/m^2 (13.9 kWh/m^2 gas use by boilers and 5.0 kWh/m^2 electricity use by heat pumps). Technical issues caused the heat pumps to malfunction with a consequence that boilers provided all the heat. Issues with the system are elaborated later.
In addition, under predictions are also seen in small power and lighting with deviation of 75% & 123% respectively. The actual electricity used by the servers is 42% less. This is due to the overestimation of the server load. The energy generated by the PVs is about the same as in design case.

Table 4: Energy use performance comparison

Criteria	Designed (kWh/m^2)	Actual (kWh/m^2)	Diff (%)
Total Energy (Gas + Elec)	14 + 57	29 + 68	+37%
Heating & Hot Water (Gas+Elec)	*13.9+5.0*	*28.85+0*	*+53%*
Cooling energy (Elec)	*0.17*	*0*	*NA*
Pumps + Mech Vent (Elec)	*1.73*	*9.97*	*+478%*
Int. Lighting (Elec)	*5.00*	*11.13*	*+123%*
Ext. Lighting (Elec)	*1.11*	*0*	*NA*
Small Power (Elec)	*16.49*	*28.89*	*+75%*
Catering (Elec)	*0.85*	*1.60*	*+89%*
Server Elec (Elec)	*26.42*	*15.19*	*-42%*
Lifts (Elec)	*0.28*	*0.72*	*+159%*
PV Generation (Elec)	31.22	30.43	-3%
Net Energy (Gas + Elec)	14 + 26	29 + 38	+67%

Table 5 shows that, based on the current performance, the building is achieving a DEC-B rating. The net carbon emission, at 25.12 kgCO_2/m^2, is 50% more than the DEC-A target of 18.78 kgCO_2/m^2.

Table 5: Carbon emissions comparison

Criteria	DEC -A	Designed	Actual
CO_2 generated (kgCO_2/m^2)	-	32.32	40.85
CO_2 offset (kgCO_2/m^2)	-	16.10	15.73
Net CO_2 (kgCO_2/m^2)	18.78	16.22	25.12
DEC Points (Rating)	25(A)	22 (A)	33 (B)

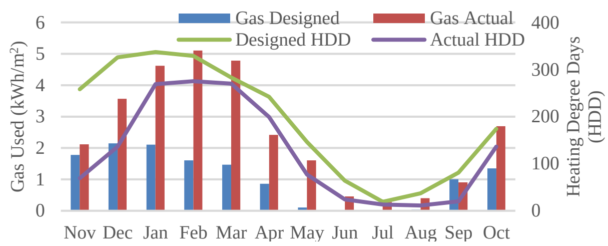


Figure 2: Monthly gas use (Nov-15 to Oct-16)

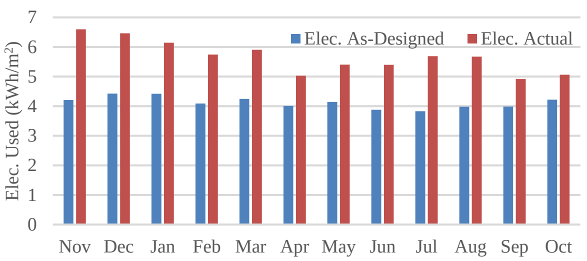


Figure 3: Monthly electricity use (Nov-15 to Oct-16)

[6] All emissions are calculated using *emission factor in the UK for gas and electricity. 0.198 kgCO_2/kWh for gas and 0.517 kgCO_2/kWh for electricity. Emissions factor for each fuel is provided by UK government in a Central Information Point (CIP) file.*

It should be noted that comparing the current performance with the very stringent target shows a magnified level of underperformance for an otherwise, contextually, well performing building. Table 6 compares the building's performance with similar buildings in the UK and UK benchmarks[7]. Compared with other similar naturally ventilated open-plan public office buildings in the UK, this building's emissions are 43% less than the median (Hong & Steadman, 2013) and 54% less than the mean (Armitage, et al., 2015). It is in the top 15% of such buildings. The committed engagement of the design team, the contractors and the client, since project inception, has ensured that performance targets are kept in sight.

