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A comparative study of benchmarking approaches for non-domestic buildings: Part 2 – Bottom-up approach

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Abstract

The bottom-up methods for energy benchmarking aim to derive a yardstick for energy performance based on a theoretical analysis of a building. While the top-down methods drive performance improvement by ranking a building against its peers, the bottom-up methods are focused on the building's specific context. Consequently, the bottom-up methods can help identify how performance improvement could be materialised. These two complementary approaches can improve design practice and facilities' management. Two bottom-up methods that could be used for energy benchmarking have been reviewed using UK schools as case studies: Building physics and aggregated end-use. The aim is to demonstrate how these methods could be used for benchmarking and identify their benefits and limitations. When all energy components are included in a model under expected operating conditions, the building physics method can be used to establish a *baseline* for energy performance. It is demonstrated that where this method is used under standardised operating conditions and is subject to minimum energy performance requirements, as prescribed by the Energy Performance of Buildings Directive (EPBD), it can be used to establish a *benchmark* for energy performance. It is also shown how aggregated end-use methods such as CIBSE TM22 can be used to define *system level benchmarks*, and identify the root causes for discrepancy between measured performance and design intent in a systematic way.

Keywords: Energy benchmarks; Non-domestic buildings; Schools; EBPD; CIBSE TM22

1. Introduction

Buildings constitute a large part of total energy consumed worldwide. For example, energy consumption of building stock accounts for 40% of total final energy use and 36% of total CO_2 emissions of the EU member states (European Commission, 2008). Therefore, improving energy efficiency of buildings is one of the key objectives to address the challenges of climate change and energy security (Carvalho, 2012). Energy benchmarking is a useful method to inform building designers, facility managers, building owners and other stakeholders as to how a

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building is performing and what could be done to improve its energy efficiency. Currently, most mainstream benchmarking programmes are based on comparative analysis of the measured energy use of a building against other existing buildings (Perez-Lombard et al., 2009). These programmes are based on top-down benchmarking methods. These methods are dependent on statistical analysis of sample of buildings with similar, but not necessarily identical, characteristics to the building (Hong et al., 2014). While some characteristics are often shared between a building and the representative sample used for benchmarking, the building may possess unique architectural and system characteristics that are not effectively represented in the sample. The bottom-up methods, on the other hand, can help set yardsticks for energy performance of a building based on a theoretical analysis of the building including specific characteristics that may not be fully captured by top-down methods. This theoretical performance is derived from a model, which is *perceived* to represent the building's specific context. Therefore, the success of these methods in producing contextualised benchmarks depends on the accuracy of the models used. If the model is accurate, the bottom-up methods can also be used to identify improvement opportunities in energy efficiency, and for building diagnostics.

In this paper, two bottom-up methods that are widely used for energy analysis and could also be applied to benchmarking are reviewed: the building physics method and aggregated end-use. The aim is to investigate how these methods could be used for energy benchmarking, and identify their benefits and limitations. The methods are applied to a sample of educational buildings in the UK. Energy efficiency of these buildings has also been compared against their peers in accordance with the top-down methods presented in Part 1 (Hong et al., 2014) to provide a holistic picture of energy benchmarking methods for buildings.

The building physics method underpins the thermal models that are widely used to demonstrate compliance with building regulations, satisfy the requirements of sustainability rating systems, predict and analyse energy performance. This is the most commonly used bottom-up method for energy analysis thanks to ever-increasing role of computer programming in building performance analysis. The aggregate end-use method is also used for energy performance analysis and building diagnostics. The premise of this paper is that both methods can be used for energy benchmarking.

2. Methodology

First, the underlying principles of the bottom-up methods are reviewed. Next, it is explained how the application of these methods to benchmarking has been investigated in this study.

2.1. Building physics method

The building physics method estimates energy use of a building through mathematical equations that relate physical properties of the building such as external envelope's thermal characteristics, building's air permeability, type and efficiency of heating, ventilation and air conditioning systems, intensity of lighting and building services control properties to the building's energy use under specific climatic conditions. Carriere et al. adopted this method using DOE-2 calculation engine to evaluate the energy saving potential of large buildings (Carriere et al., 1999). Federspiel et al. used a series of mathematical equations to construct minimum Energy Use Intensity (EUI) for laboratory buildings (Federspiel et al., 2002). Most commercially available software packages provide user-friendly front-ends to model building geometry and define physical properties. The building is divided into thermal zones. Consequently, physical properties, building services characteristics and control attributes could be refined per zone. External weather conditions could be defined either on a monthly average basis, or on an hourly basis used in Dynamic Simulation Modelling (DSM) (CLG, 2011).

