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Assessing the Operational Performance of Educational Buildings against Design Expectations - A Case Study Approach

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I, Esfandiar Burman, confirm that the work presented in this dissertation is my own. Where information has been derived from other sources, I confirm that this has been indicated in the dissertation.

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ABSTRACT

Overwhelming evidence shows the average global temperature is rising and climate change is happening. The severity of the potential consequences and the significance of early action to limit environmental damage have led to urgent calls for a concerted action from governments across the globe to adopt appropriate policies for climate change mitigation and adaptation.

Energy consumption of buildings accounts for around 40% of total final energy use of the EU Member States and contributes to the anthropogenic CO_2 emissions that cause climate change. Therefore, improving energy efficiency of new and existing building stock is an indispensable component of climate change policy in the EU. The urge for reducing energy consumption is also driven by other factors such as energy security and fuel poverty.

The European Union has set out an ambitious target for 2050 to reduce its Greenhouse Gas (GHG) emissions by 80-95% below 1990 levels. There are also interim targets for 2020 for 20% cut in GHG emissions from 1990 levels, and 20% improvement in energy efficiency over 1990 levels.

The Energy Performance of Buildings Directive (EPBD) and its recast underpin most of the energy regulations implemented in the EU Member States to improve energy efficiency of the existing and new buildings. However, there are concerns about the effectiveness of the existing regulatory frameworks in achieving the energy saving targets set out both at the European and national levels. Building performance evaluations carried out on new buildings and major refurbishments often point to shortcomings in building procurement and failure to achieve the design targets. This shortfall in operational performance is called the performance gap. The performance gap may point to shortcomings in various performance metrics, but is often expressed as a shortfall in energy performance or carbon dioxide emissions associated with building energy use.

To gain a better understanding of the nature of the performance gap and its root causes, this Engineering Doctorate programme adopted a case study approach to assess the operational performance of five educational buildings, constructed under the Building Schools for the Future (BSF) programme in England, against design expectations. It is suggested that educational buildings, broadly speaking, have similar activity and objective systems and therefore are suitable for comparative analysis. The building performance evaluation framework used for the case studies entails detailed review of operational energy performance against the industry benchmarks and energy performance calculations performed at design stages. Those aspects of the indoor environmental quality that are directly related to energy

performance were also monitored and assessed to ensure energy efficiency measures do not compromise occupants' comfort and well-being. These measurements were complemented by Building Use Studies to seek the feedback of schools' staff about building performance and obtain a holistic view of performance in-use. Finally, a forensic review of design and as-built documentations along with the feedback received from building designers and contractors were used to identify the root causes for performance issues uncovered in the case studies.

The findings show a marked reduction in fossil-thermal fuel use of most new-build schools against the benchmarks derived from the existing building stock thanks to improvements in building fabric and air tightness standards. However, electricity use of all case studies was significantly higher than benchmarks. Although ever-increasing use of ICT equipment in modern educational buildings can partly explain this surge in electricity use, significant improvement opportunities were identified for the control of building services. It was revealed that around half the electricity used in these buildings was consumed outside the core occupancy hours. The fossil-thermal fuel use of schools can also be further improved by using the existing zoning arrangements for heating systems to isolate the unoccupied spaces during out-of-hours and half-term operation.

Assessment of the indoor environmental quality and building users' feedback points to conflicts between various environmental strategies related to thermal comfort, ventilation, acoustics, and energy performance. These conflicts must be addressed to achieve the right balance between comfort and energy efficiency.

Teachers expressed concerns about the effectiveness of open-plan learning resources specified for new schools. In addition to the pedagogical issues that may occur if teachers are not engaged in spatial planning of teaching spaces, the increasing tendency to open-plan design brings challenges for energy efficiency and building control that are not fully acknowledged during design and in operation.

The outcomes of the regulatory energy performance calculations that are often used in the discourse about the performance gap cannot be directly used as yardsticks for performance in-use. This type of performance gap is called 'the regulatory performance gap' in this dissertation. It is demonstrated that, when these outcomes are adjusted to allow for equipment and miscellaneous non-regulated loads and are subject to the same carbon emission conversion factors used for operational ratings, they are close to the 10th or 25th percentile of the national building stock and can be used as good practice *benchmarks* for building performance that take into account key building characteristics such as shape, fabric and building services' specification. However, these adjusted calculations cannot be used as *baselines* for energy performance as they are carried out under standardised operating conditions that do not necessarily represent real operation. It is recommended to move towards assessment of expected performance in-use following protocols such as CIBSE TM54 or ASHRAE 90.1 to have a better understanding of the extent of the performance gap. The performance gap determined by comparing the measured performance with the expected performance, often projected at design stages, is called 'the static performance gap' in this dissertation. While it is often more reliable than the regulatory performance gap, it is rooted in a static notion of building performance and does not take into account the longitudinal changes in building context.

The performance gap that quantifies the effect of shortcomings in building design, construction and operation could be determined when the calculated and measured performance both represent actual operating conditions. This is called 'the dynamic performance gap' in this dissertation. The word 'dynamic' in this context means the computer model initially used to project building performance is updated to reflect the changes in building context.

An appropriate measurement and verification framework is required to account for differences between modelled and actual operating conditions post-occupancy and separate the effect of human behaviour from technical issues that must be addressed to optimise operational performance. It is demonstrated how such a measurement and verification framework can work under the existing building regulations to define the energy performance gap with precision. This can help identify and address the performance gap in early stages of post-occupancy. The policy implications of this framework are explored. It is suggested that this framework can also facilitate the effective implementation of energy performance contracting which is supported by the new EU Directives, such as the Energy Efficiency Directive, and is a key step in narrowing the performance gap in new and existing buildings.

Finally, this dissertation calls for measurement, verification and disclosure of performance data in the school estate, and more widely the public sector, to achieve better value for money. This may in turn also drive disclosure of performance data and further improvements in the private sector.

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GLOSSARY OF TERMS:

AHU: Air Handling Unit

ASHRAE: American Society of Heating, Refrigeration, and Air-conditioning Engineers

bEQ: building Energy Quotient

BESTEST: Building Energy Simulation Test

BIM: Building Information Modelling

BIU: Building In Use

BMS: Building Management System

BPE: Building Performance Evaluation

BPRU: Building Performance Research Unit, University of Strathclyde

BRE: Building Research Establishment

BSF: Building Schools for the Future programme

BSRIA: Building Services Research and Information Association

BUS: Building Use Studies

CIBSE: The Chartered Institution of Building Services Engineers

CVRMSE: Coefficient of Variation of the Root Mean Square Error

DEC: Display Energy Certificate

DfES: Department for Education and Skills

DHW: Domestic Hot Water

DQM: Design Quality Method

DSM: Dynamic Simulation Method

DSY: Design Summer Year

DX: Direct Expansion air conditioning unit

EHCS: English House Condition Survey

EPBD: Energy Performance of Buildings Directive

EPC: Energy Performance Certificate

ESCOs: Energy Services Companies

ETFE: Ethylene Tetrafluoroethylene

EU ETS: European Union Emissions Trading Scheme

EUI: Energy Use Intensity

FEMP: Federal Energy Management Program

GCSE: General Certificate of Secondary Education

GDP: Gross Domestic Product

GHG: Greenhouse Gas emissions

GIS: Geographic Information System

GSHP: Ground Source Heat Pump

HEFCE: Higher Education Funding Council for England

HSE: Health and Safety Executive

HVAC: Heating, Ventilation and Air Conditioning

ICT: Information and Communications Technology

IEQ: Indoor Environmental Quality

IPCC: Intergovernmental Panel on Climate Change (IPCC)

IPMVP: International Performance Measurement and Verification Protocol

LTHW: Low Temperature Hot Water

LZC: Low or Zero Carbon

M&T: Monitoring & Targeting

M&V: Measurement & Verification

MBE: Mean Bias Error

Mtoe: Mega tonne of oil equivalent

MV: Modulating Valve

NABERS: National Australian Built Environment Rating System

NCEF: US National Clearinghouse for Educational Facilities

NCM: National Calculation Methodology (NCM)

NMBE: Normalised Mean Bias Error

PFI: Private Finance Initiatives

PIR: Passive Infrared sensors

PIR (Chapter 8): Polyisocyanurate foam boards

PMV: Predicted Mean Vote

POE: Post-Occupancy Evaluation

PPD: Predicted Percentage Dissatisfied

PROBE: Post-occupancy Review of Buildings and their Engineering

PSBP: Priority School Building Programme

RFC: the key Reasons For Concern

RH: Relative Humidity

RIBA: The Royal Institute of British Architects

SBEM: Simplified Building Energy Model

SFP: Specific Fan Power

TRY: Test Reference Year

UNFCCC: United Nation Framework Convention on Climate Change

URL: Uniform Resource Locator

VRF: Variable Refrigerant Flow

XML: Extensible Markup Language

ZCH: Zero Carbon Hub

1. Introduction

This chapter explains the main drivers behind the research programme that led to this dissertation, and defines the aim and objectives of the research. It also provides an overview of the structure of the Engineering Doctorate programme that was followed to ensure the necessary skillset and information are acquired to fulfil the research requirements. Finally, a brief description of the organisation of the dissertation and the contents of various chapters is presented.

1.1. Built environment: the energy context

Overwhelming evidence shows the average global temperature is rising. The Inter-governmental Panel on Climate Change (IPCC) states that there is now 95% confidence that human action is the dominant cause of this climate change (IPCC, 2013). The remaining uncertainty in the science of climate change is subject to intense research and fiercely contested. However, the Precautionary Principle calls for risk-prevention actions even if our knowledge about a complex problem is not perfect, especially when postponing actions may make the potential damages riskier (Gollier, et al., 2001). The severity of the potential consequences of climate change along with the significance of early action (Stern, 2006) have led most governments to acknowledge the threat and take some actions to mitigate the risk of climate change and devise appropriate adaptation strategies. Buildings constitute 35% of the global final energy consumption which contributes to the anthropogenic CO_2 emissions that cause climate change (IEA, 2013). Therefore, improving energy efficiency of new and existing building stock is an indispensable component of climate change policy across the globe.

In Europe, the European Union has set out an ambitious target of reducing its Greenhouse Gas (GHG) emissions by 80-95% below 1990 levels by 2050. There are also interim targets for 20% cut in GHG emissions and 20% improvement in energy efficiency by 2020 compared to 1990 levels (European Commission, 2010). Energy consumption of buildings accounts for around 40% of total final energy use and 36% of total CO_2 emissions of the EU Member States (European Commission, 2008). Consequently, substantial improvement in energy performance of building stock is required if the EU is to achieve its GHG and energy targets.

It should also be noted that, in addition to climate change mitigation, there are other key drivers for reducing energy consumption. Security of energy supply is a major issue in the EU where most member states are net importers of energy. Reducing energy demand could reduce capital expenditure in energy infrastructure and energy imports (DECC, 2012). Concerns for energy security and costs have also led to attempts to increase supply by using unconventional methods such as fracking shale oil and gas (CLG, 2016). There are concerns about the environmental risks associated with such methods (Frohlich, 2012), (Miller, et al., 2013). Demand reduction is a safer option to improve energy security and avoid these potential environmental damages.

Improving energy efficiency of buildings can also alleviate the effects of fuel poverty which is a serious problem even in advanced economies. For example, the latest statistics show around 10% of English households are affected by fuel poverty meaning their energy costs are above average and their residual income after paying energy bills is below the official poverty line (DECC, 2015).

The Energy Performance of Buildings Directive (The European Parliament and the Council of the EU, 2003) and its recast (The European Parliament and the Council of the EU, 2010) underpin the majority of the national legislations related to energy performance of buildings in the EU and play a key role in achieving the energy saving targets (IEE, 2011). Article 3 of the EPBD required every EU Member State to apply a methodology to calculate the energy performance of buildings. Such calculation should include, inter alia, energy use related to heating, domestic hot water, cooling, ventilation and lighting under standardised operating conditions. This was a major shift in the Building Regulations in most European countries that were traditionally focused on specific aspects of energy performance such as fabric heat loss and airtightness (Perez-Lombard, et al., 2009). This holistic approach to energy performance calculation is now used to determine compliance with energy efficiency requirements. Energy efficiency requirements are, on the other hand, regularly updated and become more stringent to deliver low energy and low carbon buildings.

The methodology developed to calculate energy performance of buildings in England, following inception of the EPBD, is called the National Calculation Methodology (NCM). A criterion to determine whether a proposed new building complies with the Building Regulations in England is to demonstrate the CO_2 emissions associated with the calculated energy performance of the proposed building is no greater than that of a notional building with similar size and shape that uses default building fabric and services. The NCM methodology governs energy performance calculations for both the proposed and the notional buildings (HM Government, 2013). The advantage of this approach over the traditional approach is twofold: 1) it takes into account energy use associated with most fixed building services and therefore is more comprehensive, 2) it aims to give more freedom to designers to trade off some aspects of performance (e.g. fabric heat loss against boiler efficiency) so long as the total regulated performance is within the target.

It is notable that what is important in complying with the regulations is the *relative* performance of the building over a notional building and not the absolute value produced for energy performance or the associated CO_2 emissions. The relativist nature of the regulatory calculations is in fact used to side-line questions raised about the accuracy of different methods and tools deemed to comply with the National Calculation Methodology (CLG, 2011, p. 13):

"The basis on a comparison minimises argument about how well the absolute carbon emissions are predicted by different NCM-compliant methods, because both the proposed and notional buildings are subject to the same calculation approach. Instead it concentrates on achieving improvements compared with the previous regulations."

The NCM-compliant methods and tools use the so-called standardised or default operating conditions defined for various building categories and, thereby, neutralise the effect of human behaviour on building performance. This is reasonable in the context of the Building Regulations where a decision has to be made about the adequacy of the energy efficiency measures allowed for the building fabric and fixed building services before a building is occupied. These methods and tools also assume default appliance loads to estimate the heating and cooling energy only and do not include the CO_2 emissions associated with these loads in the results (CLG, 2011).

Given this background, the regulatory calculations carried out in accordance with the EPBD/NCM were not meant to project buildings' absolute and total energy performance. Furthermore, there is no requirement in the EPBD and its recast to verify the regulatory calculations with actual energy performance of buildings. This is arguably a crucial missing link in the EPBD given its ultimate goal is to reduce *actual* energy use of buildings. Potential energy savings achievable as a result of implementation of the EPBD are often estimated based on modelling. However, it is not certain that these savings will actually be achieved in practice (Ekins & Lees, 2008). Shortcomings reported in the design, construction and operation of new buildings and major refurbishments that are supposed to be EPBD compliant add to the doubts as to whether these buildings can really deliver tangible improvements in overall energy performance (Carbon Trust, 2011), (Palmer & Armitage, 2014). Lack of a robust energy performance measurement and verification framework that links measured performance to the modelled performance and allows for the longitudinal changes in operating conditions and building context is a key barrier to assess the real impact of the new energy performance regulations.

The EPBD has led to accumulation of relatively large datasets that represent the outcomes of Building Regulations compliance calculations or energy performance certificates. In the absence of an EPBD-oriented measurement and verification framework, comparisons are inevitably being made between actual performance of buildings and the outcome of the EPBD calculations. Various studies report significant discrepancies that in the worst case scenarios can reach factor of five (Carbon Trust, 2011) or even ten (CIBSE, 2015 a). While some practitioners dismiss this type of discrepancy on the grounds of methodological differences, others point to the procurement and operational issues uncovered in post-occupancy evaluations and suggest the huge discrepancy between measured performance and the EPBD calculations cannot be entirely put down to methodological issues (de Wilde & Jones, 2014). What both parties would agree on is the credibility risk this problem can cause among the construction clients and general public who may take a cynical view of energy regulations. This may in turn lead to behavioural indifference that can compound the problem.

The concerns expressed by architects and their Clients about the extent of the difference between actual energy performance of buildings and the outcomes of the EPBD calculations were among the key drivers for this research programme. An architectural practice supported this programme to address the following recurring questions raised by their Clients and other stakeholders in the construction industry:

- Are new buildings completed in accordance with the new energy regulations performing better than existing buildings of similar type in practice?
- What is the relevance of regulatory energy performance calculation to actual performance? This is important as in practice the outcomes of this calculation are often the only piece of information related to the potential energy performance of a building available to building users. Standard templates used for building log books ask for this information (CIBSE, 2006). How can these be related to actual performance to be useful for facility managers?
- What are the major root causes for underperformance in new buildings?
- What is the impact of these problems on energy performance? What is the true extent of the gap between actual performance and design intent?
- What lessons can be learned from recently completed buildings to address these problems and deliver low energy buildings in practice?

1.2. Integrated approach to building performance

Energy is probably the most commonly used metric in the construction industry for building performance in recent years. This is a result of growing concerns about climate change and energy security that have led to various regulatory or market-driven policies aiming to improve energy efficiency of building stock. It is however acknowledged that a low energy building is not necessarily a good building for its users (Pegg, 2007). Building owners and occupants often use other criteria to judge a building's performance such as aesthetics, comfort, productivity, and total cost. From system perspective, energy could be viewed as an input to the building systems to provide and maintain the environmental conditions necessary for building users to achieve their objectives (Markus, et al., 1972). A low energy building that is not capable of providing a comfortable environment for its users is not a well performing building. On the other hand, an energy intensive building may or may not be able to provide adequate comfort for building users. It is therefore necessary to consider the indoor environmental quality in addition to energy to make an informed assessment about building performance. This is particularly important in the context of the new energy efficiency policies as there are concerns that decarbonisation of building stock might have unintended consequences with implications for health and well-being of building occupants (Wargocki & Wyon, 2013), (Shrubsole, et al., 2014). Some aspects of a building's environmental performance such as thermal comfort and indoor air quality can be established by measurement with reference to the relevant standards and building codes. However, buildings are constructed to be used by human beings; people have different perceptions about comfort and different expectations from buildings. It is therefore important to seek occupants' feedback about building performance. This can give context to direct measurements and also provide invaluable insights about the less tangible aspects of building performance. Therefore, an integrated approach to energy performance, indoor environmental quality, and user satisfaction is required to assess the impact of energy efficiency policies on building performance.

1.3. Case study: the education sector

In the UK schools account for almost 15% of the energy used in public and commercial buildings. There are approximately 25,000 primary and secondary schools in England and Wales with a gross floor area of 60,000,000 m² and a replacement value of £130 billion (Dasgupta, et al., 2012). The annual expenditure on the school estate is almost £7 billion. The annual spend on energy consumption in 2009 was £553 million and rising every year (James, 2011). Ten million pupils spend almost 30% of their life in schools in the UK and, therefore, schools are the second most important indoor environment after children's homes (Dasgupta, et al., 2012). Consequently, in addition to its significance in climate change mitigation and adaptation strategies, the condition of the school estate has serious implications for health and well-being of the nation.

Launched in 2003 to renew all English secondary schools, the Building Schools for the Future (BSF) programme was the most ambitious building construction programme instigated by the UK Government in the last decade. It was the most expensive departmental capital programme with a total budget of £55 billion. However, the programme was scrapped in 2010 following the economic austerity imposed by the new Government to reduce the national budget deficit and the complaints about the added value of the BSF (James, 2011). In total, 559 secondary schools were replaced or significantly renovated under the BSF programme, less than one fifth of the English secondary schools (CIBSE, 2015 a).

Most BSF schools were constructed after inception of the EPBD in the UK. The projects were well funded by a flagship programme that had the aspiration to bring educational transformation (James, 2011). The completed buildings are therefore representative of the state of the art offered by the UK construction industry at the time and constitute a perfect sample to evaluate the effect of the new energy regulations. It has also been pointed out that broadly speaking schools have similar activity and objective systems and as such are a suitable building category for statistical (Pegg, 2007). The following Figure compares the actual energy performance of 68 BSF schools for which measured performance was available with 838 secondary schools that predate the BSF programme.

Figure 1.1 shows the new schools tend to use lower energy for heating than older buildings thanks to better building fabric and airtightness standards. However, the electricity use of the new secondary schools tends to be higher than the other existing secondary schools. Ever-increasing use of ICT equipment, a tendency for mechanical ventilation to satisfy the stringent acoustic requirements for new schools, higher cooling energy required for server rooms, and the use of air conditioning systems to avoid overheating where internal gains are high are among the general trends observed in new schools (Bordass, et al., 2001 a), (Pegg, 2007). There is also a tendency to specify large open plan spaces for new schools to provide more pedagogical flexibility, bring a sense of openness, and enhance pupils' interaction and social well-being. This strategy brings challenges for the control of building services especially when the building is not fully occupied during the year; a scenario that is more pertinent to educational buildings than other building categories such as offices. Unless an effective control strategy with refined zoning is specified, the open plan space design for schools may compromise building energy performance.

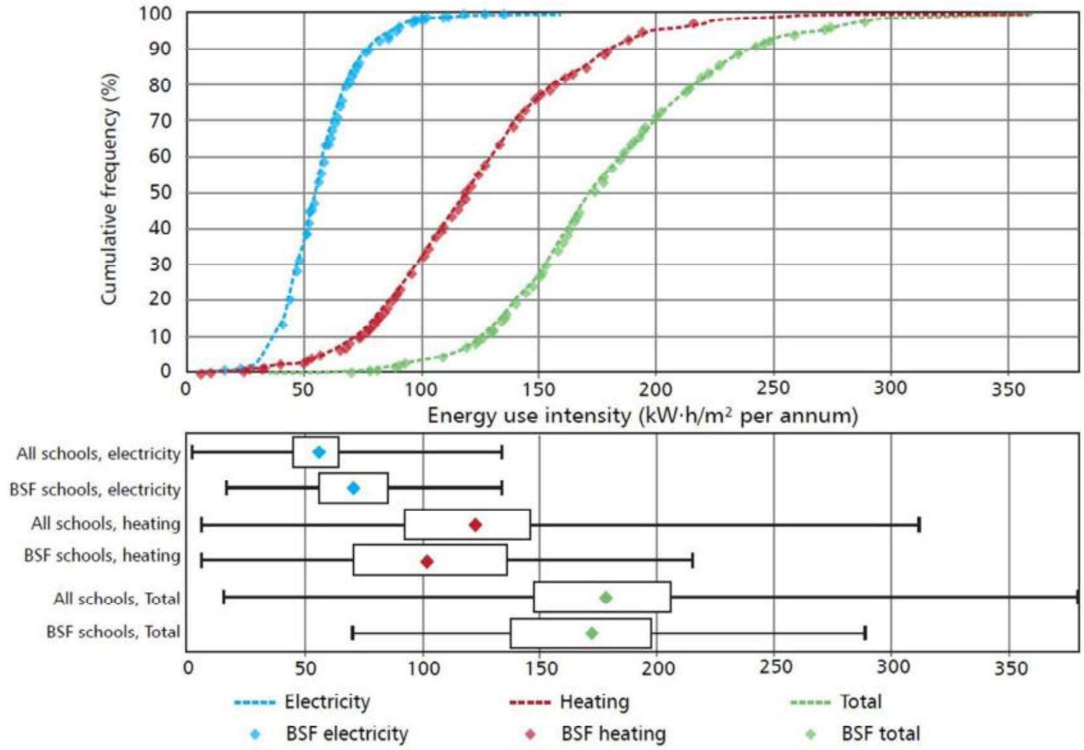


Figure 1.1. Energy performance of the BSF schools against the rest of secondary schools (CIBSE, 2015 a)

Figure 1.1 clearly shows the challenge of improving the overall energy performance of new educational buildings relative to the existing building stock in the context of wider environmental and pedagogical requirements. What is less clear is how these buildings are performing against their design expectations. A new school may use less heating energy than an old one, but still suffer from design, construction, and operational problems that compromise its true potential (Ruyssevelt & Bunn, 2001). Furthermore, the risk factors that can increase the electricity use of new schools are acknowledged in the industry. In addition to good practice design principles, designers have to specify energy efficiency measures to comply with the regulatory requirements that, if effective, must be able to mitigate some of these risks. Therefore, in addition to statistical benchmarking, it is necessary to compare the performance of a school against its design expectation and baseline. To this end, a case study approach is required to enable more detailed and in-depth investigation of BSF buildings. Lessons learned from these investigations can inform future construction projects in non-domestic sector including the Priority School Building Programme (PSBP) in the education sector. The PSBP is a £2 billion investment programme for England's most in-need schools that will be designed and built under Private Finance Initiatives (PFIs) by 2017. It is meant to be more cost-effective than the BSF programme. The average cost for BSF schools was £2,480 per square meter which for the new Academies procured under the 'Academies

Framework', a bidding process managed by Partnership for Schools (PfS), reduced to £2,069 per square meter (James, 2011). In comparison, the allocated funding for the PSBP programme in 2014 was £1,113 per square meter (Education Funding Agency, 2014). At the same time, the Education Funding Agency has set out strict energy consumption operational targets for the PSBP buildings and their major energy end-uses (Cundall, 2014). This will put huge pressure on designers and contractors to procure energy efficient schools cost-effectively. The skills acquired and lessons learned from the BSF programme are therefore invaluable to fulfil the PSBP requirements.

The architectural practice that supported this research programme has been heavily involved in the BSF and PSBP programmes. The research and development team of this practice provided access to the design documentation for five educational buildings designed by the practice and completed under the BSF programme. Access to the completed buildings was also granted by these five schools for long-term building performance investigations. The research programme was funded by the Engineering and Physical Sciences Research Council (EPSRC) and the architectural practice involved. Another stream of funding from the Innovate UK Building Performance Evaluation (BPE) programme provided the opportunity for the architectural practice, building services designers, and contractors to get involved in post-occupancy investigations, share their experience, and disseminate the lessons learned from the investigations within their organisations.

1.4. Aim and objectives of the research programme

The aim of the research programme was to investigate the root causes of the gap between operational performance of educational buildings and their design expectations, and develop a framework that can help narrow this gap

The specific objectives of the research were as follows:

- To quantitatively determine the operational energy performance of five buildings constructed under the Building Schools for the Future programme, through long term post-occupancy evaluations and compare the performances against the existing building stock and industry benchmarks,
- To quantitatively determine the most important aspects of the Indoor Environmental Quality in these buildings and compare the performances against the relevant standards and building codes,
- To investigate building user satisfaction in conjunction with the quantitative studies to assess the effectiveness of building design and operation from occupants' point of view,

- To compare the operational performance with the expected performance at design stage, identify the discrepancies, and uncover the root causes for these discrepancies,
- To outline measures that can narrow the gap between predicted and actual building performance,

The literature review and preliminary findings of the research programme identified the need to develop a robust measurement and verification framework to enable comparing actual energy performance of buildings with design expectations under identical operating conditions. This framework must be able to determine the performance gap and its root causes with reasonable accuracy and address the question of ownership of the performance gap. Consequently, the following objective emerged as the research progressed: .

- *To develop and demonstrate a measurement and verification framework that can help verify actual energy performance in relation to design expectations*

Finally, an important goal of the research programme was to disseminate and share the findings with various stakeholders and policy makers to help perpetuate a culture of continuous performance improvement in the construction sector.

The outcomes of this research programme complement and expand on the previous work done in the areas of the performance gap and building performance evaluation such as the contributions of Pegg (2007) in the education sector and more widely Bordass et al. (2001 b) in the non-domestic sector. Analysis of the performance gap in the context of the EPBD is a specific contribution of this dissertation that sets it apart from previous work. The Innovate UK Building Performance Evaluations also provided a framework to review building performance and a set of methods and tools that were predominantly based on Bordass et al. previous contributions to the field. While part of the research presented in this dissertation was undertaken under the Innovate UK Building Performance Evaluation programme, the research programme went beyond the requirements and objectives of the Innovate UK programme in the following specific areas:

- An integrated approach to energy performance, the indoor environmental quality and user satisfaction
- Quantitative study of the indoor environmental quality
- A dynamic view of the performance gap that was facilitated by Building Energy Performance Simulation
- Measurement and verification of the energy performance gap

1.5. Overview of the Engineering Doctorate programme

The research was carried out as part of an Engineering Doctorate programme at the UCL Centre for Urban Sustainability and Resilience in close collaboration with the Bartlett. The Centre for Urban Sustainability and Resilience is an interdisciplinary centre for research on how to design and adapt cities and urban infrastructure to be both sustainable and resilient. The Engineering Doctorate programme pursued was an integrated four year programme consisting of taught and research components. The first year of the programme was officially recognised as Master of Research (MRes) and the students could only carry on their EngD studies after successful completion of the MRes. In addition to the taught component, another major difference between EngD and a conventional PhD programme in the UK is the presence of an industrial sponsor on board for EngD. Therefore, an EngD programme is meant to focus on specific industrial problems and applications while maintaining the same academic rigour expected from PhD.

Being a mechanical engineer by background, the EngD programme brought a unique opportunity to the author to experience working in an architectural practice with mutual benefits for both parties. The author spent around 50% of his working hours in the offices of the industrial sponsor in the first two years of the programme closely working with the research and development team on post-occupancy evaluation of the case study buildings and other projects relevant to the research themes. This contribution was gradually diminished as the research progressed and the author spent most of his working hours in the academic environment to complete the research during the third and fourth year of the programme. Table 1.1 outlines the structure of the EngD programme, the contents of the taught component, and a broad breakdown of how the research component was fulfilled within the duration of the programme.

Table 1.1. Structure of the Engineering Doctorate programme

Programme	Academic year	Taught component		Research component
		Taught module (UCL unless stated)	Compulsory / Elective	
Master of Research (MRes) – year 1 of the Engineering Doctorate (EngD)	2010-2011	Advanced Research Methods	C	MRes Dissertation: literature review and methodology development for the EngD; start of the post-occupancy evaluations
		Built Environment: The Energy Context	E	
		Resilience	C	
		Professional Development in Practice	C	
Engineering Doctorate (EngD) – years 2-4	2011-2012	Advanced Building Simulation	E	Post-occupancy evaluations on case study buildings and analysis
		Sustainability-Implications of Environmental and Demographic Change (London Business School)	E	
	2012-2013	Systems, Society and Sustainability	E	Post-occupancy evaluations on case study buildings and analysis
		Project Management	C	
	2013-2014	*Taught component completed*	*Not relevant*	Miscellaneous field studies & literature review; dissertation write-up

A number of papers were published in academic journals and conference proceedings within the duration of the EngD programme to disseminate the research outputs, including the followings:

Journal Papers:

Burman, E., Mumovic, D., and Kimpian, J., 2014. *Towards measurement and verification of energy performance under the framework of the European Directive for Energy Performance of Buildings*, Energy 77 (2014) 153-163.

Burman, E., Hong, S., Paterson, G., Kimpian, J. and Mumovic, D., 2014. *A Comparative Study of Benchmarking Approaches for Non-domestic Buildings: Part 2 – Bottom-up approach*, International Journal of Sustainable Built Environment (2014), 3, 247-261.[1]

[1] This was a sequential paper. The bibliographic information for Part 1 is as follows:
Hong, S., Paterson, G., Burman, E., Steadman, P., and Mumovic, D., 2014. *A Comparative Study of Benchmarking Approaches for Non-domestic Buildings: Part 1 – Top-down approach*, International Journal of Sustainable Built Environment (2014), 2, 119-130.

Conference Papers:

Burman, E., Kimpian, J., and Mumovic, D., 2014. *Reconciling Resilience and Sustainability in Overheating and Energy Performance Assessments of Non-domestic Buildings*, Proceedings of the 2nd International Conference on Urban Sustainability and Resilience, 3-5 November 2014, University College London, UK.

Burman, E., Kimpian, J., and Mumovic, D., 2014. *Analysis of the applicability of the UK National Calculation Methodology to energy efficiency finance of non-domestic buildings: A case study approach*, Proceedings of IBPSA-England Building Simulation and Optimisation Conference (BSO 14), 23-24 June 2014, University College London, UK.

Burman, E., Mumovic, D., and Kimpian, J., 2014. *A comparative study of the energy certification schemes implemented in the UK and ASHRAE building energy labelling programme*, Proceedings of CIBSE ASHRAE Technical Symposium, 3-4 April 2014, Dublin, Ireland.

Burman, E., Mumovic, D., and Kimpian, J., 2013. *A Methodology for Measurement and Verification of Energy Performance under the Framework of the European Directive for Energy Performance of Buildings,* Proceedings of the 6th International Conference on Sustainable Energy & Environmental Protection (SEEP 2013), pp. 239-250, 20-23 August 2013, Maribor, Slovenia.

Burman, E., Rigamonti, D., Kimpian, J., and Mumovic, D., 2012. *Performance gap & thermal modelling: A comparison of simulation results and actual energy performance for an academy in North West England*, Proceedings of IBPSA-England First Building Simulation and Optimisation Conference (BSO 12), pp. 35-42, 10-11 September 2012, Loughborough University, UK.

The author was also among the principle authors of CIBSE Technical Memorandum 57 on Integrated School Design to disseminate the lessons learned from the building performance evaluations within the industry (CIBSE, 2015 a).

1.6. Organisation of the content

An outline of the organisation of this dissertation and the content of various chapters is presented below.

Chapter 1

- **Introduction:** explains the drivers for the research programme and its aim and objectives. It also provides a brief overview of the structure of the EngD programme and the content of this dissertation.

Chapter 2

- **Literature Review:** provides a state of the art review of the relevant literature starting from major drivers for energy efficiency such as climate change and energy security and explores the concept of energy efficiency in buildings in relation to other performance criteria. The chapter also includes a summary of the regulatory frameworks along with a review of the literature of post-occupancy evaluations and the performance gap.

Chapter 3

- **Methodology:** Provides a detailed account of the methods used for technical studies, user satisfaction surveys, and comparison between operational and designed performance. A comparative analysis of the protocols suggested for measurement and verification is also provided to set the scene for the framework and the demonstration case study presented in Chapter 9.

Chapter 4

- **The Buildings' Context:** A harmonised review of the case study buildings is presented to give context to the data presented in the subsequent chapters. For each building, basic information related to building location, school type and its geometry is provided. Building envelope characteristics, distribution of spaces, Heating, Ventilation and Air Conditioning (HVAC) strategies, critical energy efficiency measures, and operational schedules are also reviewed for each building.

Chapter 5

- **Operational Energy Performance:** Annual operational energy performances and the associated carbon dioxide emissions for all case studies are presented and compared *to* the relevant benchmarks derived from other existing educational buildings. A summary of major operational issues related to energy observed in these buildings is also presented.

Chapter 6

- **Indoor Environmental Quality:** A summary of measurements and observations related to thermal comfort, indoor air quality, acoustics, and lighting in the case studies is presented and analysed. Major operational issues that compromised the indoor environmental quality are also reviewed.

Chapter 7

- **Building Use Studies:** The outcomes of the Building Use Studies (BUS) carried out in the case studies are presented and analysed. The findings are correlated with the findings of the technical studies to provide a better understanding of building performance and underlying issues.

Chapter 8

- **Operational against Designed Performance:** The operational performance established through Post-Occupancy Evaluation for each building is compared *with* the design intent. A list of major procurement and operational issues identified in the investigations is presented and mapped against different stages of the construction project.

Chapter 9

- **A Measurement and Verification Framework for the EPBD:** A framework is presented for measurement and verification of performance in-use in reference to the EPBD calculations. The framework is applied to one of the case studies using a calibrated thermal model developed for the building. The outcomes are presented, the drivers and barriers for measurement and verification of energy performance in-reference to statutory calculations are discussed, and potential applications of the framework are outlined.

Chapter 10

- **Conclusions and recommendations for future work:** This chapter summarises the major findings of the research programme in respect of energy performance, the indoor environmnetal quality, and user satisfaction. It outlines the strategies and solutions that can help narrow the performance gap in new and existing buildings based on the findings of the research programme. A number of recommendations for future work in this field of study are also presented.

2. Literature Review

2.1. Introduction

This chapter provides a review of the relevant literature and the context that has shaped this thesis. The literature review starts by providing an overview of the latest findings in the Climate Change science as the overarching theme that drives various risk mitigation and adaptation strategies in the built environment. The focus is then shifted to energy saving in buildings as one of the most effective ways of minimising the impact of climate change. The interrelations between energy performance and other building performance metrics such as indoor environmental quality and user satisfaction are also reviewed.

A detailed account of the Energy Performance of Buildings Directive (EPBD) in the EU and its implementation in England is provided as a major policy measure that drives energy performance improvements in buildings. The concept of Post-Occupancy Evaluation (POE) is introduced as a useful method to assess the success of the EPBD in improving building performance in-use. POE studies often point to discrepancies between measured performance and design intents. The concept of the performance gap is reviewed with special focus on energy. Finally, a review of the major root causes of energy performance gap, identified in previous studies, is presented.

2.2. Climate change and its consequences

Changes in the state of the climate can be caused by natural internal processes such as the modulations of the solar cycles and volcanic eruptions or external forces such as persistent anthropogenic changes in the atmosphere or in land use (IPCC, 2014). The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have significantly increased since pre-industrial times. For example, the CO_2 concentrations have increased by 30% primarily from fossil fuel consumption and net land use changes (Stern, 2006). The increase in atmospheric concentrations of these gases has raised average global temperatures due to the greenhouse gas effect (IPCC, 2014). As the total natural radiative forcing from solar irradiance and stratospheric volcanic aerosols made only a small contribution to the net radiative forcing throughout the last century, the Intergovernmental Panel on Climate Change (IPCC), which represents a large body of the scientific community, identifies the anthropogenic changes in the atmosphere and land use as the main driver of the recent climate change (IPCC, 2014). The United Nation Framework Convention on Climate Change (UNFCCC) defines the climate change observed since the pre-industrial time as a change of climate which is attributed directly or indirectly to human activity and is *in addition* to natural climate variability observed over comparable time periods in the past (UN, 1992).

The scientific evidence for climate change in now overwhelming. In recent decades, climate change has caused impacts on natural and human systems across the globe. The fifth assessment report of the IPCC points to the strong scientific evidence that shows the impacts of global warming and shifts in precipitation patterns. There is also emerging evidence of the impacts of ocean acidification. The negative impacts of global warming on crop yields in tropical and temperate regions has generally been more common than the moderate positive impacts observed at high latitudes with implications for food security and price. The changes in precipitation and melting glaciers are altering hydrological systems and affecting water resources. Climate change has caused permafrost warming and thawing in high-latitude and high-elevation regions. The recent climate-related extreme events such as heat waves, draughts, and floods also reveal significant vulnerability and exposure of some ecosystems and human systems to climate change. The IPCC fifth assessment report identifies a number of key risks associated with climate change that can cause severe and widespread impacts on food security, compromise normal human activities by a combination of high temperature and humidity, and even lead to extinction of substantial species. While the precise thresholds for abrupt and irreversible climate change remain uncertain, the latest IPCC assessment is that a high-emission scenario with global mean temperature of 4 ^{0}C or more above pre-industrial levels poses high to very high risks for natural and human systems. There are also considerable risks with a low-emission scenario that involves a temperature increase of 1 or 2 ^{0}C above the pre-industrial levels. Therefore, appropriate adaptation strategies are required to minimise the damage even for a low-emission scenario. However, to avoid the catastrophic consequences of the high-emission scenario, it is imperative to significantly reduce the anthropogenic Greenhouse Gas Emissions (GHGs) to limit the increase of global mean temperature to 2 ^{0}C (IPCC, 2013).

Figure 2.1 shows the observed changes in global mean temperatures since 1900 and the projections for low-emission and high-emission scenarios until 2100 derived from climate models. The right hand side illustration shows the level of additional risk related to climate change imposed on five key areas of concern. The key Reasons For Concern (RFCs) were first identified in the IPCC third assessment report to show the implications of global warming and the adaptation limits for people, economies, and ecosystems (IPCC, 2001).

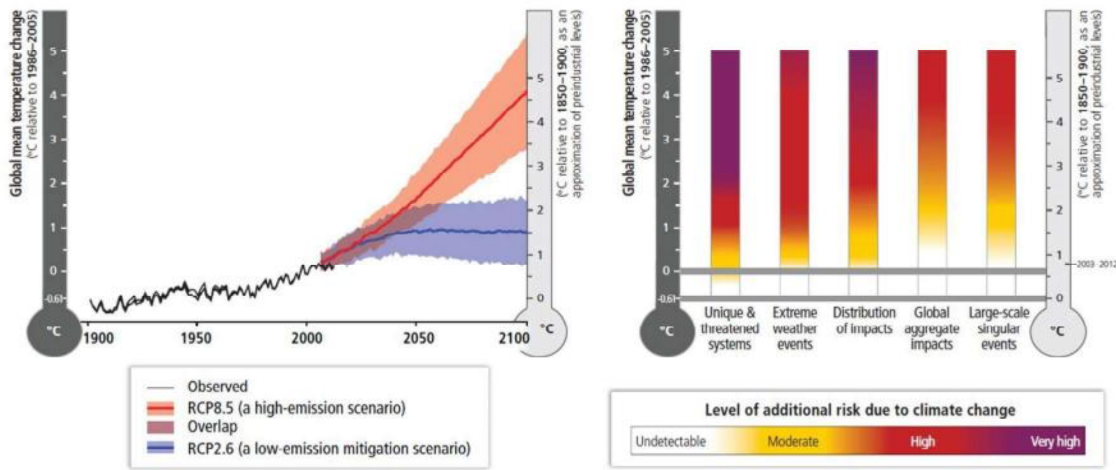


Figure 2.1. A global perspective on GHG emission scenarios and climate-related risks (IPCC, 2014)

2.3. Economics of climate change: an overview

Climate change presents huge and multi-faceted challenges that must be tackled. Economically, it is the greatest market failure ever seen with far-reaching consequences for humanity. In 2006 the Stern review, commissioned by the UK government to assess the evidence and review the economics of climate change, concluded that the cost of stabilising the greenhouse gases at levels of 500-550ppm CO_2 equivalent that is consistent with a low emissions scenario would be around 1% of annual global Gross Domestic Product (GDP) by 2050. The economic cost of inaction, on the other hand, would be a minimum 5% loss in global GDP per annum that could be increased to 20% if a wider range of risks and impacts are taken into account (Stern, 2006). In 2008 Stern revised the annual cost of achieving greenhouse gas stabilisation to 2% of global GDP to account for faster than expected climate change (Jowit & Wintour, 2008). While this is a huge cost, Stern suggests that the benefits of strong and early action on climate change outweigh the costs. Early action is vitally important as the damages from climate change will accelerate with higher mean global temperatures. It should be noted however that the effects of climate change are not evenly distributed. The evidence suggests the poorest countries and people will suffer sooner and deeper. Furthermore, North America and Europe have produced around 70% of all the CO_2 emissions related to energy production since 1850 (Stern, 2006), whereas the strong economic growth experienced in highly populated developing countries such as India and China over the recent years means the geographic pattern of greenhouse gas production is shifting. This makes it very difficult to reach a political consensus for international collective action required to implement appropriate mitigation and adaptations strategies.

Another issue is that although the total mitigation and adaptation cost seems manageable from cost and benefit point of view, achieving the technological readiness and behavioural patterns that lead to a low-emission scenario will require radical restructuring of our societies and economies. The Stern review estimated the social cost of carbon at $85 per tonne of CO_2 for business as usual case in 2005 prices (Stern, 2007). This effectively reflects the price of failure to act against climate change and follows the notion of Pigouvian tax which is used to reduce or eliminate an environmental negative externality by imposing a tax on a polluter equal to the social cost of pollution. This type of tax, first introduced by Arthur Pigou (1932), is a way to internalise market externalities and overcome the divergence between private and social interest. It must be equal to the marginal damage caused by an externality such as pollution or CO_2 emissions to ensure the maximum after tax profit of a polluter will coincide with the maximum total welfare. This in theory will reduce the pollution or emissions to a level necessary to avoid the environmental damage. However, it is very difficult to estimate the marginal damage in the context of climate change. Figure 2.2 illustrates various climatic, demographic, and techno-socio-economic factors that must be taken into account over a long time horizon to estimate the total impact of climate change. Uncertainties associated with calculating the social cost of carbon include demographics and patterns of energy use, future technologies, the science of climate change, the direct impacts of climate change, the socio-economic impacts, and the choice of discount rates assumed in the net present value calculations.

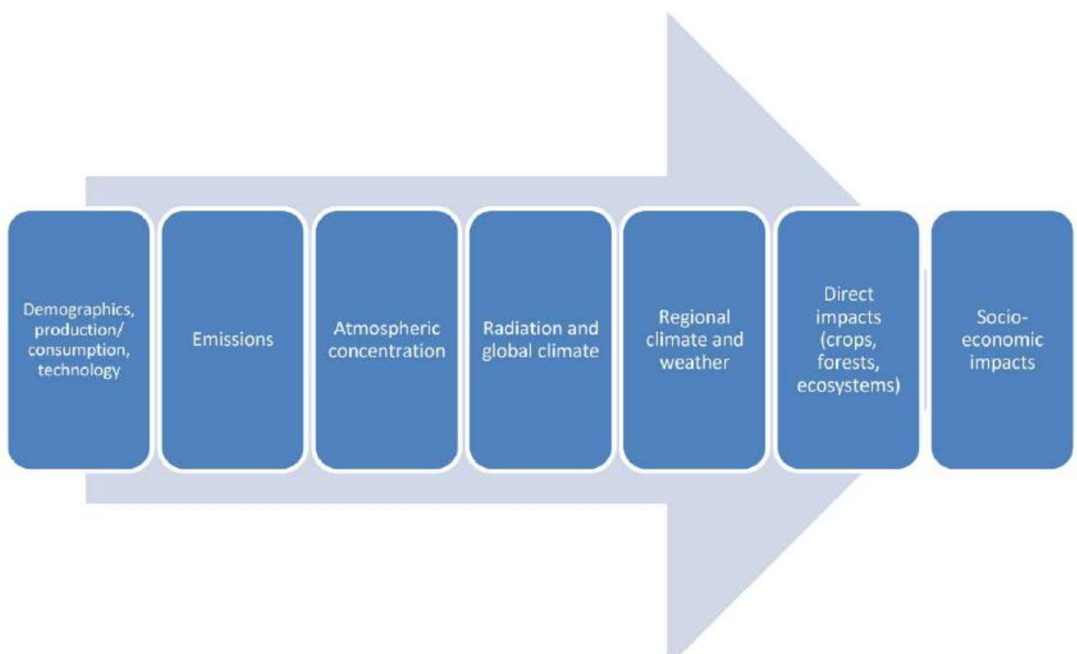


Figure 2.2. The factors involved in the integrated assessment models used to calculate the impacts of climate change, adapted from Parson and Fisher-Vanden (1997)

Large variations in estimating the social cost of carbon are therefore expected. A study commissioned by the US government that used the results of three widely available economic impact models estimated that an additional tonne of carbon dioxide in 2015 would cause $37 of economic damages (Interagency Working Group on Social Cost of Carbon, 2013). This was disputed by another study that estimated the marginal damage of carbon as high as $220/tCO$_2$. This study incorporated the recent empirical findings that suggest climate change can substantially reduce the rate of economic growth especially in poor countries (Moore & Diaz, 2015). Another study carried out in the UK in 2011 also suggested a carbon tax of $150/tCO$_2$ in the EU and $250/tCO$_2$ in the US (Hope, 2011). More climate change mitigation and adaptation measures will pass a cost and benefit analysis if the price of carbon is set higher. Yet the short term perspective and cyclical nature of political governance in most advanced and developing countries often mean, where introduced, the level of carbon levies is often significantly lower than even the most conservative estimations for the social cost of carbon. For example, the climate change levy in the UK in 2014 was in the order of $15/tCO$_2$ (HM Revenue & Customs, 2014)[2]. Australia passed a law to institute a carbon tax in 2012, at $22/tCO$_2$ (Department of Climate Change and Energy Efficiency, 2011) which was repealed two years later. The province of British Columbia in Canada began a revenue-neutral carbon tax of $9/tCO$_2$ in 2008 to shift its economic activities to lower emissions. This tax was increased every year until it reached $28/tCO$_2$ in 2012 (Ministry of Small Business and Revenue, 2008).

A rare example of incorporating the high social cost of carbon is Sweden where a carbon tax is levied since 1991 and was around $150/tCO$_2$ in 2014. This tax does not apply to electricity generation. However, high energy taxes on fuel and electricity in Sweden complement this carbon tax on fossil fuel use (IEA, 2013). The integrated energy and carbon tax regime implemented in Sweden is generally considered to be the main driver behind Sweden's shift from fossil fuels to renewable sources that accounted for 52.1% of its primary energy in 2013; this is the largest share of renewable contribution to primary energy in the EU (Eurostat, 2015). However, this achievement comes at a significant price for Swedish households who face the highest prices for natural gas which were 4.2 times more expensive than the cheapest gas price in Europe in 2011 (Eurostat, 2011). It is therefore very difficult to replicate Sweden's energy and carbon tax regime in less affluent, more populated countries with volatile political environments.

[2] All prices in this section have been converted to US dollar based on the conversion rates applicable at the time the respective policies were introduced.

An alternative economic approach to address environmental externalities is the trading approach first formulated by Coase (1960). Coase postulated that the Pigouvian approach is often not the most efficient way of treating environmental externalities. There are often lower cost opportunities to *trade* an environmental externality in the market. This principle underpins the carbon cap and trade schemes whereby the participants can find the most cost-effective abatement opportunities to offset their carbon emissions. Total number of carbon permits are fixed in each phase of the scheme and gradually reduced in subsequent phases to achieve the environmental targets set out by the regulator. These permits are initially auctioned off or allocated for free to the participants, and can be subsequently traded so that participants can cover the emissions associated with their business activities and growth. The European Union Emissions Trading Scheme (EU ETS) launched in 2005, is the world's largest carbon cap and trade scheme that covers around 45% of the EU CO_2 emissions (European Commission, 2013). The European Commission estimates 8% reduction in overall greenhouse gas emissions from big emitters covered by the EU ETS was achieved in 2010 over the 2005 baseline. However, other reports question the cost effectiveness of the scheme and point to its negligible impact on overall emissions in the EU (Sid, 2011). Over-allocation of carbon allowances and price volatility have been cited as major weaknesses of this scheme (CCC, 2008), (Newbery, 2009). The price of carbon allowances plummeted following the economic crisis in 2008 as there was no adjustment in carbon cap to allow for lower economic activity (Ellerman & Joskow, 2008). This is another example of the conflicts between short-term political decisions and the long-term perspective required to address the challenges of climate change.

In summary, there is no one size fits all economic solution for climate change. A combination of tax regimes and incentives can be used to reduce the greenhouse gas emissions.

The problem of taxation and control of externalities is well known. In 1970s William Baumol suggested a practical way to deal with this problem would be to opt for minimum acceptable standards for negative externalities and try to achieve these standards with different tax and incentives (Baumol, 1972). Consequently, a prerequisite for fiscal measures is to define minimum standards and robust regulatory frameworks in each sector enforced by the governments.

2.4. Sustainability and Resilience in the context of Climate Change

Sustainability has been a key objective in developing techno-socio-economic systems ever since the Bruntland Commission's report defined sustainable development as meeting "the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland, 1987). This is consistent with the notion of climate change mitigation that entails stabilising the anthropogenic greenhouse gas emissions at levels that keep the climatic conditions liveable for future generations.

The concept of resilience, on the other hand, has been extensively used in the field of disaster management and more recently in the context of climate change adaptation. Broadly speaking, the word resilience has been used to describe systems that undergo stress and have the ability to recover and return to their original state (Klein, et al., 2003).

A number of researchers question the notion that there exists an original state to which a so called resilient system can return after experiencing a given level of stress or perturbation. They argue that ecosystems are intrinsically dynamic and evolve continuously in response to external disturbance and, therefore, it is more pertinent to talk about different states of equilibrium rather than original state (Klein, et al., 2003). Consequently, it is possible to associate resilience with a sense of emergent behaviour that is adaptive (Dynes, 2003), (Haigh & Amaratunga, 2010). This notion of resilience is closely related to climate change adaptation which is defined by the IPCC (2014) as “the process of adjustment to actual or expected climate and its effects.” The adjustment could be achieved incrementally and naturally as suggested for example in the adaptive thermal comfort theory (Nicol, et al., 2009) or applied as an engineering solution to avoid or reduce the environmental damage (Fiksel, 2006).

Many scientists have tried to combine the concepts and theoretical approaches to sustainability and resilience to maximise the benefits for society and the environment (Chapin, et al., 2009), (Folke, et al., 2010), (Anderies, et al., 2013). However, there are inherent differences in the fundamental assumptions used in the theoretical approaches that must be carefully considered to strike the right balance between these key system objectives (Redman, 2014). For example, achieving maximum efficiency with minimum energy and resource consumption is often expected from a sustainable system. However, this may come at the expense of system resilience, a characteristic that is often enhanced through specifying energy and resource intensive capabilities (Fiksel, 2006), (Redman, 2014). Table 2.1 provides a summary of the contrasting elements of sustainability and resilience. It is suggested to keep sustainability and resilience as distinctive disciplines within an integrated framework where there are competing objectives about system outcomes and dynamics (Redman, 2014).

Table 2.1. Contrasting elements of sustainability and resilience, adapted from Redman (2014)

Sustainability	Resilience
• Action taken in anticipation of major changes • Create new order, open ended • Reorder system dynamics • Focus on system outcomes • Build agency, leadership, change agents	• Respond to shock • Maintain previous order or return to a new equilibrium • Focus on system dynamics and redundancies • Build adaptive capacity • Emergent properties guide trajectory

2.5. Improving energy efficiency in buildings: opportunities & challenges

The building sector, comprising residential and non-domestic buildings, consumes around 35% of global final energy use (Figure 2.3). Buildings are responsible for 17% of total direct energy-related CO_2 emissions, and almost one third of global CO_2 emissions when the indirect upstream emissions associated with electricity generation and heat consumption are also taken into account (IEA, 2013). De-carbonising the electricity generation grids by using renewable technologies, carbon capture schemes, and possibly nuclear energy in addition to replacing coal and oil with less carbon intensive fuels, can play a part in reducing the total carbon emissions associated with buildings' energy use. However, it is often more cost effective to invest in end-use energy efficiency improvements first (IPCC, 2007). It is estimated that the global energy saving potential of buildings is between 20 and 40% (The World Energy Council, 2013). Consequently, saving energy from buildings is a strong component of climate change policies worldwide (IEA, 2013).

Improving the energy efficiency of building stock can also help the quest for energy security for countries that are net importers of energy. An example is the UK which has been a net importer of energy since 2004 with a dependency level of 43% in 2013 (DECC, 2013). Buildings account for around 40% of the UK total energy consumption which is above the average global figure and indicative of the significance of this sector for the UK energy policy (CLG, 2015).

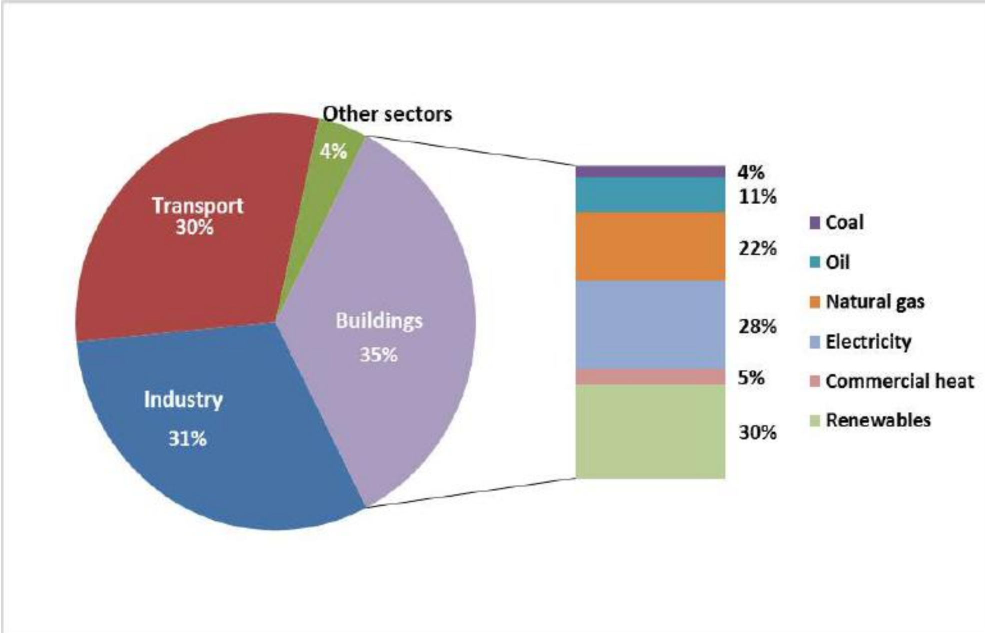


Figure 2.3. Global final energy consumption by sector and buildings energy mix in 2010, Reproduced from IEA (2013)

One of the major challenges in pursuing energy efficiency improvements, in practice, is these improvements do not necessarily lead to a lower level of resource use. This phenomenon was first observed by the economist Jevons in 1860s when technological improvements in the use of coal led to higher coal consumption in a wide range of industries (Jevons, 1866). One explanation for the increase in fuel use despite the improved efficiency is that higher efficiency generally leads to lower relative costs that may increase the demand (Blake, 2008). It is therefore suggested that unless improvements in energy efficiency are coupled with policies that keep the relative cost of a resource unchanged or higher, they may not be effective in reducing the use of that resource (Wackernagel & Rees, 1997).

There is plenty of evidence in the housing sector about the rebound effects from improved energy efficiency. A review of the empirical evidence for the rebound effect in household heating that covered the UK, Austria and Norway in Europe in addition to Canada and the US found a shortfall in expected savings of up to 68%. Most UK studies reported a mean shortfall above 50% (Sorrell, et al., 2009). Indoor temperatures in heating season are often higher than modelling assumptions as building occupants expect to be more comfortable in new or refurbished buildings. It is also likely that any perceived financial saving on energy is spent on appliances that in turn increase energy use (Herring, 2006), (Barker, et al., 2007). A review of the English House Condition Survey (EHCS) that covered 2,531 cases found that homes with better energy ratings often consume more energy than less efficient homes. It is suggested that, while energy efficiency upgrades must be adopted for homes with poor energy ratings, a combination of behavioural strategies and economic incentives must be used to ensure energy efficiency measures already implemented in housing stock lead to actual saving (Kelly, 2011). Other studies have also shown the huge impact of non-technical measures such as occupant behaviour that are often not effectively accounted for in building energy saving calculations (Sunikka-Blank & Galvin, 2012).

Technical issues related to the implementation of energy efficiency measures can also defy the expected energy saving in buildings. The technical evidence for shortfalls in energy savings will be covered in Section 2.8.

Another challenge that should be taken into account is the potential conflicts between energy efficiency and other key objectives in building performance. In non-domestic sector, clients often have a set of performance criteria that are aligned with their business objectives. Staff productivity is often a key objective and a lot of business decision makers believe that improvements in building design can influence productivity (Heerwagen, 2000). While an objective assessment of staff productivity is very difficult especially for non-repetitive work carried out in a knowledge-based economy, user surveys have shown that there is a correlation between building user satisfaction and self-assed productivity. In particular, perception of control over the indoor environmental quality appears to be strongly linked to perceived productivity (Preller, et al., 1990), (Leaman & Bordass, 2001). Spirit lifting features in the indoor environment such as daylight, window views, contact with nature and spatial design are also often specified to promote well-being and create a buffer to discomfort and stress (Heerwagen, 2000). Some of these features are taken as contributors to a sustainable design and awarded in building sustainability rating systems (BRE, 2014), (USGBC, 2013). There are often conflicts between these performance criteria and design features on one hand and energy efficiency requirements that must be reconciled.

The competing objectives of sustainability and resilience must also be taken into account in building design and performance analysis. Energy and overheating performance are examples of these competing objectives. Specifying natural or mixed-mode ventilation strategies in schools is generally encouraged in the UK. However, some experiments on the effects of classroom temperature and air quality on pupils' performance in Nordic countries and England have found that classroom temperatures higher than 20-22°C in warm weather and low outdoor supply rates that cause CO_2 concentrations higher than 1000 ppm for prolonged periods can reduce pupils performance by as much as 30% (Wargocki & Wyon, 2013). It is very difficult to achieve and maintain these levels of thermal comfort and indoor air quality predominantly with natural ventilation even under the current climatic conditions in the UK; changeover to backup mechanical ventilation and comfort cooling might therefore be necessary in the future to protect pupils from extreme ambient conditions expected as a result of climate change. This in turn will have implications for energy performance.

In summary, while improving energy efficiency of buildings could be a high-impact and cost-effective way to mitigate climate change and address the concerns related to energy security, it is important to remove the socio-economic and technical barriers to ensure expected savings are delivered in practice. Furthermore, the competing objectives of sustainability and resilience must be taken into account in building performance evaluation to ensure energy efficiency is not achieved at the expense of other performance criteria.

2.6. Energy efficiency in buildings: Policy perspective and regulatory frameworks in the EU

2.6.1. Policy landscape

An overall objective of energy efficiency policy in buildings is to consume less energy while providing equal or better indoor environmental quality. Building Regulations are often the most basic instrument used by policy makers to improve energy efficiency. European countries, thanks to their dependency on energy imports from geopolitically unstable regions, were among the first nations to develop the building envelope regulations that covered heat transfer through building fabric and air permeability. This was partly a response to the oil crisis of 1970s. The high energy prices experienced after the Gulf war in 1990s renewed the interest in energy efficiency. The Building Regulations were gradually tightened up and also extended to building services such as Heating, Ventilation and Air Conditioning (HVAC), Domestic Hot Water (DHW), and lighting (Perez-Lombard, et al., 2009).

New building energy regulations set out stringent requirements for new buildings and major refurbishments. There is also a recognition that, with new construction at a rate of less than 1% of the total building stock per year (BPIE, 2011), the majority of buildings that are targeted for energy saving by 2050 already exist. Therefore, improving energy efficiency of the existing building stock is necessary to achieve the greenhouse gas emissions targets. Figure 2.4 and Figure 2.5 show the historical trends of final energy use in the European residential and non-domestic sectors respectively, and point to the huge challenge of saving absolute energy in existing building stock. The strong correlation between onsite fuel consumption and heating degree days in the residential sector shows that space heating is the dominant end-use in this sector. It appears that improvements in building fabric performance and air tightness have been able to offset the effect of the growth in numbers of buildings and the net consumption of all fuels is stagnating. However, the significant increase in household electrical appliances is evident from the 38% increase in electricity consumption in the residential sector. The electricity use of the non-domestic buildings also shows a remarkable 74% increase over the last 20 years. While part of this trend can be explained by increasing use of ICT equipment in buildings, other electricity end-uses such as lighting, ventilation, auxiliary heating systems, and air conditioning also play a role and must be targeted by effective energy efficiency measures (BPIE, 2011).

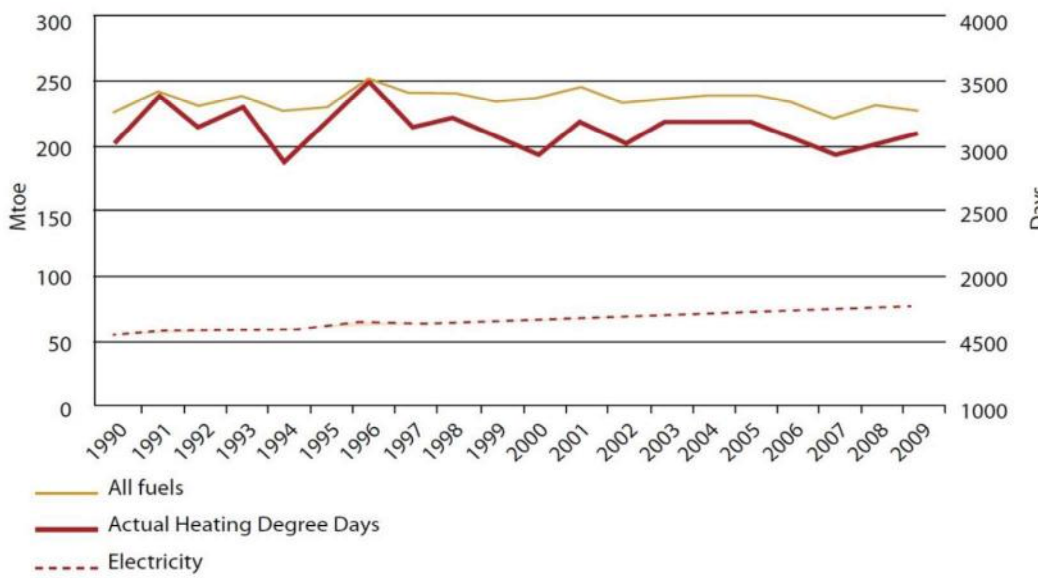


Figure 2.4. Historical final energy use in the residential sector in EU27, Norway and Switzerland (BPIE, 2011)[3]

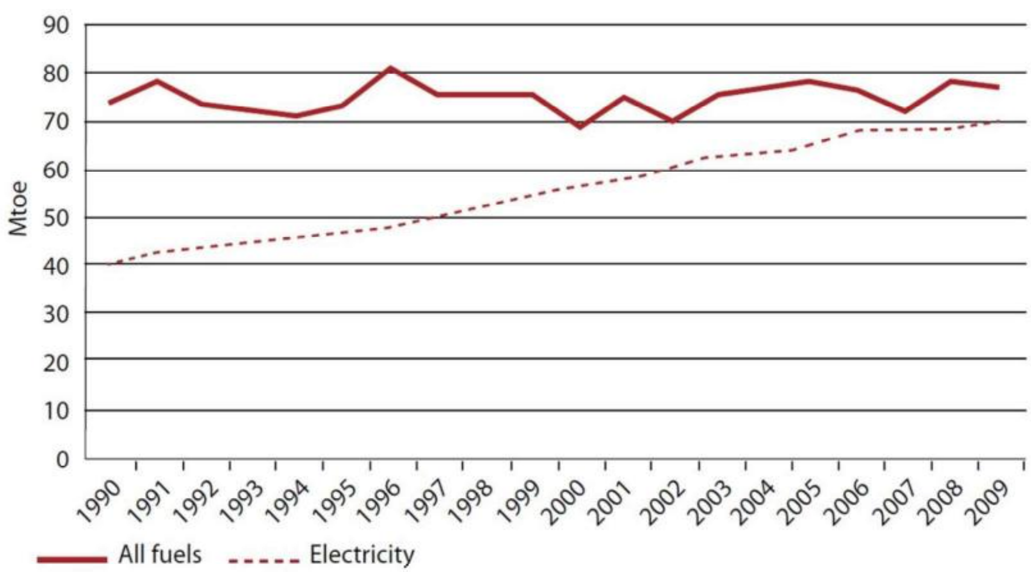


Figure 2.5. Historical final energy use in the non-domestic sector in the E27, Norway and Switzerland (BPIE, 2011)

[3] Mtoe: Mega tonne of oil equivalent

The Energy Performance of Buildings Directive (EBPD), initially introduced in 2002 (The European Parliament and the Council of the EU, 2003) and recast in 2010 (The European Parliament and the Council of the EU, 2010), is the main regulatory driver to improve energy performance of buildings in Europe (IEE, 2008). While the EPBD mainly covers building fabric and energy use related to heating, hot water, cooling, ventilation and lighting, other EU Directives such as Eco-Design and Energy Labelling Directives set out energy efficiency requirements for industrial and household appliances. These requirements support improvement of total energy efficiency in buildings (The European Parliament and the Council of the EU, 2009), (The European Parliament and the Council of the EU, 2010).

Energy performance contracting can also play a significant role in saving energy from the existing buildings. Energy Service Companies (ESCOs) can help increase energy efficiency by providing information, installing energy efficient or renewable technologies, operating and maintaining buildings under long-term contracts. The upfront capital cost required for energy performance improvements could be provided by ESCOs or third party financing arrangements and recouped through savings achieved on energy bills.

The Energy Efficiency Directive calls for identification and removal of the regulatory and non-regulatory barriers to the use of energy performance contracts and other third party financing arrangements for energy saving. This Directive also sets out a requirement for the Member States to renovate a minimum 3% of the total floor area of heated and/or cooled buildings owned and occupied by central government administrations each year to meet the minimum standards prescribed by the EPBD. It is envisaged that the exemplary role of public bodies' buildings in achieving energy saving targets can promote energy efficiency initiatives in private sector as well (The European Parliament and the Council of the EU, 2012).

An overview of the EPBD is presented in the next section as the main energy efficiency policy at building level in Europe. Next, the implementation of the EPBD in England and its implications in the context of the Building Regulations and building energy certification schemes will be reviewed.

2.6.2. Energy Performance of Buildings Directive

Table 2.2 provides a summary of the objectives and requirements set out in the first version of the EPBD (Directive 2002/91/EC).

The cornerstone of the directive is Article 3 which requires every EU Member State to apply a methodology to calculate the energy performance of buildings. This calculation methodology can then be used to set out energy performance requirements for new and existing buildings (Articles 4-6) and also for the production of Energy Performance Certificates (Article 7).

Energy Performance of a building is defined as follows (The European Parliament and the Council of the EU, 2003, p. L 1/67):

“[T]he amount of energy actually consumed or estimated to meet the different needs associated with a standardised use of the building, which may include, inter alia, heating, hot water heating, cooling, ventilation and lighting.”

Most member states have developed or adopted methodologies that comply with these *minimum* requirements (IEE, 2008). Consequently, the expected appliances (e.g. plug-in loads related to computers and other electrical appliances) and any process load that may be present in a building are not necessarily included in the energy performance calculations carried out in accordance with the EPBD. Furthermore, the EPBD calculations are performed under the standardised operating conditions that may differ from actual operating conditioned or even the operating conditions expected by the clients or the design teams before a building is completed. This standardisation may be reasonable in the context of the Building Regulations where a decision has to be made by the regulators as to whether or not building fabric and fixed building services are in compliance with the minimum energy performance requirements. In this context, the effects of actual operating conditions, occupant’s behaviour, and actual appliance loads are not relevant and may even mislead the building control officers, by masking the effects of fabric shortcomings and inefficiencies in building services, where an optimistic view of how the building will be operated is adopted by the thermal modeller. However, an unintended consequence of this policy set-up is that the outcomes of the EPBD calculations are often not directly comparable to measured energy use of a building. Any attempt to compare the measured energy use of a building with the outcome of the EPBD calculations must therefore address these methodological hurdles.

Table 2.2. A descriptive summary of the EPBD articles (Directive 2002/91/EC)

EPBD Article	Descriptive summary
1-2: Objective & definitions	The objective is to improve energy performance of building stock across the EU.
3: Adoption of a methodology	Member states are required to apply a methodology to calculate the energy performance of buildings. Such calculation shall include, as a minimum, energy use related to heating, hot water, cooling, ventilation and lighting under standardised conditions.
4-6: Setting of energy performance requirements for new and existing buildings	Minimum energy performance requirements must be defined for new buildings based on the calculation methodology. When existing buildings with total useful floor area over 1,000 m² are subject to major renovation, their energy performance must be improved to meet the minimum requirements as long as these improvements are technically, functionally and economically feasible.
7: Energy performance certificates	Energy performance certificates must be produced for buildings on construction, sale or rent for provision of information. Public buildings with total useful floor area over 1,000 m² must also display a current energy certificate in a prominent place visible to public.
8: Inspection of boilers	To improve the performance of building boilers, Member States have two options: establish a scheme for regular boiler inspection, or provision of advice to users.
9: Inspection of air conditioning systems	The member states are required to establish regular inspections for all air conditioning systems with rated output of greater than 12 kW.
10-15: Administration	Administration of the directive includes, among other things, setting up a register of independent experts to carry out energy performance calculations and provide energy advice in accordance with the Directive.

The recast of the EPBD (Directive 2010/31/EU) provides further clarifications about the objectives and the requirements of the EPBD. It also extends the scope of the EPBD in line with the current EU energy policy objectives. The major revisions and additions included in the recast of the EPBD are as follows (The European Parliament and the Council of the EU, 2010):

- Minimum energy performance requirements set out by the Member States must be *cost-optimal* across their building stock. Every new building in the EU must be *nearly zero-energy* by the end of 2020. The Member States must also create plans for increasing the overall number of nearly zero-energy buildings in the existing building stock.
- There is a call for a voluntary common EU certification scheme for non-domestic buildings.

- The scope of the original directive is extended generally by reducing or removing the area thresholds that make the EPBD requirements applicable to new and existing buildings.
- A second option for inspection of air conditioning systems is introduced which entails adequate provision of advice and possible inspections for air conditioning systems, instead of regular inspections demanded in the original Directive.
- A new article is introduced to address the financial incentives and removing market barriers. There is also more emphasis on quality assurance requirements. Another article in the recast requires the Member States to introduce effective penalties for non-compliance.

The widespread non-compliance with the EPBD requirements and lack of effective enforcement of energy certification and inspections is a serious issue that must be addressed (CIBSE, 2011).

Non-compliance with the energy-related Building Regulations is an endemic problem in Europe. A review of the implementation of the energy-related Building Regulations across all EU Member States, Switzerland and Norway found there is little attention to enforce these regulations. The study also pointed to the shortage of qualified people with appropriate level of technical expertise to undertake building control function in most European countries (BPIE, 2011). Another study suggests non-compliance with energy efficiency regulations across the EU could be as high as 50% for refurbished buildings and 33% for new buildings based on expert opinions (Fraunhofer ISI, 2009) . An investigation by Energy Efficiency Partnership for Homes that looked at a sample of 82 energy assessments carried out in accordance with the EPBD requirements in the UK revealed that all had some level of error and in 20% of cases these errors would have resulted in the assessment failing to meet the dwelling performance target (Trinick, et al., 2009). Another empirical investigation of 404 new-build dwellings constructed in the UK from 2006 to 2009 found that only a third of these buildings were compliant with the energy performance requirements set out in the Building Regulations. Lack of adequate knowledge about energy efficiency requirements of the new Building Regulations among the construction industry and building control bodies along with the paucity of enforcement were cited as the main root causes for this non-compliance. Provision of information and on-going training would be necessary to keep the construction industry abreast of the rapidly evolving energy policy landscape and new requirements (Pan & Garmston, 2012). In non-domestic sector, early findings from the Building Performance Evaluation programme point to serious shortcomings in implementation of the building energy regulations notably in system commissioning and metering provisions (Palmer & Armitage, 2014).

The fragmented nature of the supply side of the construction industry and complexities of the new technologies deployed to enhance energy performance of new buildings and major renovations mean that optimum performance in most cases cannot be achieved without a period of fine-tuning after implementation of energy efficiency measures (BSRIA, 2009). It is also very difficult for any single body to confirm compliance with all energy efficiency requirements by reviewing construction details and commissioning results. An output-oriented assessment framework that evaluates performance in-use by verifying key performance indicators would be better suited to ensure energy performance requirements have been achieved. The voluntary performance in-use frameworks, such as Soft Landings and the Energy Commitment Agreement protocol under the Australian NABERS system (largely aimed at the office and commercial sector), go beyond building handover and basic commissioning to include a period of fine-tuning and acknowledge this perspective (BSRIA, 2009), (NSW Office of Environment and Heritage, 2011). Measurement and verification of in-use performance and post-occupancy evaluations, introduced as optional credits under building sustainability rating systems such as LEED (USGBC, 2007) and BREEAM (BRE, 2011), are also indicative of the trend towards performance in-use in the industry. However, this is not reflected in the EPBD regulatory frameworks yet.

Non-compliance with the EPBD casts serious doubts about meeting new stringent requirements such as the provision on nearly zero-energy buildings included in the EPBD recast (Pan & Garmston, 2012), (Economidou, 2012).

2.6.3. Implementation of the EPBD in England

Historically, energy efficiency in the UK buildings, similar to other European countries, was determined by the Building Regulations that were primarily focused on building fabric heat loss and air permeability. The Building Regulations were gradually extended to include other energy end-uses. Prior to 2002, an elemental method was used to demonstrate compliance with the Building Regulations; the compliance of each individual component was compared with the regulatory limit. In 2002, a whole-building calculation methodology was first introduced as a means of demonstrating compliance with the regulatory requirements (DTLR, 2002). Following inception of the EPBD, a National Calculation Methodology (NCM) was developed to underpin Article 3 of the EPBD. The elemental method of compliance for new buildings was superseded in 2006 and the NCM now underpins the whole-building energy performance calculation method that is used for Building Regulations compliance calculations and Energy Performance Certificates.

2.6.4. Building Regulations

The Building Regulations are a devolved responsibility in Scotland and Northern Ireland and were also devolved in Wales after the EPBD recast, during the course of this research programme. There is an increasing divergence between the Regulations and Standards in relation to low carbon or low energy aspects of buildings in the devolved administrations. The focus of this section is therefore on England rather than the whole United Kingdom to explain the regulatory framework applicable to the work undertaken in the EngD programme.

Part L of the Building Regulations and the second tier documents that underpin it, the Approved Documents, set out Energy performance requirements for new and existing buildings in England (HM Government, 2013). For new buildings and major renovations, the cornerstone of these approved documents is a whole-building energy performance calculation method, whereby, total CO_2 emissions associated with the regulated energy in a proposed building must be no greater than a notional building that possesses minimum acceptable specification. The specification of the notional building is updated in every revision of Part L to set out ever more stringent performance targets that are in line with national energy saving targets in building sector. Part L 2010 specification was strengthened to deliver 25% carbon dioxide savings across the new non-domestic building mix relative to Part L 2006 (HM Government, 2010). The current version, Part L 2013, is meant to deliver 9% overall improvement relative to the 2010 version (HM Government, 2013). The difficulties and opportunities of performance improvements in different type of buildings are recognised and therefore saving targets are different for each non-domestic sector.

In addition to the whole-building CO_2 emissions target, the Approved Documents set out other requirements including upper limits for fabric U values and air permeability, minimum efficiencies required for building services (HVAC, DHW and lighting), and solar gain limits in different zones. These limits are generally more relaxed than what the elemental approach would have prescribed, and effectively set the boundary for possible trade-offs. Final calculation must be run following practical completion and building commissioning to ensure the as-built energy performance is consistent with (i.e. no worse than) the design stage calculations. Finally, it is required to provide information and training to building users so that they can use their buildings efficiently.

Regulatory energy performance analysis of buildings in England is predominantly based on theoretical calculations even after practical completion of a building. In non-domestic sector, these calculations are performed either with a quasi-steady-state calculation engine called the Simplified Building Energy Model (SBEM) that is based on monthly average analysis, or software packages that follow hourly Dynamic Simulation Method (DSM) (CLG, 2011).

Although the final compliance calculations must reflect the as-built conditions, there is no requirement to assess actual energy performance after building handover in reference to the compliance calculations. This is consistent with the current EPBD requirements.

2.6.5. Building energy certification

Two types of energy certification have been implemented in England in recent years. Energy Performance Certificates (EPCs) are required when new buildings are completed, and existing buildings are sold or rent out. EPC is meant to reflect the potential energy performance of a building under standardised operating conditions and, therefore, the rating included on the certificate is called the *asset rating* (CLG, 2012 a). Display Energy Certificates (DEC), mandatory for most public buildings, are based on actual operating conditions and measured energy use. Therefore, a DEC represents the *operational rating* of a building (CLG, 2012 b).

Both certificates come with recommendation or advisory reports that include a list of generic recommendations selected from a database by an accredited energy assessor in addition to any specific recommendation provided by the assessor. Following up these recommendations and improvement of performance are generally not mandatory, although from April 2018 landlords will be required to improve the energy efficiency of their buildings if the asset rating falls below a certain level. This level is currently set at EPC rating of E meaning that F and G rated buildings must be improved to be sold or rent out after April 2018 (DECC, 2011).

The introduction of these certification schemes has led to greater awareness of energy efficiency in buildings. Furthermore, a large amount of data has been collated to produce these certificates that provide invaluable information about energy performance of national building stock and key determinants of energy use (Bruhns, et al., 2011), (Godoy-Shimizu, et al., 2011), (Healy, 2013), (Hong, et al., 2014).

Figure 2.6 and Figure 2.7 show the formats and contents of EPCs and DECs. The similar colour coded ratings with categories from A to G might give the impression to general public and some practitioners that the EPC and DEC ratings are directly comparable. This is also an intuitive impression that reflects the human tendency to compare the actual performance of an entity with its true potential. However, this could be misleading.

As explained above, the EPBD is generally more focused on calculated energy performance rather than measured performance. Article 7 of the initial EPBD (Directive 2002/91/EC) and Article 13 in the EPBD recast (Directive 2010/31/EU) only demand *publicising* the energy certificates for buildings frequently visited by public. A display energy certificate based on *measured* performance is therefore not essential under the EPBD.

Following inception of the EPBD, a number of European countries opted for energy certification solely based on calculated performance. A notable example within the United Kingdom was Scotland which did not have operational rating. Public buildings in Scotland were only required to display their EPCs (IEE, 2008). The Scottish Government has only recently adopted an operational rating scheme for non-domestic buildings similar to the one implemented in England (The Scottish Government, 2016).

As calculated against measured energy performance of a building is not directly addressed by the EPBD, where countries opted for inclusion of measured performance in their certification schemes, these two types of certification were not always developed in tandem. For example, the baselines defined, energy end-uses included in the analysis, and source-site conversion factors used in the EPC and DEC schemes in England are not consistent (Healy, 2013).

A self-reference method based on the NCM is used to define the reference value for energy performance of a building under the EPC scheme, whereas the reference values used in the DEC scheme are based on CIBSE TM46 (2008) benchmarks. The TM46 benchmarks were intended to represent the median performance in each building category (Bruhns, et al., 2011). Statistical analysis of the DEC results shows that, although in most building categories the median performances are close to the benchmarks, in some building categories the median performances are as much as 30% off the TM46 benchmarks (Bruhns, et al., 2011). This is not surprising as, in some building categories, from the outset initial placeholder benchmarks were developed for TM46 based on available data to underpin the implementation of the DEC scheme. It was recognised that the benchmarks for public buildings should be reviewed and reconsidered in the light of initial DEC results (Bordass, et al., 2014). However, the TM46 benchmarks have not been revised yet since the first publication of TM in 2008.

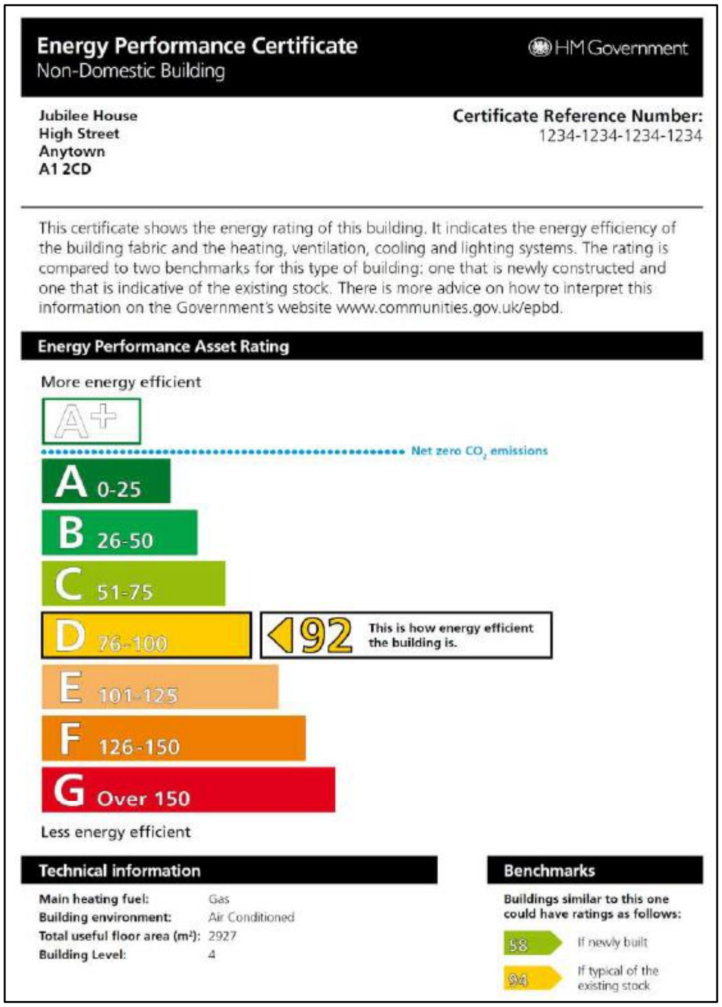


Figure 2.6. The format and content of Energy Performance Certificates (EPCs) in non-domestic sector (DFPNI, 2008)

An unintended consequence of this disjointed approach to implementation of the EPBD is the disillusionment among some field practitioners and their clients who wish to be able to compare operational rating of their buildings with asset rating to explore the effect of actual operating conditions and building management on energy performance. However, it is very difficult to compare operational performance with asset rating unless a number of adjustments are made to take into account the abovementioned methodological differences and shortcomings (Healy, 2013).

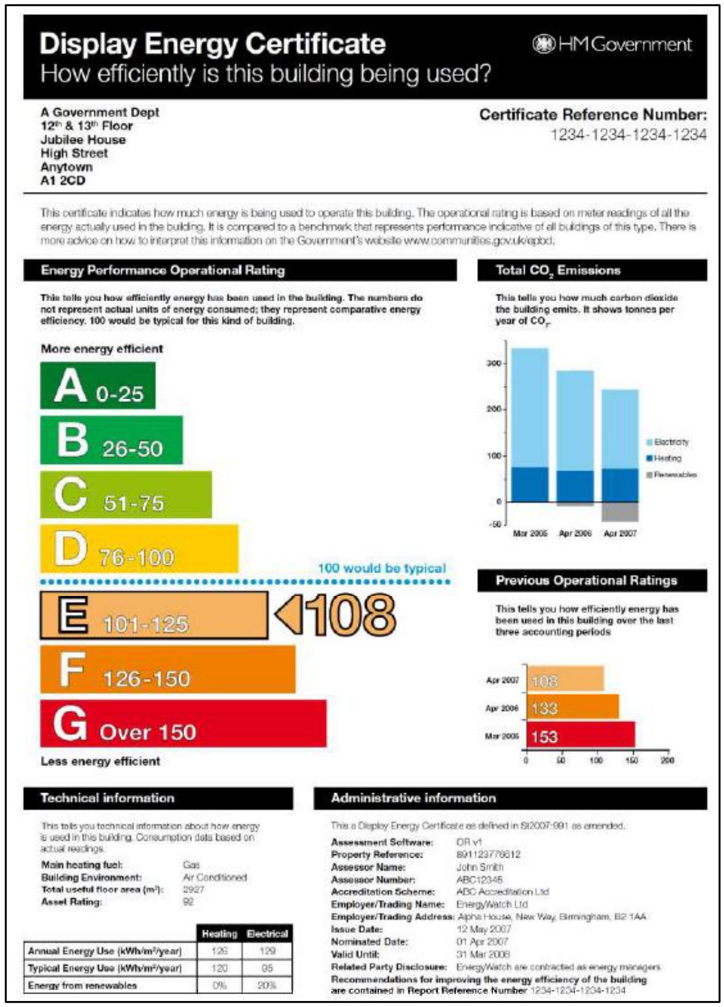


Figure 2.7. The format and content of Display Energy Certificates (DECs) ((CLG, 2012 b)

It is useful to compare the set-up of the existing certification schemes in England with an energy labelling programme which enables users to compare the asset rating of their buildings with operational rating directly.

The ASHRAE building Energy Quotient (bEQ) is an energy-labelling programme launched in 2013 that broadly follows the principles of energy certification in the EU. However, it is not primarily designed to respond to regulatory requirements and is market driven. It comprises two ratings: 'As Designed' and 'In Operation'. The 'As Designed' rating is designed to neutralise the effect of occupant behaviour and operating conditions by use of standardised input data. It can therefore compare energy efficiency of different buildings of the same type under identical operating conditions, and help prospective tenants and buyers in choosing the most energy efficient property (ASHRAE, 2013 a). The 'In Operation' rating, on the other hand, reflects the energy performance of buildings under actual operating conditions, and is designed to help building users improve their buildings' performance (ASHRAE, 2013 b).

While these objectives are almost identical to that of EPCs and DECs, the bEQ ratings are more streamlined to facilitate comparison of the performance in use with the design intents. Depending on the building type, the reference values for both the 'As Designed' and 'In Operation' labels are either based on median source Energy Use Intensities (EUIs), provided for each ASHRAE climate zone, or Energy Star methodology which in addition to activity type and gross floor area takes into account other critical building energy determinants. Either way, the same methodology is used for both asset rating and operational rating. Furthermore, all expected energy loads are included in the 'As Designed' assessment. The 'In Operation' assessment is also inclusive of all energy end-uses. Finally, the same source-site conversation factors are applied to both ratings.

Figure 2.8 shows a sample bEQ certificate that is issued by ASHRAE after reviewing the work submitted by approved professionals. Both 'As Designed' and 'In Operation' ratings are presented and compared on the same certificate. Figure 2.9 shows the bEQ Dashboard, and provides additional information about the 'As Designed' & 'In Operation' rating schemes. Table 2.3 also compares the key characteristics of EPCs and DECs with the ASHRAE building Energy Quotients.

A comparative study of ASHRAE bEQs and the energy certification schemes developed under the EPBD can help identify improvement opportunities for building energy certification.

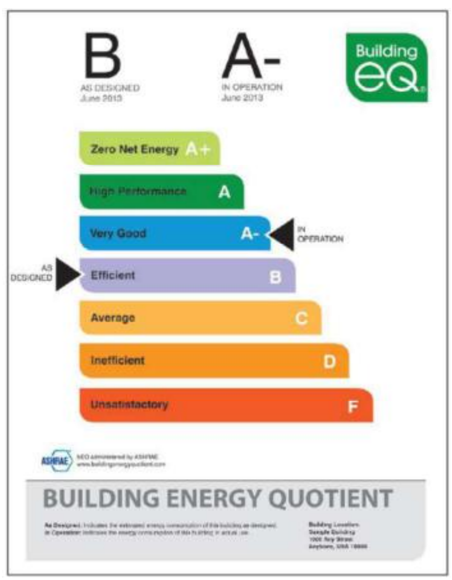


Figure 2.8. An example of ASHRAE building Energy Quotient (bEQ) comparing the 'As-Designed' with the 'In-Operation' performance (ASHRAE, 2013 c)

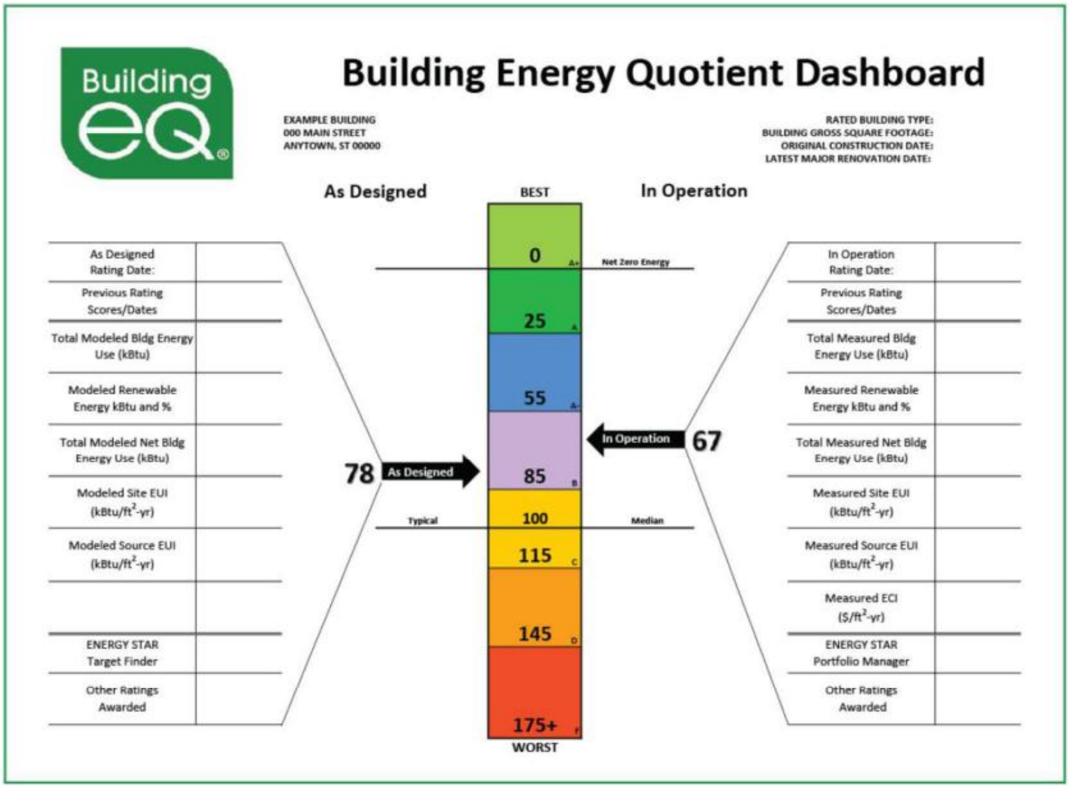


Figure 2.9. The ASHRAE bEQ Dashboard indicating the rating system and scales used (ASHRAE, 2013 c)

Table 2.3. Comparison between energy certification schemes in England and ASHRAE bEQ (CLG, 2012 b), (ASHRAE, 2013 a), (CIBSE, 2009), (ASHRAE, 2013 b)

Characteristic	EPC	bEQ (As Designed)	DEC	bEQ (In Operation)
Principle objective	Asset rating	Asset rating (for prospective tenants & buyers)	Operational rating	Operational rating (for portfolio managers and building users)
Principle driver	Regulations	Market	Regulations (public buildings only), Market for other buildings	Market
Metric used for total performance	CO_2 emissions associated with building energy performance (kg CO_2/m²/yr)	Source energy (kBtu/ft²/yr.)	CO_2 emissions associated with building energy use (kg CO_2/m²/yr.)	Source energy (kBtu/ft²/yr.)
Reference values	CO_2 emissions defined by self-reference method (Reference building emissions defined by the Building Regulations 2002 subject to average 23.5% improvement)	Median Source Energy Use Intensity (EUI) or ENERGY STAR Target Finder	As defined in CIBSE TM46 (supposed to be the CO_2 emissions of the median of national building stock for every building type)	Median Source EUI or ENERGY STAR Portfolio Manager
Source –site ratio[4]	Elec.: 0.422 kg CO_2/kWh Gas: 0.194 kg CO_2/kWh[5]	Elec.: 3.34 kBtu/kBtu Gas: 1.047 kBtu/kBtu	Elec.: 0.55 kg CO_2/kWh Gas: 0.19 kg CO_2/kWh	Elec.: 3.34 kBtu/kBtu Gas: 1.047 kBtu/kBtu
Rating	(As-built CO_2 emissions based on modelling / Reference value) × 50	(As-built Source EUI based on modelling / Reference value) ×100	(Measured CO_2 emissions / Reference value) × 100	(Measured Source EUI / Reference value) × 100
Energy end-uses not included in the rating	Equipment load	None	None	None
Energy classification bands	A+ to G (A+ indicating net exporter of energy)	A+ to F (A+ indicating zero net energy)	A to G	A+ to F (A+ indicating zero net energy)
Administration	Various certification bodies approved by the Government	ASHRAE	Various certification bodies approved by the Government	ASHRAE
Quality Assurance (QA)	Sampling (minimum 2%)	100% (certificate issued by ASHRAE after review)	Sampling (minimum 2%)	100% (certificate issued by ASHRAE after review)

2.7. Post-occupancy evaluation: from design to operation

As the regulatory frameworks stemming from the EPBD are predominantly focused on theoretical calculations, it is important to review the *actual* performance of buildings

[4] Source-site ratio is a multiplier that converts the delivered energy to a building to primary energy or corresponding CO_2 emissions. It includes the effects of losses in generation and distribution of energy nationwide.
[5] As of October 2010, 0.517 kg CO_2/kWh for electricity and 0.198 kg CO_2/kWh for gas (HM Government, 2010).

constructed or refurbished in accordance with the EPBD to assess whether the existing regulatory frameworks can deliver the energy saving targets set out for buildings. As explained in the previous sections, it is also important to consider the interrelations between energy performance and other performance criteria. Post-occupancy evaluation (POE) can be used for this purpose.

