Comparative evaluation of actual energy use, occupant satisfaction and productivity in nine low energy office buildings

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Abstract
This paper presents a comparative evaluation of datasets on modelled and measured energy use, air permeability, and perceived productivity across nine office buildings, gathered as part of the Innovate UK's Building Performance Evaluation (BPE) programme. Despite being designed to high sustainability standards, it is found that measured air permeability rates of four case study office buildings are much higher than the design target, while energy-related CO_2e emissions of three office buildings are over double the predicted CO_2e emissions rate. Statistical analysis of occupant feedback indicates that overall comfort and summer temperatures are strongly associated with perceived productivity. Surprisingly, perceived control over ventilation and heating has weak correlations with perceived productivity. Such findings can help to provide foresight for improving future building design, specifications and performance.

Keywords Building Performance Evaluation, office, occupant satisfaction evaluation, productivity, comfort

Introduction
Forty five per cent of UK CO_2e emissions are attributed to the building sector. Though only 18% of these CO_2e emissions are from non-domestic buildings (1), the public (2) and private sectors have a responsibility to demonstrate leadership in emissions reduction. Institutional buildings, for example, can act as teaching tools wherein actual performance matters publically. Furthermore, the health and performance of buildings can be a key indicator of socio-economic development of a nation, creating long lasting influence on users (3). This can have in impact on the occupants' consideration of management and efficiency of consumption at home.

Despite effort, improvements in building fabric and the deployment of innovative services and systems, a significant gap between predicted and actual energy consumption in non-domestic buildings is observed (4), leading to higher than expected energy use (5-7). It is all too common to find a significant gap between predicted and actual energy consumption (4). Continually, research demonstrates that green building rating and certification systems do not ensure greater energy performance (8), occupant satisfaction (9) or better indoor environmental quality (IEQ) over conventional buildings (10).

Wide ranging expectation from users and over-stretched building management can be further complicated by poor installation and commissioning practices, poor material or control choices and poor communication of use (11). For these reasons and other performance expectation related issues, it is important to verify the actual buildings built to sustainability standards. Bordass and Leaman (12) reveal independent evaluation of how much energy is actually used when buildings are in operation is very rare and there is a perceived lack of information and data on the actual energy performance of the UK building stock, which is likely to lead to a widening of the gap between theory and practice and a failure to achieve strategic goals (13).

From 1995 to 2002, PROBE (Post-occupancy Review of Buildings and their Engineering) investigated the performance of 23 buildings previously featured as 'exemplar designs' in the Building Services Journal (5, 7) and revealed that actual energy consumption in buildings is often twice as much as predicted. Almost 10 years later, the Carbon Trust's 'Closing the Gap' report (14) highlighted the underlying reasons behind the performance gap, underlining that as-designed predictions that achieve regulatory compliance do not account for all energy uses, with actual regulated consumption being up to five times higher than the prediction across five case study buildings.

More recently, this gap was found to be two – nine times higher than predicted in a select 29 non-domestic buildings (16 institutional buildings) from the Building Performance Evaluation (BPE) programme funded by the UK Government's innovation agency, Technology Strategy Board (now Innovate UK) from 2010 to 2014 (15). In addition, Burman et al. (16) reviewed 600 non-domestic buildings on the CarbonBuzz database of design and actual energy consumption figures in the UK and found that for education buildings the mean performance gap factor was 1.5 (that is, actual consumption is 50% higher than designed consumption) and for offices this factor was 1.6. In other European countries this factor is reportedly 1.3 for non-domestic buildings. In the USA, one study comparing the energy model predictions with actual energy performance of a LEED certified university building, found the building consuming twice the predicted energy usage while causing a high level of occupant dissatisfaction (17).