While dynamic building simulations could be beneficial in determining trade-offs between various equipment or building service strategies, the accuracy of some uncalibrated models could be very low (Norford et al., 1994; Ahmad and Charles, 2006). Calibrated building simulation could be used to increase the accuracy of the building physics model for existing buildings (Haberl and Bou-Saada, 1998; Raftery et al., 2011; Heo et al., 2012).

One of the potential root causes for inaccuracy is the operating conditions that must be defined for the calculations. Examples include building occupants' density, occupancy profile, temperature set points, windows' position and operating schedules of building services. These operating conditions are generally influenced by building users and are very difficult to predict for new buildings or establish for existing buildings with precision. Small power and equipment load used by building users also have an impact on building's energy performance and are often not fully captured for building physics calculations (Menezes et al., 2013).

Generally, there are two mainstream approaches to deal with the uncertainties associated with operating conditions. First, to use the best estimation for operating conditions based on all available information. Scenario and sensitivity analysis may then be used to determine the effect of changes in operating conditions on energy performance (Lomas and Eppel, 1992; Macdonald et al., 1999; Demanuele et al., 2010).

Second, to use standardised operating conditions for energy performance calculations regardless of actual conditions.

An example of the first approach 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, 2013). 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 outcome of a building physics 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 design projections. 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, is 92%. This suggests the whole-building simulation policy based on expected operating conditions is working at macro level (NBI, 2008).

An example of the second approach to deal with the uncertainties of operating conditions is the Energy Performance of Buildings Directive (EPBD) in the European Union. Article 3 of this Directive requires every EU member state to apply a methodology to calculate the energy performance of buildings. Energy Performance of a building is defined as follows (EU, 2003, p. 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). For example, the UK National Calculation Methodology (NCM) is used to demonstrate compliance with the Building Regulations and produce Energy Performance Certificates (EPC). Calculation engines developed based on this method calculate heating, hot water, cooling, auxiliary, and lighting end-uses under standardised operating conditions defined for different activity types. An allowance is made for equipment load solely to estimate heating and cooling loads and is subsequently excluded from energy performance calculations (CLG, 2011). Consequently, contrary to ASHREA 90.1, thermal models developed in accordance with the UK Building Regulations do not represent all energy end-uses and are based on standardised operating conditions that may significantly differ from actual conditions. Scarce resources exacerbated by the current economic climate often mean clients are reluctant to pay anything above what is required to meet regulatory requirements. Therefore, energy performances derived from the building physics method in the UK are often not directly comparable with total measured energy performance. This makes it difficult to use building physics models as baselines for energy performance (Burman et al., 2014).

CarbonBuzz is a collaborative research platform to collate data from construction projects and engage stakeholders in narrowing design vs. operational performance gap (CarbonBuzz, 2014). Educational buildings constitute the largest statistical sample currently available in CarbonBuzz with 80 buildings. The median of the measured energy performances reported for schools and seasonal buildings in this platform is almost 50% higher than the calculated performance (CarbonBuzz, 2014). While this may be an anecdotal evidence for building procurement and management issues, as most calculations reported in this platform are based on the UK NCM, these calculations cannot be used for like-for-like comparison between theoretical and measured energy performance. Using theoretical performance derived under the EPBD/NCM framework for baselining energy performance could be misleading. The possibility of adjusting and using these calculations for benchmarking will be explored in this paper.

2.2. Aggregated end-use method

The basis of the aggregated end-use method is to calculate energy use of all end-uses and, thereby, total energy use by identifying and estimating their contributing factors. Fig. 1 illustrates this methodology for lighting and ventilation systems.

A procedure called the Office Assessment Method was originally developed based on this approach for offices (Field and Jones, 1994). It was subsequently used in PROBE studies to estimate energy end-uses of non-domestic buildings and reconcile these estimates with measured performance (Cohen et al., 2001). This procedure is now called CIBSE TM22 and is the Chartered Institution of Building Services Engineers’ standard energy assessment and reporting method (CIBSE, 2006).