2.7.1. Definition

Post-occupancy evaluation is a method for systematic evaluation of building performance. The aim of POE is to determine to what extent a building satisfies the needs of its end users and identify improvement areas for building performance and future buildings design (Turpin-Brooks & Viccars, 2006).

POE aims to provide answers to the following broad questions about a building (Bordass & Leaman, 2005):

- How is this building performing?
- Is this performance intended?
- How can this performance be improved?
- How can future buildings be improved?

POE provides a human-centred framework to investigate the answers to these questions with special focus on end users' requirements. Consequently, issues such as occupant satisfaction, occupant performance, and productivity are often addressed along with, and linked to, technical evaluations (Jaunzens, et al., 2003), (Preiser & Vischer, 2005), (BCO, 2007).

POE studies are often carried out once a building has been completed and occupied for a period of time, usually more than one year, to achieve steady operation (Palmer, 2009). However, feedback from building performance during the early stages of post-occupancy could be helpful for building fine-tuning (BSRIA, 2009).

The breadth and depth of a POE could vary widely. A POE study could be used for the following purposes (Palmer, 2009):

- Benchmarking
- Design Appraisal
- Diagnostics

It has been argued that a systematic approach should be taken for the benchmarking of buildings to ensure current practices are improved and sustainability targets are achieved

(Roaf, et al., 2004). Design appraisals are required to examine the success of design solutions and learn the lessons for future projects (Pegg, 2007). Finally, POE could be used as a diagnostics tool for immediate problem solving, troubleshooting, and fine-tuning (Preiser, et al., 1988).

2.7.2. Historical background

The term post-occupancy evaluation probably originates from the Occupancy Permit which was issued after a building was completed to confirm the building was ready to be occupied (Bechtel, 1997).

The principle of evaluating a building's actual performance and feeding back the outcomes to design team was first formulated in the Royal Institute of British Architects (RIBA) Handbook in 1965. This was RIBA's first attempt to systematise the management of architectural practice (Cooper, 2001). The final part of its 'plan of work' was entitled Stage M: Feedback (RIBA, 1965).

Cooper (2001) identifies two trends which were influential in the emergence of POE in the UK: environmental psychology and the 'design methods' movement. Environmental psychology had started with the premise that human behaviour in buildings should be subject to scientific study (Canter, 1970). The design methods movement, on the other hand, was an attempt to make building design more scientific and systematic (Cross, 1984). Seeking systematic feedback from buildings and focus on human behaviour within buildings was, therefore, based on a multi-disciplinary approach from the outset.

There are also other disciplines that have been referred to as being influential on the emergence and development of POE. Derbyshire (2004) refers to Operational Research and Preiser and Vischer (2005) suggest that the theoretical foundation of building performance evaluation, of which POE is one component, is adapted from Cybernetics. The key elements that link all these fields are the role of reflection, feedback, and assessment of the interaction between the users and buildings (Pegg, 2007).

The first academic research programme carried out in the UK to get feedback from buildings was conducted at the Building Performance Research Unit (BPRU), University of Strathclyde. This programme was sponsored by twenty architectural and engineering practices, RIBA, the Architects' Journal, and the Ministry of Public Building and Works. The main focus of this programme was school buildings and the results were published in the Architects' Journal and Building Performance (Markus, et al., 1972). It was ironic that RIBA removed Stage M from its plan of work the same year Markus et al. book was published. The problem was clients were not ready to pay for feedback as an additional service. From their point of view, the main beneficiaries of the feedback received from a building were architects and design teams and not the client. RIBA, on the other hand, did not want to give the impression that architects will carry out Stage M and provide feedback as a matter of course and therefore removed this stage from its plan of work altogether (Cooper, 2001), (Bordass & Leaman, 2005).[6]

This major setback was exacerbated by the gradual decline of environmental psychology in the 1980's (Pol, 1993). It was felt that environmental psychology had very little to offer to design practitioners. Canter (1984) argued that unless social science was integrated with building design practice, it would not be able to provide effective feedback to improve the use of existing buildings and future designs from 'outside' the design process.

Following the Latham (1994) report which was commissioned by the UK government to investigate the root causes for the poor quality offered by the UK construction industry, a change in building research funding provided the opportunity for a new wave of POE studies called Post-occupancy Review of Buildings and their Engineering (PROBE). This project was conducted by a number of field practitioners with diverse backgrounds and mixed skill set led by the editor of Building Services Journal (Cohen, et al., 2001).

Table 2.4 provides a comparison between the first and second waves of POE studies carried out in the UK. The PROBE studies were more focussed on engineering aspects of building performance. This was evident not only from the background of people who conducted the project but also the tools and methods deployed. Even Building Use Studies (BUS), the occupant satisfaction survey developed for this project, reflect this engineering-oriented approach by asking more detailed questions about thermal comfort conditions, noise, lighting, and other measurable physical characteristics rather than spatial planning. There was no systematic attempt to assess spatial utilisation as in Markus et al. (1972) or Rawlinson (1984) or spatial mapping as in Kato et al. (2005). Apart from the practitioners' background and bias, this was to some extent, related to the fall of environmental psychology and the ever-increasing significance of energy conservation following the oil crisis in the late 1970s. There was also a growing recognition of the impact of disciplines other than architecture such as services engineering and the newly emerging field of facilities management on building performance (Worthing, 1994).

[6] It was only in 2003 that the RIBA Practice Committee decided to reintroduce Stage M into its published documents. Post-occupancy evaluation is now included in Stage 7 of RIBA Plan of Work (RIBA, 2013).

Table 2.4. Comparison between first and second waves of POE studies in the UK

POE Study	Professional body involved	Methods	Scope	Building type	Context
BPRU POE (1968-1972)	RIBA (The Architects' Journal)	Multi-method approach with focus on social science, spatial planning, and with some physical measurements	Academic (Research based and thorough)	School	Rise of environmental psychology, scientific and systematic approach to architecture
PROBE (1995-2002)	CIBSE (Building Services Journal)	Multi-method approach with more focus on engineering, led to development of scalable methods and tools such as TM22 energy assessment and Building Use Studies (BUS)	Academic-practical (Field-oriented, interventionist, scalable methods and tools)	Office, School, University, Surgeries, Residential training centre and Warehouse	Fall of environmental psychology, energy crisis of 1970's, outbreak of legionnaire and sick building syndrome, tendency to scale up POE

Twenty buildings were studied over the period 1995-2002 and results were published in both Building Services Journal (for field practitioners) and a special edition of Building Research and Information (for academic audience).

The methods and tools developed in the PROBE studies have informed the major subsequent building evaluation programmes in the UK such as the Building Performance Evaluations instigated by the Innovate UK. Table 2.5 provides an overview of the major POE studies carried out in the UK and internationally.

Table 2.5. Overview of the major contributions to the field of POE

Reference	Subject	Methodology	Building Type
Van der Ryn and Silverstein (1967)	Environmental analysis concepts and methods with special focus on student accommodation (Centre for Planning and Research, University of California at Berkeley)	Multi-method, rooted in physical and social ecology	Student accommodation
Preiser (1969)	Environmental performance profiles for student accommodation	Subjective and objective performance measures	Student accommodation
Markus et al. (1972)	Cost-based and systematic building performance evaluation framework	Spatial utilisation, observation, questionnaires, and interviews	Mainly schools, but the framework could also be applied to other buildings.
Rabinowitz (1975)	Comprehensive evaluation of technical, functional, and behavioural aspects of building performance	Multi-method (subjective and objective methods)	Elementary schools
Zeisel (1984)	Exploring different methods for POE studies	Multi-method, rooted in environmental psychology	Applicable to any building type
Hildon (1986) and Palmer et al. (1994)	Energy Performance Assessment of passive solar buildings in the UK	Multi-method (technical measurements, questionnaires, and interviews)	Applicable to both residential and non-domestic buildings
Preiser et al. (1988)	Reflection on a range of POE methods and techniques	Multi-method	Applicable to any building type

PROBE studies (1995-2002)	POE studies on twenty buildings in the UK	Energy audit, pressure test, occupant satisfaction survey, interviews, walk-through surveys	Office, School, University, Surgeries, Residential training centre and Warehouse
Etzion et al. (2001)	An open GIS framework to record and analyse post-occupancy changes in residential buildings in Israel	GIS-based, includes walk-through surveys	Residential neighbourhoods
The US Federal Facilities Council (2003)	State of the art review of POE	Multi-method	Mainly public sector office buildings
Zagreus et al. (2004)	Introducing a web-based indoor environmental quality survey	Web-based survey (Centre for the Built Environment, University of California at Berkeley)	Mainly office buildings but could be used in any type of building where occupants have access to the web at their workstation.
Pitts and Douvlou-Beggiora (2004)	POE study of comfort in atrium spaces	Thermal comfort measurements	Education sector
Preiser and Vischer (2005)	Building Performance Evaluation Framework	Multi-method	Applicable to any building type
Abbaszadeh et al. (2006)	Occupant satisfaction survey on 181 green buildings	Web-based survey (Centre for the Built Environment, University of California at Berkeley)	Office
Lighthall et al. (2006)	Investigated the impact of school refurbishment on student success. 18 schools were included in this research.	Exam results were collected and compared within the same socio-economic context.	Schools
CABE (2006)	Secondary schools design quality (52 UK schools)	Buildings functionality (access, space and use), quality (performance, design,	Secondary schools

		and construction), and their impact on wider community were investigated.	
CABE (2007)	User satisfaction survey in residential sector; 643 residents living in 33 developments participated in this survey. More focused studies were carried out on 6 case study developments.	User satisfaction survey	Residential
Pegg et al. (2007)	POE studies on 5 secondary schools in the UK. The study also assessed the role of POE in a design consultancy.	Energy audit, monitoring of indoor environmental quality, user satisfaction survey, walk-through survey, semi structured interviews and surveys with employees of the design consultancy	Secondary schools
Langstone et al. (2008)	User satisfaction surveys; 14 case studies in 2 years	User satisfaction with workspace, thermal comfort, visual aspects, and acoustics were assessed.	Education sector and office buildings
Mahdavi et al. (2008)	Occupants evaluation of indoor climate and environmental control systems in 5 office buildings	Interview and long term monitoring	Office buildings
Mumovic et al. (2009 a)	Environmental conditions of 9 secondary schools in winter in the UK	Indoor air quality, thermal comfort, and acoustics measured	Secondary schools
Building Performance Evaluation programme (2010-2015)	Performance evaluation of domestic and non-domestic buildings in the UK (more than 100 projects)	Energy assessments, design vs. as-built review, occupant satisfaction surveys, walk-through surveys	A variety of buildings in both residential and non-domestic sector

2.7.3. System perspective vs. process-oriented approach

As POE is a method for systematic evaluation of building performance, a sound theoretical framework for conceptual representation of building performance provides a better understanding of the role POE can play in assessing performance. Figure 2.10 represents the system perspective to building performance developed by Markus et al. (1972).

This Figure shows the relationship between the Building System (building structure, services installed and building content), the Environmental System (spatial and physical environment that is created by the building system), the Activity System (workflow, communication streams, activities that are influenced by the environmental system), and finally the Objective System (the ultimate goal an organisation targets through activities that take place within the activity system and are influenced by the environmental and building systems).

Each system in this model is subject to constraints outlined in financial, regulative, or policy terms. The overall performance will be a success if the benefit of achieving the objective is greater than total cost of procuring and managing the building, environmental and activity systems.

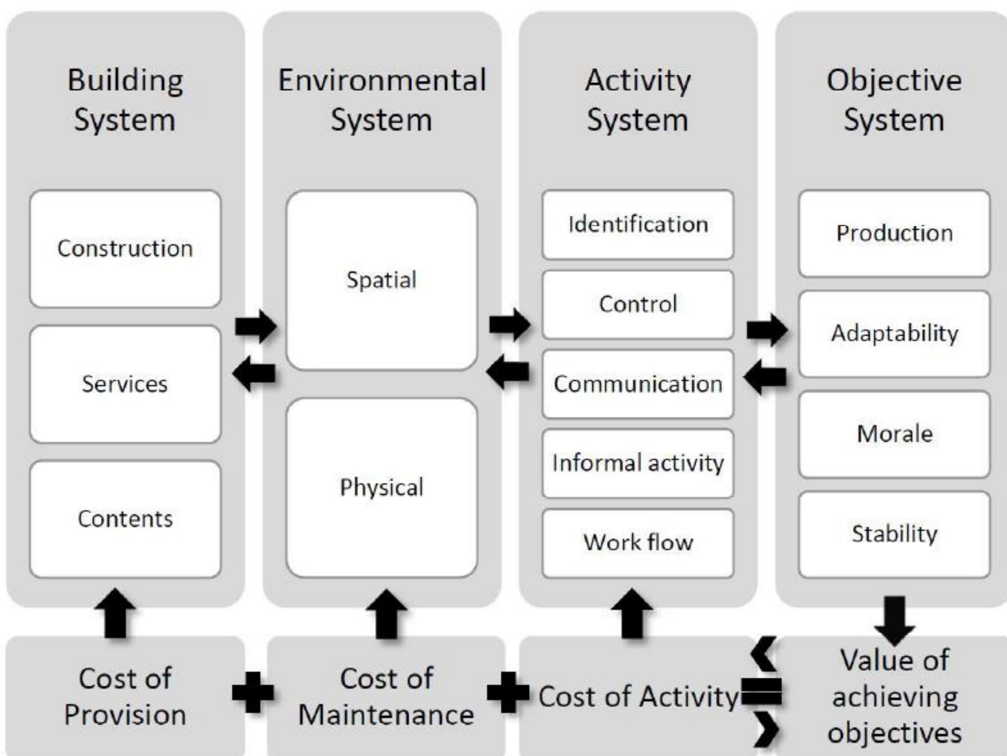


Figure 2.10. System perspective to building performance, reproduced after Markus et al. (1972)

The implications of adopting this framework for building evaluation are as follows (Pegg, 2007), (Mumovic, et al., 2009 b):

- Evaluating building performance requires an understanding of activities and objectives in addition to building and environmental systems,
- Building performance is dependent on the available resources and constraint system. Therefore, benchmarking and comparison between buildings are meaningful when objectives and resources are similar,
- Achieving better building performance means achieving fixed organisational objective with less resources or achieving higher organisational results with fixed resources,
- As this model is based on cost and benefit analysis, it is necessary to have an accurate estimation of costs. Therefore, more accurate algorithms and tools are required to estimate the total cost of constructing and managing a building. These include better algorithms and novel tools to predict energy consumption,
- It is imperative to have better understanding of the interrelationships between various systems. Examples include interaction between building occupants and control systems, and the effect of environmental and activity systems on occupants' satisfaction and productivity,
- Finally, to establish the overall performance, life cycle assessment methods should be used to take into account the total cost of building performance.

Whilst this theoretical framework provides useful insight into building performance and could be used as reference for POE practitioners to recognise the integrated nature of building evaluation and interrelationships between different systems, there are a number of limitations associated with this framework:

- The wider socio-economic context in which an organisation is run and a building performs is not reflected in this framework. Markus et al. originally proposed this framework for school buildings. A report commissioned by Department for Education and Skills (DfES) in late 1990s concluded that the effects of socio-economic factors and curriculum on pupil attainment, educational performance, and staff retention far outweigh the effect of buildings (PriceWaterhouseCoopers, 1999).
- It would be very difficult to quantify the value of achieving objectives especially in the public sector.
- In private sector, on the other hand, whilst the objective system is often clear and quantifiable (e.g. turnover, profit, etc.) the benefits are not necessarily linked to the systems included in this framework. For example, market conditions could be more influential than building and environmental systems or even staff productivity.

- Finally, on a practical level, it is very difficult to source all this data for building evaluation. A lot of information is scattered among various departments, considered to be sensitive, and difficult to source for the POE practitioner.

A process model for POE was first developed by Preiser et al. (1988) and is demonstrated in Figure 2.11.

Preiser et al. identify three phases for a POE (planning, conduction, and applying) and also three level of POE (indicative, investigative, and diagnostic). The Level of effort required for each level of POE varies but the number of phases and steps required in each phase are similar. The strength of this model is its focus on feeding back the findings to stakeholders and feeding forward the lessons learned to the next building cycle.

Preiser and Schramm (1997) developed this process model into an integrative framework for Building Performance Evaluation. POE is one of the milestones set out by this framework to take place after stable occupancy. This model sets out building performance evaluation milestones for each phase of building delivery and life cycle (Figure 2.12). Therefore, there are internal reviews and feedback loops at every stage of delivery and life cycle. Whilst traditional approaches to construction follow a product-oriented model, Building Performance Evaluation (BPE) is a dynamic, evolving and process-oriented approach developed based on the principle of continues improvement (Preiser & Vischer, 2005).

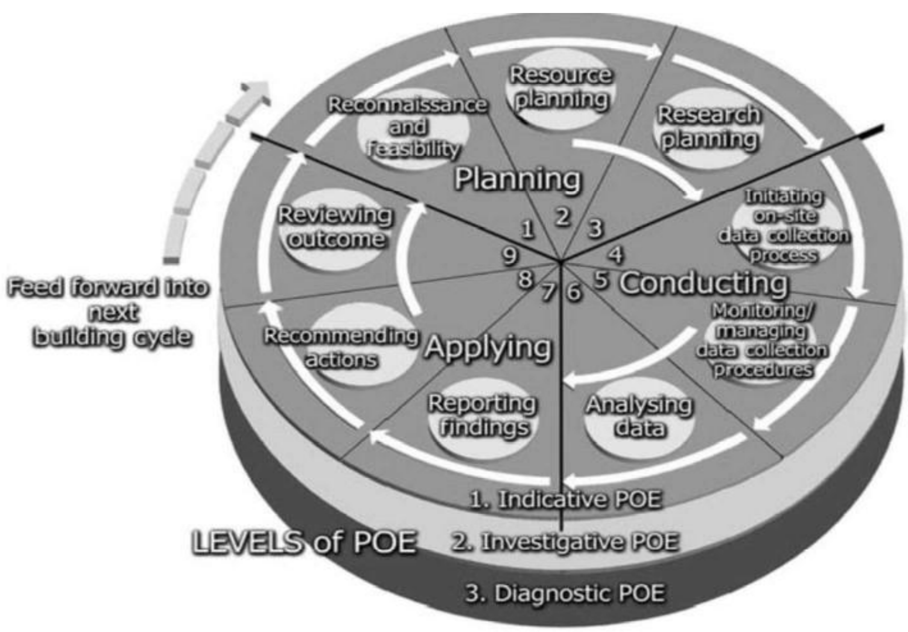


Figure 2.11. A process model for POE (Preiser & Vischer, 2005)

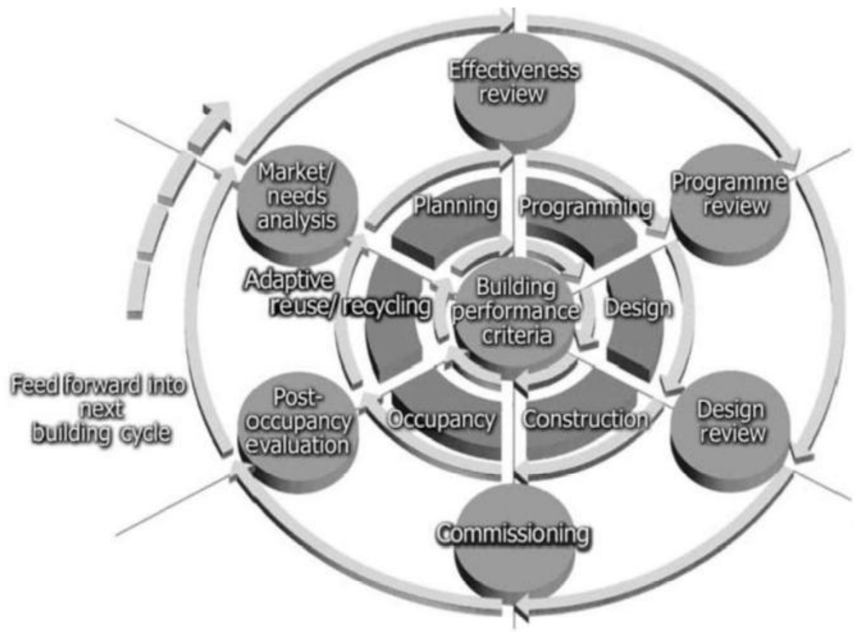


Figure 2.12. A process model for Building Performance Evaluation (Preiser & Vischer, 2005)

The implications of adopting these process-oriented models for BPE and POE are as follows:

- These models are built around conventional construction and life cycle phases and, in principle, could be easily applied to each phase.
- The BPE model acknowledges the profound impact of early stage decisions on a project and includes review and feedback for all phases of the process in addition to post-occupancy.
- The socio-economic factors are, at least to some extent, embedded into design and construction by means of project brief and regulatory requirements.
- At every stage of construction, delivery, and operation, building performance is measured against respective performance criteria. Therefore, the question of how this building is performing is divided to a number of more specific questions which should be responded in a structured way at different stages.
- The model is based on continuous improvement and perpetuates reflection and learning throughout consecutive projects.

The outcomes of a process-oriented building performance evaluation could be used for immediate problem solving in an existing building, provide direct input to the next building cycle, and feed-forward the lessons learned to a database or clearinghouse for improved design criteria (Preiser & Vischer, 2005). An example is the US National Clearinghouse for Educational Facilities (NCEF) which provides access to some public sector building evaluations (Sanoff, 2002).

2.7.4. POE methods

There are numerous methods for POE studies. The mainstream POE methods could be categorised as follows:

- Walk-through surveys (observational)
- Physical measurements (thermal comfort, ventilation, lighting, noise, energy assessment, etc.)
- Occupant satisfaction surveys (questionnaires, interviews, forums, task performance tests)
- Documentation review & analysis (as-designed, as-built, and operational performance)

A holistic POE study usually takes advantage of all abovementioned methods one way or another. Table 2.6 provides a summary of the POE methods and tools used in previous studies.

Table 2.6. Overview of the POE methods used in previous studies

Category	Method	Description
Spatial POE	Spatial utilisation	Used by Markus et al. (1972) and Rawlinson (1984) to compare level of occupancy to the capacity.
	Spatial mapping	A combination of observations, interviews, and video analysis could be used to understand how occupants use a space. Communication and circulation mapping techniques were used by Kato et al. (2005) in Japan.
User satisfaction surveys	Building Use Studies (BUS)	7 point scale questionnaire developed by Leaman and Bordass (2001) and used in PROBE studies. The aim of this type of questionnaire is to quantify the subjective assessment of building occupants. The narrow scope of these studies and the attempt to separate inextricable things within the built environment have been criticised (Markus, 2001). The interaction between physical parameters could not be captured by these surveys. For example, acoustic problems could affect people perception of thermal comfort (Meir, et al., 2009).
	Building In Use (BIU)	5 point scale questionnaire developed by (Vischer, 1999). The occupants' perception of air quality, thermal comfort, spatial comfort, privacy, lighting quality, and building noise control is assessed. Similar to BUS, the building's rating could be compared against database average.
	Occupant Indoor Environmental Quality (IEQ) survey	A web-based questionnaire developed by (Zagreus, et al., 2004). Web-based questionnaires provide better diagnostic opportunities and have lower administration costs. However, this format is more suited to office buildings.
	Building assessment questionnaire for schools	A bespoke building assessment questionnaire designed for schools and provided in CIBSE TM57 (CIBSE, 2015 a).
De Montfort method	A method based on the POE review process developed by the Higher Education Funding Council for England (HEFCE, 2006).	A brief POE study (usually one day only) based on forums and walk-through survey.
Task performance tests	Various methods available	These tests assess the impact of indoor environmental conditions on the occupants' productivity. Heerwagen (2000) reported examples of these tests

		performed mainly in office buildings. Wargocki and Wyon (2013) reported the outcomes of task performance tests in educational buildings.
Indoor Environmental Quality measurements	Thermal comfort	Dry air temperature or the mean radiant temperature, air velocity, and relative humidity are measured to establish thermal comfort levels. Clear guidelines are available as in CIBSE Guide A (2015 b). However, it should be noted that perception of thermal comfort is a subjective matter. Some researchers have proposed adaptive thermal comfort models (Nicol, et al., 2009). CIBSE Guide A (2015 b) acknowledges adaptive thermal comfort and recommends separate overheating criteria for free running buildings and mechanically ventilated buildings in accordance with BS EN 15251 (BSI, 2007). The overheating threshold for free running buildings is defined based on outdoor temperatures (CIBSE, 2015 b), (CIBSE, 2013).
	Indoor Air Quality	Ventilation rates could be inferred using CO_2 or other tracer decay methods. AIVC (1988) provides details of ventilation measurement methods. Air pollutants and volatile organic compound levels could also be measured.
	Lighting	Illuminance levels, daylight factor, and glare indices could be measured (Fontoynont & Berrutto, 1997), (DfEE, 1999), (CIBSE, 2011).
	Acoustics	Ambient noise levels, reverberation time, and speech intelligibility index could be measured in accordance with BS EN 3382 (BSI, 2009), (BSI, 2008).
Energy Audit	Energy Monitoring	Energy data could be collated on-site or sourced from the utility supplier. If the metering strategy is not comprehensive, portable instruments such as electricity profiler may be required to establish detail energy performance of building including end-uses.
	CIBSE TM22 assessment (2006)	A method originally developed by Field et al. (1997) to breakdown total energy consumption to end uses.
	Benchmarking	Energy consumption of the building could be compared to benchmarks such as those included in CIBSE TM46 (2008).
	Calibrated simulation	The International Performance Measurement & Verification Protocol (EVO, 2012) provides a concise description of various techniques to verify energy performance of buildings including the Whole Building Calibrated Simulation

		method; the thermal model of a building is calibrated based on the as-built and operational information and the results will be compared against actual energy use. The IPMVP whole building calibration is underpinned by ASHRAE Guideline 14 (2002).
External envelope studies	U value measurement	A U value probe comprising heat flux sensor and external and room temperature sensors could be used to measure the thermal performance of building fabric in accordance with BS ISO 9869-1 (2014). This method will only provide an indication of average U values and cannot detect the effect of repeating and non-repeating thermal bridges. It is also very sensitive to ambient conditions.
	Co-heating test	Is mainly used in residential sector to establish the total heat loss coefficient of a building, i.e. fabric heat loss plus ventilation loss (Wingfield, et al., 2010).
	Thermal imaging	Infrared thermography can be used in accordance with BS EN 13187 (1999) to identify construction irregularities that cause variation in surface temperature. Thermal bridges and ventilation loss could be identified by this method.
	Pressure test	The air permeability of building is measured at 50 Pa pressure difference and with all deliberate openings closed. The approved procedure for regulatory pressure tests in the UK is provided by ATTMA (2010).
Structured and multi-criteria POE	Design Quality Method (DQM)	A POE method developed by the Building Research Establishment (BRE) to assess the architecture, environmental engineering, user comfort, whole life costing, detail design, and user satisfaction of a building (Cook, 2007).
Operational Rating	CIBSE TM 47 (2009)	The protocol to produce operational rating for buildings in accordance with the EPBD requirements.
Air conditioning inspection	CIBSE TM 44 (2007)	The protocol to carry out air conditioning inspections in accordance with the EPBD requirements.

2.7.5. Drivers for and barriers to POE

The benefits and hazards of POE vary depending on the standpoint of different stakeholders (Table 2.7). The problem of ownership, cost, and litigation have been cited as major barriers to widespread use of POE in the UK (Cooper, 2001), (Bordass & Leaman, 2005).

Table 2.7. Drivers for and barrier to POE

Stakeholder	Driver	Barrier
Building developer	Feedback helpful for future projects	Liability if defects identified, ownership & cost
Building owner	Marketing edge if outcomes are positive	Risk of asset value depreciation if defects identified, ownership & cost
Designers	Learn the lessons	Litigation risk, negative publicity if defects identified, ownership & cost
Building users	Employee satisfaction, productivity assessment, health and well-being of occupants, possible savings	Time and cost involved, operational disruption, ownership & cost
Policy makers	Ensure policy instruments deliver, identify and promote good practice	Funding, relatively small statistical samples, could general conclusions be drawn independent of the specific building context?

Zimmerman and Martin (2001) also refer to the following barriers to implementing POE in North America:

- Fragmented incentives and benefits
- Lack of agreed and reliable performance criteria
- Potential liability for stakeholders
- Exclusion from building delivery expectations
- Exclusion from professional curricula

The question of POE ownership has not been resolved over the years and it is very difficult to change this from within the disintegrated construction supply chains.

Following inception of the EPBD, the regulatory requirements such as energy performance calculation after the completion of buildings, display energy certificates for public buildings, and regular inspection of air conditioning systems led to a new interest in operational performance of buildings in the UK. This was reinforced by new funding streams from the government to support building performance evaluations. Consequently, a new framework for building performance evaluation called the Soft Landings was developed by the Building Services Research and Information Association that is broadly consistent with the Preiser and Vischer (2005) framework in that it is embedded into the design process and encompasses various design and construction stages. Furthermore, it extends the aftercare duties of the designers and contractors for up to three years post-handover to ensure the performance in-use is consistent with the design intents (BSRIA, 2009). The Government Soft Landings framework which follows the same principles will be mandated in public sector by 2016 (Cabinet Office, 2013). If building performance evaluation leads to tangible benefits in public sector it is likely that private sector will also show more interest in performance in-use.

2.8. The Performance Gap

One of the findings of the PROBE studies was that energy was often poorly specified in briefing and design criteria. There was very little connection between the values assumed in design estimations and computer models and actual values found in the completed buildings. Actual energy use of most buildings in the sample was higher than the expectations and almost twice the design estimates (Bordass, et al., 2001 a). The PROBE occupant surveys also pointed to downward trends in thermal comfort, acoustic performance, perceived control, and the misfit between building performance and user expectations in the buildings that were featured as *exemplar designs* (Bordass, et al., 2001 b). Bordass et al. (2004) subsequently coined the phrase *the credibility gap* to refer to the shortcomings in a building's procurement process that lead to an in-use performance worse than expected. While the credibility gap or the performance gap may include various aspects of a building's performance, in practice it is often reported in terms of energy performance or CO_2 emissions associated with the building's energy use.

The performance gap is a very broad concept and very few attempts have been made to define the concept with precision or narrow it down to specific categories. An example is the distinction made by de Wilde (2014) between: (1) predictions derived from first engineering principles and measurements, (2) machine learning techniques and measurements, and (3) predictions and display certificates in legislation.

This dissertation is focused on the methods that are based on first engineering principles and building physics. The regulatory calculations in England, although carried out under standardised operating conditions, are also based on first principles. A detailed classification of the performance gap in the context of first engineering principles could be presented as follows:

- Regulatory performance gap
- Static performance gap
- Dynamic performance gap

2.8.1. Regulatory performance gap

Building performance evaluations carried out on new and refurbished buildings that were supposed to comply with the EPBD requirements often reveal serious shortcomings s. For example, Carbon Trust (2011) reviewed energy performance of 28 case studies from the UK Government's flagship Low Carbon Building Programme and Carbon Trust refurbishments. The projects covered a variety of building types including retail, education, offices and mixed use residential buildings. The review identified shortcomings in construction practices, control strategies, commissioning, building fine-tuning in early stages of post-occupancy, user training, building management and maintenance. It also provided a comparison between the measured energy use and the energy performances derived from EPCs for five buildings in the sample and concluded that 75% of these buildings were performing worse than 'expected'. In the worst case scenario, combination of the issues uncovered led to operational energy use being almost five times higher than 'estimates during design'. While this study points to serious and endemic procurement issues that will no doubt have a knock-on effect on performance, the reference to 'design expectation' or 'design estimates' when what was actually used was the EPC calculations could be misleading if used out of context, as these calculations are not inclusive of all energy end-uses and do not necessarily represent the expected operating conditions. The interchangeable use of the outcomes of Building Regulations compliance calculations, EPC calculations, and design predictions is prevalent in parts of the industry and can cause confusion. An example is the CarbonBuzz platform which is a collaborative research platform that aims to share information about calculated and actual energy use of buildings with a view to narrow the energy performance gap. Figure 2.13 shows the evidence presented in this platform for calculated and actual performance of schools and seasonal buildings. The total performance of the median building in the Actual Spread is almost 50% higher than the median building in the so-called 'Design Spread'. However, it should be noted the statistical samples are not identical and, furthermore, most of the data points included in the 'Design Spread' are based on Building Regulations compliance or EPC calculations.

Scarcity of data related to design predictions is one reason why platforms such as CarbonBuzz rely on compliance or EPC calculations that are more widely available. However, it is necessary to acknowledge the limitations and avoid confusion in a contentious field that comprises various stakeholders with different interests. The opposite side of the claims about factor of five (Carbon Trust, 2011, p. 2) and even factor of ten (CIBSE, 2015 a, p. 45) difference between measured and 'design predictions' is the argument put forward by some designers and contractors who question the notion of the performance gap. de Wilde and Jones (2014, p. 8) report that some practitioners use the term 'perception gap' to stress that the energy performance gap often discussed in the industry is more indicative of communication problems and perceptions of various stakeholders rather than a real gap. Both views represent the extremes in the debate about the performance gap; there is ample evidence about the shortcomings in the design and construction process that will inevitably lead to discrepancies between actual and designed performance. The early findings of the Building Performance Evaluation programme instigated by Innovate UK provide new evidence about endemic problems associated with building fabric, control strategies, commissioning, installed metering strategies and inadequate provision of training to building users as construction projects come to an end and project teams are under immense pressure to complete the building handover and move on to their next projects (Palmer & Armitage, 2014). Therefore, the energy performance gap does exist. However, the existing regulatory framework in the UK and most European countries is not capable of determining the extent of this gap with precision.

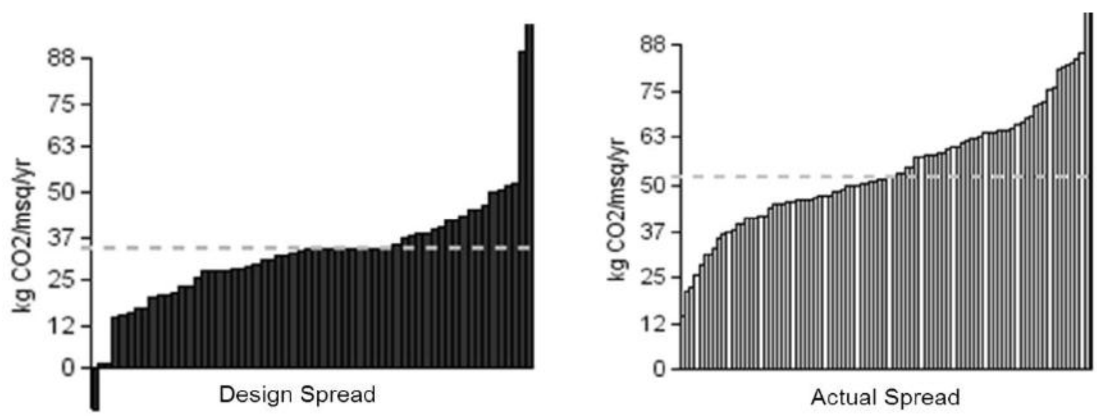


Figure 2.13. Calculated vs. actual performance for schools and seasonal buildings (CarbonBuzz, 2014)

2.8.2. Static performance gap

A more accurate estimation of the discrepancy between actual operation of a building and its potential performance is achievable where the calculated performance includes all energy end-uses and is based on expected operating conditions.

An example of this approach to energy performance is outlined in Appendix G of ASHRAE/IESNA Standard 90.1 (ASHRAE, 2007). This standard describes a method to perform whole-building simulation. The LEED rating system adopted this methodology for new constructions and major renovations (USGBC, 2007). This method requires that energy analysis is done for all energy components within and associated with a building project. As for operating conditions, it is based on using the best estimation for actual operating conditions. Therefore, the simulation outcome of a computer model developed in accordance with this approach is directly comparable with the actual performance.

A study carried out on 121 LEED certified buildings revealed that the measured performance of these buildings display a large degree of scatter, with half the projects deviating more than 25% from available design projections (Figure 2.14). While part of this discrepancy is attributable to uncertainties in operating conditions, the average modelling accuracy for all buildings, expressed as the ratio of measured to design EUI, was 92%. This suggests the whole-building simulation policy based on expected operating conditions can work at macro level (NBI, 2008).

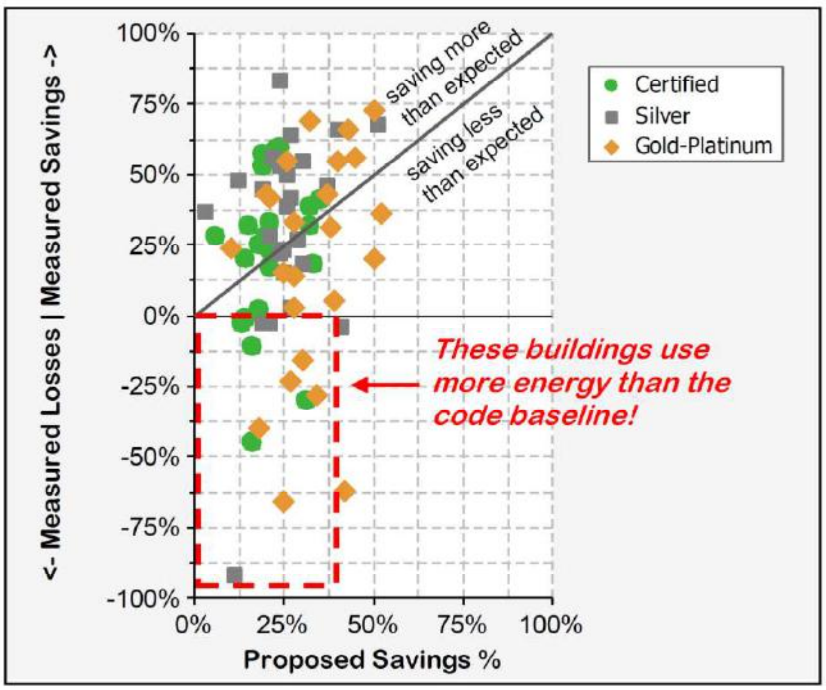


Figure 2.14. Measured vs. predicted energy savings percentages over the baseline in LEED certified buildings (NBI, 2008)

To assess the effect of uncertainties in operating conditions on a building's energy performance, scenario and sensitivity analysis may be used to define ranges rather than deterministic single-point predictions (Lomas & Eppel, 1992), (Macdonald, et al., 1999), (Demanuele, et al., 2010), (Dasgupta, et al., 2012).

In the context of the UK, this type of energy performance calculation was formulated, partly as a response to the on-going debate about the regulatory performance gap, by the introduction of CIBSE TM54 (2013).

It should however be noted that reference to the design stage calculations as a baseline for performance in effect implies a static notion of building performance which is rooted in a misconception of buildings as permanent artefacts (Canter, 1984). What is often reported as energy performance gap is the discrepancy between measured energy performance of a building during a given time period and a reference performance derived from calculations carried out under certain assumptions about the building and its occupants. However, in reality, buildings are complex, evolving and dynamic systems. Longitudinal energy performance from the start of a construction project to the end of a building's operational life is affected by many factors such as changes in client's brief, changes in design, value engineering of final design, construction practices, system installation, commissioning, building occupancy, climatic conditions, deterioration of building fabric and services, maintenance regimes and management policies (de Wilde, et al., 2011). There are different types of performance gaps that vary over time and with building context depending on the point of view of those looking at building performance (de Wilde & Jones, 2014). Energy performance gap must therefore be viewed from a dynamic perspective. A single baseline that represents a specific context that might or might not have been relevant at the time the baseline was derived is not necessarily relevant when the building context is evolved and changed.

2.8.3. Dynamic performance gap

A method to overcome the static notion of the performance gap is to calibrate the original model used for performance calculation to allow for the actual building context. Norfold et al. (1994) closely investigated the performance of an office building with actual energy use of 325 kWh/m²/annum, more than twice the predicted value of 125 kWh/m²/annum. This two-to-one discrepancy is often observed and quoted in new buildings and therefore this study provides useful insights into the differences between the static and dynamic notions of the performance gap. The design stage DOE-2 model was tuned to actual field conditions known from onsite observations or reported by various sensors installed. The authors estimated that 64% of the two-fold increase in energy use could be put down to the unanticipated tenant energy consumption, 24% to HVAC operating schedules and thermostat settings, and 12% to building pathologies including conductive heat loss and air intakes higher than design intent. This type of study provides a realistic view about the shortcomings of building procurement and operational inefficiencies. It can adjust and update the baseline to figure out what is the difference between actual performance and the true potential of a building within the time period chosen for the analysis.

The Carbon Trust (2011) study also acknowledged that, when detailed modelling and benchmarking was done on the buildings in their sample, the performance gap averaged at 16%, significantly lower than headline figures based on regulatory calculations.

Another study on an office building in Denmark found that when the calculations carried out with the Danish calculation engine for the EPBD were updated to allow for actual heating set points and weather data, the discrepancy between measured and calculated space heating was reduced from 74% to 14%. Allowing for the cooling load derived from detailed modelling which was not originally captured by the quasi-steady-state method used for the EPBD calculations also reduced the performance gap in total electricity use from 21% to 12%. The discrepancy between the measured specific fan powers of the mechanical ventilation system and the design figures was the main root cause for the electrical performance gap after adjustment (Petersen & Hviid, 2012).

A review of 18 buildings subject to LEED Canada certification found that, in aggregate, the design stage models used for LEED certification underestimated total measured energy performance by 36%. However, once simple calibration steps such as correction for weather data and revising the appliances loads based on sub-metered data were followed, the net error was reduced to 7%. A better measure to assess the gap to make sure errors do not cancel out each other is the Coefficient of Variation of the Root Mean Square Error (CVRMSE). In this study, for the monthly Energy Use Intensity (EUI) the CVRMSE was improved from 45% to 24% after calibration (Samuelson, et al., 2014). Figure 2.15 shows that in most cases the calibration process reduced the extent of the gap. This might be a reflection of design optimism in projecting the operating conditions to get more energy related LEED credits.

These studies take a rather liberal approach to calibration based on whatever data available which could be called partial-calibration. Partial-calibration can be defined as the process of bringing the energy model inputs closer to actual operating conditions as opposed to achieving specific calibration criteria (Samuelson, et al., 2014).

There are more formal calibration protocols that set out specific calibration criteria. These protocols are often used in energy efficiency finance projects to estimate the effects of various energy efficiency measures with a computer model of an existing building. They can also be used to measure the energy performance gap in performance contracts.

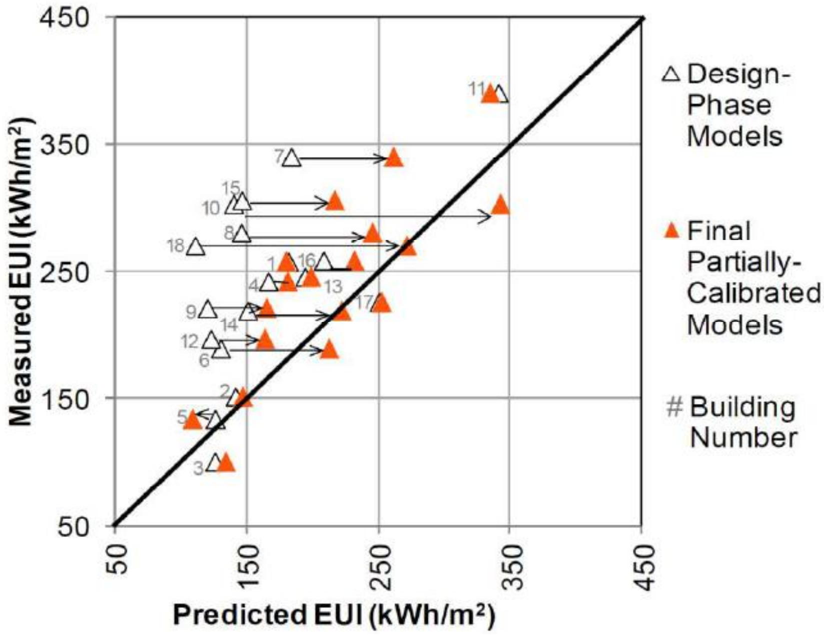


Figure 2.15. Measured vs. predicted Energy Use Intensity of buildings subject to LEED certification before and after partial-calibration (Samuelson, et al., 2014)

The mainstream building simulation calibration protocols used in the industry are ASHRAE Guideline 14 (2002), which underpins the calibration method used in the International Performance Measurement and Verification Protocol (IPMVP) (EVO, 2012), and the measurement and verification protocol developed by the US DOE for the Federal Energy Management Program (FEMP) (DOE, 2008). Mean Bias Error (MBE) and Coefficient of Variation of Root Mean Square Error (CVRMSE) are often used to define criteria for hourly or monthly calibration of energy models.

BS EN 15603 also includes a procedure for validation of the building calculation models (BSI, 2008, pp. 32-34). The aim of this procedure is to gain higher confidence in a building calculation model by comparing the outcomes with actual energy consumption data, and ensure there is *reasonable consistency* between calculated and measured energy performance. No specific criteria are provided in the standard to define reasonable consistency and, therefore, this should be determined on a case-by-case basis. This procedure includes an uncertainty analysis based on confidence intervals of input data and energy performance. Under this procedure, validation is carried out based on annual energy performance. This might be deemed sufficient for validating energy ratings produced in building certification schemes. However, unless special attention is paid to trends of energy use (e.g. day vs. night energy use, and seasonal variations), relying on annual calibration alone is often not sufficient to predict energy behaviour of a property (EVO, 2012, p. 29). Most researchers use hourly, daily or monthly calibration methods to ensure higher consistency between modelled and measured data for energy saving projects (Haberl & Bou-Saada, 1998), (Ahmad & Culp, 2006), (Raftery, et al., 2011)

Finally, it should be noted that while it is important to address building pathologies that cause the performance gap, engaging occupants in post-occupancy evaluation makes it possible to achieve further energy savings. Sensitivity analysis on various types of buildings has shown that occupancy behavioural parameters significantly influence energy use in non-domestic sector and vary according to building size and climate (Azar & Menassa, 2012), (Dasgupta, et al., 2012). Furthermore, the effect of occupant behaviour can outweigh the expected variations in technical performance of building services for a given installation (Dasgupta, et al., 2012). The effects of human behaviour on building energy performance will become even more pertinent when energy performance requirements become more stringent as in the EPBD recast provision for nearly zero-energy buildings (Economidou, 2012). A study that combined calibrated dynamic simulation with post-occupancy evaluation and user engagement on a building that was built in 2001 reported an average monthly overall saving of 20.5% for heating, cooling, lighting, auxiliary energy, and electric equipment as a result of identifying and implementing zero or low-cost energy saving measures with the aid of simulation (Pisello, et al., 2012).

2.8.4. Root causes of the energy performance gap

There are various underlying root causes for the performance gap depending on the definition used. Table 2.8 provides an overview of the most important factors covered in the literature which currently is predominantly based on a static notion of the performance gap. A dynamic approach would be able to address some of these issues throughout the calibration process.

Table 2.8. Root causes of the energy performance gap

Stage	Typical root causes of the energy performance gap
Design	• Energy targets: energy may be poorly specified in briefing and design criteria (Bordass, et al., 2001 a). For example, energy targets may be set out to satisfy the Building Regulations requirements only or to claim a number of credits in a sustainability rating system such as BREEAM without due attention to total energy performance. • Design issues: PROBE studies identified recurring design issues that may cause unnecessary energy use in practice. An example is using centralised plant to satisfy 24-hour server room load (Bordass, et al., 2001 a). Another example of design issues is the failure to specify the correct control strategy for the interface between LZC systems and their back-ups which can compromise the contribution of LZC systems (CIBSE, 2014). • Assessment method: there are a range of energy performance assessment methods that could be used at design stages. One classification is steady-state against dynamic simulation. Within each category both forward modelling (e.g. deterministic) and inverse modelling (e.g. regression analysis) could be used (Wang, et al., 2012). The choice of the assessment method will have an impact on the accuracy of the baseline. • Modelling errors: energy performance predictions are prone to modelling errors. Ahmad and Culp (2006) demonstrated the uncertainty associated with un-calibrated simulations with discrepancies higher than ±30% between the simulated and measured total annual energy use and higher than ±90% between the simulated and measured energy use of individual end-uses when a research engineer carried out simulations on four sample buildings using DOE software after surveying the buildings. Furthermore, the simulations were carried out at two levels of input data and it was found that added effort to capture more data from the buildings had not improved the accuracy of the predictions. The authors conclude that un-calibrated simulation in not reliable for predicting energy performance and relevant financial decisions. However, it could be useful to analyse the trade-offs between various design scenarios. • Software variability: The choice of software can cause uncertainty in calculating energy performance. Raslan and Davies (2009) demonstrated the uncertainty and variability of thermal modelling when one researcher used various approved software packages to calculate the regulatory energy performance of typical UK non-domestic buildings with significant variations. Tronchin and Fabbri (2010) categorised the non-homogeneities caused by data input methods used by various tools for the EPBD calculations in Italy: geometrical non-homogeneity (can cause a deviance of ±7-30%), thermo-physical non-homogeneity, and heating plant and generator non-homogeneity (can cause a deviance of ±13-30%). Earlier work by (Neymark, et al., 2002) used the Building Energy Simulation Test (BESTEST) diagnostic method to test various whole-building energy simulation software packages from Europe and the US. This study showed that in extreme cases coding errors and faulty algorithms could cause errors of up to 20-45% in predicting energy consumption or coefficients of performance. • User variability: in addition to potential internal errors in the modelling tools, the users can also cause external errors that contribute to the performance gap. A study involved 12 participants using a simulation programme to predict annual energy consumption of a house. The predictions varied from -41% to 39% of the average value (Guyon, 1997). Guyon found a lot of errors in the modelling of thermal bridges and windows and participants' use of the thermal regulations to calculate the respective properties. This is indicative of the intertwined nature of user variability and software limitations.

Construction	Poor construction practices can compromise energy performance. PROBE studies identified poor airtightness and gaps in building fabric insulation particularly at eaves, at junctions, around window and door frames, and between light and heavy weight cladding in most buildings in the sample (Bordass, et al., 2001 b). Thermal imaging also uncovered similar problems with thermal bridging in Building Performance Evaluation programme (Palmer & Armitage, 2014). An investigation on three new-build terraced houses in the UK found that, even at the centre of the insulated external walls, measured U values were 70-85% higher than the design intent. In the extreme case, the cavity walls of a house were not filled with insulation; co-heating test revealed that the measured heat loss coefficient in this house was more than twice the predicted heat loss. Several pressure tests carried out during the post-occupancy studies also revealed that the air permeabilities of the houses were higher than the design specification and around 50% higher than the air permeabilities reported by the regulatory tests on completion. The likely root cause given for this increase in air permeability was the rapid deterioration of the sealing measures (Wingfield , et al., 2013). The procurement and installation of the building services may also contribute to the performance gap. For example, measured specific fan powers are often higher than design intent (Petersen & Hviid, 2012). This could be related to deviations in ductwork installation and the specification of the final installations that induce pressure drops higher than the design estimates. Change orders and value engineering can also compromise the initial design and lead to system installations that are not fully consistent with the design intent (Bordass, et al., 2004). These deviations from the initial design are often not reflected in the energy model.
Commissioning	Project delays, budget and time constraints before completion mean that pre-handover commissioning is often very basic and in particular does not fully address the complexities of the new technologies (BSRIA, 2009). Seasonal or enhanced commissioning, on the other hand, are not always attempted unless the respective credits in sustainability rating systems such as BREEAM and LEED are targeted or the project is subject to Soft Landings. Poor building services installation and commissioning skills are among the key issues that need to be addressed to narrow the performance gap (ZCH, 2014). For example, poor commissioning of automated natural ventilation and mechanical ventilation systems is a major issue in the UK construction industry (Bordass, et al., 2001 b), ((Wingfield , et al., 2013), (ZCH, 2014).
Handover	Provision of information to building users is a key requirement in the Building Regulations (HM Government, 2013). In practice, the people who are present at handover are not necessarily the users of the building and the building log books prepared to provide users with required information may miss crucial information (Palmer & Armitage, 2014). Effective training of building users and in particular facility managers, who have control over central plant equipment, is crucial to narrow the performance gap (Carbon Trust, 2011).
Operation	Buildings are very often not fine-tuned beyond the point of handover and there is no effective measurement and verification plan for performance in-use. Facility managers and building users are key to achieve good level of performance and yet, as designers and contractors are often not involved at the early stages of post-occupancy, it is likely that design intents are not well understood and building performance is compromised (BSRIA, 2009). The control settings of thermostats and the BMS settings may differ from the design assumptions, and energy baselines must be updated to allow for contextual factors such as occupant behaviour and weather conditions which very rarely happens (de Wilde & Jones, 2014).

2.9. Summary

Climate change is a serious challenge and a threat to the future of mankind that needs to be addressed. The evidence suggests improving energy efficiency of buildings is one of the most cost-effective ways of reducing anthropogenic CO_2 emissions that contribute to climate change. However, unless improvements in energy efficiency are complemented by fiscal measures that keep the relative cost of energy unchanged or higher, they may not be as effective as expected or, paradoxically, even lead to higher overall energy consumption. An overview of the energy policies followed in the developed countries that are most able to afford higher energy prices showed, apart from some notable exceptions such as Sweden, there is currently no political appetite to go as far as required to reflect the true social cost of carbon in energy prices and taxation.

The review of the Energy Performance of Buildings Directive and its implementation in England also revealed that, when it comes to whole-building energy performance, the Directive is overwhelmingly focused on theoretical analysis of performance with no mandatory requirement for measurement and verification of performance in-use.

The fiscal and technical policy setup is therefore not as effective as required. This problem in practice is exacerbated by issues such as non-compliance with the regulatory requirements and skill shortage in the construction supply chains which cause major underperformances in most new building and refurbishment projects as identified by several post-occupancy evaluations. Given the significance of building stock in the context of energy efficiency policy, it is not surprising that the preliminary evidence suggests the EU might miss its 20% energy saving target by 2020 by a wide margin (Wesselink, et al., 2010, p. 4).

The literature review also points to a lack of consensus about the definition of the performance gap that stems from the inadequacies of the regulatory calculations in deriving appropriate baselines for total performance, and also a static notion of the performance gap that does not take into account the longitudinal changes in building context.

The following specific findings from the literature review have had a major impact on the development of this thesis:

1) Further post-occupancy evaluations are required to provide better understanding of the root causes of the performance gap. As the concept of the performance gap fundamentally entails a comparison between the measured and the expected performance, a feedback-oriented process model for Building Performance Evaluation such as the once suggested by Preiser and Vischer (2005) would be most suitable. An integrated approach to energy performance, indoor environmental quality, and user

satisfaction is also required to ensure the pursuit of energy efficiency has not compromised other performance objectives.

2) A robust measurement and verification framework is required to establish energy performance gap with reasonable accuracy and help narrow this gap. This framework must be able to allow for the building context and perform a like-for-like comparison between the measured performance and the performance baseline derived from energy performance simulation.

3. Methodology

3.1. Introduction

This Chapter reviews the research approach and the methods used throughout the EngD programme. One of the findings of the previous Chapters was the necessity for in depth investigations on a number of buildings (cases) to gain a better understanding of the nature of the performance gap and its root causes. An introduction to the case study approach is presented and the research proposition is framed in such a way to avoid the common pitfalls of this approach. Next, a process view of the research programme is presented. The rest of the Chapter provides a detailed account of the various methods used to achieve the aim and objectives of the research programme.

3.2. Case study approach

The case study approach is used in various disciplines to investigate a subject or phenomenon in depth within its contextual conditions. Robert Yin provides a twofold definition for the case study approach as a research method. This definition is particularly useful in the context of this research programme as it addresses a number of key methodological issues that one may encounter while investigating a building as a *case* or subject of investigation. The first part of the definition deals with the scope of a case study (Yin, 2014, p. 16):

"1. A case study is an empirical inquiry that

- investigates a contemporary phenomenon (the 'case') in depth and within its real-world context, especially when
- the boundaries between phenomenon and context may not be clearly evident."

The emphasis on the 'real-world context' distinguishes the case study approach from other alternative research methods one may follow in investigating building performance. For example, an *experiment* makes a deliberate attempt to separate the phenomenon from its context. An interventionist building performance evaluation might focus on few variables and control the rest of the variables to ascertain the performance of a building component under certain *controlled* conditions. While this method might be used among other methods deployed in a case study research, the case study approach essentially goes beyond this and takes into account the real context. In practical terms, the buildings investigated in this research programme were all operational with very limited scope for controlled experiments. The findings of the investigations therefore had to be placed and understood within the wider context that went beyond building physics and entailed characteristics such as building occupancy, pedagogical requirements, and management practices. This leads to the second part of the definition for the case study approach (Yin, 2014, p. 17):

"A case study inquiry

- copes with the technically distinctive situation in which there will be many more variables of interest than data points, and as one result
- relies on multiple sources of evidence, with data needing to converge in a triangulating fashion, and as another result
- benefits from prior development of theoretical propositions to guide data collection and analysis."

Triangulation is particularly important in case of building performance evaluations where sources of evidence include both physical measurements and subjective views expressed by occupants and other stakeholders including building designers, contractors, owners, etc.

A case study usually involves large amount of data collected over a sustained period of time (Creswell, 2012). This level of contextualised data and information can raise a number of concerns about the effectiveness of case study as a research approach (Yin, 2014). Two major concerns that must be particularly addressed in building performance evaluation are as follows:

- **Lack of academic rigour:** unless a structured programme of research with clear aim and objectives is undertaken, the case study approach is prone to lack of enough rigour. In case of building performance evaluation, the number of variables involved, multiple sources of evidence, the amount of data available, and the subjective views of various stakeholders, not to mention the particular interests of the researchers if they are not completely impartial, can easily influence the direction of research and its conclusions.
- **False generalisation:** As it is often very difficult to distinguish between the phenomenon under investigation and its context, generalising the outcomes of a case study research is not straightforward. It is helpful to include multiple case studies to ensure the conclusions are not dependent on a specific context and, thereby, avoid particularisation. However, case study research is a close-up and in-depth investigation by definition and this means the number of cases would often be limited. Therefore, a precise statistical generalisation would not be possible and must be avoided in case study research. One can instead try to expand and generalise theories based on case study findings. The distinction between *statistical generalisation* and *analytic generalisation* formulated by Yin is also endorsed by other researchers albeit

with different terminology such as *logical inference* against *statistical inference* by Mitchell (1983) or *case inference* against *statistical inference* by Bromley (1986).

One can see the combined threat of these potential risks; a non-structured and non-rigorous case study research in the absence of robust statistical evidence may lead to the wrong analytic generalisation. It is therefore important to draw up a robust and structured plan for research. Furthermore, it would be necessary to critically examine the internal validity of the theory derived from analytic generalisation considering all evidence. The external validity of the theory must also be checked by referring to other similar research carried out in the field. Statistical generalisation achieved as a result of a separate sampling programme could also be used to support the theory. However, the limitations associated with the data and information available from sampling often means that the theory could not have been derived merely from the sampling programme.

Finally, it is important to acknowledge that no researcher starts with a *clean slate* while trying to address a research question. A researcher starts by an initial theoretical proposition that will no doubt influence the direction of research. It is, however, necessary to ensure this theoretical proposition is modified, revised or rejected and replaced with another proposition according to the evidence obtained throughout the research. New evidence may lead to a new theoretical proposition that also requires modifications in the direction of research. This evolutionary approach to the growth of knowledge is best formulated by Karl Popper in philosophy of science (Simonton, 1999, p. 26):

"…the growth of our knowledge is the result of a process closely resembling what Darwin called 'natural selection'; that is, the *natural selection of hypotheses*: our knowledge consists, at every moment, of those hypotheses which have shown their (comparative) fitness by surviving so far in their struggle for existence."

It is therefore reasonable to start by postulating an initial theory that has guided the research. A rival theory could also be proposed to give indication of the different implications these theories would have on policy making. The outcome of the research is not necessarily meant to be in favour of the theory. To the contrary, and following Karl Popper's falsification principle (Popper, 1992), once the initial theory is acknowledged the evidence must be carefully examined to question and falsify the theory. The theory is only viable if it sustains this process. The case study approach is susceptible to confirmation bias as it often provides various and often conflicting pieces of evidence from different sources. The falsification principle could act as an effective remedy to protect the research from this bias.

Figure 3.1 provides a diagram that summarises the discussions about the case study approach presented here and the difference between analytic and statistical generalisations.

This research programme is based on case study approach. The buildings investigated are not *sampling* units so far as the research programme is concerned although the evidence collated from the buildings would feed in other sampling and benchmarking programmes. A complementary research programme focused on sampling and benchmarking was followed at the Bartlett that has informed this research programme. Reference was made to the outcome of this statistical approach in Chapter 1 and further references will be made throughout this dissertation. However, this dissertation will predominantly present the evidence collated from the case studies that will lead to analytic generalisations that may support, modify, or falsify the following **initial theory**:

The current regulatory framework for energy performance of new buildings and major renovations is not fit for delivering the energy performance improvements required in buildings. It may also have unintended consequences for wider environmental performance of buildings. It is essential to extend the regulatory requirements related to energy beyond the point of building handover and use an appropriate measurement and verification framework to verify the performance in-use in reference to the regulatory requirements.

Based on the literature review presented in the previous Chapter, one may question the comparisons often made between actual building energy performance and the so-called 'predicted' performance where what is being used as predicted performance is the outcome of the Building Regulations compliance calculations or energy performance certificates. These are not like-for-like comparisons and, hence, do not necessarily point to serious shortcoming in the existing regulatory framework. Perceived shortcomings in energy performance of new buildings and major renovations against existing building stock, identified through statistical benchmarking, must also be further examined as building contexts are different.

A **rival theory** can therefore be postulated as follows:

Anecdotal evidence gathered from various post-occupancy evaluations points to shortcomings in building procurement. However, the effect of these shortcomings on whole-building performance is not quite clear yet. There is no doubt that some benefits could be gained in building performance by extending the regulatory requirements beyond the point of handover. However, any such benefits must be balanced against the associated costs. There is not yet enough evidence to warrant major changes in regulatory requirements. Therefore, the policy default option must be to keep the regulations to minimum and do not change the status quo *other than the incremental changes that are being introduced in successive revisions of the Building Regulations.*

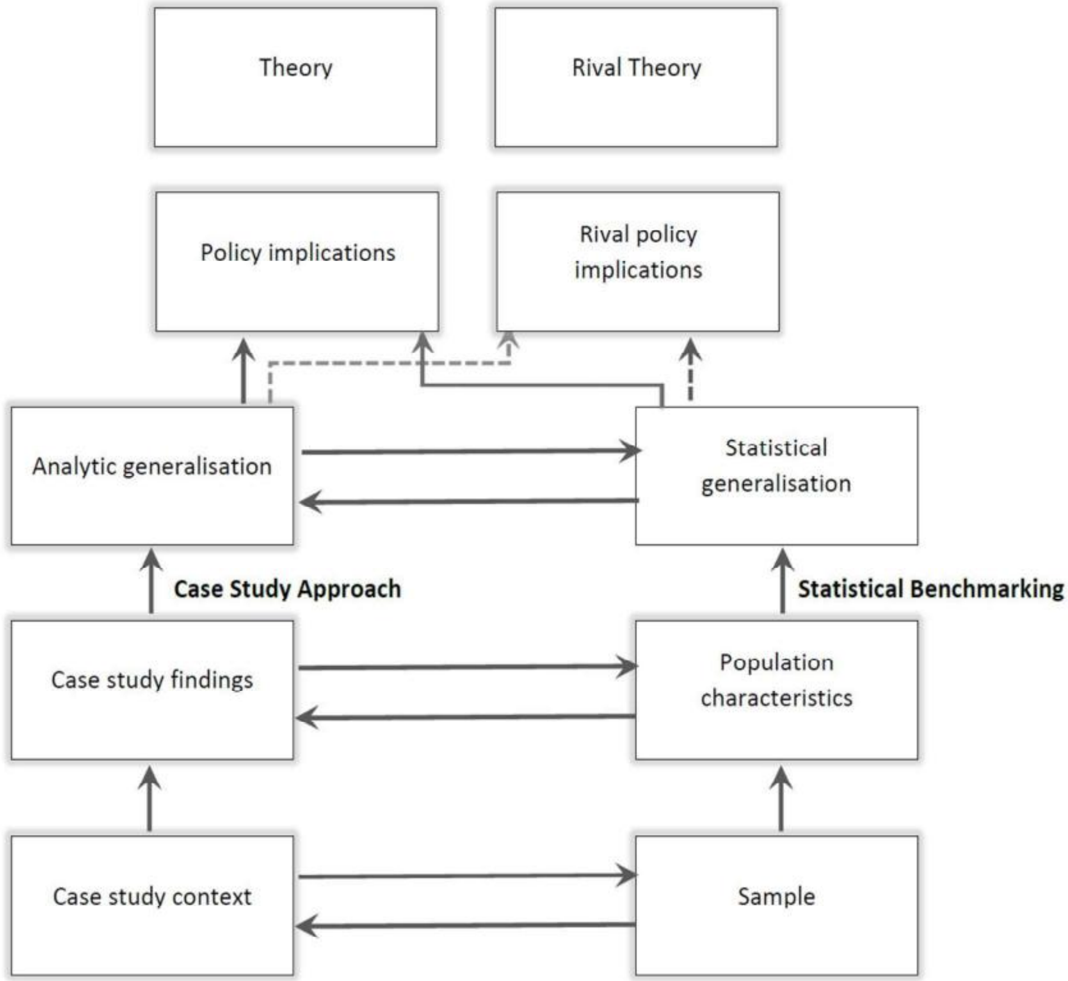


Figure 3.1. Case Study Approach vs. Statistical Benchmarking

3.3. Process view of the research programme

Figure 3.2 illustrates a process view of the research programme. A brief description of various steps is provided following the Figure.

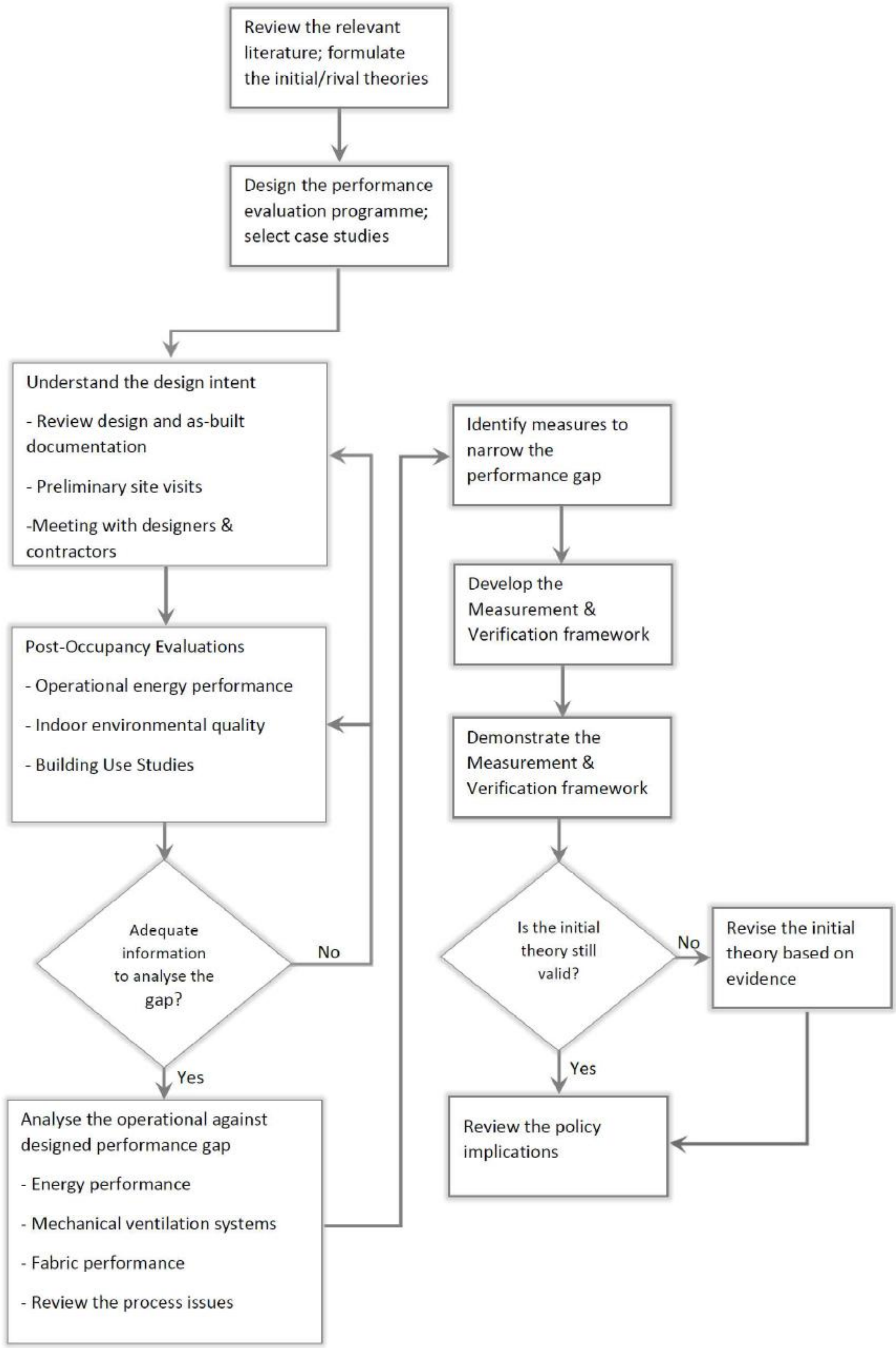


Figure 3.2. Process view of the research programme

- The first step was to review the relevant literature and formulate the initial and rival theories.
- Next step was to design the building performance evaluations and select the case studies. Five schools designed by the architectural practice that supported the Engineering Doctorate programme were selected for research. Apart from availability of buildings for post-occupancy evaluation, the case studies were carefully selected from the available pool of buildings to meet the following criteria:
  - Cover distinct climatic regions in England: 3 regions were covered by the case studies (Thames Valley, West Pennines, and North East),
  - Different management structures and phases of secondary education: secondary schools, academies, and Sixth Form education,
  - Different procurement routes: Design and Build and Traditional procurement routes were covered.

  The aim was to enable analytic generalisation expected from the case study approach without limiting the findings to a specific context.
- Next, a detailed review of the design and as-built documentations for the five case studies was carried out. Preliminary site visits were also planned to gain the first insights into buildings' operation and to brief the schools' heads, facility managers and other key staff about the aim and objectives of the building performance evaluations. All schools were supportive of the study and granted access to their buildings for the purpose of post-occupancy evaluations. Where possible, meetings were planned with the construction teams to have a better understanding of the design intents and construction practices. The architects of the buildings and one of the building services designers were supportive of the study and engaged with it from the outset. A number of building services designers and contractors also got involved as the project progressed and provided useful feedback about the root causes of the performance gap.
- The post-occupancy evaluations were focused on operational energy performance, the indoor environmental quality and Building Use Studies (BUS). Those aspects of the indoor environmental quality that were strongly interrelated with energy were identified and directly measured. Building Use Studies were used to gauge building users' satisfaction and provide feedback about those aspects of building performance that were less tangible and not directly measured.
- Next step was to compare the findings of the post-occupancy evaluations with the design intents using all available evidence including the documentation, the outcomes of building investigations, and meeting and workshops with the construction teams. Energy performance, performance of mechanical ventilation systems, and fabric performance

were specifically reviewed in reference to the design intents. The evolution of fundamental design strategies from the concept to operation was reviewed for every stage of the construction process to gain a better understanding of the underlying root causes of any shortcoming in building performance.

- The findings of the building performance evaluations were used to outline a number of measures that can help narrow the performance gap between actual performance and design expectation in the future projects. The focus here was on endemic problems and recurring themes emerging from the case studies rather than specific issues that were context dependent and limited to one building.
- Data and information available from the building performance evaluations were used to examine how the energy performance gap could be defined and measured accurately. A measurement and verification framework was also formulated to address the performance gap.
- The measurement and verification framework was demonstrated in the worst performing case study for which detailed design information was available. Two separate protocols were tested to verify the measured performance in reference to the regulatory calculations using dynamic building energy performance simulation.
- Finally, the policy implications of the building performance evaluations and the proposed measurement and verification framework were reviewed in reference to the initial theory presented in this Chapter. The evidence from the investigations was used to challenge and modify the initial theory to make measurement and verification of performance in-use applicable in the context of the current Building Regulations and construction practices.

The rest of this Chapter provides a detailed account of the methods used for *post-occupancy evaluations*, *operational against designed performance analysis*, and *measurement and verification*.

3.4. Post-occupancy evaluations

3.4.1. Operational energy performance

Metering systems installed for new buildings should be able to assign at least 90% of the estimated annual energy consumption of each fuel to various end-use categories. (HM Government, 2006). All case studies were completed after 2006 and therefore had advanced metering strategies, although not all installed sub-meters were functional and automatic data reading facilities were not always reliable. A number of sub-meters were fixed and re-commissioned for the purpose of this research. The schools were all occupied and had reached steady operation before the measurements commenced. The data from all main meters and sub-meters were collated manually during regular site visits from the main distribution boards (low voltage panels), sub-main distribution boards in the cupboards, and plantroom meters to avoid any possible inaccuracy in pulse meter readings from the BMS. Typically, one visit per month was planned for each building for one year to establish energy performance, with fewer site visits afterwards to fill the gaps and carry out other investigations. A meter reconciliation exercise was done for each building in accordance with CIBSE TM39 (2009) to ensure data collated from sub-meters add up to what was reported by main meters for each fuel. The detailed assessment method of CIBSE TM22 (2006) was also used to check the accuracy of individual electrical sub-meters following a bottom-up calculation and also fill in any gap caused by malfunctioning sub-meters. The basis of the TM22 detailed assessment method is to estimate energy use of all electrical end-uses by identifying and calculating their contributing factors. Figure 3.3 illustrates this methodology for lighting and ventilation systems.

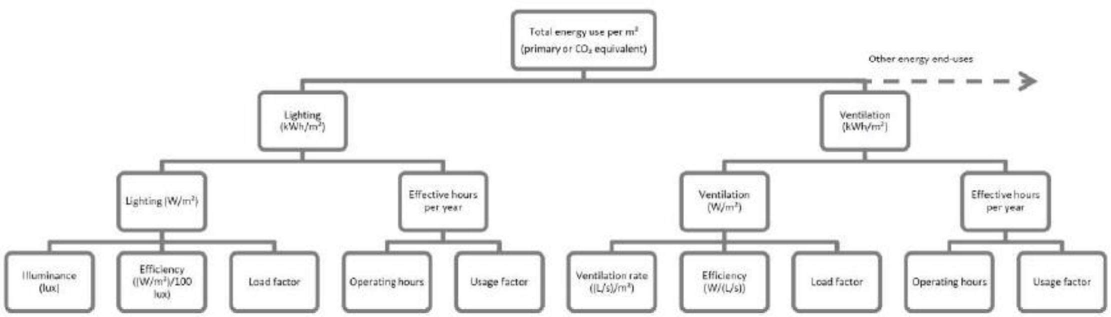


Figure 3.3. Illustration of TM22 bottom-up calculation method adapted from Field et al. (1997) and tailored based on the latest tool developed for Innovate UK TSB programme

The half-hourly electrical power demand and energy use data during the measurement period were sourced for all case studies from the utility suppliers. First, the bottom-up TM22 calculations for night-time operation were compared against the baseline power reported for each building. The baseline power generally includes the followings:

- Server room and data hub rooms and associated cooling loads
- Loads related to security systems such as closed-circuit televisions and security lights
- Standby small power loads
- Loads related to HVAC control (e.g. standby loads of mechanical control panels)
- External lights
- Loads associated with poorly controlled plantrooms and internal lighting

Once the bottom up calculations were reconciled with the baseline powers reported for the buildings, the calculations were followed for daytime operation and the resulting peak loads were compared against half-hourly data. This method helps to achieve reconciliation between bottom-up calculations and measured energy with consistent baseline and peak powers.

Observational studies and measurements were used to calculate the contributing factors related to ‘load’ and ‘usage’ for each end-use. An example of calculating the usage factor for demand-controlled mechanical ventilation systems is presented in 3.5.2.

Table 3.1 provides a summary of the condition of the installed metering in the case studies and the electrical components that were not sub-metered directly and therefore had to be estimated following a bottom-up calculation. As for non-electrical end-uses, degree-day analysis was used in two buildings to estimate domestic hot water use.

An example of degree-day analysis based on monthly gas meter readings and the corresponding heating degree-days is presented in Figure 3.4. The intercept between the trend line and Y axis represents the non-heating component of gas consumption at zero heating degree-day (i.e. 1.6 $kWh/m^2/month$). This could be used to deduce the domestic hot water use ‘by difference’ when the gas consumption related to other non-heating uses is sub-metered as was the case for catering gas in all case studies.

Table 3.1. Review of the installed metering in the case studies and the estimations made following TM22 bottom-up calculation method for electricity and degree-day analysis for gas

Energy component	Covered by metering	Estimated by calculation
Total natural gas	Metered in all buildings with accurate turbine-type meters; monthly bills also available for at least one year based on meter reading	Gas sub-meters/end-uses were reconciled with total natural gas use. The uncertainty of the meter reconciliation in all case studies was lower than 5%.
Total electricity	Metered in all buildings; monthly bills also available for at least one year; half-hourly electrical demand and electricity use available for all buildings	Electricity sub-meters/end-uses were reconciled with total electricity use. The uncertainty of the meter reconciliation in all case studies was lower than 5%.
Heating	Sub-metered in three buildings	Estimated by degree-day analysis in two buildings
Domestic hot water	Sub-metered in three buildings	Estimated by degree-day analysis in two buildings
Cooling	Metering installed in one building for chillers but not operational	Estimated by bottom-up analysis using installed capacity and running hours
Auxiliary energy (pumps and fans)	Pumps were sub-metered in all buildings; supply and extract fans sub-metered in four buildings	Bottom-up analysis for fan energy use was used in one building based on the measured specific fan power at the commissioning stage and the schedule of operation set for the air handling units (interrogated from the BMS).
Lighting	Sub-metered in all buildings; a number of panel boards were not sub-metered in one building	Lighting energy related to the panel boards not sub-metered was estimated based on the installed lighting density (W/m²), and average operation hours worked out by observational studies; the circuit ballast loss was calculated based on the available sub-metered data.
ICT infrastructure (server rooms and data hub rooms)	Server rooms and most data hub rooms were sub-metered	Energy use of data hub rooms not sub-metered was estimated based on night time electrical demand of the building and reconciled with the power reported on the display unit of the data hub room equipment.
Electrical appliances	Total small power sub-metered in all buildings	Plug meters were used to estimate energy use of equipment such as computers and lab equipment in bottom-up analysis.
Catering equipment	Sub-metered in all buildings	Not applicable

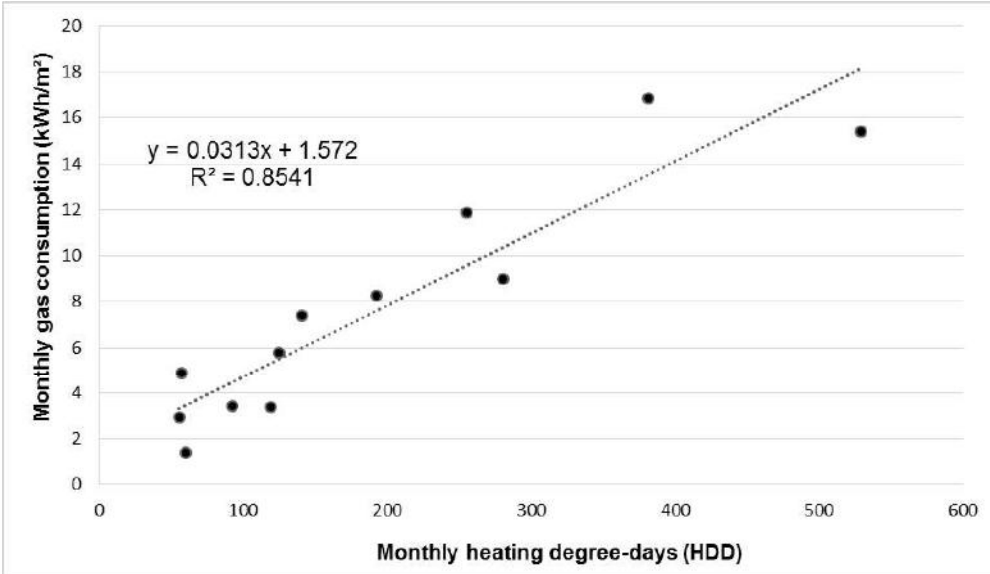


Figure 3.4. Degree-day analysis to estimate the non-heating component of gas consumption

In all case studies, the aggregate of energy end-uses directly sub-metered or estimated by TM22 / degree-day analysis was within 5% of the energy reported by the main meter for both natural gas and electricity.

The energy performances of the case studies were compared to the existing benchmarks for schools. A review of the performance of all energy end-uses in the case studies was also carried out with special focus on new trends observed in schools, building context, and operational issues leading to underperformance.

3.4.2. Indoor environmental quality

Table 3.2 explains the relevance of various aspects of the indoor environmental quality to energy performance and the potential conflicts. Table 3.3 provides major requirements set out for the indoor environmental quality of schools at the time the case studies were constructed. The actual environmental performance of the case studies can be compared against these criteria.

It should be noted that some of these criteria have been revised since the case studies were constructed and are not used for new buildings. For example, assessment of overheating risk for free running buildings now follows the adaptive thermal comfort theory and is carried out in accordance with CIBSE TM52 (2013). However, following the Preiser and Vischer (2005) framework for Building Performance Evaluations, in this dissertation actual performance of the case studies is compared against the design criteria prevalent at the time the buildings were constructed. Where appropriate, attention is drawn to the changes in design criteria and their implications for buildings' performance in the next Chapters.

An assessment of the critical factors affecting energy performance in-use led to a selection of parameters for monitoring listed in Table 3.4.

Table 3.2. Potential conflicts between the indoor environmental quality and energy use

Environmental condition	Conflicts with energy performance
Thermal comfort	Indoor thermal conditions expected by building occupants are critical for energy performance. High temperature set points in winter and low cooling set points where air condition is installed can compromise energy performance. There is also a risk of conflict between the operation of heating and cooling systems if an effective dead-band between the respective set points is not specified. On the other hand, it is important to verify the installed building services are capable of providing acceptable level of thermal comfort.
Indoor air quality	Achieving the acceptable level of indoor air quality has a direct impact on the choice and the management of the ventilation system and therefore is closely related to energy performance. It is also important to verify the installed building services and strategies are capable of providing and maintaining acceptable indoor air quality.
Acoustics	Protecting indoor environment from excessive ambient noise levels may trigger mechanical ventilation which is a major risk factor for energy performance if not managed well. On the other hand, using thermal mass as a passive measure to moderate indoor temperatures may lead to excessive reverberation in the absence of acoustic absorption rafts. Therefore, assessment of internal noise and reverberation times is closely linked to the assessment of ventilation strategy, thermal comfort, and energy performance.
Lighting	Lighting control is critical to save electricity. Daylight factor is a measure of how day lit a space is. Zones close to natural day light should have separate manual and automated lighting control to help save energy. Zoning of lighting sensors, sensitivity of daylight sensors, and sensitivity and time offs of presence/absence detection sensors have an impact on energy performance.

Table 3.3. Major indoor environmental design criteria applicable to the case studies

Environmental condition		Requirement	Source
Overheating criteria		To demonstrate the proposed school designs will not suffer from overheating, two out of the following three criteria must have been met when using CIBSE Test Reference Year weather files: • Air temperature in the classrooms should not be above 28 °C for more than 120 hours. • The difference between internal air temperature and external air temperature should not exceed 5°C. • The internal air temperature when the space is occupied should not be higher than 32° C.	Building Bulletin 101 (DfES, 2006)
Indoor air quality		• The average concentration of CO_2 should not exceed 1500 ppm during the teaching day. • Maximum concentration of CO_2 should not exceed 5000 ppm. • At any occupied time, the occupants should be able to reduce CO_2 concentration to 1000 ppm.	Building Bulletin 101 (DfES, 2006)
Ventilation		• All occupied areas shall have controllable ventilation at a minimum rate of 3 l/s/person. • Teaching and learning spaces shall be capable of being ventilated at a minimum rate of 8 l/s/person.	Building Bulletin 101 (DfES, 2006)
Acoustics	**Noise levels**	The indoor ambient noise levels includes noise from external sources and building services; the indoor ambient noise level in class rooms and general teaching areas shall not exceed 35 dB L_{Aeq},30min.	Building Bulletin 93 (DfES, 2003)
	Reverberation	The acoustic design should provide suitable reverberation time. In secondary schools, the mid-frequency reverberation time in unoccupied rooms should be less than 0.8 seconds. The mid-frequency reverberation time is the arithmetic average of the reverberation times in 500 Hz, 1000 Hz, and 2000 Hz octave bands.	Building Bulletin 93 (DfES, 2003)
Lighting		The minimum maintained illuminance level in teaching spaces must be 300 lux (CIBSE, 2011). Minimum daylight factor of 2% in 80% of occupied spaces was also specified in the case studies to get one BREEAM credit.	Lighting Guide SLL LG5 (CIBSE, 2011)

Table 3.4. Monitoring parameters and conditions for indoor environmental quality

Environmental condition monitored	Equipment used	Measurement uncertainty	Measurement frequency, duration and sampling	Measurement standard
air temperature (ºC)	U12 HOBO Data Logger	± 0.35 ºC from 0 ºC to 50 ºC	Every 10 minutes, minimum one year, various classrooms	BS EN ISO 7726 (BSI, 2001)
Dry bulb, wet bulb, and globe temperatures (ºC)	Thermal environment monitor (QUESTempº 36)	± 0.5 ºC from 0 ºC to 100 ºC	Every one minute, one day per classroom, three classrooms per building	BS EN ISO 7726 (BSI, 2001)
Relative humidity (%)	Thermal environment monitor (QUESTempº 36)	± 5%	Every one minute, one day per classroom, three classrooms per building	BS EN ISO 7726 (BSI, 2001)
Air speed (m/s)	Thermal environment monitor (QUESTempº 36)	±(0.1 m/s + 4%) of measurement value	Every one minute, one day per classroom, three classrooms per building	BS EN ISO 7726 (BSI, 2001)
CO_2 concentration (ppm)	Indoor quality monitor (AQ5000 Pro)	±3% of reading ±50 ppm within the range of 0 to 5000 ppm	Every one minute, one day per classroom, three classrooms per building	BS EN 15251 (BSI, 2007)
Ambient noise level (dB)	SoundPro DL Class 2 with QE7052 microphone	±2 dB frequency response within the range of 20 Hz to 17 kHz	Measured in at least two classrooms per building, noise levels averaged over 30 minutes time period under steady conditions.	BS EN ISO 3382-2 (BSI, 2008)
Reverberation time (s)	SoundPro DL Class 2 with QE7052 microphone	Depends on the uncertainty in measurement of noise levels; repeating measurements and spatial averaging were used to minimise the uncertainty.	Impulse method was used to measure the reverberation time in at least two classrooms in each building.	BS EN ISO 3382-2 (BSI, 2008)
Illuminance levels (lux)	U12 HOBO Data Logger (indoor) & Testo 435-2 lighting sensor (outdoor)	1% calibration uncertainty	The probes were used for spot checks of illuminance levels and daylight factors in typical teaching spaces	BS EN 13032-1 (BSI, 2004)

The monitoring was carried out in two modes:

- Air temperatures in a number of classrooms, representing various environmental strategies deployed in each building, were monitored continuously for one year to ascertain annual indoor temperatures and assess the risk of overheating. The recorded temperatures also indicate the set points used by the users and the range of indoor temperatures likely to happen in educational buildings compared to the assumptions made in the computer models. External climatic data for the same period were sourced from the nearest Met Office weather station with hourly resolution.
- The rest of the environmental conditions were monitored during one-week intensive studies organised for each building. A Vaisala WXT520 weather station with pole top adaptor was also mounted on the roof of the buildings during intensive studies to record the local climatic conditions including dry and wet bulb temperatures and external CO_2 concentrations. The intensive studies were carried out in winter when achieving acceptable indoor air quality is often more difficult as operable windows are less used. Furthermore, although air conditioning systems were installed in parts of all case studies to respond to local needs such as high ICT loads throughout the year, the operation of heating systems was more critical for buildings' whole-performance. Therefore, heating season was chosen for intensive studies.

In addition to this structured monitoring, observational studies and spot checks with portable instruments were carried out during regular site visits throughout the year to inform the investigations.

Thermal comfort: Measurements of thermal comfort conditions were taken place at the seated head height away from any local heat source and direct sunlight in representative locations of the classrooms, typically on teacher's desk in longitudinal measurements of air temperature and centre of classroom in the intensive studies. Hobo data loggers were used to record air temperatures in 10-minute intervals for one full year. In the intensive studies a thermal comfort monitor equipped with a black-globe thermometer was used to measure the globe temperature and the velocity of air surrounding the globe in addition to air temperature and relative humidity every minute. The black-globe thermometer takes into account the effect of surface radiation of the enclosure. Its spherical shape also can give a reasonable approximation of the human body's head in the case of a seated person. The mean radiant temperature can be derived from the observed simultaneous values of globe temperature, air temperature, and air speed at the vicinity of the thermal comfort monitor (BSI, 2001). These thermal comfort measurements also make it possible to calculate the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD). These thermal comfort indices, first introduced by Fanger (1982), represent a mathematical model of human thermal physiology calibrated with feedback received from people in climate-controlled experiments. The PMV combines the effect of air temperature, mean radiant temperature, air speed, and humidity with that of clothing and activity level to predict the thermal response of people on a thermal sensation scale (CIBSE, 2015 b). The percentage of people dissatisfied can be predicted from the PMV. The PPD index was calculated for the sample classrooms monitored in the intensive studies. However, it should be noted that there are discrepancies between findings of various field studies and the PMV/PPD model notably in high ambient temperatures (Humphreys & Nicol, 2002) and in naturally ventilated buildings where people are generally tolerant of a wider range of temperatures than what is predicted by the static PMV/PPD model (de Dear & Brager, 2002). The PPD index is therefore more applicable to the mechanically ventilated case studies. However, it can also be applied to the naturally ventilated case studies as a stringent test for thermal comfort.

Indoor Air Quality: A non-dispersive infrared CO_2 sensor was located at the seated head height away from local heat sources with its base on the teacher desk. CO_2 concentrations were monitored every minute on a typical day in three classrooms per building. The classrooms covered various ventilation strategies deployed in each building. The ventilation rates were also inferred from CO_2 levels using the following equation from CIBSE Am 10 (2005):

$$C_t = C_{ex} + \frac{G}{Q} + \left(C_{in} - C_{ex} - \frac{G}{Q}\right) e^{-\frac{Q}{V}t} \qquad (1)$$

Where,

C_t: CO_2 concentration at time t (ppm)

$C_{ex:}$ External CO_2 concentration (ppm)

G: CO_2 generation in the time period t (cm^3/s)

Q: air exchange rate (m^3/s)

C_{in}: initial concentration of CO_2 (ppm)

V: room volume (m^3)

t: time (s)

The estimated rates of CO_2 generation used for adults and children were 0.0054 and 0.0041 litre per second respectively in accordance with Coley and Beisteiner (2002). The number of occupants and the positions of the openings were closely observed and recorded throughout the monitoring day. The inherent uncertainty associated with the CO_2 generation rates means the inferred ventilation rates are subject to high level of uncertainty. However, they are good indicators of the order of magnitude of the air exchange and in conjunction with the CO_2 concentrations provide a reasonable assessment of indoor air quality and the effectiveness of the ventilation strategy in-use. More accurate tracer gas methods that involve using sulphur hexafluoride or perfluorocarbons could not be used to infer the ventilation rates due to health and safety regulations and concerns.

It should also be noted that, in addition to the intensive studies, the CO_2 concentrations in 20 naturally ventilated classrooms in one of the case studies were monitored during heating season via the permanently installed sensors in the classrooms. The permanently installed sensors were compared against the calibrated sensor used in the intensive studies and generally reported concentration levels within ±100 ppm of the calibrated sensor. Records of CO_2 concentrations with 15-minute frequency were extracted from the BMS. The results of this large sample are used to assess the effectiveness of the innovative ventilation strategy used in this building.

Acoustics: According to Building Bulletin 93 (DfES, 2003), where external noise levels are higher than 60 dB L_{Aeq},30min, simple natural ventilation solutions may not be appropriate as the openings installed for natural ventilation will also let in noise. Proximity to congested roads and airport were the main drivers for choosing mechanical ventilation for a number of case studies. In addition to the effect of external noise, the airborne sound insulation between spaces is also important to ensure there is no disruption during a lesson. Monitoring of indoor noise levels can thus indicate the success or failure of the combination of ventilations strategies and sound protection measures. The noise levels were measured in at least two sample vacant classrooms per building and averaged over 30 minutes to be comparable with the design specification. The microphone was positioned at 1.2 m height, the ear height of an average seated listener. Spatial sampling was used to reduce the uncertainty of the measurements. Measurements were taken in at least three representative locations not close to reflective surfaces in each classroom. Microphone positions were at least 2 m apart.