Table 6: Comparison with benchmarks

Criteria	Energy Use (Gas + Elec) (kWh/m^2)	CO_2 emission (kgCO_2/m^2)	Diff from benchmark
Current Performance	97 (29+68)	41	-
Similar UK public office[8]	227 (85+142)	90	54% Less
Similar UK public office[9]	187 (84+103)	70	43% Less
CIBSE Guide-F Best Prac[10]	139 (54+85)	55	25% Less

Reasons for the performance gap

To investigate the performance gap causes, firstly the existing documentation and design stage risk matrix were analysed. Then specific potential reasons of deviations from design assumptions were catalogued through walkthrough audits, analysing meter data and semi-structured stakeholder interviews. Finally, using the information, a calibrated energy model was generated to help identify the main contributing parameters.

The design team monitored the predicted performance of the building by keeping an energy budget that addressed various end-uses. Figure 4 shows the energy use projection at various design stages against the actual use.

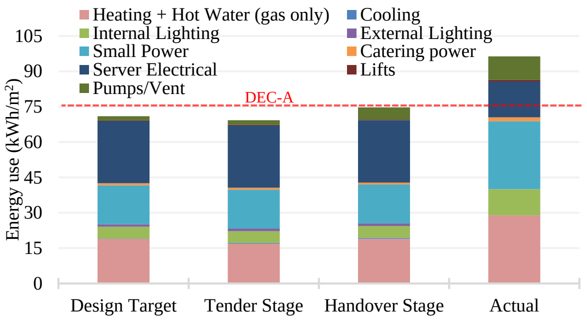


Figure 4: Energy use at multiple design stages

In Figure 4, deviations are seen in the energy use predicted for HVAC system and fans/vent between the design and handover stage due to some specifications changes. For example, due to recalculations, there was a significant increase in the rating of pumps. It increased from 2.5kW to 7.5kW. However, as the schedules and occupancy assumptions were consistent in all calculations until the handover, the emission estimate was still under the DEC-A threshold, at 18.15 kgCO_2/m^2. The actual energy use, appears to be higher than design stage. Despite all the checks and balances in the measures to ensure energy performance, a significant factor for the energy performance gap appears to relate to integration and follow-up in the design and construction processes.

Heat pumps: The building has a complex interdependent heating and cooling strategy. The evidence suggests that the heat pumps have not been very effective as a primary source for heating and cooling because of technical issues with the buffer vessel's heat exchangers and the flow rates. This is also confirmed by both sub-metering and simulation. Consequently, almost the entire heating load of the building has been shifted to the gas boilers and there is no active comfort cooling being provided. Server cooling is also provided by two backup unitary DX chillers. Review of technical specification of heating terminals suggests that the sizing of these terminals is not consistent with the low temperature heating flow required for energy efficient operation of the heating system.

Server room capacity: The original design concept allowed for a server cooling load of 29kW. Whilst the larger cooling load may occur in the future, the current connected load is only 15kW. If, as planned, heat pumps would be providing the cooling, there would be an adverse impact on the efficiency of the heat pumps as there is significantly less free heat available.

Metering: The metering and monitoring strategy was also compromised. As the BMS integration of the meters was not undertaken correctly, identifying of parasitic loads by monitoring the disaggregated energy use is difficult.

Occupancy Pattern: Occupancy was a critical risk in the pre-tender risk register. Use of a smart card to activate thin client or people counter camera was considered to record occupancy, if extended hours were to be used in DEC assessment. However, subsequent documents do not show it being taken forward, thus, making it difficult to create a more accurate benchmark for DEC calculation[11].

Deterministic design assumptions: Certain operational and design assumptions have also contributed to underestimation of operational energy. As per the onsite observations, there is 25-30% higher occupancy and longer occupancy hours in the building, than those assumed in design calculations. This has partially contributed to the higher small power and lighting energy use. Also, as per the BMS settings, the heating set point is 2°C higher. Hot desking, using thin-client IT system, was initially planned for optimum space-time use of building by using flexible work stations and hydraulic isolation of heating and cooling systems in unoccupied zones. However, this was not followed in practice, leading to inefficiencies in the building services operation during out-of-hours use of the building.

These factors are beyond the designers control and the assumptions used appear to be reasonable. But, the documents show that the same assumptions were carried through the entire design, construction, and post-

[7] *The carbon emissions offset by energy generated is not considered*
[8] *Mean value as per DEC rating records* (Armitage, et al., 2015)
[9] *Median value as per DEC rating records* (Hong & Steadman, 2013)
[10] *Reference benchmark for offices* (CIBSE, 2012)
[11] *Relaxed benchmarks can be used if longer occupancy can be proved.*

occupancy stages. Thus, the magnitude of deviations, retrospectively, highlights the need to review and check these throughout building procurement process.