The difficulties associated with the use of building physics models for baselining energy performance in the UK are compounded with some evidences of shortcomings in front-end software accuracy and consistency (Raslan and Davies, 2009).The aggregated end-use method has, thus, been cited as the most accurate method for predicting energy performance (Carbon Trust, 2011).

A new version of TM22 tool has been developed and is being used in the Building Performance Evaluation Programme funded by the Technology Strategy Board (TSB, 2014). The previous versions of TM22 were predominantly used for high level and intermediate level energy assessments of existing non-domestic buildings or detailed assessments that involved reconciliation of end-use energy estimations with metered data. The new version includes additional functionalities, including, estimation of energy performance at design stage for new buildings and quantifying energy saving opportunities for existing buildings.

This method helps differentiate the contributing factors to end-use energy consumption in a systematic way and, therefore, could be used to define system level benchmarks.

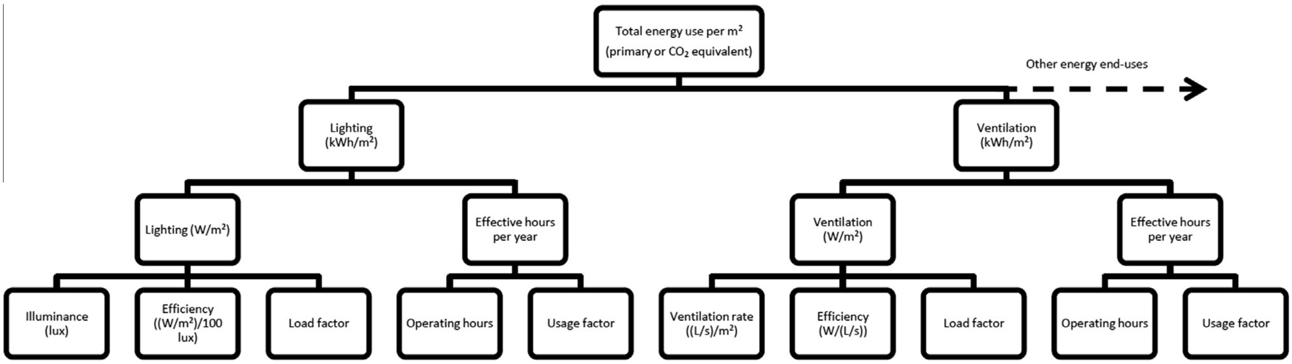

Fig. 1. Illustration of the aggregated end-use method adapted from Field et al. (1997) based on the latest tool developed in accordance with this method (TSB, 2014).

2.3. Application of bottom-up methods to benchmarking

Following inception of the Energy Performance of Buildings Directive, the National Calculation Methodology was developed for Building Regulations compliance and energy performance calculations in England and Wales. The cornerstone of compliance calculations is a comparison between the estimated energy performance of a building with energy performance of a notional building that possesses the minimum specification prescribed by the current version of the Building Regulations. If the energy performance associated with fixed building services (i.e. heating, hot water, cooling, auxiliary energy and lighting) is not greater than that of the notional building, a building is deemed to comply with the whole-building energy performance criterion of the Building Regulations. There are additional requirements for conservation of fuel and power in the Building Regulations (HM Government, 2013). One is the requirement to comply with minimum energy efficiency requirements related to building fabric and fixed building services. Therefore, the Building Regulations in England and Wales set out the minimum energy efficiency requirements for specific thermal elements and building services in addition to an overall cap for theoretical energy performance associated with fixed building services. Building designers can exercise their freedom of choice for system type and energy efficiency within these limits. Minimum energy efficiency requirements and whole-building energy performance targets are updated with every new version of Building Regulations.