Long reverberation time of several seconds will cause syllables to be prolonged and degrades speech intelligibility. Applying acoustic absorption on the surfaces and reducing the ceiling heights can help reduce the reverberation time. There is a particular risk of high reverberation time where hard wall and ceiling surfaces are specified in large spaces (DfES, 2003). This can happen where thermal mass is exposed as part of the building service strategy to moderate indoor temperatures. The impulse method explained in BS EN ISO 3382-2 (2008) was used to measure the reverberation time in the sample classrooms. In this method the acoustic environment is disrupted by a short transient high level sound. This disruption was introduced by bursting balloons in the sample classrooms. The reverberation time, expressed in seconds, is the time required for the sound pressure level to decrease by 60 dB after the source emission has stopped. The source and microphone positions used to measure the reverberation times correspond with the requirements for Engineering Measurements defined in BS EN ISO 3382-2 (2008).

Lighting: The operation of the lighting installations was reviewed in the observational studies with special attention to the zoning arrangements, the sensitivity of daylight sensors, and the sensitivity and time offs of passive infrared sensors (PIR).

The illuminance levels were measured at working plane level (desk level) in typical teaching spaces to ensure the minimum illuminance level is achieved at all points.

Daylight factor is defined as the percentage of horizontal diffuse illuminance outdoors under overcast sky received at a point indoor (DfEE, 1999). Daylight factors were measured in sample classrooms in two case studies where overcast sky condition was present. High variation in illuminance levels monitored in the other case studies meant the overcast sky condition had not been achieved to enable measurement of daylight factors with reasonable accuracy. The measurement method used for daylight factor followed the procedure developed by Fontoynont and Berrutto (1997) to measure the daylighting performance of European buildings. Two lux meters were used to measure the indoor illuminances at working plane level and outdoor horizontal illuminances simultaneously at regular time steps.

3.4.3. Building Use Studies

The BUS survey is a succinct 7 point scale self-completion questionnaire which is designed to be completed quickly. The questionnaire used in the non-domestic sector asks for the following information from the occupants that regularly use a building:

- Basic information about the respondent's age, gender, and work station that could be provided in an anonymised format
- Overall building review: overall design, needs, space, image, safety, cleaning, availability of meeting rooms, and suitability of storage arrangements
- Work space conditions: work requirements, furniture and space available
- Various aspects of the indoor environmental quality related to thermal comfort, air quality, noise, and lighting
- Personal control on environmental conditions (provision and importance of control)
- Perception of the impact of the building on productivity, health, and personal behaviour

- Speed and effectiveness of the facilities management.

One of the strengths of this method for user satisfaction survey is the existing dataset that currently includes the outcomes of BUS surveys for around 650 buildings in the non-domestic sector. This enables benchmarking the performance of a building against other buildings in the dataset. Scores based on the average responses to a particular question are compared with the benchmarks derived from the last 50 buildings in the dataset. Confidence intervals are also defined with 95% confidence limits to allow for sample sizes, variance of responses and random fluctuations. 95% confidence limits for a normally distributed sample can be defined as follows (Easton & McColl, 1997):

$$Upper\ limit = mean + 1.96 \times \frac{\sigma}{\sqrt{n}} \quad (2)$$

$$Lower\ limit = mean - 1.96 \times \frac{\sigma}{\sqrt{n}} \quad (3)$$

Where, n and σ represent the size and the standard deviation of the sample respectively.

Figure 3.5 illustrates the composition of the BUS benchmark dataset used for the case studies. Schools constitute the second building category most represented in the benchmark dataset. However, it should be noted that more than half of the buildings in the benchmark dataset are office buildings. In addition to benchmarking against the BUS benchmarks, it is therefore important to consider the scores against the survey midpoint scale and also compare and contrast the results obtained for the case studies.

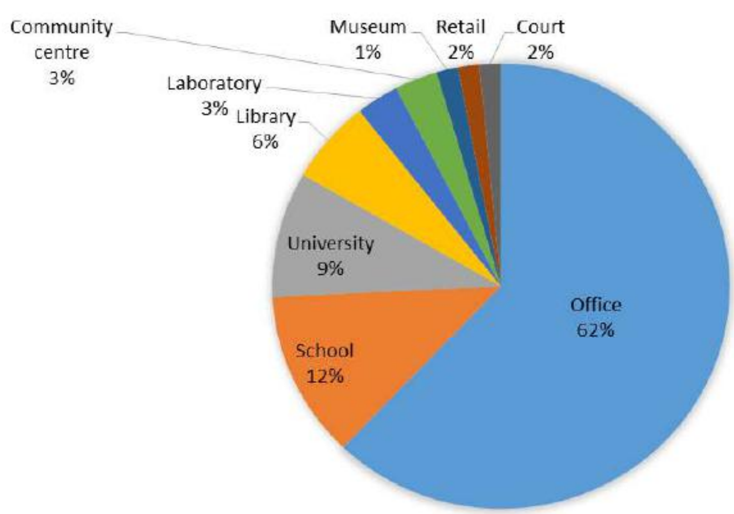


Figure 3.5. Composition of the BUS benchmark dataset used for the case studies (Courtesy of Arup)

A colour code system is used to report the results of the survey. The green colour shows that the building's score compares favourably against both the midpoint scale (the absolute reference scale for the building) and the benchmark scale (the reference scale derived from 50 other buildings); the red colour shows the building performance is poor from occupants' point of view both in respect of the midpoint scale and the benchmark scale, and amber shows the building's score compares favourably against only one scale (Figure 3.6).

The survey result for each variable is also presented on a percentile scale to compare the performance of the building against other buildings in the sample.

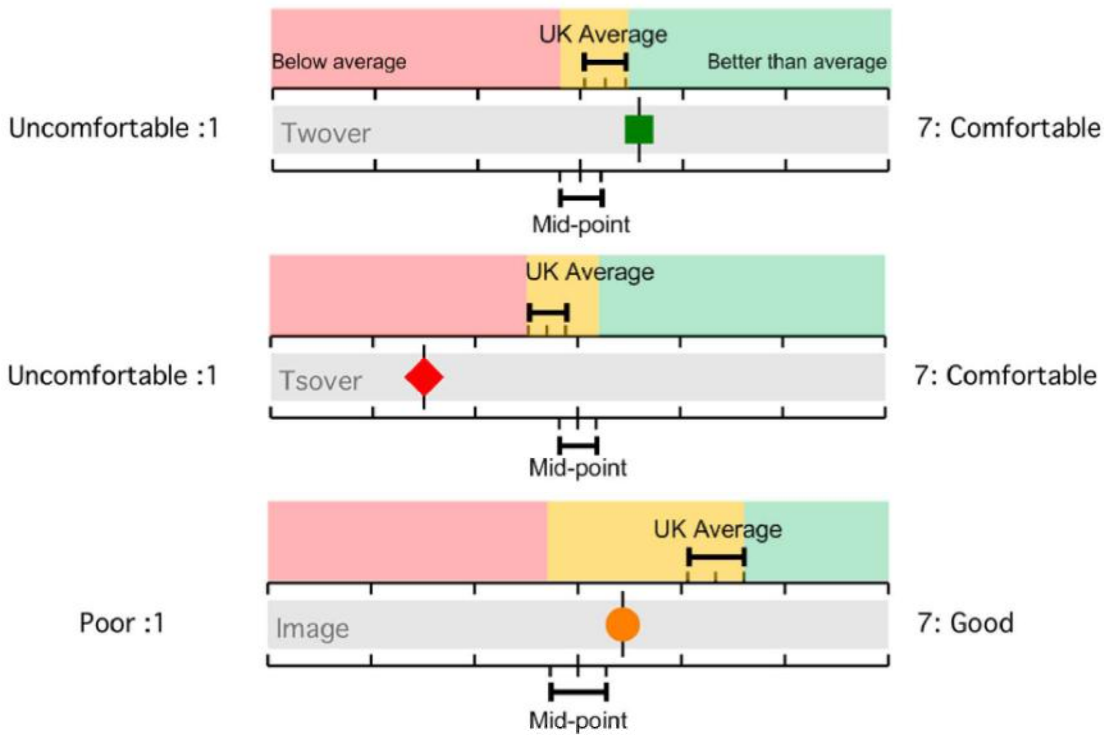


Figure 3.6. BUS slider results graphics (McKerrow, 2011)

The questionnaire includes 46 key variables. It is therefore important to define a number of performance indices to summarise the results. BUS uses the following indices:

- **Comfort index**: the arithmetic average of the standard scores for summer and winter temperature and air quality, lighting, noise, and overall comfort
- **Satisfaction index:** the arithmetic average of the standard scores for design, needs, productivity, and health

For each study variable, the standard score is defined as follows:

$$Standard\ score = \frac{study\ score\ on\ the\ 7\ point\ scale - benchmark\ mean}{benchmark\ standard\ deviation} \quad (4)$$

Standard scores put variables on a common scale with a mean of zero and standard deviation of one.

- **Summary index:** the arithmetic average of comfort and satisfaction indices

Another useful derived variable that could be indicative of building occupants' tolerance to environmental conditions is the Forgiveness index (Leaman & Bordass, 2007). It is defined by dividing the building score for overall comfort by the arithmetic average of building scores for temperature and air quality in winter and summer, overall lighting and overall noise.

In addition to the 7 point scale used, the BUS questionnaire also provides space for specific comments respondents may have in each section.

BUS is a well-established method of collating occupants' feedback. However, factors that affect people perception of a space are often inextricably linked and it is very difficult to separate them and score individual factors objectively. It is important to get feedback from a large number of a building's occupants to draw statistically sound conclusions from subjective views expressed by the respondents. The findings must also be compared and contrasted against physical measurements and observations to tease out anomalies. Analysis of user comfort merely based on physical measurements of parameters such as temperature is not entirely reliable due to its narrow scope, inherent limitations, and uncertainties associated with the standards used to determine human comfort which do not necessarily include the effect of behavioural and cultural differences (Meir, et al., 2009). Equally, judging a building's performance purely based on occupant feedback is prone to error as the judgment may bear no relationship to physical reality but rather to social reality as demonstrated in the famous Hawthorne experiment (Parsons, 1974), (Markus, 2001). Therefore, the outcomes of BUS must be reviewed in conjunction with technical studies.

The BUS questionnaire in paper format was used in the case studies to get feedback from permanent teaching and support staff. The questionnaires were given to all teaching and support staff to be completed and returned on the same day. The response rate varied in each building and was generally above 60%.

In addition to BUS numerical scores, the comments provided by respondents were critical to understanding the building performance. The various themes emerging from the comments were categorised and are reported in Chapter 7 if identified by more than 5% of respondents.

3.5. Operational against designed performance

3.5.1. Energy performance

The outcomes of the Building Regulations compliance calculations and the Energy Performance Certificates were the only records of calculated energy performance available for most case studies. The planning permission for one building was granted before inception of the EPBD in the UK and therefore this building only had a simplified regulatory calculation and no EPC. The total performance reported in these calculations is based on CO_2 emissions associated with annual energy performance. For the reasons explained in Chapter 2, a direct comparison between measured performance and these calculations is not sound. The following adjustments were made to make such a comparison relevant:

- The equipment loads assumed in the calculations to estimate heating and cooling loads, but not reported in the compliance report, were extracted from the regulatory calculations and added to the energy performance to ensure most energy end-uses are accounted in the calculated performance.

- The same carbon emissions factors for all fuels were used for both calculated and measured performance.

A comparison was then made between the measured and the adjusted calculated performance. However, as the regulatory energy performance calculations are based on standardised operating conditions that do not necessarily represent actual operating conditions, they cannot be used for *base-lining* the performance. Furthermore, as the regulatory compliance calculations are based on relative performance comparing calculated total CO_2 emissions of a building with the CO_2 emissions of a notional or reference building, depending on the assessment type, it is not certain that the absolute values could be used for *benchmarking* the performance even after the above-mentioned adjustments.

The standardised operating conditions used in the regulatory calculations are generally consistent with energy efficient operation. For example, the heating set point prescribed in the NCM for classrooms over working hours is 18 ºC. An operating schedule between 5:00-18:00 is assumed for schools' heating systems over working days, which allows for preheating period in winter and cleaning time or extracurricular activities after 15:30. The yearly profiles follow the normal academic calendar in England. Post-occupancy observations on the case studies revealed that most activities outside normal operating hours constitute partial use of schools by a fraction of nominal occupants, often less than 10% of maximum occupancy. Under these circumstances, it is often possible to isolate heating zones that are not occupied and minimise energy use. It could be argued that there is no need to adjust the benchmark if such strategy is adopted as the effect of these extracurricular activities on annual energy performance would be insignificant. This argument is consistent with the current energy benchmarking protocol used for non-domestic buildings whereby definition of annual occupancy hours is based on number of hours that building occupancy exceeds 25% of the nominal maximum number in offices, or number of hours a building is fully open to public in schools (CIBSE, 2008).

Therefore, the standardised operating conditions assumed in the NCM are consistent with the normal operating hours and energy efficient use of buildings.

To test the feasibility of using the calculations carried out in accordance with the EPBD/NCM for benchmarking, the following criteria are proposed:

- Total energy performance calculated by thermal models for buildings constructed after inception of the EPBD should be equivalent to or better than the 25th percentile of national building stock when an allowance for equipment and miscellaneous loads is included. Good practice energy benchmarks defined for non-domestic buildings in the UK are often based on the 25th percentile of existing buildings. New buildings with improved fabric, lower air permeability, higher building services efficiencies and better control should have a benchmark equivalent to the 25^{th} percentile of the existing stock or better (CIBSE, 2012).

- The energy performances derived from EPBD/NCM calculations are only acceptable as *benchmarks* if the bulk of the difference between measured performance and calculated performance could be quantitatively attributed to the shortcomings and inefficiencies uncovered in the post-occupancy evaluations. It is expected that part of this discrepancy will be related to the differences between standardised and actual operating conditions. However, this effect would be limited in a well-managed building.

To test the first criterion, the adjusted calculated performance of all case studies were compared to the benchmarks derived from the national building stock. As for the second criterion, the original computer models were not available for the case studies. Therefore, new computer models were developed and dynamic simulations run for the best and worst performing case studies. The models included all design, construction, and operational issues uncovered in the BPE studies, not reflected in the original regulatory calculations, to closely match the measured performance. These procurement and operational issues were subsequently addressed in the computer model assuming design intents had been met to check to what extent the outcome of the energy performance simulations under real operating conditions would be close to the regulatory calculations carried out under the NCM standardised conditions. If they were close enough, it could be concluded that the adjusted regulatory calculations are useful for benchmarking actual and total building performance.

3.5.2. Analysis of mechanical ventilation systems

A trend observed in school design in recent years is a tendency to specify mechanical ventilation to ensure acoustic and overheating criteria are met. The energy performance requirements of mechanical air distribution systems are often met by specifying high efficiency systems and demand-controlled ventilation. If these strategies fail in practice, the energy performance can be severely compromised. It is, therefore, critical to assess the performance of mechanical ventilation systems installed in schools.

Full load performance: Mechanical ventilation was either the main ventilation strategy or part of the ventilation strategy in all case studies. A measure to determine full load performance of the mechanical air distribution systems is Specific Fan Power (SFP) which is defined as follows in the Building Regulations (HM Government, 2006):

$$SFP = (P_{SF} \times P_{EF})/q \tag{5}$$

Where,

SFP: specific fan power of the air distribution system (W/ (l/s))

P_{SF}: total fan power of all supply air fans at full load including power losses through switchgear and controls associated with powering and controlling the fans (W)

P_{EF}: total fan power of all extract air fans at full load including power losses through switchgear and controls (W)

q: flow rate through the system; the greater of either the supply or extract air flow (l/s)

The absorbed fan power for each supply and extract fan can be estimated at design stage based on the pressure drop calculated for the system index run, fan air flow, and fan efficiencies (CIBSE, 2005):

$$P = (\frac{1}{1000}) \times (q\Delta p)/\eta_f \eta_m \tag{6}$$

Where,

P: fan absorbed power (W)

q: flow rate (L/s)

Δp: pressure drop (Pa)

η_f: fan total efficiency (%)

η_m: fan motor efficiency (%)

However, mechanical air distribution systems are susceptible to a number of shortcomings in installation such as changes in ductwork route and aspect ratios as a result of spatial constraints, sharp ductwork bends, air leakage, and change of specification within the air handling units not reflected in pressure loss calculations. Actual fan absorbed powers may therefore be significantly higher than design assumptions.

The *as-built* SFP must be reflected in the final Building Regulations compliance calculations and reported in the compliance reports (BRUKL reports). On the other hand, it is possible to calculate the as-built SFP based on the information reported in the fan test sheets at the commissioning stage. This method can be used to test the accuracy of the SFP values used in the regulatory calculations.

Fans with low power demand (usually less than 1kW) are served by single phase power circuit. Their absorbed power can be calculated using the following text book equation (Toliyat & Kliman, 2004):

$$P = V_P \times I_P \times PF \tag{7}$$

Where,

P: fan absorbed power (W)

V_P: phase voltage (V)

I_P: phase current (A)

PF: power factor

The main air handling units with higher power demands in the case studies were served by three phase power circuit and had a star connection with a neutral wire. The following equation can be used to calculate fan power in these circumstances (Toliyat & Kliman, 2004):

$$P = \sqrt{3} \times V_L \times I_L \times PF \tag{8}$$

Where,

P: fan absorbed power (W)

V_L: line voltage (V)

I_L: line current (A)

PF: power factor

The phase and line currents were measured and recorded at the commissioning stage. The phase and line voltages in the UK are 240 V and 415 V respectively. The power factor was estimated based on the rating of the fan's motor and percentage of the full load reported in the test sheets (DOE, 1997). The flow rates were also measured and recorded at the commissioning stage. Therefore, it was possible to estimate the as-built SFPs and compare these with the values reported in the Building Regulations compliance reports. It should also be noted that good practice design is to allow for the pressure drop caused by dirty air filters over time in calculating SFPs (BSRIA, 2007). Therefore, the SFPs derived at commissioning stage with clean filters are conservative benchmarks that could be used to assess the efficiency of the installed air distribution systems against the design intents and the limiting SFPs specified by the Building Regulations.

Demand-controlled ventilation: the air distribution systems installed in the case studies were primarily specified to provide fresh air for the occupants and were designed to be controlled based on CO_2 concentrations. It is useful to define a benchmark usage factor for these systems representing the equivalent time system should be at full load divided by the enabled time. The existing guidelines recommend having a modular variable speed control with fan inverters capable of bringing the flow rate down to 30% of the maximum flow to optimise the energy saving benefit of demand-controlled ventilation (Carbon Trust, 2011). However, the available design documentation for demand-controlled ventilation in the case studies show the minimum flow rate specified for the fans was more conservative than the guidelines at 50% of the nominal flow to ensure enough background ventilation is provided at all times during the operation of the air handling units. Consequently, the inverter setting assumed for the benchmark usage factors involves minimum flow rate equal to 50% of the nominal rate ramping up to 100% based on buildings' demand. Changes in occupancy level and infiltration rates are reflected in the CO_2 concentrations detected by CO_2 sensors. Inverters respond to these changes by modulating fans' speeds to ensure the CO_2 levels are maintained within acceptable limits. Where full mechanical ventilation was specified for the case studies the main driver was the external ambient noise levels. Therefore, operable windows were not meant to be the main means of controlling CO_2 levels. The case study buildings that predominantly use natural ventilation also had a number of classrooms and office spaces located in the core spaces that had no direct access to external facades. These areas were mechanically ventilated. Consequently, for benchmarking purpose and in accordance with the design intent, it was assumed that CO_2 concentrations closely follow the occupancy levels. This sets the maximum usage factor expected for the fans as in practice operable windows used by occupants also help reduce CO_2 concentrations. Fan flow rate could be inferred from occupancy level using the following equation.

$$\begin{cases} q = 0.5 \times q_{100\%} & if\ o \leq 0.5 \\ q = o \times q_{100\%} & if\ o > 0.5 \end{cases} \quad (9)$$

Where:

o: occupancy level (0-1)

q: flow rate (l/s)

$q_{100\%}$: flow rate at full load (l/s)

The fan Cube Law states that fan power varies as the cube of its flow rate (CIBSE, 2005). However, in practice operational losses mean actual fan power at part load is often higher than what is predicted by the theoretical cube law. The following empirical equation was used to estimate power at part load (ASHRAE, 2007).

$$P_{frac} = 0.0013 + 0.1470 \times \left(\frac{q}{q_{100\%}}\right) + 0.9506 \times \left(\frac{q}{q_{100\%}}\right)^2 - 0.0998 \times (\frac{q}{q_{100\%}})^3 \quad (10)$$

Where P_{frac} denotes fraction of full-load fan power (0-1).

Figure 3.7 shows how usage factor can be established for a typical school day. The occupancy profile used is the NCM standard profile for classrooms (BRE, 2010). This occupancy profile is a good approximation of occupancy patterns in schools and is broadly consistent with the post-occupancy observations. Fifty per cent occupancy level between 12:00-14:00 is well justified given the lunchtime break, and pupils spending time in atrium space or schools courtyards. This profile can be modified to allow for any difference in occupancy profile observed in schools.

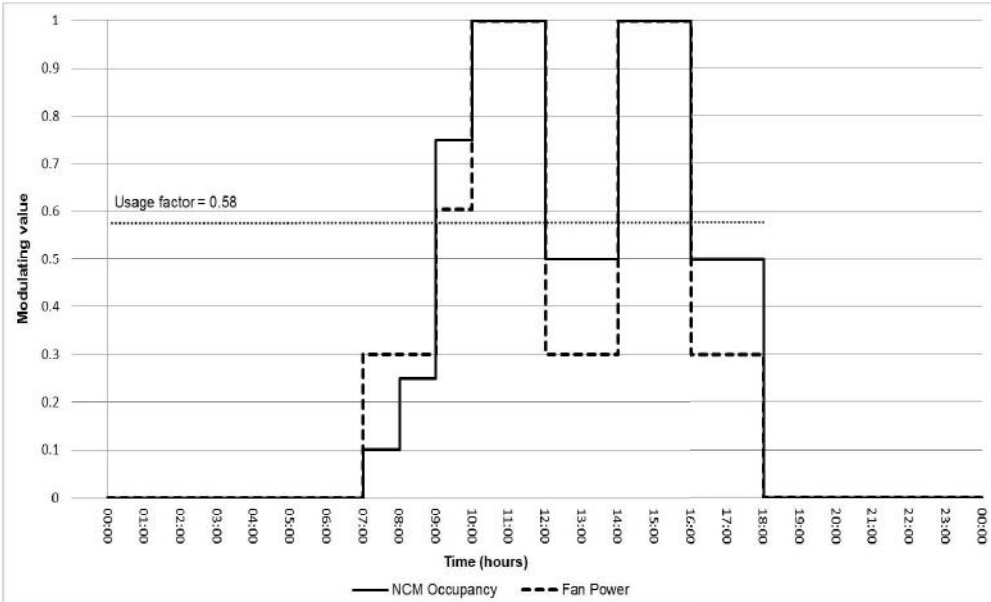


Figure 3.7. Usage factor related to demand-controlled ventilation for a typical school day

To calculate the average usage factor for one year, night schools and extra-curricular activities in each case study should also be taken into account. The following equation was used to work out the benchmark usage factors for mechanical ventilation systems.

$$Usage\ factor = 1/n \sum_{i=1}^{i=n} 1/h_i \sum_{o=1}^{o=h_i}((\frac{P_o}{P_{100\%}}) \times \Delta t_o) \quad (11)$$

Where:

Usage factor: related to demand controlled ventilation, calculated for the whole year

P: fan power (W)

$P_{100\%}$: fan power at full load (W)

t: time (hr)

h: number of operation hours per day

n: number of days with separate operating hours

Actual usage factors were estimated based on site observations as the inverter status was reported on the digital display units mounted on the air handling units. Usage factors are also used in TM22 analysis and therefore reconciliation of fans' energy use with the bottom-up calculations for ventilation systems was used to confirm the average usage factor for the whole year. These factors were compared against the benchmark usage factors to assess the effectiveness of demand-controlled strategy.

3.5.3. Fabric performance

The Innovate UK Building Performance Evaluation programme provided the opportunity for the architects to review and report the as-built U values. The average as-built U values reported in the statuary Building Regulations reports were compared against the U values reported by the architects. From process point of view, this is important as energy models are often developed by building services engineers and although architects provide the architectural drawings and other necessary information, the responsibility to calculate the U values is often not clearly defined. Where there was a significant discrepancy between the U value used in the regulatory calculations and the U value reported by the architects, the construction documents and calculations were reviewed to identify the root cause for this discrepancy. Review of U value calculations was carried out in accordance with 'BR 443: Conventions for U-value calculations' (Anderson, 2006).

In addition to average U values, the Approved Document Part L refers to the guidelines that can be followed to limit thermal bridging and air leakage at the joints between construction elements. The guidance provided in the document entitled 'Robust construction details' (DEFRA and DTLR, 2001) was prevalent at the time the case study buildings were constructed (HM Government, 2006). The 2010 edition of the Approved Document Part L also refers to the guidelines provided in 'Accredited construction details' (CLG, 2007). The construction details and thermographic evidence from the case studies were reviewed to identify improvement opportunities in limiting non-repeating thermal bridges at the joints between construction elements.

3.5.4. Review of process issues

The major building procurement and operational issues were identified in the case studies during the post-occupancy evaluations by comparing actual performance against design intents. Subsequently, an investigation was carried out to identify the root causes. This investigation was retrospective. As the researcher was not involved in the original procurement process, it was also to a large extent dependent on the input provided by various stakeholders. While the feedback from schools' management, facility managers, and building users were sought during site visits, designers and contractors were also engaged, thanks to the funding provided by Innovate UK, to give feedback on discrepancies between operational and designed performance. Building services design practices involved in the procurement process provided their feedback in form of a report for each case study. However, only on one occasion the personnel involved in the initial design also carried out the post-occupancy review; in all other cases other personnel carried out the review as the people involved in the design process either had other commitments within their respective organisations or had left the organisations. Meeting and workshops were also organised with the authors of these reports and the contractors to provide a better understanding of the issues. Based on the input received from the stakeholders and a forensic review of building documentation, the researcher developed a process map of the procurement and operational issues to show at what stage of the building procurement a problem occurred, what was the root cause of the problem, and how this was evolved and possibly compounded by other issues at the project progressed. Feedback received from stakeholders were only included in this analysis if confirmed by at least two independent sources. This information is provided for each building in tabular format in Chapter 8.

3.6. The measurement and verification framework

Although a number of adjustments were made to the outcomes of the regulatory calculations to derive *benchmarks* for performance in-use, the regulatory calculations can only be used as *baselines* for performance in-use if the comparison is made under identical operating conditions. There are two ways to do such a comparison:

- Updating the original model used for regulatory calculations to reflect the operational building and its operating conditions. The energy performance derived from this model could then be compared with the measured performance.
- Reverting a computer model calibrated with the actual performance to the operating conditions assumed in the regulatory conditions. The energy performance derived from this model could then be compared with the outcomes of the original regulatory calculations.

The first approach seems intuitive and is often offered by consultants where Clients wish to have theoretical baselines for building energy performance. If the original computer model is available, it can be updated to reflect actual operating conditions in addition to any changes in building fabric and HVAC systems. If the original model is not available, a new computer model can be developed based on the latest as-built and operating conditions to be used for base-lining energy performance, building diagnostics and optimisation.

However, there are two major shortcomings with this approach. First, while the energy modeller will make an attempt to update the model based on actual conditions, there is no measure to confirm the accuracy of this model. For example, the energy modeller may believe they have captured all details whereas, in reality, specific technical defects or details of operating conditions in part of a building are not identified and reflected in the model (e.g. exact number of occupants and out-of-hours use). This will lead to a distorted view of building performance. Second, if the aim of base-lining is to determine the performance gap with reasonable accuracy to inform policy it must be done under standard operating conditions. Otherwise, the results will be skewed depending on operating conditions. This is particularly important if verification of the performance gap is meant to inform policies such as carbon tax or environmental levy in future. A contractor might be responsible for a number of shortcomings in building construction that are identified in the measurement and verification process. However, the impact of these shortcomings on energy performance must be assessed under standard operating conditions for consistency and kept independent of operating conditions adopted by the building user.

The second approach to measurement and verification addresses both issues: calibrating a thermal model with the measured performance confirms the accuracy of the model; reverting this calibrated model to standardised operating conditions makes it possible to determine the performance gap related to the construction process independent of actual operating conditions used by building occupants. This performance gap is called *the procurement gap* henceforth in this dissertation.

Figure 3.8 depicts the principle of using calibrated thermal models to verify the performance calculated under the EBPD standardised conditions. The forward path shows how actual energy performance could be significantly higher than calculated performance under the EBPD conditions. The backward path shows how a calibrated thermal model could be used to verify the EPBD calculation and establish if there is any procurement gap. The procurement gap in this context represents shortcomings in building design, construction process, system installation, implementation of control strategy, and building commissioning.

The following definitions are useful to separate the performance gap related to the construction process from the performance gap related to building operation:

$$Procurement\ gap = EPBD_{verified} - EPBD_{intended} \tag{12}$$

$$Operational\ gap = Measured\ performance - EPBD_{verified} \tag{13}$$

$$Total\ performance\ gap = Procurement\ gap + Operational\ gap \tag{14}$$

Where,

EPBD verified: energy performance derived from a calibrated thermal model under the EPBD settings

EPBD intended: regulatory EPBD calculation carried out following completion of a building

Measured performance: actual annual energy performance based on metering or utility bills

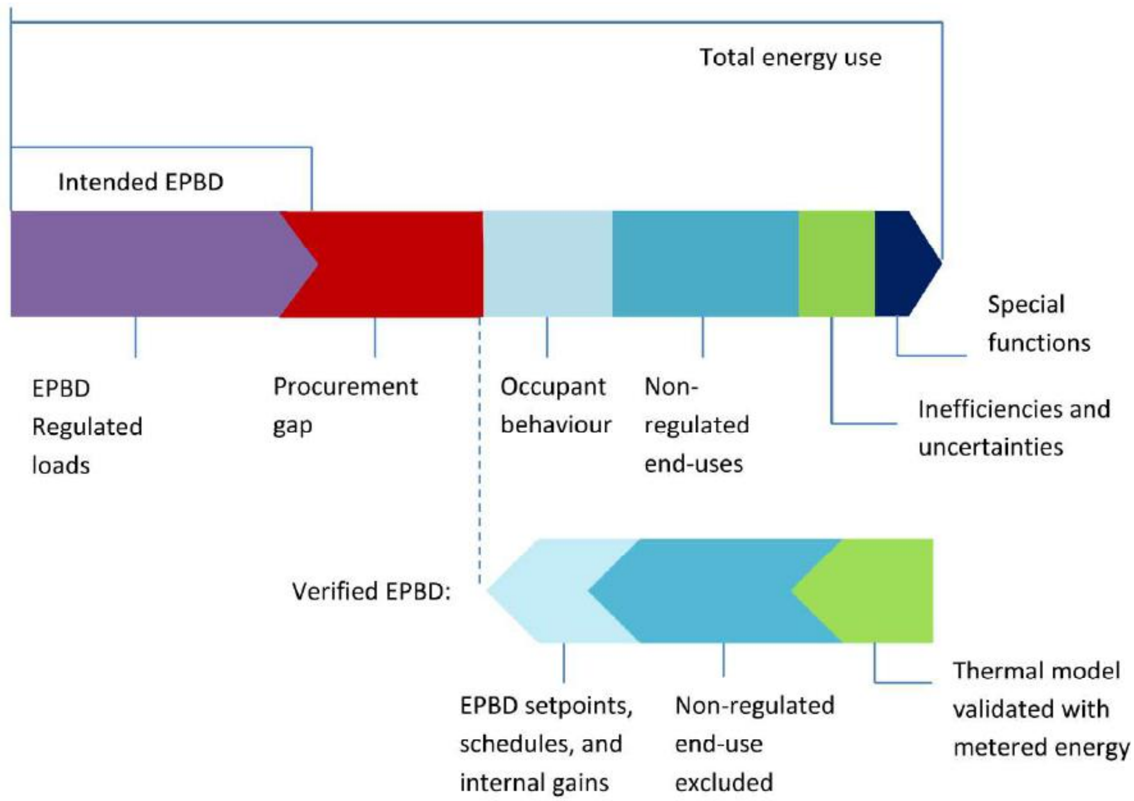


Figure 3.8. Measurement & verification of energy performance under the EPBD

There are two protocols that can be used to establish the procurement gap following the framework illustrated in Figure 3.8.

3.6.1. International Performance Measurement and Verification Protocol (IPMVP)

The International Performance Measurement & Verification Protocol (IPMVP) provides a method for calibration of thermal models for energy saving projects where whole-building simulation is required (EVO, 2012). This method is underpinned by ASHRAE Guideline 14 (ASHRAE, 2002). Calibration is achieved by adjusting the computer model of a building to reflect the as-built status (e.g. as-built fabric U values, pressure test results, and commissioning results of HVAC systems) and actual operating conditions (e.g. occupancy pattern, operational schedules of HVAC systems, temperature set points, and actual weather conditions). The outputs of the adjusted computer model are then compared against the measured performance to check if the model can reasonably reflect actual operation of the building. The calibration process is based on hourly or monthly energy data and is determined by the Coefficient of Variation of the Root Mean Square Error (CVRMSE) and Normalised

Mean Bias Error (NMBE). Table 3.5 provides the calibration criteria used for hourly and monthly calibration of a computer model.

Table 3.5. The calibration criteria for building energy performance simulation (ASHRAE, 2002)

Calibration Method	Calibration indices	
	CVRMSE	NMBE
Hourly Calibration	30%	10%
Monthly Calibration	15%	5%

The calibration indices are defined as follows:

$$\mathrm{CVRMSE} = 100 \times [\textstyle\sum_{i=1}^{n}(y\mathrm{i} - \hat{y}\,\mathrm{i})^2 / (\mathrm{n}-1)\,]\ 1/2\ /\ \bar{y} \quad (15)$$

$$\mathrm{NMBE} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{yi}-\hat{\mathrm{y}}\mathrm{i})}{(\mathrm{n}-1)\times\bar{\mathrm{y}}} \times 100 \quad (16)$$

Where:

yi : measured hourly or monthly energy use

$\hat{y}i$: hourly or monthly energy use derived from computer model

$\bar{y}$: average hourly or monthly energy use for the measurement period

n: number of data points (n=8,760 for hourly calibration, n=12 for monthly calibration)

The CVRMSE criterion ensures hourly or monthly energy errors do not cancel out and are all taken into account in the calibration process. The NMBE criterion, on the other hand, looks for systematic bias in the model. Both criteria must therefore be satisfied for calibration. These calibration indices represent how well a mathematical model describes the variability in measured data and therefore deal with the modelling uncertainty (ASHRAE, 2002).

In the context of the IPMVP, whole-building calibrated simulation after one year of steady post-refurbishment occupancy could be used to establish energy savings achieved when pre-refurbishment energy performance is not available or difficult to establish (e.g. multiple buildings on one site without sub-metering). Once the thermal model is calibrated with actual performance post-refurbishment, systems and settings may be changed to pre-refurbishment conditions to establish the initial baseline. The energy saving achieved is the difference between energy performance derived from calibrated thermal model under pre-refurbishment conditions, and the actual energy performance measured after refurbishment work.

The same principle could be used to draw up a measurement and verification plan under the EPBD framework. A computer model that reflects the steady post-occupancy operation of a building for at least 12 months could be developed and compared against actual performance. Once calibration is achieved under actual operating conditions, the model could be reverted to the EPBD standardised settings to establish the verified performance under the EPBD conditions.

3.6.2. BS EN 15603 procedure

This energy performance of buildings standard includes a procedure for validation[7] of building calculation models (BSI, 2008, pp. 32-34). The aim of this procedure is to gain higher confidence in a building calculation model by comparing the outcomes with actual energy consumption data, and ensure there is reasonable consistency between calculated and measured energy performance. Operational information such as climatic data, air permeability of building envelope, ventilation rates, system efficiencies, occupant numbers, and indoor temperatures should be collected from building documentation and surveys to update the original model. The confidence intervals of all data should also be estimated. Appendix F of the standard gives indications on typical distribution profiles and standard deviations of several variables used in building calculation models (BSI, 2008, p. 53). If the confidence intervals of the calculated energy and the measured energy are acceptable and overlap significantly, it is assumed the calculation model of the building is plausible. Subsequently, the calculation model is run once more with standard input data rather than actual input data to yield a verified standardised energy performance or energy rating. This procedure is focused an annual energy performance calculations or ratings only, and there is no requirement for hourly or monthly calibration.

This procedure is consistent with the measurement and verification framework illustrated in Figure 3.8. However, it is less prescriptive than ASHRAE Guideline 14 in terms of calibration criteria and does not provide any definitive limit to determine if the confidence intervals of the calculated energy and the measured energy are acceptable and overlap significantly. Its approach to uncertainty analysis is also different than ASHRAE Guideline 14. Inclusion of the confidence intervals in the calculation model effectively requires an analysis of the sensitivity of the model to input data. Such a sensitivity analysis not only must investigate the effect of variations in single variables on energy performance, but also must be able to examine the

[7] The key objective of BS EN 15603 procedure is to ensure the computer model of a building is accurate. This is achieved by comparing the outputs of the computer model with the measured performance. The term validation is thus used to emphasise this focus on the validity of compute model outputs. The term measurement and verification is used elsewhere in this dissertation to emphasise the focus on actual building performance in keeping with the terminology used in the industry where actual performance of a building is of interest (for example in the IPMVP and DOE FEMP frameworks).

effect of the interrelations between variables. As a full factorial analysis that entails exploring all possible interrelations between input variables is practically not feasible for most projects in the domestic sector, Monte Carlo-based sensitivity analysis which relies on repeated random sampling (Macdonald, 2002) can be used for this type of validation.

These measurement and verification and validation protocols were used to determine the procurement and operational gaps in the worst performing case study for which an EPBD regulatory calculation was available. The objective was to explore how the measurement and verification framework presented here can help determine the performance gap with reasonable accuracy and, thereby, inform future policy.

3.7. Summary

It is important to differentiate the case study approach that entails detailed investigation of one *case* or a number of *cases* to deduce analytic generalisations from benchmarking approach that investigates a *sample* to derive statistical generalisations. Consequently, the word *sample* will not be used in this dissertation henceforth in reference to the case studies to emphasise the approach. An initial theory was formulated to recognise the researcher's background and bias and a rival theory was also put forward to summarise the objections to the theory. The falsification principle means the findings of the Building Performance Evaluations must be used to challenge the theory rather than merely support it with various pieces of evidence selected from a vast array of available information from the case studies. The conclusions of this research programme are also bound to be analytic generalisations consistent with the case study approach although reference could be made to the findings of other research programmes that use statistical benchmarking to support the conclusions.

A process view of the research programme was presented to explain how detailed investigation of the building procurement process and post-occupancy evaluations will be used to challenge the theory, identify measures to improve energy performance of educational and other non-domestic buildings, and propose a measurement and verification framework to determine the energy performance gap with reasonable accuracy.

Finally, the methods used for post-occupancy evaluations, operational against designed performance analysis, and measurement and verification of performance in-use in reference to the regulatory calculations were reviewed in detail.

4. The Buildings' Context

4.1. Introduction

This Chapter provides an overview of the case studies to give context to the data presented in the next Chapters.

First, the basic information about these buildings is presented. Subsequently, each section provides an overview of one of the case studies. Finally, the key information about buildings' context are reviewed in a comparative style.

Full sets of layout plans for all case studies are also provided in Appendix A.

The schools are treated anonymously throughout this dissertation. The alphabetic order used to name buildings is based on the dates of the first site visits and merely represents the way the author has codified these building from the outset of the research.

4.2. Overview of the case studies

Four secondary schools or academies and one Sixth Form were included in the research. Table 4.1 includes the basic information about these buildings.

Table 4.1. Overview of the case study buildings

Building	Total Useful Floor Area (m^2)	Building type	Location	Building Regulations class	Completion	Capital cost (£/m^2)
Bldg. A	10,418	Academy	North West England	Part L 2006	Autumn 2008	2,100
Bldg. B	2,843	Sixth Form	North West England	Part L 2006	Summer 2010	2,500
Bldg. C	10,172	Academy	North East England	Part L 2006	Summer 2009	2,200
Bldg. D	14,610	Secondary School	London	Part L 2006	Spring 2010	2,800
Bldg. E	10,490	Academy	London	Pat L 2002	Summer 2007	2,400

The fundamental difference between secondary schools and academies is that academies are directly funded by the Department for Education rather than through the local authorities. All secondary schools and academies in Table 4.1 include a Sixth Form which in British education system represents the final two years of secondary education. Building B was erected next to an existing secondary school to accommodate its Sixth Form intake and therefore is entirely devoted to the final two years. In addition to secondary education, Building C includes a primary school that takes around 20% of its total useful floor area.

The buildings represent three distinct geographic locations in England. All buildings were procured under the BSF programme and were designed by the architectural practice that supported the research. The same contractor was involved in the procurement of Buildings B and D. This was the main reason to include Building B in the study despite having much smaller floor area than other buildings. Furthermore, as this building is located next to the main school, fewer out-of-hours activities take place in it compared to other case studies. This may also have implications for energy performance that must be explored. The same building services design practice was involved in the procurement of Buildings A and E. There was no other commonality between the construction teams.

All buildings, except Building A, were completed following the Design & Build procurement route which means the contractors were involved from the outset and employed designers and other members of the construction teams to deliver the projects. Building A followed a traditional procurement route and the main contractor was novated at tender stage after detailed design had been completed.

4.3. Overview of Building A

Building A is an academy located in North West England which replaced an old community school on the same site in 2008. The academy is a 4-storey steel frame building with cavity wall and brick facades comprising lower ground, ground, first and second floors. The building is under the air path of Manchester airport. Therefore, mechanical ventilation strategy was adopted to meet BB93 acoustic requirements (DfES, 2003). Classrooms facing external facades have at least one operable top-hung window, internal blinds, and no external shading with the exception of some classrooms in the south orientation that have retrofitted solar film applied. A central atrium space connects different parts of the building and is meant to provide opportunities for performance, display, and informal interaction. Classrooms, sport hall, dining area, and office spaces are all located around the central atrium.

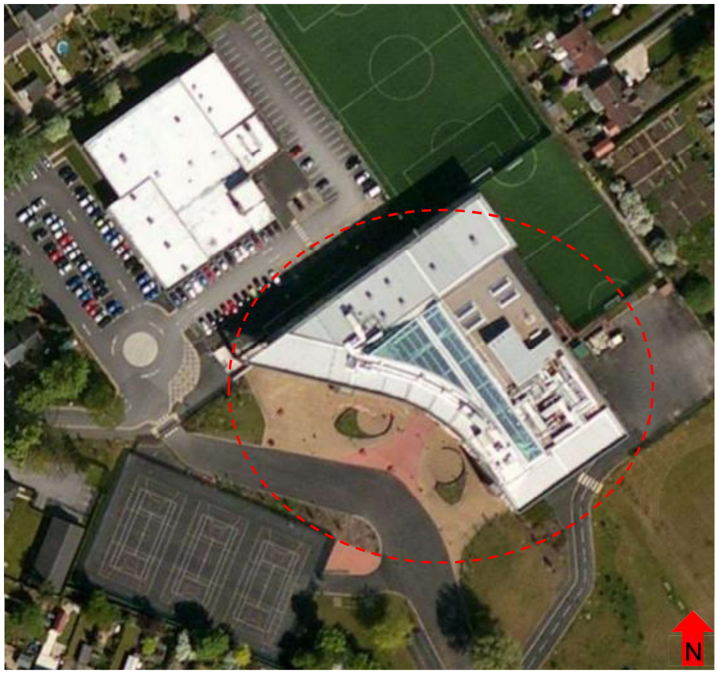


Figure 4.1. Aerial view of Building A and its surroundings

The academy has been designed as a 1,150 pupil facility. Nominal occupancy during post-occupancy evaluation was 900 (800 pupils + 100 teaching and support Staff). The academy follows schools' calendar year in England. The occupancy hours including the hours spent for tutorial sessions and extra-curricular activities are 9:00-18:00 with cleaning hours being 07:00-9:00 and 18:00-20:00. A night school was also running between 18:00-21:00 on Tuesdays and Thursdays during the post-occupancy evaluation. Occasionally, some extra-curricular activities and events take place after 18:00 during week days or on Saturdays.

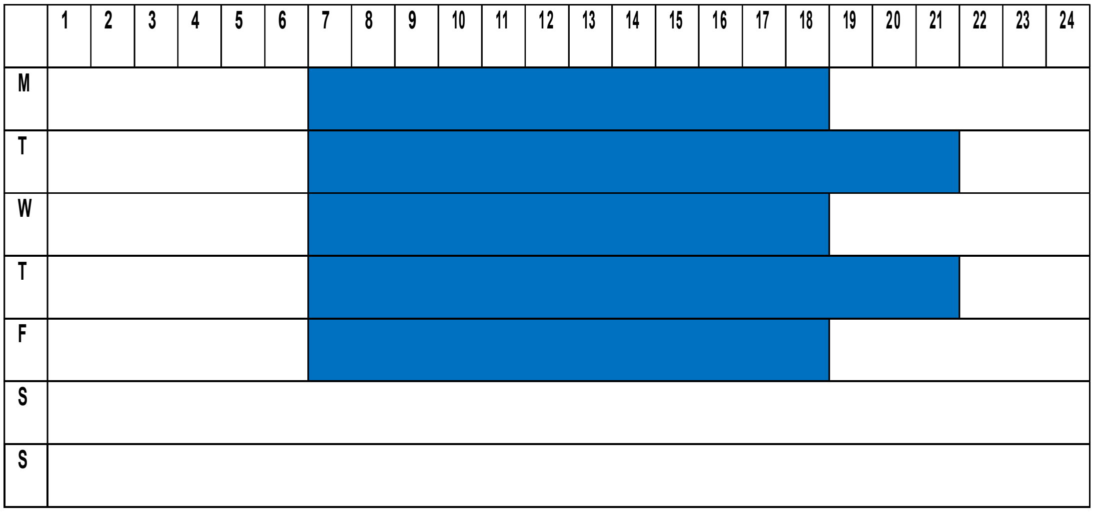
Figure 4.2. Building A: view of the south façade (left), central atrium space (right)

Table 4.2. Brief description of the building services strategy for Building A

Service	Description
Heating	Gas-fired condensing boilers serve the constant temperature loop (heating coils in the air handling units) and the variable temperature loop which feeds the radiators (heating terminals in typical classrooms) and the radiant panels (heating terminals in the corridors and science labs). A ground source heat pump system was designed as the lead heating system, supplemented by the gas-fired boilers, to serve the under-floor heating system (heating terminals in high ceiling spaces such as the Academy's main hall), and the chilled beams installed in ICT enhanced spaces. Total installed heating capacity is 1500 kW including domestic hot water use.
Ventilation	The building is predominantly mechanically ventilated. Heat recovery is provided by the thermal wheels and plate heat exchangers installed in the air handling units. All main supply and extract fans have inverters installed that can change fans' speed. The central atrium has low and high level openings for natural ventilation. The sport hall and the Academy's main hall are also naturally ventilated with wind catchers.
Comfort cooling	Areas with excessive internal heat gain such as ICT rooms have chilled beams installed to provide comfort cooling. The chilled beams are served by the ground source heat pumps. Total cooling capacity available from the ground source heat pumps is 300 kW.
Domestic hot water	Hot water service generation and storage is provided by a calorifier vessel fed from the low temperature hot water heating system.
Lighting	T5 fluorescent lamps in classrooms with daylight sensors and Passive Infrared Sensors (PIR), compact fluorescent lamps in corridors with PIR sensors, and high level metal halide lamps in high ceiling spaces are installed. The design average daylight factor in classrooms was 2%.

Figure 4.3. Internal view of a typical classroom (left), an ICT classroom with chilled beam (right)

Table 4.3. The main heating schedule set up in the Building Management System for Building A during the post-occupancy evaluation



4.4. Overview of Building B

Building B is located in North West England next to an existing secondary school to accommodate the Sixth Form intake. It is a 3-storey L-shaped building with light wells comprising the ground, first, and second floors. The building is steel frame with ground bearing in situ concrete slab and composite deck upper floors. GluLam timber columns and beams are located in lightwell areas. External walls are cavity construction. Heavy thermal mass of floors and walls help regulate internal temperatures. An overhanging canopy on the south façade provides external solar shading for the atrium space and a number of classrooms. The building is close to a main road and therefore mechanical ventilation strategy was specified to meet BB93 acoustic requirements. All classrooms have internal blinds and at least two operable top-hung windows.

Figure 4.4. Aerial view of Building B and its surroundings

The school has been designed as a 300 pupil facility. Nominal capacity during the post-occupancy evaluation was 250 (200 pupils + 50 teaching and support staff). The school follows schools' calendar year in England. The occupancy hours are 8:15-18:00 including tutorial sessions and extra-curricular activities. Cleaning hours are 6:15-8:15 over weekdays. A night school was also running between 18:00-21:00 on Tuesdays and Thursdays during the post-occupancy evaluation. Occasionally, some extra-curricular activities take place after 18:00 or on Saturday.

Figure 4.5. Building B: entrance elevation on north façade (left), courtyard elevation on south façade (right)

Table 4.4. The building services strategy for Building B

Service	Description
Heating	Gas-fired condensing boilers serve the ceiling mounted radiant panels in the classrooms and the atrium space, the main air handling unit (installed to provide tempered fresh air), and the down flow heaters over the entrance doorways and lobby. Total installed heating capacity is 345 kW including domestic hot water use.
Ventilation	The building is predominantly mechanically ventilated. Mechanical ventilation is provided by a central inverter driven air handling unit with heat recovery achieved by a thermal wheel. Kitchen and toilets have their bespoke local extract fans. Natural ventilation is provided to the atrium space by motorised vents. The system installed in the atrium also includes automatic controls that were designed to respond to high CO_2 concentrations and warm weather.
Comfort cooling	A Variable Refrigerant Flow (VRF) system is installed to provide comfort cooling in addition to heating in a number of spaces including business suites and ICT enhanced classrooms.
Domestic hot water	Flat solar thermal panels were installed to preheat water. The boiler plant was meant to be the supplementary system to provide domestic hot water through a plate heat exchanger.
Lighting	T5 fluorescent lamps in classrooms with daylight sensors and Passive Infrared Sensors (PIR), compact fluorescent lamps with PIR sensors in corridors, and high level metal halide lamps in high ceiling spaces are installed. Internal lighting was designed to have a better efficiency than 2.5 W/m²/100 lux.

Figure 4.6. Internal view of a seminar room with ceiling mounted radiant panel (left), the motorised vents in the atrium are open to reduce CO_2 levels (right).

Table 4.5. The main heating schedule set up in the Building Management System for Building B during the post-occupancy evaluation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
M																								
T																								
W																								
T																								
F																								
S																								
S																								

4.5. Overview of Building C

Building C is an academy located in North East England which replaced an old community school on the same site in 2009. It is a cluster of interlinked buildings around a central court with walkaways between the individual buildings. The buildings are mixture of 2-storey and 3-storey steel frame buildings with cavity wall construction and south facing mono-pitch passive sections. Solar shading is applied to the south façade. The building houses general classrooms, laboratories, and theatre as well as the main performance hall, sports hall, and office spaces. The majority of spaces are naturally ventilated with manually operable windows. To supplement natural ventilation, manually operated extract fans have been installed to enhance cross ventilation when required.

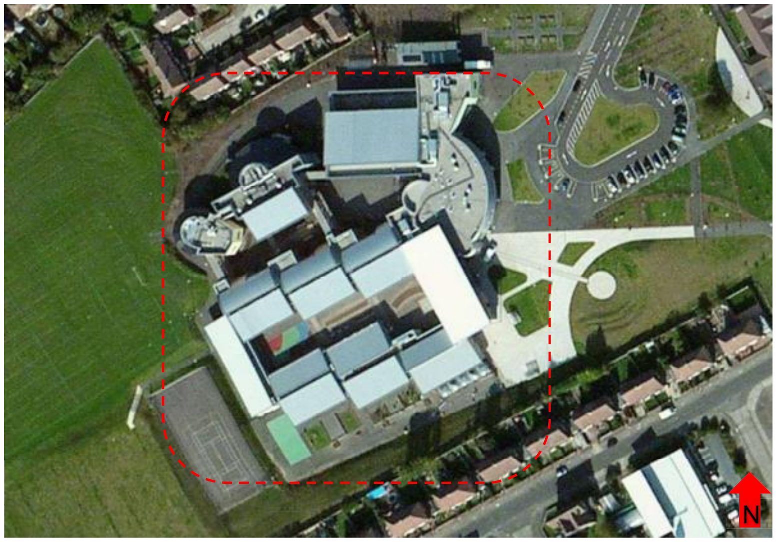


Figure 4.7. Aerial view of Building C and its surroundings

The academy has been designed as a 1,200 pupil facility. The nominal occupancy during the post-occupancy evaluation was 1,100 (1000 pupils + 100 teaching and support staff). The school follows schools' calendar year in England. The core occupancy hours are 8:00-15:30. Cleaning hours are 7:00-8:00 and 15:30-18:00 over weekdays. Some extra-curricular activities take place after 15:30 and over the weekends.

Figure 4.8. Building C: external view of the interlinked buildings (left), south facing mono pitch classrooms (right)

Table 4.6. The building services strategy for Building C

Service	Description
Heating	The design intent was to have a biomass boiler as the lead heating source backed up by two gas-fired condensing boilers to serve the radiators (installed in general classrooms), the under-floor heating system (installed in high ceiling spaces), and the radiant panels (installed in labs and science rooms). The heating coils installed in the main air handling units that serve part of the building are also served by this heating system via a constant temperature heating loop. Each boiler was sized to meet a nominal 50% of the design load. Total installed heating capacity is 1200 kW including domestic hot water use.
Ventilation	The building is predominantly naturally ventilated. General classrooms have operable windows at low level and operable windows and booster extract fans at high level to provide the facility for cross/stack ventilation. Science and technology classrooms, music classrooms, and ICT rooms are provided with full fresh air mechanical ventilation. Tempered air is also supplied to the dining, assembly and sport halls to ensure these spaces are flexible for other potential activities such as examinations and communal events. All main air handling units are inverter driven and have plate heat exchangers for heat recovery. Kitchens also have bespoke inverter driven mechanical ventilation system with heat recovery.
Comfort cooling	Most office spaces and ICT rooms have comfort cooling. VRF systems provide comfort cooling in addition to heating to these spaces.
Domestic hot water	Hot water is preheated by a solar thermal system and is supplemented by the boiler plant through a plate heat exchanger.
Lighting	T5 fluorescent lamps in classrooms with daylight sensors and Passive Infrared Sensors (PIR), compact fluorescent lamps in corridors, and high level metal halide lamps at the entrance and high ceiling spaces are installed.

Figure 4.9. Ventilation strategy in Building C: manually operable clerestory windows and extract fans enable cross/stack ventilation in classrooms (left), extract fans are activated by a manual switch if teachers feel ventilation has to be improved (right).

Table 4.7. The main heating schedule set up in the Building Management System for Building C during the post-occupancy evaluation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
M						■	■	■	■	■	■	■	■	■	■	■	■	■						
T						■	■	■	■	■	■	■	■	■	■	■	■	■						
W						■	■	■	■	■	■	■	■	■	■	■	■	■						
T						■	■	■	■	■	■	■	■	■	■	■	■	■						
F						■	■	■	■	■	■	■	■	■	■	■	■	■						
S								■	■	■	■	■	■	■										
S																			■	■	■	■		

4.6. Overview of Building D

Building D is a secondary school located in East London which replaced an old building on the same site in 2010. It is a 3-storey building comprising the ground, first and second floors. There are also two small 4-storey elements within the building. The external skin is formed from pre-cast concrete panels finished with brick tiles to achieve air permeability less than 5.0 $m^3/(h.m^2)$ at 50 Pa. Vertical perforated fins are positioned on east and west elevations to provide solar shading. Two ribbons of teaching spaces are separated by landscaped courtyards and enclosed at either end by a pod, one a library and resource center (north orientation), the other the main assembly hall and refectory (south orientation).

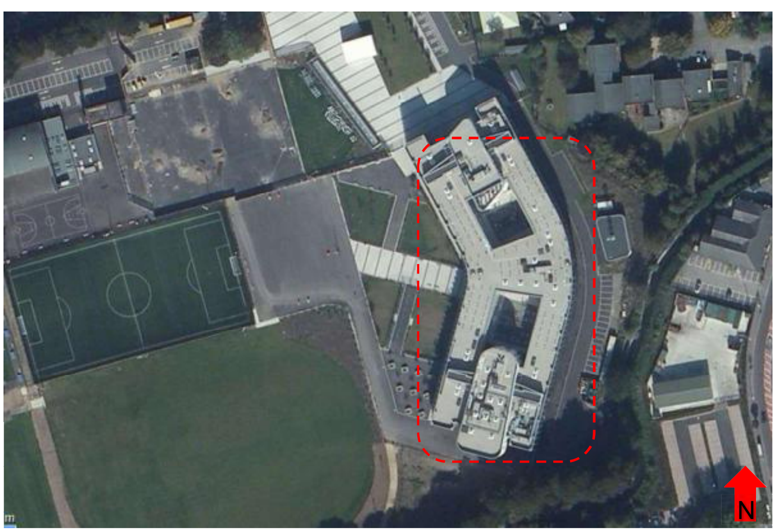


Figure 4.10. Aerial view of Building D and its surroundings

The building has been designed as a 2,000 pupil facility. Nominal occupancy during the post-occupancy evaluation was 2,000 (1,800 pupils + 200 teaching and support staff). The occupancy hours are 8:30-15:30. Cleaning hours are between 7:00-8:30 and 15:30-18:00 over weekdays. A night school was also running between 18:00-22:00 on Wednesdays during the post-occupancy evaluation. Occasionally, some tutorials and extra-curricular activities take place after 15:30 during week days or on Saturdays.

Figure 4.11. Building D: entrance elevation on north façade (left), courtyard elevation with perforated fins on west façade (right)

Table 4.8. The building services strategy for Building D

Service	Description
Heating	The design intent was to have a ground source heat pump system as the lead heating source supplemented by gas-fired condensing boilers. Radiators are installed as heating terminals in most spaces. Total installed heating capacity is 1380 kW including domestic hot water use.
Ventilation	The building is predominantly naturally ventilated. Demand-controlled mechanical ventilation with heat recovery achieved by plate heat exchangers is provided to internal spaces that have no access to external facades, the kitchen, and acoustically sensitive spaces (e.g. drama studio, music and rooms for pupils with special needs).
Comfort cooling	A number of spaces with high internal gain such as ICT classrooms are provided with comfort cooling. Free cooling is provided to the active chilled beams installed in these spaces. No refrigerant is used in the ground source heat pump system.
Domestic hot water	A hot water calorifier is served by the low temperature hot water loop through a plate heat exchanger to provide domestic hot water.
Lighting	T5 fluorescent lamps are installed in classrooms with daylight sensors and Passive Infrared Sensors (PIR). Recessed compact fluorescent lamps with PIR sensors are installed where there is false ceiling such as in the corridors, cellular office spaces and sanitary spaces. Internal lighting was designed to have a power density of 7 W/m² @ 300 lux in classrooms.

The majority of spaces within the school are naturally ventilated. Cross ventilation is provided to most classrooms by operable windows on the external façade and motorised vents on the courtyard side that are linked to the classrooms via a plenum in the corridor. Feedback from a traffic light control system prompts teachers to use manually operated windows to reduce CO_2 levels. Secure night-time ventilation is also provided by louver mounted operable windows. The motorised vents are controlled by the BMS. Some classroom and office spaces on top floor have stack ventilation with the same control strategy. Stack ventilation is also specified for the central atrium space.

Figure 4.12. Cross ventilation strategy for Building D: operable windows (left), plenum air intake (middle), and motorised vents on the corridor side (right)

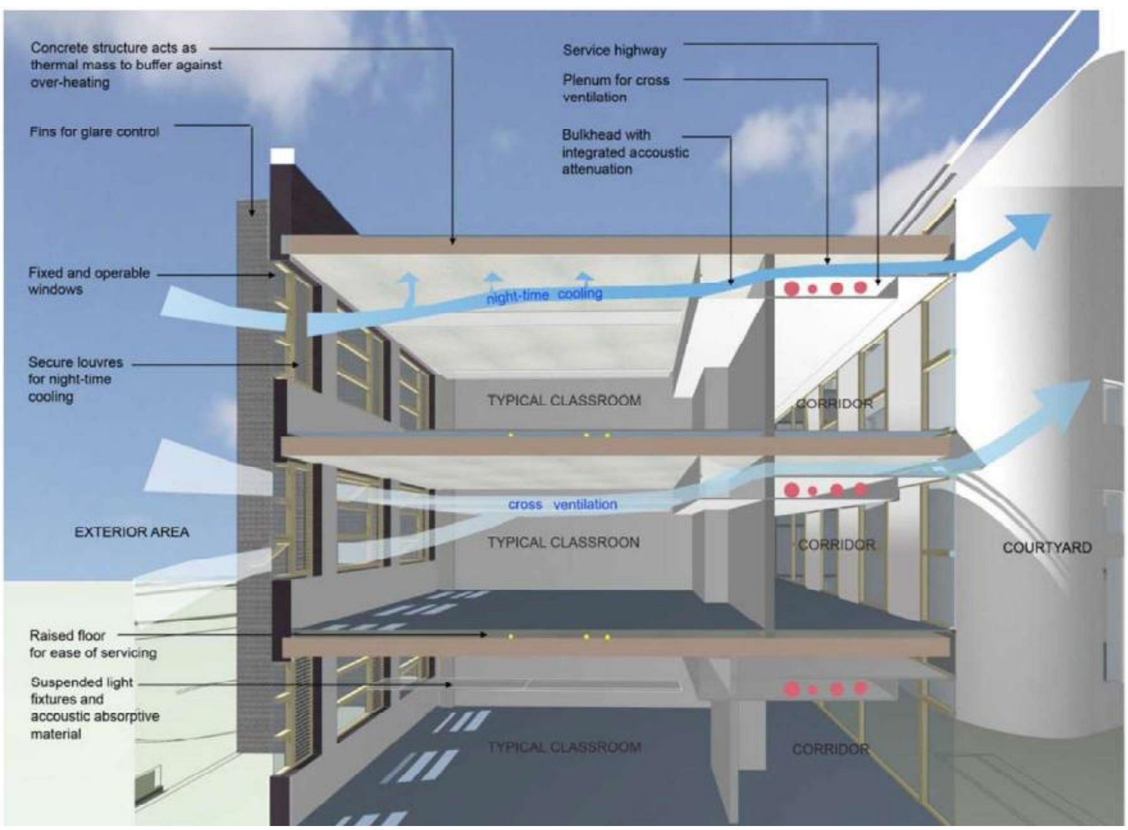


Figure 4.13. Building D ventilation strategy, extracted from the building log book (Courtesy of Max Fordham Engineers)

Table 4.9. The main heating schedule set up in the Building Management System for Building D during the post-occupancy evaluation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
M								■	■	■	■	■	■	■	■	■	■							
T								■	■	■	■	■	■	■	■	■	■							
W								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
T								■	■	■	■	■	■	■	■	■	■							
F								■	■	■	■	■	■	■	■	■	■							
S																								
S																								

4.7. Overview of Building E

Building E is an academy located in East London which replaced an old community school on the same site in 2007. It is a 4-storey concrete frame and precast slab with exposed ceiling comprising the lower ground, ground, first, and second floors. The external envelop of the building consists of lightweight curtain wall with solid panels, internal blinds, and some rendered facades. This deep plan building comprises two triangular wings located either side of a central atrium. The classrooms and staffrooms are located around this central space. Two larger facades of the building face North East and North West and, therefore, the design team decided that there is no need for external shading.

The building is located close to a main road. Therefore, mechanical ventilation strategy was adopted to meet BB93 acoustic requirements. Each classroom has one top-hung operable window. Comfort cooling is also provided to a number of classrooms with high internal gain via chilled water loop and fan coil terminals.

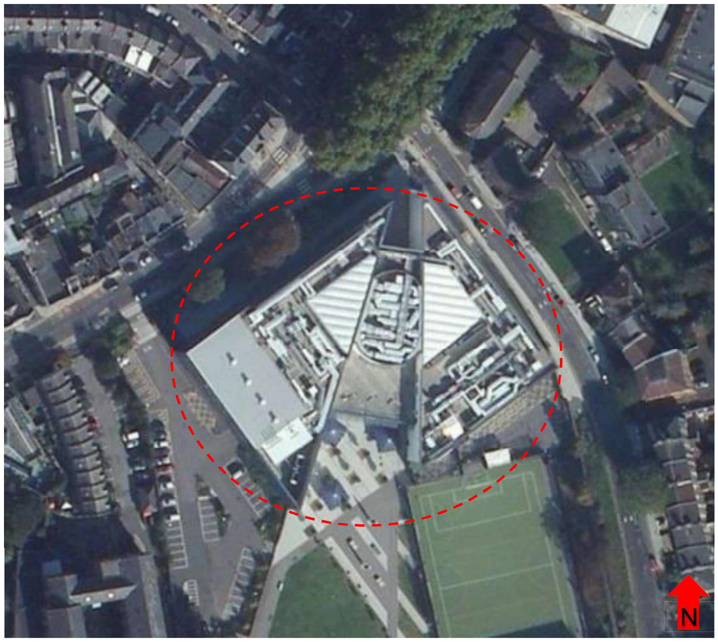


Figure 4.14. Aerial view of Building E and its surroundings

The academy has been designed as a 1,200 pupil facility. Nominal occupancy during the post-occupancy evaluation was 1,000 (900 pupils + 100 teaching and support staff). The occupancy hours are 8:00-16:00. Cleaning hours are between 6:00-8:00 and 16:00-20:00 over weekdays. Occasional extra-curricular activities and events take place after 16:00 during week days and over the weekends.

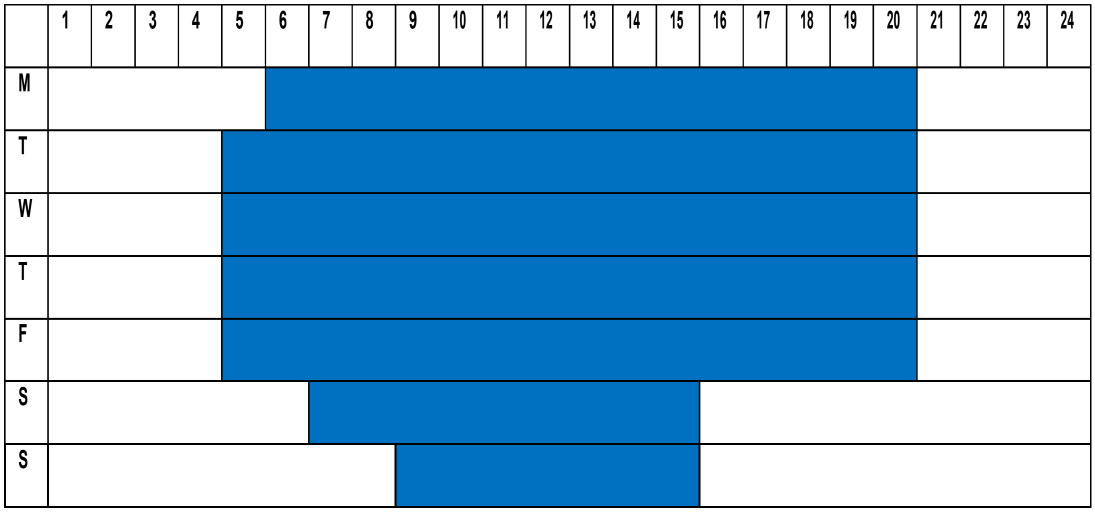
Figure 4.15. Building E: entrance elevation on north façade (top), courtyard elevation on south façade (bottom)

Table 4.10. The building services strategy for Building E

Service	Description
Heating	Heating is provided by gas-fired condensing boilers that serve the heating coils installed in the main air handling units (constant temperature heating loop), the radiators (installed in classrooms and staff rooms), and the under-floor heating system (installed in dining and sport halls). Total installed heating capacity is 1080 kW.
Ventilation	The building is predominantly mechanically ventilated. All main air handling units have plate heat exchangers or run around coils for heat recovery and were designed to be inverter driven. A night time cooling strategy was also specified for summertime operation to take advantage of the heavy thermal mass associated with the exposed ceilings. The main air handling units were designed to operate over night until the common return air temperature is 15 °C.
Comfort cooling	2 central air-cooled chillers with total installed capacity of 417 kW provide cooling to the chilled water loop that serves the two-pipe fan coil units installed as cooling terminals in a number of spaces including ICT enhanced class rooms, music rooms, food technology, and drama studio. The cooling load of the server room and data hub rooms is also satisfied by the same central chilled water system.
Domestic hot water	Domestic hot water is provided via a single pipe system by three stand-alone gas-fired heaters and a packaged booster set.
Lighting	T5 fluorescent lamps with Passive Infrared Sensors (PIR) in classrooms, compact fluorescent lamps in corridors, and high level metal halide in the atrium are installed.

Figure 4.16. Internal view of a typical classroom with exposed ceiling and one operable window (left), the outlets for mechanical ventilation (right)

Table 4.11. The main heating schedule set up in the Building Management System for Building E during the post-occupancy evaluation



4.8. Comparative Context

The following Tables and Figure represent the buildings' comparative context from external conditions to indoor context: Table 4.12 compares the regional 10 year average heating degree-days for the case studies. Table 4.13 presents the external envelope characteristics. Table 4.14 and Figure 4.17 provide the schedules of accommodation. Table 4.15 identifies the HVAC system types and the areas served by each system. Table 4.16 presents the areas served by different ventilation strategies. Table 4.17 summarises the major energy efficiency measures prescribed by designers. Finally, Table 4.18 presents the outcomes of the regulatory energy performance calculations and other sustainability credentials achieved.

Table 4.12. Average heating degree-days (HDD) over the period 1998-2007 (CIBSE, 2008)

Degree-day information	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Degree-day region	West Pennines	West Pennines	North Eastern	Thames Valley	Thames Valley
HDD over the base temperature of 15.5 °C	2,037	2,037	2,237	1,709	1,709

Table 4.13. External envelope characteristics reported in the Building Regulations compliance reports[8]

Building	External wall U value (W/m²°K)	External floor U value (W/m²°K)	Roof U value (W/m²°K)	Windows and roof lights U value (W/m²°K)	Doors U value (W/m²°K)	Air tightness (m³/(m².hr) @50 Pa)
Building Regulations limit	0.35	0.25	0.25	2.2	2.2	10
Bldg. A	0.35	0.25	0.25	2.19	2.19	9.20 (measured)
Bldg. B	0.20	0.21	0.16	2.03	1.97	9.09 (measured)
Bldg. C	0.35	0.25	0.25	2.11	2.19	10 (target)[9]
Bldg. D	0.35	0.25	0.25	2.15	2.2	4.36 (measured)
Bldg. E	0.35	0.25	0.25	Windows: 2.2 Roof lights: 2.6	2.2	9.78 (measured)

[8] The quoted U values are the area-weighted average U values used in the regulatory calculations.
[9] The pressure test result for this building was not available in the building documentation.

Table 4.14. Schedules of accommodation, extracted from as-built architectural drawings (% of total useful floor area)

Activity type	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Cellular office	2.0 %	2.1%	2.6 %	1.3 %	2.3 %
Changing facilities	2.1 %	0.0 %	2.1 %	0.4 %	1.7 %
Circulation areas	20.0 %	20.7 %	20.0%	24.3 %	21.8 %
Classroom	19.6 %	20.6 %	28.5 %	25.8 %	31.4 %
Common room/staff room	4.4 %	3.2 %	2.2 %	1.4 %	1.5 %
Dry sport halls	5.8 %	1.4 %	7.4 %	0.0 %	6.5 %
Eating/drinking area	3.2 %	5.1 %	2.1 %	2.8 %	4.5 %
Food preparation area	1.3 %	2.1 %	1.5 %	1.3 %	1.5 %
Hall/lecture theatre/assembly area[10]	6.9 %	2.2 %	11.0%	8.2 %	7.4 %
High density IT work space	3.1 %	8.0 %	4.2 %	5.0 %	2.0 %
IT equipment	0.6 %	0.5 %	0.6 %	0.3 %	0.3 %
Laboratory	7.3 %	8.2 %	4.7 %	9.1 %	6.3 %
Meeting Room	0.6 %	1.1 %	0.3 %	0.2 %	0.5 %
Open plan office	2.2 %	2.6 %	0.4 %	1.0 %	1.9 %
Plantroom	1.6 %	2.7 %	1.2 %	2.6 %	1.5 %
Reception	0.8 %	1.5 %	1.2 %	0.3 %	0.2 %
Storage area	7.4 %	5.7 %	3.7 %	4.5 %	4.4 %
Swimming pool	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
Toilet	3.0 %	2.3 %	3.5 %	3.3 %	2.3 %
Workshop	8.1 %	10.0 %	2.8%	8.2 %	2.0 %

[10] Includes open-plan learning resource spaces.

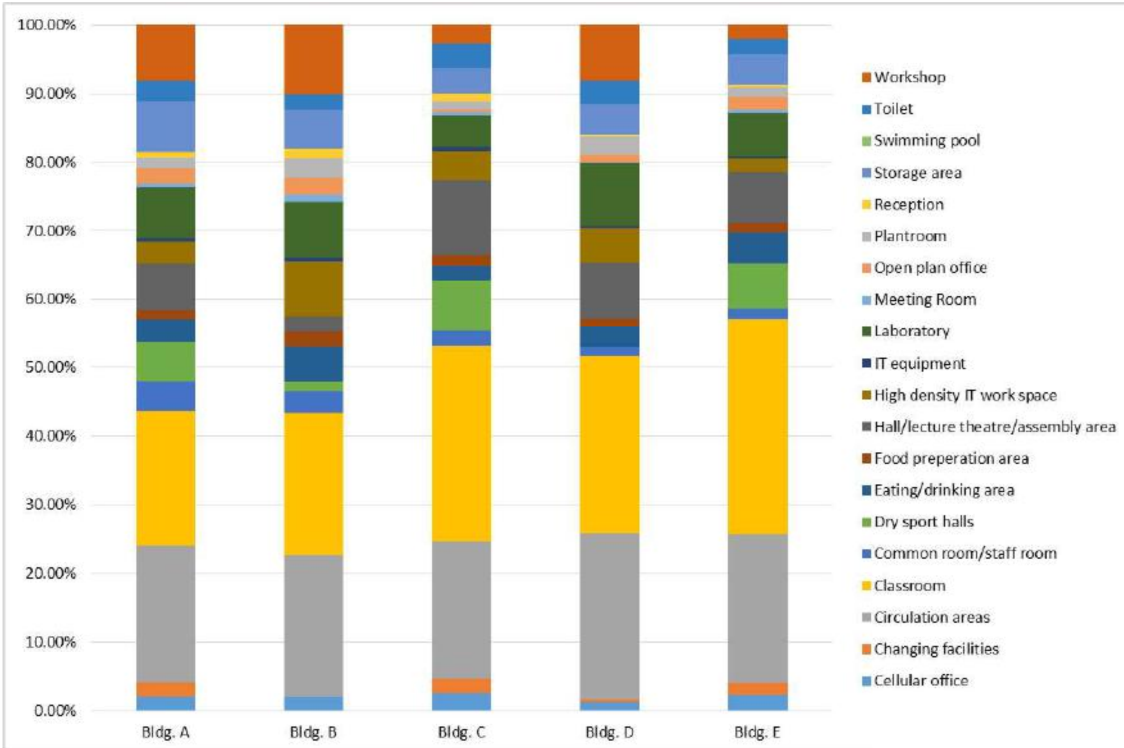


Figure 4.17. Illustration of schedules of accommodation
(Extracted from as-built architectural drawings)

Table 4.15. HVAC system type, extracted from as-built engineering drawings (% of total useful floor area)

HVAC system type	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Central heating using water: radiators and radiant panels	71.9 %	78.6 %	57.0 %	88.3 %	71%
Central heating using water: floor heating	14.6 %	0.0 %	17.0 %	0.0 %	10.5%
Chilled beams	11.3 %	0.0 %	0.0 %	8.8 %	0.0 %
Split or multi-split systems[11]	0.6 %	18.7%	16.1 %	0.3 %	0.0 %
Fan coil systems (two-pipe units, cooling only)	0.0 %	0.0 %	0.0 %	0.0 %	17%
Constant volume system (variable fresh air rate)	0.0%	0.0 %	8.7%	0.0 %	0.0%
No heating or cooling	1.6 %	2.7 %	1.2 %	2.6 %	1.5 %

Table 4.16. Ventilation strategy, extracted from as-built engineering drawings (% of total useful floor area)

Ventilation Strategy	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Natural ventilation	12%	17%	72%[12]	78%	10%
Mechanical ventilation	88%	83%	28%	22%	90%

[11] Includes Variable Refrigerant Flow (VRF) systems and also split systems used for the cooling of server rooms and data hub rooms.

[12] Most classrooms in Building C have booster extract fan facility to enhance ventilation if required (See Figure 4.9). However, the default mode of operation is natural ventilation.

Table 4.17. Major design measures prescribed to achieve good level of energy performance

Design measures	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Passive measures	Average design U value reported for external envelope including glazing: 0.54 W/m²°K Air permeability: No greater than 10 m³/(m².hr) at 50 Pa Solar shading applied to some south-facing classrooms (retrofitted)	Average design U value reported for external envelope including glazing: 0.17 W/m²°K Air permeability: No greater than 10 m³/(m².hr) at 50 Pa	Average design U value reported for external envelope including glazing: 0.42 W/m²°K Air permeability: No greater than 10 m³/(m².hr) at 50 Pa Solar shading applied to the south facade	Average design U value reported for external envelope including glazing: 0.51 W/m²°K Air permeability: No greater than 5 m³/(m².hr) at 50 Pa External shading on east and west facades	Average design U value reported for external envelope including glazing: 0.61 W/m²°K Air permeability: No greater than 10 m³/(m².hr) at 50 Pa Exposed ceiling (heavy thermal mass)
Energy efficiency measures	Condensing gas-fired boilers (Gross seasonal efficiency: 94%) Heat recovery and variable speed control for mechanical ventilation system Efficient lighting with automated control	Condensing gas-fired boilers (Gross seasonal efficiency: 95%) Heat recovery and variable speed control for mechanical ventilation system Efficient lighting with automated control	Condensing gas-fired boilers (Gross seasonal efficiency: 95%) Predominantly naturally ventilated (limited mech. vent.) Heat recovery and variable speed control where mechanical ventilation is used Efficient lighting with automated control	Condensing gas-fired boilers (Gross seasonal efficiency: 95%) Predominantly naturally ventilated (limited mech. vent) Heat recovery and variable speed control where mechanical ventilation is used Efficient lighting with automated control	Condensing gas-fired boilers (Gross seasonal efficiency: 96%) High efficiency chillers (Energy Efficiency Ratio: 3.28) Mechanical ventilation with heat recovery and variable speed control specified Efficient lighting with automated control
Low or Zero Carbon (LZC) systems	Ground source heat pumps for heating and cooling	Solar thermal panels for domestic hot water	Biomass boiler and solar thermal panels	Ground source heat pumps for heating and free cooling	None

Table 4.18. Asset ratings and BREEAM ratings of the case studies

Rating	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Asset rating (EPC)	B/47	B/41	B/34	B/31	n/a
BREEAM rating	None	Very Good	Very Good	Excellent	Good

4.9. Summary

The case studies represent five schools in three climatic regions across England that predominantly provide secondary education and all were procured under the BSF programme. They also represent various design strategies including passive measures related to building form, fabric, external shading, daylight provision, and natural ventilation to more active measures such as efficient heating, mechanical ventilation, and comfort cooling. Furthermore, a variety of Low or Zero Carbon systems were installed in these buildings. These case studies therefore provide an opportunity to carry out in-depth investigations without being distracted by particular issues and systems prevalent in one or two buildings that may lead to particularisation and impede analytic generalisation.

5. Operational Energy Performance

5.1. Introduction

This Chapter provides a review of the operational energy performance of the case studies. First, the operational benchmarks available for schools are introduced. Then the annual energy performances of the case studies are compared against the most relevant benchmarks. The average annual electrical power demands of the case studies are also presented and analysed. Finally, the key operational root causes of underperformance identified through the forensic POE studies are discussed along with a number of improvement opportunities for energy end-uses.

5.2. Operational Benchmarks

Operational energy benchmarks used for buildings are often based on statistical samples of existing buildings compiled for each building category. In the UK, the median of an appropriate sample is taken as *typical* benchmark, while the 25th percentile is referred to as *good practice* benchmark. Table 5.1 includes a number of benchmark Energy Use Intensities (EUIs) available for schools.

Table 5.1. Operational benchmarks for schools

Benchmark	Fossil-thermal EUI (kWh/m²/annum)		Electricity EUI (kWh/m²/annum)	
	25th percentile (Good practice)	Median (Typical)	25th percentile (Good practice)	Median (Typical)
DEC dataset:				
- **primary**	97	122	36	44
- **secondary**	94	121	42	51
CIBSE TM 46	-	150	-	40
CIBSE Guide F:				
- **primary**	113	164	22	32
- **secondary**	108	144	25	33
ECG073:				
- **primary**	126	173	20	28
- **secondary**	136	174	24	30

The benchmarks set out in Energy Consumption Guide 73 are based on the 1995/1996 energy records of over 2,000 schools from 18 local education authorities obtained through the former Department of the Environment, Transport and the Regions' (DETR's) Energy Efficiency Best Practice programme (BRECSU, 1996). CIBSE Guide F benchmarks for schools, first reported in Good Practice Guide 343 (GPG 343), are also based on recorded energy data for 2,000 schools in England in 1999-2000 (Carbon Trust, 2003). Guide F benchmarks underpin CIBSE TM46 benchmarks that are used for statutory operational ratings. However, TM46 benchmarks are more condensed and updated to take into account additional available data (CIBSE, 2012). Regional weather differences are taken into account in TM46 and the respective benchmarks have been adjusted for a baseline of 2021 degree-days which is the average heating degree-days with a base temperature of 15.5 °C for the UK over the period 1998-2007 (CIBSE, 2008). TM46 benchmarks currently do not differentiate between primary and secondary schools.

More up to date benchmarks can be derived from the records available for Display Energy Certificates (operational ratings). The benchmarks reported from DEC dataset in Table 5.1 are based on the UCL review of the records available for 6,686 primary schools and 1,045 secondary schools subject to the same weather correction baseline used in TM46 (CIBSE, 2015 a). Two clear trends can be observed from reviewing the DEC data: reduction in fossil-thermal energy use, and a statistically significant difference in electricity use between primary and secondary schools. None of these is reflected in the current statutory benchmarks for operational ratings.

While these benchmarks are useful to inform the assessment of schools' energy performance, they have their limitations and must be applied with caution especially in the case of new-build schools. They are based on historic records available for existing buildings and are not necessarily indicative of what is achievable with the current construction practices and standards. For example, while a school with fossil-thermal use less than good practice benchmark may be judged to be a well performing building, it is not certain whether it has met its expected performance given the fabric and airtightness specified for it. Furthermore, benchmarks derived from past data cannot effectively represent the emerging trends in building design. The operational against designed review presented in Chapter 8 therefore complements the preliminary benchmarking provided in this Chapter.

5.3. Annual energy performance

Table 5.2 includes the breakdown of the fossil-thermal use for all case studies. To be comparable, the heating consumptions over the monitoring period were normalised based on 2021 heating degree-days in accordance with CIBSE TM46. Natural gas is the fossil fuel used in all buildings. The biomass boiler installed for Building C was not operational during the monitoring period. Figure 5.1 compares the annual fossil-thermal performance of the case studies against the operational benchmarks. Good practice and typical benchmarks derived from the secondary schools represented in the DEC dataset and the TM46 benchmark for operational ratings have been used for benchmarking. The ECG073 typical benchmark for secondary schools is also included to represent the historical trend of fossil-thermal benchmarks that have come down over the years.

Table 5.2. Annual fossil-thermal performance of the case studies

Energy Use Intensity (kWh/m²/annum)	**Bldg. A**	**Bldg. B**	**Bldg. C**	**Bldg. D**	**Bldg. E**
Space heating	60.1	39.6	97.2	84.9	136.3
Domestic hot water	9.9	14.2	20	20	12.4
Catering and lab	9	0	1.4	5.6	7
Total fossil-thermal use	**79**	**53.8**	**118.6**	**110.5**	**155.7**

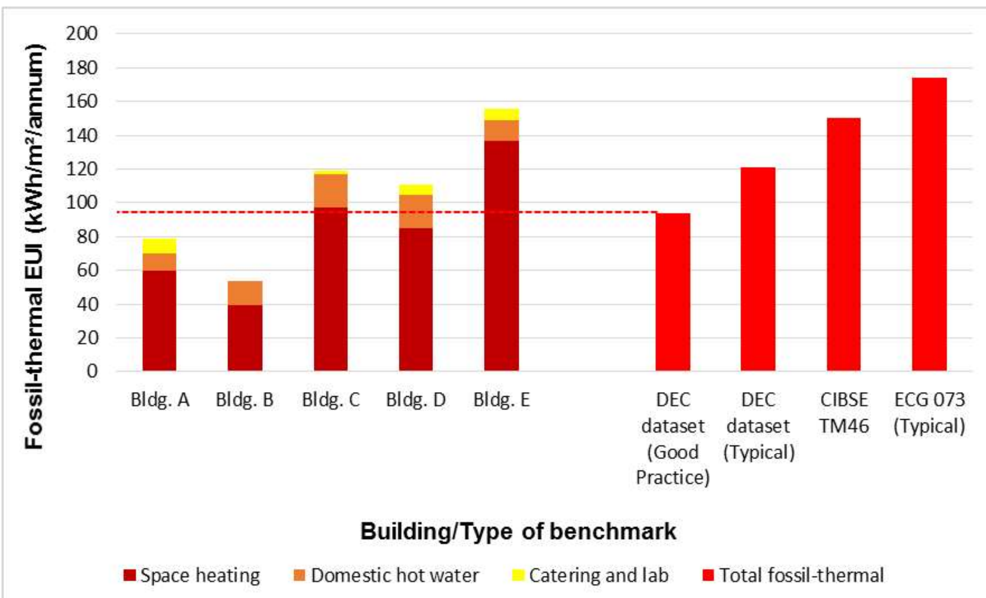


Figure 5.1. Annual fossil-thermal performance of the case studies against the benchmarks for secondary schools

Buildings A and B perform better than the good practice benchmark derived from the DEC dataset by 16% and 43% respectively. The performances of Building C and D fall between good practice and typical benchmarks derived from the DEC dataset. The worst case study is Building E with a total fossil-thermal performance which is 29% worse than the typical benchmark derived from the DEC dataset and 4% worse than the TM46 benchmark which was meant to represent the median existing stock. Figure 5.2 presents the cumulative frequency of the fossil-thermal energy use intensities extracted from the DEC dataset and identifies the case study buildings on the graph.

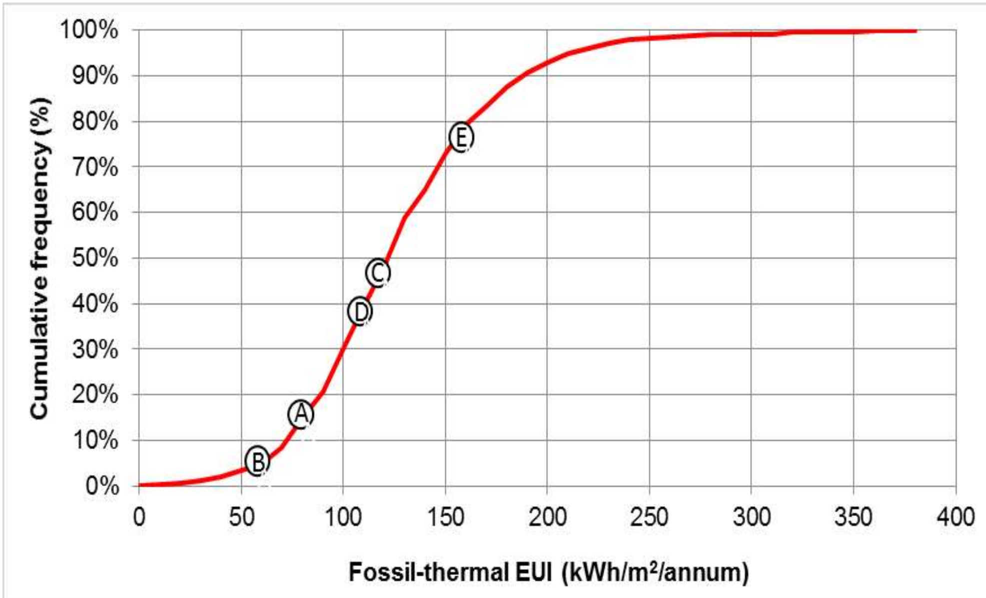


Figure 5.2. Cumulative frequency of the fossil-thermal EUIs for secondary schools from the DEC dataset

Table 5.3 includes the breakdown of the electricity use for all case studies. Auxiliary energy includes energy used for all supply and extract fans, pumps, and control. ICT equipment includes server rooms, data hub rooms and their associated cooling energy, while desktop computers, laptops, and other plug-in loads are covered by ‘small power’ end-use. This convention is consistent with CIBSE energy assessment and reporting methodology (CIBSE, 2006).

Figure 5.3 compares the annual electricity use of the case studies against the operational benchmarks for secondary schools. Electricity use of all case studies is worse than all benchmarks. The best performers are Building D and Building B with relatively close total electricity use despite different ventilation strategies. Electricity use of Building D is around 37% higher than the typical benchmark derived from the DEC dataset and 75% higher than the TM46 benchmark. Figure 5.4 also shows that the cumulative frequency of the electricity use in all case studies is above 80% indicating that these buildings are among the 20% worst performers in the sample. Electricity use associated with ICT equipment and plug-in loads in modern secondary schools and academies are to some extent responsible for this performance. However, it should be noted that typically more than half the electricity use in these case studies is consumed by building services. This is as high as 72% in the worst performing building (Building E) which is indicative of the effect of building services and control strategy on this poor performance.

Table 5.3. Annual electricity use of the case studies

Energy use intensity (kWh/m²/annum)	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Space heating	3.9	3.3	2	1.8	5.9
Cooling	0.8	6.8	3.8	0	6.6
Auxiliary	47.5	9.9	15.7	22.3	61.6
Internal lighting	29	17.4	32.5	15.7	30.1
External lighting	4.6	1.4	2.3	1.7	2.9
Small power	15.2	12.9	12.8	9.4	14.4
ICT equipment	16	16.9	22	14.6	20.3
Catering	8.4	7.5	7	4.3	6.5
Lift	0.2	0.4	0.2	0.1	0.3
Total electricity	**125.6**	**76.5**	**98.3**	**69.9**	**148.6**

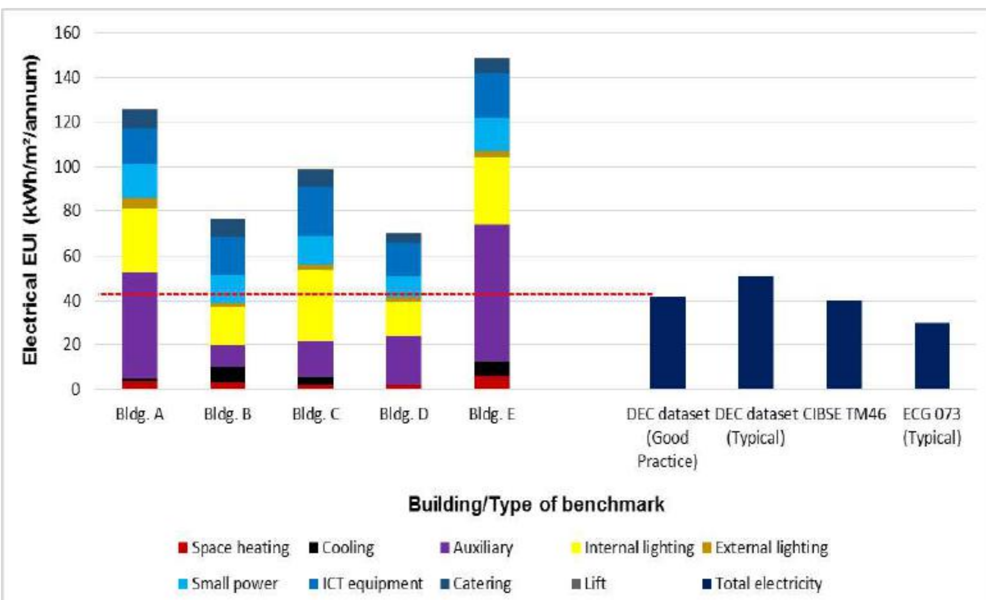


Figure 5.3. Annual electricity use of the case studies against the benchmarks

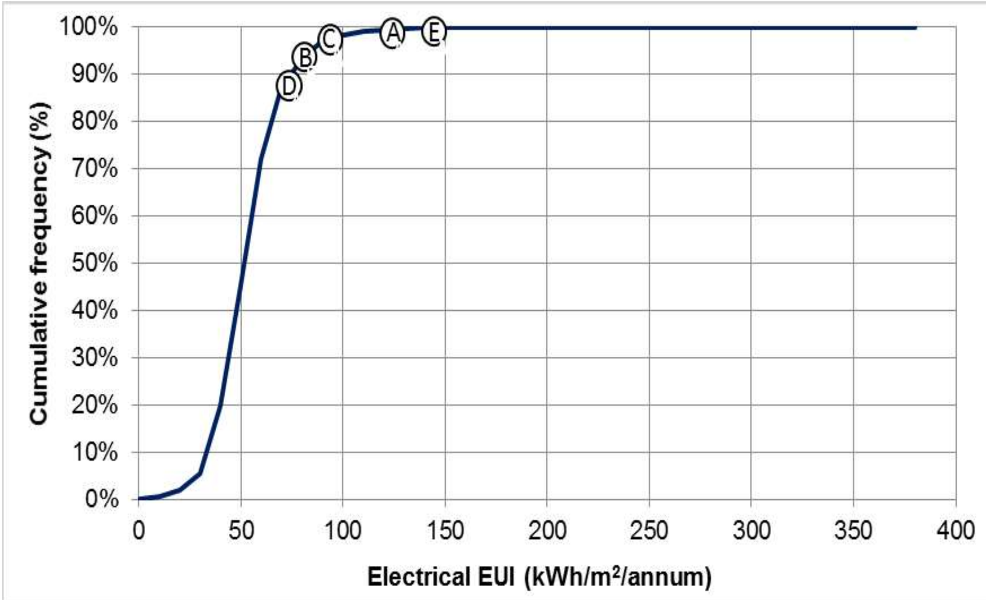


Figure 5.4. Cumulative frequency of the Electrical EUIs for secondary schools from the DEC dataset

Figure 5.5 compares the total performance of the case studies against the benchmarks using CO_2 emissions associated with energy use as the performance metric. The CO_2 emissions' conversion factor used for gas and electricity are 0.19 and 0.55 kg CO_2/kWh respectively in accordance with CIBSE TM46.