From 2010 to 2014 the UK Government's Technology Strategy Board (now Innovate UK) ran an £8 million national research programme on BPE, to address the performance gap challenge in new domestic and non-domestic buildings. In total, the programme has completed 101 studies, 48 of which cover non-domestic buildings, providing insights on the performance of design strategies, building fabric, actual energy use, construction methods, occupancy patterns, handover and operational practices (15). This paper presents a cross-project evaluation of nine BPE studies of office buildings from this programme, to systematically examine datasets of designed and measured building fabric and energy performance as well as feedback on occupant experiences gathered from the nine office buildings, designed to low energy standards. The study draws on datasets covering designed and measured building fabric performance (Air permeability test results), energy use (energy models and CIBSE TM22 datasets), and occupant perception (Building Use Studies (BUS) surveys). Statistical correlations are drawn between fabric performance and energy use (space heating) and also between perceived occupant productivity and perceived environment (e.g. comfort, indoor temperature, and air quality) and non-environment variables (e.g. design and image to visitors). The study is first introduced through the methodology; the results are then presented which are arranged in three categories of analysis: energy consumption, air permeability and occupant productivity. The paper is then closed with a discussion and conclusion.

Methodology

The evaluation conducted for nine low energy office buildings, focussing on energy use, building fabric performance and occupant feedback is explained below:

1. *Energy consumption* (energy) – metered (actual) energy use data collected through CIBSE's TM22[1] approach.
2. *Air permeability* (fabric) – data on designed air permeability (intended goal set before construction) and as-built air permeability as measured following ATTMA[2] technical standards (L2 for non-dwellings).
3. *Perceived occupant productivity* – data collected through BUS[3] survey results

The study uses primary datasets as listed in table 1, which are linked through unique identification numbers for each building (table 2) (Innovate UK assigned identification numbers are not revealed in this paper).

Data collected	Method	Undertaken by
Energy consumption data: meters and sub-meters for gas, electricity, or other fuels with remote data collection;	Long term monitoring (required performance measurements)	BPE project teams
As-designed air permeability **As-built air permeability data** (post-construction measurement)	Required performance measurements as per BPE – ATTMA technical standards	typically contracted third party
Occupant opinion / satisfaction: BUS surveys covering 47 questions	BUS survey	BPE project teams

Table 1 – Summary of BPE monitoring and evaluation methods and data collected which were evaluated for this paper

Office building	Area m^2	Environmental rating	BUS responses (rate)
O1	110	Unknown / not reported	12 (100%)
O2	1,450	Unknown / not reported	16 (53%)
O3	3,907	BREEAM Excellent	56 (93%)
O4	4,258	BREEAM Excellent	111 (37%)
O5	705	BREEAM Very Good	7 (88%)
O6	2,728	Unknown / not reported	171 (95%)
O7	5,630	BREEAM Excellent	86 (54%)
O8	3,270	BREEAM Excellent	181 (74%)
O9	37,000	Unknown / not reported	210 (4%)

[1] The Chartered Institution of Building Services Engineers (CIBSE) produced TM22: Energy Assessment and Reporting Methodology as a method for assessing the energy performance of an occupied building based on metered energy use.
[2] The Air Tightness Testing & Measurement Association
[3] The Building Use Studies (BUS) methodology is an established way of benchmarking levels of occupant satisfaction within buildings using a structured questionnaire where respondents rate various aspects of performance on a scale of 1-7.

Table 2 – List of office buildings

Results

The results of the evaluation are presented in three categories; energy consumption, air permeability and productivity.

Energy consumption

Mean annual energy consumption for the nine office buildings was found to be 156 kWh/m^2, in contrast, the mean for buildings (with energy data) covered in the non-domestic BPE programme report (n=47) is 191 kWh/m^2 (18). Table 3 details the overall statistical data for the energy consumption of the nine office buildings. Fuel[4] and electricity data are provided separately and also combined for a total energy figure. In the lower half of the table, office O9 is excluded for comparison as it is both a high consumer outlier and had a limited period for which energy data was reported (incomplete year).

		Mean	Median	Standard Deviation	Min.	Max.	Number of offices
Office	*Total energy (kWh/m2)*	156	152	55.4	95	296	9
	Fuel (kWh/m2)	61	69	29.2	13	107	8*
	Electricity (kWh/m2)	102	92	68.6	37	283	9
Office (ex. O9)	*Total energy (kWh/m2)*	123	147	50.3	95	182	8
	Fuel (kWh/m2)	68	75	24.5	33	107	7*
	Electricity (kWh/m2)	80	86	26.3	37	120	8

Table 3 – Statistical details of annual energy data *O1 uses only electricity

The high standard deviation (σ) for electricity (as compared to the σ for fuel) is an indicator that the nine office buildings are a mix of buildings with differing consumption patterns. Specifically at first glance, this could indicate a mix of buildings that do and do not consume electricity for space heating. When the buildings that do not use fuel for space heating (O1 & O9) are excluded, the σ for electricity is 27.4 (with a mean of 77.5 kWh/m^2). However, ignoring the fuel or electricity for space heating question and viewing O9 as an outlier with extraordinarily high electricity consumption (figure 1) thereby excluding it from the sample, a σ of 26.3 with a mean of 79.7 kWh/m^2 is the result. As is shown in figures 2 and 3, O9, appears to be fabric efficient but unlike the other office buildings, has high consumption in areas like small power and ICT.

Figure 1 shows that all office buildings fall below the TM46 fuel benchmark but three exceed the electricity benchmark. Though O1 uses electricity for space heating, it only just meets

[4] For the purposes of this paper *fuel* is used to identify gas or other non-electricity fuel consumption.

the electricity benchmark which assumes that electricity is not consumed primarily for space heating. This indicates O1, for example, is performing well (exceedingly better than the benchmark in reality). Figures 2 and 3 show the energy use breakdowns from sub-metering data. Figure 2 is pattern coded to clearly see the regulated energy consumption and figure 3 is coded to highlight the un-regulated consumption.

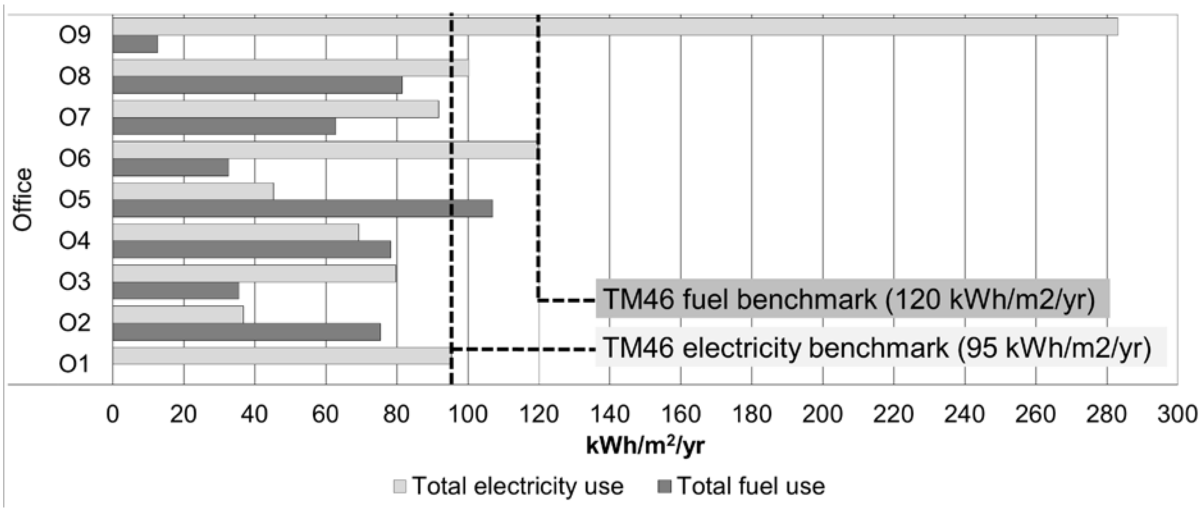

Figure 1 – Energy consumption of office buildings with TM46 *general office* benchmarks

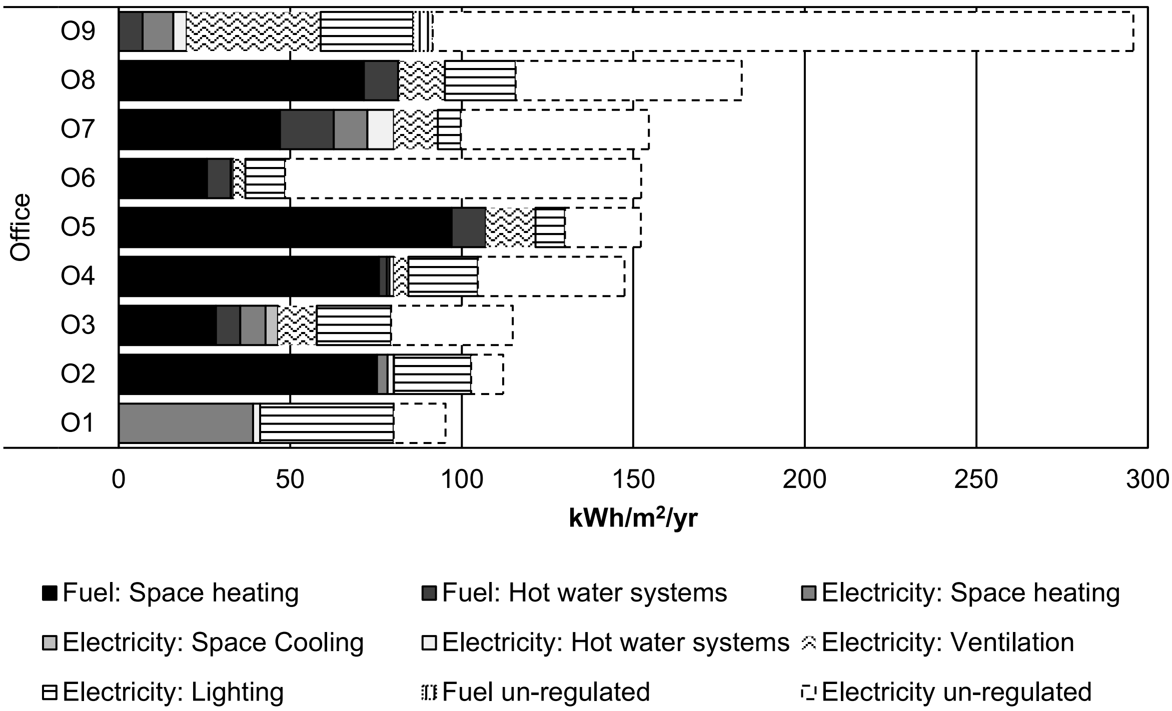

Figure 2 – TM22 end-use breakdown with focus on regulated loads

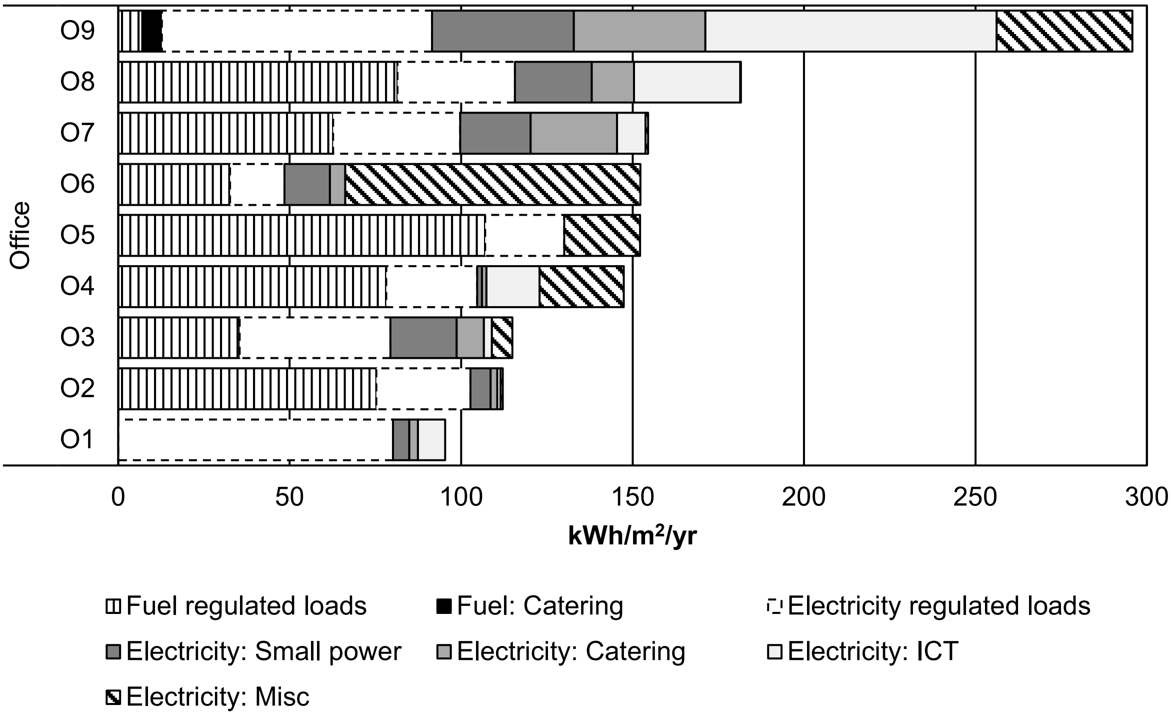

Figure 3 – TM22 end-use breakdown with focus on un-regulated loads

Seven of the nine office building (O2 – O8) have available Building CO_2e Emission Rates (BER) UK Building Regulation calculated CO_2e emissions for the expected performance of the regulated areas of the building (i.e. space heating, cooling, ventilation, water heating and lighting). Table 4 lists the BER against measured (regulated consumption) CO_2e emissions for the seven office buildings. Only one building O7 consumed the same or less than expected.

Office building	BER (kgCO_2e/m2)	Measured emissions (kgCO_2e/m2)	Per cent increase over BER
O2	25.7	29.1	13%
O3	12.4	29.8	140%
O4	21.1	29.2	38%
O5	15.9	33.1	108%
O6	13	14.7	13%
O7	**32**	**31.5**	**-1%**
O8	13.7	33.9	147%

Table 4 – Estimated and measured CO_2e emission rates (n=7)

Air permeability

Each project is required to report design target 'air permeability', as part of the UK Building Regulations Part L (BRUKL). This measures unwanted infiltration of warm or cool air through gaps in construction and/or materials, when a building is pressurised to a 50 Pascal differential above the air pressure outside (18). The air permeability data collected during the BPE programme included both design and measured (as-built) air permeability (Figure 4).

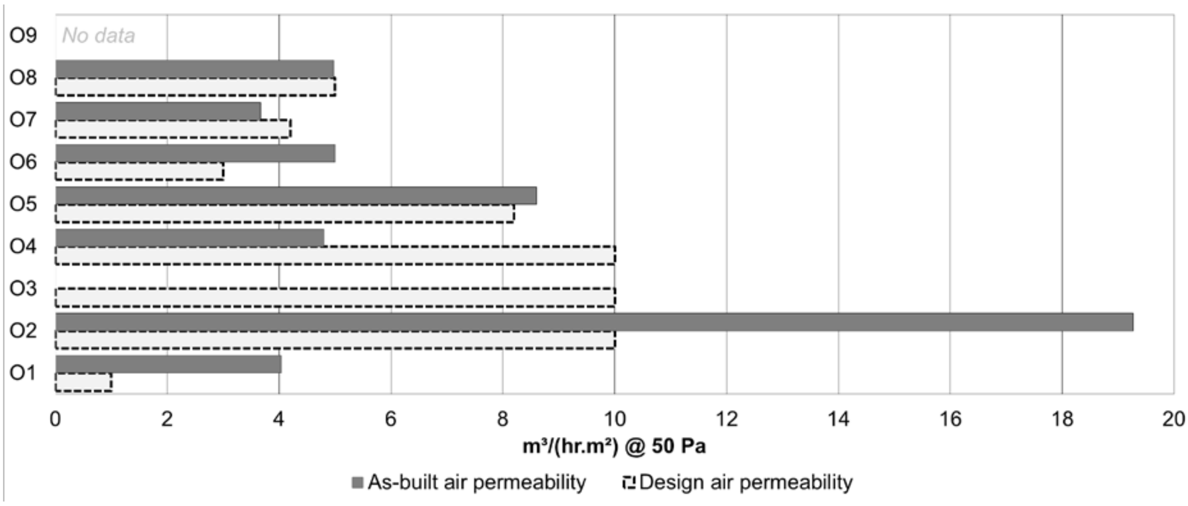

Figure 4 – Designed and as-built air permeability

In the eight office buildings for which there is data, the mean design and measured air permeability was 6.0 and 5.6 $m^3/h.m^2$@50Pa, respectively. As-built air permeability ranged from 3.7 to 19.3 $m^3/h.m^2$@50Pa. Two buildings, O4 and O7, achieved better air permeability ratings than the design target. In contrast, the Innovate UK non-domestic BPE report (18) shows that 50% of buildings perform better than designed; education buildings represented the sector with the most buildings attaining air permeability better than design targets. According to the sample (n=36) in the Innovate UK report, the mean air permeability for all buildings are 6.5 $m^3/h.m^2$@50Pa design and 6.1 $m^3/h.m^2$@50Pa measured air permeability.

In the Innovate UK report (18), all but two projects met the UK Building Regulations (2010) requirement to achieve airtightness below 10 m3/h.m2@50Pa; one of these is O2. O2 had the poorest airtightness, equivalent to an air change rate of six air changes per hour. The office had much better airtightness for individual rooms; however, settlement affected the whole building, and there are reportedly serious leaks, especially in the basement (18). The correlation between designed and as-built air permeability is strong in both the office building sample (r=0.6) and the Innovate UK report's sample (r=0.7). This would indicate that for the most part builders are able to get relatively close to the designed air permeability target; however this does not tell the whole story since, theoretically, a poor correlation, where all as-built air permeability ratings are lower than designed, would be satisfactory. Therefore, figure 5 shows the association of the designed and as-built air permeability with the centre line drawn. This line is where the marker should lie if building strictly to meet the target; otherwise, above the line is worse and below the line is better.

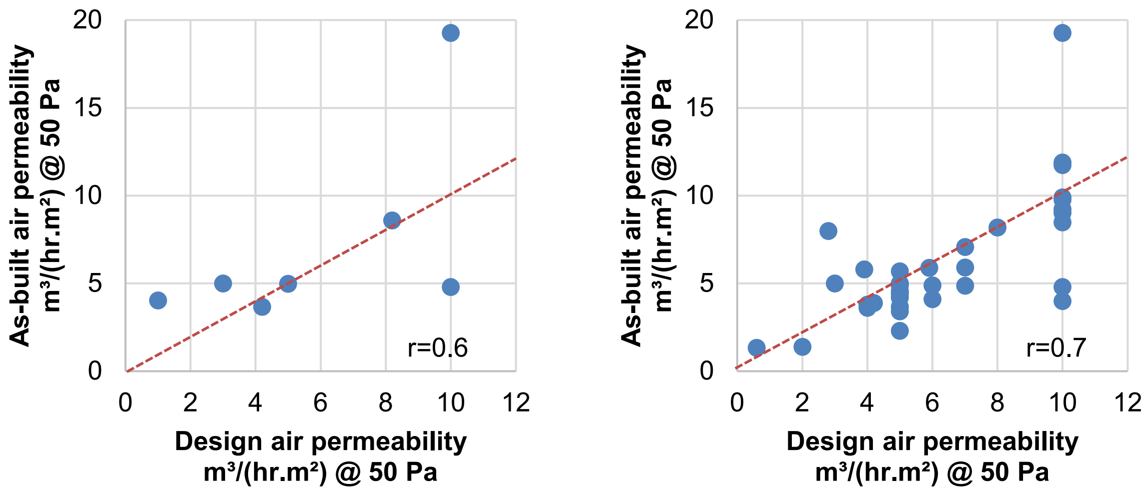

Figure 5 – Association between design and as-built air permeability for office buildings (N=7) (left), and buildings in non-domestic BPE report (n=36) (right). *Note: the line drawn is the line on which the marker should fall, not the regression line.*

Figure 6 shows the regression line and association between as-built air permeability and space heating consumption in seven office buildings (where available).

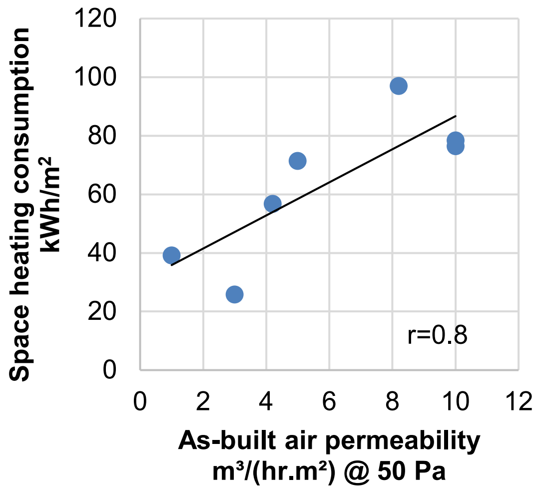

Figure 6 – Association between as-built air permeability and space heating consumption for office buildings (N=7)

For these offices, the correlation of as-built air permeability and space heating consumption is strong (r=0.8). Though this is a small sample size, this should indicate that there is value in achieving air tightness in buildings from a space heating perspective.

Perceived Productivity

Perception of occupants for a range of environmental and non-environmental variables was gathered through BUS surveys implemented by the BPE project teams in each of the office buildings. Possible correlations were explored between perceived productivity and BUS variables, which are listed in table 5 along with their Spearman's rank correlation coefficient (r_s).

Variable (building overall)	**Mean (scale of 1-7)** 1: unsatisfactory 7: satisfactory	**r_s**	**Rank (mean)**
Safety	6.0	0.45	1
Image to visitors	6.0	0.66	2
Needs	5.3	0.93	4
Design	5.3	0.92	5
Variable (personal)			
Overall comfort	5.1	0.85	6
Health (perceived)	4.0	0.40	13
Variable (environment)			
Air in summer - Overall	4.3	0.73	11
Air in winter - Overall	4.5	0.68	10
Temperature in summer – Overall	4.1	0.82	12
Temperature in winter – Overall	4.5	0.23	9
Noise - Overall	4.9	0.76	7
Lighting - Overall	5.4	0.64	3

Table 5 – The ranked association between perceived productivity and BUS variables for office buildings (n=9 office buildings).

The evaluation indicates that *needs*, *design* and *overall comfort* are the variables most strongly associated with perceived productivity. It is important to remember that these are not conventional buildings but new exemplar green buildings. As Leaman and Bordass (20) tentatively conclude, "users tend to rate design, image, needs and health as much better in green buildings, but these also may disguise many detailed flaws". Table 5 and figure 7 show how this is also the case for the office buildings in this study. In fact, design, image and needs are within the top five ranked variables and show a strong correlation with perceived productivity. After a few years however, the opinion of the design and other variables may subside, resulting in less bias. For this reason, there would need to be a follow up evaluation after occupants have become accustomed to their environment and no longer influenced by the newness of the buildings.

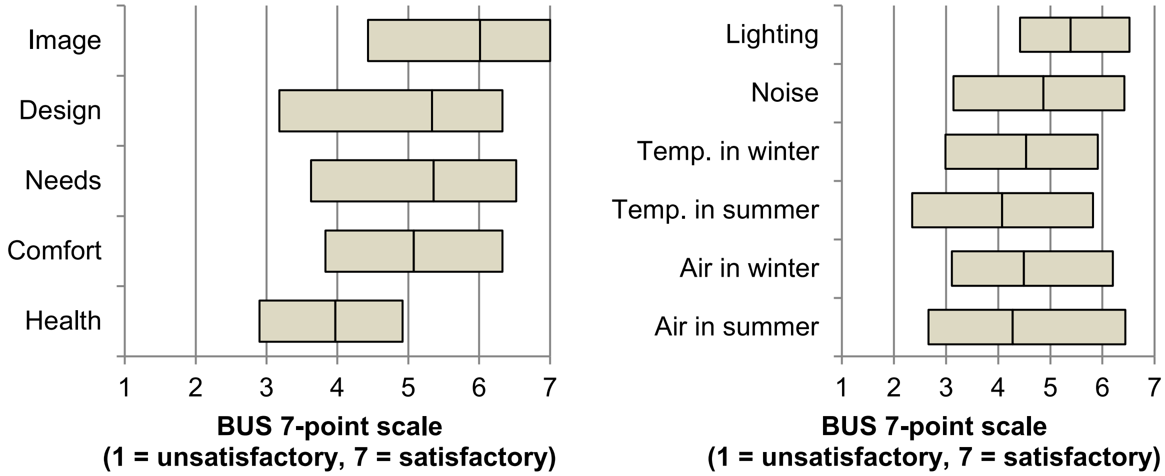

Figure 7 – Overall BUS variables for office buildings showing minimum to maximum vote ranges with the mean vote within the bars (n=9).

Overall in the office buildings, occupants were more satisfied with winter temperatures (all but two building ranked satisfaction with winter temperatures higher than summer temperatures). Interestingly however, the correlation of summer temperature with perceived productivity (r_s=0.82) was significantly stronger than that of indoor winter temperatures (r_s=0.23). It is perhaps a sign that people are more forgiving of unsatisfactory winter temperatures than unsatisfactory summer temperatures. Similarly, all but one office building ranked satisfaction with winter air quality as higher than with summer air quality. However, there was only a slightly higher correlation between summer air quality and perceived productivity. Surprisingly control over ventilation and heating had weak negative correlations with perceived productivity (r_s= -0.24) and (r_s= -0.39) respectively. It is hypothesized that if asked directly, few people would agree that loss of control over heating would increase their productivity; however, perhaps trusting someone or something else with providing ideal heating or ventilation control would enhance productivity by taking away an extra task or concern from the working occupant.

Discussion

The case study buildings are designed to low energy performance standards, yet key performance indicators such as air permeability, final CO_2e emissions and energy use exceeds targets and benchmarks in a number of cases.

- Though all office buildings performed better than the corresponding TM46 fuel benchmark, three case study buildings exceeded the electricity benchmark (O6, O8, and O9).
- Offices O3, O5, and O8 had a final CO_2e emission rate at least twice that of their BER.
- Surprisingly however, the two buildings which had significant gaps in designed air permeability (O2 and O6) show only a 13% increase in measured CO_2e emissions. This is however not a perfect association since regulated consumption also includes water heating and lighting which are not affected by air permeability.

A strong positive correlation for the case study offices between measured air permeability and measured space heating energy use indicates good thermal performance of the fabric and the effectiveness of that effort. In contrast, however, the non-domestic BPE report by Innovate UK (18) showed that for n=34 buildings there is almost no correlation between as-built airtightness values and total CO_2e emissions. One problem with this association is that in non-domestic buildings, a large proportion of total CO_2e emissions can be attributed to non-heating related uses and can be from electricity sources which are responsible for higher CO_2e emissions. This is especially true in office buildings (18). To demonstrate this, referring back to figure 2, six of the nine office buildings consume non-heating electricity for over half of total consumption. As an example, O6 emits 5.2 $kgCO_2e$ for space heating / cooling, and emits 63.1 $kgCO_2e$ for non-space heating / cooling.

When occupants were satisfied with their indoor environment (such as indoor temperature, light, noise levels) their perceived productivity was found to increase for the most part. Non-environmental (functional) factors (design, facilities, and image to visitors) are also found to be important to occupants and have an impact on perceived productivity. In addition, though not analysed through primary data, similar building performance issues were discovered in many of the nine buildings, related to poor handover and guidance, maintenance issues and poor integration of systems with user experience leading to unexpected consequences and energy consumption.

Conclusions

The intent behind the study of building projects like those in the BPE programme is to measure the gap between intent and outcomes, and identify the likely areas which lead to the performance gap, e.g. higher than designed energy consumption. It is obvious that the BPE programme is beneficial in capturing learning from projects by providing a source of empirical evidence and lessons learned. As was accomplished in this paper, it is essential that learning from such programmes is continued and also considered in the planning of further programmes, to bridge the gap between expectations (targets) and practice (delivery). Otherwise, there is a risk that buildings (new or retrofit) will continue to save less energy than expected, and meaningful CO_{2e} reduction targets will be unmet.

In order to improve building performance now and in the future, it is vital that all stakeholders (clients, designers, constructors, supply chain) use BPE studies to develop foresight for improving future building design, specifications and performance. To achieve this, future work is suggested where funding from the BPE studies led to changes in energy or building performance. As for example, the mechanical and electrical engineer still assists the FM staff of O8 in managing the building to improve performance, so a kind of ongoing BPE. The impact of this level of ongoing aftercare for improving building performance could serve as a case study for further research.

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