Calculation method: A review of design calculation showed that the building's performance during the transient periods, when the internal heat gain is not sufficient to heat up the building, could not be assessed as dynamic simulation was not used during the concept design. Similarly, the impact of variable volume of air coming by natural ventilation (both for manual and CO_2 based automatic controls) on the heating demand could not be assessed accurately. Use of the same calculation method in further stages kept these issues hidden.

Overall, the available evidence points to the following technical reasons for the energy performance gap:

1. Specification of some of HVAC system components
2. Modifications to the control strategy to overcome the shortcomings with the systems
3. Issues with commissioning
4. Optimistic design stage assumptions
5. Lack of SA for critical factors using dynamic BPS throughout the design and construction process

Testing of the issues by model calibration

A calibrated model was made using the actual operational inputs. Table 7 shows the assumptions and sources of information. DesignBuilder Software using EnergyPlus was used for the simulations. Figure 5 and Figure 6 show the calibrated results. The calibrated model has monthly gas use CVRMSE (Coefficient of Variation of Root Mean Square Error) of 12% and NMBE (Nominal Mean Bias Error) of 3%. For monthly electrical use CVRMSE is 7% and NMBE is 3%.

Table 7: Calibration model settings

Input	Source
Weather	Nearest CIBSE weather file used. Degree Days from Nearest weather station used to normalize the heating use (degreedays.net)
Geometry and Construction	As per Architectural Drawings
Operation and Occupancy	As per site observation and feedback from the facility management team. (specifically, for out-of-hours use)
HVAC and Lighting Controls	As per actual BMS controls and feedback from the facility management team.
Ventilation and Infiltration control	Calculated ventilation and infiltration (*EnergyPlus AIRNET method*). Operation is as per actual BMS controls.
Loads (Lighting, Equipment, Small power, Server etc.)	Load and profiles as per observations on site and feedback from the facility management team.
Heating and Cooling System	As present status, boilers (no heat pump or comfort cooling) with 95.6% efficiency.

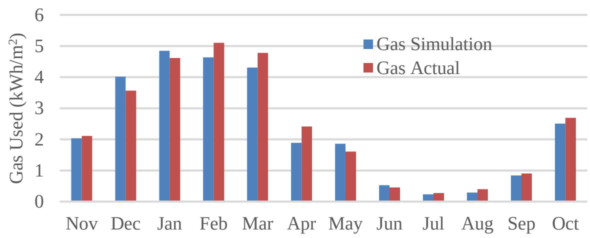


Figure 5: Calibrated Gas Use (Nov-15 to Oct-16)

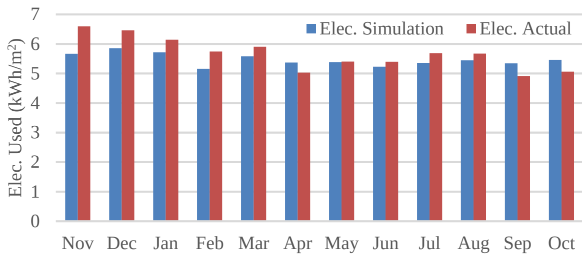


Figure 6: Calibrated Electricity Use (Nov-15 to Oct-16)

Therefore, using the correct weather data, operational assumptions, loads and system configuration, this building's monthly energy use profile could be estimated with an acceptable accuracy as per ASHRAE Guideline 14 (ASHRAE, 2014), i.e. CVRMSE < 15% and NMBE < ±5%.

Scenario Analysis

The calibrated energy model was used for assessing the *'what if'* scenarios, for factors under the design team's control. Figure 7 shows CO_2 emissions for various cases. The first scenario being studied is: *'What if, with current usage patterns, the building systems were technically functional as per the design intent?'* The results show that even if the systems were working as intended, the carbon emissions would be higher than DEC-A benchmark at 22.9 $kgCO_2/m^2$. This is mainly because the lower server room load leads to less heat being dissipated from the condenser of the cooling system installed for server room. Consequently, the free heating available from server room cooling system is significantly lower than expected.

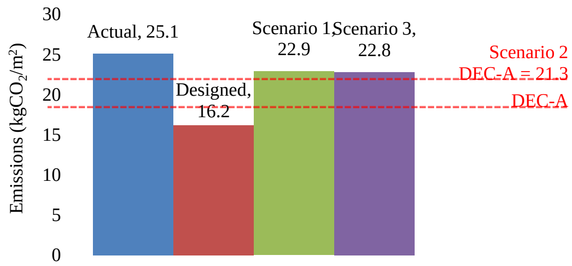


Figure 7: Carbon emissions in various scenarios

In the second scenario, the question is: *'What if the occupancy monitoring was incorporated and a revised DEC benchmark was used?'* It is calculated that if the extended occupancy was factored in, the DEC-A benchmark would increase to 21.3 $kgCO_2/m^2$.

The third scenario is: *'What if dynamic BPS was used to assess the DEC rating at the design stage?'* The net emissions calculated by the BPS were 22.8 $kgCO_2/m^2$. Table 8 shows the comparison between design estimates and BPS prediction. Modelling of transient occupancy in BPS highlighted the underestimation of design estimate in heating, lighting and small power use.

Scenario analysis concludes that even if the building's technical parameters were in order, without the alterations in the factors beyond the designers control, the building might not be able to achieve the desired DEC rating. Also, had BPS been used for design estimates, then the patterns for operation and occupancy would have been modelled more usefully, highlighted the vulnerability of the EPC target to the variations.

Table 8: Design stage energy use performance (kWh/m^2)

Criteria	Design Estimate	Using BPS	Diff.
Total Energy (Gas + Elec)	14 + 57	19+68	5+11
Heating & Hot Water (Gas+Elec)	*13.9+5.0*	*18.8+5.0*	*4.9+0*
Cooling energy (Elec)	*0.17*	*0.23*	*0.05*
Pumps + Mech Vent (Elec)	*1.73*	*2.06*	*0.33*
Int. Lighting (Elec)	*5.00*	*9.93*	*4.93*
Ext. Lighting (Elec)	*1.11*	*1.11*	*0*
Small Power (Elec)	*16.49*	*21.98*	*5.49*
Catering (Elec)	*0.85*	*0.85*	*0*
Server Elec (Elec)	*26.42*	*26.42*	*0*
Lifts (Elec)	*0.28*	*0.37*	*0.09*
PV Generation (Elec)	31.22	31.22	0
Net Energy (Gas + Elec)	14 + 26	19+37	5+11

Sensitivity Analysis

Differential Sensitivity Analysis (DSA) is used to answer a final what-if question: *What if SA used to quantify the risks? Could that be more informative?* For this, impact of variations in design stage assumptions was calculated for some factors that were beyond the designers control.

Table 9 lists the Upper Bound (UB) and Lower Bound (LB) value for each factor. The percentage variation, from the base case of the net emissions for each factor, is shown in Table 10. Net emissions for base case is the design stage result calculated by BPS (Scenario 3 above).

The UB and LB values are the worst values in terms of deviation from the base case. These have been defined either based on the BS EN 15603:2008 (BSI, 2008) or taken in as the value used at design stage or as observed

The assumptions for heating set-point, lighting and equipment in the design case were optimistic vis-à-vis energy use. Thus, LB of heating set-point, lighting and equipment have been taken as the base case value.

Operational hours, occupancy and the UB value of lighting and server load are assumed as in BS EN 15603:2008. As some variation in actual building were beyond the code recommendations, the UB value of heating set-point and equipment load and LB value of server load are based on the actual load in the building. PV capacity is assumed to vary by 20%.

Apart from the numerous building specific findings in this case, the variation in DEC calculations, seen in Table 9 suggest that, overall, design stage energy projections are highly susceptible to reasonable deviations in assumptions used for input data. The major variations in net emissions are seen when end uses impacting electricity use are varied, such as operational hours, occupant number, small power, etc. Despite a large change in heat demand due to variation in set-point the impact on net emissions is not high because of the lower emission factor of gas used for heating by the boilers. More than 50% of variation in net emissions is due to user behaviour and operational strategy, highlighting the significance of control and mitigation measures for these risk factors. Therefore, it is imperative that explicit responsibility to evaluate user behaviour during operational stage and adapt operational strategies and/or energy budgets should be defined in the EPC at the outset.

Table 9: Variations assumed for DSA

Criteria	Lower Bound	Base As Designed	Upper Bound
Heating Set point (°C)	19	19	21
Operation Hrs/day[12]	9	12	15
Occupants Nos.	364	455	546
Lighting (W/m^2)	5	5	7.5
Equipment (W/m^2)	10	10	15
Server Load (kW)	15	29	35
PV Capacity (kWp)	168	210	252

Table 10: DEC results (kgCO$_2$/m^2)/ (% Change)

Criteria	Lower Bound	Base as Designed	Upper Bound
Heating Set point	22.8(0%)		23.8 (5%)
Operation	17.3 (-24%)		29.0 (+27%)
Occupants	20.5 (-10%)		25.0 (+10%)
Lighting	22.8(0%)	22.8	25.3(+11%)
Equipment	22.8(0%)		27.9(+22%)
Server Load	17.1 (-25%)		24.9(+9%)
PV Capacity	27.4(+20%)		18.2 (-20%)

It should be noted that this comparison is not intended to assess all possible variations, but is focused on some critical factors that can have a significant impact on energy targets. The aim is to highlight the importance of *quantitative* risk assessment against the assumptions so that informed decisions can be taken at the design stage vis-à-vis safeguarding them.

The building, designed for a high performance, had a little margin of deviation in its CO_2 emissions if it were to have a DEC-A rating. Hot desking, a strategy to optimise out-of-hours use, could have been employed with a stronger emphasis if the margins with occupant behaviour change were available quantifiably. Similarly, more caution would have prevailed if the potential distortion of the energy budgets would have been quantified for the server room specifications, that are often overestimated. Thus, critical determinants of energy performance could have been preserved if major risk factors had been quantified.

Building IEQ Performance

To assess the summer overheating and IAQ in the heating season, detailed IEQ is being monitored by the research team. Preliminary results for typical weeks and snapshot days are presented in this paper to explore the intricate interrelationship of energy performance and IEQ. The parameters recorded are temperature, CO_2 concentration, and $PM_{2.5}$ concentrations. As there was no specific IEQ performance target to achieve in the EPC, the building is compared to the criteria mentioned in Table 11.

Table 11: IEQ performance parameters

Category	Criteria
Temperature: Summer overheating	Guide A (28): CIBSE TM52[13] based on BS EN 15251[14],
CO_2 Concentration	BB101 recommendations[15]
$PM_{2.5}$ Concentration	WHO Guidelines[16]

[12] *Includes Occupancy, Lighting, Equipment, Pumps*

[13] *(CIBSE, 2013); Air temperature can be used instead of operative temperature if there are no very hot or cold surfaces in the room.*

[14] *(BSI, 2007)*

[15] *(Building Bulletin 101, 2006); BB101 is for schools. But it is used as the criteria here as there is no specific guideline for offices in the UK and it provides a compromise between the need to dilute pollutants, to save energy, and to save money (Jones & Kirby, 2012).*

[16] *(WHO, 2005)*

All sensors used were calibrated. Temperature loggers were with an accuracy of ± 0.35 °C from 0°C to 50°C. CO_2 concentration was from the BMS. PM levels, based on laser/light scattering principle, had a counting yield of 50% at 0.3µm, 98% at 0.5µm

Summer period overheating

In a naturally ventilated building, summer overheating is a concern. As per TM52 (CIBSE, 2013) air temperature inside a naturally ventilated building is compared to a maximum acceptable temperature (T_{max}), based on mean outdoor air temperature. Figure 8 shows air temperatures inside key building spaces during a typical summer week in August. While the open plan offices, cooled by natural ventilation, are comfortably within the T_{max} limit, the meeting rooms, which do not have a functional comfort cooling, are near to the T_{max} value and risk overheating. It is seen in a hot spell in July that when the peak outside air temperature was 33.2°C. (Figure 9), the indoor air temperatures exceeded the T_{max} significantly.

An assessment of the natural ventilation strategy revealed some operational issues which could be partly responsible for such high indoor temperatures in the room. The vents were only open in the nights when indoor temperature was above 19°C. This made the night cooling strategy ineffective. This was done by the FM team as, within the limitations of the present controls, it was the only way to avoid overcooling of the space to the extent that heating is required when the office opened in the morning.

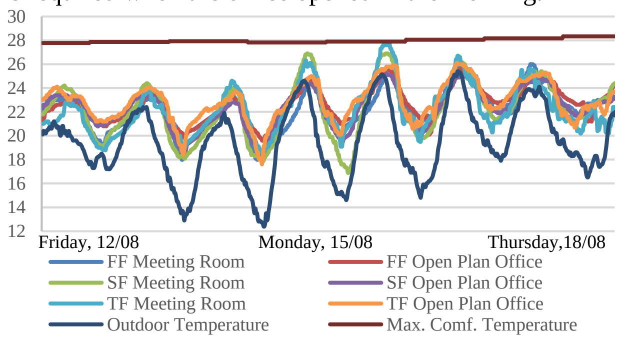


Figure 8: Indoor temperatures in a typical summer week

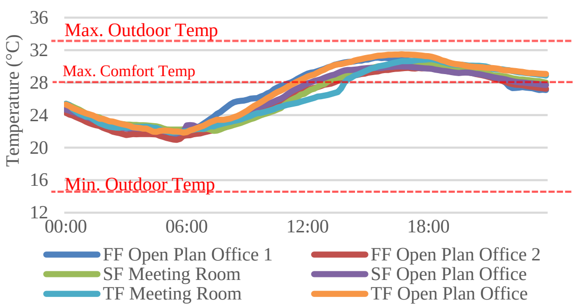


Figure 9: Indoor temperatures on a hot summer day

A full summer is needed to ascertain the overheating in the building. However, the initial results show that, using the night cooling appropriately, the building *can* maintain 2-3 °C less than peak outdoor temperatures.

Winter Period IAQ

Fresh air is predominantly provided via vents controlled by the BMS system. Therefore, to maintain good IAQ and not use excessive energy, the demand controlled ventilation system should work optimally and maintain appropriate CO_2 and $PM_{2.5}$ concentrations. BB101 recommends that during occupied hours, average CO_2 concentrations should not exceed 1500 ppm. Figure 10, reproduced from the BMS data, shows the indoor CO_2 concentrations for the third-floor open plan office on a typical winters day. The average CO_2 concentrations during the working day was >1900 ppm. For, more than 90% of the working hours it was above 1500 ppm, reaching up to 2500 ppm.

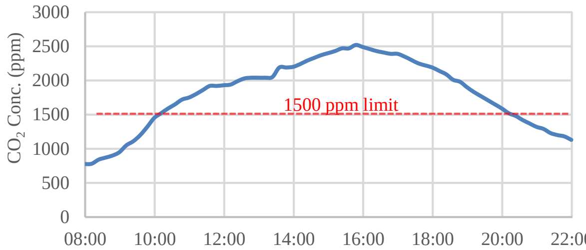


Figure 10: Indoor CO_2 concentration (reproduced)

The reason for the high CO_2 concentrations, as observed from the BMS, was that the vent opening in winters was overridden during occupied hours to address the users' thermal comfort, in areas adjacent to the floors cut-outs. While the zone air temperatures of the open plan offices were above 21°C, the users were feeling cold due to drafts caused by excessive air movements on the top floors by the stack effect. This highlights some spatial planning issues, but more importantly shows potential conflicts between thermal comfort and indoor air quality, and the risk of compromise in IEQ performance if energy targets are the only focus of building monitoring & fine-tuning.

Finally, as the building was not adequately ventilated in winter, the $PM_{2.5}$ levels increased in areas near to a café inside, an indoor source of pollutant. Figure 11 shows the $PM_{2.5}$ levels in meeting room near the café. The levels reach above the WHO prescribed daily limit of 25 µg/m³.

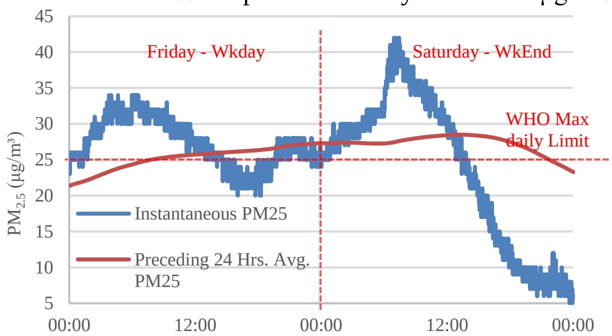


Figure 11: Indoor $PM_{2.5}$ concentration

Overall, the primary results of IEQ monitoring point to unintended consequences to health and wellbeing of occupants if IEQ parameters are not specifically covered by performance contracting and effectively addressed by FM team, post-occupancy.

Discussion

Total Performance Gap in the Building

The building energy and IEQ performance does not yet match expected levels. Despite the committed continual engagement by all the stakeholders and while ongoing improvement are still happening, the building currently is using 107% more gas and 46% more electricity than it was expected to use. Also, while the building can potentially maintain high IEQ, suboptimal operations and remedial measures to resolve technical issues make it difficult to achieve this in practice. Four root causes that contributed to the underperformance are apparent.

1. **Fragmented supply chain:** The detailed design of the building services systems was done by a different team than the concept design team due to the D&B nature of the contract. Despite the intention of both teams to have a smooth transfer, some key technical compliance parameters and assumptions were not communicated or were misinterpreted.
2. **Lack of dynamic simulation and sensitivity analysis:** It appears that the detailed design and the final energy budget were predominantly based on concept stage assumptions and calculations. Quasi steady-state models with initial assumptions, used at the concept stage, were not so useful in addressing the building's complex behaviour especially during transient occupancy.
3. **Quantification of risks:** The design team maintained a qualitative risk register regarding DEC performance. However, as quantification of risk was not done, the relative importance of risks was not fully highlighted, making necessary precautionary actions less likely.
4. **IEQ specification**: Energy performance (DEC), was the only specific quantified performance objective in EPC - no metering, monitoring, and reporting strategy for IEQ was effectively implemented.

Resoulution of some of the technical issues and operational optimisation could improve energy performance. However, due to the conflicting nature of IEQ and energy, it is much more challenging to have high IEQ, without affecting the energy use adversely.

Despite all this, it should be noted that the building is performing much better than a typical building of its type and the contractors' involvement post construction is proving beneficial in identifying and rectifying the issues.

Importance of using BPS in EPC process

Estimating energy use accurately and quantified estimation of risks associated with the variation is a key requirement in an EPC based project, especially as there are many unknowns and variables during the pre-occupancy stage, which are beyond the designers' control. Computer models are useful because factors beyond the designers' control can be screened out.

Dynamic BPS can help in assessing the behaviour of a building in cases with complex interdependent systems and control strategies, especially in transient occupancy periods, thereby flagging up number of risk factors. If the target is based on computer modelling, then it is easy to adjust and create scenarios for building operating patterns, weather and other factors.

Regular reports of estimated performance are needed to monitor progress toward the target at each construction stage. Ongoing review of the hourly BPS models used by the team provide a necessary quality control. It is important that, in an EPC project, a quantification based risk register process is used, using SA and UA done via BPS. This ensures that the team is aware of key associated risks and can identify and protect the most critical assumptions from value engineering of energy efficiency measures, especially in D&B contracts.

Other improvement opportunities in the EPC process

It is necessary that standardised operational assumptions based on actual building metered data are used in BPS. This will help in addressing inaccurate assumptions at the design stage and promote more realistic calculations from the onset. Further, to resolve the handover issues between design and construction teams, Building Information Modelling (BIM) can be used. BIM facilitates easy flow of data and assumptions throughout the construction process and beyond to the operational stage.

The DEC performance is based on 'net CO_2 emissions'. The DEC scheme allows offsetting energy used by accounting for the net electricity exported by onsite renewables. This can potentially mask the shortcomings in building operational performance. It would be better to target actual building energy demand rather than net CO_2 emissions in performance contracts to address this issue.

Finally, to deliver a high level of total performance, IEQ needs to be addressed simultaneously with energy and should be quantitatively brought within the purview of EPCs. This will help address the trade-offs that happen during operational stages and the unintended health consequences to the occupants. BPS can be useful here, to optimise and inform the stakeholders on achieving energy efficiency targets whilst maintaining acceptable level of IEQ required for occupant health and well-being.

Conclusion

The work highlights many useful lessons that can potentially be used to improve the current DEC based EPC process. Use of BPS to maintain a quantified risk register, based on scenario and sensitivity analyses, is necessary to identify and help protect the most critical energy efficiency measures. It will provide a check on the most vulnerable assumptions that may be beyond the designers' control. Use of dynamic BPS within the BIM framework also helps in easing the information transfer between various design phases and during operational phase as well. Separate attention should be given to building's energy efficiency as well as on-site generation to ensure demand is optimised first before the supply. The purview of performance contracting should account for the Total Performance (Environmental Quality and Energy) and re-cast as an 'EEPC' (Environment and Energy Performance Contract) to ensure that energy efficiency is not achieved at the expense of IEQ and other building performance aspects.

Further Work

For the building, a detailed monitoring programme for disaggregated energy use and IEQ is underway and the results will be published in due course. The impact of having short term performance targets vs longer term targets, within the life cycle of the existing environmental strategy and in the context of a changing climate will be further explored.

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