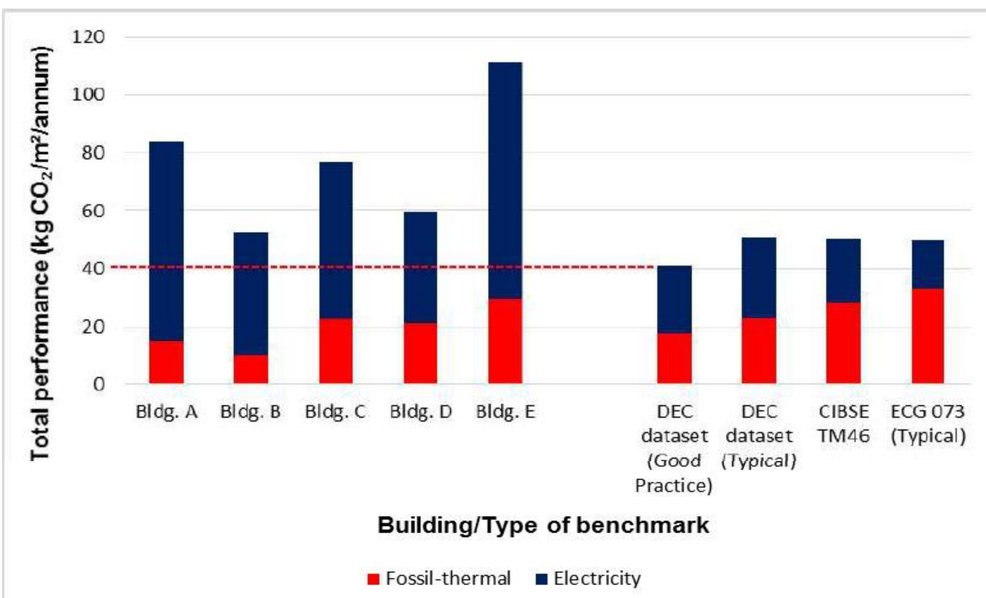


Figure 5.5. Total annual performance of the case studies against the benchmarks (Heating components are weather corrected to 2021 heating degree-days)

Total performance of all buildings falls short of the good practice benchmark derived from the DEC dataset. Furthermore, all case studies perform worse than the TM46 benchmark and therefore have operational ratings between E and G. This level of operational performance is not expected from supposedly low-carbon new-build schools and warrants further investigation.

5.4. Electrical power demand

Figure 5.6 illustrates the average daily electrical power demand curves for all case studies normalised by internal gross floor areas. These curves have been derived from the half-hourly electricity data provided by the utility suppliers for one year.

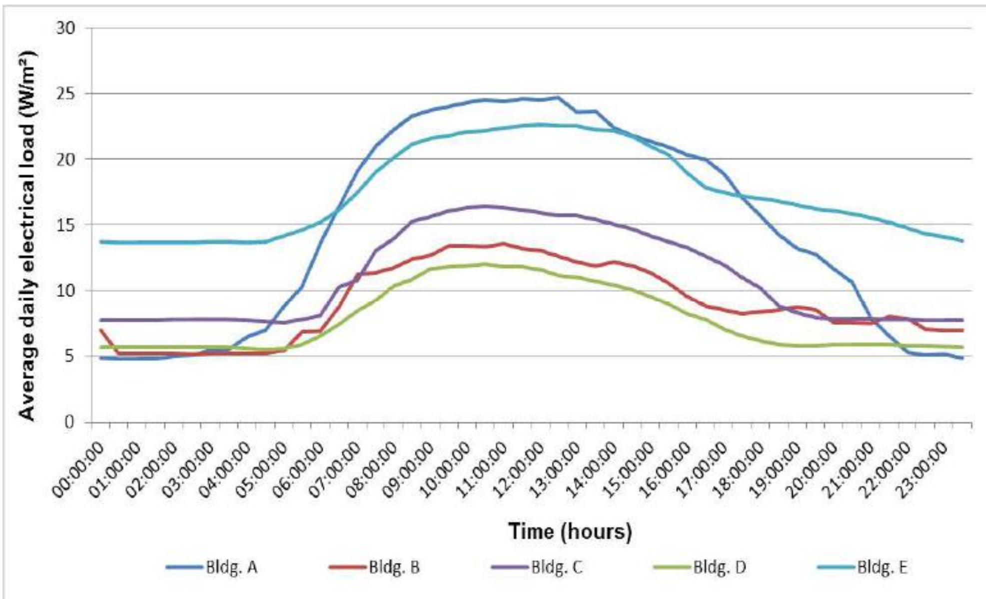


Figure 5.6. Average daily electrical loads in the case studies normalised by gross floor area

The baseloads, the shoulder hours that indicate the rate at which electrical demand raises from base to peak, and the peak loads provide a useful snapshot of buildings' operation. The baseload determines the continuous electrical demand of a building and therefore must be kept to a minimum that is essential for building operation. Buildings A and B have a reasonably low baseload demand at around 5 W/m². The baseload demand in Buildings C and D is a bit higher at around 6-8 W/m² partly due to higher installed capacity in server room and data hub rooms and partly due to the wasteful out-of-hours operation of lighting and small power in Building C and auxiliary pumps in Building D that were not effectively controlled. The baseload electrical demand of Building E is around 60% of its peak load which is excessive and indicative of serious operational problems in this Building.

Purge mechanical ventilation and night time cooling were part of the design strategy for Building E to mitigate the risk of overheating in summer. According to the BMS, six main air handling units with total installed capacity of 44 kW were programmed to provide night-time ventilation. However, the utility bills and electrical demand records do not show such a step change between summer and winter operation. Figure 5.7 and Figure 5.8 show that the minimum baseloads during typical summer and winter weeks were very close at around 150kW.

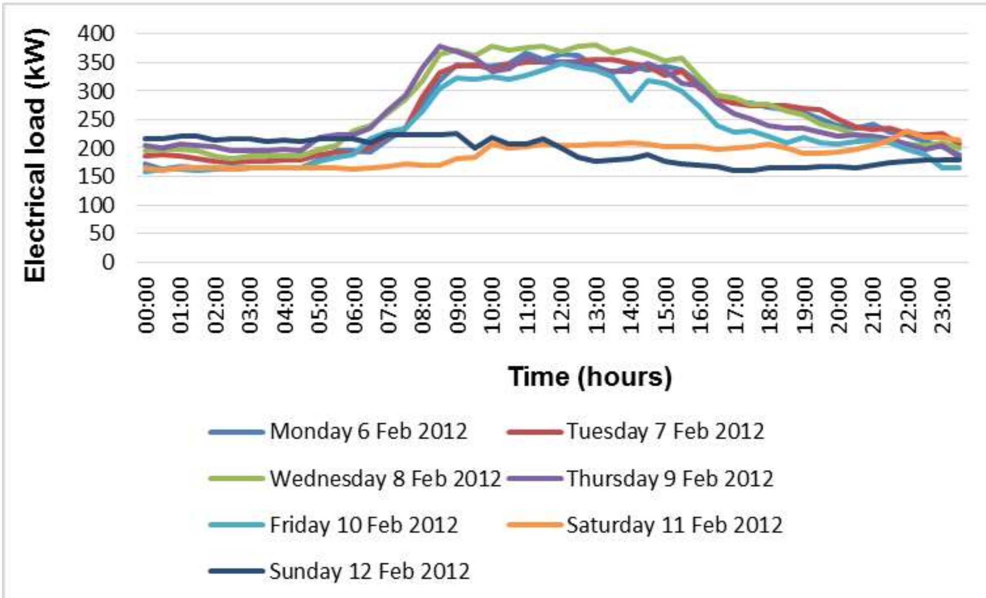


Figure 5.7. Typical term time weekly electrical demand for Building E: heating season

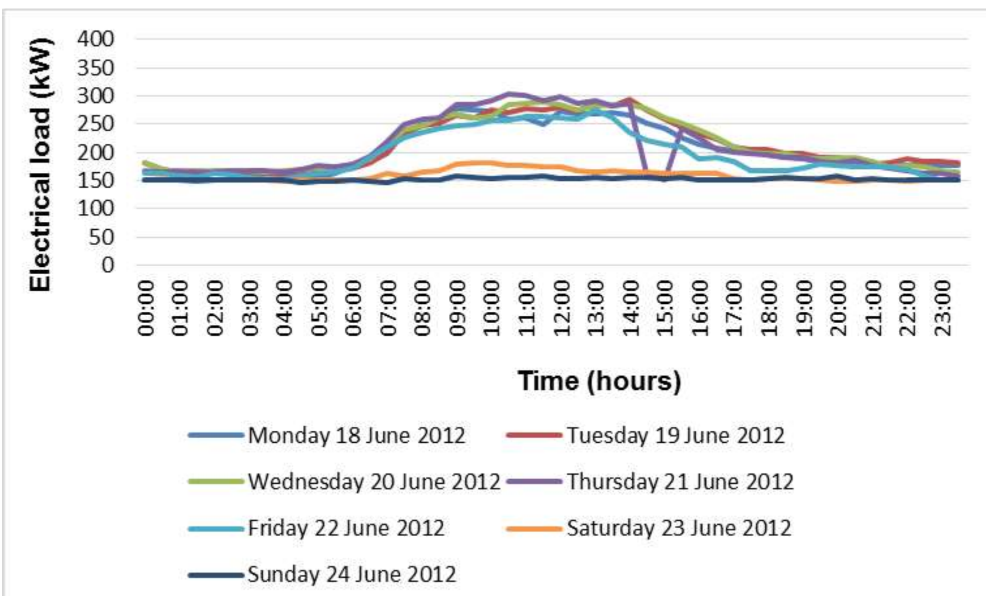


Figure 5.8. Typical term time weekly electrical demand for Building E: summer

Site inspections confirmed that the air handling units were fully operational throughout the year. This also caused problems in terms of thermal comfort especially during winter when the heating systems had to combat the unnecessary cooling effect provided by purge mechanical ventilation and the operation of chillers. Figure 5.9 shows one example of the portable electrical heaters and air conditioners used by the staff in various classrooms and offices to control temperatures in their local environment as the centralised systems were not capable of providing thermal comfort. The control strategy and the BMS system in this building had to be recommissioned only few years after construction to address these operational issues. Another problem in this building that contributed to the high electrical baseload was that 24 hours/7 days cooling to the server room and data hub rooms was provided by the chilled water loop served by the centralised chillers. This led to the continuous operation of the central cooling plant at part load overnight and unnecessary cooling effect in some spaces due to leaking cooling valves.

Figure 5.9. Examples of the portable electric heaters and air conditioners used in Building E

Daytime electrical demands of the case studies also reflect some aspects of their operation. Buildings A and E have peak loads much higher than the rest of the buildings. This is the result of mechanical ventilation with no effective demand control. All main air handling units on both buildings had inverters installed on their supply and extract fans. However, the inverters had only been used to balance the ventilation system at the commissioning stage and were not fully enabled to modulate the fans' speed based on CO_2 concentrations/occupancy levels. This had serious effect on the peak loads.

Building B was mechanically ventilated but thanks to an effective demand-controlled ventilation strategy had a peak load close to Building D that was predominantly naturally ventilated. Building C had higher peak load than Buildings B and D as a result of a higher baseload and also more intense use of internal lighting, small power, and catering facilities during daytime.

Finally, the gradual increase from base to peak load in the case studies is indicative of the improvement opportunities to optimise operational schedules of HVAC systems. Facility managers tend to specify a fixed pre-heating period to ensure the building is warm and ready when the occupants arrive. This may be at odds with weather compensation and optimisation controls that modern heating plants often utilise. It can trigger the operation of the heating plant in advance of the pre-heating period programmed, as in Building A, to provide heating when there is no real demand for it. Another issue observed in the case studies was that the schedules of operation set for mechanical ventilation plants were often coupled with the heating schedules. This meant that the air handling units often started well before building occupants arrived and carried on working after most occupants left the buildings, whereas the buildings had non-air based heating terminals and the main purpose of the mechanical ventilation plants was to provide fresh air to occupants.

5.5. Recurring issues and key lessons

Following on from the issues explained in the previous section, five key themes related to operation emerge from the post-occupancy evaluations that are covered in this section. A review of individual energy end-uses and identified improvement opportunities is also presented in 5.5.6.

5.5.1. Energy supply higher than real demand

The half-hourly electricity data and onsite observations point to an imbalance between energy supply and real demand in the case studies. Figure 5.10 illustrates the annual percentage of electrical energy use in different time periods in the case studies during one full year.

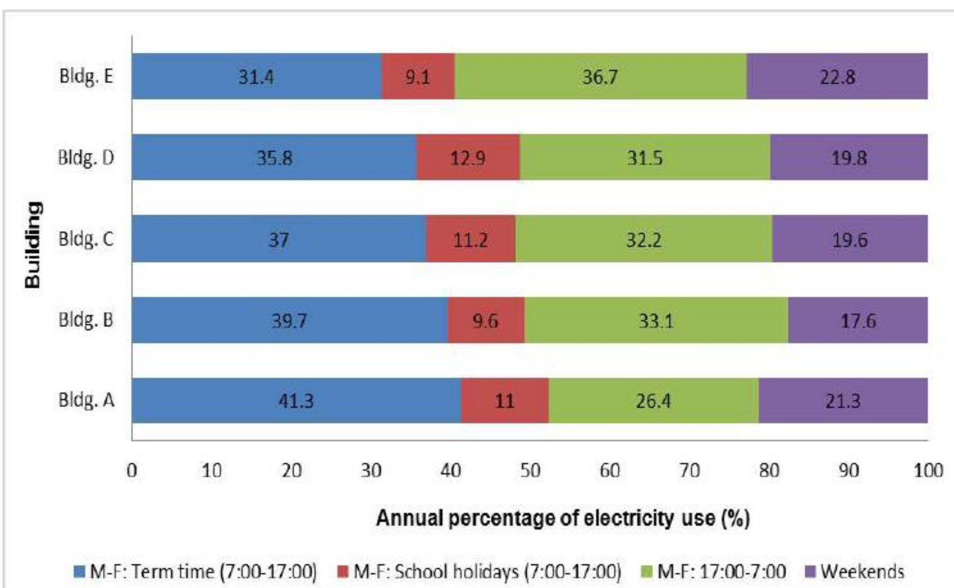


Figure 5.10. Distribution of electricity use in different time periods during a year

It is notable that in all buildings only around 30-40% of total electricity is used in the normal occupancy hours during term time. The allowance for occupancy hours in Figure 5.10 (i.e. 7:00-17:00) includes the core teaching hours plus the time required for preparation and tutorials and in most cases supportive activities such as cleaning the classrooms. Term time refers to the normal schools' calendar in England that covers 39 weeks of a year. Some extracurricular activities often take place during school holidays. Some office spaces are also in use during this time. However, even after taking into account the electricity use during school holidays, electricity use over normal occupancy hours in most cases is still less than 50% of total electricity with a maximum of 52% in Building A. This means that typically more than half the total electricity use of the case studies is consumed when the buildings are not occupied except for occasional extracurricular activities and events that often do not use much space and do not require much electrical power. Although some electrical loads are expected beyond occupancy hours such as the loads associated with server rooms, external lights, and security systems, energy audits in all buildings revealed improvement opportunities to significantly reduce the electrical demand beyond normal occupancy hours.

For example, Figure 5.11 and Figure 5.12 show the average annual electrical demand of Building A along with the range of loads experienced in every half an hour during weekdays and weekends respectively.

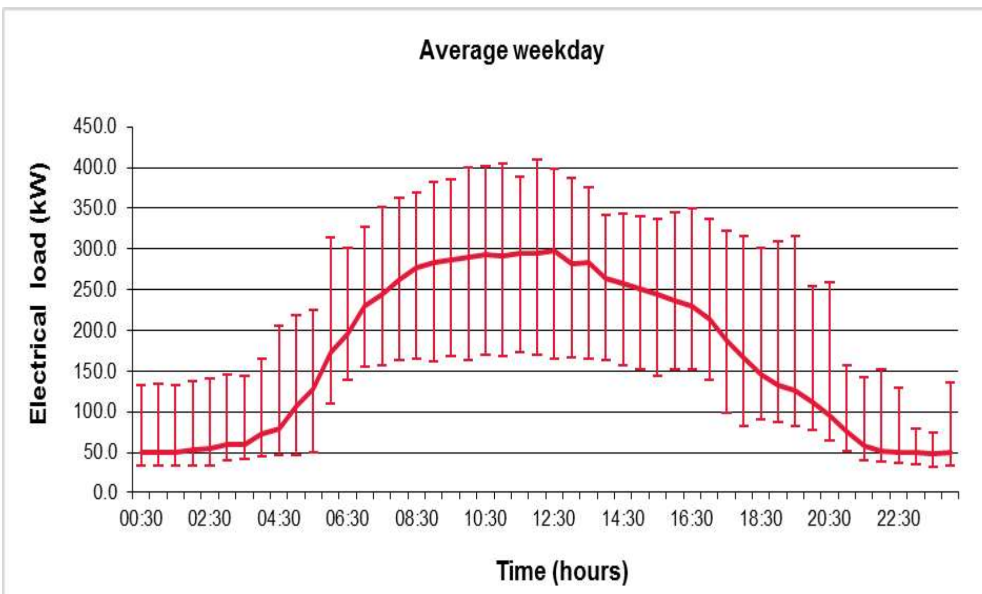


Figure 5.11. Annual weekday electrical demand for Building A

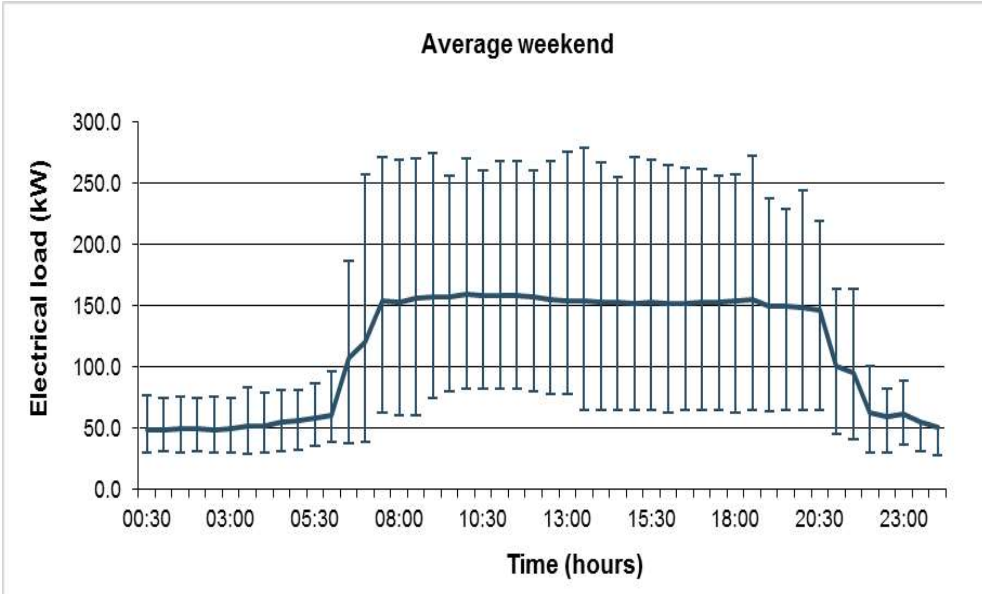


Figure 5.12. Annual weekend electrical demand for Building A

The wide variation in the baseload indicates improvement opportunities in system control and load management overnight. What is more problematic is the step change in the daytime electrical demand over the weekends. The average daytime demand over the weekends is almost constant at 150kW which is around 100kW higher than the baseload. The constant nature of the average load indicates it is related to plant room operation. Figure 5.13 provides a more in-depth view of the variation of electrical loads in Building A during a typical week in heating season.

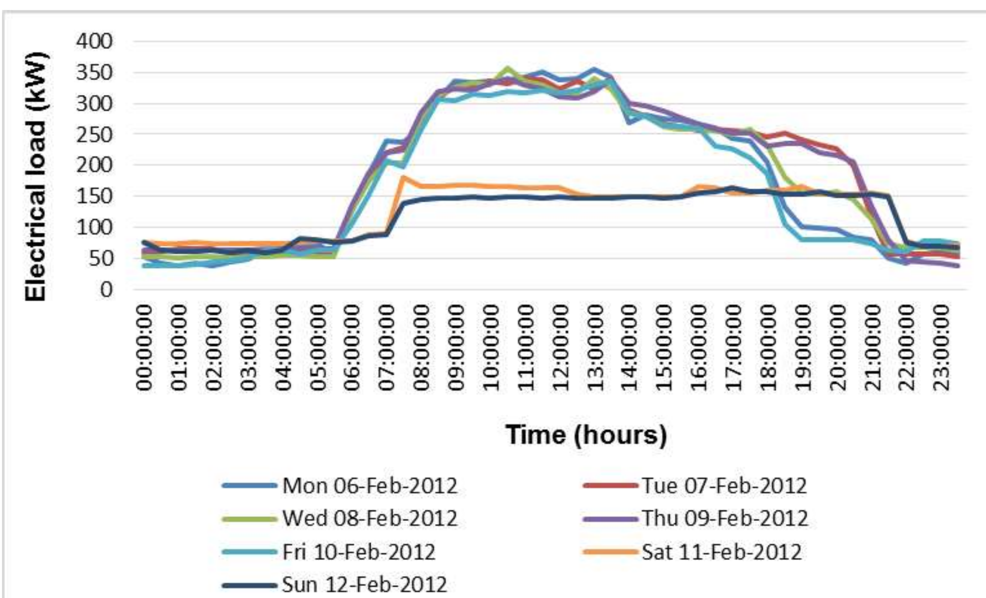


Figure 5.13. Weekly demand profile for Building A in heating season

The slight increase in daytime electrical demand over 150 kW on Saturday might be indicative of limited activity going on in the building. However, the building was categorically closed on Sundays and yet the daytime electrical demand on Sunday is much higher than the baseload. Site inspections revealed that the heating and mechanical ventilation systems were fully operational during the weekends as the default control setting assumed for these systems in the BMS was ON. The records of energy use and demand profiles also confirm this had been a prolonged problem that led to huge waste of energy.

Figure 5.14 shows the distribution of the energy used by gas-fired boilers in Building A during different time periods in a typical week in heating season based on the BMS data logs. Sample manual meter reading were compared with the BMS readings to ensure the BMS data was robust.

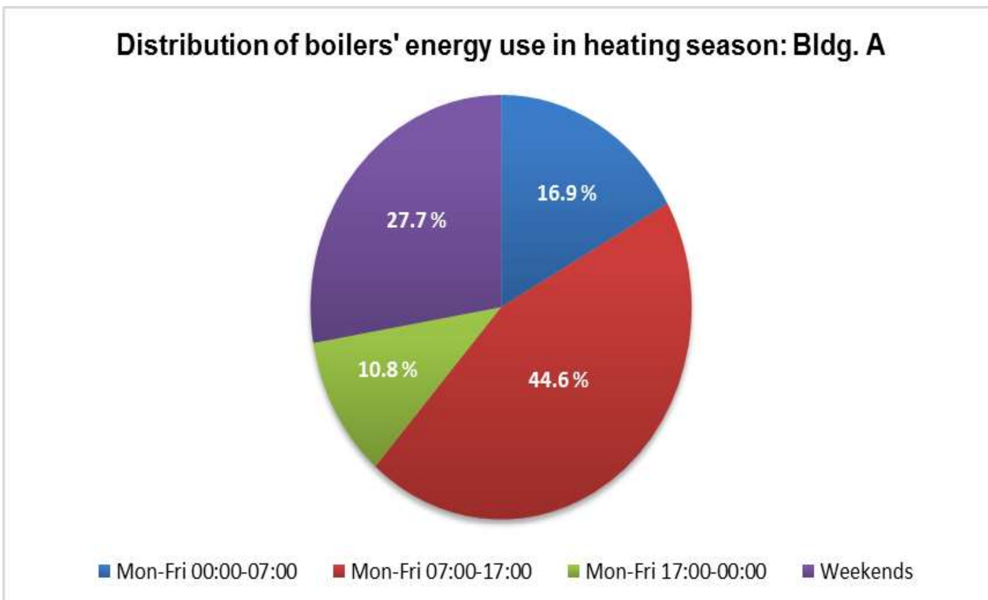


Figure 5.14. Distribution of boilers' energy use during a typical week in heating season: Building A

Figure 5.14 confirms the same problem identified with electricity use is applicable to fossil-thermal use; less than 50% of the fossil-thermal energy was used during the core occupancy hours over the working days. Almost 17% of the energy was used overnight to prepare the plant room for daytime operation, and a quarter of the energy was wasted over the weekend with no real demand.

The observations made in the other case studies also confirm the waste of heating energy in schools. The heating terminals in empty classrooms were often warm during school holidays in the heating season. The central heating plant was fully operational on the grounds that parts of the building might be occupied by staff, and thermostatic valves installed for radiators or wall mounted thermostats installed for under-floor heating systems were often not used to limit the heating provided to vacant spaces.

The waste of heating energy in Building A also confirms the shortcomings of statistical benchmarking. According to Figure 5.1, the fossil-thermal performance of Building A is better than the good practice benchmark derived from the DEC dataset, and yet Figure 5.14 reveals actual performance could have been much better. Therefore, statistical benchmarking that does not take into account building age and construction standards might send a misleading message about the performance of new buildings.

5.5.2. Poor HVAC zoning

Zoning arrangements specified for HVAC systems are very important to strike the right balance between real demand and energy supply. However, these arrangements were often not adequate and very rarely used effectively in the case studies.

The open-plan philosophy frequently adopted for offices and now increasingly specified for schools makes it difficult to optimise the energy supply as the HVAC zoning is often consistent with the spatial design for practical reasons. Manual and automated lighting control are also often not refined to adapt to the requirements and functionalities of such spaces. Few occupants in a large open-plan learning resource space can thus bring the heating system and other building services into operation for the entire zone.

It is important to take advantage of the existing zoning arrangements to limit the wasteful supply of energy to vacant spaces where possible. This is particularly important in schools where a lot of activities take place during out-of-hours and half-term breaks that do not require whole-building operation.

Figure 5.15 shows an example of the zoning arrangements specified for new schools. Building D is hydraulically split into seven heating zones. Each heating zone could be isolated with a two-port motorised valve controlled by the BMS. This strategy was designed to enable users isolate parts of building that are not used during out-of-hours operation. For example, a large open-plan learning resource space (Zone 7), the offices and classrooms in the same wing of the building (Zone 2 and Zone 3), and the classrooms in Zone 4 and Zone 6 could be separated from the other zones that may need conditioning for a special event that entails the use of the kitchen (Zone 1, ground floor) and the dining space (Zone 5, ground floor). The facility manager and the maintenance contractors in this building showed awareness of this zoning arrangement and extended the heating schedule in Zone 3 beyond 17:00 to allow for a night school that took place in a couple of classrooms in that zone. However, the post-occupancy evaluation revealed that the hydraulic isolation was not optimal and the control valves were letting by the hot water flow; warm heating terminals were regularly observed in the adjacent Zones. The hydraulic isolation of the zones and the operation of the respective two-port valves had not been checked at the commissioning stage before building handover. A seasonal commissioning was also initially planned for the building but did not take place to save costs.

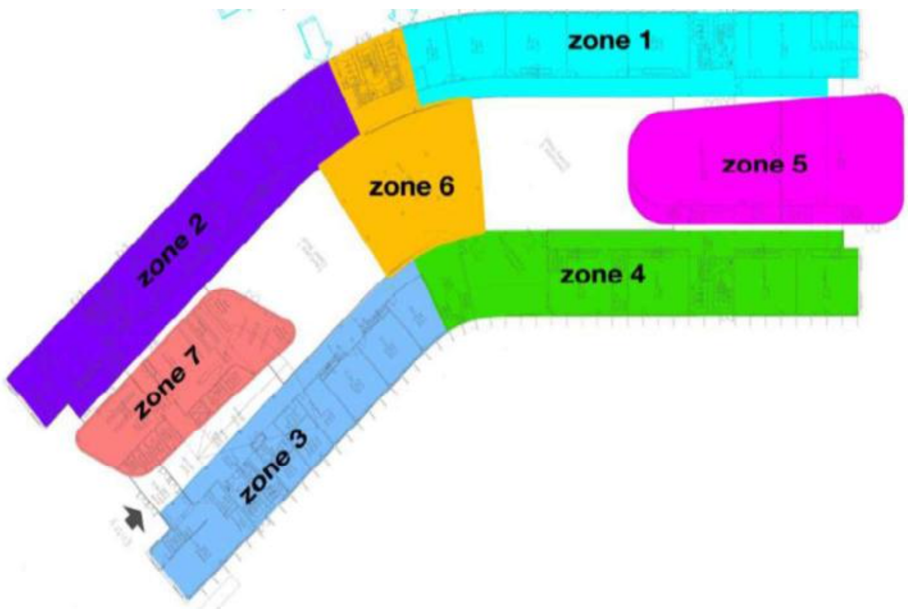


Figure 5.15. The zoning principle for the heating system: Building D
(Courtesy of Max Fordham Engineers)

The maintenance contractors in Building C also made a limited attempt to use the zoning arrangements for out-of-hours use. However, there was no evidence of using zoning arrangements in other case studies and all spaces were conditioned even if only part of the building was occupied.

5.5.3. Operational issues associated with Low or Zero Carbon systems

The contribution of the Low or Zero Carbon (LZC) systems in the case studies was significantly lower than the design assumptions.

The case studies that had LZC systems installed were meant to comply with the 2006 edition of the Approved Document Part L2A. According to this document, the performance of any LZC system should be separately monitored (HM Government, 2006). However, all metering strategies had shortcomings that made direct measurement of energy flows in and out of these systems difficult. Notably, the solar thermal systems installed in two buildings had no metering provision at all. This made it difficult to check their performance; the system installed in one building had not been commissioned properly and did not contribute to domestic hot water use until the problem was uncovered during the post-occupancy evaluation. Consequently, glycol was injected and the system was re-commissioned in the third year of building operation. Had the energy performance of the system been monitored, the problem would have probably been spotted at an earlier stage. This shows the significance of having separate metering arrangements for LZC systems. Table 5.4 provides a review of the installed systems, the respective metering conditions, and the measured or estimated contribution of these systems to building demand.

The Ground Source Heat Pump (GSHP) system installed in Building A had the highest estimated contribution compared to other systems. The GSHP system in this building met 21% of building's heating demand. This is around half the 40% design intent stated in RIBA Stage D report. However, the as-built drawings show only 26% of the total useful floor area is served by under-floor heating and chilled beams that are served by the GSHP system. The actual contribution of the GSHP system is therefore reasonably close to what is expected based on as-built drawings. There is no buffer vessel between the ground source heat pumps in this building and the gas-fired boilers. Energy to secondary heating and cooling loops is provided from a sliding header arrangement with motorised valves that respond to heating and cooling demand. The control system provides priority control for the cooling demand, with supplementary heat injected from the primary boiler plant if required (Figure 5.16).

As the ICT enhanced spaces in Building A might have cooling demand in winter due to equipment gain, the bias of the control strategy towards cooling and the setup of the interface between the GSHPs and gas-fired boilers means the heating load may be shared between the GSHP system and the boilers even when heating demand is lower than the full capacity of the GSHP system.

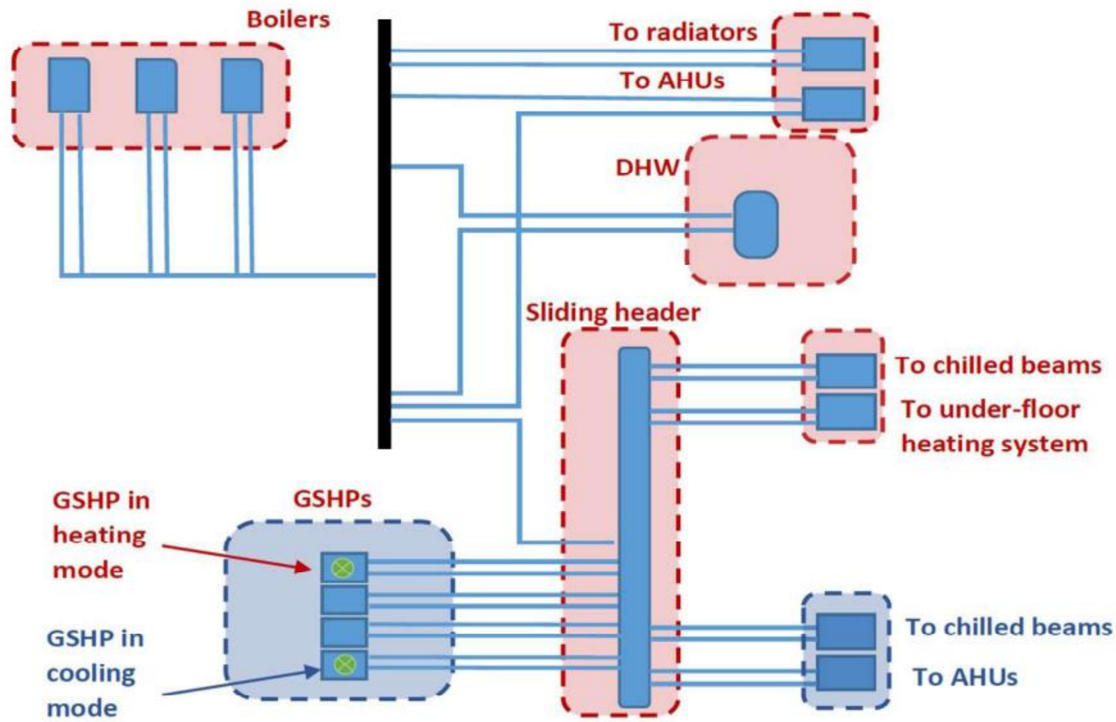


Figure 5.16. Simplified schematic of the interface between GSHPs and boilers: Building A

The solar thermal panels in Building B had not been commissioned and were not operational during the first two years of building operation. The biomass boiler installed in Building C was not utilised during the measurement period and this had a severe impact on the building's total CO_2 emissions as the biomass boiler was sized to meet 50% of the building's peak heating demand. The maintenance issues compromised system performance at the early stages of post-occupancy; the augur section stuck, the three port valve installed for the system burst, and the main pump had sprung a leak. As a full back-up gas-fired system was available, the academy decided to switch to natural gas on the grounds of the maintenance issues experienced with the biomass system and the cost of wood pellets which was higher than natural gas. The system had been commissioned before the cut-off date announced by the government for the Renewable Heat Incentive and therefore was not qualified to receive this subsidy that could have made the comparison between the cost of natural gas and wood pellets more favourable for wood pellets. The academy also received a notice warning issued by the Health and Safety Executive (HSE) about the risk of carbon monoxide generation within storage units for wood pellets. This further reinforced their decision to abandon the biomass system and fully utilise the gas-fired boilers. The delivery records reveal that only 9 tonnes of wood pellets were ever delivered to the building which amounts to a couple of weeks of building's heating demand.

Finally, the GSHP system installed in Building D was not very effective in meeting the building's heating demand, although its design was consistent with the good practice recommended by CIBSE AM 15 (2014). A number of motorised vents installed for cross ventilation were frequently malfunctioning and stuck open in heating season that caused excessive heat loss (Figure 5.17). The maintenance contractor's response to the heat loss and the thermal discomfort reported by building users was to increase the set point flow temperature for the low temperature hot water loop. Consequently, the flow temperatures were often around 80 °C even under moderate ambient conditions. The GSHP system was not operational at these temperatures and therefore the gas-fired boilers took the lead.

The operation of LZC systems in most case studies points to the steep learning curve associated with these systems in the UK construction industry and among building operators. Technical information prepared for the buildings contained errors that might be indicative of the peripheral role LZC systems have in building practitioners' perception. The following is an excerpt from the Operation and Maintenance manual prepared for Building A:

"*Central gas fired modular boilers are provided to meet the heating demand of the building. The* ***remainder*** *of the heating requirements is provided from the ground source heating and cooling system.*"[13]

The LZC systems must operate as the *lead* system supplemented by more carbon intensive systems only when required (in the case of Building A, the GSHP system was meant to be the lead heating system for the chilled beams and under-floor heating system). This is not always reflected in building documentations accurately and the evidence witnessed in the case studies suggest construction teams and maintenance contractors take a relaxed approach about the actual contribution of these systems knowing that there is a full back-up system in place to satisfy building demand. This is in contrast with the optimism expressed at design stages and the assumptions made in the regulatory calculations to ensure the CO_2 emission targets are achieved.

[13] Emphasis in form of emboldened font is from this author.

Table 5.4. Review of the metering arrangements and the contribution of the LZC systems

Building	LZC system	Metering strategy	Contribution
Bldg. A	Ground source heat pumps	Electrical intake of the GSHP was metered. The cooling output was also metered by the cooling header energy meter. The heating output was estimated using the cooling and heating Coefficients Of Performance (COPs) that were 5.2 and 4.1 in accordance with BS EN 14511-2 (BSI, 2007).	21% of the building's heating demand was satisfied by the GSHP system against 40% design target stated in RIBA Stage D report. The system also provided comfort cooling to ICT enhanced spaces equal to 0.8 kWh/m²/annum.
Bldg. B	Solar thermal panels	No sub-meter was installed for the system.	The system had not been commissioned properly and made no contribution to domestic hot water use over the monitoring period.
Bldg. C	Biomass boiler	Records of wood pellet delivery was available.	Only one batch (9 tonnes) of wood pellets was delivered for the biomass boiler at the early stages of post-occupancy; the biomass boiler was not used over the measurement period.
	Solar thermal panels	Not directly metered. Contribution to domestic hot water was estimated using the NCM algorithm. The operation of the system was also regularly checked by monitoring flow and return temperatures and hot water flow measured by a level meter.	Estimated to be around 0.4 kWh/m²/annum equivalent to 2% of domestic hot water use.
Bldg. D	Ground source heat pumps	Electricity intake was not directly metered. However, it was estimated by difference as the total electricity intake of the GSHPs, and the security and fire alarm panels was known. The heating output was metered.	The system was disabled most of the time. Less than 3% of heating energy was provided by the GSHP over the monitoring period. The system also provided limited free cooling to ICT enhanced spaces via ground source heat exchanger.
Bldg. E	None	n/a	n/a

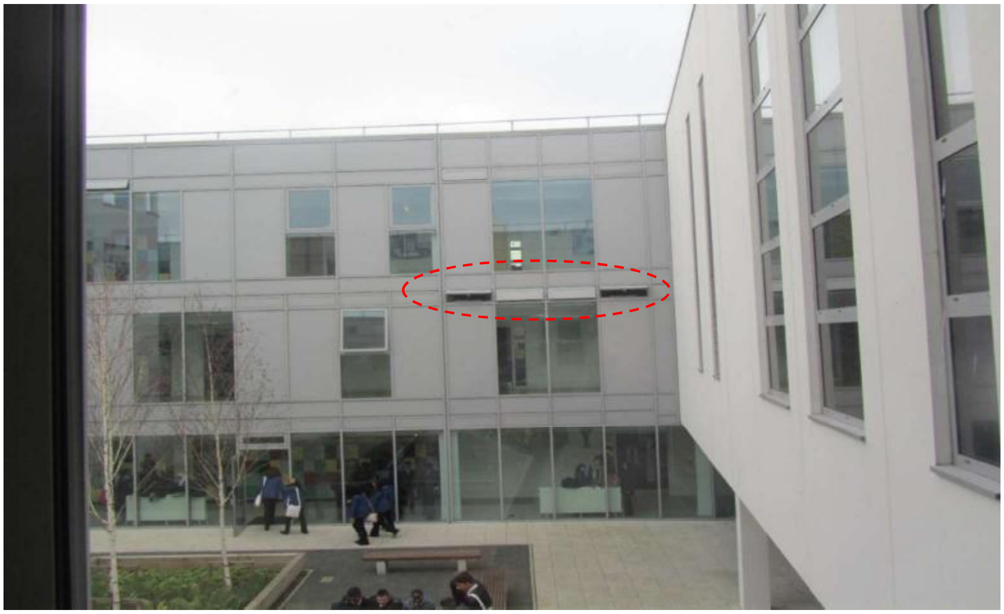


Figure 5.17. A number of motorised vents stuck open in winter in Building D: this compromised the operation of the GSHP system.

5.5.4. Lack of Monitoring & Targeting

The requirements for metering energy end-uses introduced in Part L Approved Documents led to implementation of numerous sub-meters in the case studies. However, the installed meters had not been commissioned properly and a number of them had to be fixed before the monitoring programme could be started. Not all meters had a pulse output and were connected to the BMS. This was especially the case for the gas meters that had to be read manually in most cases. The BMS interfaces available to users did not report total energy consumption per end-use and it was up to the users to work out total energy use based on individual meter readings, a laborious task that did not happen outside the research programme.

As part of the Building Regulations compliance requirements, designers and contractors of new buildings and major refurbishments are responsible to complete a building log book that is meant to explain the design intent and the most important aspects of building operation to building users in a plain and jargon free language. A log book is different than operation and maintenance manuals and aims to provide more concise and accessible information to facility managers and other building users. A standard template is provided by CIBSE TM31 (2006) that is often used by construction teams to prepare a log book. This template includes provisions to report the design estimates for end-uses and total energy use along with good practice benchmarks that could form the basis of an on-going monitoring and targeting programme after building handover.

The four buildings that were constructed after inception of Part L 2006 have building log books. However, none of these log books contains information about energy end-use estimates. The templates for total energy use and individual end-uses are often left blank as shown in the excerpt from the log book prepared for Building D (Figure 5.18). The log book for Building A includes the design estimates for total energy use per fuel and the corresponding good practice benchmarks (Figure 5.19). This is by far the most useful information available for energy performance in-use in the case study log books, although this information is provided in a section related to energy end-uses with no information provided on end-uses. The good practice benchmarks reported for Building A are based on ECG073. However, the source of the information and the baseline heating degree-days are not given to make this information more useful for building users.

12-3 ENERGY END USE COMPARISON

Annual summary of actual metered consumption per square metre and the design teams estimates versus benchmarks broken down by main end-uses.

Building energy performance for period from .... to ....

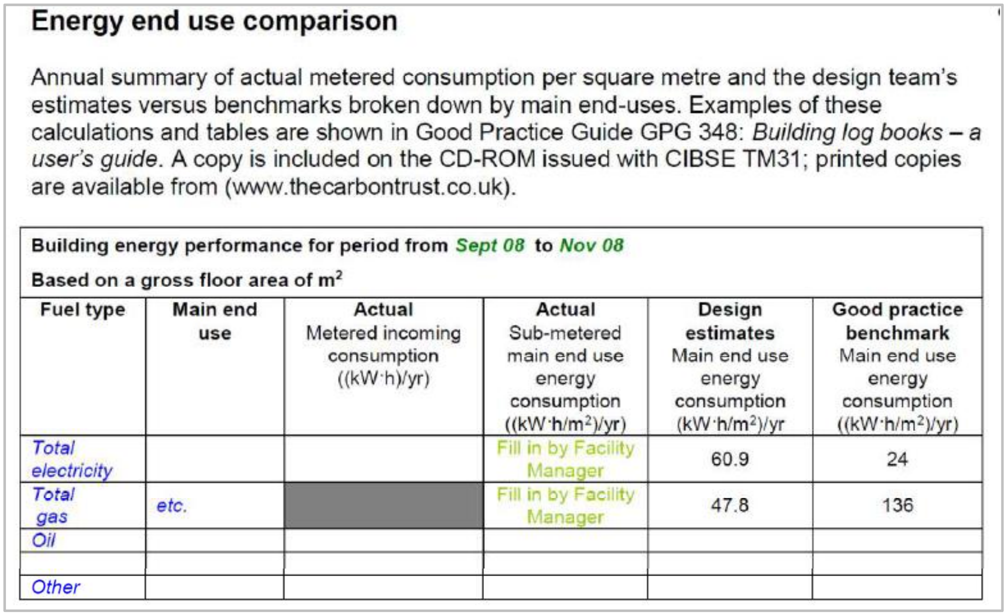
Based on a gross floor area of .... m^2

12-3-1 COMPARISON

FUEL TYPE	MAIN END USE	ACTUAL METERED INCOMING CONSUMPTION ((KW H)/YR)	ACTUAL SUB-METERED MAIN END USE ENERGY CONSUMPTION ((KW H/M^2)/YR)	DESIGN ESTIMATES MAIN END USE ENERGY CONSUMPTION (KW H/M^2)/YR	GOOD PRACTICE BENCHMARK MAIN END USE ENERGY CONSUMPTION (KW H/M^2)/YR
ELECTRICITY	FANS				
ELECTRICITY	LIGHTING				
ELECTRICITY	PUMPS				
ELECTRICITY	ETC.				
TOTAL ELECTRICITY					
GAS	SPACE HEATING				
GAS	ETC.				
TOTAL GAS					
OTHER					

Figure 5.18. Estimated performance in-use for Building D: excerpt from the log book

These Figures show the problems facing building operators in devising effective monitoring and targeting programmes. As for energy end-uses, the existing benchmarks for schools and most other building categories lack the granularity required for benchmarking. It is therefore important for designers to estimate and report energy end-uses for their buildings in building log books based on energy performance calculations. On the other hand, the installed energy data collection facilities in most new buildings are not capable of providing an automatically generated account of energy end-use performances ready to be exported to platforms such as CarbonBuzz or iSERV that can crowdsource data and help develop robust energy end-use benchmarks for future use. Unless robust energy performance estimations and benchmarks are defined and effective automated data collection facilities installed, investing in detailed but not functional metering strategies appears to be futile.


Energy end use comparison

Annual summary of actual metered consumption per square metre and the design team's estimates versus benchmarks broken down by main end-uses. Examples of these calculations and tables are shown in Good Practice Guide GPG 348: *Building log books – a user's guide*. A copy is included on the CD-ROM issued with CIBSE TM31; printed copies are available from (www.thecarbontrust.co.uk).

Building energy performance for period from *Sept 08* to *Nov 08*

Based on a gross floor area of m²

Fuel type	**Main end use**	**Actual** Metered incoming consumption ((kW·h)/yr)	**Actual** Sub-metered main end use energy consumption ((kW·h/m²)/yr)	**Design estimates** Main end use energy consumption (kW·h/m²)/yr	**Good practice benchmark** Main end use energy consumption ((kW·h/m²)/yr)
Total electricity			Fill in by Facility Manager	60.9	24
Total gas	*etc.*		Fill in by Facility Manager	47.8	136
Oil					
Other					

Figure 5.19. Estimated performance in-use for Building A: excerpt from the log book

As for total fuel use, the available statistical benchmarks may be helpful but need to be adjusted and can be misleading for new buildings. On the other hand, even when design estimates for total fuel use are provided, there is often no information about the corresponding operating conditions to put the estimated figures into context.

In the absence of robust energy baselines, it is also very difficult to include energy targets in the maintenance contracts.

In summary, none of the case studies had a structured monitoring and targeting programme. There was no marked difference between schools financed by the local authorities and the academies that had more independence on their expenditure. Some of school heads and business managers referred to reports of energy performances and associated costs for other schools covered by the same local authority. Trend logging and comparing energy performances in successive years was also a possibility, but no attempt was made to carry out this exercise by schools in a structured way and by accounting for differences in weather conditions and building context.

5.5.5. Question of energy ownership

Lack of monitoring and targeting is also related to a wider problem that is lack of ownership of energy performance. When the problem with the weekend operation of the heating and mechanical ventilation plant in Building A was uncovered in the post-occupancy evaluation, the maintenance contractor was able to revise the control setting and fix the problem fairly quickly. When asked whether they could have noticed this before the response was "energy performance is not in our contract". This raises another question with wider implications for the industry: Who *owns* energy performance?

Until there is a clear answer to this question the type of issues reported in this Chapter can easily happen in other buildings. As far as operational energy performance in the case studies is concerned, it appears that no one single party owned the performance. The finance teams and business managers processed the utility bills, but no one was accountable for the level of performance. This was both a cause for and a consequence of lack of monitoring and targeting. The maintenance contractors ensured the building services were functional and addressed issues raised by the facility managers, but did not report on energy efficiency. The facility managers defined the widest and longest operational profiles for building services to cover all possible activities in schools as the focus was on the availability of services rather than efficient space-time system utilisation.

To understand the attitude of school management towards energy performance, it is worth considering the weight of energy costs on schools' overall budget. According to Levacic et al. (2005), expenditure on premises and facilities constitute around 7% of the total expenditure of a typical secondary school in the UK. Cost of energy is part of this expenditure. The financial data available for one of the case studies shows that energy cost is around 3% of the annual expenditure (Figure 5.20). This is almost negligible against direct and indirect expenses associated with teaching and support staff which amounts to 83% of total annual expenditure. A school head may reach the conclusion that devoting their time to improve the productivity of their staff and the educational experience of pupils will bring more benefits than the distractions caused by the level of energy performance especially when there are no clear baselines and targets. They might also be concerned about any potential negative impact of energy saving initiatives that are related to building and system management on productivity. Moreover, it might be possible to achieve savings in energy costs by means other than actual energy saving such as changing the supplier and signing a new supply contract.

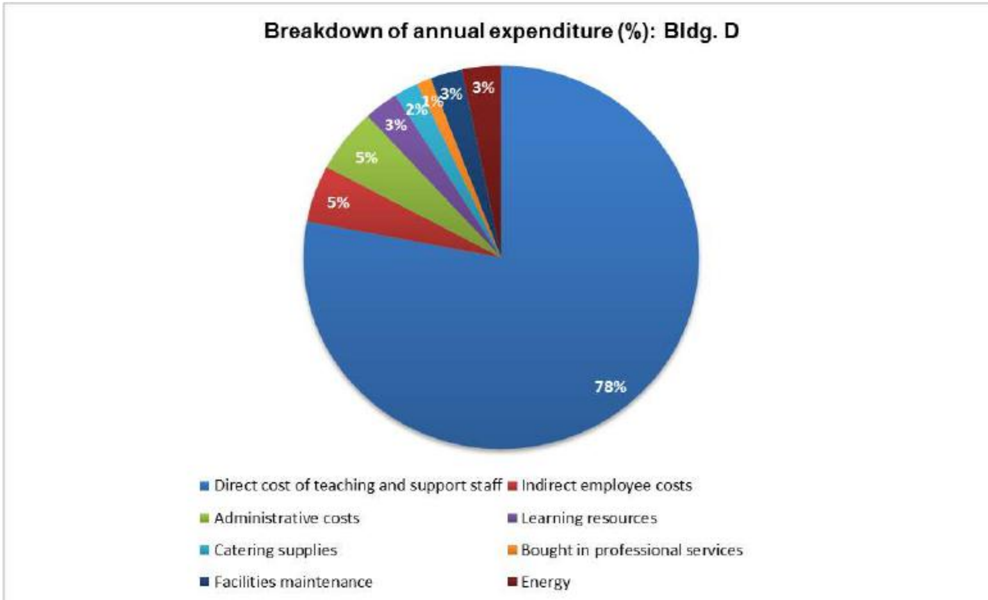


Figure 5.20. Percentage breakdown of annual expenditure in Building D

As explained in Chapter 2, the relatively low weight of energy costs on schools' budget is, at least to some extent, a consequence of the divergence between the real social cost of carbon and its existing market price. Unless this issue is addressed, it is difficult to find a reason for schools to *own* their energy performance and try to improve it. Initiatives such as switch-off campaigns and Eco Schools are important to raise awareness about energy efficiency among the pupils and can also achieve modest savings. The potential reputational damage of a poor DEC or energy league tables might also persuade schools to take more radical action to save energy. Even so, the problem with inadequate baselines and lack of information about building's performance potential persists and may compromise any such effort by schools.

One way to tackle this issue would be to hold the construction teams accountable for performance in-use during the initial period of post-occupancy for measurement and verification and then pass on the responsibility to maintenance contractors with clear baselines and targets derived from measurement and verification. Maintenance contractors can then bundle up a number of schools and other building types to take advantage of economies of scale. The relatively cheap price of energy makes it less worthwhile for schools to own their energy performance. However, maintenance and performance contractors would be able to define a good business case to benefit from energy savings achieved in a portfolio of buildings under the right policy framework.

5.5.6. Further improvement opportunities

Assuming the question of ownership of energy is addressed in a school, the following lessons learned from the post-occupancy evaluations of the case studies may be used to achieve a better performance:

Heating and domestic hot water: In addition to profiling and zoning, local control of heating terminals can be encouraged to limit both the space and the number of hours the heating system must cover. Temperature set points observed in schools were mostly in the region of 20-21 °C although heating set points as high as 25 °C were also observed. These set points are much higher than the heating set point assumed in the National Calculation Methodology for classrooms that is 18 °C. Carbon Trust estimates that turning down temperatures by 1 °C could lower annual space heating requirement by up to 8% (Carbon Trust, 2011). The upper range of this estimate is more pertinent to existing buildings, and new buildings with better fabric performance and airtightness have lower potential for energy saving if heating set points are reduced. Nonetheless, lowering heating set points can still be effective in saving energy in new buildings especially where natural ventilation is used, provided thermal comfort of occupants is not compromised. Another issue uncovered in a number of buildings was that the installed condensing boilers were running in non-condensing mode despite moderate outdoor conditions. For example, the flow temperature in the low temperature hot water loop in Building B, with condensing boiler, was constantly higher than 80° as the heating terminals were not sized for condensing mode of operation that required flow temperatures less than 60 °C (Figure 5.21 and Figure 5.22). The non-condensing mode of operation can compromise the heating efficiency; this led to around 7% reduction in heating efficiency in Building B according to the manufacturer data (87.4% efficiency in non-condensing mode against 94.7% average gross seasonal efficiency).

As for Domestic Hot Water systems, high set points specified for hot water cyclinders (often in excess of 60°C with maximum of 65°C in building E) and prolonged operational schedules (e.g. 24 hours/7 days in Building D) appeared to be an overcautious response to health and safety risks associated with legionella. However, the approved code of practice to prevent the growth of legionella bacteria in hot water cyclinders, applicable to non-domestic premises, requires the hot water cylinder content to be heated to 60 °C only for one hour each day (HSE, 2014). Where the hot water cyclinders are served by gas-fired boilers, the prolonged operation driven by the schedule set up for cylinders often leads to unnecesary and inefficient plant operation outside core hours.

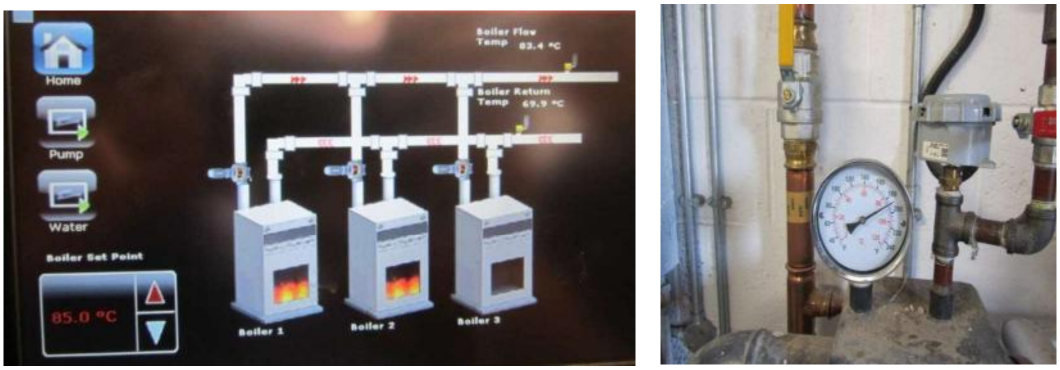


Figure 5.21. The boiler set point and actual flow temperature in Building B: these temperatures were monitored from the boilers' common header and were constantly higher than 80 °C leading to non-condensing boiler operation.

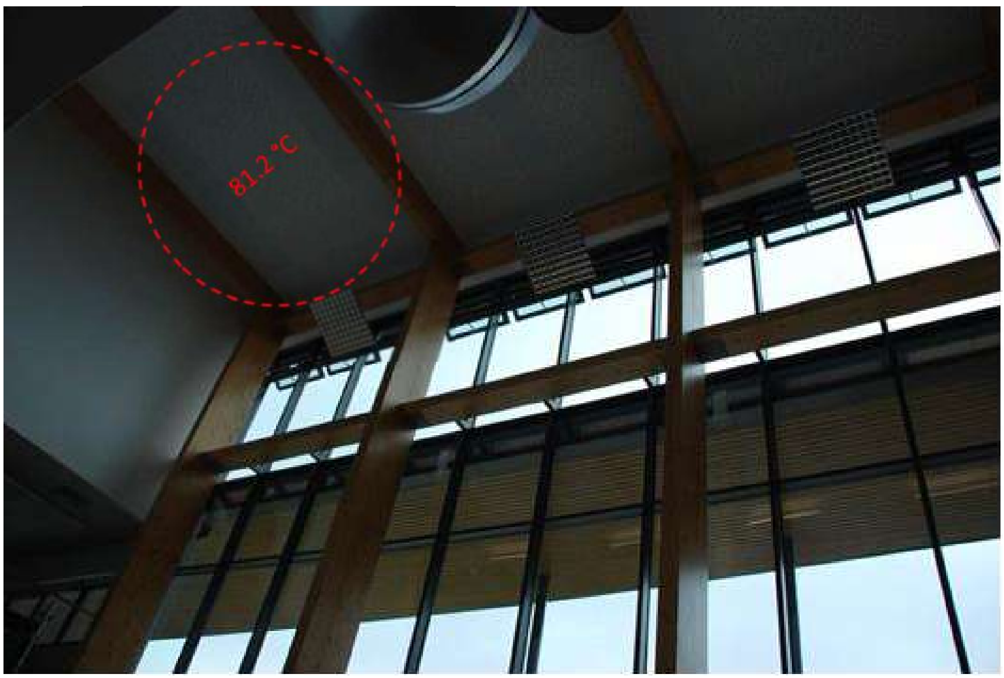


Figure 5.22. The surface temperature of the radiant panels installed on the ceiling of the Building B atrium: temperatures were measured by infrared thermometers and were often above 80 °C. The adjacent motorised vents were only responsive to CO_2 levels and were frequently open in winter which put more stress on the heating system.

Cooling: Limited cooling was provided to most case studies to mitigate the risk of overheating where internal gains were high. The overheating threshold used for the assessment of the case studies at design stages was 28 °C. Yet once the systems were installed, the actual cooling set points were often in the region of 19-21 °C. More moderate cooling set points (e.g. 23-25 °C) can help save energy and maintain an appropriate dead-band between heating and cooling set points to prevent heating and cooling systems fighting each other, a phenomenon frequently observed in the case studies.

Auxiliary energy: There was a wide variation in auxiliary energy use in the case studies as reported in Table 5.3. This is to a large extent driven by the type and operation of the ventilation systems. The message emerging from the post-occupancy evaluations is that mechanical ventilation strategy could be effective if procured and managed well. However, it is a high risk option and must be specified and managed with diligence. The auxiliary pumps in all building were running longer than expected. The worst case scenario was Building D with a plantroom electrical load of 40-50 kW overnight that was triggered by the 24/7 profile set up for domestic hot water and poor control strategy. It is worth checking the operation of the mechanical plant room during out-of-hours to identify problem areas that often stem from interlock issues between the BMS and the HVAC systems and the prolonged schedules set up for some services. Energy performance analysis in the UK is heavily focused on annual performance. Providing a baseline for daily electrical demand of a building derived from a simulation that takes into account the expected operation can be hugely beneficial for day to day building management. This information can be included in log books for building users. Historical half-hourly records can also be used to have a better understanding of building demand. Checking the building electrical power demand on the main electricity meter installed for the building after core occupancy hours in reference to the predicted demand or historical trend can point to anomalies in plant room operation and/or untoward energy use of other end-uses.

Lighting: There was a factor of two difference in internal lighting use in the case studies. The main root cause for low lighting energy use in Building B and Building D was the low lighting density installed (7.5-9 W/m^2 in most teaching spaces compared to 9-12 W/m^2 in other buildings) combined with better manual control. The caretakers in both buildings checked the lights after normal occupancy hours and switched them off in vacant spaces. The automated lighting controls were not very effective in the case studies. The zoning of lightings in circulation spaces had not been refined during the commissioning and it was quite common to observe lights in the whole circulation space coming ON in response to a movement in part of the space (Figure 5.23). Time offs of the PIR sensors and the sensitivity of daylight sensors were also not consistent in different classrooms. As for external lights, there was scope to save energy by defining separate schedules for security lights, overriding the fixed time schedules with appropriate threshold illuminance levels for automated control, and effective management of flood lights where outdoor sport facilities were frequently used as in Building A.

Figure 5.23. Internal lights ON in the entire circulation space in Building C outside core occupancy hours

Equipment: Energy use related to equipment (including small power, ICT equipment, catering facilities, and other miscellaneous loads) amounts to around 30-50% of total electricity use and up to 11% of total gas use in the case studies. This is a huge component of total energy consumption that also affects heating and cooling loads. The existing Building Regulations do not take into account these so-called unregulated loads in energy performance analysis, although the latest edition of the Approved Document Part L calls for consideration of centralised power down management systems so that facilities managers can switch off appliances when they are not needed instead of relying on individual users (HM Government, 2013). This is a reasonable step to acknowledge the profound effect of appliances on building energy performance. There was one desktop computer or laptop for every 2-4 occupants in the case studies. It was common to see computers and monitors left ON and unattended after core occupancy hours, although the absorbed power of these systems at standby mode were generally low at around 1-2 watts. Server room and data hub rooms' direct energy use varied between 7-12 kWh/m²/annum, while their associated cooling requirements were higher than expected. ASHRAE thermal guidelines for data processing environments recommend a temperature range of 65 to 80 °F for air cooling of server rooms (ASHARE, 2011), i.e. 18.3-26.7 °C. The cooling set points observed in these rooms were close to the lower end of this range between 19-21°C. A more moderate cooling set point can save the 24/7 energy used for ICT infrastructure without compromising its performance. The server room utilisation levels were also low at around 30-40% in most cases. Virtualisation techniques whereby fewer servers operate at higher utilisation levels can help save energy. Server rooms' direct load and their cooling requirements constitute a major component of schools' baseload electrical demand and therefore must be a key target for energy saving.

5.6. Summary

The case studies are new-build and therefore are expected to perform equal to or better than good practice benchmarks derived from existing buildings. However, only two case studies (Buildings A and B) performed better than the good practice benchmark for fossil-thermal use and all case studies used more electricity than the good practice benchmark derived from the DEC dataset. Furthermore, the evidence collated from the case studies shows that even good practice benchmarks derived from existing buildings do not necessarily reflect the true energy performance potential of new buildings. It is therefore important to have robust benchmarks or baselines for new buildings. This will be further explored in Chapter 8.

The Education Funding Agency has set out operational targets for the new schools procured under the Priority School Building Programme (PSBP). Total fossil fuel and electricity consumption of PSBP schools is expected to be less than 60 and 50 kWh/m²/annum respectively (Cundall, 2014). Although the case studies were procured under a separate and earlier school building programme, Table 5.2 and Table 5.3 show the challenge of meeting these operational targets for new-build schools.

The post-occupancy evaluations identified a range of improvement opportunities. Optimised operational profiles that reflect actual building occupancy and requirements and using the HVAC zoning arrangements to isolate the unoccupied spaces can help achieve the right balance between energy supply and actual demand. The operational profiles set up for building services in the case studies were not optimised; in most buildings more than half of the electricity was used outside the core occupancy hours. Wasteful space heating was also observed in all case studies especially during half-term breaks and out-of-hours operation. Another problem was the contributions of most installed low or zero carbon systems were significantly lower than expected.

Lack of clear energy baselines is a barrier against monitoring and targeting which could be a means to identify and address operational issues. A more fundamental problem that is related to this issue is the lack of energy ownership observed in the case studies. It is suggested that the relatively low cost of energy compared to other school expenditures is hardly an incentive for school management to follow a structured approach to energy management.

Involving designers and contractors at early stages of post-occupancy to fine-tune their buildings and verify the performance in-use would help optimise building performance and define baselines. These energy baselines could form the basis of effective monitoring and targeting programmes that could be executed by maintenance and performance contractors who can take advantage of economies of scale by managing a number of buildings and thereby define a business case for operational energy savings.

Table 5.5 lists a number of major recommendations for various stakeholders in the construction industry tailored for schools and based on the findings of the post-occupancy evaluations. These recommendations are focused on operational energy performance and could be adopted at different stages of building procurement to achieve a reasonable level of performance in-use compared to the benchmarks.

Table 5.5. Recommendations for energy efficient facilities management

Recommendations for energy efficient facilities management	
Clients (schools / local authorities, etc.)	Ask for specific design measures for out-of-hours and extracurricular use of school.
	Ensure energy performance is taken into account during defects liability period. This could uncover some problems that could otherwise go unnoticed.
	Ensure building FM and other personnel involved in day-to-day operation of school are trained adequately (especially in case of staff turnover).
	Appoint someone to own energy consumption. Consider signing a performance contract with the maintenance contractor.
	Commission a Display Energy Certificate 12 months post-occupancy. Compare and contrast the operational rating with the energy baseline defined by designers/contractors. (This is an independent verification of annual performance and not merely a compliance issue).
Designers and Contractors	Opt for simple, passive design strategies that require low intervention so far as possible (schools often do not have the resources and budget for a high intervention building management scenario).
	Schools are seasonal buildings and should be designed and procured as seasonal buildings with flexibility for extracurricular activities without compromising energy performance.
	Ensure a working draft of building log book is prepared by RIBA stage D/E (especially for Design & Build contracts).
	Ensure zoning arrangements and control strategy for out-of-hours and partial use of school are properly explained in the building log book.
	Introduce a list of critical energy efficiency measures in building log book. Include tips for the facility manager to ensure these measures are implemented and working as intended.
	Define building energy baseline clearly in log book (total thermal fuel and electricity & estimations for all energy end-uses). Provide the underlying assumptions and help building occupants benchmark their building's performance against this baseline.
	Ensure the metering strategy is implemented as intended and is working effectively. Train building occupants how to use the metering strategy for monitoring and targeting.
Facilities Managers (All activities to start within the first year of post-occupancy and continue thereafter)	Review the building log book and make sure baselines for energy performance along with underlying assumptions are defined.
	Review the metering strategy in building log book and other documentation to understand how the strategy works.
	Carry out a meter reconciliation exercise following the methodology explained in CIBSE TM39 to ensure the metering strategy is robust and sub-metered data is reliable. Record any faulty sub-meter in the defects log.
	Implement a monitoring and targeting strategy in early stages of building occupancy. Compare and contrast the outcomes with baselines and make sure critical energy efficiency measures are implemented and working as intended.
	Where a performance contract has been signed with the building maintenance contractor, ask the maintenance contractor for regular updates on energy efficiency measures and building energy performance. Compare energy performance with the baselines defined in the building log book.
	Treat the building log book as a 'live' document. Update the log book with results of energy measurements, M&T outcomes, and any other in-use investigations (e.g. Display Energy Certificates, Air Conditioning Inspection reports, etc.)
	Review the operation of operable windows / motorised vents in naturally ventilated spaces and demand-controlled ventilation in mechanically ventilated spaces regularly. Ensure air quality and thermal comfort is maintained without compromising energy performance.
	Ensure the schedules of operation defined for HVAC systems reflect actual occupancy and the seasonal nature of school's operation.
	Ensure the last member of staff who leaves the school in the evening checks building's demand on the electrical smart meter installed on-site. Investigate overnight operation of building if building's demand is unusually high.

6. Indoor Environmental Quality

6.1. Introduction

This Chapter provides the results of the long-term and short-term intensive studies carried out to investigate the indoor environmental quality of the case studies. The interrelation between energy performance and indoor environmental quality was a major driver in drawing up the monitoring plans for these studies and is a key theme in the discussion presented in this Chapter.

The long-term studies covered one full year and entailed monitoring of indoor air temperatures in a number of classrooms in each building to review the range of indoor temperatures during heating season and summer. An important component of these studies was to investigate overheating in reference to the BB101 criteria which had been used to assess the risk of overheating at design stages (DfES, 2006).

In each building, more detailed investigations were carried out during a typical week in heating season. These studies covered the indoor air quality, thermal comfort, acoustics, and lighting.

First the results and findings of these studies are presented. Next, the key lessons learned from these studies that may help achieve better performance in future projects are reviewed.

6.2. Long-term monitoring

The BB101 overheating criteria applicable to the case studies and reported in Chapter 3 were defined based on the CIBSE Test Reference Years (TRYs). The Test Reference Years have been selected as good statistical representation of past weather data and are available for 14 locations in the UK. They are usually used for energy performance calculations. CIBSE recommends using Design Summer Years (DSYs) to assess the risk of overheating. The Design Summer Years represent high summer temperatures occurred in the past 20 years and constitute a more stringent set of data for overheating analysis (CIBSE, 2015 b). The BB101 criteria are therefore based on more moderate summertime temperatures than what is represented in the DSYs.

The summer temperatures during the long-term monitoring were also moderate. However, the buildings were inevitably subject to weather conditions different than what is represented in TRYs. Therefore, the outdoor temperatures, recorded during the long-term studies by the nearest Met Office weather station to the building sites, were sourced and have been compared against the weather data used for BB101 overheating assessment at design stages to give context to the recorded temperatures and overheating analysis.

6.2.1. Building A

Figure 6.1 compares the peak and average summer temperatures recorded by the nearest Met Office weather station to Building A against the TRY weather data applicable to the building. While the average dry-bulb temperatures are reasonably close, the TRY peak temperatures in July and August are 4-5 °C higher than recorded temperatures during the monitoring period. However, the maximum summer temperature recorded during the monitoring period was 28.5 °C in June which was reasonably close to the maximum summer temperature in the TRY weather file which was 29.6 °C in August.

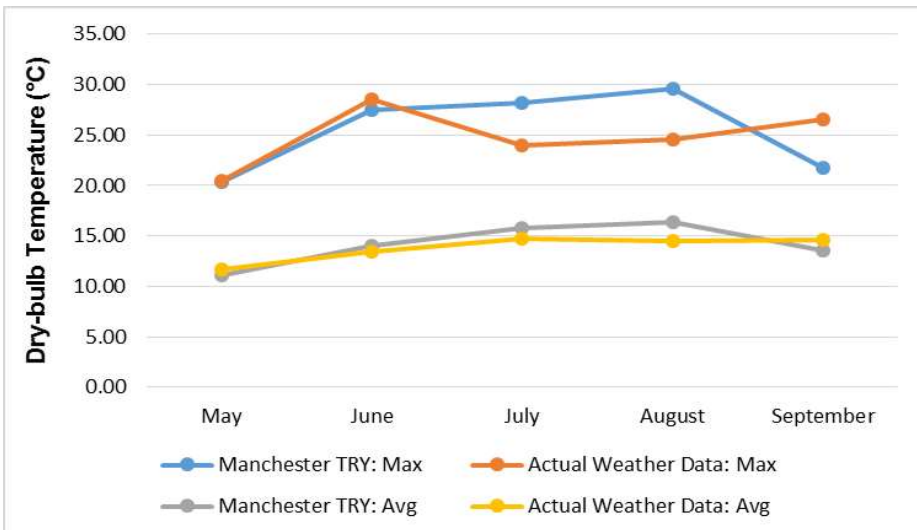


Figure 6.1. Actual peak and average outdoor temperatures against TRY data: Building A

Table 6.1 provides an analysis of the indoor air temperatures recorded in Building A during the monitoring period. The standard occupied hours specified by BB101 have been used for this analysis: 9:00-15:30 Monday to Friday. The statistics of the indoor temperatures are presented separately for the summer and the heating season. In addition to summertime overheating hours, annual overheating hours are also reported to reflect the overheating caused by internal factors such as internal gains or poor control of heating systems. Finally, in addition to the temperature thresholds specified by BB101, a lower temperature threshold of 25 °C has also been used to provide a better understanding of the building's response to ambient conditions. This temperature represents a threshold for thermal comfort beyond which increasing number of building occupants may become uncomfortable and productivity may be compromised (CIBSE, 2015 b). This standard format for presenting indoor temperatures has been applied to all case studies. The monitored classrooms are also highlighted on the layout plans in Appendix A.

Table 6.1. Building A indoor air temperatures over the period May 2011 – April 2012

Classroom: Location / Orientation / Glazing to wall ratio	Air temperature (°C), May-September (9:00-15:30, Monday-Friday)				Air temperature (°C), October-April (9:00-15:30, Monday-Friday)				Annual overheating hours (9:00-15:30, Monday-Friday)			Summer overheating hours, May-September (9:00-15:30, Monday-Friday) **(BB101 criteria)**		
	Min	Avg.	Max	SD	Min	Avg.	Max	SD	>25 °C	>28 °C	>32 °C	>25 °C	**>28 °C**	**>32 °C**
CR1: GF/North East/25%	18.2	20.2	22.7	1.0	15.3	19.8	22.2	0.7	0	0	0	0	0	0
CR2: FF/South West/44%	19.1	22.2	24.8	1.2	19.8	22.2	24.9	0.8	0	0	0	0	0	0
CR3: FF/North East/27%	17.2	20.9	24.9	1.4	17.7	20.4	22.9	1.1	0	0	0	0	0	0
CR4: FF/South/ 29%	18.2	20.4	23.9	1.0	16.8	20.1	22.7	0.9	0	0	0	0	0	0
CR5: SF/Core space/0%	19.2	22.1	25.1	1.4	19.2	21.4	24.7	1.2	1	0	0	1	0	0
CR6: SF/South/ 55%	17.2	21.4	26.3	1.4	17.9	20.7	23.4	0.9	5	0	0	5	0	0
CR7: SF/North East/36%	17.8	21.7	25.1	1.6	19.2	21.2	23.3	0.8	2	0	0	2	0	0

All classrooms presented in Table 6.1 are mechanically ventilated. Radiant panels are used in CR3 (science lab) for heating. All other classrooms are served by wet radiators. The g values (solar transmittance) specified for the glazing were between 0.68-0.75, reduced to 0.36 on the south, southeast and southwest elevations.

The sample classrooms in Building A did not experience temperatures above 28 °C during the monitoring period. Few incidences of temperatures above 25 °C were recorded during summer on the second floor, and the maximum recorded temperature was 26.3 °C in the south orientation. No incidence of temperatures above 25° was recorded in the heating season.

Figure 6.2 and Figure 6.3 illustrate the variation bands of air temperatures in the sample classrooms during summer and heating seasons respectively. The low variation bands for temperatures in heating season suggest the heating control strategy is effective in providing acceptable level of thermal comfort. CIBSE Guide A (2015 b) recommends a temperature range of 19-21 °C for teaching spaces in heating season. The average recorded temperatures and respective standard deviations show the sample classrooms are often within this range or very close to it, although few incidences of relatively low temperatures were recorded on ground floor and first floor.

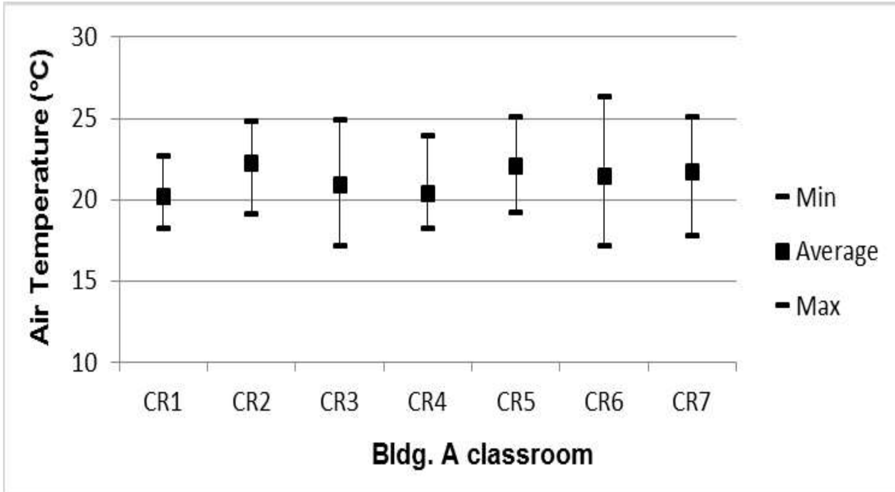


Figure 6.2. Boxplot of Building A indoor temperatures, May-September: occupied hours

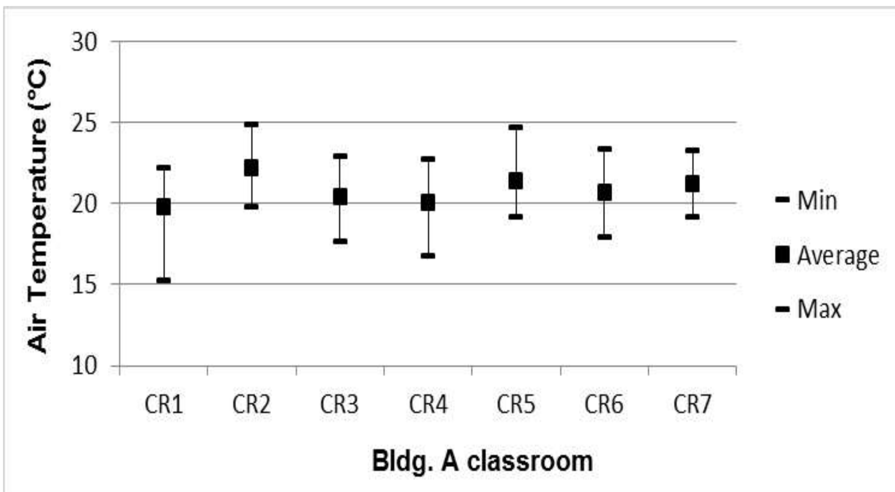


Figure 6.3. Boxplot of Building A indoor temperatures, October-April: occupied hours

Figure 6.4 shows the summertime performance of CR6 which is the classroom with the highest incidences of temperatures above 25 °C. The difference between indoor and outdoor air temperatures during peak times in this classroom was always less than 5°C. Overall, the sample classrooms in Building A, which represent various floors, orientations and environmental strategies deployed in this building, show good resilience against high outdoor temperatures.

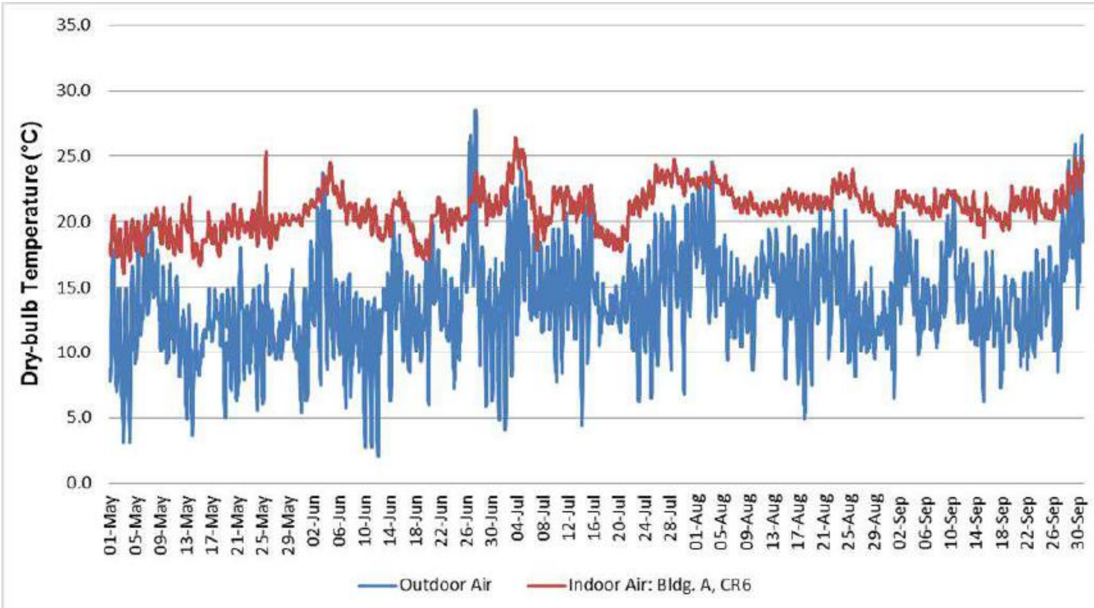


Figure 6.4. Indoor against outdoor hourly air temperatures for CR6: Building A

6.2.2. Building B

Building B is located in North West England and was subject to overheating assessment under the outdoor conditions represented by the TRY weather file for Manchester. The same outdoor weather data presented in the previous section are therefore applicable to Building B.

Table 6.2 presents the outcomes of the statistical analysis carried out on the recorded air temperatures in the sample classrooms of Building B. All classrooms are mechanically ventilated. CR1 (music classroom) and CR10 (business and ICT classroom) use variable refrigerant systems for heating and cooling. The rest of the classrooms use radiant panels for heating and have no provision for mechanical cooling. The g value specified for the glazing in the monitored classrooms was 0.68.

Similar to Building A, few incidences of temperatures above 25 °C were recorded in Building B. The overheating incidences that occurred outside summer point to the effect of internal gains and heating control on annual overheating hours in this building.

Figure 6.5 and Figure 6.6 illustrate the variation bands of air temperatures in the sample classrooms during summer and heating seasons respectively. The wide variation bands of the recorded temperatures in heating season point to problems in heating control.

The data presented in the previous Chapter show Building B had a relatively low heating energy use compared to the other case studies. However, the recorded indoor temperatures show this level of energy performance is not necessarily indicative of energy efficiency and there are shortcomings in provision of heating to teaching spaces. While the average temperatures in most classrooms are within the recommended comfort range, the average temperatures recorded in CR1, CR3 and CR4, their respective standard deviation, and the minimum air temperatures recorded during the occupied hours in heating season show the expected comfort conditions were not met in all teaching spaces.

Table 6.2. Building B indoor air temperatures over the period May 2011 – April 2012

Classroom: Location / Orientation / Glazing to wall ratio	Air temperature (°C), May-September (9:00-15:30, Monday-Friday)				Air temperature (°C), October-April (9:00-15:30, Monday-Friday)				Annual overheating hours (9:00-15:30, Monday-Friday)			Summer overheating hours, May-September (9:00-15:30, Monday-Friday) **(BB101 criteria)**		
	Min	Avg.	Max	SD	Min	Avg.	Max	SD	>25 °C	>28 °C	>32 °C	>25 °C	**>28 °C**	**>32 °C**
CR1: GF/South/16%	17.4	19.7	21.9	0.6	12.1	18.0	21.3	1.5	0	0	0	0	0	0
CR2: GF/West/22%	18.6	21.2	24.9	1.1	14.5	20.7	24.6	1.8	0	0	0	0	0	0
CR3: GF/West/14%	18.3	20.5	24.1	1.0	11.0	18.6	24.4	2.3	0	0	0	0	0	0
CR4: FF/South East/16%	18.0	21.8	25.7	1.3	9.6	18.8	24.2	2.3	3	0	0	3	0	0
CR5: FF/West/15%	18.8	21.7	26.7	1.2	12.9	22.0	26.2	2.0	5	0	0	2	0	0
CR6: FF/North West/12%	18.7	21.5	25.2	1.0	13.9	20.6	24.6	1.4	1	0	0	1	0	0
CR7: FF/North/26%	19.6	22.1	26.8	1.1	14.2	22.2	25.6	1.7	18	0	0	5	0	0
CR8: SF/North/26%	19.8	22.0	25.7	1.1	14.3	20.2	25.3	1.9	5	0	0	4	0	0
CR9: SF/South/22%	19.7	22.8	28.4	1.3	13.5	22.1	26.7	1.9	18	1	0	9	1	0
CR10: SF/West/11%	19.2	20.9	23.6	0.6	17.4	20.9	23.2	0.9	0	0	0	0	0	0

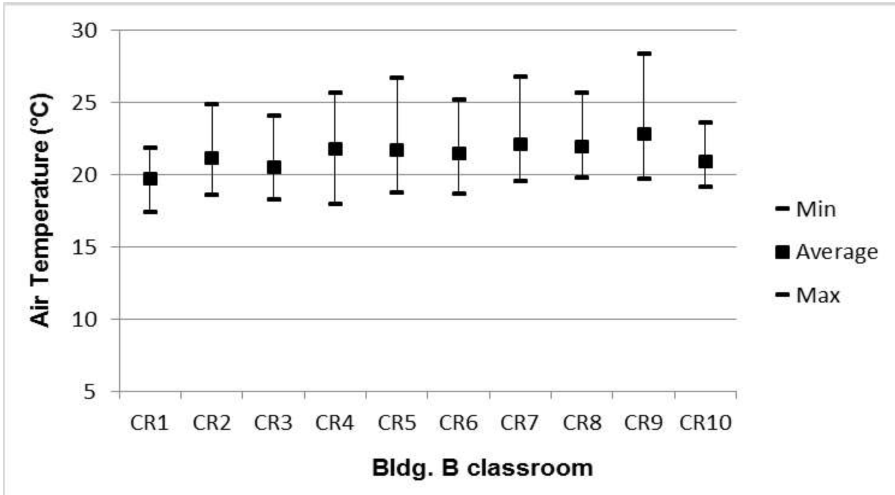


Figure 6.5. Boxplot of Building B indoor temperatures, May-September: occupied hours

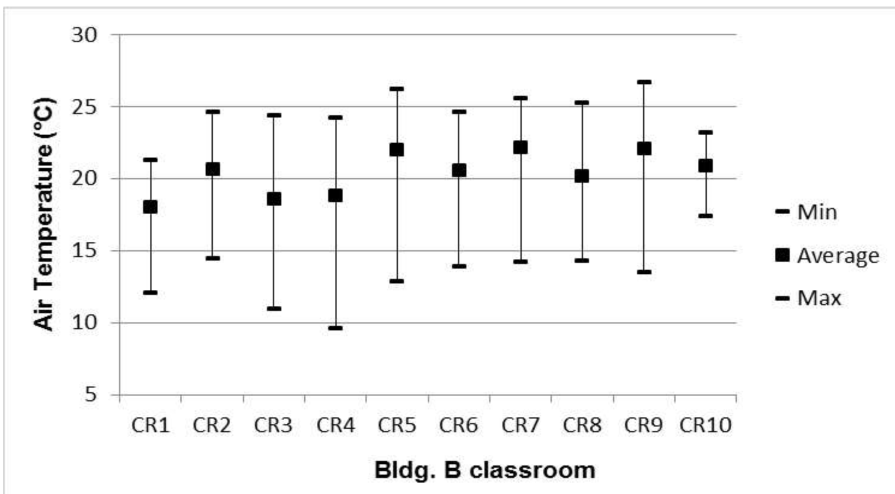


Figure 6.6. Boxplot of Building B indoor temperatures, October-April: occupied hours

Figure 6.7 shows the summertime performance of CR9 which is the classroom with the highest incidences of temperatures above 25 °C. The difference between indoor and outdoor air temperatures during peak times in this classroom was always less than 5°C. The maximum recorded indoor temperature for this classroom during the measurement period was 28.4 °C which occurred in late September when the outdoor temperature was 26.6 °C.

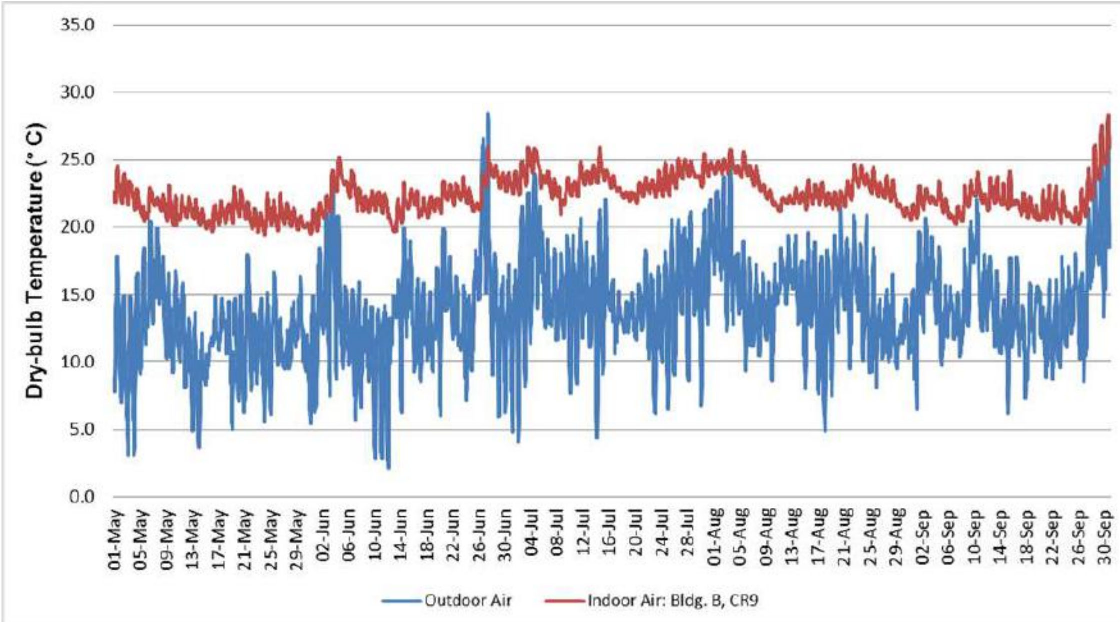


Figure 6.7. Indoor against outdoor hourly air temperatures for CR9: Building B

6.2.3. Building C

Building C was subject to overheating assessment under the outdoor conditions represented by the TRY weather file for Newcastle. Figure 6.8 compares the temperatures recorded by the nearest Met Office weather station to the building site during the measurement period against the TRY data.

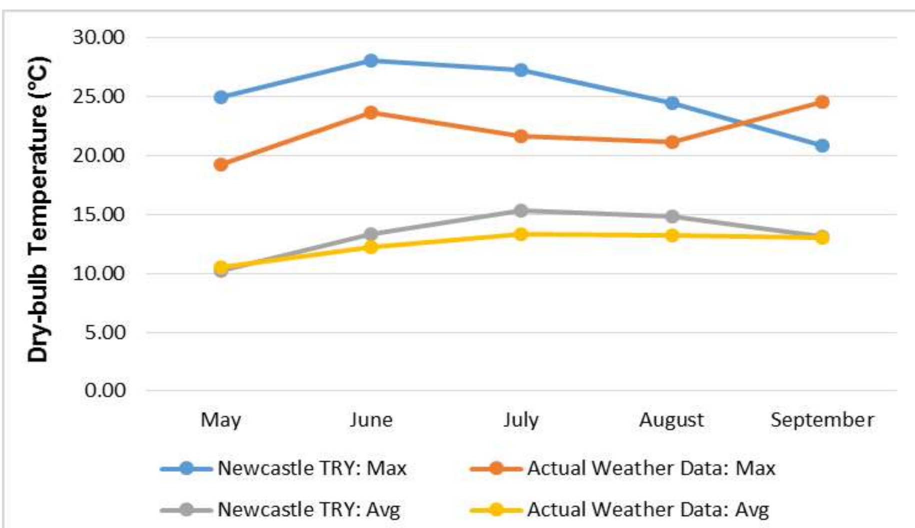


Figure 6.8. Actual peak and average outdoor temperatures against TRY data: Building C

While the average temperatures are reasonably close, the peak summer temperatures represented in the TRY for Newcastle are significantly higher than the peak temperatures experienced during the measurement period. The maximum TRY temperature for summer is

28.1 °C in June whereas the maximum summer temperature experienced during the measurement period was 24.6 °C in September. This means the actual outdoor temperatures were not close to the TRY weather data and the overheating hours must not be compared against the initial BB101 overheating assessment or be taken as a definitive assessment of overheating in Building C.

Table 6.3 presents the outcomes of the statistical analysis carried out on the recorded air temperatures in the sample classrooms of Building C. All classrooms except CR7 (science lab) are naturally ventilated and have minimum opening area equivalent to 4% of the classroom area plus provision for cross or stack ventilation. The g values specified for the glazing was 0.68. Solar shading was also applied to the south orientation. CR6 is an open-plan innovative learning zone which is served by a variable refrigerant system that provides both heating and cooling. The rest of the classrooms use wet radiators for heating.

Table 6.3 Building C indoor air temperatures over the period May 2011 – April 2012.

Classroom: Location / Orientation / Glazing to wall ratio	Air temperature (°C), May-September (9:00-15:30, Monday-Friday)				Air temperature (°C), October-April (9:00-15:30, Monday-Friday)				Annual overheating hours (9:00-15:30, Monday-Friday)			Summer overheating hours, May-September (9:00-15:30, Monday-Friday) **(BB101 criteria)**		
	Min	Avg.	Max	SD	Min	Avg.	Max	SD	>25 °C	>28 °C	>32 °C	>25 °C	**>28 °C**	**>32 °C**
CR1: GF/South/33%	17.2	21.5	26.6	1.5	15.1	21.8	26.6	1.5	16	0	0	6	0	0
CR2: GF/South/14%	19.7	22.1	26.2	1.1	15.0	20.9	25.0	1.4	6	0	0	5	0	0
CR3: GF/South/20%	17.9	21.5	26.5	1.2	14.9	19.5	24.2	1.6	3	0	0	3	0	0
CR4: GF/East/70%	18.9	22.4	25.0	1.1	15.7	21.4	24.7	1.5	0	0	0	0	0	0
CR5: GF/South/30%	18.0	20.6	24.5	1.2	15.6	20.1	27.3	1.5	1	0	0	0	0	0
CR6: FF/Core space/0%	20.5	22.7	24.3	0.4	19.4	22.0	24.3	0.9	0	0	0	0	0	0
CR7: FF/East/30%	17.0	21.8	26.1	1.6	13.1	21.4	25.3	1.9	6	0	0	4	0	0
CR8: FF/South/30%	18.5	21.6	25.5	1.4	16.7	22.3	25.4	1.8	6	0	0	2	0	0
CR9: SF/South/30%	16.7	20.9	25.9	1.6	16.6	21.3	25.1	1.6	4	0	0	3	0	0

Table 6.3 shows no incidence of temperatures above 28 °C with few incidences above 25 °C that are partly driven by internal gains and building services' control strategy.