Building physics models developed to demonstrate compliance with these regulations reflect actual geometry, proposed building fabric, proposed building services and efficiencies. These models estimate energy performance of fixed building services under standardised operating conditions. Standardised operating conditions are generally consistent with energy efficient operation. For example, the heating set point prescribed for classrooms over working hours is 18 °C. A 5:00–18:00 operating schedule 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 and Wales. Post-occupancy observations on the case studies reported in this paper confirm that most activities outside normal operating hours constitute partial use of schools by a fraction of nominal occupants, often less than 10% of nominal maximum occupancy in large modern schools constructed under Building Schools for the Future (BSF) programme. 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, it appears that the standardised operating conditions assumed in the National Calculation Methodology are consistent with the normal operating hours and energy efficient use of buildings. The main methodological hurdle to test feasibility of using outcomes of NCM calculations for benchmarking is that small power and equipment loads are not included in total energy performance reported for buildings. However, an allowance is made for these loads to estimate heating and cooling energy. Excluding these loads where a decision is to be made about compliance of a building and its fixed building services with the regulatory requirements may be justified. However, the heating and cooling energy reported in final compliance reports are dependent on the equipment load assumed and, therefore, it is reasonable to integrate the energy use associated with this load into total performance for benchmarking purposes. Furthermore, an allowance will have to be made for miscellaneous loads not allowed for in compliance calculations such as external lights, lifts and special energy use if applicable.

To test the feasibility of using building physics models compliant with the EPBD/NCM for benchmarking, the following criteria are proposed:

- 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 lower benchmark (CIBSE, 2012). Therefore, total energy performance calculated by building physics models for buildings constructed after inception of the EPBD should be better than the 25th percentile of national building stock when an allowance for equipment and miscellaneous loads is included.
- Post-occupancy evaluations help identify procurement and operational issues related to energy performance. The energy benchmarks derived from EPBD/NCM calculations are only acceptable if the bulk of the difference between measured performance and energy benchmark could be quantitatively attributed to the identified inefficiencies. However, it is expected that deviations from standardised conditions also account for part of this difference.

It should be noted that NCM calculations carried out on completion of buildings must reflect the as-built status, including any procurement issues. However, the investigations on the case study buildings included in this study showed this is often not the case. The final Building Regulations and energy performance calculations of these buildings reflect the most notable outcomes of building completion and commissioning such as pressure test results. However, more subtle procurement issues can go unnoticed and designers and contractors, under usual time and resource pressure towards the end of their projects, often assume the design intents have been met. Therefore, where feasible, the effects of both procurement and operational issues must be quantified with building physics models.

3. Case studies

The Building Performance Evaluation programme provided the opportunity to collate measured energy performance data from a number of educational buildings in England and investigate the post-occupancy operation of these buildings. First, an overview of the case study buildings is presented. Next, the sequence of operations carried out on the case studies to investigate the application of bottom-up methods to benchmarking is explained.

3.1. The context

Four schools, procured under the BSF programme and constructed in accordance with the Building Regulations 2006, were subject to a two-year post-occupancy evaluation. Actual energy performances of all buildings were established using energy bills and installed meters. The outcomes of the Building Regulations compliance and energy performance calculations were available to the research team.

Table 1 provides background information about the case studies used for this study.

3.2. Applying the benchmarking methods to the case studies

The following steps were undertaken to apply the bottom-up benchmarking methods:

Table 1
Background information about the case study buildings.

Building type,location, and nominal occupancy	Year built	Gross internal area (m^2)	HVACstrategy	Term time operating schedule for heating systems	
A: Academy, North West England, 1250 occupants (pupils and staff)	2008	10,418	Mechanically ventilated, Ground Source Heat Pumps supplemented by gas-fired condensing boilers for heating, limited cooling to ICT enhanced spaces is provided by chilled beams served by GSHP	Monday, Wednesday, Friday: 6:00–18:00	Tuesday and Thursday: 6:00–21:00
B: Sixth Form, North West England, 350 occupants	2010	2843	Mechanically ventilated, gas-fired condensing boilers for heating, variable refrigerant flow system for ICT enhanced spaces, solar thermal panels for domestic hot water	Monday, Wednesday, Friday: Pre-heating: 4:00–6:00, heating: 7:00–17:00	Tuesday and Thursday: Pre-heating: 4:00–6:00, heating: 7:00–20:30
C: Academy, North East England, 1200 occupants	2009	10,172	Mixed-mode ventilation (natural ventilation boosted by extract fans), biomass-boiler supplemented by gas-fired condensing boilers for heating, cooling and mechanical ventilation provided to ICT enhanced spaces and core areas	Monday to Friday: 7:00–17:00	
D: Secondary School, East London, 2000 occupants	2010	14,610	Natural ventilation, ground source heat pumps supplemented by gas-fired condensing boilers for heating, cooling and mechanical ventilation provided to ICT enhanced spaces and core areas	Monday to Friday: 8:00–17:00	

- Total energy performances of fixed building services under standardised conditions, produced following completion of the buildings, were adjusted to allow for equipment and miscellaneous loads. The standardised equipment loads for the buildings were extracted from the Energy Performance Certificate files lodged with the national register (Landmark, 2014). An allowance was made for external lights following ASHRAE 90.1 guidelines (ASHRAE, 2007). An allowance was also made for lifts based on the number of lifts, their power ratings, and expected hours of operation.
- The adjusted energy performance was compared with the measured energy performance for each building. The metric used for total performance in the UK is carbon dioxide emissions. For each fuel, the same carbon emission conversion factors used in building physics models were applied to the measured performance.
- For each building, the adjusted performance under standardised conditions was compared to the 10th percentile, 25th percentile, and median of national stock derived from the statistical analysis reported in Part 1. The same carbon emission conversion factors used in building physics models were applied to national building stock.
- Schools with the best and worst measured performances were selected for further investigation. As the original building physics models were not available, the research team developed new models for these two buildings using IES Apache dynamic simulation tool (Fig. 2).
- The building physics models were calibrated with actual performance. The calibration process followed the principles outlined in the International Protocol for Measurement and Verification (DOE, 2002). Reasonable consistency between calculated and measured power demand curves, mean bias errors of less than 10% for monthly fossil thermal and electrical use, and less than 7% discrepancy between the measured and modelled annual performances were achieved. Burman et al. provide detail description of the calibration process for Building A (Burman et al., 2013).
- There were discrepancies between fabric *U* values reported in the Building Regulations compliance reports and as-built *U* values. The initial models used maximum allowable *U* values to assess the performance under the so-called ‘worst case scenario’ and the *U* values were not updated for final calculations after completion of the buildings. As-built average *U* values in both buildings are lower than the Building Regulations limits and ther-

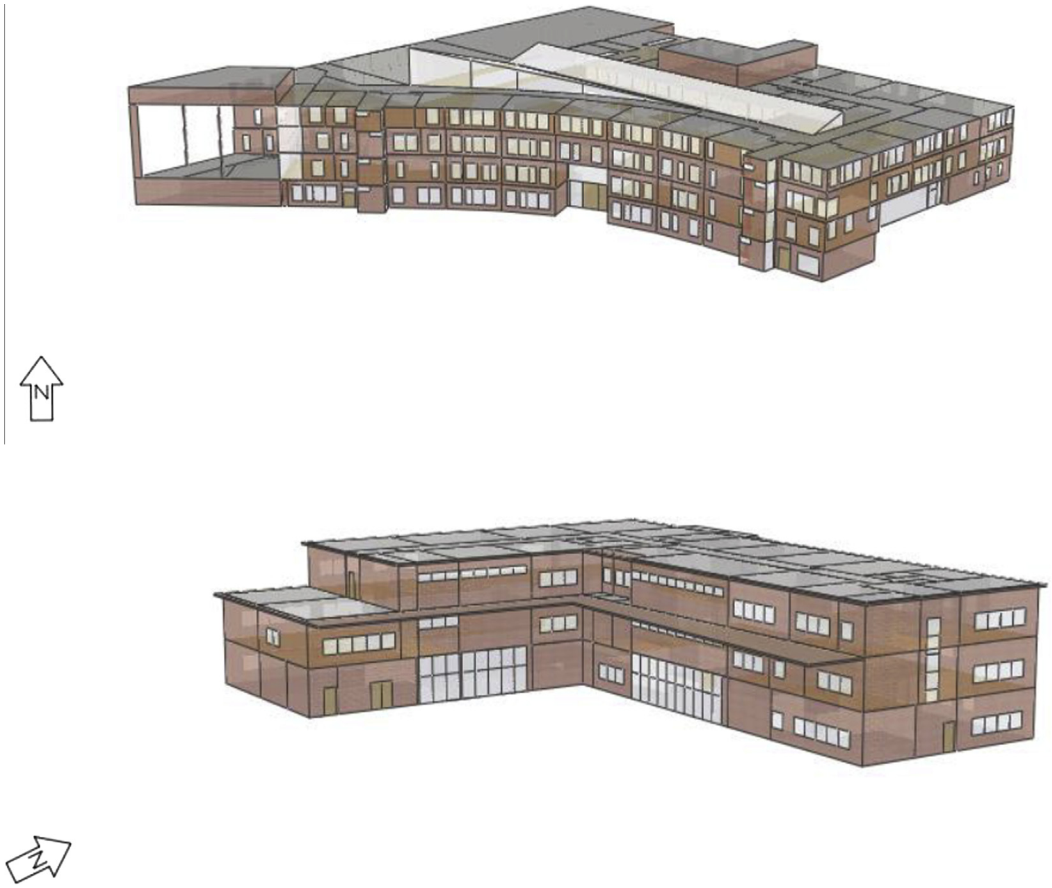

Fig. 2. Axonometric view of the building physics models developed for Buildings A (top) and B (bottom); both buildings are fully exposed with no adjacency.

mal imaging did not point to any serious shortcoming in the build quality or thermal bridging. Therefore, the calibrated models were used to re-establish the NCM performance based on as-built *U* values. Other settings in the calibrated NCM performance were consistent with the design intents. Consequently, as the effect of as-built fabric was factored in the calibrated models, it was expected that building services performance and their control settings account for the most part of the discrepancy between measured performance and calibrated NCM benchmarks.

- The calibrated models were then used to quantify the effects of procurement issues and operational inefficiencies observed throughout the post-occupancy studies. The effects of two scenarios on energy performance were investigated with the calibrated models:
  1. It was assumed that none of the uncovered procurement and operational issues exists, and the calibrated models were adjusted accordingly. The outcome is a theoretical performance that could have been achieved had the procurement process and building management been optimal for energy efficiency. If this theoretical performance is reasonably close to the NCM adjusted performance, it can be concluded that the NCM adjusted performance is a good benchmark for energy performance.
  2. Once a building is completed and building services commissioned, it is often not practical and cost effective to address all procurement related issues. For example, ductwork installation has an impact on total system pressure drop and thereby specific fan power. Therefore, it may not be practical to reduce system specific fan power to the design target after completion. Consequently, in the second scenario it is assumed that only operational issues are addressed to assess energy performance potential of buildings after completion.
- Finally, as both best and worst performers were schools with mechanical ventilation strategy, the aggregated end-use method was used for system level benchmarking to explore why energy use of ventilation systems in these buildings varies significantly.

4. Outcomes

The outcome of the stock-level analysis is presented first followed by building physics and aggregated end-use analysis. Next, an overview of the key lessons learned is presented.

4.1. Stock-level analysis

Fig. 3 compares the calculated performance of each building under Building Regulation standardised conditions with its measured performance, and to the measured performance of the national stock. The heating energy is weather corrected in all buildings.

The largest discrepancy between calculated and measured performances belongs to Building C. This is mainly the result of switching from biomass to gas-fired boilers following operational and maintenance issues experienced with the biomass boiler in this building. The worst and the best performers in terms of measured energy performance are Buildings A and B respectively. Therefore, these two buildings were selected for further investigation.

Fig. 3 also shows that the calculated performance in Building A is close to the 25th percentile of the national stock, and the calculated performances of the other buildings are comparable to the 10th percentile of the national stock.

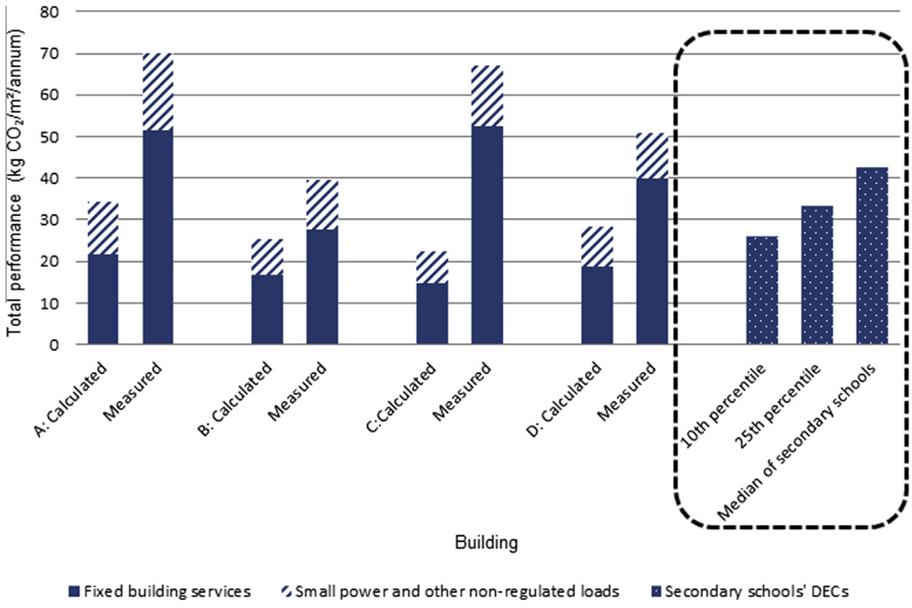

Fig. 3. Total performance of the case studies compared to the national building stock.

4.2. Building physics analysis

Table 2 includes a summary of the major procurement and operational issues uncovered during post-occupancy studies for Building A.

Fig. 4 illustrates the process of using a calibrated model to re-establish the NCM performance and perform scenario analysis for Building A. When all issues listed in Table 2 are resolved in the calibrated building physics model, the performance of the fixed building services is almost identical to the NCM benchmark. However, total performance associated with this scenario is 31% higher than the NCM benchmark mainly because of equipment energy use. The equipment energy use is almost 68% higher than the allowance made in the NCM benchmark. Actual equipment load is used in the calibrated model and for scenario analysis, whereas standardised equipment load is used for the NCM benchmark. Excess in equipment energy use in Building A over the benchmark is expected given the ICT infrastructure installed and the amount of equipment left ON out of hours.

Table 3 includes a summary of the major procurement and operational issues uncovered during the post-occupancy studies for Building B.

Fig. 5 illustrates the process of using a calibrated model to re-establish the NCM performance and perform scenario analysis for Building B. When the issues listed in Table 3 are resolved in the calibrated building physics model, all energy end-uses are close to the NCM end-uses. Total performance associated with this scenario is only 4% higher than the NCM benchmark. Scenario analysis also reveals that the effect of procurement issues has not been detrimental to energy performance and the as-built school has the potential to perform within 7% of the NCM benchmark.

4.3. Aggregated end-use analysis

Buildings A and B are both mechanically ventilated, constructed in accordance with the same version of the Building Regulations, and yet display different levels of

Table 2
Major procurement and operational issues uncovered in Building A.

Procurement issues	Issues related to the operating conditions
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.	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.
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.	The heating and ventilation zoning were not used to isolate parts of building not in use during night schools and extracurricular activities.
Actual fresh air ventilation rate was 73% higher than what is required.	Maintenance issues: dirty air filters and other problems related to maintenance increased total system pressure drop by 20% (system pressure drop was calculated based on sub-metered fans' energy use and fans' absorbed power).
Lighting automated controls were NOT commissioned properly: inconsistent and long time-offs (> 20 minutes) for presence and absence detection sensors; high sensitivity; poor zoning.	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.

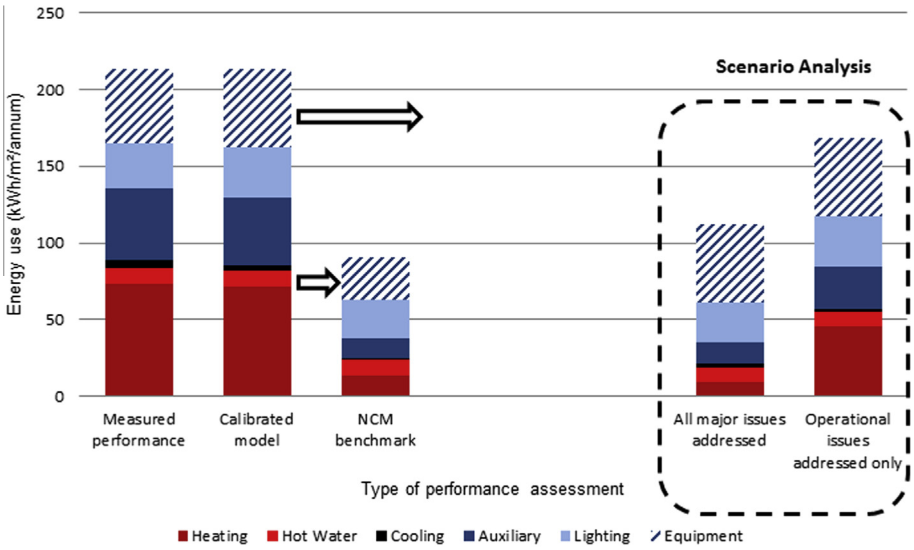

Fig. 4. NCM benchmark and scenario analysis derived from calibrated model for Building A.

Table 3
Major procurement and operational issues uncovered in Building B.

Procurement issues	Issues related to the operating conditions
Gas-fired boilers were NOT operating in condensing mode; the hot water flow temperature in the 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 NCM set points in the spaces served by gas-fired boilers. Furthermore, the variable refrigerant flow units were programmed to maintain 21 °C. This compares with NCM heating set point of 18 °C and cooling set point of 23 °C for classrooms, where comfort cooling is provided.

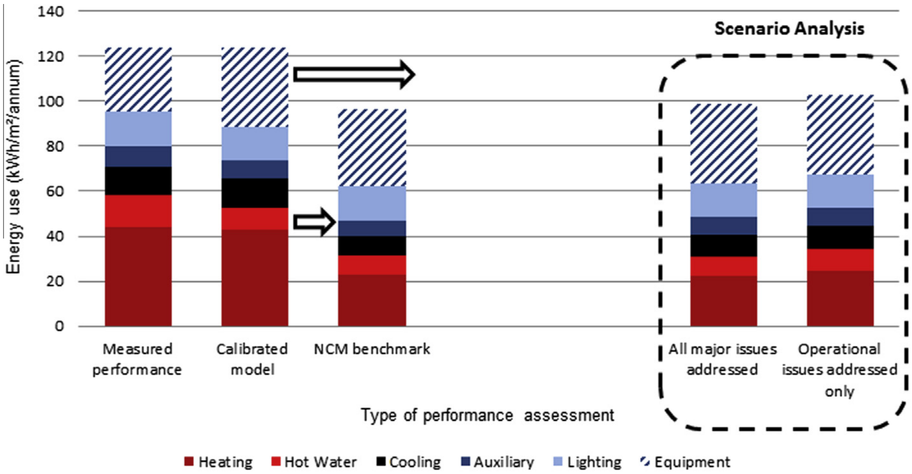

Fig. 5. NCM benchmark and scenario analysis derived from calibrated model for Building B.

energy performance. While the measured performance of auxiliary energy use in Building A is significantly higher than the NCM benchmark, the measured auxiliary energy use in Building B is very close to it. 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, the aggregated end-use method was used for system level benchmarking of the main air-handling units supplying fresh air to building occupants in these buildings.

Table 4 includes the outcomes of the detailed analysis of these systems following the tree diagram depicted in Fig. 1. 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 in 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

Table 4
TM22 system-level benchmarking for Buildings A and B.

Building	Ventilation rate (L/s)/m^2	Efficiency (W/(L/s))	Load factor	Annual operating hours	Usage factor	Ventilation (W/m^2)	Effective hours per year	Ventilation (kWh/m^2/annum)
A: actual	1.66	3.82	1.20	3454	1.00	7.61	3454	26.3
A: benchmark	0.96	2.50	1.00	2318	0.56	2.40	1298	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	3089	0.15	6.47	463	3.0
B: benchmark	0.98	1.50	1.00	2318	0.56	1.47	1298	1.9
B: actual/ benchmark	2.32	1.90	1.00	1.33	0.27	4.40	0.36	1.58

Notes:
(1) Actual values are based on the commissioning results (building A), final specification (building B), and post-occupancy evaluations (both buildings). Fans energy use is sub-metered in both buildings.
(2) Benchmark sources: Ventilation rates were calculated based on nominal occupancy and BB101 requirements for fresh air (DfES, 2006). Efficiencies were extracted from the Building Regulations compliance calculations. Annual hours of use were calculated based on normal working hours for schools plus extracurricular activities (e.g. night schools).

factor in Building A was derived from the measured fan energy use. In Building B the efficiency is quoted 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. According to the fan Cube Law, fan power varies as the cube of its speed and, therefore, a low usage factor for Building B is expected (CIBSE, 2005). Actual usage factor in Building B was derived from the measured fan energy use. 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. The decision to install mechanical ventilation systems in both buildings stems from external ambient noise levels. