Towards a framework to evaluate the 'Total' performance of buildings

Jonathon Taylor[1], Yanchen Liu[2*], Borong Lin[2], Esfand Burman[1], Sung-Min Hong[1], Juan Yu[2], Zhe Wang[2], Dejan Mumovic[1], Clive Shrubsole[1], Daan Vermeer[1], Mike Davies[1]

Affiliations:

[1]UCL Institute for Environmental Design and Engineering, University College London, UK

[2]Department of Building Science and Key Laboratory of Eco Planning & Green Building, Tsinghua University, Beijing, China

***Corresponding author**

Yanchen Liu, Department of Building Science and Key Laboratory of Eco Planning & Green Building, Tsinghua University, Beijing, China

Email: liuych_hvac@126.com

Abstract

Internationally, buildings are a major contributor to carbon emissions. Despite significant advances in the technology and construction of energy-efficient buildings, in many cases a performance gap between designed and actual performance exists. While much research has investigated the drivers of the building energy performance gap – both static and transient– there has been considerably less research into the *total* performance gap, defined here as performance gaps in building energy use, occupant satisfaction and Indoor Environmental Quality (IEQ) parameters such as thermal comfort and air quality which may impact on occupant health and wellbeing. This paper presents a meta-analysis of building performance data from buildings in the UK and China – selected due to their contrasting development environments - which illustrate the presence of and complexities of evaluating total performance gaps in both countries. The data demonstrate the need for 1) high end-use, spatial granularity and temporal resolution data for both energy and IEQ, and 2) developing methodologies that allow meaningful comparisons between buildings internationally to facilitate learning from successful building design, construction methodologies and policy environments internationally. Using performance data from a UK building, a potential forward path is illustrated with the objective of developing a framework to evaluate total building performance.

Practical Application

While much research has examined building energy performance gaps, Indoor Environmental Quality (IEQ) and occupant satisfaction gaps are rarely included despite their relationship to energy. We use a meta-analysis of energy, IEQ, and occupant satisfaction data from buildings in the UK and China to illustrating the presence of and complexities of evaluating total performance gaps for buildings in the two countries, and the need for high resolution dynamic buildings data and novel methodologies for comparison between buildings across different contexts. Illustrative case studies are used to demonstrate potential future directions for evaluating 'total' building performance.

1. Introduction

Internationally, buildings account for one third of total greenhouse gas emissions [1], meaning that reducing building energy consumption is critical to achieve emissions reduction targets. One of the primary means for achieving this is to increase the energy efficiency of the stock, through the construction of energy-efficient buildings, or the retrofit of existing buildings. However, evidence internationally suggests that there is often a large energy performance gap – or a difference between the designed and operational energy use of buildings [2–8]. Energy performance gaps may have a variety of underlying causes, including uncertainty in design-based modelling, occupant behaviour, and poor operational practices [9], causes which may occur at various stages of the building life cycle.

Indoor Environmental Quality (IEQ) factors such as indoor air quality, temperature, and light levels are also linked to building energy efficiency via fabric performance and the service strategy specified for the building, and a performance gap between designed and actual IEQ conditions may, for example, occur in energy efficient buildings whose *energy* performance may otherwise meet or exceed design criteria. While a number of studies have evaluated building energy performance gaps internationally, building IEQ performance is rarely systematically investigated [10]. In addition, the majority of both energy and IEQ performance evaluations focus on steady-state performance rather than adopting a whole life approach which may help track and identify underperformance in real-time. Similarly, the subjective opinions of building occupants – obtained via occupant surveys – may also indicate areas of building underperformance. Therefore, the concept of the 'total' performance gap [11], i.e. the gap between the designed and actual energy and IEQ performance, and occupant satisfaction under transient lifecycle of the building, is critical to investigate to reduce carbon emissions whilst maintaining healthy indoor environments.

Total building performance – or underperformance – is not solely due to building design, procurement methods, construction, and operation, but also the wider context of the building. The performance gap is a socio-technical parameter, influenced by national building regulations and/or international policy frameworks such EU Building Performance Directive. International differences in building regulations limit like for like comparison of the performance gap internationally, both directly by imposing different calculation methods and assumptions of various complexity, and indirectly by selection of different building performance tools. The TOP project (Total Performance of buildings) seeks to develop methods to allow meaningful dynamic total performance gap comparison in the UK and China, which would be flexible enough to allow for national context variations; this could then be used to evaluate how the wider context may act as a driving force for low carbon building development. China and the UK offer interesting and contrasting contexts in which to compare total performance gaps, due to differences in policy, construction, climate, as well as potential differences in occupant behaviour.

1.1. UK

In the UK, buildings account for 34% of the total greenhouse gas emissions [12], with a relatively slow rate of building construction and turnover, and a focus on refurbishing the existing stock. In July 2015, the UK Government declared that it was abandoning the zero carbon buildings policy first announced in 2007, meaning both the 2016 zero carbon homes target and the 2019 target for non-domestic zero carbon buildings have been withdrawn. Currently the UK is still committed to all new buildings being 'nearly zero energy' from January 2021 through the European Energy Performance of Buildings Directive (EPBD). Building energy use is defined through Part L of the UK building regulations [13], while several additional voluntary criteria for energy-efficient construction are used in the UK including BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design). Local authorities in the UK may also require new developments to exceed national standards.

IEQ in UK buildings is also addressed through building regulations. Whilst Part L, to some extent, addresses overheating by ensuring adequate passive measures are in place to control solar gain as well as energy, it is Building Regulations Part F (Means of Ventilation) [14] that deals with issues of Indoor Air Quality (IAQ). The voluntary WELL standard, which defines criteria for human health and wellbeing design in buildings in a similar manner to BREEAM or LEED do for energy and environment, is increasingly common in the UK. It is essential that standards and regulations such as Parts L and F are joined up sufficiently to ensure that alongside the energy goal, healthy, comfortable and productive indoor environments are achieved [10,15]. To date, there has been limited research on the performance gap between design and operational IEQ in the UK, but some research in schools for example [15,16] suggests the IAQ parameters may exceed design thresholds.

Several studies have examined the performance gap in UK buildings. The PROBE study, for example, found that actual energy use of sampled buildings was higher than expected and almost twice the design estimates [2], and occupant surveys pointed to downward trends in thermal comfort, acoustic performance, perceived control, and the misfit between building performance and user expectations [17]. Innovate UKs Building Performance Evaluation (BPE) studies [18] found that, on average, buildings were using 3.6 times as much energy as what the Building Regulations compliance calculations project. The building performance evaluations carried out after implementation of the Energy Performance of Buildings Directive (EBPD) in the EU show the challenges of meeting increasingly stringent energy regulations in practice [5,19].

1.2. China

In contrast to the UK, China is undergoing rapid urbanization and energy efficient buildings are predominantly new constructions rather than refurbished. The addition of significant floor space will lead to an increase in building stock energy consumption and carbon emissions, meaning the construction of energy-efficient buildings is crucial to meet China's commitment to reach peak carbon emissions in 2030. Buildings account for 25% of the total greenhouse gas emissions in China [20]. A series of energy saving standards for building energy efficiency design and assessment has been developed by both the central and local government in China since the 1980's. The latest publication, the *Standard for energy consumption of building - GB/T51161*[1] [21] – covers a wide range of commercial and non-domestic building types and provides building energy consumption benchmarks according to building types and local climate conditions.

[1] In China, standards starting with GB are mandatory standards, while standards starting with GB/T are non-mandatory standards. T is short for 'Tuijian', which means recommendation in Chinese.

Additionally, relevant policies and incentive mechanisms such as GB/T 50378 have promoted the development of so-called 'green buildings', which in addition to energy efficient building design, minimise land and water use, pollution, and building materials, and aim to provide occupants healthy, efficient service space, throughout the building's life-cycle. Due to these policies, there has been a rapid increase in green building in China, with the floor area of buildings with green building certification accounting for 4.3%, 7.2% and 11.2% of new construction in 2013, 2014 and 2015, respectively [22–24]. Several regions such as Beijing and Jiangsu province have stipulated that all local new constructions should meet standard GB/T 50378. Additionally, as of 2014, all new public buildings invested by national and local governments, or public buildings with an area of more than 20000m^2, should meet GB/T 50378.

Comfortable and healthy IEQ – including temperature and humidity control, sufficient natural ventilation, solar radiation protection, natural lighting and illumination, noise level and indoor air quality- is required in the green building standard [25]. However - as in the UK - investigations into the energy and IEQ performance of many new and conventional buildings in China have indicated the presence of performance gaps between designed and actual performance. For example, a study performed in 35 cities in the north of China found that energy consumption of residential buildings was 1.35 times higher than the designed level [26]. An investigation into the application of energy-saving technologies in a green building constructed as part of the Tianjin SC-EC project showed an energy consumption around 17 KWh/m^2 higher than the design expectations [27]. IEQ performance gaps have been found in green buildings, including for lighting [28] and summer and winter temperatures [29].

1.3. Objectives

Research interest in comparing the energy performance of buildings in different countries is increasing, as it enables the investigation of how the wider context of buildings may influence building performance, including – for example - regulations, energy supply, whether the building is new or refurbished, and occupant cultural behaviours and preferences [30,31]. Such international comparisons are hampered by technical and methodological differences, including different data acquisition systems, data output formats, and energy analysis platforms, as well as a lack of common data analysis methods [30]. Additionally, most international studies have tended to focus on energy performance, without accounting for the interrelation between energy and IEQ. In this paper, rather than attempting to compare building performance between China and the UK, a meta-analysis of building energy, IEQ, and occupant satisfaction data collected by the authors is used to illustrate the total performance gaps in both countries, and then used as a basis of a discussion of the associated methodological issues and endemic contributing factors. Five different analyses are presented that demonstrate the total performance gaps of energy performance relative to the existing stock and design calculation, indoor temperature, Relative Humidity (RH), CO_2 concentration, and occupant satisfaction. Finally, a case study is presented that uses high granularity buildings data to demonstrate the inter-relation between building energy and IEQ performance, and a potential forward path for the evaluation of building total performance. As such, the work provides a basis for developing methods which would enable comparisons of total building performance between the two countries.

2. Methods

In this study, we make use of several datasets developed by the authors to illustrate energy and IEQ performance gaps (Table 1). Datasets cover both actual and designed energy performance, IEQ, and occupant satisfaction in both conventional and energy-efficient buildings. In both countries, existing data has been collected using different methodologies, for buildings with different functions, and powered by different energy sources. Therefore, the intention of the paper is not to make comparisons between buildings in the two countries, but to use currently available data to provide insight into the total performance gap in buildings in each country, methodological differences in data collection and analysis, and to explore the data requirements to assess total building performance. For the purposes of this paper, all buildings built to high energy-efficiency standards will be henceforth referred to as 'energy-efficient'.

2.1. Datasets

For the UK, this paper refers to datasets describing top-down energy performance of schools, collected via the UK's Display Energy Certificate (DEC) scheme, a mandatory scheme implemented in the UK since 2008 under EPBD, and bottom-up energy and IEQ data collected in follow-up studies. Three UK datasets were analysed, including: 1) energy use in conventional secondary schools, acquired through DEC; 2) energy use in secondary schools that were rebuilt, remodelled or refurbished in the past decade under the UK government's the Building Schools for the Future programme (BSF) [32], also through DEC, and; 3) monitored bottom-up energy and IEQ data for several BSF schools obtained through the BPE programme. The sample representing the conventional school stock was derived from a dataset of English schools previously developed by Hong et al. (2013), which was cleaned and filtered to exclude records that were deemed uncertain, erroneous, or that referred to BSF schools. Energy-efficient BSF schools – or schools constructed under Part L 2006 onwards - were extracted from DEC using a list of all BSF schools obtained from Education Funding Agency (EFA)[2], further filtered to remove those without valid records, primary schools, and those with recent DECs that would not have corresponding Heating Degree-Days (HDD) data for normalisation. This resulted in data for 244 schools. Bottom-up energy and IEQ data was available for five BSF schools that were subject to long-term post-occupancy investigations, instigated by the authors under the Innovate UK BPE programme [34].

Existing data for Chinese buildings was for office buildings rather than schools, and includes three datasets: 1) conventional office buildings portraying the energy use of offices constructed before the inception of new energy efficiency regulations; 2) energy use of 31 office buildings that obtained green building certification in three different climate zones (15 cases in cold zone (north of the Yantze River), 10 cases in hot summer-cold winter zone, and 6 cases in hot summer- warm winter zone); and 3) monitored IEQ and questionnaire survey data for energy efficient buildings obtained through the Building Thermal Environment programme. The sample representing the conventional office building stock was derived from a dataset of Chinese office buildings previously developed by Xiao (2011), which was further cleaned to exclude uncertain records, and included information on building and energy use such as location, gross floor area, electricity consumption and heating degree-days (HDD) data for normalisation. This resulted in data for 481 office buildings, including 110 cases in cold zone, 306 cases in hot summer-cold winter zone and 65 cases in hot summer-warm winter zone. The datasets on energy use and IEQ of energy efficient buildings were obtained directly

[2] For EFA, see https://www.gov.uk/government/organisations/education-funding-agency

from previous research projects [36], of which eight buildings were selected due to being in zones with comparable climates to the UK, six of whom had calculated energy performance data and five of which had IEQ data.

Table 1. Data available for initial analysis of Chinese and UK buildings. * denotes an energy-efficient building.

	Building Type	Data Type	Parameter	Temporal Resolution	Granularity	Period	Sample Size	Reference
UK	Conventional Schools	Electricity & Fossil-thermal energy	Measured energy consumption (kWh/m^2)	Annual	Whole Building	2008-2012	6600 Primary and 1000 Secondary	[33]
	BSF Low Carbon Schools*	Electricity & Fossil-thermal energy	Calculated and measured energy consumption (kWh/m^2)	Annual	Whole Building	Post-2010	244 Schools	Current publication
		IEQ, energy, user survey	Temperature (T), RH, CO_2	1 minute (CO_2) 10 minutes (T, RH)	Whole Building	Post-2010	5 Secondary	[34]
			Energy	Electricity; half-hourly; fossil-thermal fuel: monthly				
			Building Use Study (BUS) survey	N/A	N/A			
China	Conventional Office Buildings	Electricity energy	Measured energy consumption (kWh/m^2)	Annual	Whole Building	2010-2011	481 Buildings (including 110 Cold Zone, 306 hot summer & cold winter, 65 hot summer & warm winter)	Current publication
	Low Carbon Office Buildings*	Electricity energy	Calculated and measured energy consumption (kWh/m^2)	Annual	Whole Building	2009-2014	31 Buildings (including 15 Cold Zone, 10 hot summer & cold winter, 6 hot summer & warm winter)	[37]
		IEQ	T,RH, CO_2	10 minutes	End use	2013-2014	5 Buildings	
			Questionnaire survey	N/A	N/A	2013		

2.2. Analyses

Five different analyses were preformed to illustrate total performance gaps in both countries.

2.2.1. Top Down Energy Performance Comparison

Top-down analysis focused on examining whole-year energy use in energy-efficient buildings relative to conventional buildings within each country to explore whether energy efficient buildings use less energy than conventional buildings. To do this, low granularity annual building energy data was used to estimate a climate-normalised Energy Use Intensity (EUI) (kWh/m2) for all buildings in Table 1 using an adapted version of the equation used for producing mandatory DECs (CIBSE, 2009a) (Appendix 1).

For UK buildings, EUI were adjusted to 2021 HDD, which is deemed to be the average UK climate [38]. Moreover, this adjustment assumed that around 80% of fossil-thermal EUI is used for space heating in English schools [39]. Monthly HDD figures for various climate regions in the UK were obtained from the Central Information Point [40], and annual HDDs for specific locations were derived by adding monthly HDD figures preceding the date when the monitoring was deemed to have ended. In the absence of such information for BSF schools, the 'nominated date', which can be up to 3 months after the end of monitoring period, was deemed to provide the closest representation of the weather conditions for the preceding 12 months [40]. In Chinese buildings, energy sources for heating and cooling varied by region. In cold-region Chinese buildings, heating was provided via district heating, and so the mean actual heating energy consumption of conventional district heated office buildings were calculated as coal consumption (15.1 kgce/m^2) [41], which was converted into electricity consumption (46.5kWh/m^2) without weather correction as per the electricity equivalent conversion method [42]. Elsewhere in China, electricity is used for cooling and heating. For this reason, electricity consumption for cooling was adjusted to average Cooling Degree Days (CDD) of each climate zone using CDD figures for various cities in China, obtained from the Thermal Design Code for Civil Buildings [43]. Chinese buildings were adjusted to a base HDD temperature of 18°C, in comparison to 15.5°C which is the base temperature used for HDD analysis in the UK [38]. Insufficient occupancy data was available to adjust the building energy consumption for occupation levels or times in either country.

2.2.2. Bottom Up Energy Benchmarking

To explore the gap between energy design and use in both countries, the regulatory energy performance calculations were compared against monitored energy use for four UK BSF schools (A, B, C, and D) and six (A, B, E, F, G, H) Chinese office buildings using annual energy performance data. The buildings used in this analysis were selected based on available design data. For UK schools, monitoring of energy use associated with all fuels and the sub-metered energy end-uses was performed for one full year after the first year of operation and when the buildings had reached their steady mode of operation. The CIBSE TM39 [44] protocol was used to reconcile the sub-metered data with the mains energy and the CIBSE TM22 protocol [45] was used to estimate the miscellaneous loads that were not directly metered. The measured performances of these buildings were subsequently compared against the as-built calculations, broken down as fossil fuel and electrical energy use. The allowance used for equipment load in as-built calculations to calculate heating and cooling loads was included in the analysis, to ensure all energy end-uses are represented. For the offices in China, electrical energy consumption was established after the first year of operation through long-term monitoring of energy use associated with electricity use and the sub-metered energy end-uses. The heating components for each case study have been weather-corrected, based on the heating degree-days during the measurement period, to ensure the modelling results and measured performance are comparable.

2.2.3. Bottom Up IEQ

The buildings used in this analysis were selected based on available high granularity and temporal resolution IEQ data. Thermal comfort conditions and CO_2 concentrations, as a proxy for the indoor air quality, were used to illustrate IEQ performance gaps in the two countries. In the UK BSF dataset, temperature and RH were recorded every ten minutes, while CO_2 was available every minute in typical weekly blocks during the heating season [34] for five buildings (A,B,C,D,E) following the guidelines set out in BS EN ISO 7726 (2001) and BS EN 15251 (2007). In the Chinese low carbon dataset, temperature, RH and CO_2 measurements were available ten minutes over the whole year in five office buildings (A,B,C,D,E) [37].

2.2.4. Occupant Satisfaction

Occupant satisfaction data is available from Building Use Studies (BUS) surveys in UK BSF schools [34], while in China this data has been collected for the energy-efficient buildings through occupant surveys developed by Tsinghua University [37]. BUS surveys seek occupants' feedback about their buildings using a succinct self-completion questionnaire. The questionnaire for non-domestic buildings covers various aspects of the indoor environmental quality in addition to general questions about building design, work space conditions, and the impact of building on occupants' health and behaviour [48,49]. Scores based on the average responses to a particular question are compared with the benchmarks derived from the last 50 buildings in the BUS dataset. For the UK, teachers and admin staff in all case study schools were subject to BUS survey with response rates higher than 70%. In this paper, the results for the key IEQ variables and the occupants' overall satisfaction with their buildings are presented along with the mean benchmarks derived from the BUS dataset.

In China, occupant satisfaction is derived from occupant surveys, in this case a questionnaire designed by Tsinghua University that covers IEQ satisfaction, such as thermal, visual, acoustic environment, indoor air quality, and general questions about the workplace, as well as occupants' habits of using indoor equipment and availability of adaptive adjustments [36]. Anonymous questionnaires are distributed by hand to at least 20% of staff to collect occupant subjective evaluations, with a minimum of 20 collected questionnaires per building. A 'benchmark' value is also used in the Chinese surveys to relate the buildings to previously evaluated stock – in this case, the results of 238 questionnaires from eight conventional office buildings.

2.2.5. Case study – UK School A

In the UK, several methodological issues in the current regulatory framework make it difficult to compare the 'as-built' performance of a building with the actual performance. It is also important to consider the operational requirements of the building including the occupancy, schedules of operation of building services, and actual small power load. To illustrate the importance of high granularity and temporal resolution data on identification of total performance gaps, half-hourly electrical demand and energy use data is used to examine temporal variations in total building performance in UK School A. A standardised method of comparing operational and expected energy and IEQ performance is also suggested that can be used to evaluate and illustrate the total performance.

3. Results

3.1. Top Down Analysis

Figure 1 shows the annual fossil and electrical energy consumption of UK conventional and energy-efficient schools. Results show that energy-efficient schools show only modest improvement in energy consumption relative to conventional schools, with the EUIs of a considerable proportion of energy-efficient buildings higher than the stock median. This contrasts with the belief that new buildings are more energy efficient than conventional buildings due to, for example, reduced heat loss through building fabric resulting from higher specifications. Notably, energy efficient schools show a greater electrical energy consumption than conventional schools which can lead to higher carbon emissions associated with building energy use in new buildings, as the current carbon intensity of the UK national grid is higher than natural gas and other fuels used for heating. Energy consumption data for the Chinese offices can be seen in Figure 2. As in the UK, energy efficient buildings do not necessarily have lower energy use than conventional buildings. Taking buildings in China hot summer & warm winter region for example, close to half of these new buildings are using energy more intensively than the median performance of existing buildings, and some exceeding the 75th percentile. This evidence, emerging from two locations with vastly different techno-socio-economic contexts, points to the challenges of improving the energy efficiency of building stock in practice and is indicative of improvement opportunities in procurement and operation of new buildings in different countries.

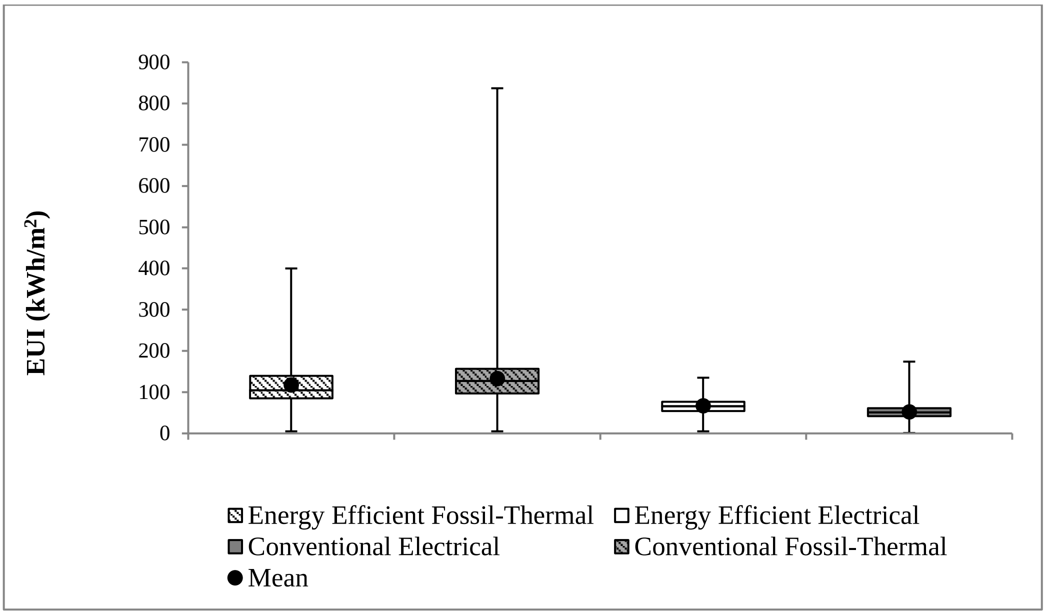


Figure 1. Energy use intensity in conventional and energy-efficient buildings in the UK. EUI is divided into fossil-thermal EUI for heating and electrical EUI for other building services and equipment.

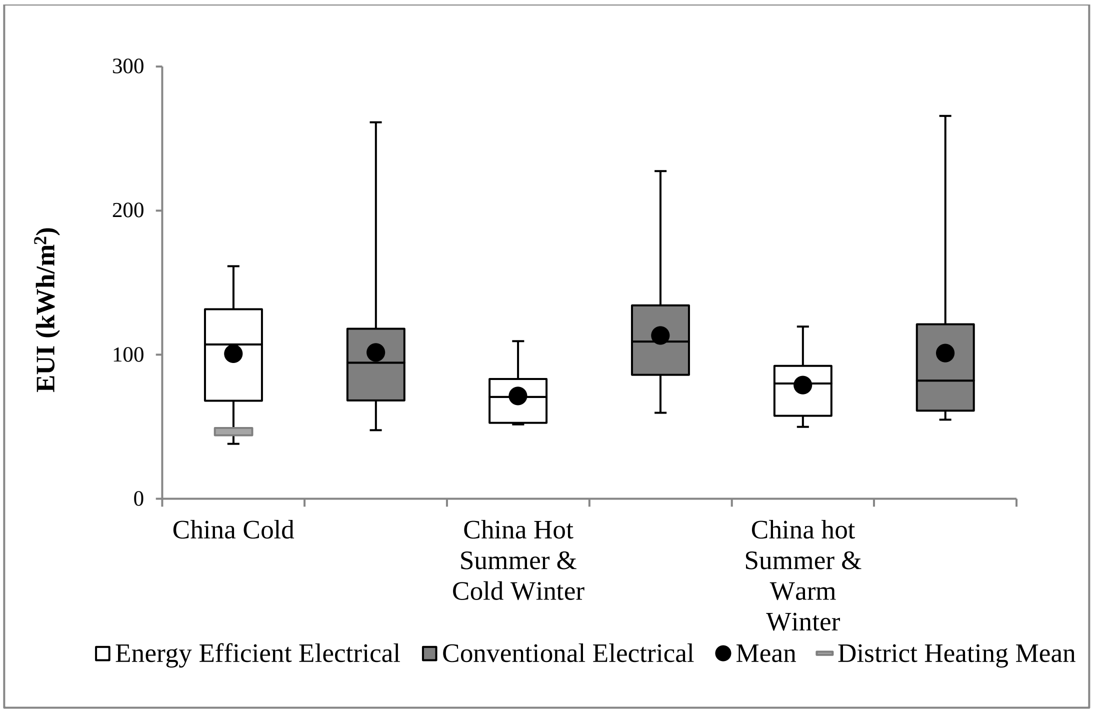


Figure 2. Energy use intensity in conventional and energy-efficient buildings in the China by climate region. The energy efficient buildings in the China cold region are heated by district heating for which only a stock-level mean building estimate is available (district heating mean). In all other buildings, heating and cooling is electrical.

3.2. Bottom Up Energy Analysis

Bottom-up energy performance analysis examined the actual and target energy consumption data in the UK and China. Figure 3 shows the deviation of the operational performance of the UK schools from the final as-built calculations, indicating greater energy consumption than was predicted in the design calculations caused by, for example, the effect of extra-curricular activities such as night schools and inefficient space-time control strategies to respond to these activities [50]. Figure 4 shows the same results for Chinese offices, where some cases performed better than calculations owing to effective control of the environmental strategies (Building A) or partial occupancy (Building F). However, more than half of the cases use more energy than design.

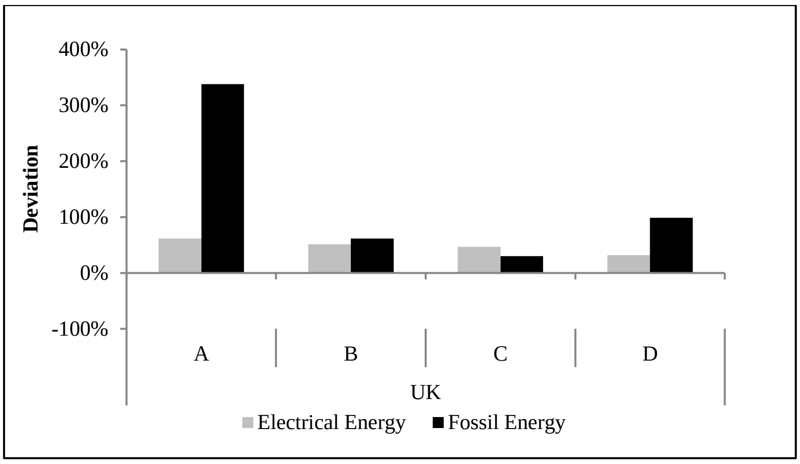


Figure 3. Deviation of actual from target energy consumption for the UK schools (Measured - As-built)/(As-built).

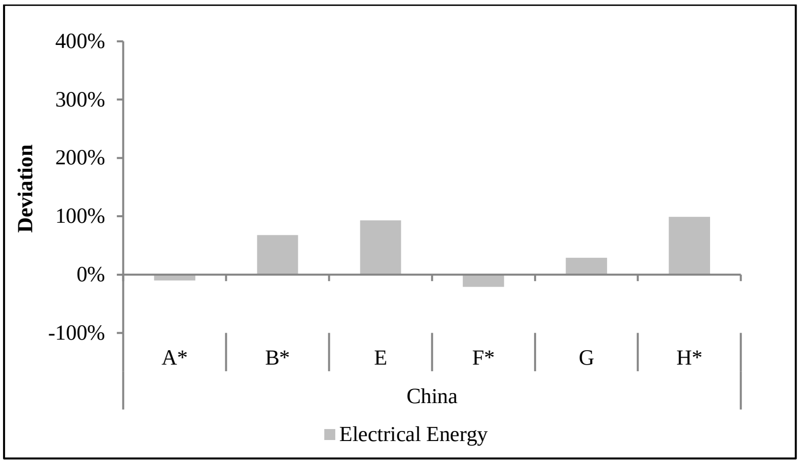


Figure 4. Deviation of actual from target energy consumption for the Chinese offices (Actual-Design)/Design. (*) denotes buildings located in the cold zone; all other are in the hot summer/cold winter zone.

3.3. Bottom Up IEQ Analysis

Building IEQ data was available at high temporal resolution for both UK schools and Chinese offices, enabling evaluation of the indoor environment during different times of the year. Figure 5 shows the ranges of indoor CO_2, temperature, and RH recorded in classrooms in energy-efficient schools in the UK. The CO_2 concentrations in UK buildings closely follow the ventilation strategies with mechanically ventilated buildings (A, B, E) generally showing lower CO_2 levels than naturally ventilated schools (C, D) which exceeded the UK school regulatory limit of 1500ppm CO_2. RH in all schools was often close to or below the lower limit of the 40-70% comfort range recommended by CIBSE; RH levels below 40% are not unusual during heating season in the UK buildings that often do not use humidification [51]. Air temperatures in the UK schools are predominantly above the acceptable range of 19-21 °C in winter, with very few hours above the overheating threshold of 28 °C in either season. Poor thermal comfort instances observed in the case studies were due to a reliance on radiant panels in most classrooms and no perimeter heating around the building (School B) or conflicts between heating and cooling systems where the dead-band specified for respective set points was not sufficient and the control strategy was compromised as a result of operational issues (School E).

The results for the Chinese offices can be seen in Figure 6. CO_2 concentrations in the case study buildings are predominantly below the office limit of 1000ppm CO_2, although instances where CO_2 concentrations significantly exceeded the limit also were observed. Indoor temperatures differ greatly due to different climate zones, especially in winter, with temperatures in buildings in the hot summer and cold winter zone (C, D and E) significantly below the lower limit of the 18-24°C comfort range. The primary driver of this discrepancy is the heating system type and control strategy, which differs between climate zones. RH levels showed significant regional and seasonal differences, ranging from below 30% in the cold zone, and up to 80% during the summer in the hot zone. The differences in temperatures and RH levels between winter and summer in China buildings are markedly larger than those in UK buildings, and it is therefore likely that energy consumption in

China would increase if IEQ performances were to be improved and maintained in a relative stable comfort range.

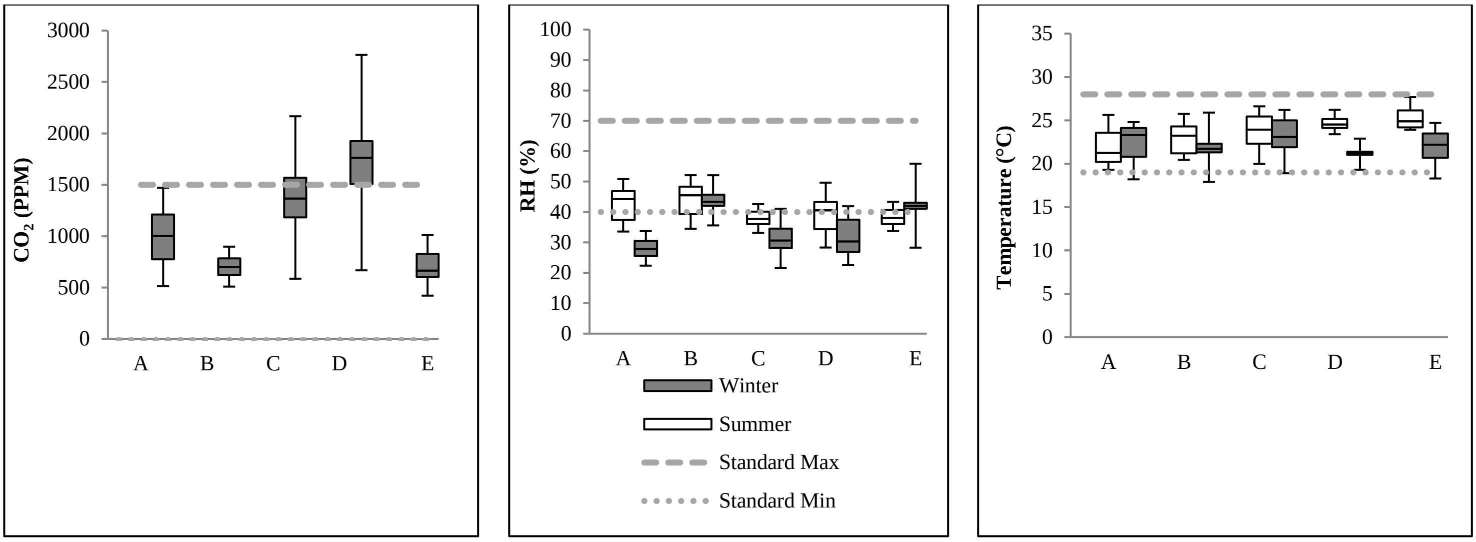


Figure 5. Distributions of monitored IEQ variables for energy-efficient schools in the UK, aggregated seasonally. Dashed lines show the target static maximum and minimum criteria as defined by UK building regulations, design guidelines, and schools' building bulletins.

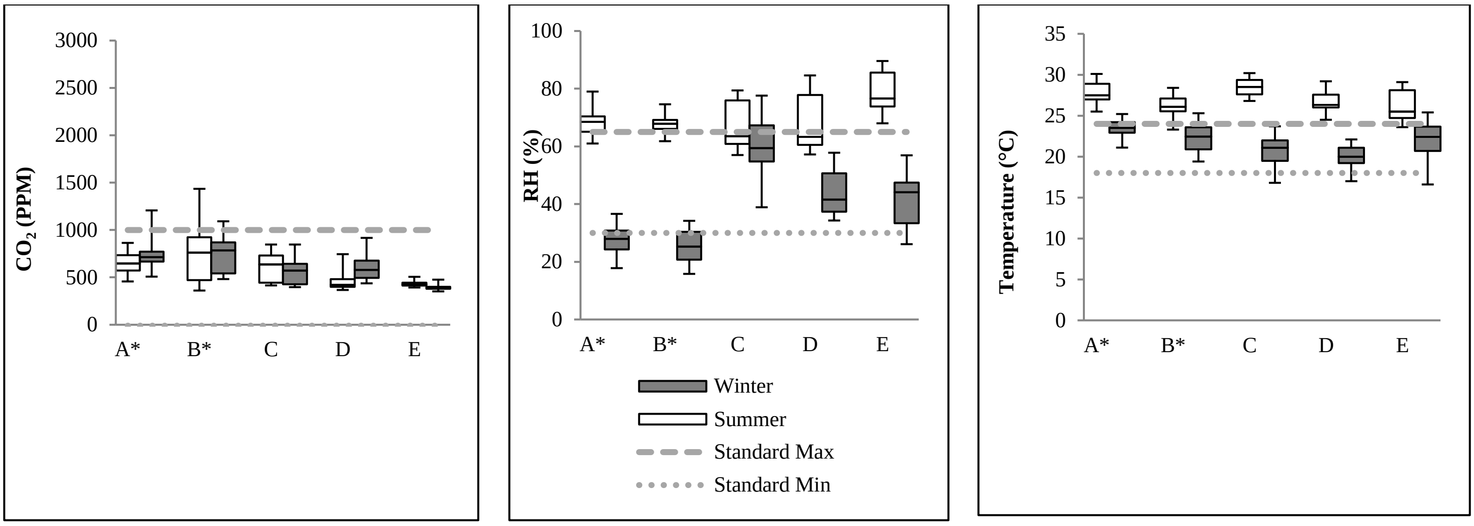


Figure 6. Distributions of monitored IEQ variables for energy-efficient offices in China, aggregated seasonally. Dashed lines show the target static maximum and minimum criteria as defined by local building regulations. (*) denotes buildings located in the cold zone; all other are in the hot summer/cold winter zone.

3.4. Bottom Up Occupant Satisfaction Analysis

Figure 7 shows the aggregated results of the UK BUS surveys for schools. Examples of problems that caused dissatisfaction among school occupants were the noise levels stemming from open-plan design of educational spaces (School C) and summertime temperatures and poor indoor air quality caused by the poor buildings services control which led to the Building Management System being recommissioned few years after building completion (School E). Satisfaction with temperature and air quality varied from building to building depending on specific situations, which meant buildings services control strategy did play an important role in operational performance. In the case of the UK School E, this was due to shortcomings in building procurement process that resulted in an operational performance significantly worse than the design intent and cause dissatisfaction among building occupants.

Figure 8 shows the aggregated results of the Chinese occupant surveys, presented in a similar manner to the BUS survey. Energy-efficient buildings showed a higher score on IEQ and overall satisfaction than conventional offices. Like UK School C, almost all buildings had a low score for noise, the major cause of which could be explained by open-plan layout design. The available data indicates that, despite different building types, occupant demographics, and methods of collecting satisfaction data, issues with building services control and open plan design led to underperformance in both countries. Given that building occupants have the greatest experience with the building's operation, occupant satisfaction surveys such as the ones above are useful mechanisms for identifying performance gaps.

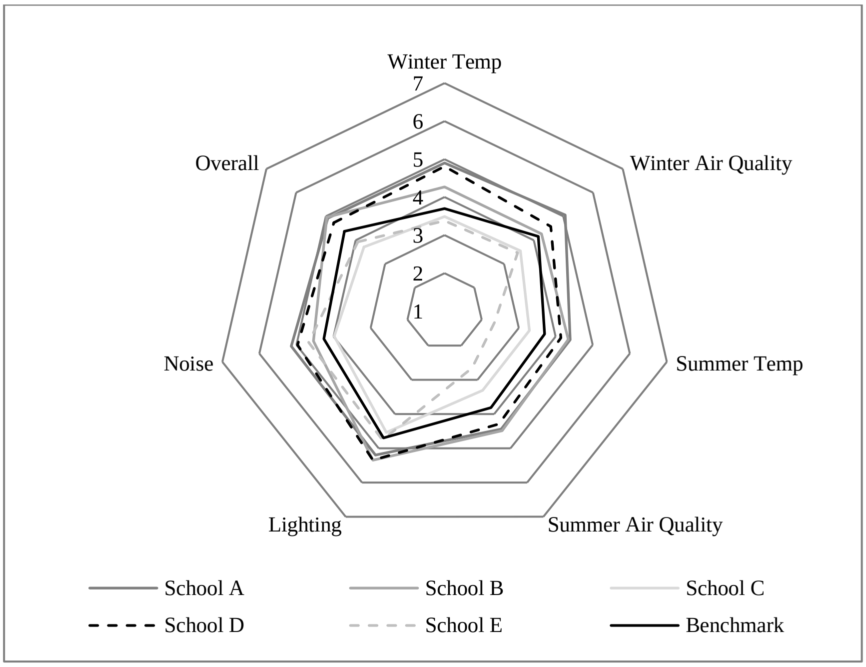


Figure 7. Aggregated results for the UK BUS survey in energy-efficient schools.

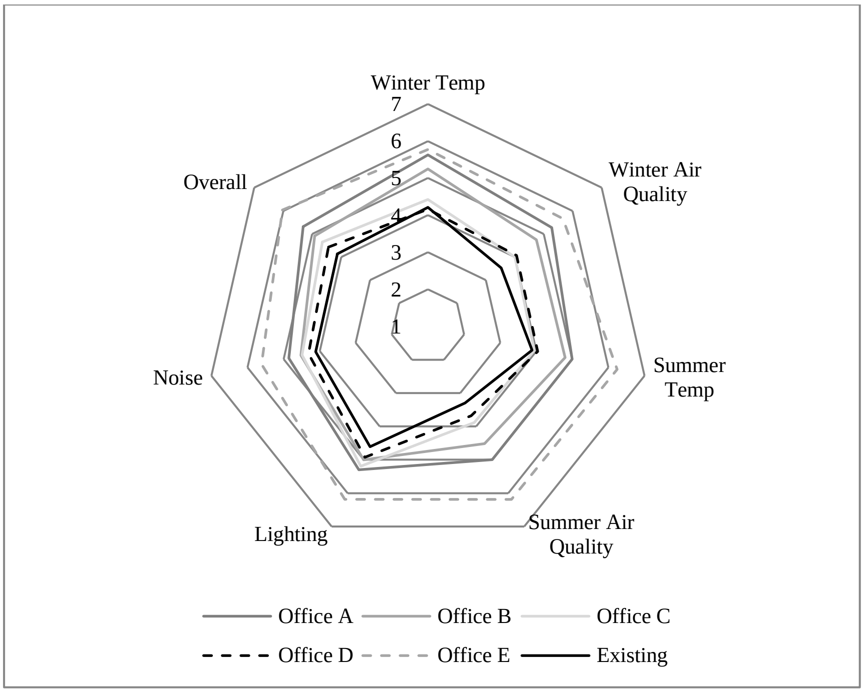


Figure 8. Aggregated results for the Chinese occupant survey in energy-efficient offices.

3.5. Case study

Monitored data for School A, a mechanically ventilated secondary school in North West England constructed in 2008, was used to illustrate the requirement for high granularity and temporal resolution data to diagnose issues with building performance. Figure 9 shows the as-built performance derived from a computer model and a weather-corrected operational baseline, derived from the same model after adjustments for actual occupancy and weather data, against the actual performance for School A in the UK. The operational baseline considers the actual operating conditions including the significant equipment loads that were not accurately known at design stages and are not regulated under the building regulations. Using end-use specific, high granularity data enables comparison of the measured performance with the operational baseline, and can help determine the real performance gap caused by technical issues and operational inefficiencies.

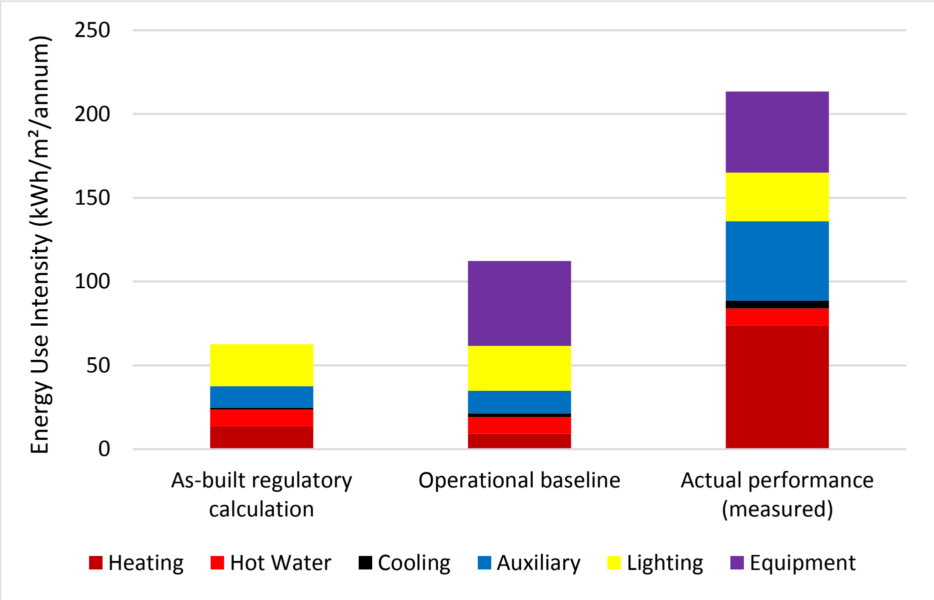


Figure 9. Modelled as-built performance, weather-corrected operational baseline, and actual performance for School A.

Figures 10 and 11 depict the range of variation along with average electrical demand for 24 hours based on annual half-hourly electricity data sourced for School A for weekdays and weekends, respectively. This is an example of how temporal resolution of data can provide useful insights into the problem of the performance gap, which can be subsequently followed-up with further investigations. While the shape of the weekday electrical demand curve is indicative of potential flaws in the demand-controlled ventilation strategy of the building, the constant nature of the daytime electrical demand over the weekends shows unnecessary and regular use of a mechanical plant. Further investigation confirmed that the demand-controlled ventilation strategy initially envisaged for the building had not been effectively enabled, and the schedules of operation for the heating system and mechanical ventilation plant were defaulted to ON over the weekends, even when the building was completely closed with no heating and ventilation requirements. Such issues can explain a large part of the performance gap observed between actual performance and baseline.

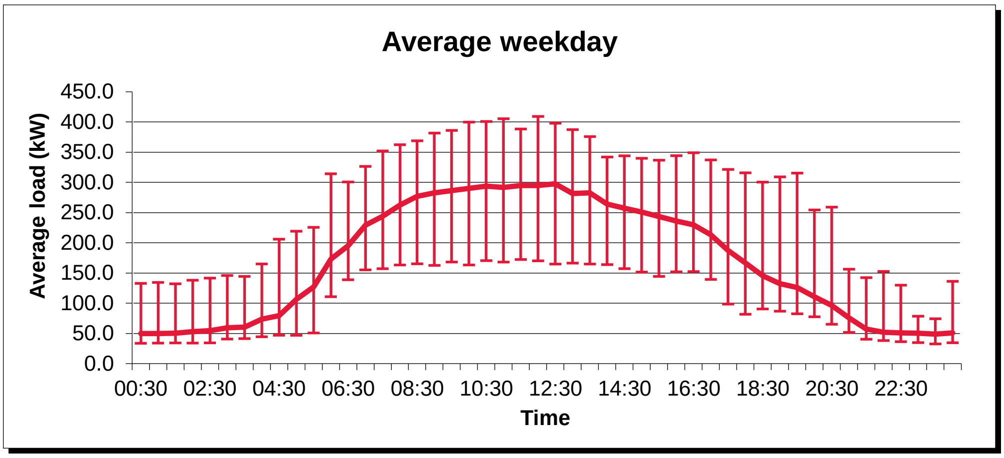


Figure 10. Average and range of 24-hour electrical demand in School A, weekdays.

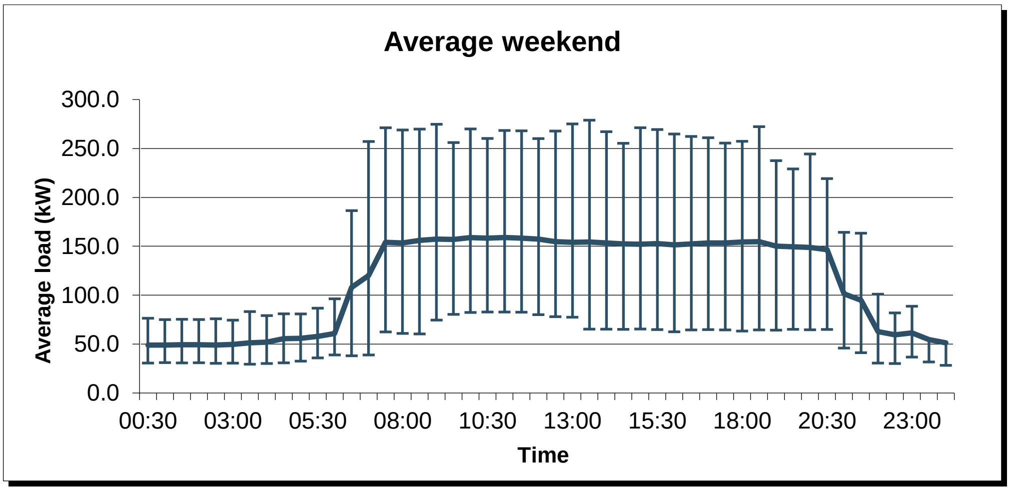
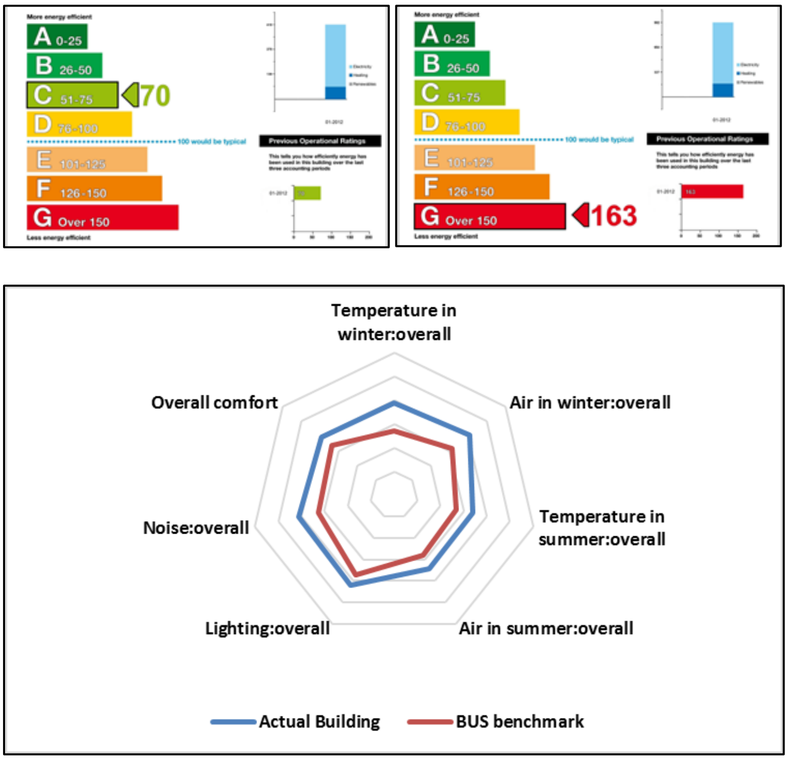


Figure 11. Average and range of 24-hour electrical demand in School A, weekends.

The ventilation system in School A was specified to provide air flows slightly higher than the minimum regulatory requirements. While this can increase building' energy use, it may also bring some improvements in indoor air quality and pupils' performance; it is therefore necessary to have an integrated view of energy and indoor environmental quality.

DECs are energy quotients that may be produced by dividing energy performance over the benchmarks defined in CIBSE TM46 to produce operational ratings; in principle, the same method could be used to convert the operational baselines derived from a computer model to an energy band. Figure 12 shows both projected and actual energy performance for School A in DEC format, as well as IEQ satisfaction scores obtained from the BUS survey. The results show a marked decline in energy performance compared against its baseline on an A/G scale, but an increase in IEQ relative to the BUS benchmarks; this enables visualisation of the poor energy performance of School A but corresponding IEQ benefits. Using the same analysis for School C in the UK would reveal that both energy and IEQ performance are significantly worse than expected in that building. While shortcomings in energy performance in School A can to a large extent be addressed by optimising the schedules of operation and utilising demand-controlled operational strategies, poor combined energy and IEQ results in School C are indicative of more fundamental problems that reflect both technical issues occurred during the procurement process. In addition, there are significant shortcomings in operational strategies and building management practices related to energy and environmental performance of the building. Figure 12 provides a suggested format for standardised presentation of energy and IEQ performance in a way that is easy to understand for building users and industry practitioners, and can help identify performance metrics compromising total performance.

Projected energy performance **Actual energy performance**



IEQ performance

Figure 12. Projected and actual energy performance for School A in DEC format, and corresponding IEQ performance relative to BUS benchmark.

4. Discussion

We have presented an initial investigation of energy and IEQ performance gaps using available quantitative building performance data, and via a case study which demonstrates how high resolution and granularity data may be used to identify the source of building underperformance.

The above results indicate varying degrees of total performance gap in both countries that need to be addressed if the energy efficiency of the building stock is to be improved without unintended consequences to the health and comfort of occupants. Additionally, the analysis provides some initial insight into the challenges and opportunities in comparing building performance across national boundaries.

The top-down analysis of building energy consumption indicates that energy-efficient buildings in the UK and China do not necessarily have lower energy consumption when compared to conventional buildings. However, it is not possible to identify the driving factors behind the underperformance of the energy efficient buildings relative to the conventional stock due to the poor temporal resolution, low granularity of the data, and the lack of concurrent occupancy and weather data. Similarly, such data provides only a partial window into overall building performance, as buildings may perform very well by energy standards but have a very poor IEQ. The analysis performed for buildings in both countries is based on the UK CIBSE methodology, which was adapted to fit the Chinese buildings. This resulted in several methodological issues, including the need for different sets of assumptions on HDDs, CDDs, and base temperatures; the conversion from coal consumption to electricity consumption, and the lack of consideration of building use. If the objective was to compare across countries, additional analyses would have been possible – for example normalising for occupancy, or a conversion of energy to a carbon equivalent. A common framework for data collection and tools which would enable dynamic total performance analysis would enable detailed comparative analysis between the two countries.

Poor energy performance of energy-efficient buildings relative to their design standards was examined further using bottom-up data to analyse the actual versus targeted energy use of the low-carbon buildings; results demonstrated both negative and positive deviations from targeted performance. The UK BPEs identified significant gaps in primary energy use in the region of 30-350% between energy performance in-use and energy performance calculations carried out on completion of the buildings when an allowance for equipment use was considered in the as-built calculations, a discrepancy which may be attributable to a range of technical and human-related factors (Burman, 2016). The Chinese offices also demonstrated a range of values, indicating both less and greater actual energy consumption than predicted. Cases where energy consumption was overestimated was likely due to under-occupancy of the building, which obscures any conclusions from being drawn regarding the performance of the building itself. One of the key methodological differences between the UK and China are different assumptions when calculating design energy; for example, in the UK regulatory framework the equipment load and some miscellaneous loads such as external lights are not regulated under the Approved Document Part L. An allowance is made for equipment load to estimate internal gains affecting heating and cooling energy but is subsequently removed from final building regulations compliance and EPC calculations. Conversely, in China, equipment load is estimated according to related building design standards and is included in final energy consumption calculations. This demonstrates how national building regulations may impose different performance calculation methods, and select different tools, which limits the scope for like-for-like comparisons between buildings internationally.

Analysis of the IEQ in the energy-efficient buildings indicated issues with high summer indoor temperatures and RH in some Chinese buildings and high winter CO_2 levels in some UK schools. Contributing factors to these differences are likely to be external climate in addition to services strategy – for example, the Chinese buildings will be subject to higher summertime temperatures and humidity levels than the UK buildings. All three IEQ variables are of interest in energy-efficient buildings, which may be at an increased risk of overheating or indoor air pollution relative to conventional buildings [36,52–54]. That some of these buildings show elevated levels demonstrates the important link between energy and IEQ performance gaps in energy-efficient buildings. Due to the limitations of CO_2 as a proxy for IAQ, further building performance research should include the measurement of indoor air pollutants from both internal and external sources. The higher temporal resolution and granularity of the data enable the seasonal exceedance of IEQ guidelines to be identified. Similarly, annual energy performance relative to design calculations (Figures 3 and 4) may be contrasted with IEQ to develop an overall understanding of building performance. A common framework for monitoring and analysing IEQ data in China and the UK would help address some of the methodological issues that are apparent. These include the fact that buildings have been designed to meet different IEQ standards, and that distributions of IEQ values relative to static standards do not provide insight into adaptive comfort, nor the frequency and duration of occupant exposure to poor IEQ.

As building occupants are likely to have the greatest experience of the IEQ in the buildings, it is important to obtain their subjective opinions through surveys to evaluate building performance. Similar issues to energy use are apparent, where the energy efficient UK schools do not necessarily outperform the benchmarking stock. Like the other analyses, direct comparison between the two countries is not currently meaningful due to methodological issues such as the phrasing of survey questions, occupant subjectivity and prior experiences, and the qualities of the benchmarking stock. In this case, the benchmarking stock includes conventional buildings in China, whereas in the UK only the previous 50 surveyed buildings are included, which would be biased towards new-builds.

4.1. Challenges and opportunities

This analysis has indicated varying degrees of performance gap across different criteria, and demonstrated how high resolution and high granularity data may provide the solution to identifying when and how buildings are under-performing. The data analysis did not, however, examine the causes of the various energy, IEQ, or satisfaction performance gaps, which are numerous, and may occur at different stages of the building lifecycle [9]. A full account of the technical and occupant-related causes of underperformance in the UK bottom-up cases is provided by Burman (2016) while the Chinese bottom-up cases have been discussed by Liu (2015b) and Zhang (2014). The purpose of this paper however is to 'demonstrate' the performance gaps, identify methodological differences, and point to endemic problems across the construction industry in both countries that impede meeting the expected performance in new buildings constructed in accordance with energy efficiency requirements. Table 2 discusses some of the key root causes of the performance gaps identified by the authors in the UK and China along with mitigation measures that can help improve total performance of buildings. Some of these measures are project based and may be adopted by clients and project teams, some may be of interest to policy makers and regulators.

There are various opportunities to improve a building's energy and IEQ performance without compromising the wider aspects of the building performance. A building will not achieve its full performance potential and the design intents unless building designers and contractors are engaged in a concerted action post-occupancy to optimise the building and its systems and provide effective training to the occupants. Reasonably detailed frameworks and key performance indicators are required to determine the extent of post-occupancy activities and evaluate their success with objective metrics. Appropriate incentives and policy measures are also required to integrate post-occupancy building performance optimisation and much needed feedback arising from it into the building procurement processes.

This paper did not seek to directly compare building performance between the two countries. Differences in building performance between the two countries are complex, and likely driven by several factors, including different policy contexts, standards, climates, building uses, and data collection methodologies. A meaningful comparison between the UK and China was not possible due to: 1) the lack of building energy and IEQ data available for similar building types in both countries, 2) the lack of concurrent energy and IEQ data at sufficiently high temporal resolution and granularity, and 3) the complexity of evaluating building performance for buildings in different countries. The latter is due to the methodological issues discussed above, as well as contextual differences such as different climates, building regulations and design standards, and energy sources [30,31]. The results and complexity of comparative analysis of buildings data from different countries highlights the need for consistent definitions and methodologies which may make such comparisons possible, and emerging standards and frameworks such as ISO 12655 and IEA Annex 53 are leading the way to make such comparisons possible for energy performance. Opportunities exist to incorporate IEQ and occupant satisfaction into international frameworks, enabling a more holistic understanding of building performance.

Table 2. Major root causes for energy and IEQ performance gap and potential mitigation measures

Root causes for the performance gap	Description	Potential mitigation measures
Poor definition of performance objectives in design briefs	Energy and IEQ performance defined to comply with regulatory requirements only or with the requirements of BREEAM, LEED or green building certification in China	• Specify 'operational' targets for energy and IEQ metrics • Agree on a robust Measurement and Verification protocol to ensure these targets are achieved
Conflicts between energy & IEQ performance objectives	Potential conflicts are often not fully explored at design stage and in construction (airtightness vs. overheating risk, natural ventilation vs. outdoor pollution, thermal mass vs. acoustic performance, etc.)	• Follow an integrated approach to energy efficiency and IEQ performance • Develop and track a risk register that considers the links between energy strategy and IEQ objectives throughout the project
Building procurement methods	Traditional contracts where architects and engineers work from concept design through to detailed design are more likely to achieve performance objectives compared to Design & Build contracts where contractors are responsible for detailed design [19]	• Keep the original design team on board to carry out or review the detailed design where possible • Identify the key determinants of energy and IEQ performance at early stages of a project • Protect key determinants of energy and IEQ from 'value engineering'
Skillset among construction supply chains	Lack of adequate skills related to new and rapidly evolving energy efficiency and sustainable building regulations is an endemic problem across construction supply chains in both countries	• Clear guidelines & approved and up to date training schemes • Key areas for improvement: low or zero carbon systems, control strategies, and commissioning (seasonal and monitor based)
Building control function	Non-compliance with the energy-related Building Regulations is an endemic problem in the industry [55,56]	• Invest in improving the technical expertise of building control bodies • Move towards output-oriented and performance based assessment frameworks

Lack of Post-Occupancy Evaluation (POE)	Few projects are subject to routine POE; fragmented incentives & benefits, lack of agreed performance criteria, and litigation risks are among the main barriers [57]	• Focus on life-cycle potential savings for buildings with Landlord occupiers • Follow voluntary frameworks such as the Soft Landings [58] or performance contracting
Knowledge gap between building designers and constructors/operators	In China, building designers are always college level educated, while building constructers and operators are more likely to be roughly middle school level educated. This knowledge gap might lead to the building performance gap between design and operation [59]	• More engagement from building designers in the construction and operation stage • Training sessions for building constructors and operators
Occupant behaviour	Occupancy behavioural parameters significantly influence energy use and are not well known specially at design stage [60]	• Apply simulation techniques such as sensitivity and scenario analysis and devise appropriate measures (isolation switches, provision for hot desking, refine Heating, Ventilation, and Air Conditioning (HVAC) zoning, demand-controlled strategies, etc.)

4.2. Future

Further work will develop a framework for dynamic total building performance monitoring, including highly-granularity and temporal resolution monitoring of total building performance, that is flexible enough to allow for national context variations. Furthermore, the role of the wider system in building performance will be evaluated using System Dynamics investigations of the various external factors which may enhance or inhibit the development of a low carbon building stock.

5. Conclusions

This paper has presented the results of an analysis of sets of monitored building energy, IEQ performance, and occupant satisfaction data from China and the UK, illustrating total building performance gaps in both countries. Analyses are presented at different granularities and temporal resolutions, and a case study presented to demonstrate how concurrent energy and IEQ data is necessary to identify the root causes of building underperformance in a holistic manner. By taking a 'total' approach to building performance, the inter-relation between building energy and IEQ performance may be accounted for, while occupant surveys provide important subjective balance to the quantitative building data. By developing frameworks for dynamic benchmarking of total building performance, it will be possible to compare performance between two contrasting locations such as China and the UK and investigate the influence of the wider system, including dominant construction types, building regulations, and government policy.

6. Acknowledgements

Funding: The *Total Performance of Low Carbon Buildings in China and the UK* is funded by the Engineering and Physical Sciences Research Council (EPSRC) grant (EP/N009703/1) and the National Natural Science Foundation of China (NSFC) grant (51561135001).

We would like to give special thanks to all the owners and managers of surveyed buildings, who provided kind help for the on-site measurement.

7. References

1. IEA. Transition to Sustainable Buildings: Strategies and Opportunities to 2050. Paris: 2013.

2. Bordass B, Cohen R, Standeven M. Assessing building performance in use 3: energy performance of the Probe buildings. *Building Research & Information [Internet].* 2001 [cited 2017 May 2];29(2):114–128. Available from: http://www.tandfonline.com/doi/abs/10.1080/09613210010008036

3. Samuelson H, Ghorayshi A, Reinhart C. Post-Occupancy Evaluation and Partial-Calibration of 18 Design-Phase Energy Models [Internet]. In: Proceedings of 2014 ASHRAE/IBPSA USA, Building Simulation Conference. Atlanta, GA: 2014 [cited 2017 May 2]. Available from: https://www.researchgate.net/profile/Holly_Samuelson/publication/270890014_Post-occupancy_evaluation_and_partial-calibration_of_18_design-phase_energy_models/links/54b7df800cf28faced609561.pdf

4. Bannister P. Why good buildings go bad while some are just born that way. *Ecolibrium,(Australian Institute of Air-Conditioning, [Internet].* 2009 [cited 2017 May 2];Available from: https://scholar.google.co.uk/scholar?q=Why+good+buildings+go+bad+while+some+are+just+born+that+way&btnG=&hl=en&as_sdt=0%2C5

5. Carbon Trust. Closing the gap, Lessons learned on realising the potential of low carbon building design. London, UK: 2011.

6. Palmer J, Armitage P. Building Performance Evaluation Programme–Early Findings from Non-Domestic Projects. 2014 [cited 2017 May 2];Available from: https://scholar.google.co.uk/scholar?q=Building+Performance+Evaluation+Programme%2C+Early+Findings+from+Non-Domestic+Projects%2C+report+prepared+for+Innovate+UK&btnG=&hl=en&as_sdt=0%2C5

7. Voss K, Herkel S, Pfafferott J, Löhnert G, Wagner A. Energy efficient office buildings with passive cooling – Results and experiences from a research and demonstration programme. *Solar Energy [Internet].* 2007 [cited 2017 May 2];81(3):424–434. Available from: http://www.sciencedirect.com/science/article/pii/S0038092X06001149

8. Turner C, Frankel M. Energy performance of LEED for new construction buildings. *New Buildings Institute [Internet].* 2008 [cited 2017 May 2];Available from: https://www.acca.com/legalresources/publications/greenhousecounsel/upload/Docs3930.pdf

9. van Dronkelaar C, Dowson M, Spataru C, Mumovic D. A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings. *Frontiers in Mechanical Engineering.* 2016 Jan 13;1(17).

10. Mumovic D, Palmer J, Davies M, Orme M, Ridley I, Oreszczyn T, et al. Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England. *Building and Environment.* 2009;44(7):1466–1477.

11. Hartkopf V, Loftness V, Mill P. The concept of total building performance and building diagnostics. *Building performance: Function, [Internet].* 1986 [cited 2017 May 2];Available from: http://www.astm.org/DIGITAL_LIBRARY/STP/PAGES/STP23009S.htm

12. Committee on Climate Change. Factsheet: Buildings [Internet]. 2015;Available from: https://www.theccc.org.uk/wp-content/uploads/2014/08/Fact-sheet-buildings-updated-July-2015.pdf

13. HM Government. Building Regulationd Part L - Conservation of Fuel and Power. London, UK: 2016.

14. HM Government. Approved Document F. London, UK: 2010.

15. Chatzidiakou L, Mumovic D, Summerfield AJ, Tàubel M, Hyvärinen A. Indoor air quality in London schools. Part 2: long-term integrated assessment. *Intelligent Buildings International.* 2014;7(2–3):130–146.

16. Chatzidiakou L, Mumovic D, Summerfield A. Is CO2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO2 levels, ventilation rates and selected indoor pollutants. *Building Services Engineering Research and Technology.* 2015;36(2):129–161.

17. Bordass B, Leaman A, Ruyssevelt P. Assessing building performance in use 5: conclusions and implications. *Building Research & Information [Internet].* 2001 [cited 2017 May 2];29(2):144–157. Available from: http://www.tandfonline.com/doi/abs/10.1080/09613210010008054

18. Innovate UK. Building Performance Evaluation Programme. Swindon, UK.: 2016.

19. Palmer J, Godoy-Shimizu D, Tillson A, Mawditt I. Building Performance Evaluation Programme: Findings from domestic projects Making reality match design. Swindon, UK.: 2016.

20. Liu S. The present situation and prospect analysis of building energy saving in China. *Shanxi architecture.* 2010;36(16):226–227.

21. MOHURD. GB/T 51161-2016. Civil building energy consumption standard. 2016.

22. NBSPRC. China Statistical Yearbook. Beijing: 2013.

23. NBSPRC. China Statistical Yearbook. Beijing: 2014.

24. NBSPRC. China Statistical Yearbook. Beijing: 2015.

25. MOHURD. Assessment standard for green building. 2014.

26. Wei J, Yan W, Yao Z. The energy consumption status and energy saving potential in China. *Journal of Shenyang Architectural and Civil Engineering Institute.* 1994;10(2):185–190.

27. Zou F, You H. Post-occupancy evaluation of green building energy consumption. In: The tenth international conference on green and energy efficient building and new technologies and products expo. Beijing: 2014.

28. Pei Z. Research on post occupancy evaluation of operation performance of green office buildings. 2015;

29. Wang Z, Zhao H, Lin B, Zhu Y, Ouyang Q, Yu J. Investigation of indoor environment quality of Chinese large-hub airport terminal buildings through longitudinal field measurement and subjective survey. *Building and Environment [Internet].* 2015 Dec [cited 2017 Jul 4];94:593–605. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0360132315301530

30. Xia J, Hong T, Shen Q, Feng W, Yang L, Im P, et al. Comparison of building energy use data between the United States and China. *Energy and Buildings [Internet].* 2014 [cited 2017 May 2];78:165–175. Available from: http://www.sciencedirect.com/science/article/pii/S0378778814003533

31. Amecke H, Deason J, Hobbs A, Novikova A, Xiu Y. Buildings Energy Efficiency in China, Germany, and the United States [Internet]. San Francisco: 2013 [cited 2017 May 2]. Available from: http://www.ikem.de/wp-content/uploads/2017/03/Novikova_etal_CPI-Report_2013_Buildings-Energy-Effiviency-in-China-Germany-and-the-United-States.pdf

32. NAO. The Building Schools for the Future Programme: Renewing the secondary school estate. London, UK: 2009.

33. Hong SM, Paterson G, Mumovic D, Steadman P. Improved benchmarking comparability for energy consumption in schools. *Building Research & Information.* 2013;42(1):47–61.

34. Burman E. Assessing the operational performance of educational buildings against design expectations - a case study approach. 2016;

35. Xiao H. Study on Distribution Features and Influencing Factors on Energy Use in Office Buildings by Statistical Method and Survey. 2011;

36. Pei Z, Lin B, Liu Y, Zhu Y. Comparative study on the indoor environment quality of green office buildings in China with a long-term field measurement and investigation. *Building and Environment.* 2015;84:80–88.

37. Lin B, Liu Y, Wang Z, Pei Z, Davies M. Measured energy use and indoor environment quality in green office buildings in China. *Energy and Buildings.* 2016;129:9–18.

38. CIBSE. CIBSE TM46 Energy benchmarks. London, UK: CIBSE Publications; 2008.

39. Hong SM, Paterson G, Burman E, Steadman P, Mumovic D. A comparative study of benchmarking approaches for non-domestic buildings: Part 1 – Top-down approach. *International Journal of Sustainable Built Environment.* 2014 Apr;2(2):119–130.

40. CIBSE. CIBSE TM47 Operational Ratings and Display Energy Certificates. CIBSE Publications; 2009.

41. Tsinghua University Building Energy Research Centre (THUBERC). Annual Report on China Building Energy Efficiency. Beijing: 2015.

42. Yi J, Xiu Y. Electricity Equivalent Conversion Method in Energy Analysis. *Energy of China.* 2020;32:5–11.

43. MOHURD. GB 50176. Thermal Design Code for civil building (draft for approval). Beijing: 2015.

44. CIBSE. TM39 Building Energy Metering. London: 2009.

45. CIBSE. TM22 Energy assessment and reporting method. London: 2006.

46. ISO. BS EN ISO 7726:2001 Ergonomics of the Thermal Environment, Instruments for Measuring Physical Quantities. Geneva, Switzerland: 2001.

47. ISO. BS EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Geneva, Switzerland: 2007.

48. Cohen R, Standeven M. Assessing building performance in use 1: the Probe process. *Building Research & Information.* 2001;29(2):85–102.

49. Leaman A, Bordass B. Are users more tolerant of "green"buildings? *Building Research & Information.* 2007;35(6):662–673.

50. Burman E, Mumovic D, Kimpian J. Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings. *Energy.* 2014;77:153–163.

51. CIBSE. CIBSE Guide A: Environmental Design. London: 2015.

52. Liu Y, Lu B, Pei Z, Lin B. Field investigation of operational energy consumption and environmental quality for Environmental Conventions Building. *HV&AC.* 2015;45(3):22–27.

53. Liu Y, He Q, Pei Z, Lin B, Li C. Operational performance research of Tenio office building. *HV&AC.* 2015;45(4):45–51.

54. Zhang Y, Yang J, Wang R. Green building operation performance research of SRIBS Xinzhuang Comprehensive Building. *HV&AC.* 2014;44(11):1–7.

55. Eichhammer W, Fleiter T, Schlomann B, Faberi S, Fioretto M, Piccioni N, et al. Study on the energy savings potentials in EU member states, candidate countries and EEA countries : final report. 2011 Nov 24 [cited 2017 Jul 4];Available from: https://epub.wupperinst.org/frontdoor/index/index/docId/3926

56. Economidou M, Atanasiu B, Despret C, Maio J, Nolte I. Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings. *Institute Europe (BPIE).* 2011;

57. Zimmerman A, Martin M. Post-occupancy evaluation: benefits and barriers. *Building Research & Information [Internet].* 2001 Mar 18 [cited 2017 Jul 4];29(2):168–174. Available from: http://www.tandfonline.com/doi/full/10.1080/09613210010016857

58. Way M, Bordass W. The Soft Landings Framework: for better briefing, design, handover and building performance in-use. Bracknell: 2009.

59. Bin S, Haiyan L, Bo S, Halverson M, Evans M, Xiaojiao Z. Feedbacks from Focus Group Meeting on Training and Implementation of Building Energy Codes in China. 2011 [cited 2017 Jul 4];Available from: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-20138.pdf

60. Azar E, Menassa C. Sensitivity of Energy Simulation Models to Occupancy Related Parameters in Commercial Buildings [Internet]. In: Construction Research Congress 2012. Reston, VA: American Society of Civil Engineers; 2012 [cited 2017 Jul 4]. p. 1381–1390.Available from: http://ascelibrary.org/doi/10.1061/9780784412329.139