It is notable that most classrooms with incidences of temperatures above 25 °C are south facing despite the solar shading applied. The pattern of overheating is also different than what was observed in Buildings A and B; classrooms with higher incidences of temperatures above

25 °C are located on the ground floor. Post-occupancy evaluations revealed that teachers in these zones, allocated to primary education, often did not use the full extent of opening area provided for natural ventilation. This may explain the incidences with temperatures above 25 °C in these rooms.

Figure 6.9 and Figure 6.10 illustrate the variation bands of air temperatures in the sample classrooms during summer and heating seasons respectively.

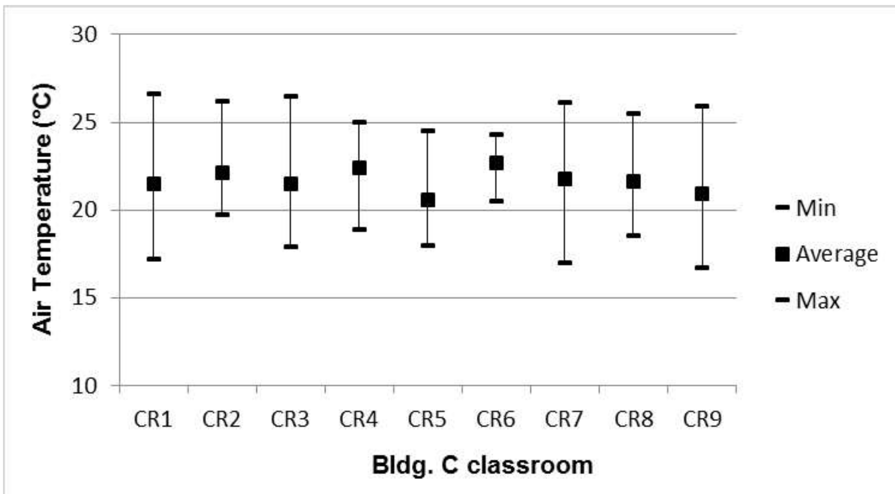


Figure 6.9. Boxplot of Building C indoor temperatures, May-September: occupied hours

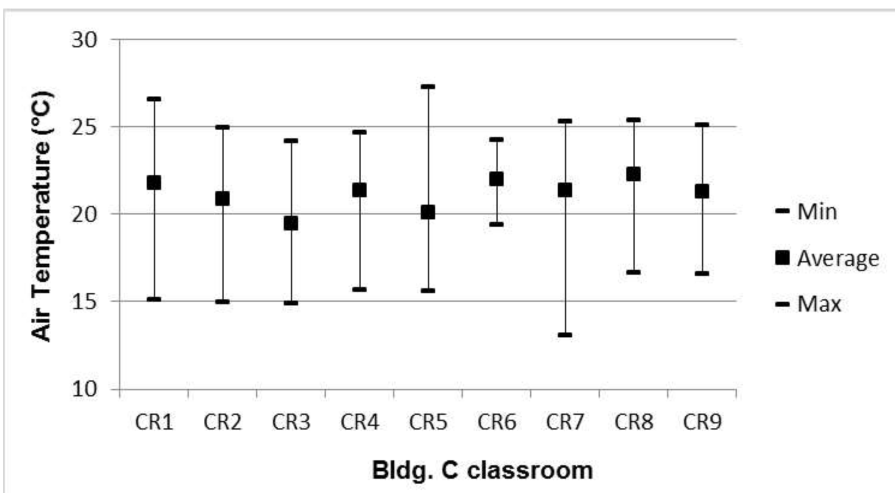


Figure 6.10. Boxplot of Building C indoor temperatures, October-April: occupied hours

Figure 6.11 shows the summertime performance of CR1 which is the classroom with the highest incidences of temperatures above 25 °C. The maximum recorded indoor temperature for this classroom during summer was 26.6 °C which occurred in late September when the outdoor temperature was 22.6 °C.

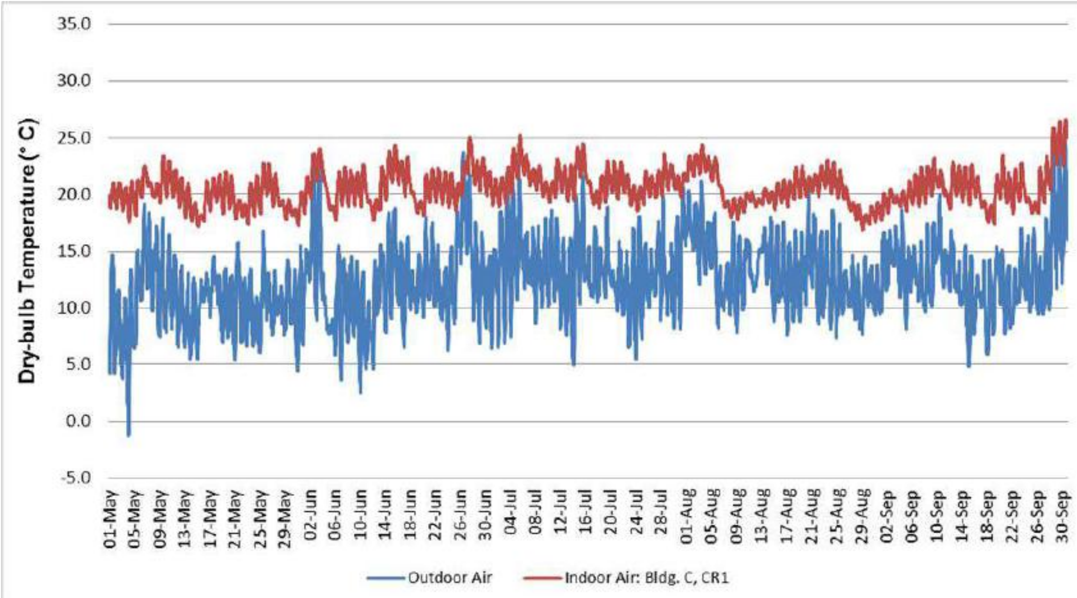


Figure 6.11. Indoor against outdoor hourly air temperatures for CR1: Building C

6.2.4. Building D

Building D was subject to overheating assessment under the outdoor conditions represented by the TRY weather file for London. Figure 6.12 compares the temperatures recorded by the nearest Met Office weather station to the building site during the measurement period against the TRY data. Although the peak temperatures in the TRY weather data are often higher than the peak temperatures recorded during the measurement period, the average and peak temperatures are reasonably close between the two datasets. The maximum TRY temperature for summer is 31.8 °C in June and the maximum summer temperature experienced during the measurement period was 30.2 °C in the same month.

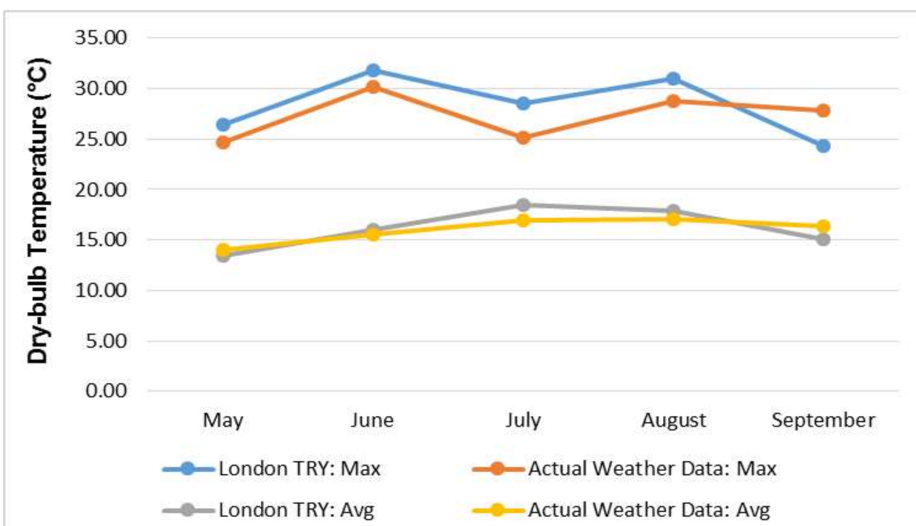


Figure 6.12. Actual peak and average outdoor temperatures against TRY data: Building D

Figure 6.13 illustrates the actual weather data and respective TRY data with hourly resolution. Overall, the actual weather data are very close to TRY data. This means the operational data can be used to assess the overheating performance of Building D against the BB101 assessment criteria with reasonable accuracy.

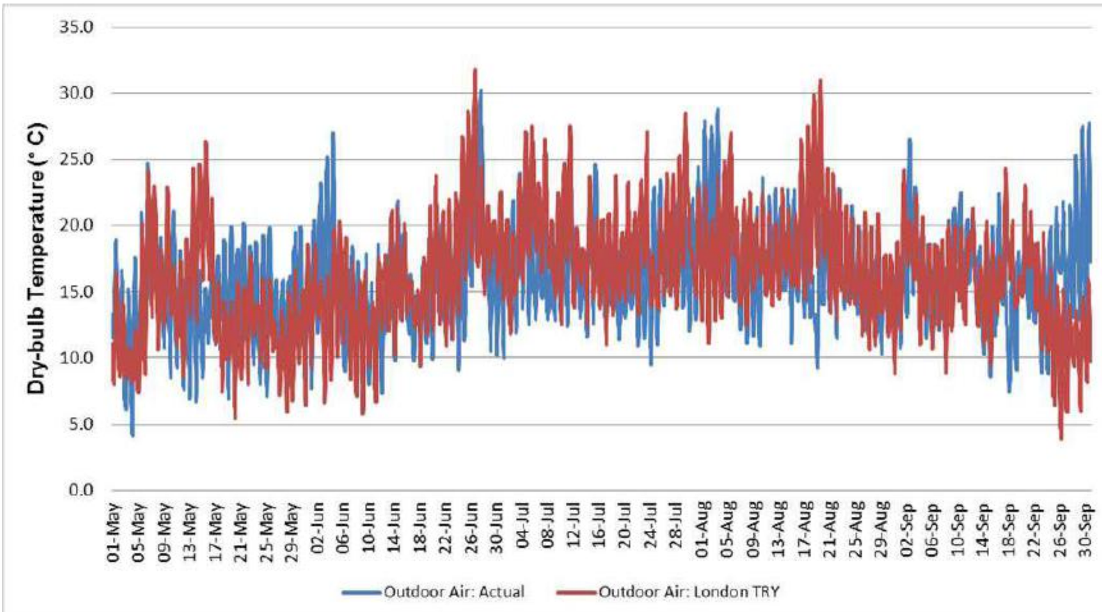


Figure 6.13. Hourly outdoor temperatures against TRY data: Building D

Table 6.4 presents the outcomes of the statistical analysis carried out on the recorded air temperatures in the sample classrooms of Building D.

CR7 (business and ICT classroom) is mechanically ventilated and is provided with limited comfort cooling in addition to heating, supplied by the installed chilled beams. Other classrooms are naturally ventilated with wet radiators as heating terminal. Naturally ventilated classrooms in this building have opening areas around 7% of the classroom area plus provision for cross or stack ventilation. The g values specified for the glazing were between 0.45-0.5.

There are very few incidences of temperatures above 28 °C and no incidence of temperatures above 32 °C in Table 6.4. The maximum summertime temperature recorded in the sample classrooms was 29.1 °C in the south orientation of the third floor in a classroom in which the manual switch for the stack vent was blocked by furniture and not accessible to use.

Overall, the sample classrooms meet the BB101 requirements with a healthy margin when exposed to outdoor temperatures close to the TRY temperatures. However, all sample classrooms experienced incidences with temperatures above 25 °C. Enabling the thermal triggers for the motorised vents installed on the west and east facades can help reduce the overheating incidences. These vents were only responsive to CO_2 concentrations during the long-term studies. The post-occupancy evaluation also revealed that the louvered windows installed in the classrooms to facilitate night-time cooling where not effectively used by building occupants.

Table 6.4. Building D indoor air temperatures over the period May 2011 – April 2012

Classroom: Location / Orientation / Glazing to wall ratio	Air temperature (°C), May-September (9:00-15:30, Monday-Friday)				Air temperature (°C), October-April (9:00-15:30, Monday-Friday)				Annual overheating hours (9:00-15:30, Monday-Friday)			Summer overheating hours, May-September (9:00-15:30, Monday-Friday) **(BB101 criteria)**		
	Min	Avg.	Max	SD	Min	Avg.	Max	SD	>25 °C	>28 °C	>32 °C	>25 °C	**>28 °C**	**>32 °C**
CR1: GF/West/26%	18.0	22.1	28.2	1.6	13.6	21.6	26.6	2.0	22	1	0	11	1	0
CR2: GF/North (Library)/28%	19.7	22.4	25.5	0.9	18.0	21.3	24.7	0.7	1	0	0	1	0	0
CR3: FF/West/40%	18.7	22.3	26.5	1.4	12.8	22.7	27.9	2.6	60	0	0	7	0	0
CR4: FF/West/17%	19.3	22.7	28.4	1.4	17.9	21.2	26.4	1.5	13	1	0	12	1	0
CR5: SF/South/18%	21.2	23.3	26.5	0.9	19.5	23.0	26.5	0.9	17	0	0	8	0	0
CR6: SF/South/75%	21.6	24.1	27.7	0.9	18.9	22.4	27.4	1.8	61	0	0	37	0	0
CR7: SF/Core space/0%	20.5	22.8	27.1	0.9	19.9	22.0	26.5	0.8	7	0	0	5	0	0
CR8: TF/South/20%	18.9	23.0	29.1	1.2	16.7	21.1	25.8	1.4	17	1	0	16	1	0

It is notable that a significant proportion of the incidences above 25 °C happened outside summer in CR1, CR4, CR6 and were related to internal factors. Furthermore, all rooms, with the exception of the library space (CR2), experienced temperatures above 25 °C in heating season. Increasing the low temperature hot water flow temperature to combat the heat loss in parts of the building with open doors and vents led to excessive temperatures in other parts of the building. This explains the high temperatures recorded in heating season in this building.

Figure 6.14 and Figure 6.15 illustrate the variation bands of air temperatures in the sample classrooms during summer and heating seasons respectively.

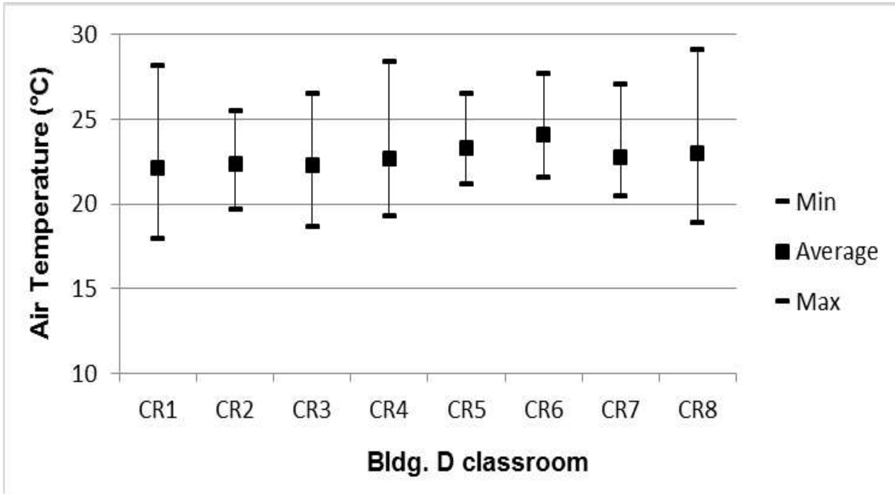


Figure 6.14. Boxplot of Building D indoor temperatures, May-September: occupied hours

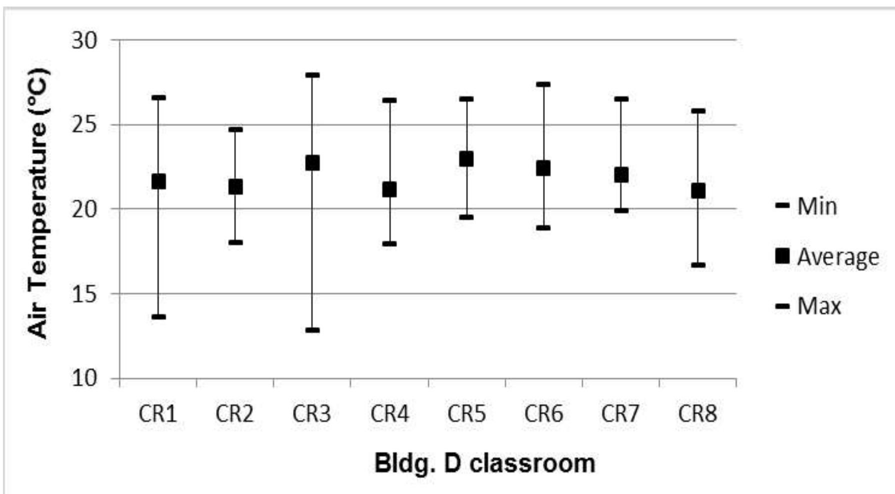


Figure 6.15. Boxplot of Building D indoor temperatures, October-April: occupied hours

Figure 6.16 shows the summertime performance of CR6 which is the classroom with the highest incidences of temperatures above 25 °C. The maximum recorded indoor temperature for this classroom during summer was 27.7 °C which occurred in late September when the outdoor temperature was 22.2 °C, that is, a temperature difference higher than 5 degree Celsius.

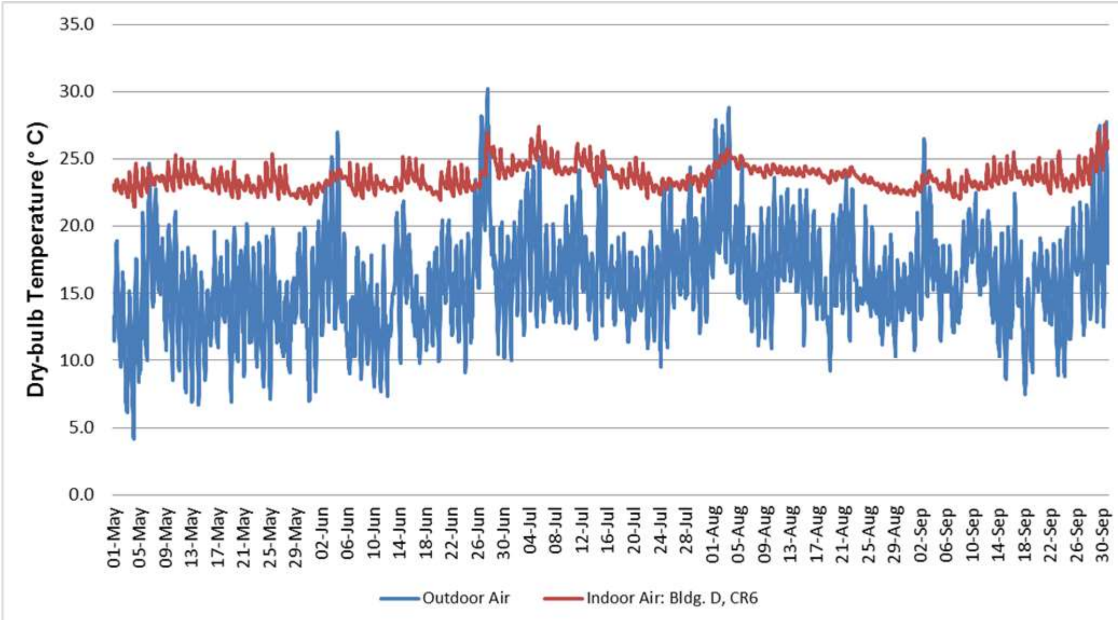


Figure 6.16. Indoor against outdoor hourly air temperatures for CR6: Building D

6.2.5. Building E

Building E is located in East London and was subject to overheating assessment under the outdoor conditions represented by the TRY weather file for London. The same outdoor weather data presented in the previous section are therefore applicable to Building E.

Table 6.5 presents the outcomes of the statistical analysis carried out on the recorded air temperatures in the sample classrooms of Building E.

All classrooms presented in this table are mechanically ventilated and have wet radiators installed as heating terminals. The g value specified for glazing in this building was 0.75, reduced to 0.5 on the south façade.

The sample classrooms meet the BB101 overheating requirements. However, it is notable that the incidences above 25 °C in summer in Building E were higher than Building D which is also located in an urban area in East London, although all teaching spaces in Building E are mechanically ventilated.

Table 6.5. Building E indoor air temperatures over the period May 2011 – April 2012

Classroom: Location / Orientation / Glazing to wall ratio	Air temperature (°C), May-September (9:00-15:30, Monday-Friday)				Air temperature (°C), October-April (9:00-15:30, Monday-Friday)				Annual overheating hours (9:00-15:30, Monday-Friday)			Summer overheating hours, May-September (9:00-15:30, Monday-Friday) **(BB101 criteria)**		
	Min	Avg.	Max	SD	Min	Avg.	Max	SD	>25 °C	>28 °C	>32 °C	>25 °C	**>28 °C**	**>32 °C**
CR1: GF/East/40%	19.0	23.0	27.6	1.5	16.4	21.3	27.3	1.9	24	0	0	18	0	0
CR2: FF/North East/21%	17.9	22.8	28.3	1.9	15.9	20.4	29.2	2.4	32	4	0	24	2	0
CR3: FF/North West/21%	19.1	22.4	26.2	1.4	10.6	16.9	25.2	2.9	10	0	0	9	0	0
CR4: SF/East/33%	17.9	22.8	27.7	2.0	15.2	21.0	28.3	1.9	30	1	0	21	0	0
CR5: SF/North West/33%	19.0	22.7	26.6	1.5	13.2	18.2	28.1	2.8	21	1	0	15	0	0
CR6: SF/South East/44%	19.1	23.4	28.1	1.9	16.0	21.3	28.6	1.8	30	4	0	27	3	0
CR7: SF/North East/21%	18.9	23.0	27.7	1.6	13.2	19.2	26.5	2.7	36	0	0	31	0	0

Figure 6.17 and Figure 6.18 illustrate the variation bands of air temperatures in the sample classrooms during summer and heating seasons respectively. Building E has the widest variation bands in heating season among the case studies. The minimum and maximum temperatures recorded in the occupied hours of heating season were 10.6 °C (CR3) and 29.2 °C (CR2) respectively. The maximum temperature recorded in heating season was higher than the maximum temperature recorded in summer. This is indicative of serious shortcomings in the building services control strategy of this building.

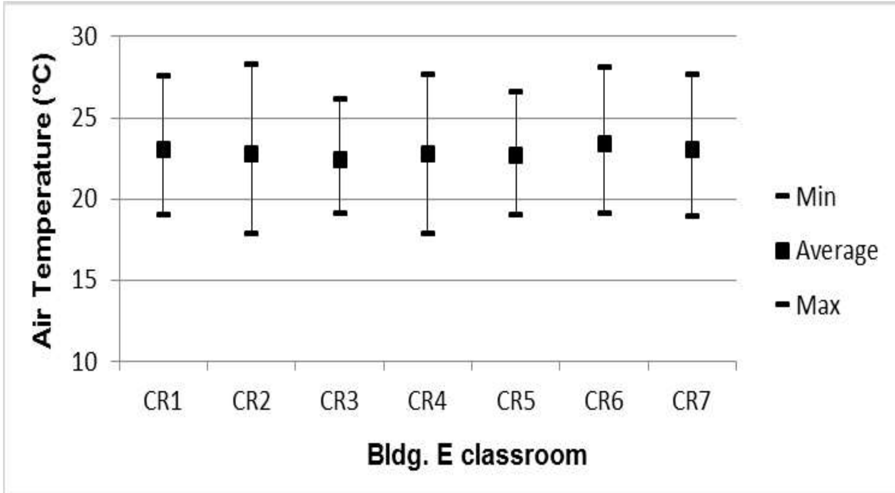


Figure 6.17. Boxplot of Building E indoor temperatures, May-September: occupied hours

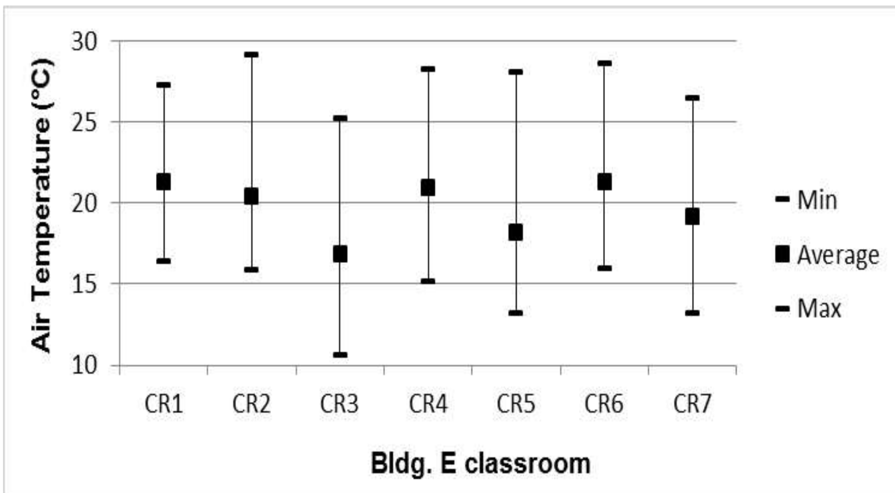


Figure 6.18. Boxplot of Building E indoor temperatures, October-April: occupied hours

Figure 6.19 shows the summertime performance of CR7 which is the classroom with the highest incidences of temperatures above 25 °C. The maximum recorded indoor temperature for this classroom during summer was 27.7 °C which occurred in late June when the outdoor temperature was 27.9 °C. Maximum temperature difference between outdoor and indoor temperature during summer was less than 4 °C.

Figure 6.20 shows the performance of CR3 which is the classroom with the lowest average and minimum temperatures in heating season. The post-occupancy evaluation revealed that the air handling unit serving this classroom was operating out-of-hours and overnight in the heating season. This put the heating system under stress, led to very low indoor temperatures in winter, and caused thermal discomfort for occupants.

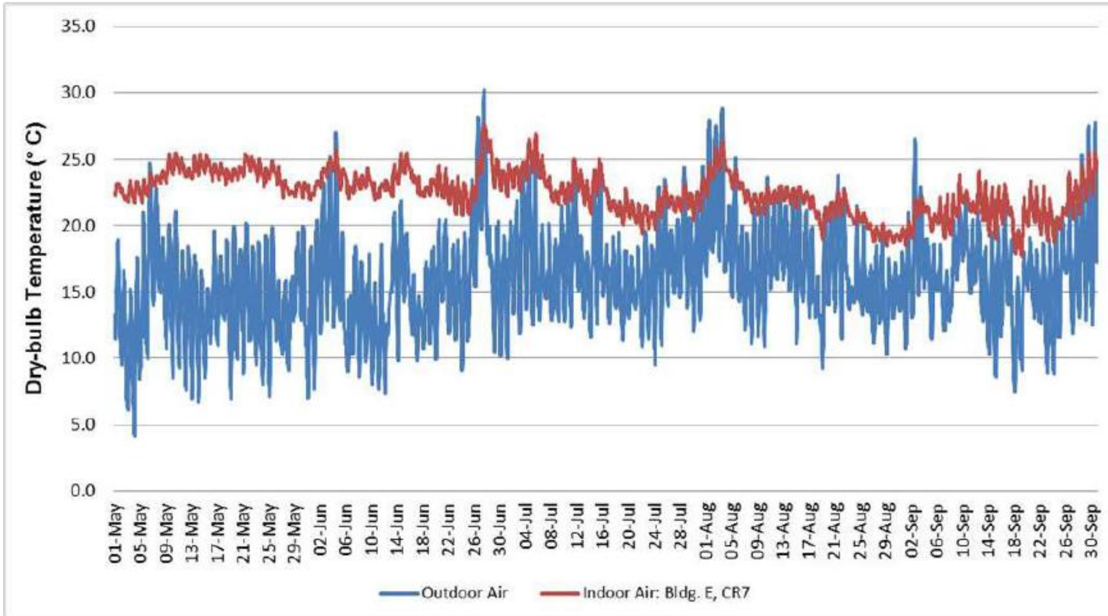


Figure 6.19. Indoor against outdoor hourly air temperatures for CR7: Building E

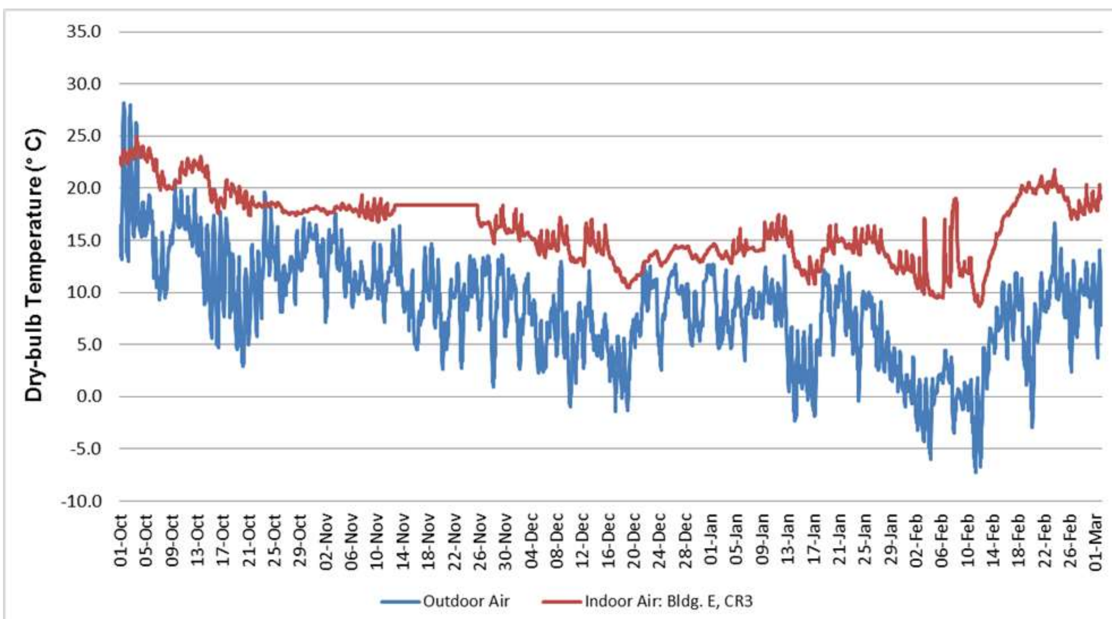


Figure 6.20.Hourly air temperatures for CR3 during the heating season: Building E

6.2.6. Notes on the new overheating criteria

Buildings D and E met the BB101 (2006) overheating criteria under outdoor temperatures very close to the TRY data.

The new overheating criteria proposed by CIBSE TM52 (2013) for free running buildings are based on adaptive overheating threshold temperature derived from the average outdoor temperatures in previous days (the running mean of the outdoor temperatures defined in BS

EN 15251). This is applicable to summertime performance of Building D. An allowance of 3% of occupied hours is defined for temperatures above this overheating threshold. Severity of overheating is also assessed by calculating the daily weighted exceedance over the overheating threshold, a factor that must be no greater than 6 degree-hours. Finally, an absolute upper limit for indoor operative temperature is defined which is 4 °C above the overheating threshold. A room or building that fails any two of these criteria is classed as overheated. One way of assessing the overheating risk of mechanically conditioned buildings is to use the same criteria albeit with a fix overheating threshold which is 26 °C for classrooms in accordance with BS EN 15251 (2007). This can be applied to Building E.

While the overheating analysis presented in this Chapter is based on the design criteria applicable to the buildings at the time they were constructed, the monitored classrooms in Building D pass the hourly exceedance and daily weighted exceedance criteria as the adaptive overheating threshold defined during the hot spells in June, July and September is higher than 28 °C and very few incidences of temperatures above 28 °C were recorded during the monitoring period. The monitored classrooms in Building E, on the other hand, pass the hourly exceedance and the upper limit criteria. However, this analysis is based on moderate outdoor conditions that were close to the TRY data. It is also assumed that the difference between the recorded air temperatures used for BB101 assessment and the operative temperatures used for TM52 assessment are small, a reasonable assumption where temperature sensors are not exposed to direct radiation from the sun or high temperature radiant sources (CIBSE, 2015 b).

Failure to enable critical design measures specified to mitigate the risk of overheating, such as thermally responsive motorised vents and louvered windows for night-time ventilation, increases the risk of overheating if Building D is exposed to higher outdoor temperatures. The risk of overheating in Building E is also extremely high when the building is exposed to higher outdoor temperatures expected in future with new overheating threshold defined at 26 °C .

6.3. Short-term intensive monitoring

The aim of the short-term intensive monitoring was to provide a broader consideration of thermal comfort that, in addition to air temperatures, takes into account radiant mean temperatures, relative humidity, and air speed, and also to review other aspects of the indoor environmental quality. These studies were performed during typical working weeks in heating season when there is usually a higher risk of poor indoor air quality. This also made it possible to monitor the performance of all building services, including heating systems, and explore the interrelations between energy use and the indoor environmental quality.

6.3.1. Indoor air quality and thermal comfort

In each building, the indoor air quality and thermal comfort conditions in three sample classrooms were closely monitored for one typical day. The classrooms were carefully selected to represent the variety of environmental strategies deployed in these buildings, although practical consideration related to availability of classrooms for monitoring also played a role in selecting the rooms.

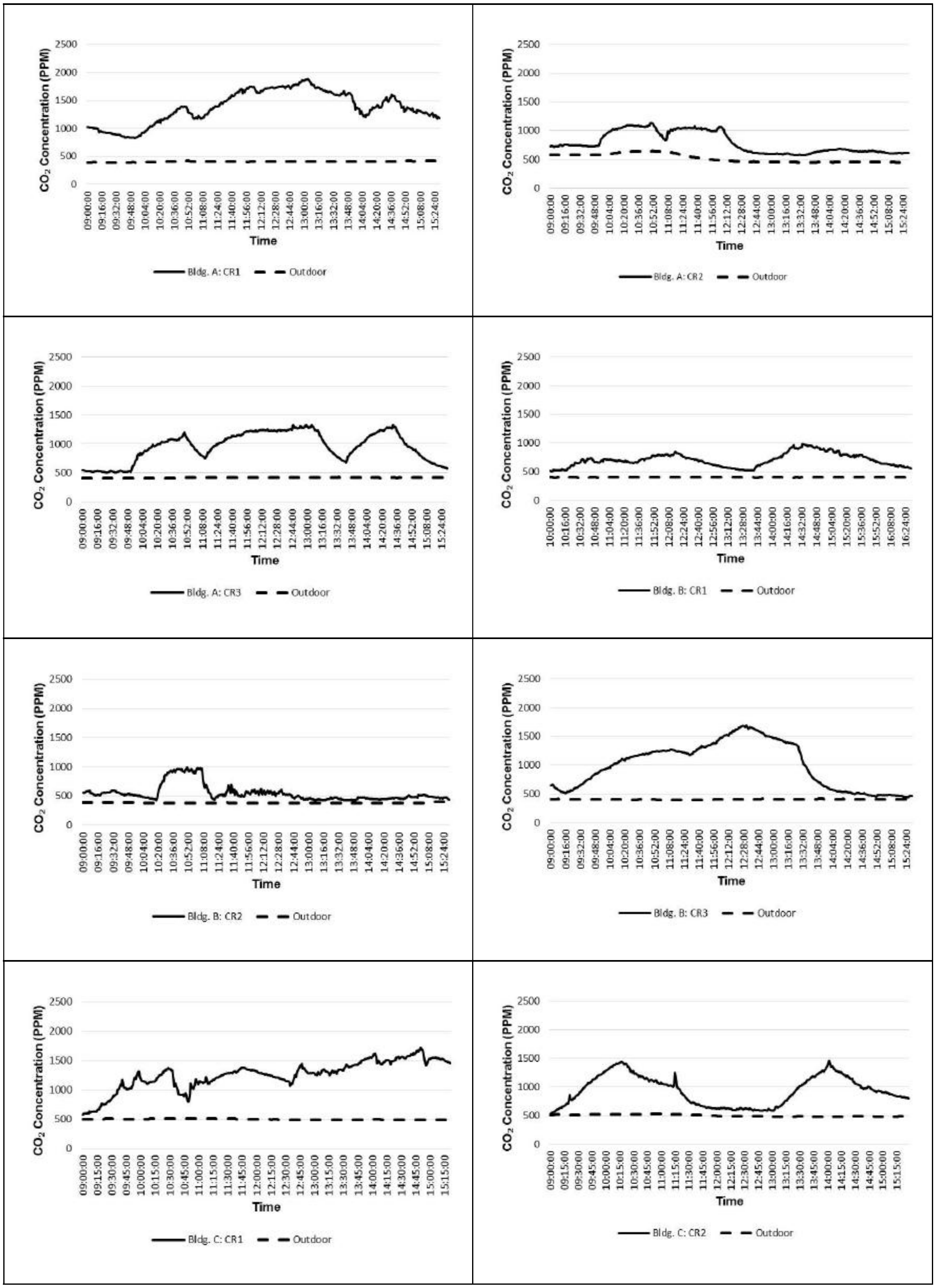
Table 6.6 includes a list of these classrooms along with key information that is meant to give context to the monitoring data.

Figure 6.21 illustrates the indoor CO_2 concentrations against the outdoor concentrations for all monitored classrooms. The peak CO_2 concentrations represent the maximum occupancies reported in Table 6.6.

Table 6.7 reports the statistics related to the indoor air quality, the ventilation rates inferred from CO_2 concentrations when the room conditions were close to steady-state, minimum and maximum radiant mean temperatures, minimum and maximum relative humidity, and the PPD index that is derived from the measurements of temperatures, relative humidity, and air speed. The activity and clothing levels assumed for PPD calculations are 1.4 met and 1.0 clo in accordance with the CIBSE recommendations for teaching spaces (CIBSE, 2015 b).

Table 6.6. Information related to the classrooms monitored for air quality and thermal comfort during heating season

Building	Classroom code	Classroom type / location / orientation	Classroom size (m²)	Maximum occupancy during study (nominal occupancy)	Environmental strategy	Operable windows
Bldg. A	A CR1	Textiles/ground floor/core space	87	18 (20)	Wet radiators for heating, Mech. Vent.	None
	A CR2	English/first floor/south	58	27 (30)	Wet radiators for heating, Mech. Vent.	1 × top-hung
	A CR3	Business & ICT/second floor/core space	65	16 (20)	Chilled beams for heating and cooling, Mech. Vent.	None
Bldg. B	B CR1	Res. Materials/ground floor/west	99	10 (20)	Radiant panels, Mech. Vent.	3 × top-hung
	B CR2	Seminar room/first floor/north	43	23 (25)	Radiant panels, Mech. Vent.	2 × top-hung
	B CR3	Business & ICT/second floor/west	53	13 (20)	VRF units for heating and cooling, Mech. Vent.	2 × top-hung
Bldg. C	C CR1	Primary education/ground floor/south	58.5	24 (25)	Split units for heating and cooling, Nat. Vent.	2 × top-hung
	C CR2	Science lab/first floor/east	89	25 (25)	Radiant panels for heating, Mech. Vent.	4 × top-hung
	C CR3	Maths/second floor/ north	59.5	22 (25)	Wet radiators, Nat. Vent.	2 × top-hung + 2 × top-hung (stack ventilation)
Bldg. D	D CR1	Maths/first floor/east	60	30 (30)	Wet radiators, Nat. Vent.	6 × top-hung + 3 louvered side windows
	D CR2	Science lab/second floor/west	85	30 (30)	Wet radiators, Nat. Vent.	8 × top-hung + 4 louvered side windows
	D CR3	ICT/second floor/core space	75	23 (25)	Chilled beams for heating & cooling, Mech. Vent.	None
Bldg. E	E CR1	Communications/first floor/north west	52	20 (25)	Wet radiators, Mech. Vent.	1 × top-hung
	E CR2	History/first floor/core space	82	25 (30)	Wet radiators for heating, fan coil unit for cooling, Mech. Vent.	none
	E CR3	Maths/second floor/south east	65.5	26 (30)	Wet radiators, Mech. Vent.	1 × top-hung


CO$_2$ Concentration (PPM)
Time
Bldg. A: CR1
Outdoor
Bldg. A: CR2
Outdoor
Bldg. A: CR3
Outdoor
Bldg. B: CR1
Outdoor
Bldg. B: CR2
Outdoor
Bldg. B: CR3
Outdoor
Bldg. C: CR1
Outdoor
Bldg. C: CR2
Outdoor

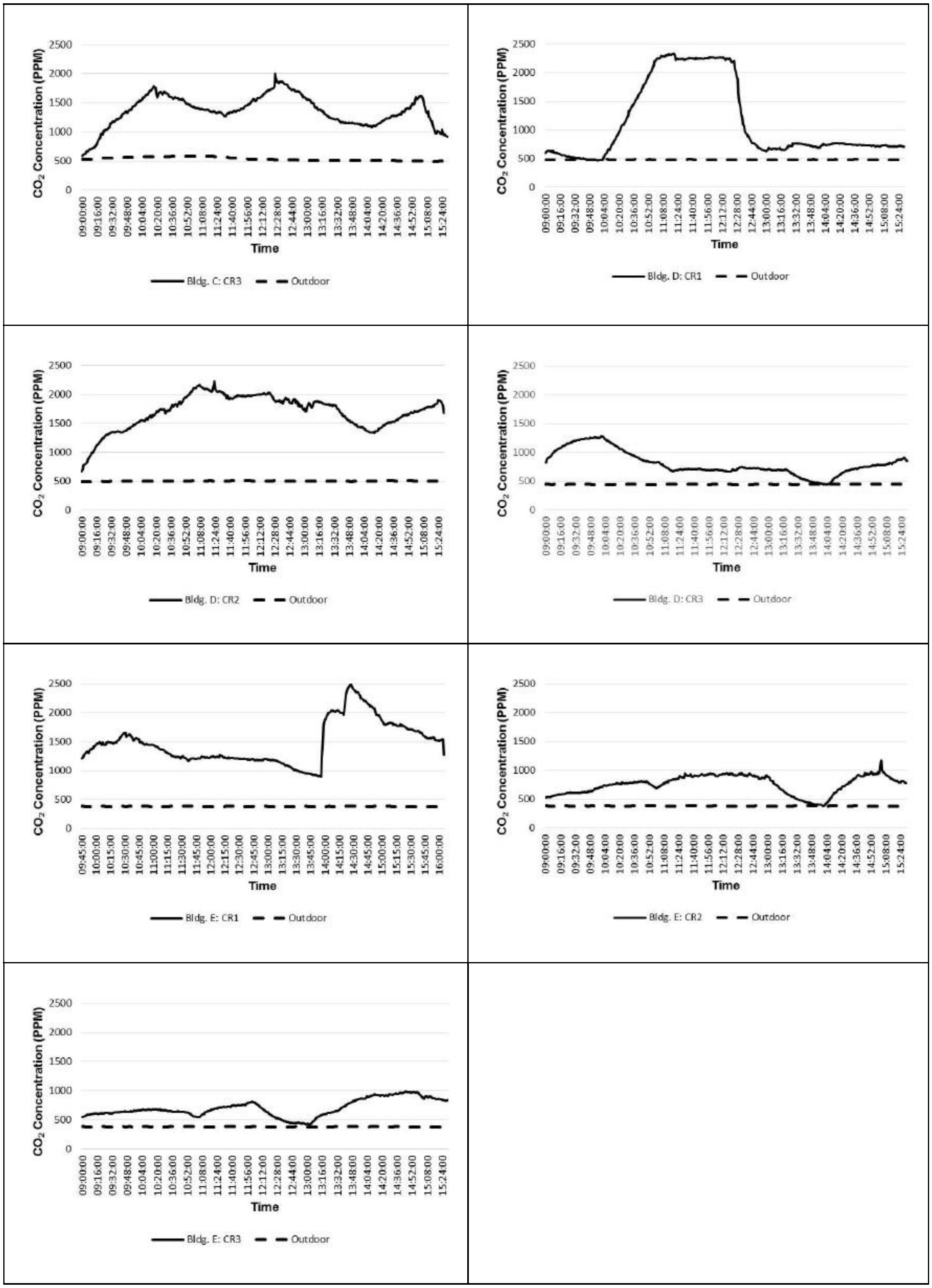


Figure 6.21.Outdoor and indoor CO_2 concentrations in the sample classrooms during occupied hours in heating season

Table 6.7. Indoor air quality and thermal comfort conditions in the classrooms

Room	CO_{2MAX} (ppm)	CO_{2AVE} (ppm)	CO_{2STD} (ppm)	Steady flow rate (l/s/p)	T_{MIN} (°C)	T_{MAX} (°C)	RH_{MIN} (%)	RH_{MAX} (%)	PPD (%)
A CR1	1884	1378	294	3.8 (18p)[14]	22.8	24.7	26	35	<18
A CR2	1132	785	185	10.0 (27p)	21.4	23.6	25	30	<10
A CR3	1331	960	254	6.2 (16p)	17.7	21.0	27	33	<25
B CR1	982	707	116	12.5 (8p)	18.1	21.5	42	50	<10
B CR2	989	549	144	8.8 (22p)	21.8	26.0	39	45	<28
B CR3	1690	1000	401	6.0 (9p)	21.2	22.4	36	50	<10
C CR1	1724	1252	248	4.8 (22p)	17.9	22.9	33	41	<22
C CR2	1451	936	260	5.6 (24p)	22.7	25.3	25	39	<13
C CR3	1994	1362	267	3.9 (15p)	20.6	23.7	25	36	<10
D CR1	2336	1139	679	2.9 (30p)	20.4	22.8	27	39	<10
D CR2	2234	1698	295	3.4 (16p)	19.0	21.9	31	38	<14
D CR3	1282	804	214	6.2 (23p)	20.6	21.2	23	30	<10
E CR1	2498	1475	369	4.5 (11p)	22.1	24.4	34	56	<12
E CR2	1164	752	161	9.1 (25)	17.7	23.3	36	42	<24
E CR3	986	698	149	9.1 (24p)	18.2	22.3	40	44	<19

Indoor air quality: the variations of CO_2 concentrations presented in Figure 6.21 closely follow the ventilation strategies; mechanically ventilated classrooms had concentration levels lower than 1500 ppm for most of the occupied time, whereas the indoor air quality in naturally ventilated classrooms was determined by the number of occupants and how they used the operable windows. However, there were a couple of exceptions that indicate the risk factors associated with mechanical ventilation strategy. The air handling units serving A CR1 and E CR1 were not operating during the technical studies due to parts' failure. A CR1 is an atrium-facing classroom located in the core of the building with no direct access to external facades. E CR1, on the other hand, is only provided with one small operable window. Maximum occupancy in both classrooms during the investigation was lower than the nominal classroom capacity. Yet the CO_2 concentrations exceeded 1,500 ppm in A CR1 for a couple of hours and E CR1 reached the highest CO_2 concentration recorded in the monitored classrooms (2498 ppm). Teachers and pupils in both classrooms complained about lack of fresh air and some

[14] The figure in bracket represents the number of occupants in the steady mode of operation that was used to infer the ventilation rate.

had experienced headaches as this was a prolonged problem. The facility manager at Building A was not aware of this problem until it was flagged up during the investigations. The problem with the respective supply fan was subsequently addressed by the maintenance contractor. The facility manager at Building E was informed about the problem. However, the school was still undecided about accepting a quotation received weeks ago to repair the air handling unit due to budget constraints.

The only classroom with average CO_2 concentration higher than 1500 ppm that did not meet the BB101 requirement for indoor air quality was D CR2 (CO_{2AVE} = 1698 ppm). This prompted a longer term investigation of indoor air quality in naturally ventilated classrooms in this building. The CO_2 concentration levels in 20 classrooms were monitored during a typical week in heating season via the BMS. Five classrooms (25% of the classrooms) experienced average concentration levels higher than 1500 ppm for at least one day during the working week. The maximum CO_2 concentration recorded for these classrooms was 2006 ppm. Figure 6.22 shows the variation of CO_2 concentrations in a typical classroom that met the BB101 requirements during the week.

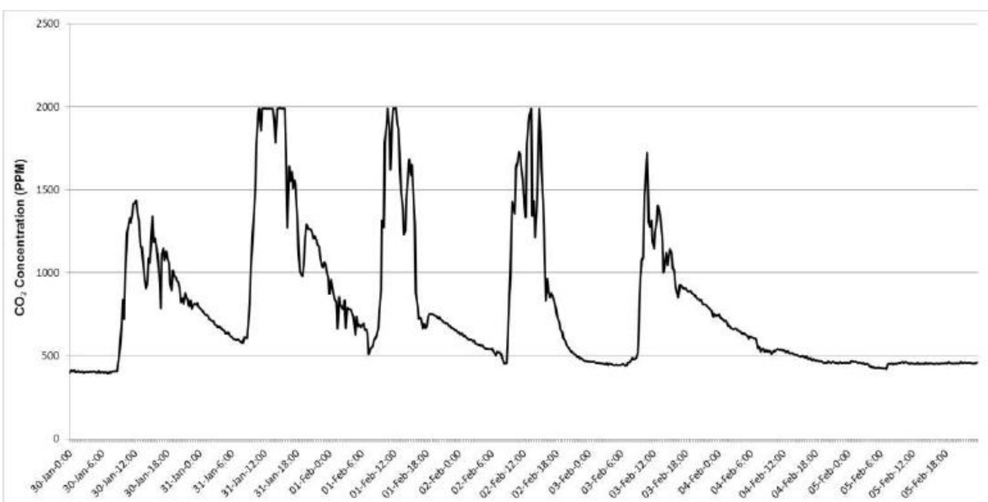


Figure 6.22. Variation of CO_2 concentrations in a typical classroom: Building D (Maximum daily CO_{2AVE} = 1436 ppm)

Figure 6.23 shows the variation of CO_2 concentrations in the worst case classroom that experienced average CO_2 concentrations higher than 1500 ppm for four days per week.

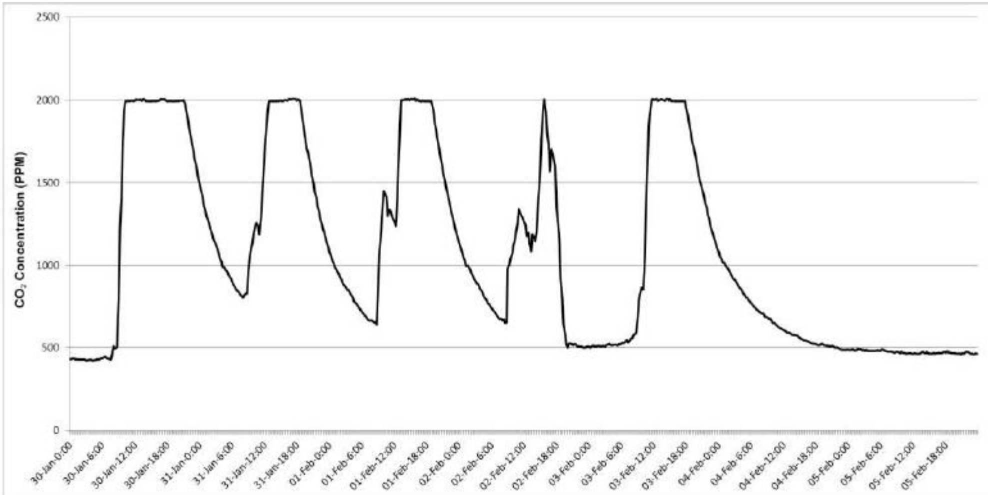


Figure 6.23. Variation of CO_2 concentrations in the classroom with highest average concentration levels: Building D (Maximum daily CO_{2AVE} = 1888 ppm)

These Figures show that, where fully functional, the motorised vents installed for naturally ventilated classrooms in Building D were capable of limiting CO_2 concentration to around 2000 ppm. The threshold concentration level defined for the operation of motorised vents in heating season was 1200 ppm. Reducing this threshold level may help improve the indoor air quality. However, cross/stack natural ventilation was also an important component of the ventilation strategy specified for this building. Manually operable openings had been installed to facilitate cross and stack ventilation. Figure 6.24 shows the traffic light control interface installed in the naturally ventilated classrooms to prompt teachers to open the windows if the indoor air quality is worse than expected.

Figure 6.24. Traffic light control system installed to help teachers improve air quality by opening windows when required: Building D

The post-occupancy evaluation revealed most teachers were not quite clear about different modes defined on this interface. The amber mode was specified to ensure windows are kept closed in winter when air quality is good and thereby save heating energy. However, some teachers found the label used for this mode misleading. Teachers were especially confused when the windows were closed and they faced with the amber mode during breaks or when the classroom was almost empty with extremely low CO_2 concentrations. The instructions provided for this control interface during a switch-off campaign led by the school are visible in Figure 6.24 and are reproduced in Table 6.8 to compare the users' understanding of the control modes with the design intent. Users' understanding of the amber mode and the design intent were diametrically opposed and this led to waste of heating energy when teachers did not turn off the heating. Furthermore, some teachers, facing with persistent amber mode when windows were open, lost their confidence in the control interface and ignored the traffic light signals altogether.

Table 6.8. Traffic light control modes: the design intents and users' interpretations

Traffic light control signal	**Label**	**What designers meant**	**What users thought**
	"Inadequate Ventilation"	CO_2 level is high; open the windows.	"Too much CO_2, open the windows and turn off the heating."
	"Excessive Ventilation"	CO_2 level is good; if winter, make sure the windows are closed.	"Poor CO_2 level, open the windows slightly and turn off the heating."
	"Ventilation Adequate"	CO_2 level is acceptable; no action is required.	"The CO_2 levels are good, No need to open the windows."

The inferred ventilation rates show all classrooms achieved the minimum ventilation of 3 l/s/person with the exception of D CR1 with a borderline ventilation rate of 2.9 l/s/person. Buildings C and D are predominantly naturally ventilated with operable window areas higher than the minimum prescribed by BB101. Typical classrooms in Building C have opening areas equivalent to 4% of classroom area specified for natural ventilation with provision for cross or stack ventilation and a manually operable booster extract fan. In Building D, typical classrooms have higher opening areas at around 7% of the floor area for single-sided ventilation with provision of motorised vents for cross or stack ventilation. These opening areas are higher than the BB101 guidelines for opening areas that are 5% of floor area for single-sided ventilation and 2% of floor area for cross ventilation (DfES, 2006, p. 41). Based on the CO_2 levels monitored during out-of-hours, it is estimated that the naturally ventilated classrooms in both buildings are capable of achieving 8 l/s/person at their nominal occupancy level if all openings and extract fans are used. However, it was not possible to examine this boost mode during occupied hours. Buildings A, B and E are mechanically ventilated and the ventilation rates reported in Table 6.7 show the ventilation systems, where fully functional, are capable of achieving 8 l/s/person in most classrooms. However, the inferred ventilation rates in A CR3 and B CR3 were lower than 8 l/s/person at occupancy levels lower than nominal occupancy. This points to imbalances in the air distribution system in these buildings. The ventilation rates in building E were consistent and higher than 8 l/s/person at occupancy levels close to nominal occupancy where the respective air handling units were operational.

Thermal comfort: the lowest temperature of 17.7 °C was recorded in the classrooms that were provided with comfort cooling in addition to heating (A CR3 and E CR2). This is indicative of conflicting heating and cooling systems in these classrooms, a phenomenon that was observed in most classrooms that had heating and cooling provisions. A better control strategy that allows for a wide dead-band between heating and cooling modes can help save energy and improve thermal comfort. The low temperature recorded in C CR1 (17.9 °C) was influenced by the operation of a rear door that was frequently used by teachers and students to get access to the courtyard for outdoor activities. The highest temperature of 26 °C was recorded in B CR2 on a day that the heating system was mal-functioning as the control valve for the variable temperature heating loop was mistakenly fixed back to front by the maintenance contractor. This led to excessive heating when actual demand for heating was negligible.

RH levels in all buildings were often lower than 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 (CIBSE, 2015 b). Low humidity levels make people more sensitive to odours and may affect their perception of indoor air quality (Fang, et al., 1998). The minimum RH level recorded was 25%. Relative humidity levels below 25% are associated with increasing discomfort and dryness of skin that can lead to irritation. Low relative humidity also increases static electricity that can cause discomfort (Nathanson, 1995).

It is notable that the 19-21 °C temperature range and other comfort criteria recommended by CIBSE for designing teaching spaces are defined to achieve a PPD level not greater than 5% in heating season. However, the PPD calculations assume RH level of 50% and air speed of 0.15 m/s (CIBSE, 2015 b). The RH levels in the monitored classrooms were often much lower than 50%. The air speeds, partly driven by natural ventilation, were also frequently higher than 0.15 m/s. Therefore, achieving a maximum PPD level of 5% in heating season was practically not feasible in most classrooms for the reasons that go beyond the design strategies specified for these buildings and are representative of wider trends in the UK construction industry. Based on the technical measurements, maximum 10% PPD is a more realistic yardstick to assess thermal comfort conditions in these buildings. The uncertainties and limitations of the Fanger comfort indices aside, this yardstick is useful for the review of user satisfaction results in the next Chapter.

Building E was the only building with maximum PPD higher than 10% in all monitored classrooms; other buildings had at least one or two classrooms with maximum PPD levels lower than 10%. This is consistent with low and high temperatures recorded during heating season in the long-term studies if it is assumed other parameters were close to the conditions recorded during the intensive studies. The number of overheating hours recorded for this building during the long-term studies was also higher than the other buildings. A high percentage of people dissatisfied with thermal comfort is therefore expected in this building.

6.3.2. Acoustics

According to BB93, the indoor ambient noise level in unoccupied spaces includes contributions from buildings services and external sources outside school, but excludes the contribution from teaching activities within the school premises (DfES, 2003). Sound insulation between spaces is supposed to attenuate the airborne sound transmitted between spaces through walls and floors. The post-occupancy observations point to the significance of airborne sound insulation between internal spaces as internal noise from pupils and staff in the case studies were the main source of noise that affected the measurements of sound levels in unoccupied spaces. While this effect was more pronounced in classrooms close to open-plan teaching spaces and circulation areas, the noise levels from the adjacent classrooms during teaching hours were also disruptive and frequently led to ambient noise levels much higher than 35 dB, the upper limit for indoor ambient noise levels in unoccupied classrooms. The noise levels and reverberation times of the sample classrooms reported in Table 6.9 have therefore been measured when the adjacent spaces were unoccupied, to exclude the effect of internal noise caused by building occupants. All rooms can be classified as normal classroom in the context of BB93 with the exception of Room1 in Building C which is a science lab with a higher upper limit for ambient noise levels at 40 dB. As the air distribution systems proved to be a key driver of noise levels during the tests, the ventilation strategy for each room is also listed in Table 6.9. Mechanically ventilated classrooms generally had higher noise levels than naturally ventilated classrooms even though windows were kept open in naturally ventilated classrooms to represent indoor ambient noise levels under expected operating conditions. The mechanically ventilated classrooms in Building A had indoor ambient noise levels higher than 35 dB L_{Aeq}, 30min which were caused by poor attenuation of the mechanical ventilation systems. Room 2 in Building D also suffered from a technical problem in the active chilled beam terminal that caused excessive noise level. Room 2 in Building B was located underneath the roof plant room. The noise and vibration caused by the operation of the main air handling unit was noticeable in the classroom and the indoor ambient noise levels were constantly higher than 35 dB even during out-of-hours when the building was almost empty. The noise levels in both mechanically ventilated classrooms in Building E were also higher than 35 dB limit.

Table 6.9. Indoor ambient noise levels and reverberation times in unoccupied classrooms

Building	Classroom	Noise level , L_{Aeq}, 30min (dB)	Reverberation Time (seconds)
Bldg. A	Room 1 (Mech. Vent.)	47	0.5
	Room 2 (Mech. Vent.)	40	0.5
Bldg. B	Room 1 (Mech. Vent.)	35	0.4
	Room 2 (Mech. Vent.)	37	0.4
Bldg. C	Room 1 (science lab) (Mech. Vent.)	38	0.5
	Room 2 (Nat. Vent.)	36	0.4
Bldg. D	Room 1 (Nat. Vent.)	33	-
	Room 2 (Mech. Vent.)	49	-
Bldg. E	Room 1 (Mech. Vent.; exposed ceiling)	41	0.7
	Room 2 (Mech. Vent.; suspended ceiling)	39	0.4

The reverberation times were typically measured twice in 3-5 locations. The impulse was generated in a location close to teacher's desk or lectern. When there was a significant discrepancy between two measurements in one location, further tests were carried out to figure out the reverberation time with accuracy. The values reported in Table 6.9 represent the average of reverberation times measured in 500 Hz, 1000 Hz, and 2000 Hz. It was not possible to complete the measurements in Building D as a number of out-of-hours activities were taking place during the tests and the impulse method could have been disruptive. A key measure used in this building to control reverberation in teaching spaces is the use of suspended rafts for absorption (Figure 6.25).

The average measured reverberation times were all lower than the 0.8 seconds limit specified by BB93 for teaching spaces. However, there was a marked difference between the reverberation times in the classroom with exposed ceiling and the classroom with suspended ceiling that had high sound absorption quality in Building E (Figure 6.26).

Figure 6.25. Acoustically absorbing material and suspended acoustic rafts are used to control reverberation in Building D

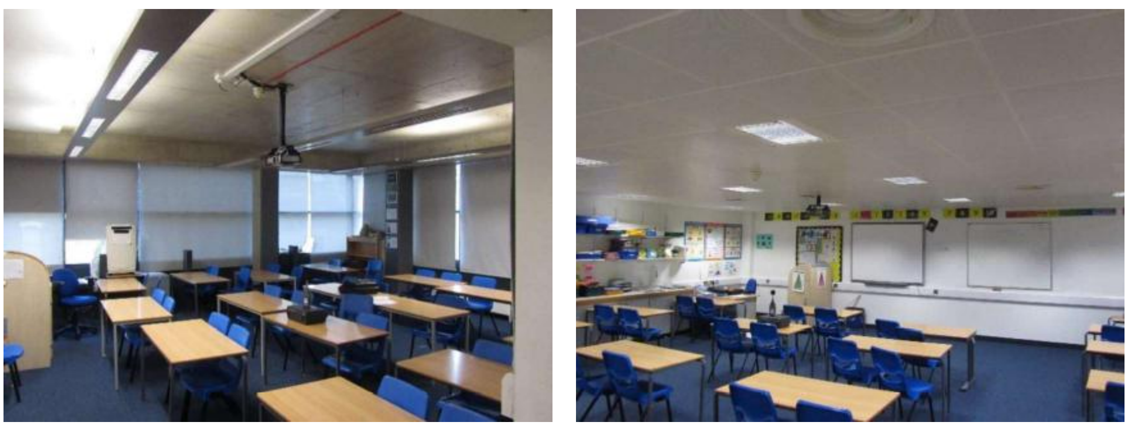


Figure 6.26. The classroom with exposed ceiling (left) had a reverberation time almost twice the reverberation time measured in the classroom with suspended ceiling (right): Building E

Another test was carried out in a similar-sized classroom with exposed ceiling in Building E that was covered with flags during the summer of 2014 to celebrate the football World Cup (Figure 6.27). The reverberation time in this classroom was around 0.5 seconds, much lower than other classrooms with exposed ceiling. Using permanent suspended acoustic tiles or rafts can help reduce reverberation time when exposed thermal mass is part of the environmental strategy (CIBSE, 2015 a).

Figure 6.27. This classroom in Building E had lower reverberation time than the other classrooms with exposed ceiling (Tmf = 0.5 seconds).

Concerns about external noise levels were the main driver to specify mechanical ventilation as the main ventilation strategy in three case studies. Yet, the external noise from the main roads close to Buildings B and E, measured during typical days, were lower than 60 dB L_{Aeq}, 30min at the boundary of schools. This is the external noise level that may trigger acoustically attenuated natural ventilation or mechanical ventilation (DfES, 2003). The evidence from these case studies suggests designers take a cautious approach when the external noise levels are close to this border line. However, once mechanical ventilation strategy is selected, less attention is paid to minimise the conflicts between mechanical ventilation, energy performance and user comfort. As explained in the previous Chapter, the operational energy performances of Buildings A and E suffered from poor procurement and management of mechanical ventilation systems. The acoustic tests also show most mechanically ventilated classrooms did not meet BB101 criteria in the case studies.

6.3.3. Lighting

Simultaneous measurements of indoor and outdoor illuminance levels in Buildings A and B found the average daylight factors in most teaching spaces were higher than 2%, a target which had been set out for 80% of occupied spaces in these buildings to achieve a BREEAM credit. The first row of pupils' desks close to the windows had daylight factors in the region of 5-6% and illuminance levels higher than 300 lux with natural daylight. Therefore, these zones could be considered as well day lit. However, almost in all sample classrooms observed in Buildings A and B and other case studies, the installed electrical lights covering day lit zones were constantly in use during occupied hours. The problem was twofold: where automated daylight control had been specified by designers, the threshold lux level for electrical lights had not been defined and commissioned correctly to enable automated dimming.

Furthermore, the manual control switches installed for lighting system in most buildings were driven by the location of whiteboard/projector rather than windows (Figure 6.28). The only exception to this rule was Building D where the first row of desks parallel to windows had separate manual control with both ON/OFF and dimming modes. However, even in this building teachers usually did not use the manual switch to control the day lit zones separately from other zones. Consequently, the benefits of day lit zones in teaching spaces for electrical energy was almost nil.

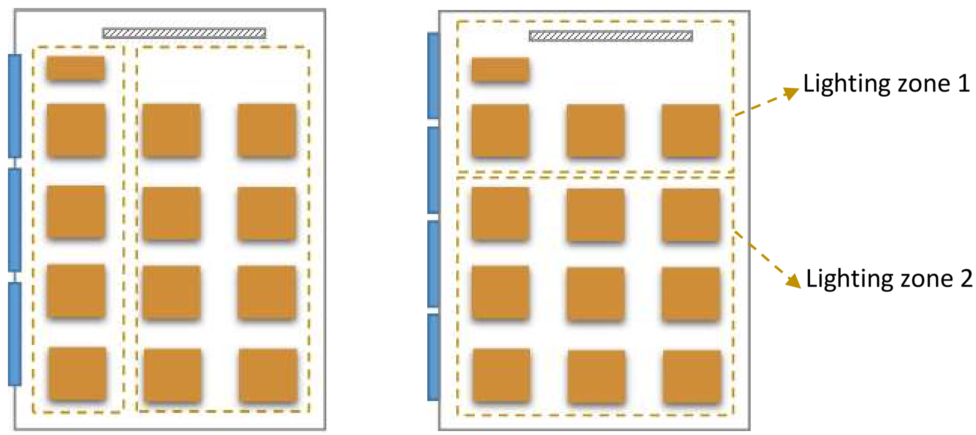


Figure 6.28. Manual lighting control arrangement specified for Building D (left) against other case studies (right)

Spot checks of indoor illuminance levels on working planes in all case studies showed the illuminance levels in teaching spaces were generally higher than the minimum requirement of 300 lux. Designers have a tendency to over-specify the lighting levels to ensure the minimum 300 lux is achievable at all points. This sometimes leads to average illuminance levels much higher than required. The average illuminance levels measured on working plane in Buildings B and D sample classrooms, covering all desks, were around 350 lux. Other buildings had higher illuminance levels. The highest illuminance levels were measured in Building A sample classrooms with an average illuminance of 450 lux, i.e. 50% higher than the minimum requirement. As pointed out in Chapter 6 this has implications for electricity use. It also brings higher risk of glare for building occupants which will be further explored in the next Chapter.

6.4. Emerging themes and key lessons

The key lessons emerging from the studies of the indoor environmental quality in the case studies are as follows:

6.4.1. Thermal comfort: fabric first principle against mechanical solutions

Comparing the thermal comfort conditions in Buildings D with conditions in Building E points to the significance of fabric first principle and the merits of passive design.

Both buildings are located in similar climate but have fundamentally different designs strategies. Building D has a narrow plan with two main east and west facing facades. These orientations are exposed to lower sun angles in summer and therefore are prone to overheating as shown in previous studies (Pegg, 2007). The designers adopted fabric first principle to mitigate this risk. The measures specified include windows with low g-values, vertical perforated fins on both east and west facades, heavy thermal mass, and opening areas significantly higher than minimum requirements. Two additional measures that were not commissioned or used in practice are thermally responsive motorised vents to facilitate cross/stack ventilation and manually operable louvered windows for night-time cooling. While there is an opportunity to enable thermal triggers for the motorised vents in a seasonal commissioning, the louvered windows can already be used by school caretakers to provide night-time cooling. Therefore, the building has further potential to mitigate the risk of overheating if exposed to high ambient temperatures in future. The building is predominantly naturally ventilated with wall mounted wet radiators as heating terminals. The radiators are locally controllable by thermostatic valves that most occupants are familiar with and comfortable to use them in heating season.

The monitored classrooms in Building D met the BB101 overheating criteria over the measurement period under external temperatures that were reasonably close to the TRY data. The temperatures in the monitored classrooms were above 25 °C in summer for 100 hours in total. In heating season, the sample classrooms had a stable performance and only one classroom had a maximum PPD index higher than 10%.

Building E, on the other hand, is to a large extent dependent on mechanical solutions to provide thermal comfort. The building does not have any solar shading applied and has a lightweight external envelope that can negate the effect of exposed ceilings. It is mechanically ventilated and comfort cooling is also provided to parts of the building.

The monitored classrooms in Building E met the BB101 overheating criteria. However, total number of hours with summertime temperatures higher than 25 °C was more than 50% higher than Building D. Furthermore extreme temperatures as high as 29 °C were recorded in heating season and all monitored classrooms during intensive studies had maximum PPD levels higher than 10%. This environmental performance must also be put in the context of the excessive energy use reported for this building in the previous Chapter.

6.4.2. Indoor air quality and ventilation strategy

The investigations show the challenges and risks involved in achieving good level of indoor air quality with various ventilation strategies.

Mechanically ventilated classrooms in the case studies generally had lower CO_2 levels than naturally ventilated classrooms. However, the failure mode of mechanical systems must be taken into account. Reasonable opening areas for natural ventilation or alternative contingency measures are required to protect occupants from poor indoor air quality when mechanical systems fail.

The fact that around 25% of the monitored classrooms in Building D had average CO_2 levels higher than 1500 PPM for at least one day per week, despite the amount of the opening areas available for single-sided ventilation and cross-ventilation facility, points to the challenges of achieving good level of indoor air quality with natural ventilation. Lowering the CO_2 threshold level for the operation of the motorised vents and providing the required information about the operation of the control interface for operable windows to teachers can help achieve better air quality. However, in general, maintaining CO_2 levels lower than 1,000 ppm, which is reported to be critical for cognitive performance of pupils (Wargocki & Wyon, 2013), during peak occupancy periods would be very challenging and may trigger mechanical ventilation if adopted as good practice in future. In that case, it is crucial to identify and mitigate various risk factors associated with mechanical ventilation both in terms of air quality and energy performance.

6.4.3. Ergonomics of design and provision of information

A user-centred approach to defining the control interfaces is essential to achieve good environmental quality.

The labelling of the traffic light system installed to control CO_2 levels in Building D is an example of the gap between designers' technical understanding of system operation and the clear instructions users need. Some teachers also thought the manual control installed for dimming the electrical lights in Building D was not user friendly. In all buildings there were opportunities to improve the functionality of control interfaces. A manually operable row of lights in circulation space of Building A had been in use 24 hours a day before the respective switch was found remote from the zone during the post-occupancy evaluation. The radiant panel thermostats in Building B were installed at high level and not accessible to users. There was no manual switch for lights in a number of classrooms in Building E and the lighting was entirely controlled by PIR sensors with inconsistent settings.

Provision of information about control units was also not very effective. Very few information is included about the advanced natural ventilation strategy specified for Building D in its log book. Notably, there is no mention of the traffic light control system and its operation modes. These issues are often overlooked at design stages and throughout the procurement process.

6.4.4. Intricate relation between ventilation strategies, comfort, and acoustics

The mechanically ventilated case studies represent the potential for a vicious cycle in environmental design of schools in the UK that must be carefully avoided or addressed: acoustic performance requirements are key determinants of ventilation strategy and yet mechanical ventilation brings risk factors that, if not mitigated, can compromise acoustic performance with further repercussions for comfort.

There are various technical and economic constraints that drive the design of mechanical ventilation systems. For example, spatial constraints for ductworks and cost considerations may lead to specification of higher air velocities and fewer air diffusers in the ductwork and at the outlets. This problem can be further exacerbated if the system is not balanced and may cause thermal discomfort in some zones. It can also lead to indoor ambient noise levels higher that the limits specified by guidelines as uncovered in the case studies. More careful system design and effective attenuation are required to ensure acoustic performance is not compromised.

6.4.5. Lighting specification and control

Post-occupancy observations point to inconsistencies between daylight provision and the control strategies specified for electrical lighting in most case studies.

It is acknowledged that natural daylight can bring benefits other than saving lighting energy. However, specification of glazing area is a compromise between heat loss, heat gain and daylight. The first two components can increase heating and cooling loads (or risk of overheating) when daylight factor increases. It is therefore necessary to save electricity by switching off electrical lights in day lit zones to balance these effects. Daylight sensors that are effectively specified and commissioned are the best option to achieve this. Better coordination between Client’s requirements, architects, and electrical services designers is required to ensure electrical lighting control supports daylight strategy. Furthermore, detailed specification of automated lighting control at design stages and effective commissioning are essential to achieve the expected environmental benefits.

Over specification of lighting levels in teaching areas is another issue observed in the studies that can increase lighting energy use and glare risk.

6.5. Summary

Monitoring of air temperature in sample classrooms of the case studies over one full year showed all case studies met the BB101 (2006) overheating conditions with very few incidences of temperatures above 28 °C and no incidence of temperatures above the 32°C limit. However, it should be noted that the buildings were not exposed to a particularly warm summer during the measurement period. A number of key design features that can improve building resilience against future overheating were not operational.

The average CO_2 concentration levels monitored during intensive studies were generally lower than 1500 ppm prescribed by BB101. The only exception was a naturally ventilated classroom in Building D. Further investigation on 20 naturally ventilated classrooms in this building revealed 25% of the classrooms had average CO_2 concentration higher than 1500 ppm for at least one day per monitoring week. Lowering the CO_2 threshold level for operation of motorised vents and better use of cross ventilation facility can improve indoor air quality in this building.

The ventilation rates inferred from CO_2 concentration levels were generally higher than 3 l/s/person in the monitored classrooms. Typical classrooms in naturally ventilated buildings had opening areas higher than the minimum requirements prescribed by BB101. In mechanically ventilated classrooms, the ventilation rates were significantly higher than naturally ventilated classrooms when the respective air handling units were fully operational. However, a number of mechanically ventilated classrooms did not achieve 8 l/s/person ventilation rate at full load which points to shortcomings in air balance and ductwork air leakage.

It is notable how the key findings of the IEQ studies are also related to energy performance: although Building B had the best overall energy performance, there were shortcomings in thermal comfort and system control in heating season. In addition to its implications for thermal comfort, the difference between passive measures specified in Building D and the mechanical solutions specified in Building E is a key determinant of operational energy performance in these buildings. It was revealed that ventilation strategy can have profound effect on acoustic performance and comfort. Analysis of half-hourly data in the previous Chapter also showed the significance of ventilation strategies and system performance on electricity use. Operation of motorised vents and operable windows are, on the other hand, among the key determinants of heating demand in naturally ventilated buildings. Finally, the lighting levels and control are directly linked to energy performance. Consequently, any systematic attempt to determine and address the energy performance gap must also look into the indoor environmental quality to understand the real context and adjust energy baselines and performance expectations accordingly.

7. Building Use Studies

7.1. Introduction

This Chapter provides a review of the results and major findings of the Building Use Studies.

First, an overview of the survey conditions and the numerical scores achieved for overall variables are presented to be used as reference point for the subsequent sections of this Chapter.

Next, the results for BUS overall variables are presented in graphic format for each building, and the major issues raised in the comments received from building occupants are categorised in tabular format. This combination helps to identify the specific issues in each building that are subsequently further examined by analysing the detailed results obtained for the relevant BUS variables. Where applicable, reference is also made to the findings reported in the previous two chapters and technical investigations.

Once the results for individual buildings are reviewed, a comparative analysis of the BUS indices is provided. Finally, the common themes and the lessons learned from BUS surveys are reviewed.

7.2. Survey conditions and overall results

Table 7.1 includes basic information about total number of teaching and support staff present on the day of survey and the respondents in each building.

Table 7.1. Information about the BUS respondents in the case studies

Building	Total number of teaching and support staff	Number of respondents	% of respondents	Female respondents	Male respondents
Bldg. A	100	75	75%	65%	35%
Bldg. B	52	52	100%	58%	42%
Bldg. C	166	107	64%	70%	30%
Bldg. D	195	146	75%	65%	35%
Bldg. E	106	76	72%	60%	40%

Table 7.2 includes the results obtained for the BUS overall variables along with the information about the corresponding benchmarks and scale midpoint percentiles. These results will be presented in graphic format for each building in the following sections and analysed.

The full sets of BUS data for the case studies are also available via the following URLs:

Building A: http://busmethodology.org/9018

Building B: http://busmethodology.org/9019

Building C: http://busmethodology.org/9033

Building D: http://busmethodology.org/9049

Building E: http://busmethodology.org/9052

Table 7.2. BUS overall results for the case studies

BUS overall variable	Bldg. A		Bldg. B		Bldg. C		Bldg. D		Bldg. E		Benchmark mean	95% confidence interval	Scale midpoint percentile
	Study mean	building percentile	Study mean	building percentile	Study mean	building percentile	Study mean	building percentile	Study mean	building percentile			
Air in summer: overall	4.44	82th	4.49	84th	3.31	21st	4.29	68th	2.66	6th	3.82	± 0.18	54th
Air in winter: overall	5.06	90th	4.26	55th	3.55	15th	4.57	71st	3.46	15th	4.15	± 0.18	44th
Comfort: overall	5.29	84th	5.25	82th	3.89	15th	4.74	56th	4.07	33rd	4.51	± 0.20	20th
Design	5.27	69th	5.69	84th	3.18	5th	4.90	46th	4.16	18th	4.82	± 0.22	13th
Health (perceived)	3.62	49th	4.37	90th	3.17	20th	3.64	49th	3.40	36th	3.62	± 0.16	70th
Image to visitors	6.00	67th	6.46	90th	4.79	27th	5.74	57th	5.91	66th	5.33	± 0.27	14th
Lighting: overall	5.20	75th	5.35	81th	4.54	31st	5.35	81st	4.76	46th	4.70	± 0.20	13th
Needs	4.98	57th	5.50	82nd	3.63	6th	4.92	46th	4.27	18th	4.88	± 0.18	10th
Noise: overall	5.14	93th	4.54	69th	3.98	28th	4.97	90th	4.67	83rd	4.26	± 0.14	32nd
Productivity (perceived)	2.83	76th	5.80	91th	-7.01	23th	2.96	75th	-8.23	13th	-2.03	± 1.57	60th
Temperature in summer: overall	4.39	81th	4.34	79th	3.29	30th	4.14	68th	2.35	3rd	3.70	± 0.18	60th
Temperature in winter: overall	4.90	82nd	4.27	49th	3.49	18th	4.81	74th	3.38	15th	4.24	± 0.20	40th

7.3. BUS results for Building A

Figure 7.1 presents the BUS overall results for Building A. All variables score better than the scale midpoint and benchmarks, with the exception of 'perceived health' and 'needs'. The score for perceived health is worse than the scale midpoint and within the 95% confidence interval of the respective benchmark. The score for needs, on the other hand, is much better than the scale midpoint, but cannot outperform the upper confidence level for the respective benchmark.

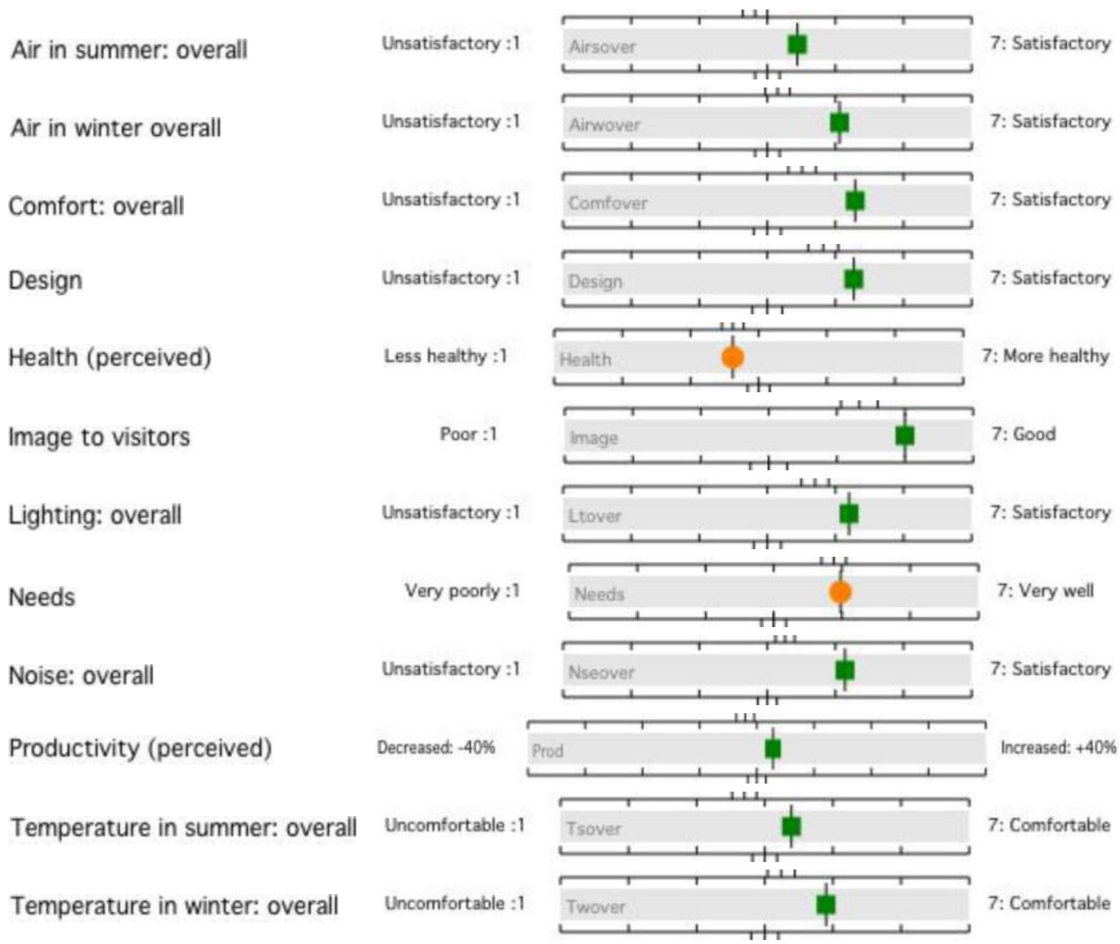


Figure 7.1. BUS overall results for Building A

Table 7.3 shows the major issues that were raised by more than 5% of survey respondents. The representative comments quoted are meant to provide further clarification and give context to the issues.

It should be noted that the BUS questionnaire asks specific questions about availability of meeting rooms and suitability of storage arrangements with separate space for commenting below respective questions. This might have an impact on the number of comments received related to these items. Other issues listed in Table 7.3 were extracted from the space provided for more general comments and therefore no bias was introduced by the questionnaire.

Table 7.3.Summary of the major issues raised by users: Building A

Emerging themes	Representative comments	% of related comments to total BUS respondents
No enough storage for teachers and students	“There is not much storage space either for teaching, departments, or support departments.” “Not enough storage for students work.” “Nowhere near enough storage.” “More storage would be good”	27%
Problems with glare and ineffective blinds	“Teaching rooms on the playground side have issues using the blinds when sun is too bright, students cannot see board even when the blinds [are] down.” “Too many lights on during bright days (waste of energy). Blinds ineffective and sun in eyes.” “We’ve had blinds fitted but not on all the windows.” “The blinds are not good enough.”	11%
Meeting rooms’ number and size not adequate	“Not enough meeting rooms.” “Could do with more.” “Too small and closed in.” “Very small and lack of natural light.”	11%
The atrium design is not practical for school	“Atrium seems to be a bit of a waste of space.” “I think the big open spaces are intimidating as is the height of the atrium. There are too many places to hide for disruptive students. The design is pretty bad for a school – might work for a prison.” “Bit noisy – atrium noise reverberates to all areas – difficult when running exams.” “It feels a bit like a shopping mall or office block!” “We are a school. It gets noisy in the atrium at lunch and outside when window open.”	10%
Perception of extreme indoor temperatures	“Sometimes can be irritable when too hot.” “When we get too hot we get agitated.” “Heating – often the classroom is too cold.” “Heating – often too hot or too cold.” “It is too hot in the building, my productivity can decrease slightly.”	8%

The comments received about the problems experienced with glare, level of lighting, and ineffectiveness of the blinds make it necessary to have a closer look at the lighting variables. Figure 7.2 shows the BUS results for lighting variables. It is notable that the results obtained for most individual components of lighting are not in line with the positive feedback received for overall lighting (Figure 7.1). This phenomenon is also reported by Leaman and Bordass (2007) in their analysis of users' tolerance of buildings that are perceived to be green; BUS rating scores for 'green' buildings tend to be better than conventional buildings in all embracing summary variables such as overall comfort and overall lighting. However, when these variables are divided into their individual components, the users' favourable responses to 'green' buildings are less clear-cut. This also shows the significance of analysing the comments received from building users in determining the potential issues and closer investigation of individual variables.

The level of artificial lights in Building A appears to be high from users' perspective. This is consistent with the technical studies that revealed the lighting levels in most teaching spaces were around 450 lux, 50% higher than the minimum required illuminance. Poor automated lighting control also contributed to excessive level of lighting when enough daylight was available to provide the required illuminance without artificial lighting. Glare from both internal lights and sun appears to be a problem for users and according to the comments received from users the installed blinds were not very effective in protecting teachers and pupils from glare.

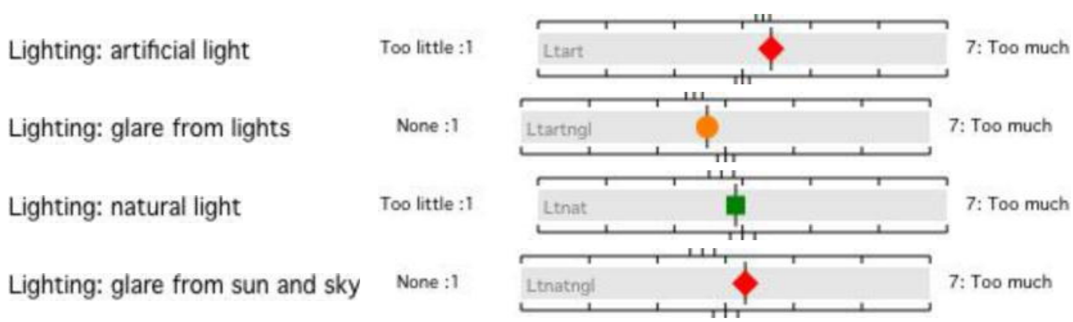


Figure 7.2. BUS results for lighting variables: Building A

The occupants also expressed strong views about the atrium space in Building A. Some were concerned about space utilisation given that the atrium space in Building A was effectively used as a transitional space with no regular activity. To put it in the context, poor utilisation of this space must be compared against the comments about lack of meeting rooms and storage facilities. Furthermore, some occupants were concerned about the effect of the atrium and open-plan spaces on noise levels. Figure 7.3 confirms that building users are particularly concerned about noise stemming from unwanted interruptions and external sources. The atrium space is an internal source for noise especially during break times. As for external noise, mechanical ventilation was specified for this building to protect the building against the noise from airplanes that regularly fly over the building. However, one of the observations of the post-occupancy evaluations was building users tend to use operable windows regardless of the ventilation strategy. Furthermore, poor attenuation of the installed air distribution system in Building A was a contributory factor to classroom noise levels that were regularly higher than 35 dB limit specified by BB93.

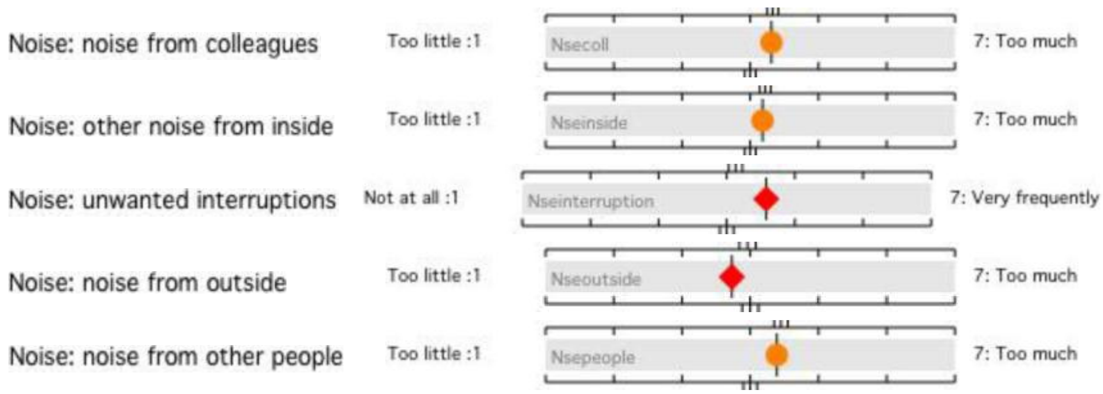


Figure 7.3. BUS results for noise variables: Building A

In addition to space utilisation and ingress of noise, other negative comments about the atrium space point to issues related to pupils' supervision in large spaces.

A number of building occupants were also not satisfied with the indoor temperatures. Figure 7.4 shows despite positive feedbacks on overall temperatures in winter and summer, a nuanced view is detectable from individual components of temperature; the scores for all components lie between the midpoint scale and the respective benchmarks. The cold draught from the single and wide entrance door in winter was particularly problematic for the admin staff working in the office space next to the reception. Double door lobby can reduce building heat loss and improve thermal comfort conditions.

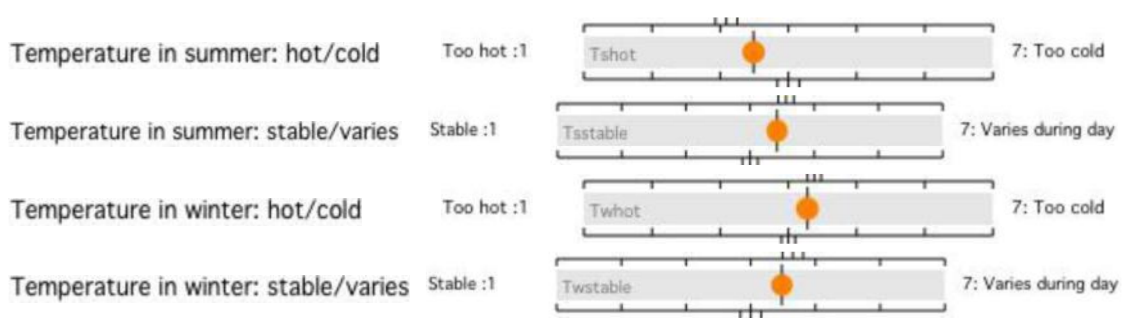


Figure 7.4. BUS results for temperature variables: Building A

As for building facilities and features that worked well, the BUS comments show that occupants were satisfied with the ICT space and spaciousness and design of classrooms.

7.4. BUS results for Building B

Figure 7.5 presents the BUS overall results for Building B. All variables score better than the scale midpoint and benchmarks, with the exception of temperature and air in winter. These variables score better than the scale midpoint but slightly lower than the upper confidence level for the respective benchmarks.

Table 7.4 shows the major issues that were raised by more than 5% of survey respondents. Similar to Building A, teachers and support staff in Building B thought more storage space was required when specifically asked about storage arrangements. However, the comments received show they were content with the number and size of the meeting rooms. Around 1% of total useful floor area (approximately 1 m² per every teacher) is allocated to meeting rooms in this Sixth Form building compared to less than 0.6% in the other case studies.

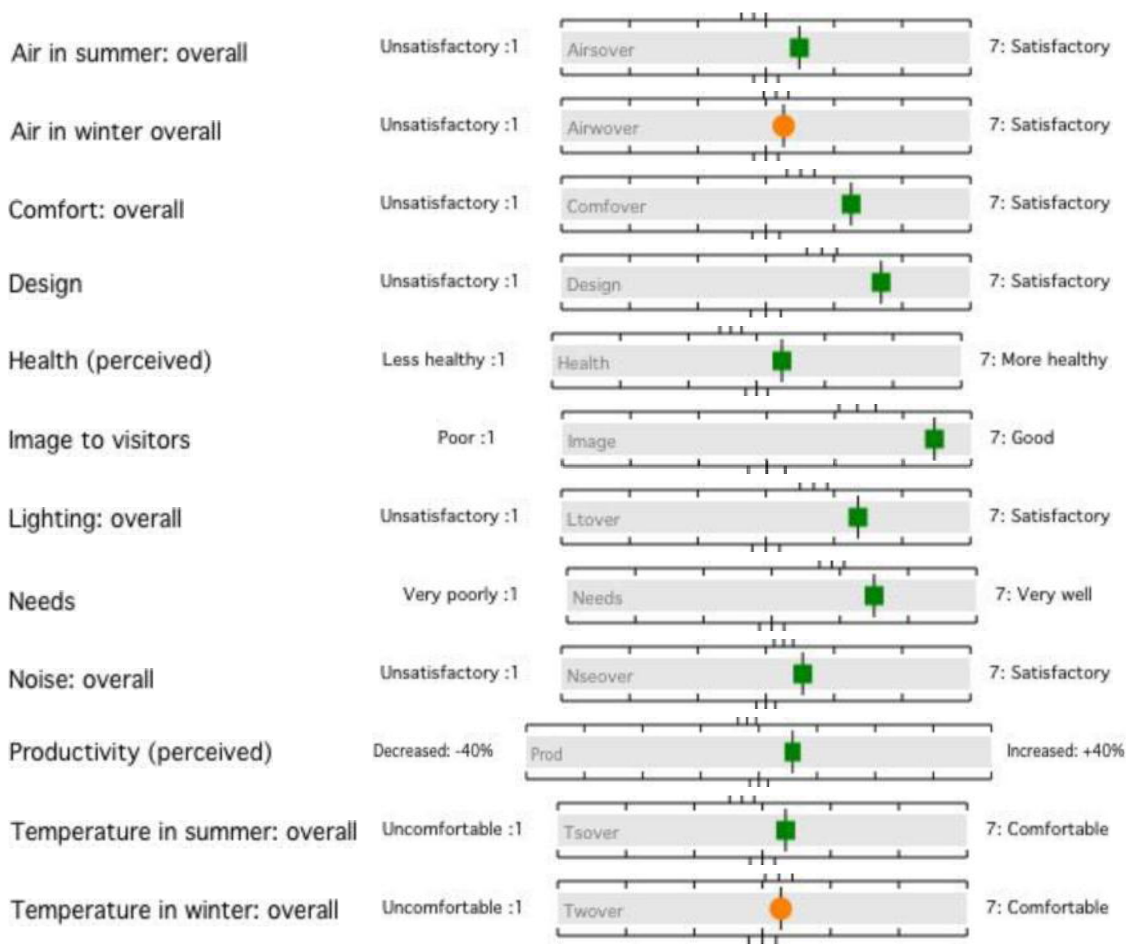


Figure 7.5. BUS overall results for Building B

Table 7.4. Summary of the major issues raised by users: Building B

Emerging themes	Representative comments	% of related comments to total BUS respondents
Some occupants feel cold in winter	"Heating is a problem." "Temperature is a big issue." "Wear more clothes to keep warm." "When it is cold it affects mood." "Huge draughts in areas next to doors to outside, need two sets of doors." "The heating does not perform very well – some areas are freezing cold sometimes."	21%
No enough storage for teachers and students	"Not enough cupboards in classrooms." "Not enough storage space for students work in technology and photography." "Storage poor in the art room." "Lack of storage."	15%
The atrium design is not practical for school	"I think a huge atrium is a waste of space." "Noisy in the atrium." "Noise from coffee shop travels up – heard in seminar rooms." "Wasted space." "Not always possible to read due to 'open-plan'."	12%

According to the occupants' comments, the main issue appears to be winter indoor temperatures and cold draughts from the wide entrance door that similar to Building A is a single door with no buffer space. An electric heater was used in the work station close to the entrance door to combat the heat loss and cold draught.

A number of other factors may have contributed to people's perception of cold indoor temperatures:

- The perimeter circulation spaces and stair cores in this building were not directly heated and therefore had no heating terminal installed. This caused a temperature gradient between these spaces and the core building.
- The heating terminals installed in most classrooms and labs were ceiling-mounted radiant panels. No radiator was installed underneath the windows to combat the heat loss and cold draughts.

- The thermostats for radiant panels were installed at high level in most rooms as no conduit was installed within the wall partitioning (Figure 7.6). This made it difficult for users to adjust the heating set points locally.
- The ICT enhanced spaces used a variable refrigerant flow system for both heating and cooling with a tight set point at 21 °C which frequently led to changeover from heating to cooling and vice versa in a short period of time.
- The atrium motorised vents were only responsive to CO_2 concentrations and not temperature. This led to heat loss and cold draughts in winter in the atrium space.
- As explained in the previous Chapter, maintenance and control issues were also responsible for incidences of extreme temperatures in heating season (e.g. the regulating valve of the variable temperature hot water loop being fixed back to front).

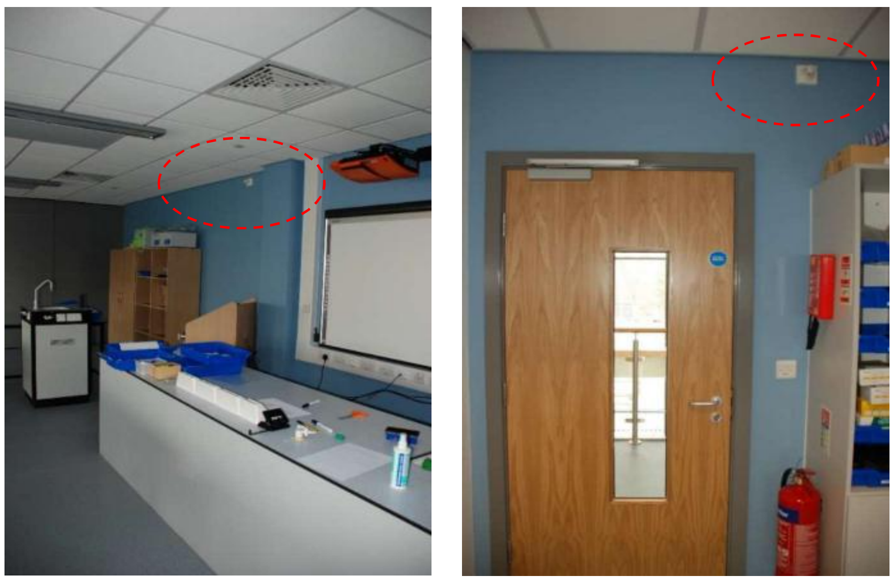


Figure 7.6. Room thermostats for ceiling mounted radiant panels were installed at high level. Occupants did not have effective local control over heating set points in these rooms.

The results of the long-term monitoring reported in Chapter 6 also showed that the average temperatures in sample classrooms in Building B were generally lower than Building A. Temperatures in Building B had wider variation bands than Building A with incidences of very low temperatures in heating season. Both buildings are located in West Pennines region with similar climatic conditions. The difference in indoor temperatures in these buildings to some extent reflects the differences in the heating schedules reported in Chapter 4. However, the shallow L-shape plan of Building B, compared to the deep plan of Building A, also makes it more difficult to preserve internal gain; the volume to external wall area (building depth ratio) of Building A is 10.7 m compared to 6.4 m for Building B.

The occupants' feedback about cold temperatures in Building B is significant as this building had by far the lowest fossil-thermal energy use in the case studies. Therefore, the users' feedback raises the question whether it is possible to provide better thermal comfort without compromising energy performance. Apart from issues related to building design, minor improvements in operational settings could have further reduced energy used for space heating and provided more stable thermal comfort conditions. For example, a wide dead-band between heating and cooling set-points could have improved the energy performance of the variable refrigerated flow system and led to more stable indoor temperatures. Furthermore, although it would have been better to link the operation of the atrium's motorised vents to outdoor temperatures in addition to CO_2 levels, a practical compromise for the facility manager given the installed system was to increase the threshold CO_2 concentrations level for the motorised vents in winter as the space was primarily used for dining and social interaction between students and not teaching. In addition to more stable temperatures, this would have reduced the frequency of vents' opening and thereby building heat loss.

Building occupants also expressed concerns about the atrium space. Space utilisation and noise coming from the atrium space were the common issues raised. Figure 7.7 shows the BUS results for noise variables.

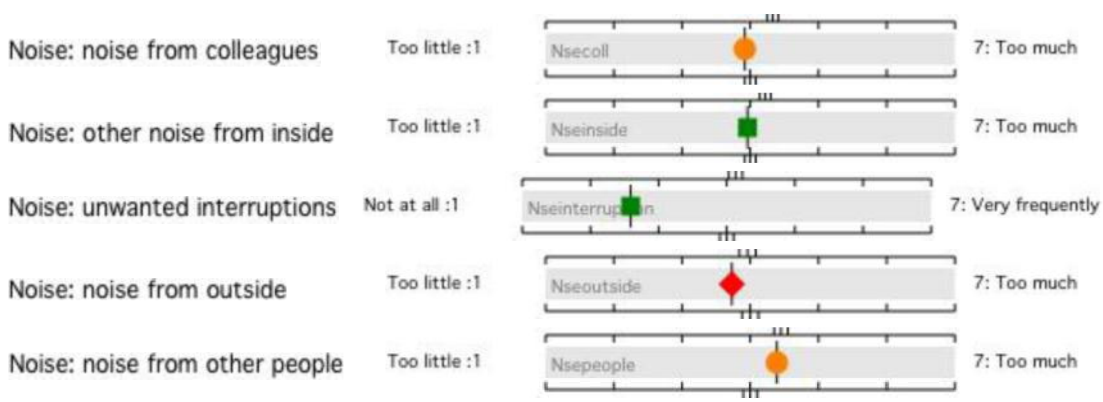


Figure 7.7. BUS results for noise variables: Building B

While occupants seem to be concerned about the internal noise transmitted in the space from other building users, it appears they also perceive external noise as a major source of noise in the building. Similar to Building A, the main driver for mechanical ventilation strategy in Building B was external noise levels as the Sixth Form is located close to a main road. However, in practice, occupants use the operable windows regardless of ventilation strategy (Figure 7.8). Negative comments about noise are predominantly focused on internal noise and it appears that external noise levels, although deemed to be high, are to a large extent tolerated.

Figure 7.8. Top-hung windows in Building B: a number of windows were frequently open regardless of the mechanical ventilation strategy and external noise levels.

As for building facilities and features that worked well, the BUS comments show that building occupants were satisfied with the size and layout of the classrooms and easy access to colleagues.

7.5. BUS results for Building C

Figure 7.9 presents the BUS overall results for Building C. The BUS scores for most variables are worse than the scale midpoint and the respective benchmarks.

Table 7.5 shows the major issues that were raised by more than 5% of survey respondents.

Contrary to Buildings A and B, the scores for some overall variables are worse than the scores obtained for their individual components. For example, Figure 7.10 shows the scores obtained for temperature variables are generally within the benchmark 95% confidence bands with the exception of temperature in winter, whereas the overall scores for temperature in summer and winter reported in Figure 7.9 are worse than the lower confidence level of the respective benchmarks. This can be indicative of low forgiveness and problems beyond the indoor environmental conditions. Figure 7.11 shows the forgiveness index for Building C is in the 28th percentile of the dataset, significantly lower than the forgiveness index for Building B which is in the 85th percentile of the dataset.

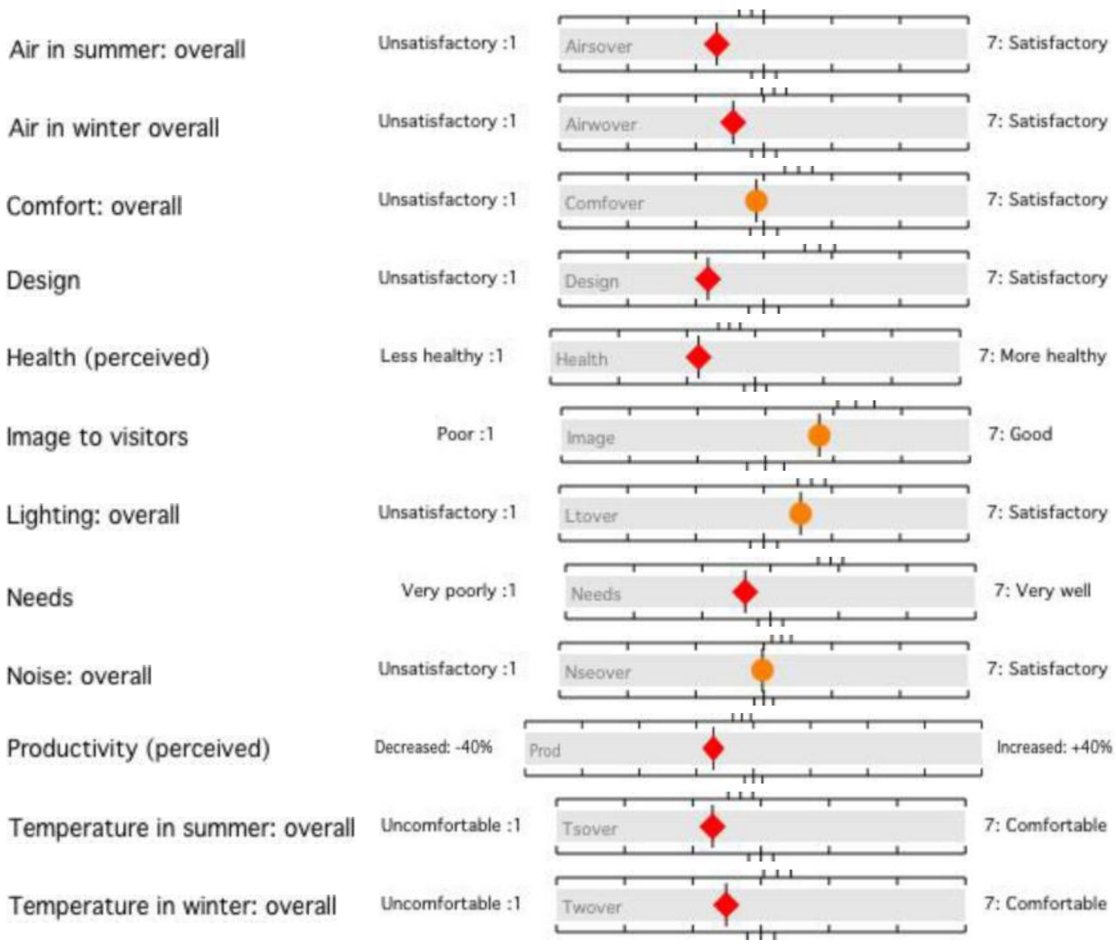


Figure 7.9. BUS overall results for Building C

Table 7.5. Summary of the major issues raised by users: Building C

Emerging themes	Representative comments	% of related comments to total BUS respondents
No enough storage for teachers and students	"Not enough storage space in all areas of the building." "A lot more storage is needed." "Very little storage and what there is seems to be in the corridors."	37%
Open spaces are not practical for school	"Balconies and open spaces are terrible for teaching and controlling behaviour." "Pupils run in open areas and wander. Pupils often shout and want the attention in open areas – staff also talk way too loudly." "I feel that the open access design is not suited for a school environment and also feel the academy could use more office/storage space." "Most areas too small. Too many open spaces." "Not designed for children." "Not fit for purpose – it's a school, not an office 'space'." "Open plan spaces not ideal for teaching and learning."	32%
Not enough meeting rooms	"Not enough space for meeting." "Not enough space to meet or plan lessons." "Not enough meeting rooms – need to be close to entrance."	19%
Complexity of layout and access routes	"Have to go outside to get from one block to another." "[Design] does not flow – areas not clearly defined or spaced." "Poor layout, wasted space." "Too many exits for children. Easy exit for children."	5%

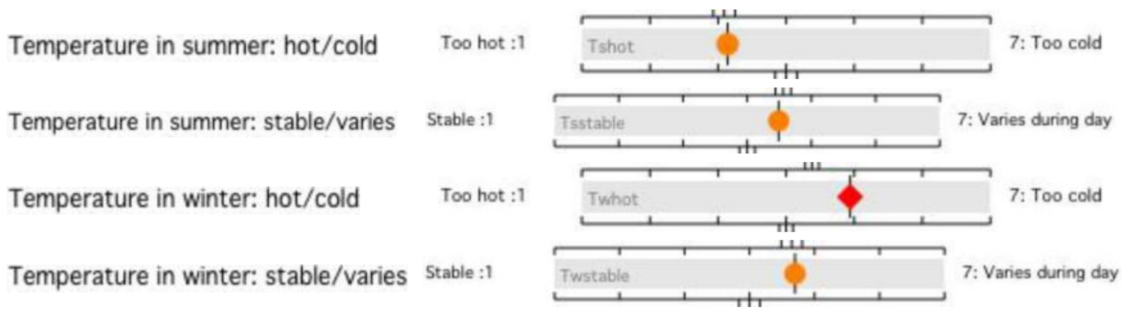


Figure 7.10. BUS results for temperature variables: Building C

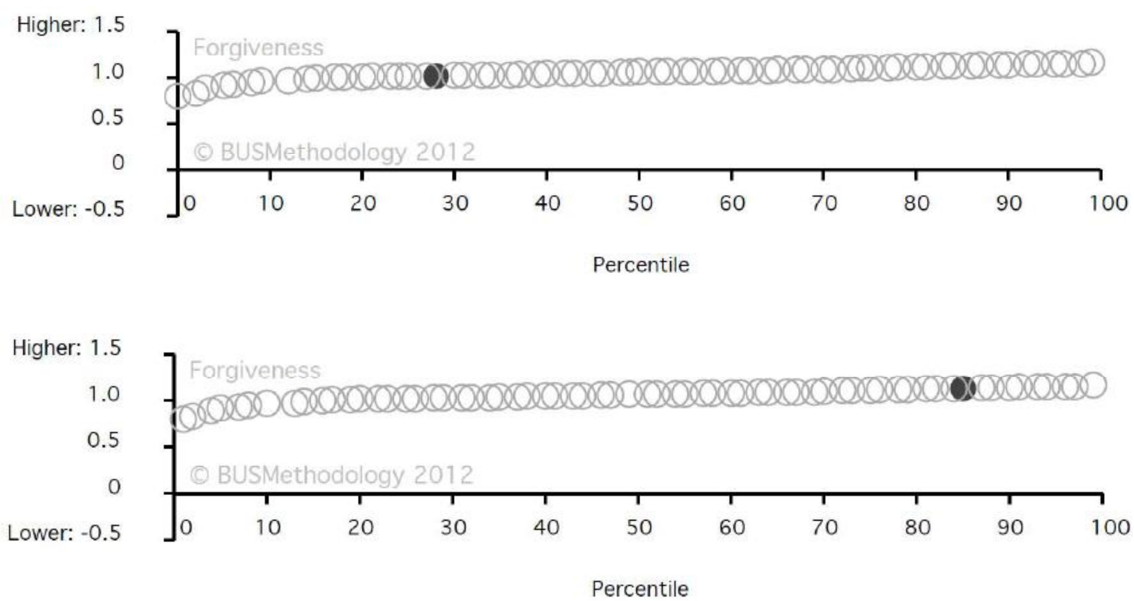


Figure 7.11. Forgiveness index for Building C (top) against the dataset and the forgiveness index for Building B (bottom)

Technical studies in this building did not point to a serious shortcoming that can justify the poor BUS scores related to thermal comfort and indoor air quality. It is also notable that the comments received in the BUS survey were predominantly focused on spatial design. Occupants thought storage arrangements and meeting room facilities were not adequate. Furthermore, they expressed very strong views against open-plan spaces. They thought these spaces are not suitable for teaching and learning activities, cause distraction for pupils, and disruption for teachers. Comments also strongly linked the inside noise to the open-plan spaces. Figure 7.12 shows the BUS results for noise variables.

Complexity of the layout and access routes was another issue raised by the occupants. The architect's intent was to create a 'village feel' by providing external access routes and linking several parts of the building spread across a rather large foot print. In practice, the layout was too complex for occupants and multiple routes of access also caused problems for supervising pupils' attendance and behaviour.

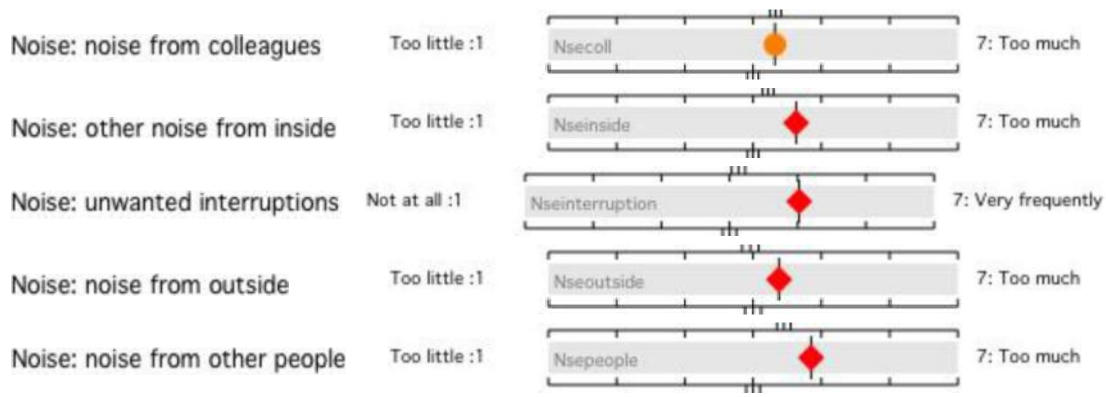


Figure 7.12. BUS results for noise variables: Building C

It should also be noted that around 20% of the academy's space was allocated to primary education. This may have contributed to problems with pupils' supervision and noise particularly in large open-plan spaces. Teachers expressed strong views about building design and linked it to their stress as in the following statement:

"*This building causes people to become annoyed more quickly (due to stress caused by design).*"

The occupants were satisfied with the enclosed classrooms. However, the negative feedback about the open-plan space in this building was overwhelming. The noise and disruption caused by these spaces may have had a knock-on effect on occupants' responses to questions related to other indoor environmental conditions. The intricate relation between noise and perception of thermal comfort has been demonstrated in previous studies (Pellerin & Candas, 2003).

While the relatively poor BUS results in this building reflects occupants' feelings about their working environment, it may also be related to the wider socio-economic context that cannot be captured by the BUS survey. The academy had the highest deprivation index among the case studies; an index used by the Department for Education to identify the schools with the greatest need for funds. Furthermore, the survey was conducted in 2012 in the midst of the government's austerity programme and educational reforms. A number of staff had been laid off in the same year. It is reasonable to assume these factors had an effect on people's feeling about their working environment, although it is difficult to measure this effect. What is certain is that the findings of the technical studies alone cannot fully explain the occupants' negative feedback related to the indoor environmental quality in this building.

7.6. BUS results for Building D

Figure 7.13 presents the BUS overall results for Building D. Most overall variables score better than both the scale midpoint and the respective benchmarks. However, the scores for building design, perceived health in the building, adequacy of the facilities for needs, and temperature in summer lie between the scale midpoint and respective benchmark ranges.

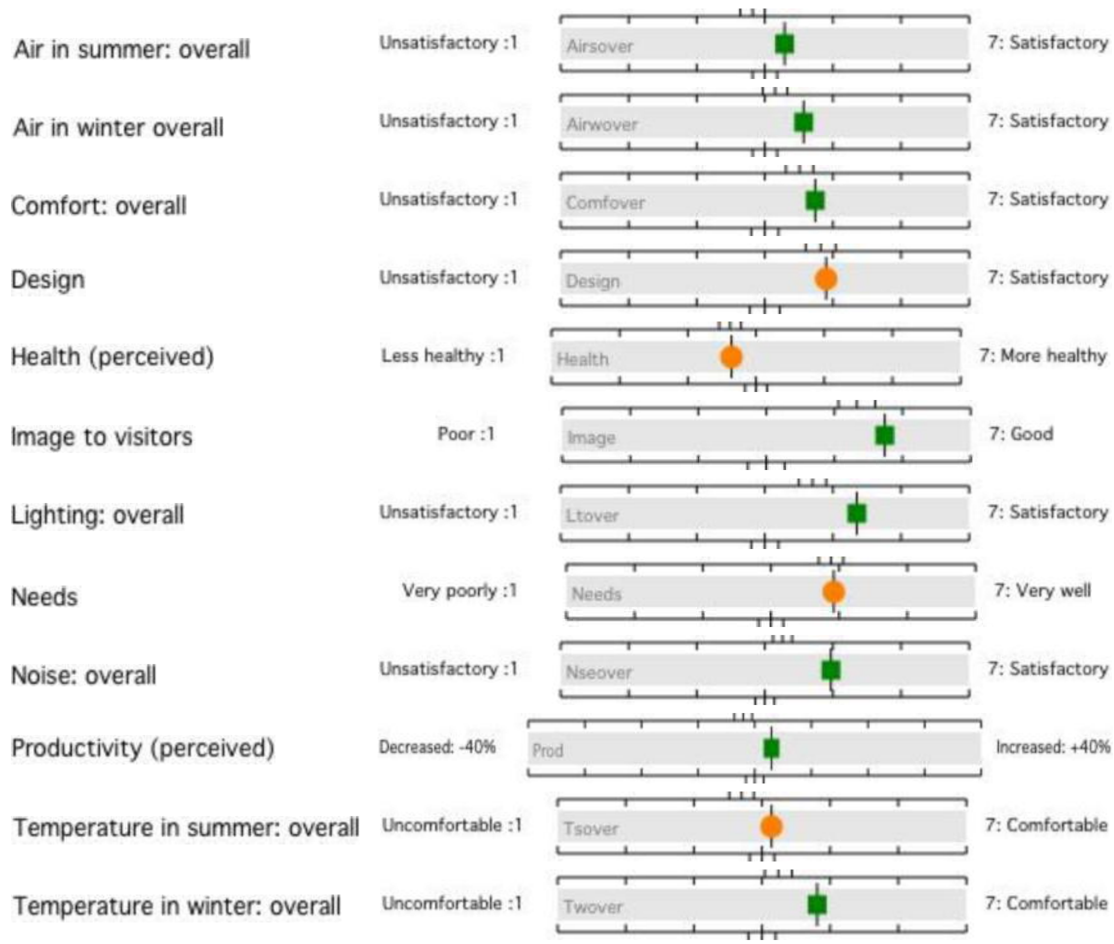


Figure 7.13. BUS overall results for Building D

Contrary to the design intent, the motorised vents installed to enable cross and stack ventilation were only responsive to CO_2 concentrations and not temperature. This applied to the naturally ventilated classrooms and the plenum vents in the atrium (Figure 7.14). The thermal triggers specified by the designers for these motorised vents had not been programmed at the commissioning stage. This can compromise building performance during summer.

Figure 7.14. Thermal triggers for stack ventilation in the atrium space had not been programmed in Building D.

Teachers working in areas close to the ground floor transition doors reported problems with cold draught and low temperatures in winter. These doors, which were regularly used to transit from one part of the building to the other part, and the courtyard escape doors could not be opened from outside without a key. Therefore, they were left open which caused excessive heat loss and cold draughts in winter (Figure 7.15). This problem along with the classroom vents that stuck open in winter led to an increase in the low temperature hot water flow for the heating system that disabled the ground source heat pumps. The problem with the circulation and courtyard escape doors could have been addressed with a dogging device which allows the latch to be retracted with a specialist Allen key during school opening hours so that the doors can be operated from outside as well as inside. However, this had not been specified by the architects.

Figure 7.15. Ground floor transition doors next to the radiators were constantly left open in heating season.

Figure 7.16 shows the BUS results for temperature variables.

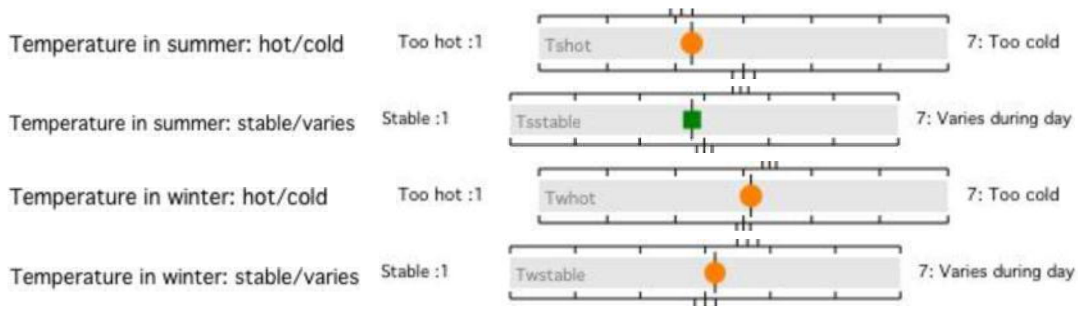


Figure 7.16. BUS results for temperature variables: Building D

Table 7.6 shows the major issues that were raised by more than 5% of survey respondents.

The occupants thought they need more storage space and meeting rooms. 8% of respondents expressed concerns about ventilation which is not unexpected in a naturally ventilated building. However, better labelling and understanding of the traffic light control system installed to inform teachers about indoor air quality might have improved the operation and occupants' satisfaction of the ventilation system.

Occupants in Building D overall were more receptive to the atrium and open-plan spaces, although the circulation spaces were affected by cold draughts caused by open doors on the ground floor. Contrary to Building C, the open-plan teaching and learning resource zones specified in this building had clear boundaries with the corridors and general circulation spaces. This made it easier to manage open-plan teaching and learning activities with less disruption for other classrooms.

As for building facilities and features that worked well, the occupants appeared to be very satisfied with the size and layout of the classrooms, manually operable windows (although some were not entirely satisfied with window handles), and daylight available in the atrium and classrooms. However, respondents reported problems related to 'random' operation of lighting sensors. In particular, low sensitivity of PIR sensors in some classrooms meant lights turned off when the classrooms were still occupied.

Table 7.6. Summary of the major issues raised by users: Building D

Emerging themes	Representative comments	% of related comments to total BUS respondents
Not enough storage	"Not enough storage, less storage than old building but being asked to provide more resources than previously." "Not enough suitable space for science requirement." "Not enough [storage] – much of it open plan." "Classroom(s) need to have more storage for resources."	24%
Not enough meeting rooms	"Cramped in office not really suitable for meetings." "Designed meeting rooms would be useful." "Teachers complain there are not enough meeting rooms."	14%
Inadequate fresh air	"Room stuffy and smelly. No air ventilation or circulation." "More headaches due to poor ventilation." "Lack of fresh air in classrooms and offices." "Windows handles very badly designed." "Windows un-openable."	8%
Issues with the atrium and corridors	"Whilst the open areas are very good to look at they are cold and hard to manage." "Very stylish, though open-plan over all floors can cause draughts." "Corridor cold in winter and can get locked into inside quad. Classrooms cannot get hot." "Cold traps and atrium a problem. Doors left open and access an issue."	5%
Perception of high indoor temperatures in some classrooms	"Too hot makes pupils sleepy and agitated." "Very hot and headaches." "Heating – can overheat."	5%

7.7. BUS results for Building E

Figure 7.17 presents the BUS overall results for Building E. Most overall variables score worse than the scale midpoint or the respective benchmarks. The scores obtained for air in summer, air in winter, temperature in summer, and temperature in winter correspond to the bottom 15th percentile of the BUS dataset (See Table 7.2). Poor scores for thermal comfort and indoor air quality are consistent with the technical measurements reported in Chapter 6. Pupils also expressed strong views about 'extreme temperatures', 'stuffy air' and 'headaches' they experienced in the building in semi-structured interviews. The evidence available from energy performance, thermal comfort, indoor air quality, and occupants' feedback all point to serious shortcomings and underperformance of the mechanical building services, control strategy, and building maintenance in this building.

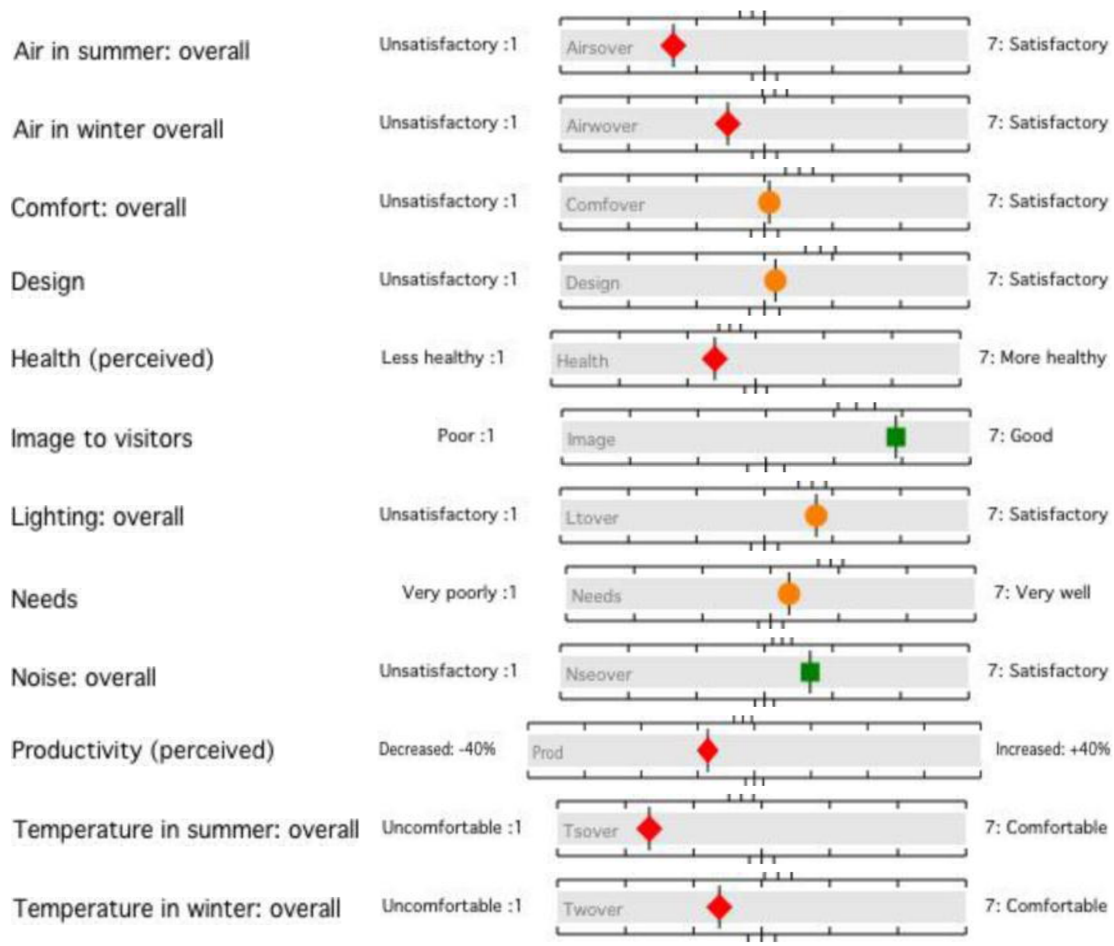


Figure 7.17. BUS overall results for Building E

Table 7.7 shows the major issues that were raised by more than 5% of BUS survey respondents.

Table 7.7. Summary of the major issues raised by users: Building E

Emerging themes	Representative comments	% of related comments to total BUS respondents
Not enough storage	"Consider how much work is stored in art, we haven't got enough space." "Not enough storage especially when most don't have a classroom." "Not enough storage space."	27%
Thermal comfort conditions not satisfactory	"Heating is awful! We have radiators and air cons [on] all the time." "Too cold in winter. Too hot in summer." "Heating on/off at incorrect times." "Really poor heat transfer." "We have to wear a coat. Open the door – anything to keep cool/warm."	20%
Not enough operable windows	"Not enough windows to open and air system unsatisfactory." "Unsatisfactory ventilation in several rooms. Office needs a window that opens." Windows need to be open and there are large windows that distract kids. They look out of the classrooms." "Not enough fresh air – no opening windows, constantly caching respiratory infections."	17%
Not enough meeting rooms	"Not enough meeting rooms for more than 6 people." "Not enough meeting rooms available."	10%
Blinds not effective to protect occupants against glare	"Blinds don't block sun." "Need better blinds." "Too much glare reflected on the interactive white board. Makes it difficult for children to watch videos or see the board clearly."	7%
Triangular corners in classrooms are not practical	"Too many tight corners; insufficient use of room space." "Triangular classrooms do not work." "Sharp corners look nice but vital space is lost."	5%
Not enough science labs	"Not enough class rooms and science labs in particular." "Insufficient science labs for the number of science lessons in a period. Without proper facilities (gas, sinks, etc.) cannot carry out fully effective lessons."	5%

The occupants thought the storage space and the number of meeting rooms and science labs were not adequate. Several comments were related to thermal comfort and poor ventilation. Staff were particularly concerned about lack of control over ventilation with few operable windows installed in the building. According to the BUS comments, these issues were the main root causes for low self-assessed productivity obtained for this building against the BUS dataset (Figure 7.18).

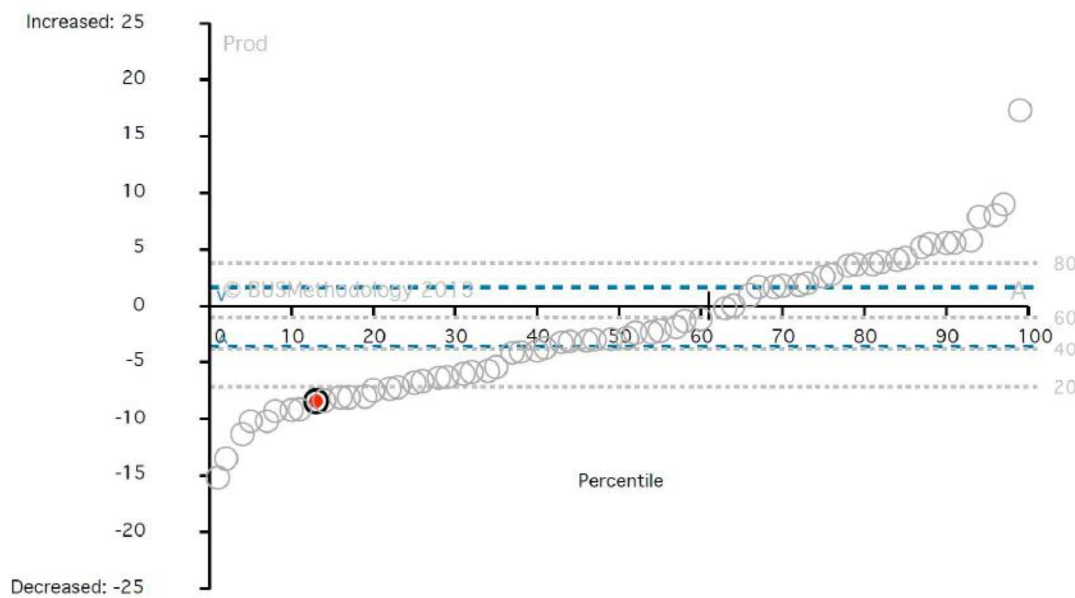


Figure 7.18. Perceived productivity of occupants in Building E compared to the BUS dataset

The extent of the glazing provided and ineffective blinds caused problems with glare and can also increase the risk of overheating under extreme ambient temperatures (Figure 7.19)

Figure 7.19. Typical classroom with light-coloured blind and one operable window

Although the noise from the atrium was mentioned in a number of comments, the occupants overall did not see noise as a major issue in this building and were more receptive to the atrium space which accommodates the dining space and an ICT zone for pupils.

Finally, the special form and layout of this building led to a number of classrooms with sharp corners on north and south orientations (Figure 7.20). Some teachers perceived this as waste of space and not practical for a classroom. These corners were often used as storage space. However, teachers did not have bespoke classrooms in this academy and this meant classroom storage was less utilised than staff room storage space. A number of teachers also reported problems in managing these classrooms with some pupils hiding in the corners.

Figure 7.20. Example of a sharp corner in a classroom in Building E

Apart from this issue, the BUS comments show teachers were satisfied with the size of the classrooms and also the daylight available.

7.8. Comparative analysis of the BUS results

Table 7.8 reports the BUS indices obtained for the case studies. Buildings A and B have the highest comfort index and satisfaction index respectively. Figure 7.21 and Figure 7.22 compare these indices against the BUS dataset and could also be used to put the comfort and satisfaction indices obtained for the other case studies in the context of the BUS dataset.

Buildings C and E both have low comfort and satisfaction indices. However, it appears that occupants are more concerned about factors other than comfort in Building C, whereas dissatisfaction with comfort variables is by far the main issue in Building E. This is consistent with the BUS comments and the findings of the technical measurements reported in Chapter 6. Given the issues uncovered with comfort, it is notable that forgiveness index in remarkably high in Building E. This indicates that people acknowledge the other merits of the building and perhaps wider social context present in the academy, and this to some extent can overcome their frustration with poor comfort. Forgiveness is lower in Building C and the occupants seem more dissatisfied. This building has the lowest summary index and hence the poorest BUS result overall.

Table 7.8. BUS indices for the case studies

Index	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Comfort index	1.03	0.62	-0.65	0.72	-0.76
Satisfaction index	0.46	1.06	-0.82	0.34	-0.23
Summary index	0.75	0.84	-0.73	0.53	-0.49
Forgiveness index	1.09	1.16	1.05	1.01	1.15

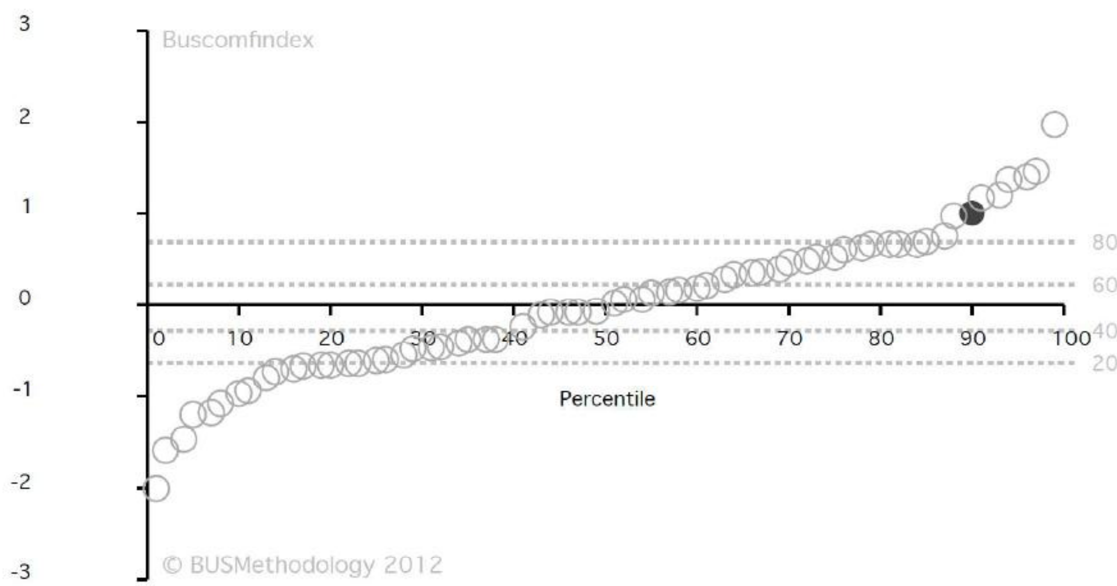


Figure 7.21. Comfort index of Building A against the BUS dataset

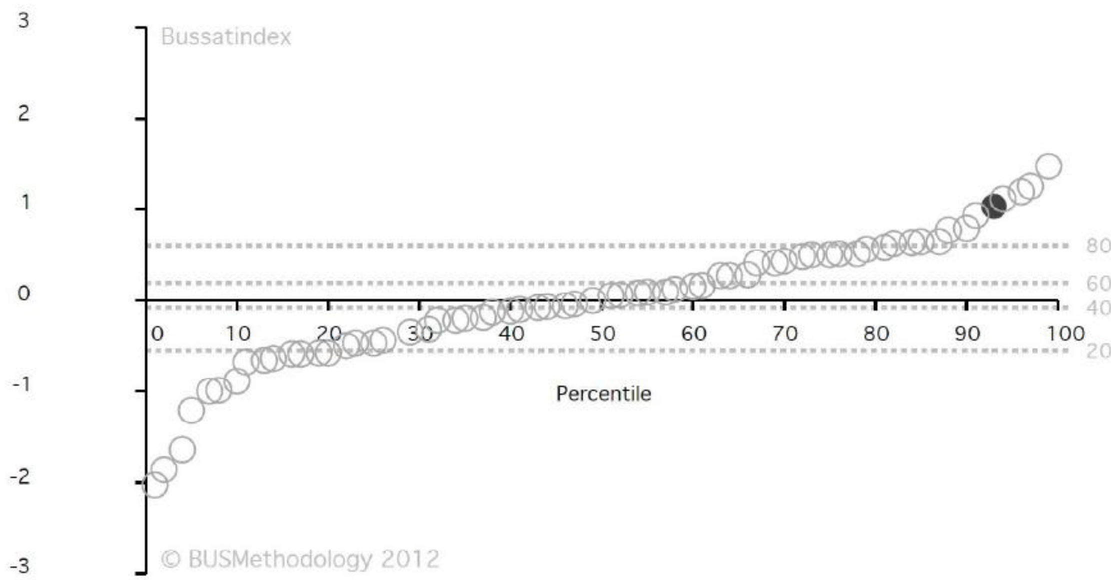


Figure 7.22. Satisfaction index of Building B against the BUS dataset

7.9. Emerging themes and key lessons

The following themes and key lessons emerge from the BUS results, the comments received from buildings' occupants, and the schools' performance:

7.9.1. User satisfaction and productivity

The BUS summary index can be interpreted as the overall user satisfaction score for a building. This index is strongly correlated with self-assessed productivity and health in the case studies.

The BUS summary index for Building C and Building E is negative. While occupants of the other case studies report an increase in their productivity at work, the occupants in Building C and Building E report a decline in their productivity at work as a result of the environmental conditions experienced in these buildings. They also feel less healthy than the other case studies and more than 60% of the BUS dataset (Table 7.2). This may have serious implications for academic performance and pupils' attainment.

It would therefore be useful to review the performance of pupils in these case studies and compare these performances against the results obtained in the previous schools that were replaced by these buildings. The metrics often used for analysis of the educational performance of secondary schools are as follows (Rintala & Griggs, 2009), (Williams, et al., 2015):

Level 2 attainment: Percentage of pupils that achieved 5+ GCSEs at grade ‘C’ or higher,

Level 1 attainment: Percentage of pupils that achieved 5+GCSEs at grade ‘G’ or higher,

Total absenteeism: Percentage of half days missed by students per year; this includes authorised and unauthorised absence.

These performance data are made publicly available by the Department for Education and are reported in Table 7.9 for the case studies. This Table compares the latest records available for academic performance of all case studies that replaced pre-existing schools with the latest records available for the old schools. The latest data available for the new buildings belong to the academic year 2013-2014, which is between 3-6 years after the completion of the buildings and therefore is representative of long-term and steady performance so far as the construction project is concerned. Building B is a new Sixth Form erected in the vicinity of a high school that did not have a Sixth Form. Therefore, it was not possible to compare the educational performance of this school (A level results) with previous records.

Table 7.9. Academic performances of the case studies against the performances achieved in the previous buildings

Performance metric	School A		School C		School D		School E	
	2005-2006	2013-2014	2007-2008	2013-2014	2008-2009	2013-2014	2002-2003	2013-2014
Level 2 attainment	36%	65%	41%	32%	77%	84%	19%	72%
Level 1 attainment	74%	100%	85%	82%	99%	100%	82%	96%
Total absenteeism	11%	5.3%	11%	7.1%	6.2%	5.2%	14%	4.3%

Figure 7.23 illustrates the results. All schools experienced significant improvements in all performance metrics with the exception of School C that has experienced a decline in both Level 2 and Level 1 attainment, although the level of absenteeism in this school has improved similar to the other schools. It is remarkable that School E has achieved the strongest improvement in Level 2 attainment and absenteeism *in spite of* poor environmental performance. School C, on the other hand, has not been able to overcome the poor level of user satisfaction expressed in the BUS survey which goes beyond comfort. This indicates the significance of factors other than the built environment in pupils’ attainment. One of the ambitions of the BSF programme was to achieve educational transformation by providing *inspirational* buildings for pupils and teachers. The results achieved in these case studies demonstrate that where such transformation has occurred, it has been less related to tangible aspects of the building and more related to the human related factors such as the change in management structure and pedagogical practices in the case of school E when the old community school transformed to a sponsor led academy. In fact these factors seem to have

overcome the significant environmental shortcomings uncovered in this building both by the technical measurements and user satisfaction survey. Where such successful transition did not occur (i.e. School C), the academic performance actually deteriorated despite the significant capital investment in procuring a new and iconic building for the community.

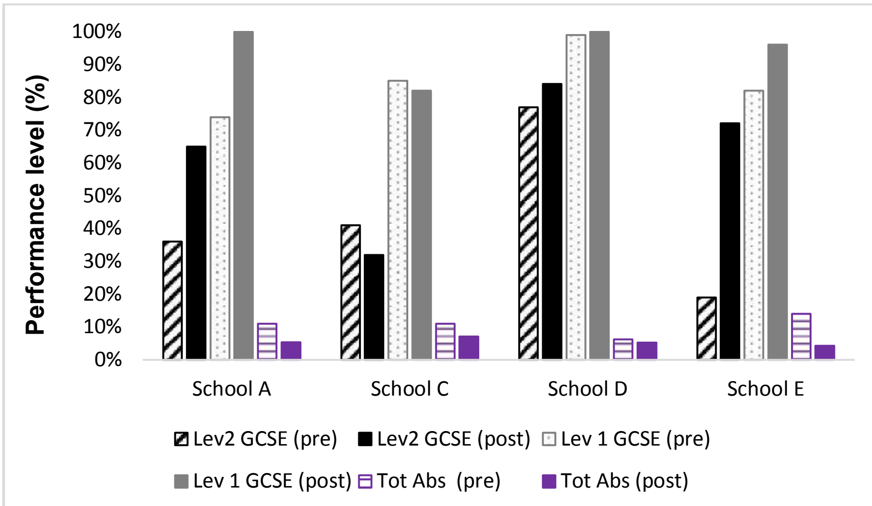


Figure 7.23. Academic performances of the case studies against performances achieved in the previous buildings

While the environmental conditions of schools are very important for health and well-being of pupils and the conventional educational performance metrics are not necessarily the best metrics to evaluate schools' performance, this finding can nonetheless have profound implications for the planning of the future educational buildings. One which takes into account the important role of a school building and its environmental conditions without an over-optimistic view of its impact on users' aspirations, and at the same time makes an attempt to provide adequate support structures related to management and pedagogical practices to achieve better overall results at lower costs.

7.9.2. The challenges of open-plan design

There are lessons to be learned from the way open spaces were designed and used in the case studies.

Overall, teachers were content with the open-plan teaching/learning spaces where these spaces had clear boundaries with the rest of the building as a separate zone with a designated activity (e.g. open-plan learning resource zones in Building D). Where there was no boundary between an open-plan space and corridors and circulation areas, the space was either not used effectively or was subject to ingress of noise and distraction (Figure 7.24-Figure 7.26).

Furthermore, teachers seem to like attractive but small and functional atriums and circulation spaces that do not compromise space available for essential functions of the school. They may form strong opinions against vast open-plan spaces especially when they find basic facilities such as storage space, meeting rooms, science labs, and so on are not adequate.

Figure 7.24. Atrium space in Building A: Although the activity studio was made open to the atrium space, the vast atrium space and the balcony above the activity studio were not effectively used. Some occupants perceived this as a waste of space.

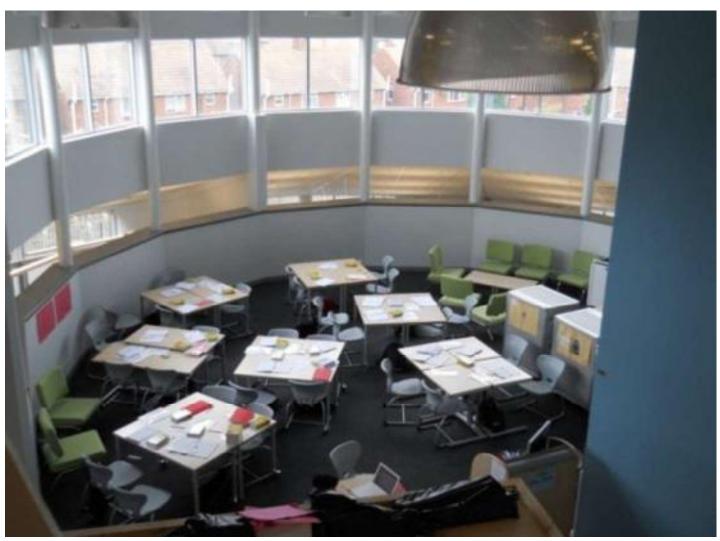


Figure 7.25. An example of a semi-open plan teaching space in Building C. This space is open to the corridor and circulation space on the next floor which brings noise and causes distraction.

Figure 7.26. Part of the atrium space in Building E that was used as an ICT zone for pupils. This was an effective use of a given space although it was not always easy for pupils to concentrate on their tasks.

Open-plan spaces, large working groups, and greater mix of activities were among the risk factors identified by the PROBE studies that are likely to cause dissatisfaction with the working environment and lead to decline in occupants' tolerance. Yet openness of the physical space, and flexibility and adaptability that it brings are often praised by architects and their clients. Open plan spatial planning is often mistakenly taken as manifestation of an open and liberal organisational culture (Leaman & Bordass, 2001).

The tendency for open-plan spatial design in schools originated in 1960s and most of the problems observed in the case studies have been reported for schools with similar design philosophy (IDEA, 1970), (Rivlin & Wolfe, 1985). However, as Canter and Donald (1987) point out, what is crucial is the combination of the schools' educational philosophy and physical layout; a special form of physical layout does not bring universal effect. A major finding of the previous studies on open-plan schools was the necessity to engage teaching staff to understand the potential of space. It is also important to involve staff and parents in planning and implementation of educational programmes in the physical space (IDEA, 1970). The feedback received from building users suggests such engagement and involvement did not happen in the case studies. If teachers are not actively engaged in shaping educational policies within the context of spatial planning they are less likely to change their teaching habits within the space. For example, Rivlin and Rothernberg (1976) found most teachers do not take advantage of the flexibility an open-plan space provides to them, teach from the front, and do not move the furniture. The risk is the potential benefits of these spaces may not be used while the negative aspects such as noise and distraction can compromise educational performance.

It is therefore vitally important to engage all staff in the planning and use of these spaces to maximise the benefits and manage the potential risks.

7.9.3. Value engineering against building resilience

A recurring problem observed in the case studies was that value engineering at design stages or construction had compromised operational performance.

For example, the double entrance doors and lobbies had been value engineered to save costs. This led to cold draughts and excessive heat loss in winter especially where the over door heating systems installed were not effective. The temperature triggers for the motorised vents installed in two buildings had not been programmed. This may compromise the resilience of these buildings against overheating when the buildings are subject to high ambient temperatures expected in future. The decision to provide only one small operable window per classroom in Building E on the grounds that the building will be mechanically ventilated meant people had no effective control over their local environment when the mechanical building services did not perform as expected. This is essentially a conflict between a short-term and narrow perspective to save costs against a longer term and more risk averse perspective that considers building resilience. There is no easy choice here. However, it is important to consider the available evidence and protect critical measures that are vital for building performance and user satisfaction. For example, several studies have shown the significance of providing local control over indoor environmental conditions and power of intervention for building users (Baker, 1996), (Leaman & Bordass, 2001), (Huizenga, et al., 2006). The BUS feedback in the case studies corroborates this evidence.

7.9.4. Need for simple and passive measures

The best design principle for schools is to use simple and passive measures as much as possible. This may not be enough to comply with the ever stringent regulatory CO_2 emissions targets. Nonetheless, measures that require complex control strategies and high management and maintenance requirements must be kept as last options.

The BUS respondents were generally content with the responsiveness of facility managers when they requested changes to their environmental conditions, but were less satisfied with the corresponding changes. The facility managers in the case studies were under-resourced, over-stretched with little or no technical background in energy and environmental management. The only exception was the head of the Sixth Form (Building B) who had a background in the construction industry with general knowledge of building services and managed the building systems. This building was also small and simple to run. It is not a coincidence that this building, overall, had the best energy performance and user satisfaction score among the case studies. In other buildings, the facility managers were not resourced to manage the complex systems installed in their buildings effectively and efficiently. This is very often the case in schools. It appears that very little attention had been paid at design stages to the management and maintenance requirements of the complex strategies and systems specified.

7.9.5. User satisfaction and energy performance

From system perspective, energy can be viewed as an input to the building overall system while the indoor environmental conditions are the outputs. User satisfaction surveys are inevitably focused on the outputs. A straightforward relation between the outcomes of these surveys and energy performance is therefore not expected.

Nonetheless, it is useful to draw lessons by comparing the BUS results with energy performances. For example, it is notable that Buildings A and E with the worst energy performance levels among the case studies received diametrically opposite feedbacks from their occupants: Building A had the best comfort index among the case studies (90th percentile of the BUS dataset), whereas Building E had the worst BUS comfort index (14th percentile of the BUS dataset). A poor BUS comfort index is often indicative of problems in building services that might have also compromised energy performance. However a good comfort index merely reflects a satisfactory output level and often does not reveal any information about energy efficiency. In either case, information provided in the BUS comments could be invaluable for identification of problem areas and building diagnostics.

7.10. Summary

The outcomes of the Building Use Studies (BUS) carried out on the case studies point to the strong correlation between self-assessed productivity and health with BUS overall scores, necessity of engaging teachers in designing and managing open-space educational spaces, and significance of protecting critical design measures against value engineering to ensure health and well-being of building users will not be compromised. It is important to use simple and passive design strategies especially in case of schools that often do not have the resources required for proactive management of a complex building.

The consistency between the BUS scores and comments and the technical studies of the indoor environmental conditions in most cases is indicative of the value of an effective user satisfaction survey for quick identification of major problem areas in a building as a starting point for building performance evaluation. This has important implications especially for more condensed and shorter term BPE studies in the industry. A caveat to be taken into account however is the BUS and similar questionnaires are mainly focused on environmental conditions and, to some extent, spatial design. They are therefore prone to miss important but less tangible aspects of performance that affect people's perception of building physics. Special attention to the building and organisational context is required to have a better understanding of these aspects of performance.

8. Operational against designed performance

8.1. Introduction

Chapter 5 compared the operational energy performance of the case studies against the statistical benchmarks derived from existing buildings and outlined a number of measures that can improve building *operation* based on the findings of the post-occupancy evaluations. However, no reference was made to the energy performance calculations at design stages.

This Chapter compares the operational performance against the energy performance calculations carried out following the completion of the case studies. Furthermore, it outlines major discrepancies between the design intents and actual performance, and aims to provide a better understanding of the underlying process issues that caused these discrepancies based on the findings of the building performance evaluations.

Consequently, this Chapter is primarily focused on the *procurement* issues and processes. Where necessary, reference is also made to the operational issues uncovered in the previous Chapters.

First, the operational energy performances of the case studies are compared against the outcomes of the regulatory energy performance calculations performed on completion of buildings.

The energy performance of a building is ultimately determined by the performance of its key components. Two components that are particularly prone to procurement issues and had clear design targets are considered in this Chapter: mechanical ventilation systems and building fabric.

Finally, a process map of the root causes identified for the key performance issues is presented based on a review of the design and as-built documentation and interviews with the construction teams. The aim here is to identify the process improvements that can help prevent these issues in future projects.

8.2. Technical conventions

The following notes must be considered in comparing the performances reported in this Chapter with the data presented in Chapter 5:

- The energy end-use categories used for regulatory calculations are different than the categories used for the analysis of operational performance. This reflects the difference between CIBSE TM22 methodology which uses a more detailed end-use classification and the NCM methodology used for regulatory calculations. The end-use categories reported in this Chapter follow the NCM conventions as more detailed calculated data consistent with TM22 were not available for all case studies. The operational data presented in Chapter 5 have thus been converted to be consistent with the NCM classification.

- Server room cooling energy is reported under ICT equipment category in CIBSE TM22, whereas any cooling energy calculated for these spaces in the NCM is reported as part of cooling end-use. The NCM convention is used in this Chapter.
- External lighting was not included in whole-building regulatory calculations in the 2002 and 2006 editions of the Approved Document Part L. Measured energy for *internal* lighting is therefore compared against the lighting energy reported in the regulatory calculations. External lighting energy is merged into Equipment energy for the purpose of this comparison.
- Equipment energy reported for the measured performance of the case studies includes all equipment and miscellaneous loads not regulated by Part L of the Building regulations. The default equipment load used in the NCM to estimate heating and cooling loads is reported and compared against operational data to give an indication of the underlying assumptions made in the regulatory calculations and the difference between these assumption and reality.
- The carbon emission conversion factors used for gas and electricity in the regulatory calculations are different than the conversion factors used for operational ratings. In this Chapter, the same conversion factors used for the regulatory calculations have been applied to the measured performance. The conversion factors used are 0.194 kg CO_2/kWh for gas and 0.442 kg CO_2/kWh for electricity in accordance with Part L2A (HM Government, 2006).

8.3. Energy performance

8.3.1. Regulatory performance gap

Table 8.1 compares the measured annual performance of the case studies against the outcomes of the regulatory calculations.

The calculated performance reported for Building E is derived from a calculation carried out based on Building Bulletin 87 as a means of compliance with the ‘whole building method’ of the Approved Document L2 (2002). This calculation predates the NCM and does not include all energy end-uses. Notably, no allowance is made for calculation of cooling energy although 17% of the total useful floor area in this building is provided with cooling. Furthermore, there is no allowance for auxiliary energy related to the operation of heating and domestic hot water pumps. The allowance considered for equipment load is 5 W/m² which corresponds to miscellaneous small power loads only and does not take into account the server room and data hub rooms. Finally, this calculation is based on a steady state spreadsheet based tool with an optimistic view of the effect of internal gains on space heating requirements that is reflected in the extremely low heating energy projected by the tool. This calculation is thus not representative of total performance and is indicative of the shortcomings of the methods and tools used before inception of the EPBD/NCM. The calculated performance reported for other buildings are based on the NCM.

Table 8.1. Annual measured performance of the case studies against the regulatory calculations

Bldg.	Analysis	Heating kWh/m²	DHW kWh/m²	Cooling kWh/m²	Auxiliary kWh/m²	Lighting kWh/m²	*Equipment kWh/m²*
A	Regulatory calculations (NCM-DSM)	16.5	19.9	1.0	7.0	24.5	*27.7*
	Measured	68.1	9.9	4.5	47.5	29.0	*49.7*
B	Regulatory calculations (NCM-SBEM)	11.3	9.9	1.5	10.9	15.4	*18.0*
	Measured	44.5	14.2	13.2	9.9	17.4	*32.1*
C	Regulatory calculations (NCM-SBEM)	80.4	21.1	3.8	20.8	28.4	*16.4*
	Measured	123.5	20.0	13.6	15.7	32.5	*35.9*
D	Regulatory calculations (NCM-DSM)	12.1	2.8	0.0	2.8	15.4	*20.3*
	Measured	71.8	20.0	6.4	22.3	15.7	*29.3*
E	*Regulatory calculations (BB87)*	*4.6*	*18.5*	*n/a*	*10.8 (fan only)*	*7.8*	*9.0 (small power only)*
	Measured	*115.0*	*12.4*	*13.8*	*61.6*	*30.1*	*44.2*

The following remarks aim to provide context for the figures reported in Table 8.1:

- **Heating:** generally, there is a significant gap between calculated space heating and measured values. This discrepancy will be further explored through thermal modelling for a couple of case studies in section 8.4. However, besides specific procurement and operational issues in the case studies, it should be noted that the NCM operational profiles assumed for schools are based on 39 weeks operation per annum that is consistent with the schools' calendar in England. It is assumed that heating systems and other building services are not operational outside this period. As explained in Chapter 5, this was not the case in the case studies. Furthermore, the NCM heating set point for classrooms is 18 °C (BRE, 2010), lower than the set points used in the case studies which were above 20 °C in almost all classrooms and teaching spaces. The infiltration is also often higher than what is assumed in the regulatory calculations due to the operation of windows which is not taken into account in the regulatory calculations for mechanically ventilated buildings.

- **DHW:** the differences between calculated and measured performance for domestic hot water energy seem reasonable in all case studies with the exception of Building D, where an error in defining activity types might have been responsible for the extremely low projection of DHW energy. Buildings A and C have large sport halls and changing facilities as reported in their schedules of accommodation in Chapter 4. The NCM allowance applicable to the case studies for domestic hot water use in changing rooms was 30 l/day/m² (BRE, 2010). This can explain high projection for DHW energy use in the regulatory calculations for these buildings compared to other buildings.
- **Cooling:** server room cooling constitutes a large component of the cooling requirement in the case studies. The server room load allowed in regulatory calculations is based on default values that may be lower than actual loads and lead to underestimation of cooling energy. It is also important to attribute the correct activity type to these spaces. For example, the NCM allowance for data centre activity type which is appropriate for the server room and data hub rooms in the case studies with 'high internal gain' is 500 W/m². However, there is another choice for 'computer server spaces with 24hr low-medium internal gain' in the NCM with 50 W/m² internal gain (BRE, 2010). The choice of the activity type can therefore have a significant impact on cooling requirements.

  It is notable that the calculated cooling energy for Building D is nil, although split DX air conditioners had been specified and were installed for server room cooling.
- **Auxiliary energy:** calculations of auxiliary energy in the case studies assumed effective demand-controlled ventilation. The widest gap between calculated and measured auxiliary energy in the NCM calculations is in Building A where this strategy was not implemented in practice. Similar to other end-uses, the projection of auxiliary energy for Building D seems very low and difficult to justify with a bottom-up calculation of the requirements of the air and water distribution systems present in this building.

It must however be noted that pump energy use in the NCM is determined by pump configuration and heating/cooling system type using default power densities and not actual powers (CLG, 2011). This along with the heating schedules assumed in the regulatory calculations for schools can lead to underestimation of pump energy use.

- **Lighting:** in all NCM calculations reported in Table 8.1 calculated lighting is reasonably close to the measured performance. This shows, despite shortcomings reported in previous chapters, manual switching and automated lighting controls installed in the case studies can reasonably limit the unnecessary operation of lights. Therefore, lighting in majority of spaces closely follows the operating hours assumed in the NCM even if parts of the building are used in half-term breaks or during out-of-hours. **Equipment:** The models used to produce the Building Regulations compliance reports and energy performance certificates were not available to the author. However, it was possible to check the activity types defined in these models from the EPC XML files lodged with the Landmark. None of the certificates had allowed for data centre activity type, which corresponds to 24hr operation of IT equipment with high internal gain, in their calculations. Adjusting the equipment load to allow for server room load in the case studies will yield a default equipment energy which is reasonably close to the actual energy used by the equipment.

  Although not regulated and based on default values defined for various activity types, the NCM calculated equipment energy can be used as benchmark for performance in-use provided an allowance is also made for the items that are not included in the model such as external lights and lifts.

8.3.2. Calculated performance against national building stock

Figure 8.1 compares the outcomes of the regulatory calculations against the measured data and the benchmarks derived from the DEC dataset for secondary schools. No adjustments were made to the outcomes of the regulatory calculations and therefore the discrepancy between measured performance and calculated performance depicted in this graph includes the effect of possible modelling errors in addition to procurement issues and operating conditions. This figure is meant to give an objective view of the discrepancy between measured performance and what was reported as ‘as-built’ performance after completion of buildings. The discrepancy between measured performance and ‘as-built’ performance in the case studies is in the region of 80-120% when the ‘as-built’ performance is used as the reference point.

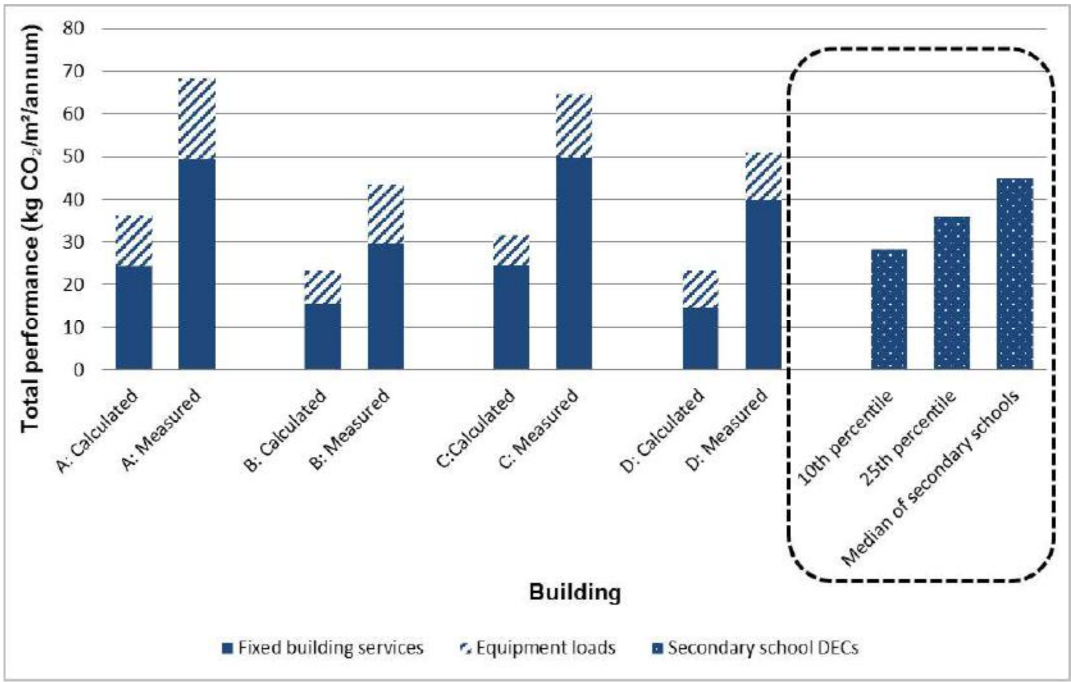


Figure 8.1. Total performance of Buildings A-D compared to the DEC dataset for secondary schools (carbon emission conversion factors used for natural gas and electricity are 0.194 and 0.422 kg CO_2/kWh respectively.)

The calculated performance for Buildings A is very close to the 25th percentile of secondary schools, the calculated performance of Building C lies between the 10th and 25th percentile, and the calculated performance of Buildings B and D are better than the 10th percentile of secondary schools. These calculated performances therefore possess the first requirement set out for benchmarking new buildings in Chapter 3, that is, they are equivalent or better than the good practice benchmarks for the existing building stock. If the bulk of the discrepancy between measured and calculated performance can be attributed to identified procurement and operational issues, it can be concluded that the calculated performances can be used as benchmarks for performance in-use. This second requirement can be examined with the aid of modelling. A large component of the discrepancy between the measured and calculated performance in Building C can be explained by the academy's decision to switch from biomass with a conversion factor of 0.025 kg CO_2/kWh to natural gas with a conversion factor of 0.194 kg CO_2/kWh. Part of the discrepancy between measured and modelled performance in Building D is also related to modelling issues that were outlined in the previous section. It was therefore decided to further examine the discrepancy between measured and calculated performance for the buildings with the worst and best measured performance, namely, buildings A and B respectively.

8.4. Calculated performance as benchmark for performance in-use

As the original computer models were not available, new models were developed for Buildings A and B using IES software. These models reflect the findings of the building performance evaluations and actual operating conditions. Therefore, they are referred to as TM54 models in this Chapter to emphasise that they are based on real operating conditions and not the NCM default values. An adjustment was made to the modelling results, in accordance with CIBSE TM54 (2013), to allow for the miscellaneous loads that were not defined in the models such as external lights and lifts. Total allowances for the miscellaneous loads added to TM54 modelling results for buildings A and B were equal to 1.7% and 2.4% of the modelled electricity respectively. The results of theTM54 models were compared against the measured performance to ensure the models provide a reasonable representation of the actual operation.

A list of major procurement and operational issues was compiled for each building based on building performance evaluations.

The TM54 models were subsequently used to derive NCM benchmarks assuming none of the procurement issued occurred and the buildings met all design intents. This was to establish the NCM benchmarks with accuracy and avoid the effects of any potential modelling error in the original NCM calculations. All operating conditions were automatically set to the NCM standardised conditions by the software once the model was imported into the IES module for the UK compliance calculations.

The TM54 models were also used to derive an optimised performance for each building by addressing all identified procurement and operational issues in the model. This optimised performance was then compared against the NCM benchmark to assess the effectiveness of the NCM benchmarks.

The dynamic simulation route, using IES Apache simulation engine, and the TRY weather file representative of the location of the buildings were applied to these models. The heating components of the modelling results were weather adjusted, based on the actual heating degree-days, to be comparable with the measured performance.

8.4.1. Demonstration: Building A

Figure 8.2 illustrates an axonometric view of the model developed for Building A. Table 8.2 provides a review of the key input data used to develop the TM54 model for this building.

Table *8.3* compares the actual operating conditions in Building A against the NCM standardised conditions in typical zones. Table 8.4 lists the major procurement and operational issues uncovered in this building. Finally, Figure 8.3 compares the outcome of the TM54 model against the measured performance, and also presents the NCM benchmark and the optimised performance level derived from the TM54 model.

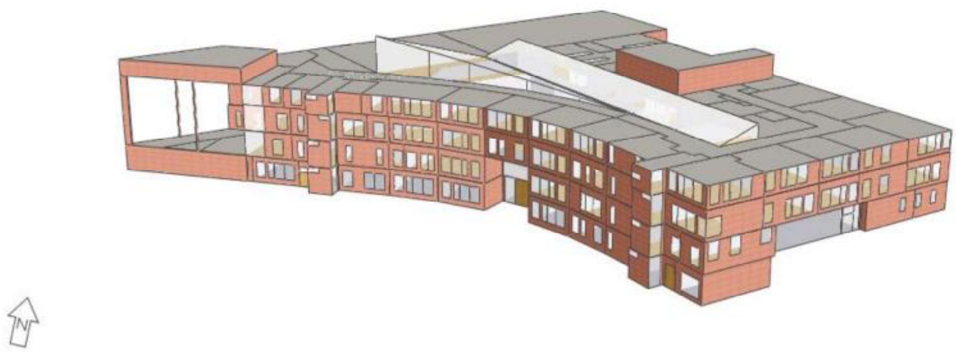


Figure 8.2. Axonometric view of the building physics model developed for Building A

Table 8.2. Input data used for Building A TM54 model based on performance evaluation

Building characteristics	Thermal model inputs
Heating	Bivalent heating system: 21% of heating demand is satisfied by the Ground Source Heat Pumps; gas fired boilers supplement the GSHPs. Coefficient of Performance for the GSHPs: 4.1 Gross efficiency of gas-fired boilers in condensing mode: 95.2% Gross efficiency of gas-fired boilers in non-condensing mode: 88.0%
Ventilation	Specific Fan Power of 3.8 W/(l.s) for main air handling units based on the commissioning results; no demand control ventilation enabled. Air handling units have thermal wheels or plate heat exchangers for heat recovery.
Cooling	Ground source heat pumps Energy Efficiency Ratio: 5.20 Server room DX units Energy Efficiency Ratio: 3.27
Hot water	Hot water tank capacity: 2,000 litres with 0.0026 kWh/l/day loss.
Lighting	All lighting wattages based on as-built drawings; average lighting density is 12 W/m². Automatic daylight sensing with an average daylight factor of 2% within 6m of the building perimeter, absence detection sensors in classrooms and presence detection sensors in circulation areas
External envelope	The building external wall is brick block with insulated cavity. Average U value for the external envelope including glazing (based on as-built drawings): 0.48 W/m²°K
Air permeability	9.2 m³/(m².hour) @ 50 Pa (based on the pressure test result)
Equipment loads	Zone level equipment loads defined based on post-occupancy evaluation and reconciled with the energy end-uses reported in Table 5.2 and Table 5.3

Table 8.3. Standardised against actual operating conditions: Building A

Operating conditions	The NCM operating conditions assumed for schools	Actual operating conditions
People density (person/m²)	Typical classrooms: 0.55 ICT classrooms: 0.20 Office space: 0.07	Typical classrooms: 0.50 ICT classrooms: 0.30 Office space: 0.06
Heating Set point (ºC)	Classrooms: 18 Offices: 22	Classrooms: 21 ± 2 Offices: 21 ± 2
Cooling Set point (º C)	Classrooms: 23 Offices: 24	Classrooms: 21 Offices: 21
Ventilation rate (l/s/person)	Classrooms: 5 Offices: 10	Classrooms: 8 Offices: 14
Schedules of operation:	Occupancy: 7:00-18:00 Mon-Fri; term time (standard diversity factors applied) Heating & Cooling: 5:00-18:00 (Mon-Fri; term time) Mechanical Ventilation:7:00-18:00 (Mon-Fri; term time)	Occupancy: 7:00-18:00; extended to 21:00 on Tuesdays & Thursdays for night school (diversity applied based on post-occupancy studies) Heating , Cooling and Mechanical Ventilation: 6:00-18:00 weekdays; extended to 21:00 on Tuesdays & Thursdays for night school (Weekdays and school holidays)

Table 8.4. Major procurement and operational issues uncovered in Building A

Procurement issues	Operational issues
The commissioning results reveal that total Specific Fan Power of the main air-handling units was 53% higher than the maximum allowable SFP in the Building Regulations. Demand Controlled Ventilation was NOT enabled: inverters were installed on supply and extract fans but only used to balance the system at the commissioning stage. No CO_2 sensor was installed in the ductworks or classrooms to trigger variable speed control. Actual fresh air ventilation rate was 73% higher than what is required. Lighting automated controls were NOT commissioned properly: inconsistent and long time-offs (> 20 minutes) for presence and absence detection sensors; high sensitivity; poor zoning	Operating schedules were not programmed in accordance with the seasonal operation of the school. The heating system and all air-handling units were fully operational during half term breaks and school holidays. The heating and ventilation zoning were not used to isolate parts of building not in use during night schools and extracurricular activities. Maintenance issues: dirty air filters and other problems related to maintenance increased total system pressure drop by 20% (system pressure drop was estimated based on sub-metered fans' energy use and fans' absorbed power). Actual heating set points were often higher than the set points allowed in the NCM. Actual cooling set points were lower than the cooling set points allowed in the NCM.

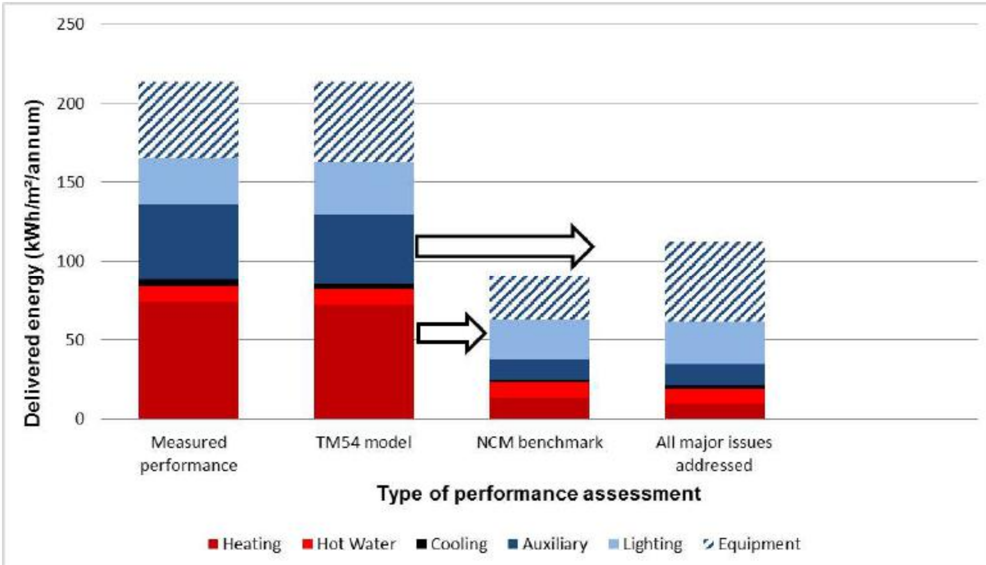


Figure 8.3. The NCM benchmark and optimised performance derived from TM54 model: Building A

The outcomes of the TM54 model for Building A are reasonably close to the measured performance. The total modelled annual energy performance is within 3 % of the measured performance. When all major procurement and operational issues listed in Table 8.4 are addressed in the model, the performance of the fixed building services is very close to the respective NCM end-uses. However, total performance is higher than the NCM benchmark mainly as a result of equipment energy use. Excess in equipment energy use in Building A, over the benchmark derived from the NCM equipment loads, is expected given the ICT infrastructure installed and the amount of equipment left ON out of hours.

8.4.2. Demonstration: Building B

Figure 8.4 illustrates an axonometric view of the model developed for Building B. Table 8.5 provides a review of the key input data used to develop the TM54 model for this building.

Table 8.6 compares the actual operating conditions in Building A against the NCM standardised conditions in typical zones. Table 8.7 lists the major procurement and operational issues uncovered in this building. Finally, Figure 8.5 compares the outcome of the TM54 model against the measured performance, and also presents the NCM benchmark and the optimised performance level derived from the TM54 model.

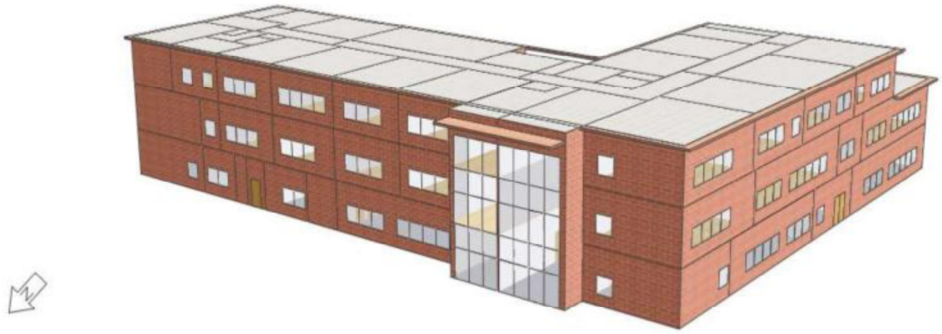


Figure 8.4. Axonometric view of the building physics model developed for Building B

Table 8.5. Input data used for Building B TM54 model based on performance evaluation

Building characteristics	Calibrated thermal model inputs
Heating	Gas fired boilers operating in non-condensing mode. Gross efficiency of the boilers in non-condensing mode: 87.4% Coefficient of Performance for the variable refrigerant flow system: 4.24
Ventilation	Specific Fan Power of 2.85 W/(l.s) for the main air handling unit based on the specification; demand control ventilation enabled. The main air handling unit utilises a thermal wheel for heat recovery.
Cooling	Energy Efficiency Ratio for the variable refrigerant flow system: 3.84 Server room DX units Energy Efficiency Ratio: 3.1 (ground floor server), 2.6 (second floor server)
Hot water	Hot water tank capacity: 900 litres with 0.005 kWh/l/day loss.
Lighting	All lighting wattages based on post-occupancy evaluation; average lighting density is 10 W/m². Automatic daylight sensing with an average daylight factor of 2% within 6m of the building perimeter, absence detection sensors in classrooms and presence detection sensors in circulation areas; no daylight sensor in the day lit circulation spaces facing the atrium
External envelope	The building external wall is brick block with insulated cavity. Average U value for the external envelope including glazing (based on as-built drawings): 0.43 W/m²°K
Air permeability	9.09 m³/(m².hour) @ 50 Pa (based on the pressure test result)
Equipment loads	Zone level equipment load defined and reconciled with the energy end-uses reported in Table 5.2 and Table 5.3.

Table 8.6. Standardised against actual operating conditions: Building B

Operating conditions	The NCM operating conditions assumed for schools	Actual operating conditions
People density (person/m²)	Classrooms: 0.55 ICT classrooms: 0.20 Cellular office space: 0.07	Classrooms: 0.55 ICT classrooms: 0.38 Cellular office space: 0.07
Heating Set point (ºC)	Classrooms: 18 Offices: 22	Classrooms: 21 ± 2 Offices: 21 ± 2
Cooling Set point (º C)	Classrooms: 23 Offices: 24	Classrooms: 21 Offices: 21
Ventilation rate (l/s/person)	Classrooms: 5 Offices: 10	Classrooms: 10 Offices: 10
Schedules of operation:	Occupancy: 7:00-18:00 Mon-Fri; term time (standard diversity factors applied) Heating & Cooling: 5:00-18:00 (Mon-Fri; term time) Mechanical Ventilation:7:00-18:00 (Mon-Fri; term time)	Occupancy: 7:00-16:00; extended from 18:00 to 21:00 on Tuesdays & Thursdays for night school (diversity applied based on post-occupancy studies) Heating , Cooling and Mechanical Ventilation: 7:00-16:00 weekdays; extended from 18:00 to 21:00 on Tuesdays & Thursdays for night school (Mon-Fri, term time)

Table 8.7. Major procurement and operational issues uncovered in Building B

Procurement issues	Major discrepancies between the NCM and actual operating conditions
Gas-fired boilers were NOT operating in condensing mode; the hot water flow temperature in heating season was constantly above 80 °C. Gross efficiency in non-condensing mode is 7.3% lower than the combined boiler efficiency. Solar thermal panels were NOT properly commissioned and did not contribute to the domestic hot water use in the first two years of operation.	Actual heating set points were often higher than the NCM set points in the spaces served by radiant panels. Furthermore, the variable refrigerant flow units were programmed to maintain 21 °C. This compares with the NCM heating set point of 18 °C and cooling set point of 23°C for classrooms, where comfort cooling is provided.

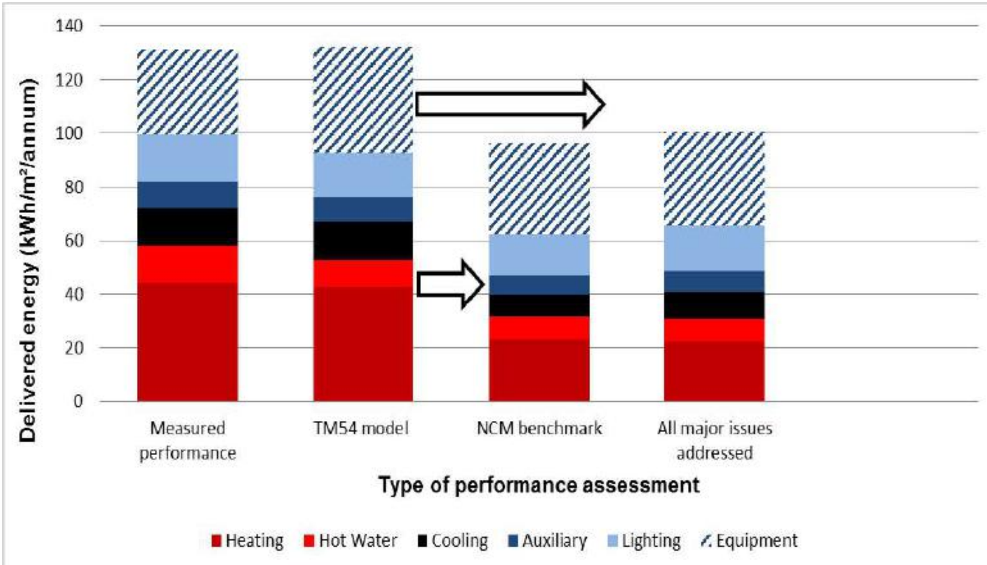


Figure 8.5. The NCM benchmark and optimised performance derived from TM54 model: Building B

The outcomes of the TM54 model for Building B are reasonably close to the measured performance. The total modelled annual energy performance is within 2% of the measured performance. When the major procurement and operational issues listed in Table 8.7 are addressed in the model, all energy end-uses are close to the NCM end-uses and the total energy performance is only 5% higher than the NCM benchmark.

Overall, it is demonstrated that, in the worst and best performing case studies, addressing the major procurement and operational issues can achieve energy performance levels very close to the projections made under the NCM standardised conditions. Therefore, it can be concluded that the NCM projections can be used as robust *benchmarks* for performance in-use of a building if the building occupancy and operating conditions do not radically differ from the typical conditions assumed for the respective building category. This has important implications and notably points to the significant improvement opportunities in thermal performance of new-buildings that, as explained in Chapter 5, are not necessarily reflected in good practice benchmarks derived from the existing building stock. The electricity use projected in the NCM benchmarks for schools is also more reasonable than what is allowed in the benchmarks derived from the existing buildings and is representative of the electrical loads expected in modern educational buildings.

8.5. Analysis of mechanical ventilation systems

As mechanical ventilation was a key determinant of energy use in the case studies, a detailed review of the performance of mechanical ventilation systems in the case studies is presented to highlight the discrepancies between actual performance and design assumptions.

8.5.1. Full load performance

Figure 8.6 shows the calculated specific fan powers against the limiting values and the 'as-built' values reported in the Building Regulations compliance reports. The calculated SFPs are derived from the information provided in the commissioning reports for all buildings, with the exception of Building B for which the required commissioning information was not available. The calculated SFP reported for Building B is based on the manufacturer's quoted absorbed powers for supply and extract fans in the main air handling unit at nominal supply air.

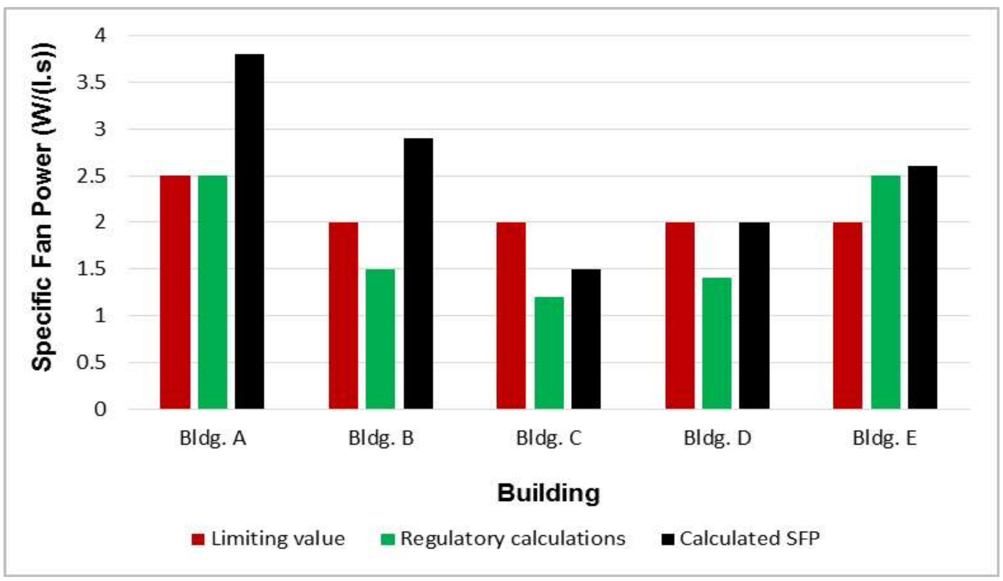


Figure 8.6. Specific fan powers of the air distribution systems in the case studies

Calculated SFPs in all cases are higher than the 'as-built' values reported for buildings in the regulatory calculations. However, it should be noted that the SFP calculations used nominal voltage values reported in the commission reports that were 240 V and 415 V for one phase and three phase power respectively. The statutory power supply specification in the UK allows for ± 6% variation in these values (Carbon Trust, 2011). This means the calculated SFP for Building E is within the expected variation range of the as-built value reported for this building. The discrepancy between calculated and reported SFPs in other buildings are well beyond this variation and are in the region of 40-90%. Furthermore, in three cases the SFPs are higher than the limiting values. The SFP reported for Building B in the regulatory calculation (1.5 W/(l.s)) is probably based on an input error as it appears the absorbed power of the main air handling unit extract fan had not been taken into account. There is also no evidence that the expected SFP was ever calculated for Building A with a complex air distribution system that comprises 10 main air handling units. The limiting value specified by the Building Regulations was used in the regulatory calculation for this building assuming the actual value would not be greater than the limiting value.

Figure 8.7 shows an example of poor ductwork installation with sharp bend and high aspect ratio in the main branch that increased system pressure drop and thereby the fan power required to overcome this pressure drop in Building A. Operational pressure drop could be even higher if the system is subject to poor maintenance and panel and bag air filters are not cleaned or replaced regularly.

Figure 8.7. Mechanical ventilation system in Building A: sharp bends and high aspect ratios increase system pressure drop and specific fan power (left), system pressure drop will even further increase if air filters pass their recommended final pressure drop.

8.5.2. Demand-controlled ventilation

Demand-controlled ventilation strategy was not effectively implemented in two mechanically ventilated buildings (Buildings A and E) with severe implications for total energy performance. Following detail design, the tender specification document for Building A required all main air handling units to have variable speed supply and extract fans. However, there was no mention of the type and location of CO_2 or other type of sensors to trigger demand-controlled ventilation. Control requirements were also described in tender documents; supply and extract fans were required to be powered from their own variable speed drives within the control panel. The control module software was required to change the speed of fans *either* manually through the panel switch operation *or* on an event driven basis. It appears that this rather loose specification of the fan control requirements made it possible for contractors to choose the low cost option of manual control only. Site inspections confirmed that no CO_2 sensor had been installed in the classrooms or extract ductworks. This meant variable speed control of 10 main air handling units was practically impossible and not consistent with the design assumption made in the regulatory calculations.

In Building E, a number of air handling units contained CO_2 sensors within their return air stream. However, fan speeds were not modulated by the CO_2 levels and the air handling units provided 100% fresh air regardless of actual demand. There was no evidence that demand-controlled ventilation strategy and the interaction between sensors and fan inverters had been checked at the commissioning stage.

Building B, on the other hand, had an effective demand-controlled ventilation that delivered low auxiliary energy.

The air handling units that served parts of Buildings C and D were also inverter driven and controlled by CO_2 levels.

Figure 8.8 compares the fan frequencies recorded for a typical main air handling unit in Building A with no variable speed control and Building D with variable speed control during a working week.

Recorded fan frequencies for Building D reported in Figure 8.8 are often lower than 35 Hz. According to the fan affinity laws, this can reduce fan power by as much as 65% compared to the full frequency of 50 Hz. This shows the significance of demand-controlled ventilation and why it must be effectively implemented especially where mechanical ventilation is the main ventilation strategy.

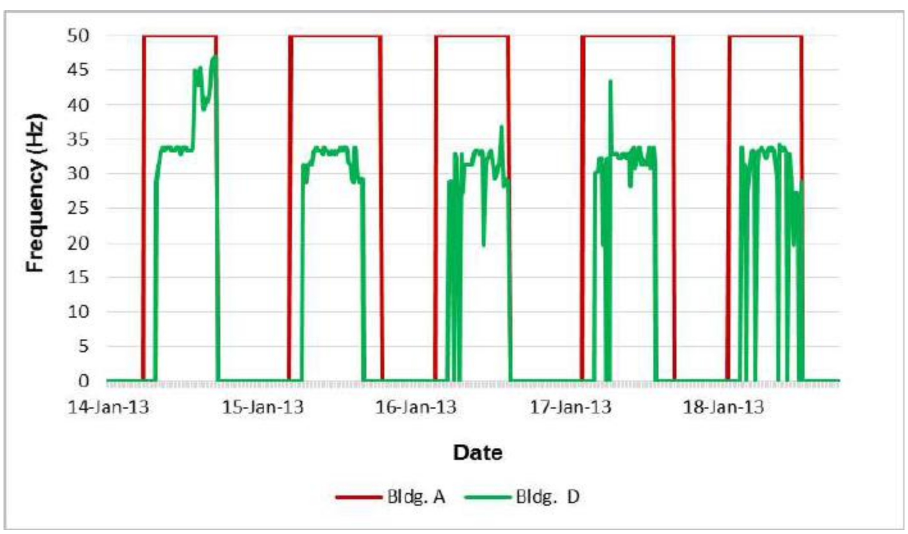


Figure 8.8. Fan frequencies in Building A with no variable speed control against Building D with variable speed control

8.5.3. System-level benchmarking

The measured auxiliary energy in Building A is much higher than the NCM benchmark, whereas the auxiliary energy use in Building B is very close to it (Table 8.1). Post-occupancy studies revealed that the main root cause for this difference in auxiliary energy performance is the specification and operation of the mechanical ventilation systems. Therefore, a bottom-up analysis was used for system level benchmarking of the main air-handling units supplying fresh air to building occupants in these buildings.

Table 8.8 provides the outcomes of this analysis following the TM22 tree diagram depicted in Figure 3.3. Every box in this diagram indicates a parameter that could be used for benchmarking (CIBSE, 2006).

Load factor is the ratio of actual absorbed power at full load to the rated power. Where efficiencies are quoted based on specific fan powers achieved at the commissioning stage, load factors represent increases in fans' absorbed power due to operational inefficiencies, in particular dirty air filters that increase total system pressure drop. The load factor in Building A was estimated from the measured fan energy use. In Building B the efficiency was quoted by the manufacturer based on the average value of initial and final pressure drops across panel and bag filters and, therefore, load factor of one was used.

Usage factor represents the equivalent time system is at full load divided by the enabled time. Hence, the effect of demand-controlled ventilation can be modelled with this factor. There is no CO_2 sensor installed in classrooms or extract ductwork for Building A to enable the inverters installed on supply and extract fans. Therefore, actual usage factor for Building A is one. In building B the maximum ventilation rate is more than twice what is required to maintain the CO_2 concentrations within the acceptable limits specified by BB101 (DfES, 2006). The minimum speed specified for the main air-handling unit supply fan is 50% of the nominal load and, therefore, the inverters operate at half the full load frequency at all times. Consequently, a low usage factor for Building B is expected in accordance with the fan affinity laws. Actual usage factor in Building B was derived from the measured fan energy use. The benchmark usage factors were calculated following the procedure explained in Chapter 3.

Table 8.8. System-level benchmarking for mechanical ventilation in Buildings A and B

Building	Ventilation rate (l/s)/m²	Efficiency (W/(l/s))	Load factor	Annual operating hours	Usage factor	Ventilation (W/m²)	Effective hours per year	Energy (kWh/m²/ annum)
A: actual	1.66	3.82	1.20	3,454	1.00	7.61	3,454	26.3
A: benchmark	0.96	2.50	1.00	2,318	0.56	2.40	1,298	3.1
A: actual / benchmark	1.73	1.53	1.20	1.49	1.79	3.17	2.66	8.48
B: actual	2.27	2.85	1.00	3,089	0.15	6.47	463	3.0
B: benchmark	0.98	2.00	1.00	2,318	0.56	1.96	1,298	2.5
B: actual / benchmark	2.32	1.42	1.00	1.33	0.27	3.30	0.36	1.20

Table Notes:

(1) Actual values are based on the commissioning results (building A), final specification (building B), and post-occupancy evaluations (both buildings).

(2) Benchmark sources: Ventilation rates are based on nominal occupancy and BB101 requirements for fresh air (DfES, 2006). Efficiencies are the limiting regulatory values extracted from the BRUKL reports. Annual hours of use were calculated based on normal working hours for schools plus extracurricular activities (e.g. night schools).

Table 8.8 shows mechanical ventilation in principle can be provided with low energy use. Building B is an example that delivered low ventilation energy in spite of its high SFP thanks to an effective demand-ventilation strategy and low usage factor. Building A, however, demonstrates the risks associated with mechanical ventilation and how small deviations from individual benchmarks could be compounded and result in a measured performance that is almost ten times the aggregate benchmark. This is illustrated in Figure 8.9.

There is an on-going debate about the appropriate ventilation strategy for educational buildings given the evidence that points to the link between poor air quality and pupils' performance and increasing risk of overheating on one hand and the drive for energy efficiency. The evidence and analysis presented here demonstrates that it is possible to reconcile the competing objectives of energy efficiency and good indoor air quality provided the risk factors associated with mechanical ventilation are identified and effectively managed throughout a construction project and in-operation. The flip side of this argument is mechanical ventilation strategy, compared to natural ventilation, is a high risk option that may severely compromise energy performance in-use if not procured and managed well. The key issue therefore is effective risk management that is missing from the current procurement methods.

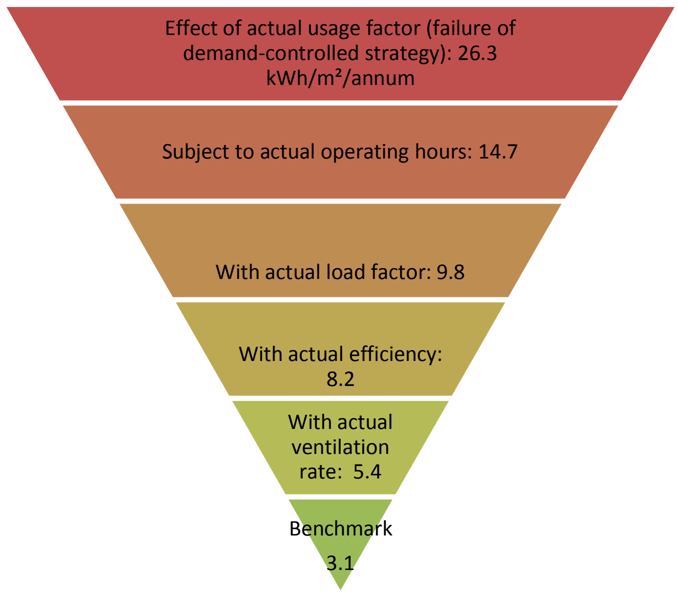


Figure 8.9. Evolution of ventilation energy from benchmark to measured performance and the effects of contributing factors: Building A

8.6. Fabric performance

The energy models used for the Building Regulations compliance calculations were developed by building services engineers who sourced the drawings and fabric details necessary for modelling from the architects. As part of the Innovate UK Building Performance Evaluation programme, the architects were asked to review the as-built performance and report the U values. Table 8.9 compares the U values calculated by the architects based on a review of the as-built drawings against the values used in the regulatory calculations (Kimpian, et al., 2013 a), (Kimpian, et al., 2013 b).

Table 8.9. . Area-weighted average U values reported in the regulatory calculations and Innovate UK Building Performance Evaluations

Building	Review stage	External wall U value (W/m²°K)	External floor U value (W/m²°K)	Roof U value (W/m²°K)	Windows and roof light U value (W/m²°K)
A	Regulatory calculations	0.35	0.25	0.25	2.2
	InnovateUK BPE review	0.28	0.25	0.15	1.8
B	Regulatory calculations	0.2	0.21	0.16	2.0
	InnovateUK BPE review	0.32	0.21	0.19	1.9
C	Regulatory calculations	0.35	0.25	0.25	2.1
	InnovateUK BPE review	0.35	0.25	0.30	2.1
D	Regulatory calculations	0.35	0.25	0.25	2.2
	InnovateUK BPE review	0.35	0.25	0.25	2.2
E	Regulatory calculations	0.35	0.25	0.25	Windows: 2.2 Roof lights: 2.6
	InnovateUK BPE review	0.34	0.25	0.25	2.0

It appears that the regulatory calculation for Building A was carried out based on the maximum allowable U values. The U values reported by the architects are generally lower than the values used in the regulatory calculation. The downside of this approach to regulatory calculations is that the area-weighted U values might not be checked assuming the as-built values will not exceeded the regulatory limits. For example, the architects reported as-built U values higher than maximum allowable U value for both the standing seam roof and flat roof in Building C (0.3 W/m²°K).

It is also important to use the final as-built details and consider the variations in insulation levels in different areas. The maximum discrepancy in Table 8.9 is related to the U value of external walls in Building B; the architects reported an average U value that is 60% higher than the value used in the regulatory calculations. Figure 8.10 shows the layers of the partially filled cavity wall specified for Building B. Common blockworks have been used as inner and outer layers. Polyisocyanurate (PIR) foam boards were specified for insulation with a thermal conductivity of 0.023 W/m°K. The design stage drawings show 100mm insulation for typical sections which yields a value close to 0.2 W/m²°K used in the regulatory calculation. However, the final construction document included in the O&M manuals refers to 80mm insulation thickness. Furthermore, the insulation level is reduced at critical points such as the wall to floor junction shown in Figure 8.10. The minimum insulation level to be maintained throughout building perimeter was 50mm which corresponds to a U value of 0.36 W/m²°K. Therefore, the average U value reported by the architects is more reasonable than the value used in the regulatory calculations. This also explains the discrepancy between the projections for heating energy use in Building B derived from the regulatory calculations and the TM54 model presented in Figure 8.5. The TM54 thermal models developed for Buildings A and B use the U values reviewed by the architects during the Building Performance Evaluations.

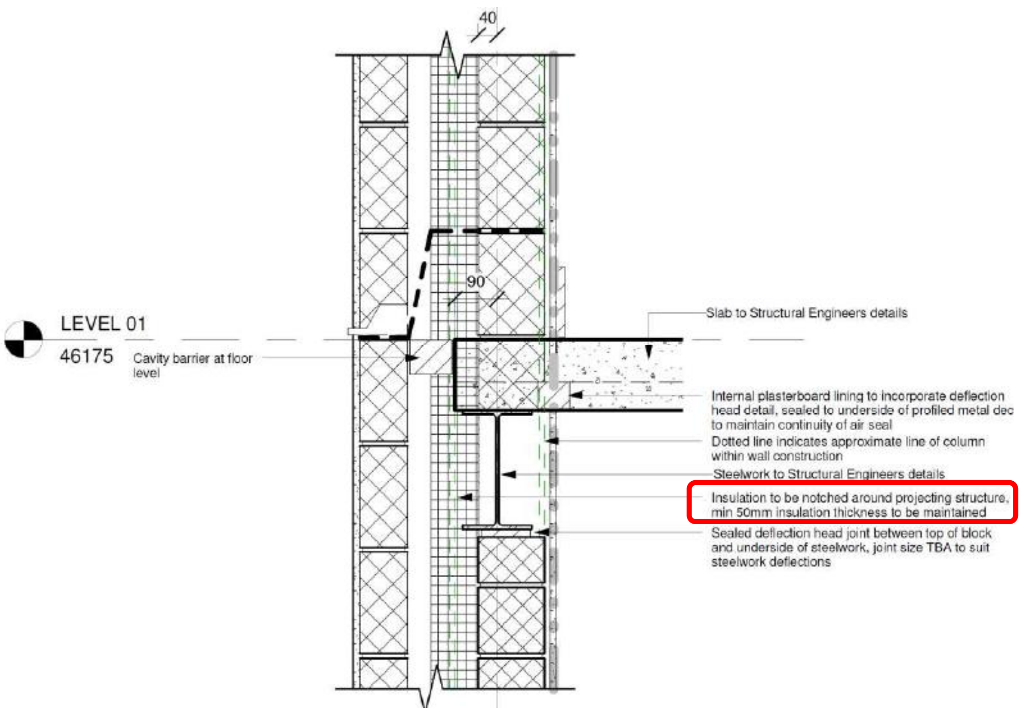


Figure 8.10. Typical external render wall/floor junction in Building B (Courtesy of AHR Global Architects): insulation thickness can be reduced to minimum 50 mm around the projecting structure.

Thermal imaging of external facades showed the insulation is reasonably continuous across the external walls. However, non-repeating thermal bridges at junctions show room for improvement both in designing and constructing the joints between construction elements. Using an inner block work leaf with a thermal conductivity lower than the rest of the block work in accordance with the accredited construction details (CLG, 2007) and improving the construction workmanship can help reduce heat loss at junctions. Figure 8.11-Figure 8.13 show examples of the thermal images captured from Buildings A-C.

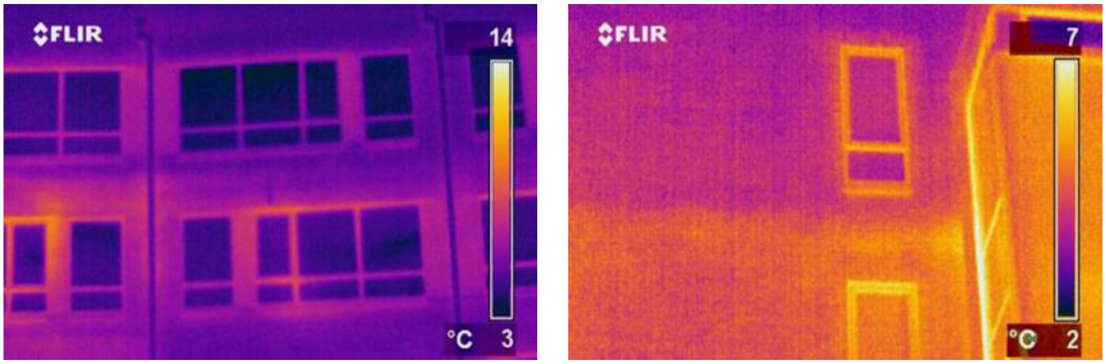


Figure 8.11. Building A thermography: reasonably continuous insulation across external walls with some shortcomings around the windows (left); thermal bridge at the junction between cavity wall and the curtain wall system (right)

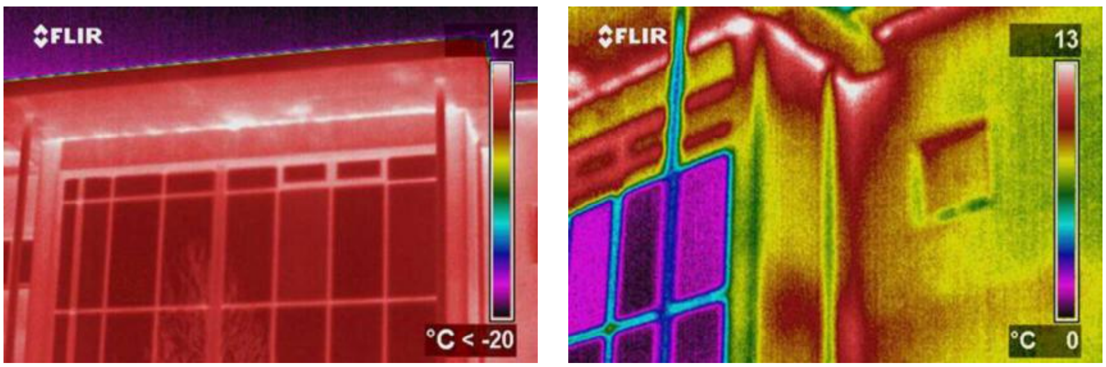


Figure 8.12. Building B thermography: thermal bridges at wall-to-roof and wall-to-wall junctions

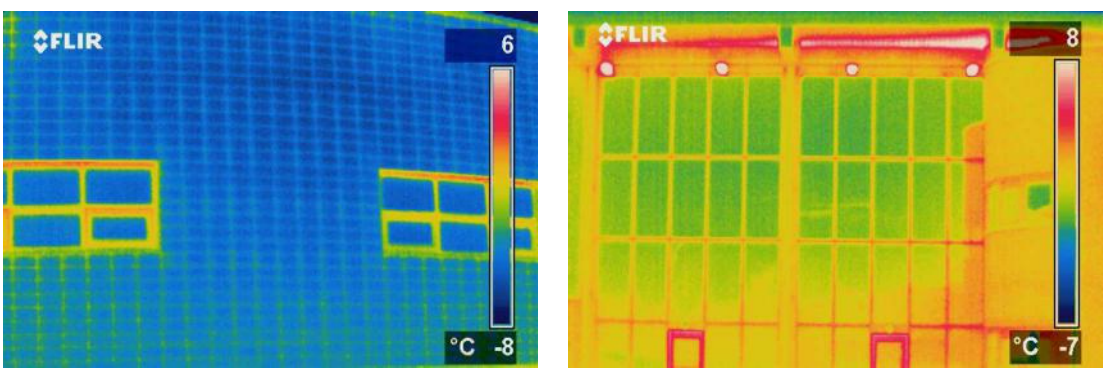


Figure 8.13. Building C thermography: reasonably continuous insulation across the external wall (left); thermal bridge at the junction between the curtain wall and the roof (right)

In Building E, where a large proportion of the external envelope is covered with prefabricated glazed and opaque panels, temperature distribution appears to be more uniform. The opaque panels have insulated spandrel backing and therefore show a better performance in the curtain wall system (Figure 8.14).

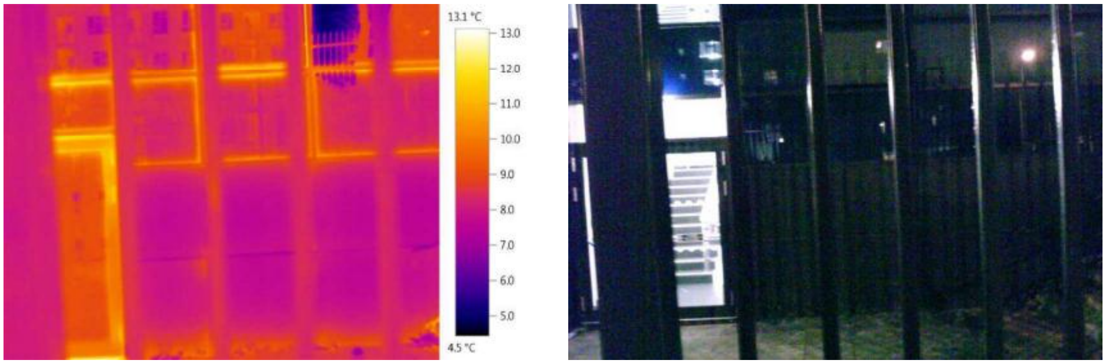


Figure 8.14. Building E thermography: the contrast between the temperature distribution across the glazed panels and the opaque elements of the curtain wall system that have insulated spandrel backing

It should however be noted that the curtain wall system (glazed and opaque panels combined) in Building E constitutes around 86% of building façade reducing the thermal mass of the external envelope. Approximately 16% of the roof area is also covered by a three layer ethylene tetrafluoroethylene (ETFE) roof light system with light weight and U value around 2 $W/m^2{}^\circ K$ (Figure 8.15). The lightweight external envelope of Building E has implications for temperature control and energy performance as reported in the previous chapters.

Figure 8.15. The lightweight ETFE roof light system covers the atrium space of Building E

The following lessons can be learned from the review of the U values and fabric performance in the case studies:

- Energy modelling is a task that cuts across disciplines and requires input from various members of the construction team. While architects provide the drawings and building fabric specification, in practice, they do not necessarily calculate the U values. It is often a perception that whoever is in charge of modelling must take this responsibility. It is therefore critical to define the responsibility to calculate the design and as-built U values at the early stages of a project. It is also important to ensure changes in fabric specification are reflected in the model and the final design and regulatory energy performance calculations are consistent with the design intent and as-built values.

- It is necessary to take into account variations in building fabric such as various types of external wall and windows and changes in insulation thickness. U value calculation based on 'typical' cross sections without taking into account the construction details might lead to an optimistic view of fabric performance in the energy model which is not consistent with the practical constraints.
- There are improvement opportunities to limit thermal bridges at junctions. The new editions of the Approved Document Part L put more emphasis on limiting the heat loss from thermal bridging at the joints between elements. A way to demonstrate reasonable provision has been made to limit these thermal bridges is to use the construction joint details calculated by a suitably qualified person (HM Government, 2013).

8.7. Process map of the performance gap

Table 8.10 provides a process map of the underlying root causes of a number of major issues observed in the case studies. It explains at what stage of the construction process the problem occurred and how it affected the performance as the project progressed.

Key lessons emerging from this review that are related to building procurement process and may help to prevent these issues in future projects are as follows:

- **Identify and protect key energy efficiency measures:** There was a systematic failure to identify and protect key determinants of energy performance and mitigate various risk factors associated with them throughout the projects. A risk register for key energy efficiency measures that is updated as project progresses would be helpful to protect them at critical stages of a project such as when designers or contractors are replaced or during the value engineering process.
- **LZC systems are key components of energy strategy:** The regulatory energy performance calculations for the case studies reflect an optimistic, and in some cases unjustifiable, view about the contribution of low or zero carbon systems to buildings' energy demand. For example, there is no projection for using natural gas in the energy performance calculations carried out for Building C. The biomass boiler meets the entire heating and DHW demand according to the EPC file lodged for this building. However, the biomass boiler was sized based on 50% of nominal heating demand and two gas-fired boilers with similar size to the biomass boiler were installed to supplement heating. The optimism expressed in the regulatory calculations is in stark contrast to the lack of detailed attention to the LZC system requirements, metering strategies, control strategies defined at the interface between these systems and their back-ups, commissioning, and finally their actual contribution. **Energy modelling**

must be fully integrated into the design process: Energy modelling is increasingly a specialist job in building services and architectural practices. Energy modellers are thus not necessarily involved in detail design and would need sufficient and up-to-date information to revise their calculations as projects progress. The feedback received from the designers of the case studies in building performance evaluations suggests closer collaboration and better communication between designers and energy modellers are required to improve the accuracy of energy performance calculations.

- **Significance of seasonal commissioning:** In all case studies, important aspects of building performance and key energy efficiency measures were not addressed at commissioning. The functionality of HVAC zoning arrangements, various triggers for motorised vents in naturally ventilated spaces, demand-controlled ventilation in mechanically ventilated spaces, automated lighting controls, and metering are common examples. Basic commissioning that takes place before building handover often cannot cover all aspects of performance for practical reasons. Enhanced or seasonal commissioning after building handover is necessary to get things right, especially for complex buildings, and must be considered for a project at the outset.
- **Measurement and Verification of performance in-use is necessary:** Finally, there is a thread that connects all process issues outlined above which is lack of measurement and verification of performance in-use in reference to the as-built calculations. An output-oriented energy performance assessment framework could be a major driver for process improvements that helps deliver low carbon buildings in practice.

Table 8.10. Process map of the key issues that compromised performance in-use in the case studies.

Project stage	Bldg. A	Bldg. B	Bldg. C	Bldg. D	Bldg. E
Strategic definition and preparation	Site noise levels triggered mechanical ventilation strategy. There is no evidence that the risks of this strategy for energy performance and all necessary mitigation measures were effectively considered.	Energy efficiency and low or zero carbon technology were the main determinants of performance.	In addition to natural ventilation strategy, energy efficiency and low or zero carbon technology were the main determinants of performance.	Natural ventilation and low carbon technology were the main determinants of expected performance.	Site noise levels triggered mechanical ventilation strategy. There is no evidence that the risks of this strategy for energy performance were effectively assessed and managed throughout the project.
Design stages	Demand-controlled ventilation was specified to save energy. However, no details were specified in the RIBA Stage D report where the energy model was discussed. The limiting value set out by the Building Regulations for Specific Fan Power was used in the regulatory calculations. There is no evidence that the expected SFP for the main AHUs was ever calculated.	The radiant panels specified for the classrooms and the atrium space were sized based on a flow temperature of 80 °C. This is not consistent with boilers' condensing mode of operation. Air source heat pumps and solar thermal panels were specified as low and zero carbon systems respectively. However, no heat meter was specified for these systems. No daylight sensor was specified for corridor lights, although a large part of circulation space is south facing and day lit.	A biomass boiler was specified and sized to meet 50% of building's heating demand. This was a critical part of the design to de-carbonise energy use and meet the regulatory Target Emission Rate. A solar thermal system was also specified to contribute to domestic hot water. However, no heat meter was specified to monitor its contribution. Absence detection sensors in teaching spaces and presence detection sensors in circulation spaces were specified for internal lights to save energy.	Ground Source Heat Pumps were specified as the lead heating system. Heat meters were specified to measure heating and cooling contribution of heat pumps. However, no electrical meter was specified to measure the electrical input of the heat pumps. The HVAC zoning was designed to enable users to hydraulically isolate zones not used during out-of-hours activities.	Demand-controlled ventilation was specified, although details of this measure are not reported in design documentation. No solar shading was provided to reduce internal gains. Central cooling was specified for parts of the building, including south facing classrooms, in addition to server room cooling. Purge mechanical ventilation and night time cooling were specified to reduce the risk of overheating. The exposed ceilings were meant to moderate indoor temperatures despite

					lightweight external envelop specified.
Pre-construction	Tender specification required all air supply and extract fans to be inverter-driven. The control module software was specified to change the speed of fans manually through panel switch operation, *or* automatically on an event-driven basis in response to carbon dioxide variations.	The original designers who were involved up to RIBA Stage D, were not involved in the final design and value engineering process due to the Design & Build nature of the contract. This caused a number of problems. For example, poor coordination of services in final design led to the thermostats being installed at high level.	There is no evidence that the technical risks of the biomass-boiler were taken into account to ensure its performance in-use will be consistent with the assumptions made in the regulatory calculations. The back-up gas-fired boilers had been sized to meet 100% of heating demand.	The motorised vents were critical in achieving effective natural cross-ventilation but were not protected from value engineering. The cladding sub-contractor was novated by the main contractor to procure vents and motors. Changing final system specification meant actuators were not fully responsive to the BMS signals.	There is no evidence that the operational risks of the combination of mechanical ventilation, lightweight external envelope, and centralised cooling for server rooms were taken into account. The value engineering process led to the specification of one small operable window per classroom only.
Construction and hand-over	There is no evidence that carbon dioxide sensors were installed in classrooms or extract ductwork to modulate supply and extract fans. It appears that an automated control option was not installed. However, the final regulatory calculations assumed an effective demand-controlled ventilation strategy. Commissioning results revealed the actual specific fan power for main AHUs was significantly higher than the statutory limit. No	The solar thermal system had not been commissioned properly. As the system was perceived not critical to building handover, the commissioning was meant to take place after handover. However, this did not happen until the post-occupancy evaluation identified the problem. Room thermostats in the majority of teaching spaces were locked in position or located at high level as no conduit was installed within the wall partitioning.	The as-built drawings do not point to any significant change from the design stages. There is no evidence that the automated lighting control and the metering strategy were effectively commissioned. The commissioning results reveal the actual Specific Fan Power was 25% higher than the design intent. No corrective action was taken.	The motorised vents had been designed to respond to carbon dioxide concentrations in classrooms and summer temperature control settings. In practice, all motorised vents were controlled based on carbon dioxide levels only. There is no evidence that hydraulic isolation of HVAC zones was included in commissioning. The commissioning results reveal actual Specific Fan Power was 40% higher than the	The as-built documentations do not point to any significant change from the design stages apart from minor changes to radiator and fan coil schedules. The operation and maintenance manuals confirm the supply fans must be able to respond to carbon dioxide levels and ramp up from 50% of maximum supply to full load based on occupancy levels. However, there is no evidence that the interaction between fan inverters and carbon dioxide sensors were

	corrective action was taken.	There is no evidence that the metering strategy, lighting controls, and atrium motorised vents, were commissioned according to the design intent.		design intent. No corrective action was taken.	checked at the commissioning stage.
Performance in-use	The post-occupancy evaluation revealed that fan inverters were not enabled for demand-controlled ventilation, and fans provide 100% fresh air regardless of actual demand. Specific Fan Powers were higher than statutory limits. This problem in practice was exacerbated by poor system maintenance that manifests itself in dirty panel and bag filters. These problems were compounded by the ventilation schedule setup in the BMS: the air handling plant provided full fresh air to the whole building during out-of-hours use and weekends, with severe implications for ventilation energy and space heating.	Boilers were running in non-condensing mode. The Solar thermal system did not contribute to building hot water use in the first two years of operation. A number of meters on the low voltage panel were not functional. Contrary to the design intent and the metering strategy, the meters were not linked to the BMS. Users had no effective control over temperature set points as the thermostats were either locked in position or not accessible. The atrium motorised vents were not responsive to temperature.	The biomass boiler did not run properly since commissioning and experienced multiple parts failure. The maintenance cost and higher cost of wood pellets compared to natural gas meant the management decided to switch to gas-boilers. This severely compromised the operational carbon dioxide emissions. The post-occupancy evaluation revealed time delay settings of the PIR sensors were often in excess of what was expected. The sensors in classrooms were also too sensitive to movements in adjacent corridors. A number of meters were not functional and linked to BMS at the start of the POE.	The post-occupancy evaluation identified malfunctioning motorised vents stuck open in winter. Open transit doors and malfunctioning motorised vents led the maintenance contractor to increase the set point for the low temperature hot water to 80ºC to overcome excessive heat loss. The GSHPs are not operational at this temperature, and therefore back-up boilers take the lead. GSHP contribution to heating, measured during the post-occupancy evaluation, was less than 3% which is significantly lower than the design intent. Individual HVAC zones cannot be completely isolated when required.	There was no effective demand-controlled ventilation as the fan inverts were not responsive to the carbon dioxide sensors installed in the extract duct works. No effective dead-band between heating and cooling systems led to conflict between the respective terminals where two-pipe fan coil units and wet radiators were installed. Poor control of purge ventilation and night-time cooling meant the systems were operating overnight throughout the year. Central chillers providing cooling to server room and data hub rooms led to inefficient operation and cooling of other spaces.

8.8. Summary

A review of the outcomes of the regulatory energy performance calculations and the available input data point to inaccuracies that may compromise regulatory calculations. Comparing the measured total performance of the case studies with the outcome of these calculations revealed discrepancies in the region of 80-120%. The extent of these discrepancies raises questions about the relevance of the regulatory calculation to real performance. However, it was demonstrated that the regulatory calculations of these buildings are comparable to the 10th or 25th percentile of the DEC dataset for secondary schools. Furthermore, dynamic simulation confirmed that the bulk of the difference between measured performance and calculated performance in the worst and best performing case studies can be quantitatively attributed to specific procurement and operational issues uncovered during the post-occupancy evaluations. It can therefore be concluded that the outcomes of regulatory calculations can be used as benchmarks for performance in-use provided actual operating conditions are not too dissimilar to the standardised conditions assumed in the NCM.

Mechanical ventilation was a major determinant of energy performance in the case studies. A review of the as-built specific fan powers showed the efficiency of air distribution systems in all case studies was worse than design intent. Furthermore, demand-controlled ventilation was not effectively implemented in two case studies with severe implications for auxiliary energy and further repercussions for heating energy. Following the tree-diagram approach of CIBSE TM22, it was demonstrated how shortcomings in the procurement and operation of a mechanical ventilation system were compounded to deliver a measured performance that is almost tenfold the design intent. This shows the importance of identifying and mitigating the risks associated with energy efficiency measures.

Comparing the U values reported by the architects in the Building Performance Evaluation programme and the U values used in the regulatory calculations points to the significance of attention to construction details in calculating area-weighted average U values. It is also important to ensure changes in fabric specification are reflected in the energy model.

A review of the origins of procurement issues identified further improvement opportunities including protection of key energy efficiency measures from value engineering, effective procurement and representation of LZC systems in energy models, closer collaboration between energy modellers and construction teams, and enhanced commissioning.

It is suggested that a robust measurement and verification framework to link energy performance in-use to as-built calculations would be required to drive these process improvements and help deliver low carbon buildings in practice. This will be further explored in the next Chapter.

9. A Measurement and Verification Framework for the EPBD

9.1. Introduction

This Chapter presents a framework for Measurement and Verification (M&V) of energy performance in-use in reference to the regulatory calculations carried out in accordance with the EPBD. The aim of this framework is to separate the performance gap related to building procurement from the performance gap related to building operation.

If the procurement component of the performance gap is separated from the operational component with reasonable accuracy, construction practitioners and building operators will have a better understanding of the performance gap and its root causes. Furthermore, responsibilities to address the performance gap can be defined clearly and concrete actions can be taken by various stakeholders to narrow it. This framework therefore may help resolve the question of ownership of the performance gap which currently is ill-defined and has led to confusions over the definition of the term, its true extent, and ways to tackle it.

First a description of the framework is provided. Next, a demonstration case will be presented using two protocols that could be applied under this framework. Finally, the implications of using this framework and the respective protocols will be discussed with special focus on the drivers for and barriers against using this framework for measurement and verification.

The M&V framework is in principle applicable to all energy performance calculations carried out under the EPBD. However, the discussion presented in this Chapter and the demonstration case are based on the implementation of the EPBD in England.

9.2. The Measurement and Verification framework

The building performance evaluations and evidence collated from the case studies reveal a pattern in building procurement and operation that leads to the performance gap: The Building Regulations energy performance compliance calculations carried out on completion of buildings often do not reflect all as-built details accurately. This is not consistent with the statutory requirements. However, the complexity of construction projects especially in non-domestic sector and the fragmented nature of the supply side of the construction industry mean it is very difficult to ensure all design intents have been met and confirm all as-built details with accuracy at the point of handover. There are often nascent problems that are not necessarily known at the point the 'as-built' calculations are carried out and reveal themselves after building handover. Some of these problems may compromise energy performance in-use. It is therefore reasonable to use the term 'the procurement gap' to refer to the effect of these issues. Energy performance in-use will also be affected by issues related to building operation such as occupancy pattern and behaviour, equipment used, building management regime, and possibly some special functions that were not or could not be included in the statutory calculations. There are also uncertainties and inefficiencies related to building operation under real ambient conditions that are not reflected in energy performance calculations. Combination of these factors may lead to a measured performance that is significantly higher than the performance projected by regulatory calculations. The forward path of the diagram depicted in Figure 9.1, first illustrated in Chapter 3 and reproduced here for clarity of discussion, summarises this description of the root causes of the performance gap.

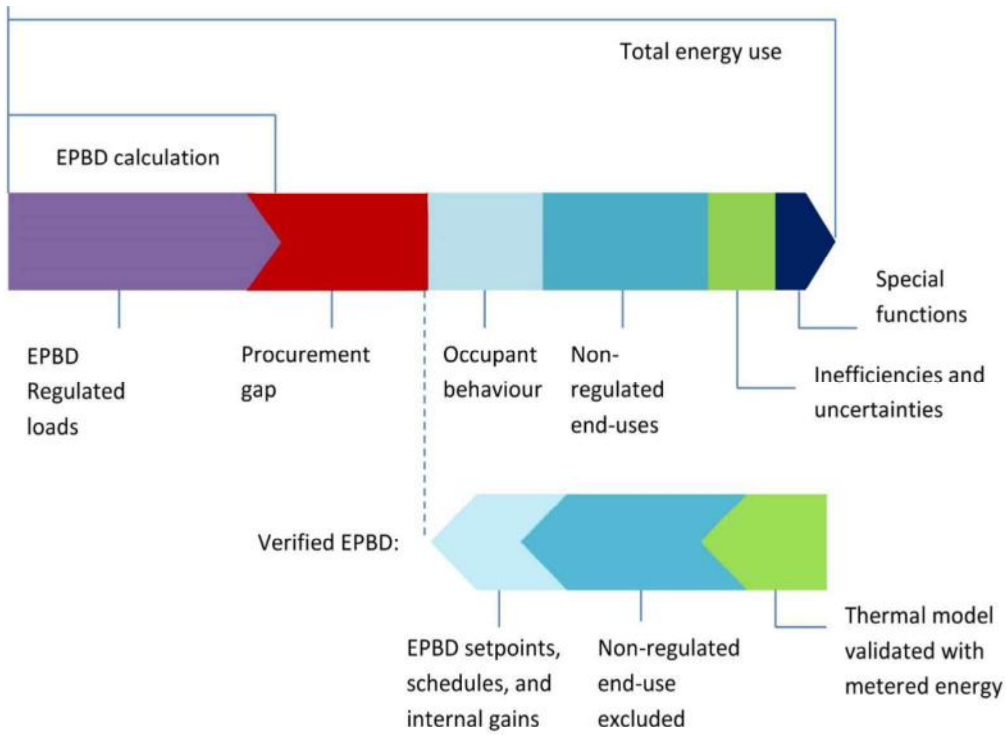


Figure 9.1. A Measurement and Verification framework for energy performance of buildings

It is useful to separate the effect of procurement issues from the gap caused by operational factors. The return path of the diagram depicted in Figure 9.1 shows how this can be done. If a computer model is developed and calibrated with measured performance, it can be reverted to the standardised conditions used in the regulatory calculations. This will neutralise the effect of occupancy and actual operating conditions, and makes it possible to compare the energy projected by a calibrated model against the original regulatory calculation under identical operating conditions. A significant discrepancy between these projections can be indicative of a procurement gap, provided both calculations use the same methodology such as the NCM and follow the same calculation route such as dynamic simulation with hourly resolution. The criterion to define ‘significant discrepancy’ can be set out by the regulator or agreed between parties in a construction contract. For example, it could be any discrepancy beyond + 5% of the projection of the original regulatory calculation.[15]

Determination of the extent of the procurement gap under standardised operating conditions in this framework is not dependent on the correct and comprehensive identification of the root causes of the performance gap, although it is expected that key issues are identified throughout the calibration process required to achieve reasonable consistency between projections of the thermal model and measured performance.

The procurement issues often will have a knock-on effect on the operational gap. For example, if the actual efficiency of an installed air distribution system is worse than what was assumed in the regulatory calculation, this issue will have a knock-on effect on performance when the operating hours of the respective air distribution system is extended by building users beyond the standardised conditions. This secondary effect of procurement issues can be investigated once the root causes are identified with the aid of the computer model. The secondary effect can therefore be quantified. However, as it would be a function of the operating conditions defined by users, its magnitude goes beyond the responsibility of building designers and contractors and therefore cannot be a basis for an environmental levy or contractual penalty imposed on the construction team.

Construction teams can be held responsible for any procurement gap under standardised conditions: they can either identify and address the root causes or pay a penalty.

If this framework is adopted by a regulatory body, the penalty could be in form of an environmental levy that would help offset the excess in CO_2 emissions over the regulatory limit by funding other carbon saving opportunities. The national CO_2 emission targets set out for various sectors including buildings ultimately reflect the requirement to control the amount of CO_2 emissions below the threshold for a high risk climate change scenario. Therefore, it is reasonable to assume an excess in energy use over the regulatory limit can disproportionately cause environmental damage. Consequently, the social cost of carbon that reflects the projected damages of future climate change can be used as the basis of such an environmental levy. This environmental levy can be worked out based on the life expectancy of the installed systems until the next major refurbishment by reference to industry guidelines such as CIBSE Guide M that can be referred to for building services.

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[15] Sensitivity analysis, similar to what is explained in 9.3.2, can be used to define the level of tolerance in a single project or more widely for various types of buildings and systems.

If, on the other hand, a penalty for any potential procurement gap is agreed by the parties involved in a construction contract, it would be payable to the project Client or withdrawn from construction teams' final payment. The respective responsibilities within a construction team will depend on the nature of the contract. For example, in a Design and Build contract the main construction contractor will be ultimately accountable for any procurement gap verified under standardised conditions. In a traditional contract in which the designers have been appointed to witness the final installations and confirm the design intents have been met, they can be held accountable. Further details in each case will have to be worked out in the contract.

This framework can also be used as a good practice measure under a voluntary Building Performance Evaluation framework such as Soft Landings. In this case, the designers and contractors engage in building fine-tuning post-handover and verify performance in-use when the steady mode of operation is achieved. They will make an attempt to identify and narrow any procurement gap and also help users have a better understanding of design intents so that operational gap can also be minimised. Currently, most Building Performance Evaluation and Post-Occupancy Evaluation frameworks used in the industry lack a robust M&V method to address the problem of the performance gap. The framework presented here may therefore be integrated into wider BPE/POE frameworks.

Practically, achieving steady mode of operation for measurement and verification may take more than one year and this may in turn require changes in contractual arrangements given that the construction team's liabilities post-handover often comes to an end after one year in non-domestic sector. However, in this respect, the proposed framework is not different than other measurement and verification frameworks such as the M&V optional credit previously defined under the LEED sustainability rating system (USGBC, 2008). The required contractual agreements therefore can be made in principle.

Finally, it is important to draw distinction between this framework and the methods used to give better prediction of performance in-use using expected or actual operating conditions such as CIBSE TM54 ((2013) and ASHRAE 90.1 (2007). There are two major differences: first, the proposed framework determines the performance gap under standardised conditions which are independent from the way operators use a building. This can pave the way to define responsibilities and tackle the problem. The other methods mentioned above make an attempt to give a more accurate account of total performance under expected/actual operating conditions. By definition, any performance gap determined by using these methods would be a function of the way a building is managed and as such cannot be a basis to hold construction teams accountable and separate responsibilities. Second, these methods do not necessarily rely on calibrated computer modelling. In fact, they are often used to project performance based on expected operating conditions and when the measured performance is not available yet. If used effectively, they are very helpful to give good indication of likely performance in-use to the construction teams and building owners/operators. However, the starting point of the proposed framework is when the steady state operation is achieved and measured performance is available. A building energy performance simulation calibrated with measured performance minimises the risk of modelling errors that are prevalent in un-calibrated modelling (Ahmad & Culp, 2006). These methods therefore have a slightly different application domain, although their underlying principles must also be used in the proposed framework to develop computer models that represent a real building with reasonable accuracy.

9.3. Demonstration of the Measurement and Verification framework

To demonstrate the proposed M&V framework, it has been applied to Building A which is the worst performing case study constructed after inception of the EPBD with serious procurement and operational issues. Two alternative protocols have been used to determine the accuracy of building energy performance simulation and their potential for wider application in the industry have also been reviewed.

9.3.1. The IPMVP protocol

The computer model developed for Building A to reflect construction issues and actual operating conditions in the previous Chapter is tested against the criteria set out by the ASHRAE Guideline 14 for monthly calibration. Subsequently, it is reverted to the standardised operating conditions following the diagram depicted in Figure 9.1 to determine the procurement gap. The calculated and measured hourly electrical demands are also compared to provide a better understanding of the strengths and limitations of the approach and the extra effort required for hourly calibration.

Monthly calibration: Figure 9.2 and Figure 9.3 show the calculated against measured monthly gas and electricity use respectively.

The measured data are based on utility bills available for 12 months and the calculated data are based on energy performance simulation. The weather data were sourced from the Met Office weather station in Woodford village, in the vicinity of the building site, to be used for simulation. However, solar radiation data were missing for two months in winter. Therefore, the CIBSE Test Reference Year weather file representing the climatic region of the building was used for simulation (Manchester TRY). The heating components of gas and electricity, derived from simulation, were weather adjusted based on actual heating degree-days experienced over the measurement period. The electricity consumption derived from modelling was also adjusted to allow for external lights and lifts.

The Coefficient of Variation of the Root Mean Square Errors and the Normalised Mean Bias Errors for gas and electricity are listed in Table 9.1 and are all within the acceptable limits set out for monthly calibration which are 15% and 5% for CVRMSE and NMBE respectively(ASHRAE, 2002).

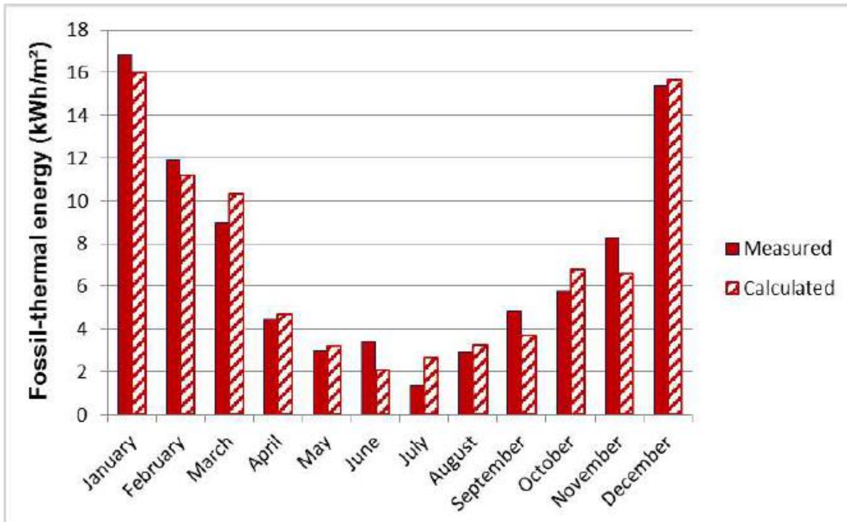

Figure 9.2. Building A monthly fossil-thermal energy use: calculated vs. measured

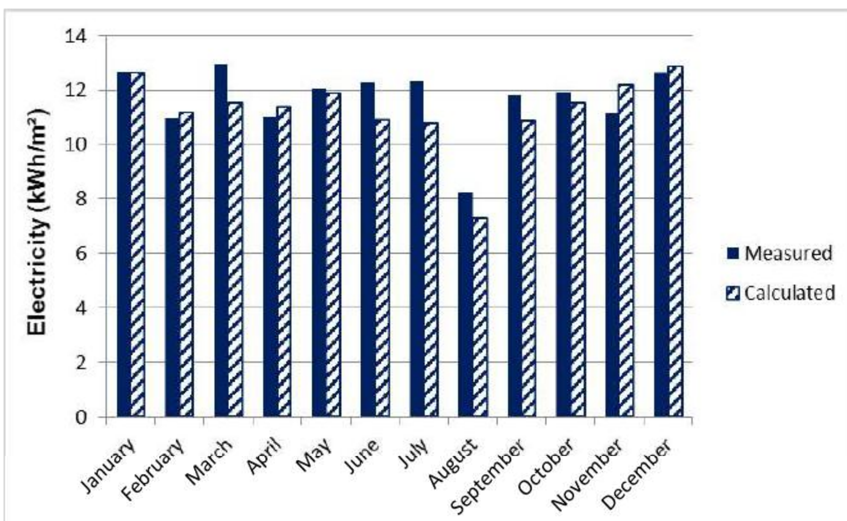

Figure 9.3. Building A monthly electricity use: calculated vs. measured

Table 9.1. Building A monthly electricity use: calculated vs. measured

Fuel	CVRMSE (%)	NMBE (%)
Natural Gas	14.4	1.4
Electricity	8.0	3.9

Calculated gas is reasonably close to the measured gas except in June and July. As the heating consumption is very low in these months, the modelling results are sensitive to slight changes in occupancy pattern which determine domestic hot water requirements. However, sensitivity to items that will be standardised for the EPBD/NCM calculations is not a major concern as long as the average error is within acceptable limits. Calculated electricity is generally very close to the measured electricity. However, the percentage of error grows in summer when the building occupancy and use are highly erratic and difficult to fully capture within the model. Again, this poses no problem for verification of the EPBD calculations as long as the overall error is within the limits set out for calibration.

The procurement and operational gaps: The outcomes of the model satisfy the criteria set out for calibration. Therefore, following the backward path of Figure 9.1, the model is reverted to the EPBD settings and conditions. This process involves removing actual small power and equipment load that are not regulated under the EPBD and replacing them with the EPBD default loads, using standard occupancy density and profile, standard heating and cooling set points, standard air flow rates for the ventilation system, and the standardised schedules of operation.

Most commercially available software for the EPBD calculations in the UK are capable of replacing actual settings with the standardised settings automatically. Therefore, once the model is calibrated based on the measured performance, following the backward path of Figure 9.1 is not time or resource intensive.

Figure 9.4 compares the annual total measured performance with the outcomes of the calibrated model, the verified EPBD calculation, and the initial EPBD calculation. The procurement and operational gaps are reported on the graph.

Comparison between the verified and intended EPBD calculations reveals that the verified auxiliary energy use associated with fans, pumps and control under the EPBD conditions is significantly higher than the intended performance. Auxiliary energy use is also the highest energy end-use in the measured performance. As explained in the previous Chapter, poor implementation of the control strategy specified for the mechanical ventilation system led to failure of demand-controlled ventilation (a procurement issue). This was in turn compounded by poor building management (an operational issue) and led to excessive auxiliary and heating energy use. This shows the knock-on effect of procurement gap on operational gap and the necessity to address it in the early stages of post-occupancy.

To assess the effect of procurement issues on operational gap, the identified root causes for the procurement gap, reported in Table 8.4 in Chapter 8, were addressed in the computer model. Figure 9.5 illustrates that addressing the root causes of the procurement gap in the case study building would not only bridge the procurement gap but also narrow the operational gap by one forth.

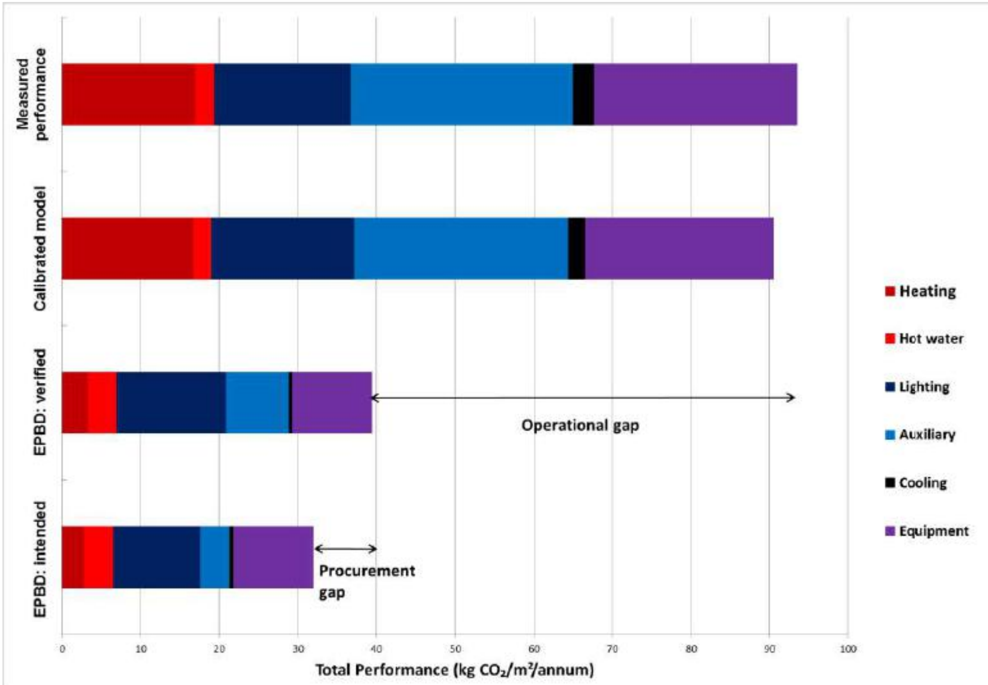

Figure 9.4. Illustration of the procurement and operational gaps in Building A (Conversion factors for gas and electricity: 0.19 and 0.55 kg CO_2/kWh respectively)

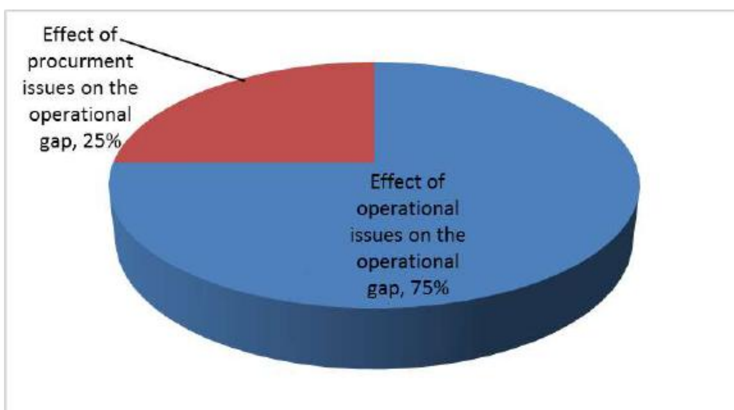

Figure 9.5. The knock-on effect of the procurement gap on the operational gap: Building A

Hourly electrical demand profiles: Figure 9.6 and Figure 9.7 show the calculated against measured electrical power demand curves for typical days in heating season and summer respectively. The measured data is based on hourly electricity data provided by the utility supplier. The calculated data is derived from the computer model and adjusted to allow for external lights and lifts. The baseline demands, peak demands, and the shape of the demand curves predicted by the model reasonably match the measured data. However, these graphs reveal that further information is required to achieve better consistency especially if a whole-building calibration method based on hourly calibration is targeted. The discrepancy between electrical demand curves is higher in the afternoon in summer as a result of transient and erratic occupancy pattern which is not fully captured in the model. For monthly calibration, on-site observations during normal occupancy hours and extracurricular activities along with the school teaching time tables and interviews with teachers were used to determine the occupancy. Using school attendance sheets (if available and reliable) or occupancy sensors can help collate data with finer resolution for hourly calibration. There is also evidence of unnecessary plant room operation in early hours of the day during summer (Figure 9.7). Depending on the level of accuracy required, appropriate sensors could be installed and data points defined within the BMS to capture detail information about building operation on an hourly basis. However, it is important to strike the right balance between calibration cost and accuracy. The analysis carried out on the case study building demonstrates monthly calibration method can achieve acceptable level of accuracy with reasonable amount of effort that is scalable for wider application in the construction industry. The monthly calibration method is also the preferred option under the IPMVP (EVO, 2012, p. 35). Using sensory equipment and other data mining techniques to capture details of occupants' behaviour and equipment use along with access to local weather data with fine resolution can achieve modelling accuracies significantly better than ASHRAE Guideline 14 limits (Lam, et al., 2014).

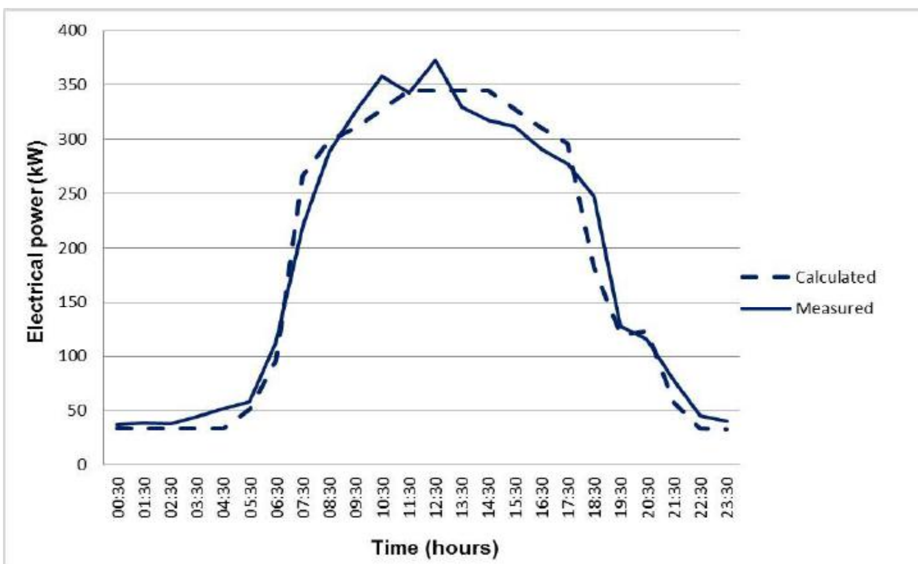

Figure 9.6. Typical hourly electrical power demand curve in heating season: Building A

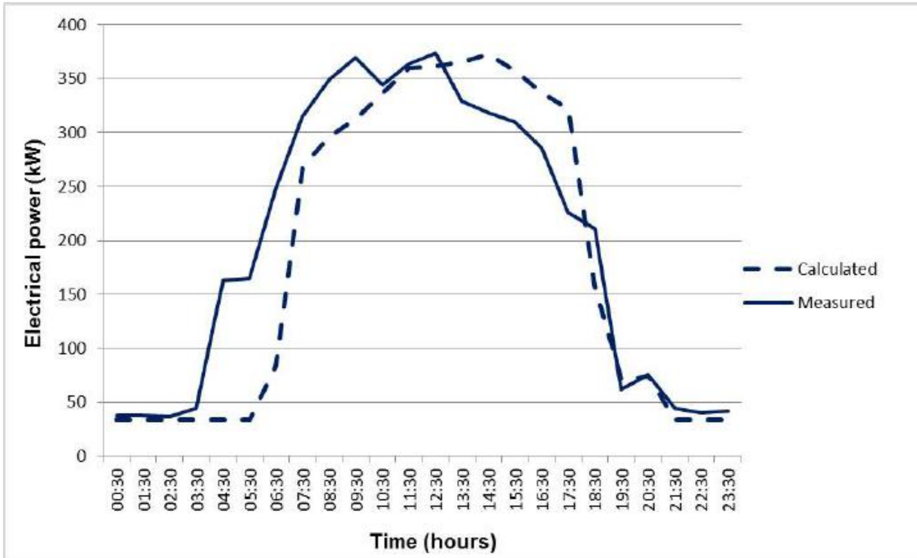

Figure 9.7. Typical hourly electrical power demand curve in summer: Building A

9.3.2. The BS EN 15603 procedure

To evaluate the effect of the uncertainties associated with input variables, a number of variables that were subject to high level of uncertainty during building performance evaluation were selected for Monte Carlo analysis. Table 9.2 includes the list of these variables, the standard deviations applied to the base values used in the IPMVP method, and the distribution profiles. These variables are related to occupant behaviour (occupancy level, infiltration, and heating set point), the efficiency of building services with high impact (heating and mechanical ventilation systems), and external envelope U values that are often subject to uncertainty as a result of construction issues and workmanship. The findings from the post-occupancy evaluation and the guidelines of BS EN 15603 were used to define the standard deviations and distribution profiles. For example, the base values for infiltration were based on pressure test results plus an estimation of infiltration caused by operable windows and vents based on the observational studies on the monitored classrooms in heating season (Chapter 6). This infiltration is directly related to occupant behaviour and is subject to high level of uncertainty. A large standard deviation is therefore applied to the base model for infiltration. The standard deviation selected for heating set point, on the other hand, is rather tight and reflects the standard deviations reported for the monitored classrooms in Building A during heating season in Chapter 6 (Table 6.1).

Table 9.2. Standard deviations and distribution profiles applied to the input variables

Variable	Standard deviation	Distribution profile
Infiltration	50%	Log normal
Occupancy	10%	Log normal
Heating set point	1 °K	Normal distribution
Heating efficiency	5%	Log normal for x and 1-x
Specific Fan Power	20%	Log normal
External wall U value	10%	Log normal
External floor U value	10%	Log normal
Roof U value	10%	Log normal
Windows U Value	10%	Log normal

The following functions available in Microsoft Excel 2013 were used to define random numbers with log normal and normal distributions:

Log Normal Distribution: LOGNORM.INV (RAND (), meanlog, sdlog)

Normal Distribution: NORM.INV (RAND (), mean, sd)

For each variable, one hundred random numbers were generated following the pertinent distribution profile and the input variables were adjusted in the base model used for the IPMVP method accordingly. Figure 9.8 illustrates the results of one hundred simulations carried out to investigate the effect of changes in input variables and their interaction on total performance. This is the minimum number of simulations prescribed for Monte Carlo analysis in BS EN 15603 (BSI, 2008, p. 53).

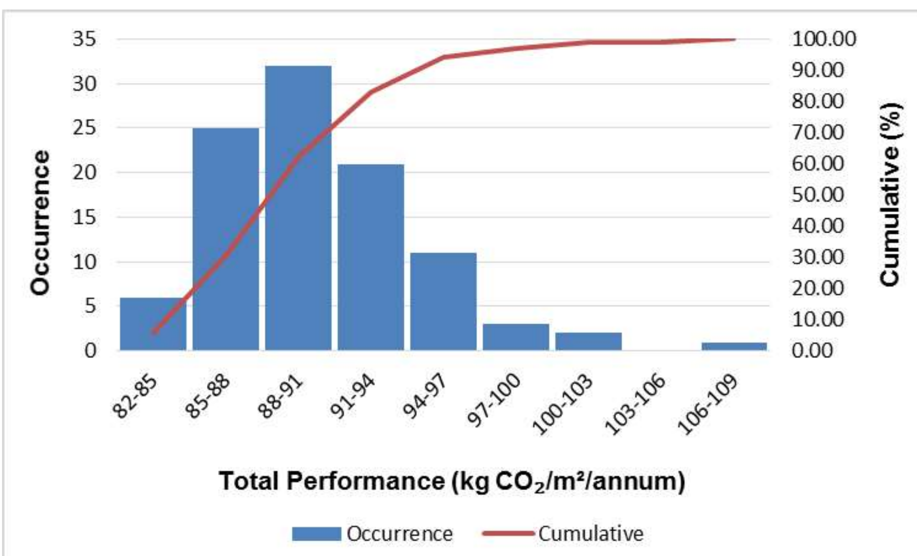

Figure 9.8. Distribution of total performance projected from one hundred simulations using the Monte-Carlo method: Building A

The mean and standard deviation of this distribution are 90.3 and 4.1 kg CO_2/m²/annum respectively. The measured and calculated total performances reported in Figure 9.4 are 93.6

and 90.7 kg CO_2/m²/annum and are both within this range. It can therefore be concluded that the base model is a reasonable representation of actual performance and could be used to derive the verified performance under the EPBD/NCM standardised conditions as presented in 9.3.1.

Monte Carlo analysis can also be used to derive confidence levels for energy performance calculations under standardised conditions and form the basis of the tolerance defined for a predicted level of energy performance in a contract. Such an analysis must take into account the uncertainties in fabric performance and the efficiency of building services under real operating conditions according to the information provided by the manufacturers or industry guidelines.

9.3.3. Review of the M&V process and the results

The IPMVP protocol and BS EN15603 procedure represent different methods of addressing modelling uncertainty. The IPMVP method adopts a normative/deterministic approach to input data and examines the accuracy and the existence of any systemic bias in outputs by applying strict criteria. The BS EN 15603, on the other hand, considers uncertainty in the input data with a more relaxed approach to outputs that entails analysis of annual performance only with no specific criteria to define reasonable consistently between measured and modelled data. The IPMVP method may be more appropriate for wider applications as it essentially uses the same method used for building energy performance simulation in the industry with robust calibration criteria. It is also a proven concept and has been used for energy efficiency finance projects under the IPMVP framework and for measurement and verification of energy under the LEED sustainability rating system.

The total measured energy performance of the demonstration case study is significantly higher than the outcomes of the regulatory calculations and the industry benchmarks. The measurement and verification plan helped differentiate the root causes for this poor performance and their effects. The single most influential factor in procurement gap is poor installation and control of the mechanical ventilation system. The underlying process issues that led to this problem were analysed in the previous Chapter.

The most influential factor related to the operational gap is the schedules of operation set for the heating and ventilation systems. Schools are seasonally occupied buildings. This means that not all building services need to serve all zones of a building at all times. The building is open to public in half term breaks and a number of teaching and admin staff may work in the building. However, the facility manager can take advantage of heating and ventilation zoning to isolate parts of building that are not used. The schedules of operation of these systems and the set points could be optimised to save energy. None of these materialised in the case study building, which led to poor energy performance.

The procurement gap under standardised operating conditions is equal to 23.5% of the initial/intended EPBD calculation performed on completion of the building. It also accounts for around 12.2% of the total performance gap. If the secondary effect of procurement issues on the operational gap is also considered, the total effects of them will amount to almost 35% of the performance gap. The remaining part of the gap is entirely related to operational issues.

Addressing the issues related to mechanical ventilation along with optimised seasonal operation of heating and ventilation systems will significantly improve the energy performance of building A.

This case study confirms the feasibility of using calibrated computer models for measurement and verification of energy performance under the EPBD framework.

A potential environmental levy can be applied to the procurement gap under standardised conditions as this component is independent of occupant behaviour and building management. Appendix 12.A1 of CIBSE Guide M (2014) estimates an indicative 20-year economic life expectancy for air handling equipment. As the procurement gap to a large extent is caused by problems associated with the air distribution system, it is reasonable to work out an environmental levy based on this life expectancy. Applying a tolerance of 5% to the initial EPBD calculation, the procurement gap under standardised conditions amounts to 74 tonnes of CO_2 per annum in Building A. The Stern review, commissioned by the UK treasury, estimated the social cost of carbon at $85 (£47) per tonne of CO_2 in 2005 prices (Stern, 2007). Consequently, if this M&V framework had been adopted, the construction team would have had the option to address the issues and demonstrate the effectiveness of any remedial work by re-verification of performance in-use, *or* be liable for an environmental levy of £70K in 2005 prices which would be around £77K in 2008 when the building was completed, assuming an annual interest rate of 3%. This levy would be around 0.4% of the construction cost for Building A.

This estimation of a potential environmental levy is significantly higher than the industry estimates for integration of the Soft Landings framework into building procurement process which is around 0.1% of construction cost. This integration may help address key procurement issues and therefore the extra cost associated with it seems reasonable if the environmental costs of any procurement gap are taken into account. If implemented effectively, a Building Performance Evaluation framework such as Soft Landings can also have significant impact on operational gap by engaging designers and contractors in fine-tuning a building post-occupancy and user training.

9.4. Notes on the readiness of the NCM for projection of performance in-use

The National Calculation Methodology was initially developed to respond to the energy performance requirements of the EPBD. The nature of whole building energy performance calculations carried out under the existing regulatory framework is based on relative performance of a building against a notional or reference building depending on the assessment type. However, there has been a shift in using NCM as the industry is moving to projection of total and absolute performance. For example, the framework developed for the Green Deal in non-domestic sector is based on the NCM. This framework in principle can be used for any refurbishment project in non-domestic sector independent of the mechanism used to finance the project. A number of changes were made under this framework to make the NCM more applicable for projection of absolute performance. The default/standardised operating conditions are now unlocked and users can *tailor* the operating conditions based on expected or real conditions. A number of *management scores* are also applied to each energy end-use to represent building maintenance and management practices. Finally, a *normalisation factor* is used to account for any remaining discrepancy between the NCM modelling outcome and measured performance. The same normalisation factor is applied after introduction of an energy efficiency measure in the model to predict its likely impact on real performance (BRE, 2012). It is notable that no limit has been defined for normalisation factor which is a tacit acknowledgement that it might be difficult to get an accurate prediction of performance in-use with the NCM even after specifying real operating conditions and applying management scores.

The framework developed for energy performance calculations under the Green Deal framework in non-domestic sector is fundamentally different than the framework presented and the methods used in this chapter. The reference to the NCM application under the Green Deal framework is only made to clarify two distinct approaches to modelling of performance in-use with far-reaching consequences. The philosophy adopted here is that an energy related shortcoming in building maintenance and management manifests itself in an input variable (e.g. HVAC operating schedules longer than required, or higher pressure drop in the air distribution system if air filters are not cleaned/replaced regularly). It is therefore *a priori* condition applied to energy performance simulation, not *a posteriori* factor applied to the results in form of so-called management scores. Furthermore, there must be a reasonable consistency between the outcomes of a simulation and measured performance. An unbounded and unexplained normalisation factor is not sufficient if the intent is to derive an accurate model that will form the basis of important decisions with financial implications.

These methodological issues stem from the relativist origin of the NCM and any attempt to use the NCM for projection of absolute performance in-use must take into account potential limitations of the methodology. Notably, the energy performance simulations carried out for the purpose of this dissertation point to a number of improvement opportunities that can be addressed in the NCM methodology or considered by users when using the NCM:

- **Performance curves:** the seasonal efficiencies used for building services in the NCM follow the definitions provided in building services compliance guides for regulatory purposes (CLG, 2006), (HM Government, 2013). For example, seasonal efficiency of boilers is defined based on a two point equation that only considers gross boiler efficiency at 30% and 100% loads (HM Government, 2013, p. 16). It is up to the user to use this equation and define the correct seasonal efficiency in the NCM model. However, calculation methodologies that target performance in-use provide users with the opportunity to define multi point performance curves to dynamically adjust efficiency based on the calculated load and the efficiency data provided by manufacturer. The same principle is applicable to other building services such as chiller efficiencies, fan performance curves, etc. The simplified method used in the NCM limits its ability to approach measured performance.
- **Pump energy use:** The NCM uses default and fixed pump power densities regardless of the length of the heating index run, actual specification, and building specific context. This can lead to large errors in projecting auxiliary energy. For example, maximum pump power density assumed in the NCM where both Low Temperature Hot Water and Chilled Water loops are present with variable speed pumping is 1.5 W/m² (CLG, 2011, p. 83). The installed pump power density for the heating and chilled water systems in Building A was 6.9 W/m² including the pumps associated with the vertical borehole closed-loop GSHP system. Pump energy allowed for in the NCM calculations performed on the case studies were systematically and significantly lower than the measured performance.
- **Demand-controlled ventilation:** The algorithm underpinning demand-controlled ventilation strategy in the NCM assumes a linear relation between fan air flow and power (CLG, 2011, p. 85). However, the fan affinity laws hold that fan power is proportional to the cube of its speed and air flow. While the cube law offers an ideal theoretical relation that does not take into account operational losses, there are a number of empirical equations that reflect fan power variation against its speed with reasonable accuracy, including the empirical equation offered by ASHRAE Standard

90.1 (2007) and presented in Chapter 3 (equation 10). It should also be noted that the minimum airflow allowed in the NCM for demand-controlled ventilation based on gas sensor is 62% of the maximum airflow (CLG, 2011, p. 68). However, Carbon Trust recommends airflows as low as 30% of the maximum airflow to take advantage of the huge saving potential of variable speed fans (Carbon Trust, 2011, p. 11). The difference between the linear equation used in the NCM and more accurate non-linear equations would be even larger at lower speeds. This can seriously compromise the accuracy of the NCM to estimate savings achievable from a well-designed demand-controlled ventilation system (Figure 9.9). It is notable that demand-controlled ventilation was a measure qualified under the Green Deal framework for non-domestic sector and yet the NCM systematically underestimates the saving potential of this measure. This is indicative of the shortcomings of the NCM that cannot be addressed with the adjustments applied in the version updated for the Green Deal or other similar energy efficiency finance projects.

A hybrid TM22-NCM approach was adopted to address the NCM limitations related to auxiliary energy use in the simulations performed for this dissertation.

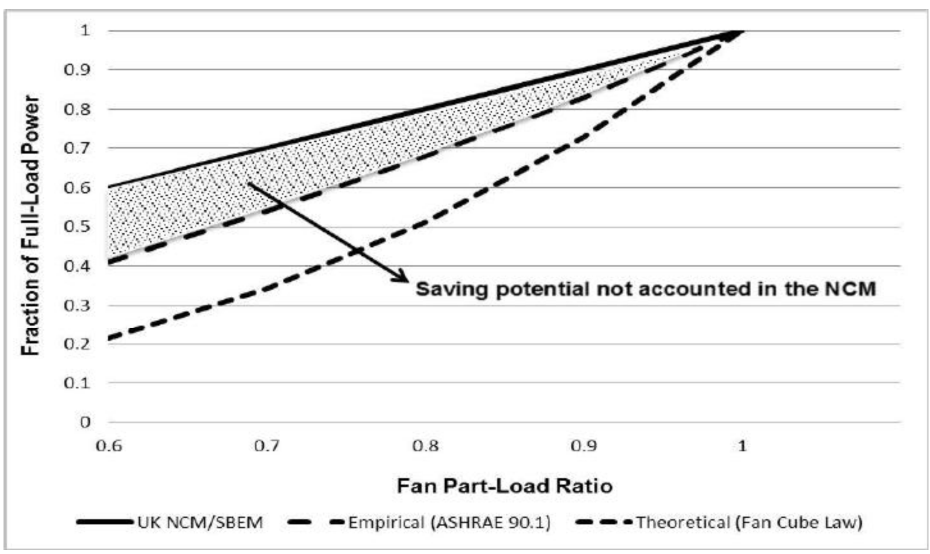

Figure 9.9. Demand-controlled ventilation saving potential not accounted in the NCM

In addition to frameworks such as the Green Deal, there are other drivers for projection of absolute energy performance. For example, the EU Energy Efficiency Directive calls for adoption of Energy Performance Contracting as an effective measure to improve efficiency of the existing building stock. To this end, the Department of Energy and Climate Change has released a model contract for energy performance contracts that includes measurement and verification requirements with explicit reference to IPMVP as an appropriate M&V protocol (DECC, 2015). Whole-building simulation may be used under these contracts to establish robust baselines for performance and for building diagnostics. There is scope for a thorough review and update of the NCM methodology to ensure it is robust for projection of absolute performance if it is to be used for energy efficiency finance and performance contracting.

9.5. From absolute performance to energy quotients: an alternative representation of the performance gap

So far the verified performance of the demonstration case study was presented in absolute format. Energy Performance Certificates and Display Energy Certificates can be viewed as energy quotients. These quotients are produced by dividing the absolute regulatory and measured performance by the standard performance and typical benchmark respectively and then multiplied by scaling factors. The absolute performances presented in this Chapter can thus be converted to energy quotients that may be more powerful in illustrating the effects of procurement and operational factors.

Figure 9.10 illustrates the formal EPC lodged for Building A on completion of the building against the verified EPC which is derived from the verified standardised performance. The ratings show the decline in performance related to procurement issues.

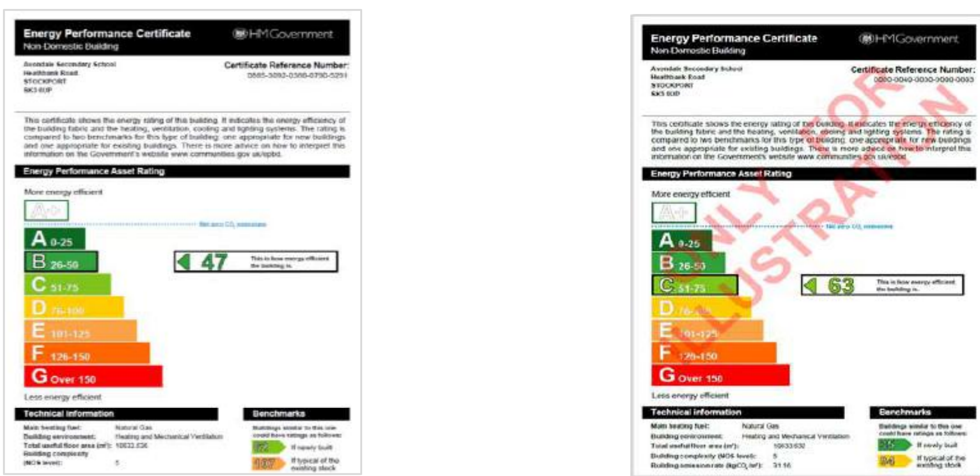

Figure 9.10. *Intended* EPC (left) against *verified* EPC: the procurement gap in Building A

As EPCs and DECs are not directly comparable, it is reasonable to define an expected DEC based on the verified standardised performance with an allowance for equipment (based on NCM values) and miscellaneous loads not taken into account in modelling. The actual DEC is however based on the measured performance. Figure 9.11 illustrates these quotients. The difference between actual and expected DEC is indicative of the operational gap that also includes the knock-on effect of procurement issues under actual operating conditions.

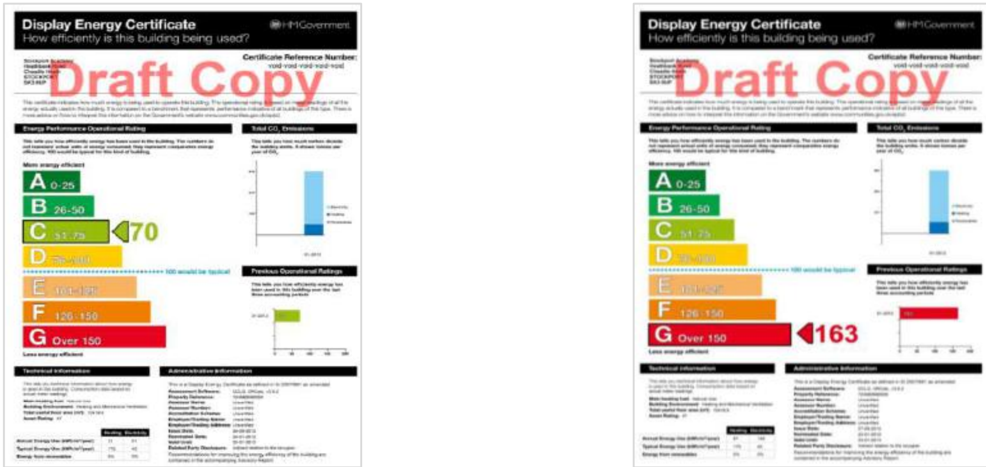

Figure 9.11. *Expected* DEC (left) against *Actual* DEC: the operational gap in Building A

This two-step representation of the performance gap in form of energy quotients can make it easier to communicate it.

As buildings with good asset rating (EPC) do not necessarily perform well in practice, people look for other key performance indicators to assess energy performance. There is a niche trend in the industry to set out a target DEC rating in the project brief, for example DEC A or DEC B. This model may work well when the project Client is also the building operator or has effective control over operating conditions. However, there are often major differences in the way a building is operated and the assumptions made at design stages. Too much emphasis on maintaining certain environmental conditions to meet energy targets may also have unintended consequences for the indoor environmental quality and user satisfaction. DEC targets are good yardsticks to guide the construction team throughout a project and make them think about potential risks that might compromise operational performance. However, it is practically very difficult to hold construction teams accountable for a specific DEC target.

The concept of *verified EPC* which represents an asset rating that has been verified with performance in-use would be a more practical target for construction teams. Verified EPCs can also be effective for non-domestic rental market in which the existing EPCs have not yet made a real impact. DECs are also not applicable or quite tailored for most organisations in private sector. Furthermore, a good DEC certificate based on a tenancy with specific operation regime is no guarantee of a good level of energy performance for a prospective tenant. Tenants will have different functional requirements. What they care for is a robust asset rating to assure them they are getting value for money as far as energy efficiency is concerned. This can make the concept of *verified EPC* attractive to Landlords and has the potential to become a market standard for truly energy efficient buildings.

The proposition of this thesis is that the boundary between asset rating and operational rating must not be blurred. This will enable a better understanding of the performance gap and clear definition of responsibilities. The two-step quotient-based representation presented here can be a powerful and effective illustration of the performance gap for building practitioners.

9.6. Drivers for and barriers against Measurement and Verification

The Energy Performance of Buildings Directive has reshaped the energy policy landscape in the EU Member States. However, regulatory frameworks that are based on un-calibrated modelling may hinder the EU countries in achieving their ambitious energy efficiency targets.

The cornerstone of the framework proposed in this Chapter is to integrate a measurement and verification plan into the EPBD to ensure measured energy performance is consistent with the intended performance under identical operating conditions. The enablers for successful implementation of this framework are:

- Growing awareness of the energy performance gap (credibility gap) and necessity to address it,
- The existing body of energy assessors trained for building performance simulation that is subject to ever stricter quality audits imposed by the EPBD and its recast through the certification schemes in the EU Member States.
- Possibility of using the existing methods and tools with minor adjustment for measurement and verification,
- Cost effectiveness of the scheme given that computer models are already being used for whole-building performance calculation of new buildings and major renovations. Updating these models after building handover and when steady mode of operation is achieved could be done with reasonable resources.
- Measurement & Verification of energy performance post-occupancy has been used under the LEED sustainability rating system and the Energy Commitment Agreement protocol for commercial buildings under the Australian NABERS system (USGBC, 2007), (NSW Office of Environment and Heritage, 2011). Total energy performance is calculated based on *predicted/expected operating conditions* under these systems. The framework presented in this paper makes it possible to use a measurement and verification plan under the EPBD *standardised/default operating conditions*.

The key question is therefore not whether it is feasible to integrate an M&V framework into the EPBD. It is whether this must be imposed as a mandatory requirement or best left to the market drivers. The initial theory formulated in Chapter 3 after a review of the relevant literature and preliminary evidence was as follows:

The current regulatory framework for energy performance of new buildings and major renovations is not fit for delivering the energy performance improvements required in buildings. It may also have unintended consequences for wider environmental performance of buildings. It is essential to extend the regulatory requirements related to energy beyond the point of building handover and use an appropriate measurement and verification framework to verify the performance in-use in reference to the regulatory requirements.

Table 9.3 summarises the arguments in support of this theory and the counter-arguments developed based on the evidence collated from the case studies.

Overall, the arguments in support of M&V that can withstand the falsification principle point towards market drivers rather than regulatory requirement. The costs especially where Clients do not have long-term interest in building energy performance, the perceived complexity, and the potential unintended consequences are among the key barriers against making M&V a mandatory requirement. A regulatory requirement to meet energy targets may impede much needed collaboration between the construction teams and building users. This collaboration is critical to gain a better understanding of performance and narrow the operational gap in addition to procurement gap. It is therefore reasonable to follow a graduated response and carefully examine the results where M&V is implemented. If the concept is proven and leads to tangible energy performance improvements and wider environmental benefits, there may be a case to integrate it into the EPBD. Successful implementation of M&V under voluntary and market driven initiatives can lead to more transparency and collaboration among the players, enhancement of the existing methods and tools, and development of the required expertise across construction supply chains, all of which can create the right environment to move towards M&V as a matter of course in future.

It is envisaged that the perceived complexity of the M&V process may be used as an argument against it. It is helpful to put any added complexity in the context of the current Building Regulations using an example to have a better understanding of the potential benefits of an effective M&V framework: design optimism about the contribution of LZC systems where supplementary and more carbon-intensive systems are specified was highlighted in the previous Chapter. This has not gone unnoticed in the latest edition of Part L. It is now a requirement to use a weighted average CO_2 emission factor when a biomass boiler is supplemented by a gas-fired boiler. The energy performance submissions to building control bodies must be accompanied by a report, signed by a suitably qualified professional, detailing how the combined emission factor has been derived (HM Government, 2013, p. 6). This is yet another layer of complexity added to the requirements set out within an input-oriented energy performance assessment framework to catch up with its unintended consequences. An alternative solution would be to use an output-oriented framework which targets the measured performance as a key performance indicator instead of relying on submission of several reports and input data that often cannot be practically assessed. An effective M&V framework can therefore replace a number of existing requirements and thereby reduce the complexity and bureaucracy of the process.

Overall, in short term, the best vehicles for the proposed M&V framework are the voluntary building performance evaluation frameworks such as Soft Landings and sustainability rating systems such as BREEAM that can endorse M&V as an optional credit. The BREEAM energy credits are currently based on standardised calculations and therefore an M&V credit that follows the framework presented in this Chapter can be introduced to ensure the measured performance is in line with the calculated performance.

In longer term, and if the concept is further tested and proven under voluntary initiatives, there is scope to integrate it into the Building Regulations as an alternative route of compliance with fewer submission requirements to building control bodies before building completion. This can be planned in such a way to ensure that M&V does not unduly add to project costs and complexity, but provides the Clients and the construction teams with a separate route for demonstrating compliance with the regulatory requirements within an output-oriented assessment framework.

Figure 9.12 shows a process view of measurement and verification and how it could be integrated into the plan of works for a construction project.

Table 9.3. Emerging themes from the case studies and supportive arguments for and counter arguments against mandatory M&V

Theme	Supportive Argument	Counter argument
The extent of the performance gap	Significant discrepancies in the region of 80-120% were uncovered between performance in-use and 'as-built' calculations in the case studies.	While a number of procurement issues were identified in the case studies, the outcomes of dynamic simulations post-occupancy show the operational factors such as HVAC schedules and building management are far more influential and outweigh the effect of procurement issues. The demonstration case shows the procurement gap accounts for merely 12% of total performance gap.
Effects of procurement issues on operation	Procurement issues have a knock-on effect on the operational performance gap as well. In the demonstration case, 35% of total performance gap is related to the procurement issues if both direct and indirect effects of the procurement issues are taken into account.	This is correct. However, this was the worst performing case study with serious procurement issues. Even so, 65% of total performance gap is caused by operational issues that can be tackled more cost-effectively without the burden of the proposed M&V framework as a new regulatory requirement.
An output-oriented assessment framework is required.	The evidence from post-occupancy evaluations shows it is practically impossible for building control bodies or indeed any single party to verify the accuracy of 'as-built' regulatory calculations given the number of variables involved and the complexity of most construction projects in the non-domestic sector. An output-oriented framework is required to ensure the environmental benefits are delivered in practice. This can in turn drive process improvements that address the endemic procurement problems observed in the industry.	An output-oriented assessment framework may be more effective for energy performance than the status quo. However, it would also be prone to errors, miscalculations and in the extreme cases unscrupulous practices. In the end, it is about the cost and benefits. Imposing a regulatory requirement for M&V may add to the cost of construction projects and complexity of contracts. Furthermore, there is yet no conclusive evidence that it can bring the perceived environmental benefits. If the concept is proven in the industry, it may then be introduced as an alternative compliance route in the Building Regulations.
Educational benefits of M&V for building users	The M&V framework requires building fine-tuning in the early stages of post-occupancy to achieve performance targets. This can help building users better understand design intents and follow good practice building management and system maintenance. The educational benefits of having designers and contractors on board after building handover can help narrow the operational gap as well as the procurement gap.	A mandatory/regulatory requirement for M&V may erode potential indirect benefits derived from collaboration between the construction teams and building users. These improvements are best achieved under a voluntary initiative. Most designers and contractors had reservations to share their models and assumptions even for the purpose of this research programme. With this background, it is perhaps not practical to impose a new regulatory requirement for M&V and at the same time expect openness and transparency from the construction teams.

Costs of the proposed M&V framework	The industry estimation for cost of Soft Landings in a typical project is around 0.1% of the construction costs. A lot of information required for M&V are also required for Soft Landings. There is a case for integration of the proposed M&V framework into the Soft Landings framework at little or no extra cost especially where M&V is integrated into the project at the outset, the required data points are defined in the BMS, and the same thermal model developed throughout the project is used for M&V. Industry trends such as Building Information Modelling (BIM) and advancement of monitoring platforms reinforce cost-effective implementation of M&V and its integration into a building optimisation programme.	There is a case for voluntary adoption of the proposed M&V framework. However, only Clients who have an interest in life-cycle performance of their buildings such as Landlord operators would be able to justify the extra cost of implementing such a framework on the grounds of expected savings. Clients with shorter term perspectives such as those with speculative developments or in rental market may be less enthusiastic about M&V unless prospective building users demand it. The success of the Energy Star programme in the US shows buildings with verified performance in-use might be able to command a premium in the market (RICS, 2009). This must be tested with a robust M&V framework in the context of the UK.
Unintended consequences of the current regulatory framework	The unintended consequences of energy strategies must also be taken into account. Poor system design and commissioning in Building E led to extreme temperatures recorded in technical measurements and reported by BUS respondents. Poor system maintenance of two mechanically ventilated buildings (Buildings A and E) led to high CO_2 concentrations in parts of these buildings. Value engineering process and basic commissioning also compromised buildings' resilience as in the case of installed motorised vents that were not responsive to temperature. An M&V framework provides the opportunity to identify and address these issues after building handover. It can also make construction teams more cautious about protecting key determinants of energy performance during value engineering process.	A mandatory M&V framework may address some of these issues and help improve building resilience. However, the evidence from case studies do not point to a serious problem that has severely affected performance beyond design and guideline limits. Thermal comfort conditions in Building E were worse than expected. However, based on the respective criteria, the building did not overheat. The maximum CO_2 concentration in the spaces with failed mechanical ventilation were around 2,000 ppm which is significantly less than the 5,000 upper limit prescribed by BB101, and the average concentrations were not worse than naturally ventilated case studies. It is difficult to justify a mandatory M&V framework based on this evidence. Whether M&V can help to protect energy efficiency measures from value engineering is not proven and must be tested before moving towards mandatory M&V.
Conclusion	The current regulatory framework for energy performance of new buildings and major renovations is not sufficient for delivering the energy performance improvements required in buildings in practice. Some improvements in energy performance are expected if the regulatory requirements are extended beyond the point of handover to verify performance in-use. However, the evidence points to the huge impact of operational issues and the intertwined nature of major procurement and operational problems. Therefore, a concerted action from construction teams and building users is required to optimise energy performance. Making measurement and verification of performance in-use mandatory with possible penalties or environmental levies imposed on players may impede the required collaboration and cause unintended consequences for energy and environmental performance of buildings. In short term, voluntary market-driven building performance evaluation initiatives that entail robust measurement and verification frameworks in reference to the design stages or as-built calculations are best suited to engage all stakeholders in performance improvements. If the concept is proven in the industry, there may also be an opportunity to integrate it into the Building Regulations as an alternative compliance route in future. There is a strong case to offer a robust measurement and verification framework to Landlord operators of new buildings and major refurbishments, and verified Energy Performance Certificates to the rental market in non-domestic sector. Verified performance can bring confidence to the market and encourage further investments in energy efficiency that can perpetuate a virtuous cycle of improvement.	

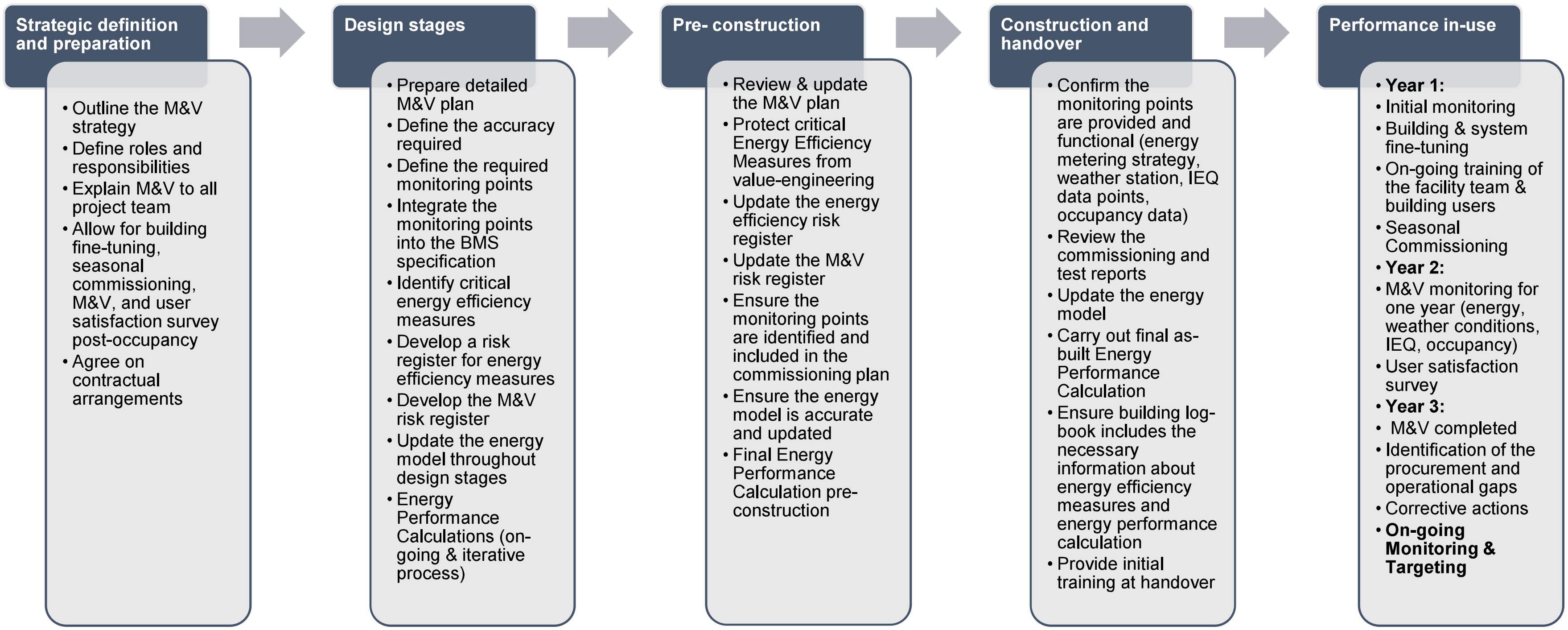

Figure 9.12. The Measurement & Verification process

9.7. Summary

This Chapter proposed a framework for Measurement and Verification of energy performance in-use in reference to the regulatory calculations performed in accordance with the EPBD. A demonstration case based on the UK Building Regulations was also presented. It was demonstrated how the effects of procurement and operational issues could be separated and quantified. This enables a clear definition of various components of the performance gap and the responsibilities of construction teams and building operators. It is suggested that verification of performance in-use and involvement of construction teams in building fine-tuning can address key procurement issues and bring wider educational benefits that lead to improvements in building operation. However, these wider benefits can best be achieved if construction teams and building operators are engaged in a concerted action. Making measurement and verification a regulatory requirement may impede this collaboration before the concept is well established in the industry. It may also add to the cost and complexity of projects which will not be justified where project clients do not have a stake in the long-term performance of their buildings. Therefore, a graduated approach to implementation of M&V is suggested. Voluntary and market driven initiatives such as Soft Landings can be used to assess the effectiveness of the proposed measurement and verification framework in the short term. Once the concept is proven in the industry through voluntary initiatives, there is scope to integrate M&V into the Building Regulations as an alternative compliance route within an output-oriented assessment framework that entails less paper work and bureaucracy compared with the existing regulatory framework.

It was demonstrated how the performance gap can be represented using building energy quotients under the existing certification schemes in England. The concept of verified EPC can be attractive to the Landlord and tenants in non-domestic rental market as a means to verify a building's asset rating with measured performance. This can help increase customer confidence and encourage further investment in energy efficiency.

Finally, the building energy performance simulations carried out on the case studies point to a number of limitations and improvement opportunities in the National Calculation Methodology. It is necessary to consider these limitations and improve the NCM to support the policy and market drivers for projection of absolute performance in-use exemplified by the drive for energy efficiency finance and energy performance contracting.

10. Conclusions

The Engineering Doctorate programme that underpinned this dissertation led to amalgamation and documentation of data related to energy performance, various aspects of the indoor environmental quality, and Building Use Studies for five educational building. This amount of data is relatively scarce in the education sector and more widely in non-domestic sector; most studies are focused on one aspect of building performance for example energy performance *or* environmental quality. This study therefore complements other studies that made an attempt to collate similar data and may lead to a better understanding of the holistic performance of schools.

This Chapter provides a summary of the major findings of the Engineering Doctorate programme. First, major findings are reviewed under three categories: energy performance, indoor environmental quality, and building users' satisfaction. Where the findings are relevant to more than one category and reflect the interdependencies between these categories, this is explicitly acknowledged in the text by explaining the relevance. Next, the main conclusion of the programme will be discussed in reference to the theory and the rival theory postulated in Chapter 3. Finally, a number of recommendations for future work in this field are proposed.

10.1. Major findings of the Engineering Doctorate programme

10.1.1. Energy performance

Analysis of the operational performance of five educational buildings procured under the Building Schools for the Future (BSF) programme along with detailed review of their design and as-built documentation led to the following findings:

- In terms of fossil-thermal energy use, only two case studies performed better than the 25th percentile of the DEC dataset for secondary schools. Nonetheless, there were opportunities to save considerable amount of fossil-thermal energy in both buildings. This shows good practice benchmarks derived from the operational data available for existing buildings do not necessarily represent the true potential of new buildings and must be applied with caution. Better benchmarks or baselines that consider the building context are required to assess operational performance.
  Another two case studies fell between the 25th percentile and the median of the DEC dataset. The worst performing case study had a total fossil-thermal performance which was 29% worse than the median of the DEC dataset and 4% worse than the CIBSE TM46 benchmark for schools and seasonal public buildings, a benchmark that is meant to represent the median of the existing building stock.

- As for electricity use, all case studies performed worse than good practice and typical benchmarks and are among the worst 20% of existing secondary schools. Typically, more than half the electricity use in these buildings was consumed by building services. Furthermore, around half of the electricity use in these buildings was consumed outside normal occupancy hours. This points to a great energy saving potential in new educational buildings.
- Optimising the operational schedules set up for building services can save energy without compromising the indoor environmental quality during occupancy hours. It is also important to use building services' zoning arrangements to isolate parts of a building that are not occupied. Facilities managers or maintenance contractors tend to specify operational schedules that cover all potential scenarios and don't require change. This often leads to significant waste of energy to condition unoccupied spaces. Optimum space-time utilisation is the key to save energy in buildings with seasonal operation and different occupancy patterns especially during out-of-hours use.
- The financial data available for one of the case studies show the cost of energy is around 3% of total annual expenditure of the school compared to 83% direct and indirect cost of employees. The school management in all case studies were not proactive in identifying energy saving opportunities and following a structured monitoring and targeting plan. Energy performance contracting can be a route to create economies of scale for external bodies such as Energy Service Companies (ESCOs) by aggregating a number of buildings for energy management. The energy saving potential uncovered in the case studies suggest this model can yield significant savings in educational buildings.
- The building log books for most case studies did not contain any information about predicted energy performance of the buildings and breakdown of energy use. Only one building log book contained information about the predicted total performance with no mention of the underlying assumptions or breakdown of energy end-uses.
- The stringent CO_2 emission targets set out by the Building Regulations have led to installation of various Low or Zero Carbon systems in new buildings. However, the contributions of these systems were significantly lower than expected in most case studies. The worst case was the solar thermal system installed in Building B that had not been commissioned effectively after building handover. Another example of poor performance was the installed Ground Source Heat Pump system in Building D which was often lagging behind the gas-fired boilers and consequently had negligible contribution to the building's heating demand. The energy outputs of a number of these systems were not sub-metered contrary to the Building Regulations' requirements. It

is important to ensure any input energy (in case of low carbon systems) and the output of these systems are sub-metered. The evidence suggests there is a steep learning curve associated with LZC systems in the UK construction industry. The control strategy, the design of the interface between these systems and the back-up systems, and the effect of changes in operating conditions on their performance must be taken into account at design stages and in operation to achieve the expected environmental benefits.

- Review of the Building Regulations compliance reports and the commissioning results revealed a number of shortcomings in building procurement that can seriously compromise performance in-use. The specific fan powers of the air distribution systems calculated from the information available in the commissioning reports were 40-90% higher than the specific fan powers used in the final regulatory calculations. Errors in calculating SFPs, poor installation of ductworks, ductwork air leakage, and changes in the specification of the air handling units were among the root causes for these discrepancies. In some cases, there had been a tendency to use regulatory limiting values for SFPs and construction U values assuming the as-built performance would be better than these limiting values. Furthermore, there was no information about key energy efficiency measures such as automated lighting control or testing the hydraulic isolation of HVAC zones in the commissioning repots. The evidence points to inadequacies of basic commissioning that is used for most buildings and the need for seasonal or enhanced commissioning.
- Given the complexity of construction projects and the number of variables involved, it is very difficult for any single party, including building control bodies, to check the accuracy of all input data used in Building Regulations' compliance reports. The emphasis of the regulatory calculations is on relative performance of the proposed building against a notional or reference building, and outcomes of these regulatory calculations are not directly comparable with actual performance. Therefore, in the absence of required information and under immense time and resource pressure often experienced towards the end of construction projects, energy modellers and designers may *assume* all design intents have been met in final regulatory calculations. The evidence from the case studies shows this assumption is often not valid and can compromise performance in-use.
- One way of addressing these issues is to make the regulatory calculations comparable with total performance in-use. It was demonstrated that the Building Regulations' compliance calculations performed for four schools constructed post-2006 in England yield performance levels that, when an allowance for equipment loads is included and

consistent CO_2 emission factors are used, are comparable to the 10^{th} or 25^{th} percentile of the DEC dataset. Furthermore, a significant part of the discrepancy between the actual performance and regulatory calculations of the worst and best performers among these schools was quantitatively attributed to specific procurement and operational issues using dynamic thermal simulation. It can therefore be concluded that regulatory calculations can be used as good practice *benchmarks* for performance in-use so far as building operating conditions is not too dissimilar to the standardised operating conditions assumed in the Building Regulations.

- However, as the standardised operating conditions used in the regulatory calculations often do not represent actual operating conditions, the outcomes of these calculation cannot be used as *baselines* for energy performance. Protocols such as CIBSE TM54 or ASHRAE 90.1 can be used to define robust baselines for performance in-use based on actual or expected operating conditions.
- An appropriate measurement and verification framework is also required to compare actual performance with regulatory performance under identical operating conditions and determine the performance gap with precision. Such a framework must be able to separate the effect of human behaviour from technical issues that must be addressed to optimise operational performance. It was demonstrated how such a measurement and verification framework can work under the existing regulations. Applying the proposed measurement and verification framework to the worst performing building constructed post-2006 revealed that the verified performance was 23.5% worse than the intended performance as a result of procurement issues related to building design, construction, and commissioning. The procurement issues are compounded by operational issues and lead to a measured performance that is often significantly worse than the performance projected under standardised operating conditions. In the demonstration case, the main root causes identified for the procurement gap were the higher than expected specific fan power for the air distribution system and lack of demand-controlled ventilation. In total, these issues were responsible for 35% of the discrepancy between the measured performance and the regulatory calculations carried out on completion of the building.

  At system level, it was demonstrated that the effect of all procurement and operational issues on the mechanical ventilation system led to an almost tenfold increase in fan energy consumption with further repercussions for space heating.
- Finally, the post-occupancy simulations point to a number of shortcomings in the National Calculation Methodology (NCM) for projection of performance in-use with reasonable accuracy. Notably, the algorithm currently used for demand-controlled

ventilation in the NCM does not take into account the variable torque nature of fans and assumes a linear relation between fan power and flow rate. Consequently, the NCM underestimates the potential saving of variable speed drives controlled by gas sensors by approximately a third. It is necessary to review and update the NCM to support projection of total performance in-use which is driven by various trends such as credibility gap, energy efficiency finance, and performance contracting.

10.1.2. Indoor Environmental Quality

Technical measurements of the indoor environmental conditions in the case studies led to the following findings:

- Few incidents of air temperatures above 28 °C were recorded in sample classrooms in summer and all buildings met their design overheating criteria. However, air temperatures higher than 25 °C were frequently recorded in Buildings D and E. Both buildings are located in East London with fundamentally different environmental strategies. Building D is predominantly naturally ventilated and is constructed with special focus on building fabric and passive measures. Building E is a mechanically ventilated building with limited attention to passive measures and is heavily reliant on building services to provide thermal comfort. The total number of hours the sample classrooms in Building E experienced indoor air temperatures above 25 °C was 150 hours, more than 50% higher than Building D. Temperatures above 25 °C can impede performance and are not expected in a mechanically ventilated building with partial comfort cooling. Building E had also the worst energy performance among the case studies with conflicting heating and cooling systems and a malfunctioning Building Management System that required re-commissioning few years after building completion. The incidences of extreme temperatures and shortcomings associated with the control strategy in Building E point to the risk factors associated with mechanical solutions and the significance of giving precedence to passive measures in environmental design.
- While thermal comfort conditions in most buildings were acceptable in summer, a number of measures specified to protect the buildings against future overheating were not installed or commissioned. Notably, the motorised vents installed in Buildings B and D were only responsive to CO_2 levels and not temperature. In Building B this led to cold draughts in winter and put the heating system under stress. In Building D the cross natural ventilation strategy is entirely dependent on the operation of the motorised vents and failure to enable thermal triggers specified

by designers at the commissioning stage may compromise thermal performance of the school when it is subject to high ambient temperatures.

- Overall, indoor air quality was acceptable in the buildings and maximum CO_2 concentrations were often lower than 2,000 ppm. However, the naturally ventilated classrooms did not necessarily conform to the BB101 criteria. It was revealed that around 25% of naturally ventilated classrooms in Building D had average daily CO_2 concentrations higher than 1500 ppm for at least one day during the monitoring week. A traffic light control system had been installed in this building to inform teachers to open the windows when the CO_2 concentrations are high. However, the labelling was confusing for some teachers and led them to ignore the traffic lighting control interface altogether. It is important to use plain and jargon-free labelling for control interface that is understandable to all users.
- The air quality in mechanically ventilated buildings was generally better than naturally ventilated buildings. However, on a number of occasions, failure of supply fans and maintenance issues led to prolonged periods of operation with limited ventilation where only one small operable window had been installed or no ventilation in case of internal spaces. Maintenance requirements of these systems and contingency plans to maintain the resilience of the building in case of operational failure must be taken into account at design stages. More operable windows may cost more but will protect building users against operational failures and will keep them satisfied.
- Where mechanical ventilation had been specified for the case studies, the main driver was invariably the acoustic requirements set out by BB93. However, in practice, the indoor ambient noise levels in mechanically ventilated classrooms were often higher than the 35 dB limiting value specified by BB93 due to the poor attenuation of the mechanical ventilation systems. Both technical measurements and occupants feedback also showed internal noise was a major issue and the classrooms were often not adequately soundproofed to screen the noise from the adjacent spaces. Occupants frequently used the available operable windows in the mechanically ventilated buildings and appeared to be more tolerant to external noise. Measurements of the reverberation times revealed the potential conflicts between using thermal mass to moderate indoor temperatures and the acoustic requirements. It is necessary to specify suspended acoustic rafts with high absorption quality to strike the right balance between thermal mass and reverberation times where exposed thermal mass is part of the environmental strategy.

- The lighting levels specified in classrooms were generally higher than the requirement for teaching spaces to ensure the minimum illuminance level of 300 lux is provided to the obscured areas such as classroom corners. However, the average indoor illuminance levels were up to 50% higher than this minimum requirement. Over specification of lighting has implications for energy performance and glare.

  The main issue related to electrical lights was poor automated control. The zonings of the presence or absence detection sensors were not refined to enable an effective response to occupancy. This led to lights being ON in large open-plan spaces if part of the space was being used. There were inconsistencies in the time offs and sensitivities of the PIR sensors installed in various classrooms. In extreme cases, the lights were turned off when the classroom was still occupied (e.g. Building D). The threshold illuminance levels for daylight sensors were also not correctly set and this led to waste of energy when enough daylight was available. It is also important to coordinate lighting zones with the daylight strategy to ensure the day lit zones can be separately controlled. These issues were observed in all case studies and point to the improvement opportunity that exists in specification and commissioning of lighting controls.

10.1.3. User satisfaction

The outcomes of the Building Use Studies carried out in the case studies point to the followings:

- The BUS overall result has strong correlation with occupants' self-assessed productivity and health. Out of five new buildings investigated, three buildings received overall positive feedback from occupants with self-reported increase in their productivity. However, occupants in two buildings were not satisfied with their buildings and reported a decline in their productivity at work as a result of the environmental conditions experienced in the buildings. They also felt less healthy than the other case studies and more than 60% of the BUS dataset. The BUS results for Building E are strongly correlated with the technical studies of the indoor environmental quality with people complaining about extreme temperatures and poor ventilation. However, the problems in Building C appear to go beyond environmental conditions and point to the intricate relation between perception of building physics and wider management and socio-economic context that cannot be fully captured by Building Use Studies.

- In most case studies, some teachers expressed serious concerns about the ingress of noise from open-plan spaces and inadequacies of these spaces for teaching. These views were more prevalent in Building C where 32% of BUS respondents thought open-plan teaching and learning spaces are not practical and cause distraction for pupils. Around 10-12% of teachers expressed strong views about open-plan spaces and space utilisation in Buildings A and B. It should also be noted that these spaces pose a challenge for energy management as building services' zoning arrangements often follow the spatial design and this leads to waste of energy especially during out-of-hours operation when these zones are only partially utilised. Based on the comments received from building users, clear physical boundaries between general circulation spaces and open-plan learning zones can help reduce the noise and distraction. Furthermore, it is vitally important to engage teachers and parents in spatial planning and management of these spaces to achieve the expected educational benefits. People expressed their strong desire for local control of ventilation especially where mechanical ventilation had failed and was not fixed for a prolonged period as in Buildings A and E.
- Building occupants were generally content with the responsiveness of facility managers when they requested changes to their environmental conditions, but were less satisfied with the corresponding changes. Most facility managers in the case studies were under-resourced, over-stretched with little or no technical background in energy and environmental management. Simple and passive design measures work best where building managers are not resourced for the proactive approach required for complex building systems. The relation between building user satisfaction and energy performance is not straightforward. Building Use Studies are focused on system outputs. However, where people are not satisfied with the level of comfort, there are often problems related to building services that may have also compromised energy performance. Poor BUS comfort index in Building E was entirely consistent with the poor level of energy performance. A good comfort index however may be indicative of a relatively good energy performance (e.g. Building B) or be achieved at the expense of an overall poor energy performance (e.g. Building A). The structured feedback received from BUS questionnaire point to the key problem areas in a building that could inform building performance diagnostics. BUS is therefore a fast track route for building diagnostics that could be especially helpful for shorter term post-occupancy evaluations in the industry.

10.2. Main Conclusion: the framework and prospects for measurement and verification of performance in-use

The initial theory formulated by this thesis postulated that a mandatory requirement for building fine-tuning and achieving performance targets in-operation would be necessary to narrow the performance gap. A rival theory was formulated to show the counter-arguments that could be used to question such a mandatory requirement. Two key questions raised by this rival theory were related to the extent of the performance gap and the effectiveness of the mandatory requirement. This section summarises the main findings of the dissertation with respect to the initial and rival theories. It also outlines the key recommendations emerging from the building performance evaluations carried out in this research programme that could inform industry practitioners and policy makers to address the problem of the performance gap.

The Building Performance Evaluations identified significant gaps in the region of 80-120% between energy performance in-use and energy performance calculations carried out on completion of the buildings. All case studies experienced a number of procurement issues at various stages of construction projects that had knock-on effects on performance in-use. An overarching finding was that designers, in their endeavours to meet the ever stringent regulatory targets, specified various measures that had not been subject to thorough risk assessment from operational point of view. This problem was often compounded by value engineering process in which critical measures that could have provided redundancy modes for environmental systems and thereby improve system resilience were taken out from the schemes to save resources. There was also no systematic attempt to fine-tune buildings in the early stages of post-occupancy. Consequently, these buildings were left to users who did not have in-depth training, the experience or the adequate resources to manage them in accordance with the design intents.

This method of building procurement will inevitably lead to operational issues that are more pronounced in complex buildings. Measurement and verification of performance in-use can help address the issues outlined above by getting the designers and contractors involved post-occupancy in a concerted action to achieve clearly defined performance targets. A measurement and verification framework consistent with the existing regulations in England was proposed in Chapter 9 to verify energy performance in-use in reference to the regulatory calculations. The cornerstone of this framework is to separate the effect of shortcomings related to design, construction, system installation, implementation of the control strategy, and commissioning (the procurement gap) from the effect of shortcomings in building operation and management (the operational gap). A computer model calibrated with actual operation is reverted to the standardised operating conditions used in the Building Regulations calculations to facilitate this process. This measurement and verification framework can address the question of ownership of the performance gap by holding the construction teams accountable for the procurement gap whilst identifying improvement opportunities to narrow the operational gap.

The proposed framework can be a cost-effective means of ensuring energy performance targets have been achieved especially where the project Client has an interest in long-term performance of their building. The cost of measurement and verification and any remedial work can be quite reasonable compared to energy savings achievable during building life-cycle. The cost of M&V can also be substantially reduced if it is integrated into the construction project from the outset with the monitoring variables and points clearly defined in the BMS system and the design model available for post-occupancy calibration work. It was demonstrated that measurement of the performance gap with reasonable accuracy under standardised operating conditions also paves the way to introduce a carbon tax or environmental levy for any excess in energy use over the regulatory limit.

However, extending the current regulatory requirements to include performance in-use for all buildings might be a step too far and must be introduced with caution and in a graduated way. For start, the steady state operation required for performance measurement and verification is often achieved more than one year after building completion when the defects liability period for most non-domestic projects comes to an end and construction teams are practically not accountable for the project. While in principle contractual arrangements can be made to allow more time for measurement and verification, it is likely that this will add to project costs and complexity. Split incentives between stakeholders is another issue; if the Client of a construction project does not own energy performance in-use as in the case of speculative developments or future tenancy agreements, the Client/Landlord may not be able to recoup the extra cost associated with measurement and verification in a competitive market. Consequently, this can be perceived as yet another regulatory burden that adds to the cost of business, and impede effective implementation of M&V. Making measurement and verification of performance in-use a regulatory requirement may also impede collaboration between construction teams and building users. Designers and contractors may become too pre-occupied with achieving their performance targets and consequently pay less attention to user training and actual building context. This would be an unfortunate and unintended consequence as the findings of this research programme point to the significance of collaboration between construction teams and building users. Finally, calibrating computer models and achieving the required accuracy can be a huge task in complex buildings. While implementation of the EPBD and the availability of qualified energy assessors facilitate performance measurement and verification, the steep learning curve experienced in implementing the EPBD in the past decade and the required changes in the existing software tools and BMS platforms necessitate a period of sea trial for measurement and verification.

The initial theory formulated in this dissertation is therefore revised to address these issues and lead to a practical solution for the industry. It is recommended that measurement and verification of performance in-use in reference to the Building Regulations compliance calculations is integrated into the existing voluntary Building Performance Evaluation frameworks such as Soft Landings first before considering its integration into the Building Regulations.

Implementation of the framework on a voluntary basis in response to the market drivers rather than regulations can help develop the required tools and supply chains in an orderly fashion. This will pave the way for future developments that may include provision for measurement and verification of performance in-use in the Building Regulations if evidence points to its effectiveness in variety of sectors and when the industry is ready for its uptake. Performance measurement and verification can also be used as an *alternative* way of demonstrating compliance with the Building Regulations that replaces a number of current measures specified to help building control bodies evaluate the accuracy of input data. This alternative pathway to compliance would be client-driven and output oriented. It would provide the Clients (and in public sector, the tax payers) with a means to check whether their buildings meet energy targets in practice and could help uncover the root causes of underperformance.

The evidence collated during Building Performance Evaluations point to skill shortage in the construction supply chains and regulatory bodies that can hamper delivery of low-carbon buildings. The specific areas that can be targeted for upskilling are: building energy performance simulation, design and commissioning of control strategies especially where LZC systems are involved, enhanced commissioning skills, measurement and verification, and post-occupancy building fine-tuning. It is also important for Building Control Bodies to be resourced to keep pace with the rapidly evolving energy-related Building Regulations.

Finally, this dissertation calls for measurement, verification and disclosure of performance data in the schools estate, and more widely public sector, to inform the public about delivered value for money and to inform the supply chains about how to deliver better value for money. This can also drive similar initiatives in the private sector. The success of the Energy Star and NABERS schemes to collate large scale performance data and inform the building procurement process in the US and Australia shows the value of a data-driven and performance oriented approach. The trend towards collection and disclosure of data has been accelerated over the recent years by initiatives such as the commitment to share energy consumption data for LEED projects (LEED v4) and the New York City Benchmarking and

Transparency Policy (Local Law 84) (USGBC, 2013), (NYC Council, 2009). The findings of this research programme point to the significance of similar initiatives for the UK, and more widely the EU, to embed a performance oriented culture in building procurement and operation.

10.3. Recommendations for future work

The findings of this research programme point to the potential benefits of the following research that may be undertaken to complement and expand on the present work:

- Post-occupancy evaluations of the schools procured under the Priority School Building Programme (PSBP) to assess the effectiveness of the operational targets introduced by the Education Funding Agency.
- An investigation into the intricate relation between educational building physics and pupils' performance. Such an investigation must consider factors related to building physics such as building form, spatial planning, space utilisation, and the indoor environmental quality along with both self-assessed and objective metrics of performance.
- Assessment of the effectiveness of measurement and verification of performance in-use on a number of buildings in various sectors as part of the Soft Landings framework. Application of measurement and verification in the context of energy performance contracting promoted by the Energy Efficiency Directive and the recast of the EPBD. To facilitate uptake of these projects in the industry, innovative data capture methods from existing buildings and identification of building pathologies in a semi-automated way will be essential to achieve reasonable accuracy in computer model calibration at low cost.
- Development of an integrated as-built/in-operation and market-driven building energy labelling scheme that can visualise the performance gap for building operators with reasonable accuracy and clarity.

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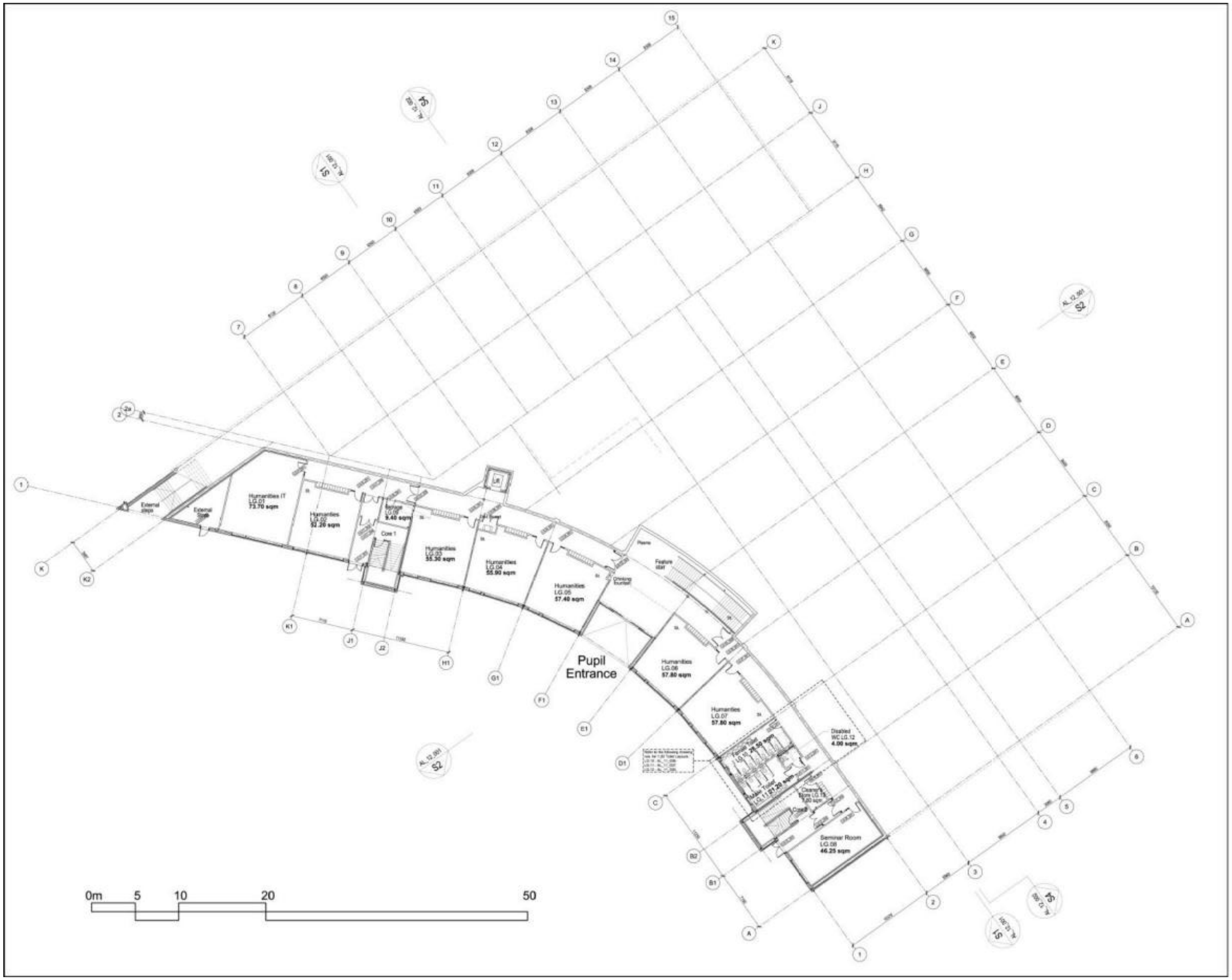
12. Appendix A: Layout plans for the case studies

BUILDING A



NOTES

POSITIONS OF MOVEMENT JOINTS TO BE AGREED WITH THE STRUCTURAL ENGINEER

NOTE.
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REFER TO AVT DRAWINGS FOR LAYOUT.

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Aedas

Aedas Architects

client: UNITED LEARNING TRUST

project: [redacted]

drawing: LOWER GROUND FLOOR

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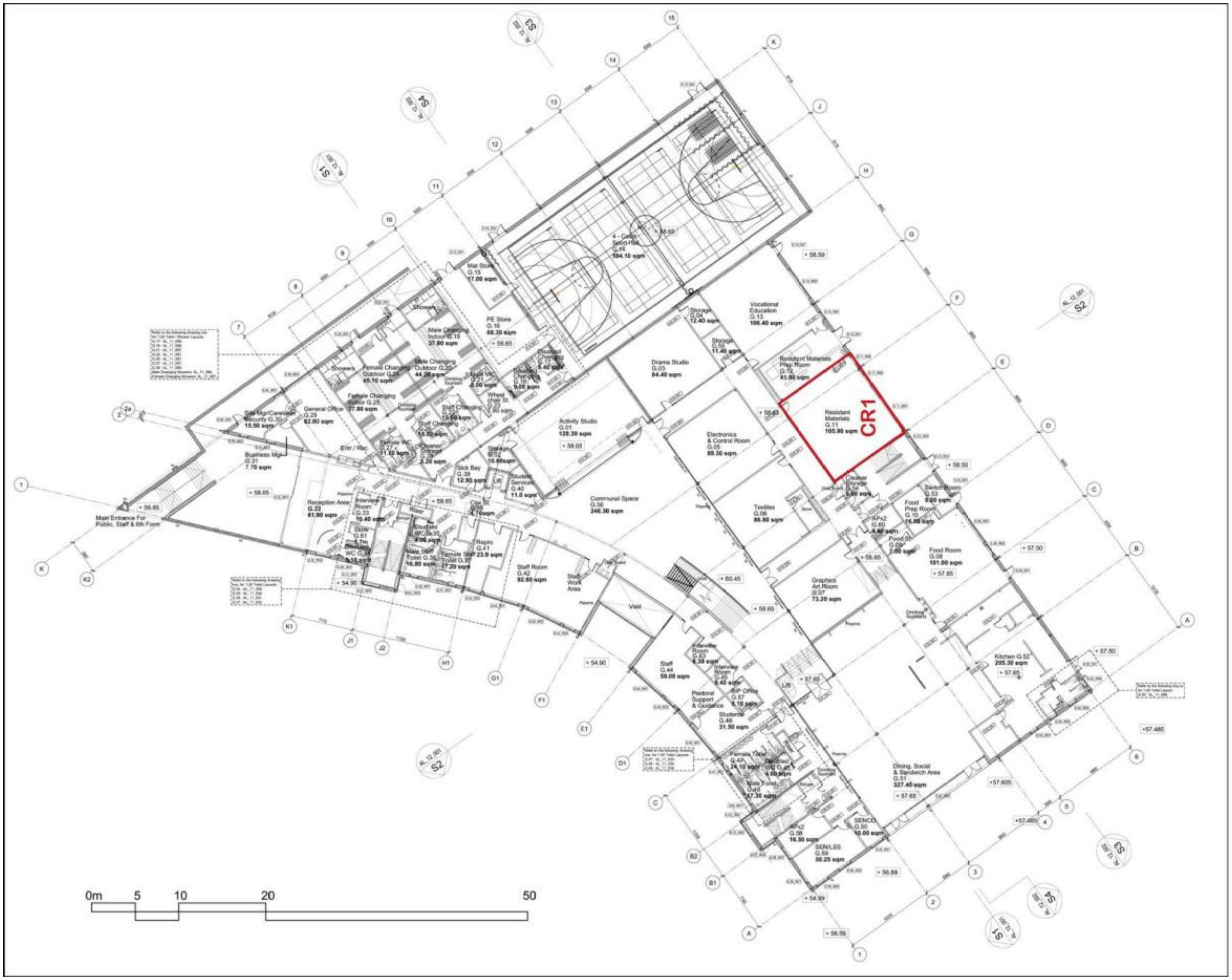

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NOTES

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Aedas

Aedas Architects

UNITED LEARNING TRUST

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GROUND FLOOR

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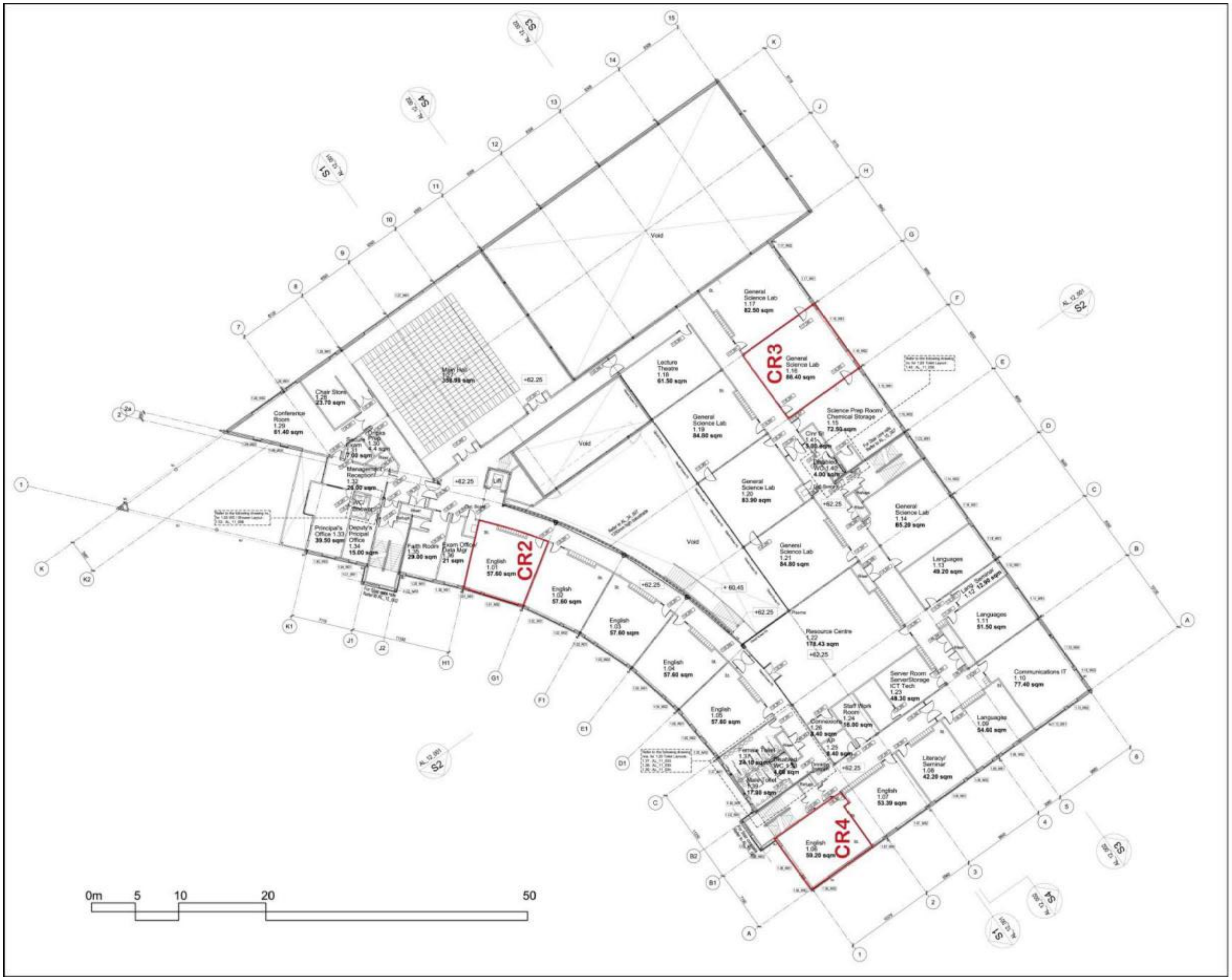

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Aedas

Aedas Architects

client
UNITED LEARNING TRUST

project

drawing
FIRST FLOOR

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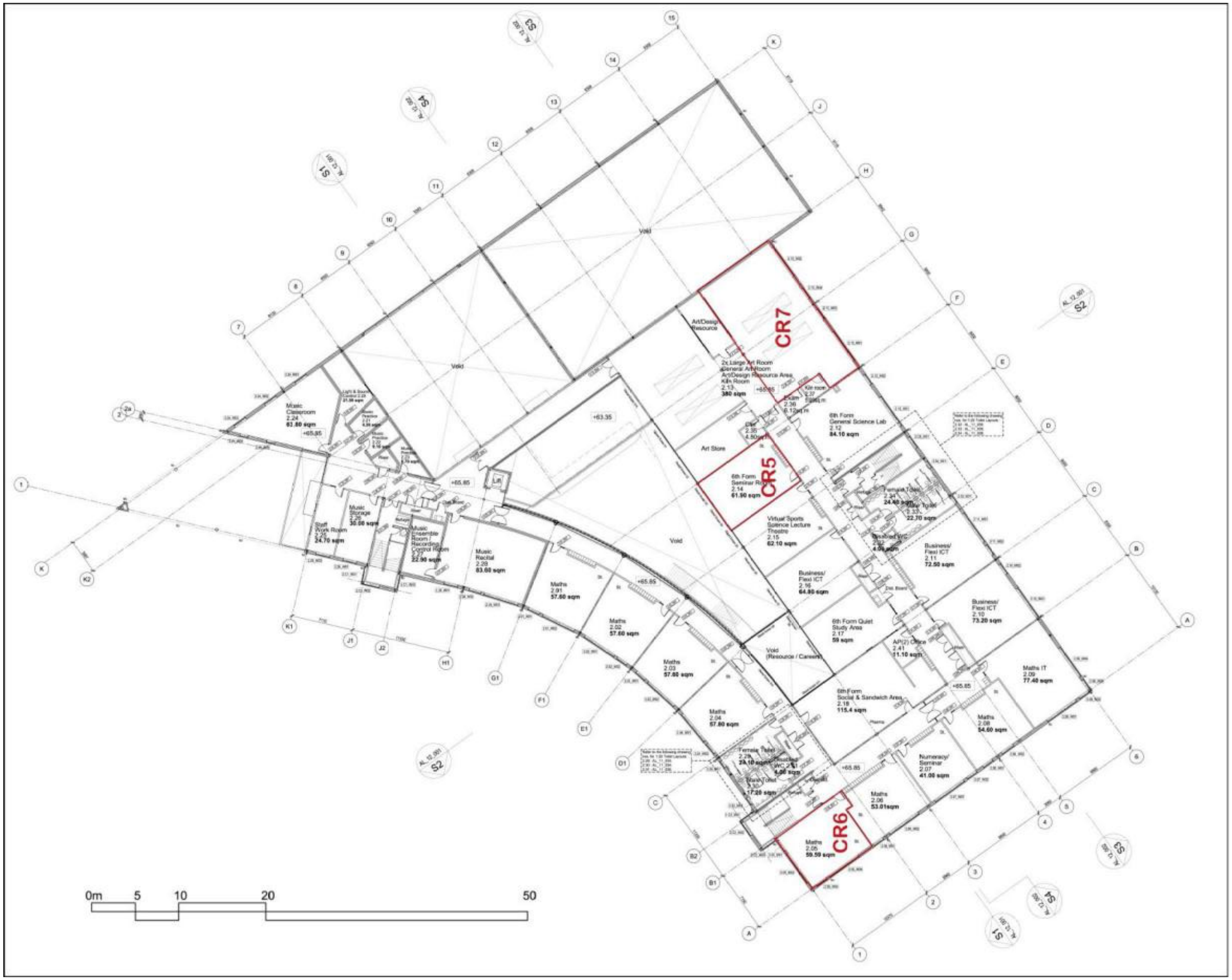

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Aedas

Aedas Architects

client
UNITED LEARNING TRUST

project
[redacted]

drawing
SECOND FLOOR

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drawing number	rev	issue status
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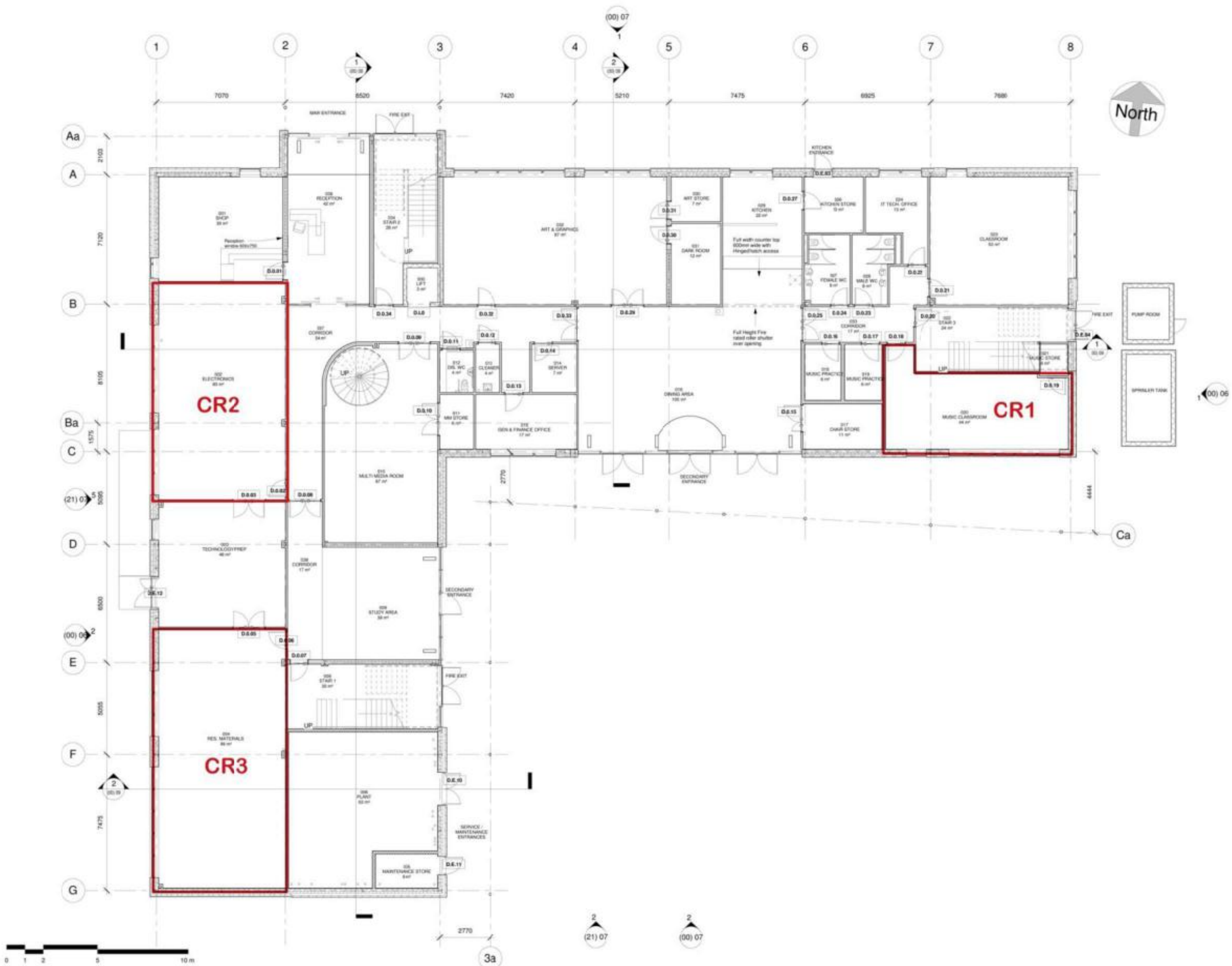
BUILDING B

Notes:

1. Architectural drawings refer to:
(00) series for General Arrangement only (refer to package drawings below for construction detail and setting out information).
(9) series for External Works
(21) series for External Walls
(22) series for Internal Walls
(24) series for Stairs and Balconies
(27) series for Roofs and Soffits
(31) series for External Windows and Doors
(32) series for Internal Windows and Doors
(35) series for Ceilings
(40) series for Internal Finishes and Ceilings
(68) series for Escape and Access Plans
(50) series for Fixtures and Fittings
(52) series for Above Ground Drainage
(90) series for External signs and Miscellaneous Services Buildings

2. Any structure, services and external works shown are for coordination purposes only, refer to other Consultants drawings for information.



1 Level 00 - Ground Floor GA Plan
1 : 100

Rev	Description	Date	Dr by	App by
J	Final Construction Issue	27/05/10	JH	
I	Doors D.E.04 and D.E.12 changed to unequal pairs (type E7)	09/03/10	JH	
H	Music classroom partition returned to straight and centre at request of client. Partition added / doorway position in kitchen amended at request of kitchen specialist	19/01/10	JH	
G	Door no. tags added. Rooms 25 & 35 omitted at client request	16/12/09	JH	
F	Door D.0.04 omitted at client request	04/11/09	JH	
E	Music practice room partitions splayed. Plant rooms walls to be blockwork	27/11/09	JH	
D	CONSTRUCTION ISSUE	21/07/09	JH	
C	Reception desk and window added. Kitchen servery hatch amended. Urinals omitted from all Male WC.s and replaced with toilets. Sliding doors and glazed screen added to reception. Door omitted from stair 1 ground floor and store 035 amended. Steelwork updated to current S.E. plans	15/07/09	SE	
B	Resistant materials store omitted at request of client	05/06/09	JH	
A	Window location within wall construction updated. Room number amendments to match room data sheets. Grid lines for canopy added and column set out adjusted	16 Apr 09	WD	JH

original by: WD
date created: 04/02/09 JH

Aedas

Aedas Architects

client name: WILLMOTT DIXON & CHESHIRE EAST COUNCIL

project: [redacted]

drawing: Ground Floor GA Plan

plot date: 27/05/2010 16:18:41

project number: 2008.0721.001

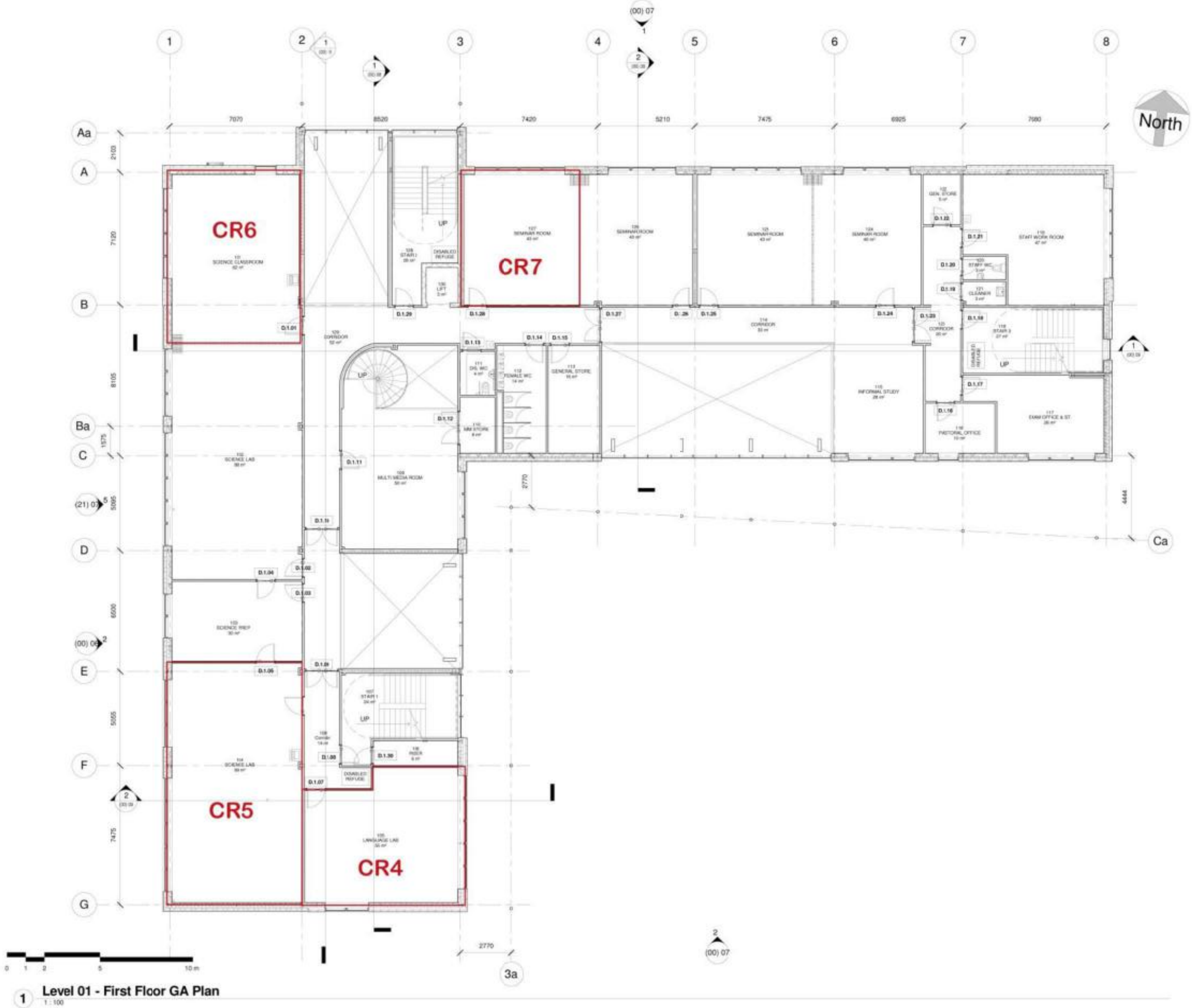
scale: As indicated @A1

drawing number: (00) 02

rev: J

issue status: CONSTRUCTION

This drawing is to be read in conjunction with all related drawings. Do not scale from this drawing. All dimensions must be checked and verified on site before commencing any work or producing shop drawings. The originator should be notified immediately of any discrepancy.



Notes:

1. Architectural drawings refer to:
(00) series for General Arrangement only (refer to package drawings below for construction detail and setting out information).
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(31) series for External Windows and Doors
(32) series for Internal Windows and Doors
(35) series for Ceilings
(40) series for Internal Finishes and Ceilings
(68) series for Escape and Access Plans
(50) series for Fixtures and Fittings
(52) series for Above Ground Drainage
(90) series for External signs and Miscellaneous Services Buildings

2. Any structure, services and external works shown are for coordination purposes only, refer to other Consultants drawings for information.

Rev	Description	Date	Dr by	App by
F	Final Construction Issue	27/05/10	JH	
E	Door no. tags added. Riser door added. Door 1.0.8 moved at request of client	16/12/09	JH	
D	CONSTRUCTION ISSUE	21/07/09	JH	
C	Male WC urinals omitted and replaced with toilets. Steelwork updated to Current SE plans.	15/07/09	SE	
B	Store 122 window removed. Seminar Room 126 window extended. Louvre heights amended to suit lintel detail	01 May 09	WD	JH
A	Window location within wall construction updated. Room number amendments to match room data sheets. Grid lines for canopy added and column set out adjusted	16 Apr 09	WD	JH

originated by: WD | date created: 04/06/09 | JH

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client name
WILLMOTT DIXON & CHESHIRE EAST COUNCIL

project
[redacted]

drawing
First Floor GA Plan

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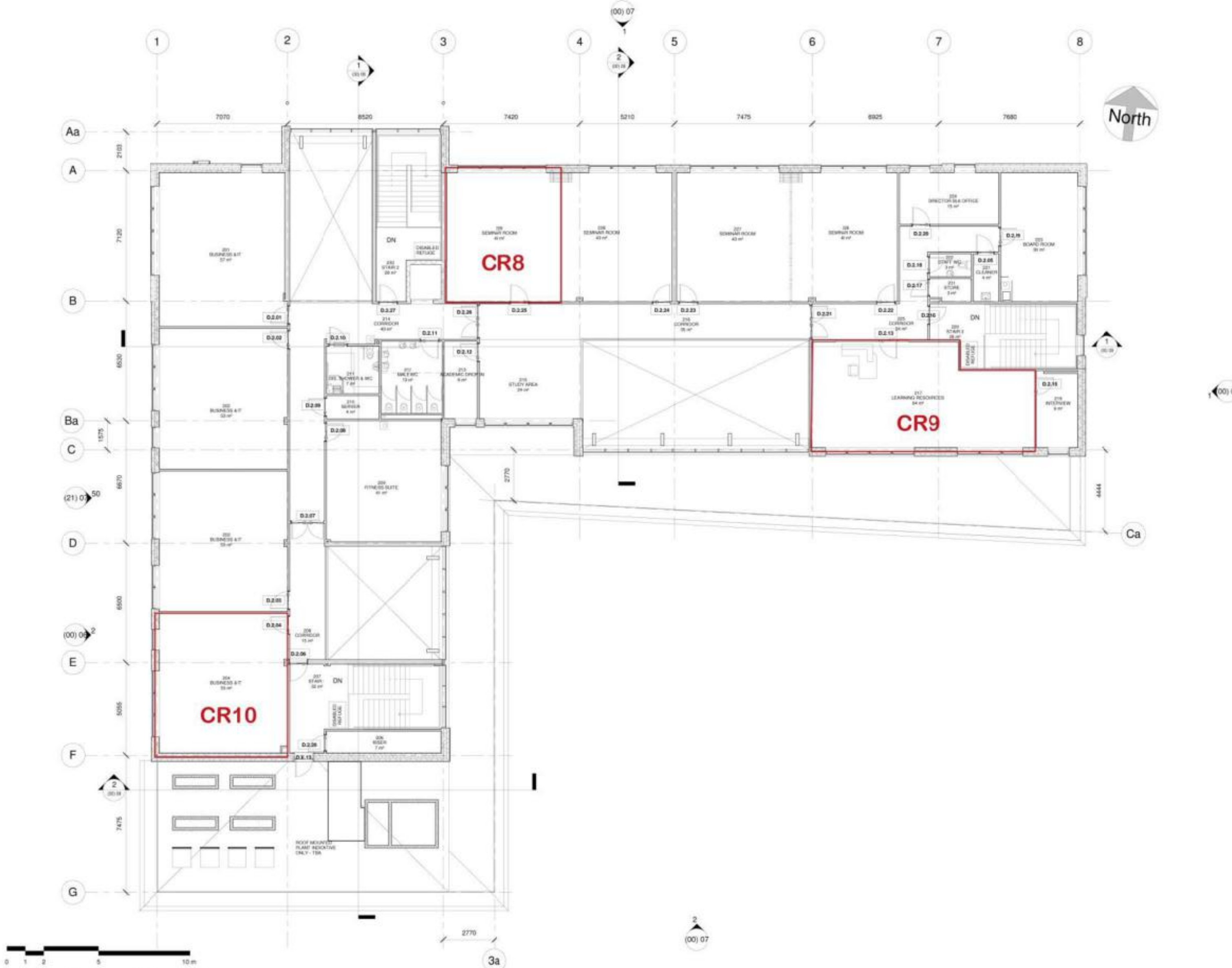

1 Level 02 - Second Floor GA Plan
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Notes:

1. Architectural drawings refer to:
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(22) series for Internal Walls
(24) series for Stairs and Balconies
(27) series for Roofs and Soffits
(31) series for External Windows and Doors
(32) series for Internal Windows and Doors
(35) series for Ceilings
(40) series for Internal Finishes and Ceilings
(68) series for Escape and Access Plans
(50) series for Fixtures and Fittings
(52) series for Above Ground Drainage
(90) series for External signs and Miscellaneous Services Buildings

2. Any structure, services and external works shown are for coordination purposes only, refer to other Consultants drawings for information.

Rev	Description	Date	Dr by	App by
F	Final Construction Issue	27/05/10	JH	
E	Setting out amended to co-ordinate with new partition specifications following VE meeting with subcontractor. Glazed screen removed between Learning Resources and Connexions at client request. Connexions omitted.	16/12/09	JH	
D	CONSTRUCTION ISSUE	21/07/09	JH	
C	Male WC urinals omitted and replaced with toilets. Steelwork updated to Current SE plans.	15/07/09	SE	
B	CORRIDOR TO ROOF OMITTED. LAYOUT AMENDMENT TO AREA BETWEEN GL6-8 TO INCREASE SIZE OF LRC & DIRECTOR'S OFFICE, & RE-CREATE WALK IN STORE	05/06/09	JH	
A	Window location within wall construction updated. Room number amendments to match room data sheets. Grid lines for canopy added and column set out adjusted	15 Apr 09	WD	JH

original by: WD | date created: 04/06/09 | JH

Aedas

Aedas Architects

client name: WILLMOTT DIXON & CHESHIRE EAST COUNCIL

project: [redacted]

drawing: Second Floor GA Plan

plot date: 27/05/2010 16:18:46

project number: 2008.0721.001

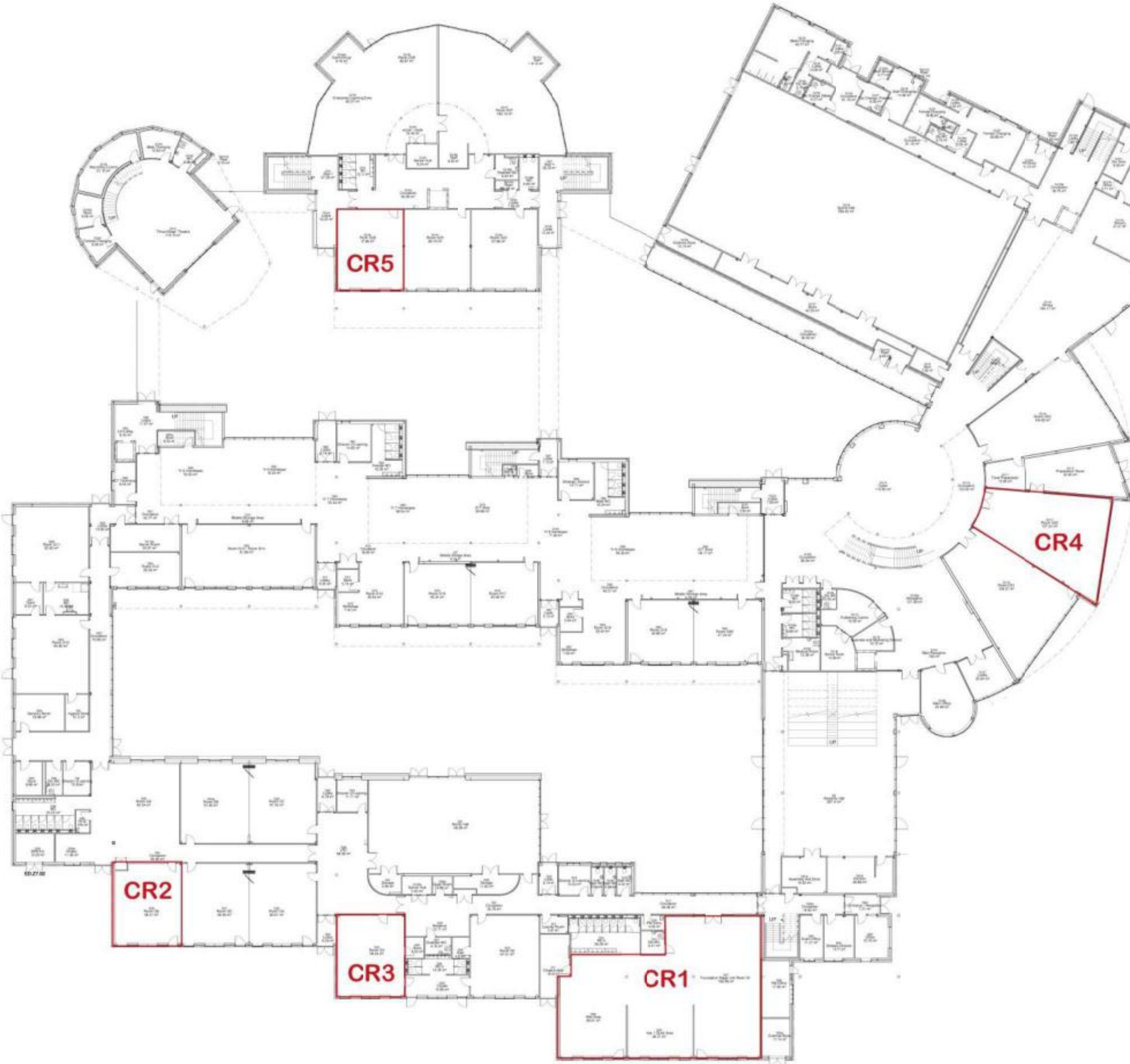
scale: As indicated @A1

drawing number: (00) 04

rev: F

issue status: CONSTRUCTION

BUILDING C



Proposed Ground Floor Plan
1 : 150

JAV/AWB 07/02/08

Aedas

Balfour Beatty Construction Ltd

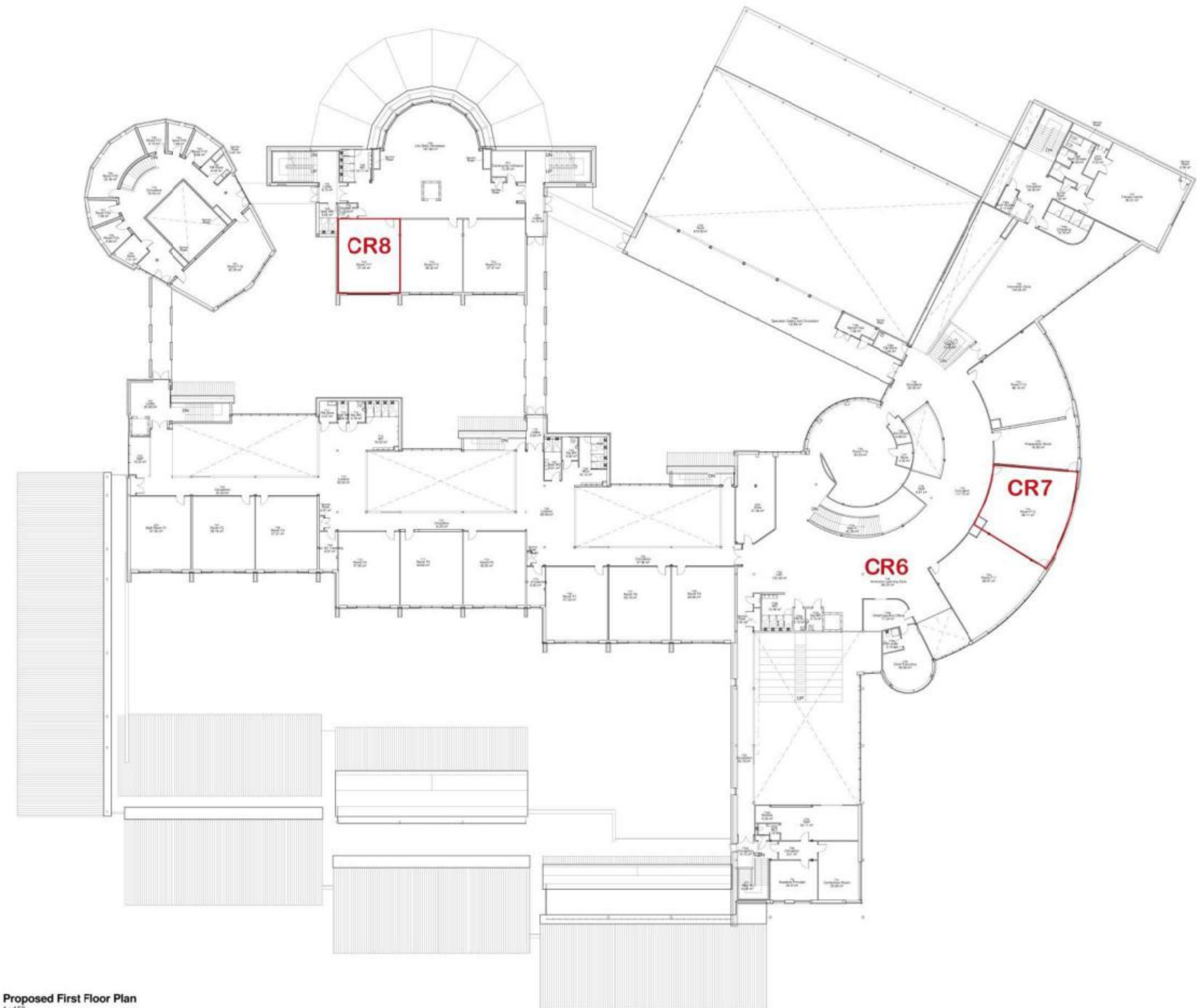
Proposed Ground Floor Plan

27/05/2009 10:35:56

2007.01724

1 : 50 @A0

PQV-ADA-20-001 V As Constructed



Proposed First Floor Plan
1 : 150

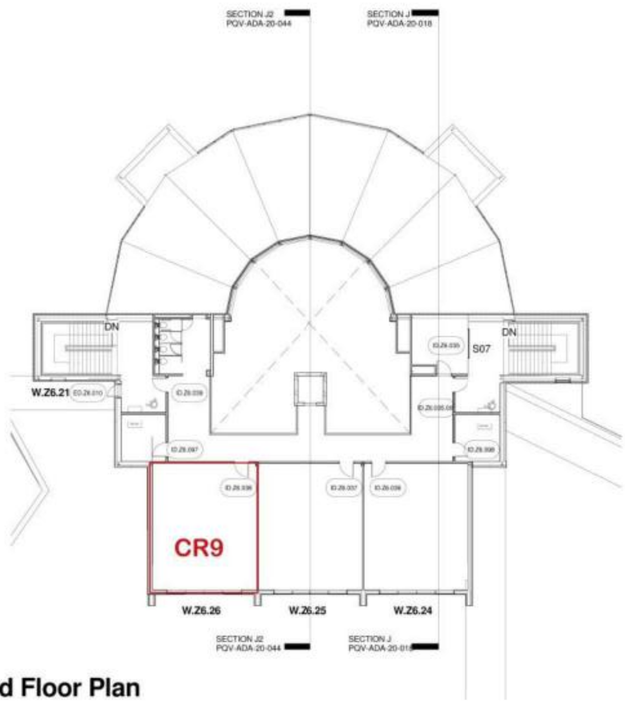
JAV/AWB	17/02/08	PS

Aedas

Balfour Beatty Construction Ltd

Proposed First Floor Plan

	9/05/2009 11:15:34	
2007.01724	1 : 150	@A0
PQV-ADA-20-101	Q	As Constructed



Key Second Floor Plan

1 : 200

rev	description	date	dr by	ap by
A	As constructed	02.06.09	AWB	

original by: Author — Approver

Aedas

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E manchester@aedas.com
aedas.com

client name: Balfour Beatty Construction Ltd

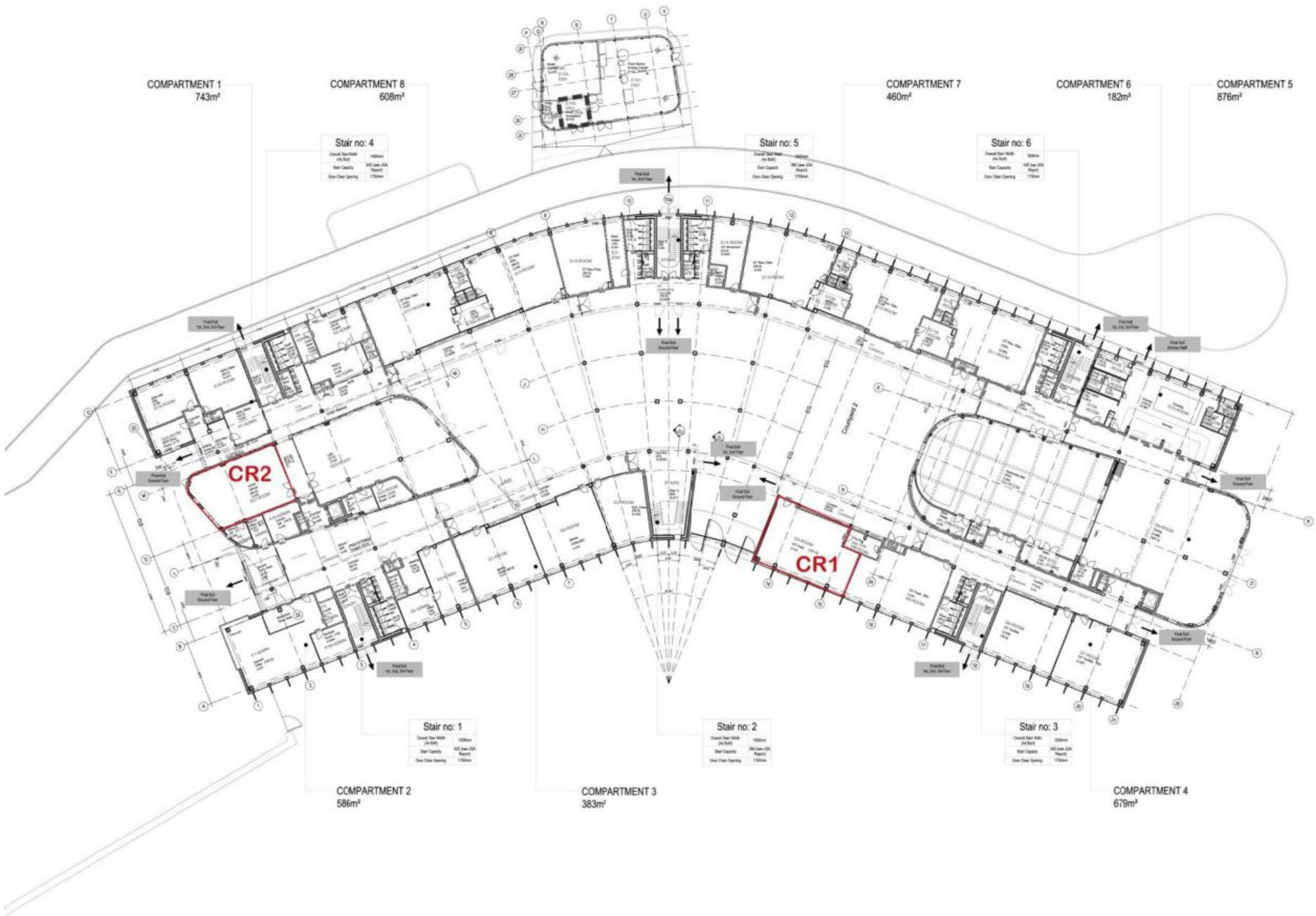
project: [redacted]

drawing: Key Plan Second Floor

computer file		plot date 10/06/2009 12:04:36	
project number 2007.01724		scale 1 : 200	@A2
drawing number PQV-ADA-20-203	rev A	issue status As Constructed	

This drawing is to be read in conjunction with all related drawings. Do not scale from this drawing. All dimensions must be checked and verified on site before commencing any work or producing shop drawings. The originator should be notified immediately of any discrepancy. This drawing is copyright and remains the property of Aedas.

BUILDING D



1 GROUND FLOOR GA 1:250@A1

General Notes

1. this drawing to be read in conjunction with Aedas fire service access drawing (AR.LON.2007.00142.000.10.201 Proposed Site Plan), door strategy & door schedule.
2. this drawings to be read in conjunction with M&E drawings and related specifications (P[3-] Series-Penetration Details, S[63] Series-Sprinklers, V[21] Series-Lighting and W[50] Series-Fire Alarm) together with relevant sub-contractor drawings and specifications.
3. this drawing to be read in conjunction with JGA Fire Engineering report,
4. any discrepancies on drawings and related documents to be notified to the architect immediately,
5. all dimensions on this drawings are in millimeters unless otherwise specified,
6. do not scale from drawing,
7. all room areas are indicative only

FIRE STRATEGY KEY

- 60 MINUTE SEPARATION
- 30 MINUTE SEPARATION
- 240 MINUTE SEPARATION

Notes

Cavity Barriers
Cavity barriers will be provided in all continuous ceiling and floor voids at every 20 meters.

Fire Stopping
Fire stopping provided at junctions between compartmentwalls and floors. Service fire stops in builder's works openings through floors and walls after services or as required through fire resistant walls.

Fire Resistance of Structure
Concrete structure 60 minutes fire resistance.
Steel structure to assembly hall to be fire protected 60 minutes. Beams and fixings' fire resistance achieved through the use of intumescent paint. Columns to be boxed in.

Emergency voice communications points
The emergency voice communications points are shown into MF W[50] Series and indicated with the "disabled refuge remote and base station" symbols (refer to legend). MF W[50] Series illustrates principles only and the detailed design will be undertaken by specialist sub-contractor.

rev	description	date	dr by	ap by
0	FINAL CONSTRUCTION ISSUE	18.03.10	MH	AS

original by: KL — 28.03.08 — AS

Aedas

client: [redacted]

project: **New School**

drawing: **Ground Floor Fire Strategy**

	plot date: 04.04.08	
project number: 2007 . 00142 . 000	scale: 1:250	
drawing number: 20.161	rev: 0	issue status: CONSTRUCTION

General Notes

1. this drawing to be read in conjunction with Aedas fire service access drawing (AR.LON.2007.00142.000.10.201 Proposed Site Plan), door strategy & door schedule.
2. this drawings to be read in conjunction with M&E drawings and related specifications (P[3-] Series-Penetration Details, S[63] Series-Sprinklers, V[21] Series-Lighting and W[50] Series-Fire Alarm) together with relevant sub-contractor drawings and specifications.
3. this drawing to be read in conjunction with JGA Fire Engineering report.
4. any discrepancies on drawings and related documents to be notified to the architect immediately.
5. all dimensions on this drawings are in millimeters unless otherwise specified.
6. do not scale from drawing.
7. all room areas are indicative only

FIRE STRATEGY KEY

- - - - 60 MINUTE SEPERATION

.... 30 MINUTE SEPERATION

Notes

Cavity Barriers
Cavity barriers will be provided in all continuous ceiling and floor voids at every 20 meters.

Fire Stopping
Fire stopping provided at junctions between compartmentwalls and floors. Service fire stops in builder's works openings through floors and walls after services or as required through fire resistant walls.

Fire Resistance of Structure
Concrete structure 60 minutes fire resistance.
Steel structure to assembly hall to be fire protected 60 minutes.
Beams and fixings' fire resistance achieved through the use of intumescent paint. Columns to be boxed in.

Emergency voice communications points
The emergency voice communications points are shown into MF W[50] Series and indicated with the "disabled refuge remote and base station" symbols (refer to legend). MF W[50] Series illustrates principles only and the detailed design will be undertaken by specialist sub-contractor.

rev	description	date	dr by	ap by
0	FINAL CONSTRUCTION ISSUE	18.03.10	MH	AS
original by KL		04.04.08		AS

Aedas

client

project
New School

drawing
First Floor
Fire Strategy

project number	scale	
2007 . 00142 . 000	1:250	
drawing number	rev	issue status
20.162	0	CONSTRUCTION

General Notes

1. this drawing to be read in conjunction with Aedas fire service access drawing (AR.LON.2007.00142.000.10.201 Proposed Site Plan), door strategy & door schedule,
2. this drawings to be read in conjunction with M&E drawings and related specifications (P[3-] Series-Penetration Details, S[63] Series-Sprinklers, V[21] Series-Lighting and W[50] Series-Fire Alarm) together with relevant sub-contractor drawings and specifications,
3. this drawing to be read in conjunction with JGA Fire Engineering report,
4. any discrepancies on drawings and related documents to be notified to the architect immediately,
5. all dimensions on this drawings are in millimeters unless otherwise specified,
6. do not scale from drawing,
7. all room areas are indicative only

FIRE STRATEGY KEY

60 MINUTE SEPERATION

30 MINUTE SEPERATION

Notes

Cavity Barriers
Cavity barriers will be provided in all continuous ceiling and floor voids at every 20 meters.

Fire Stopping
Fire stopping provided at junctions between compartmentwalls and floors. Service fire stops in builder's works openings through floors and walls after services or as required through fire resistant walls.

Fire Resistance of Structure
Concrete structure 60 minutes fire resistance.
Steel structure to assembly hall to be fire protected 60 minutes. Beams and fixings' fire resistance achieved through the use of intumescent paint. Columns to be boxed in.

Emergency voice communications points
The emergency voice communications points are shown into MF W[50] Series and indicated with the "disabled refuge remote and base station" symbols (refer to legend). MF W[50] Series illustrates principles only and the detailed design will be undertaken by specialist sub-contractor.

0 FINAL CONSTRUCTION ISSUE 18.03.10 MH AS

rev description date dr by ap by
original by
KL 04.04.08 AS

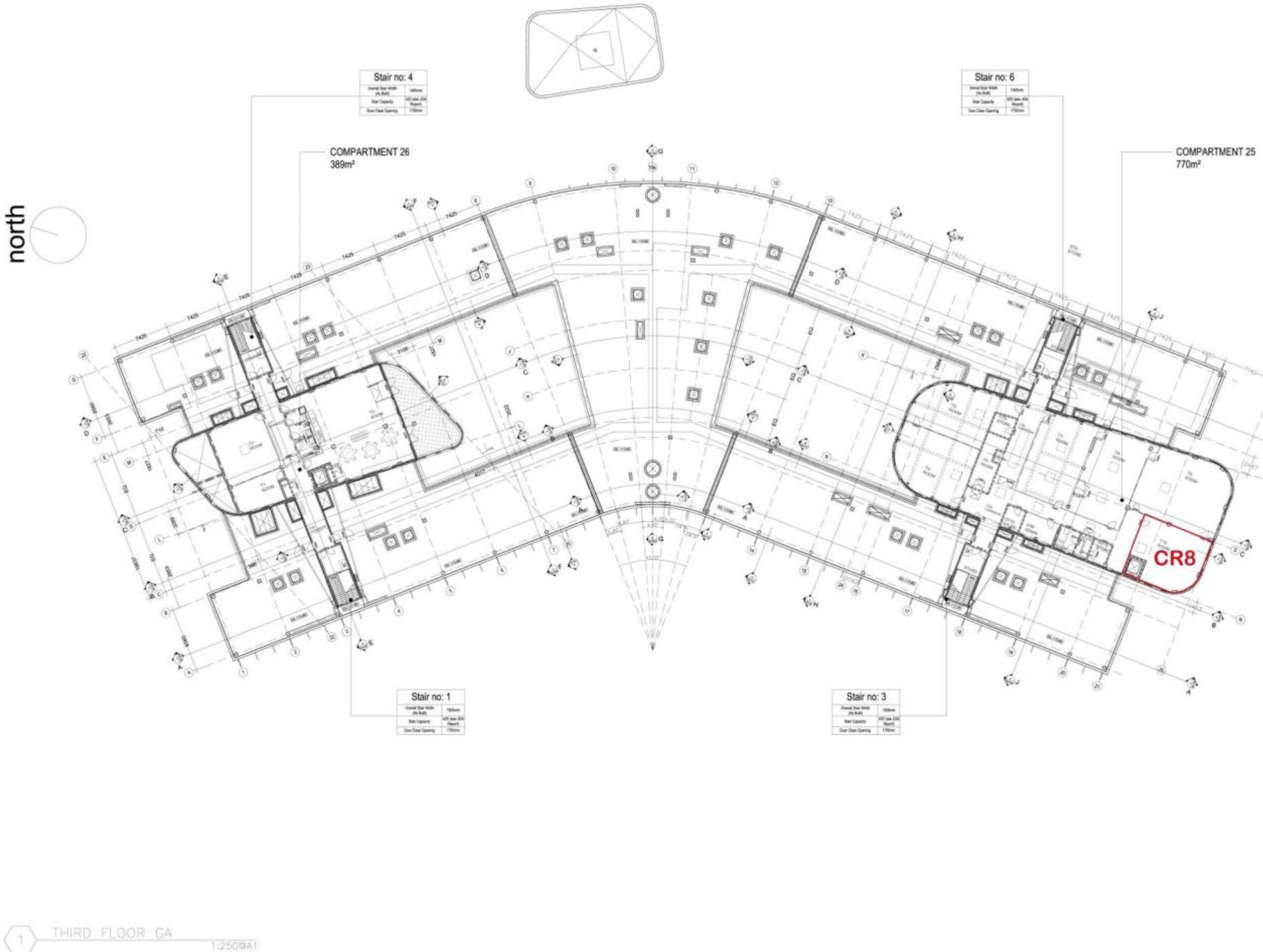
Aedas

client

project
New School

drawing
Second Floor
Fire Strategy

project number 2007.00142.000
scale 1:250
drawing number 20.163
rev C
issue status CONSTRUCTION



General Notes

1. this drawing to be read in conjunction with Aedas fire service access drawing (AR.LON.2007.00142.000.10.201 Proposed Site Plan), door strategy & door schedule.
2. this drawings to be read in conjunction with M&E drawings and related specifications (P[3-] Series-Penetration Details, S[63] Series-Sprinklers, V[21] Series-Lighting and W[50] Series-Fire Alarm) together with relevant sub-contractor drawings and specifications.
3. this drawing to be read in conjunction with JGA Fire Engineering report.
4. any discrepancies on drawings and related documents to be notified to the architect immediately.
5. all dimensions on this drawings are in millimeters unless otherwise specified.
6. do not scale from drawing.
7. all room areas are indicative only

FIRE STRATEGY KEY

60 MINUTE SEPERATION

30 MINUTE SEPERATION

Notes

Cavity Barriers
Cavity barriers will be provided in all continuous ceiling and floor voids at every 20 meters.

Fire Stopping
Fire stopping provided at junctions between compartmentwalls and floors. Service fire stops in builder's works openings through floors and walls after services or as required through fire resistant walls.

Fire Resistance of Structure
Concrete structure 60 minutes fire resistance.
Steel structure to assembly hall to be fire protected 60 minutes. Beams and fixings' fire resistance achieved through the use of intumescent paint. Columns to be boxed in.

Emergency voice communications points
The emergency voice communications points are shown into MF W[50] Series and indicated with the "disabled refuge remote and base station" symbols (refer to legend). MF W[50] Series illustrates principles only and the detailed design will be undertaken by specialist sub-contractor.

rev	description	date	dr by	ap by
0	FINAL CONSTRUCTION ISSUE	18.03.10	MH	AS

original by: KL — 04.04.08 — AS

Aedas

client: [redacted]

project: **New School**

drawing: **Third Floor Fire Strategy**

plot date:

project number: **2007 . 00142 . 000**

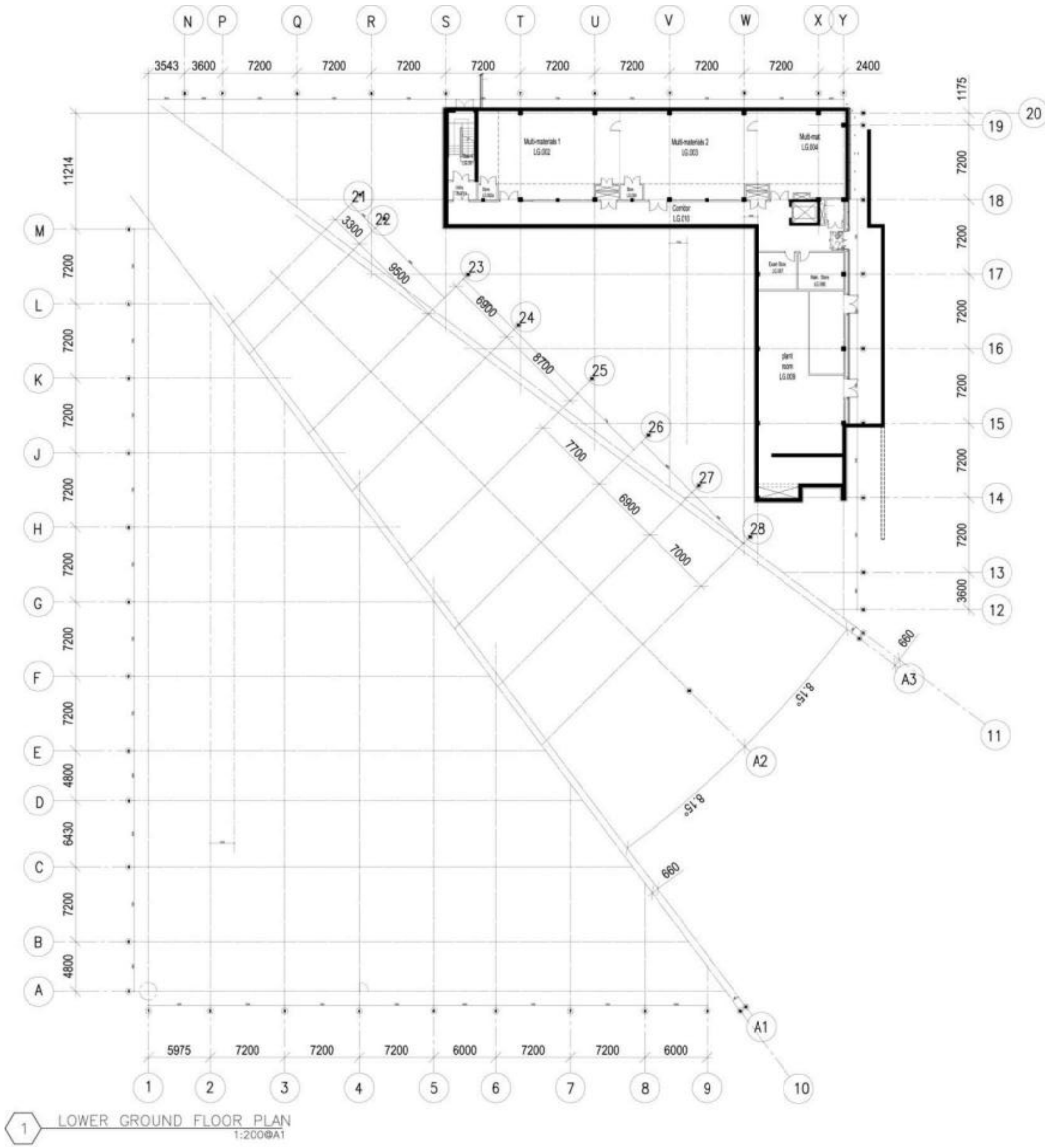
scale: **1:250**

drawing number: **20.164**

rev: **0**

issue status: **CONSTRUCTION**

BUILDING E



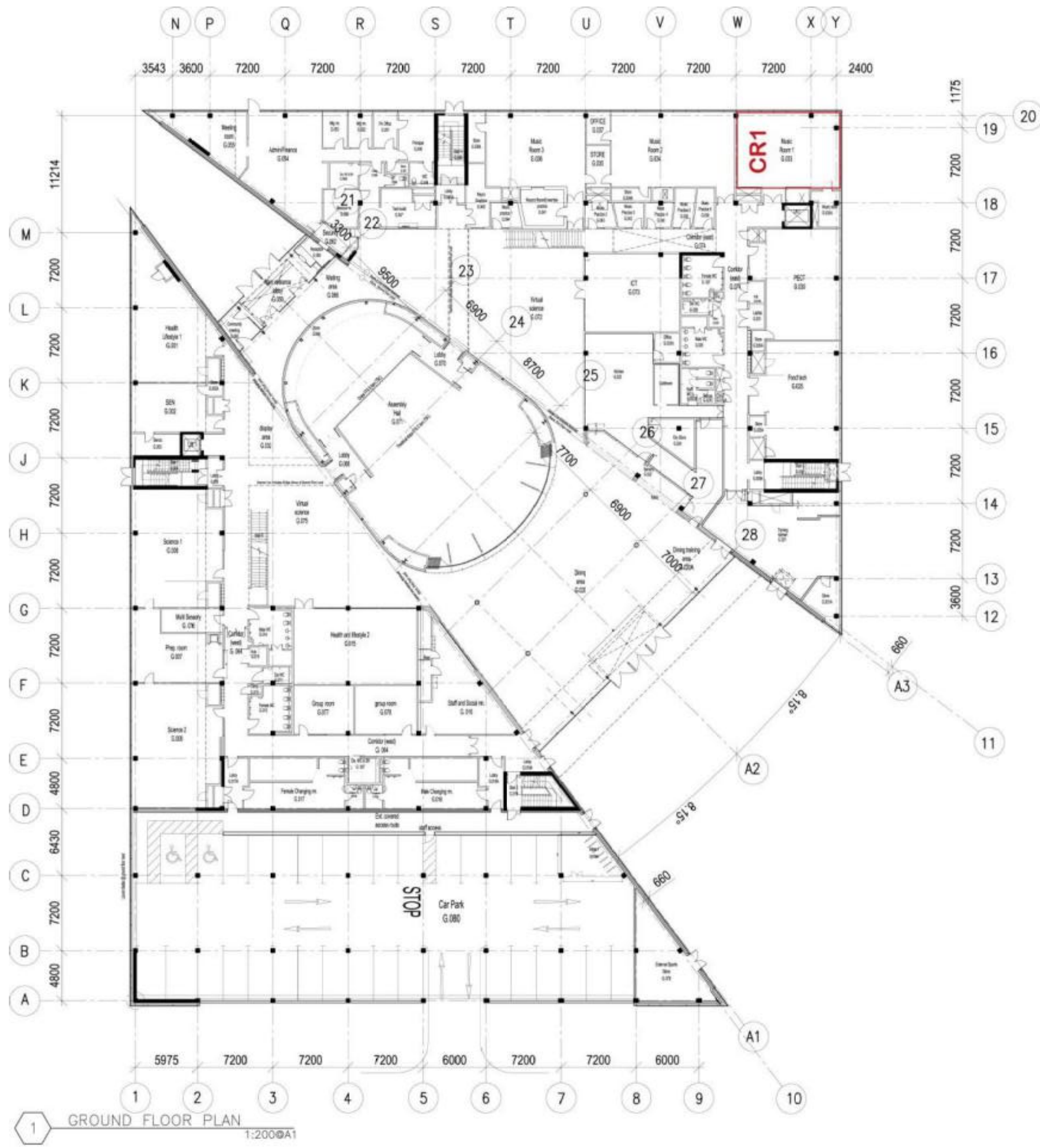
H	AsBuilt issue	3-8-2007	
original by	JL	03.05.05	

Aedas

client: DfES & The Jack Petchey Foundation

drawing: Lower ground floor

computer file: 2004-0425-A00100	plot date: 3-8-2007	
project number: 2004.0425.00	scale: 1: 200@A1	
drawing number: A 00 100	rev: H	issue status: As Built



1 GROUND FLOOR PLAN 1:200@A1

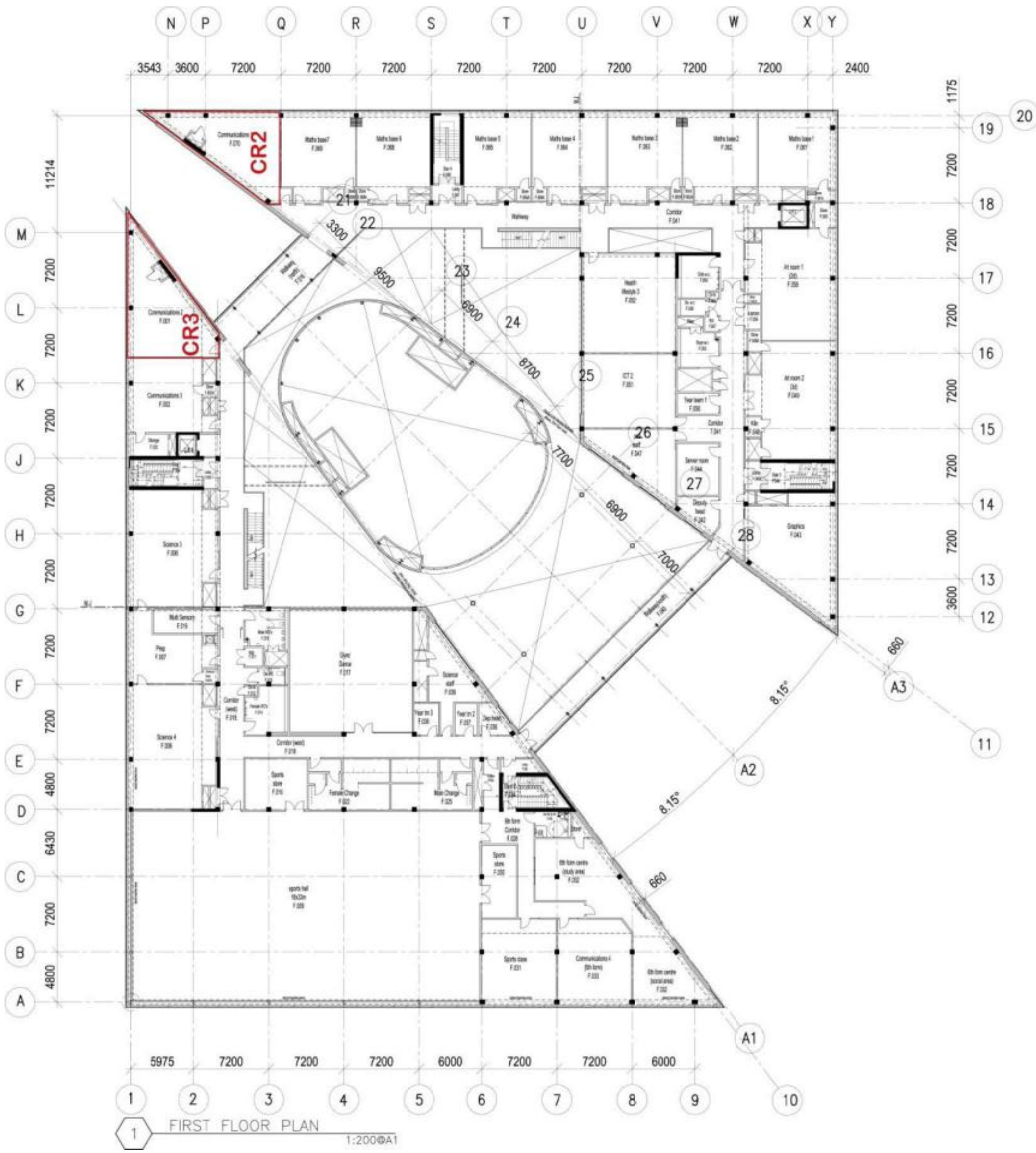
J	As Built Issue	3-8-2007	DD	RH
JL		03.05.05		

Aedas

client: DfES & The Jack Petchey Foundation

drawing: Ground floor plan

computer file: 2004-0425-A00110	plot date: 3-8-2007	
project number: 2004.0425.00	scale: 1: 200@A1	
drawing number: A 00 110	rev: J	issue status: As Built



G	As Built Issue	3-8-2007	DD RH
JL		03.05.05	

Aedas

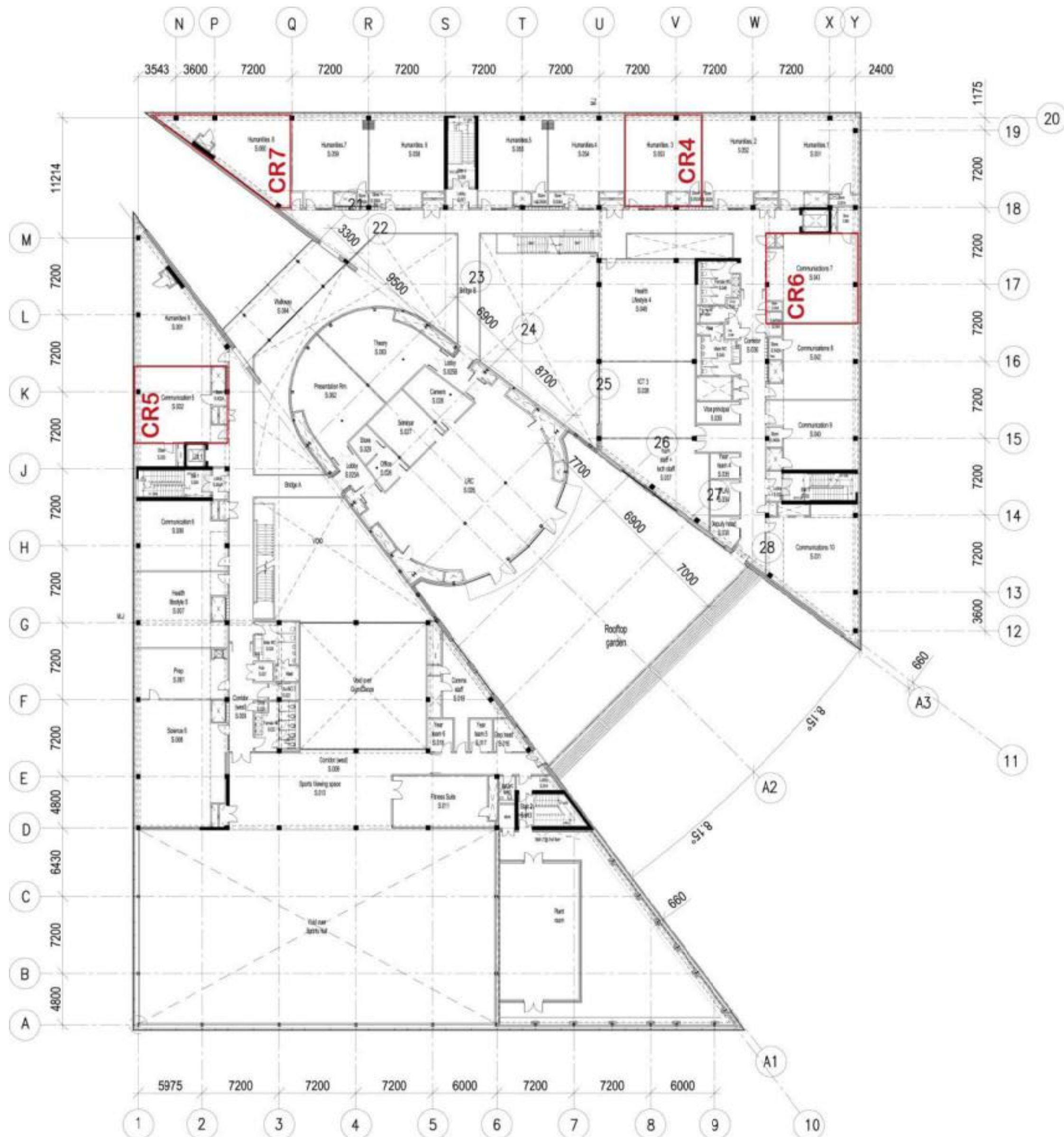
Aedas Architects

client
DfES & The Jack Petchey Foundation

project

drawing
First floor plan

computer file	plot date
2004-0425-A00120	3-8-2007
project number	scale
2004.0425.00	1:200@A1
drawing number	rev / issue status
A 00 120	G / As Built



SECOND FLOOR PLAN
1:200@A1

rev	description	date	dr by	ap by
G	As Built issue	3-8-2007	DD	RH

originated by: A. — 03.05.05

Aedas

client: **DfES & The Jack Petchey Foundation**

project: [redacted]

drawing: **Second floor plan**

computer file: 2004-0425-A00130	plot date: 3-8-2007
project number: 2004.0425.00	scale: 1: 200@A1
drawing number: A 00 130	rev: G — issue status: As Built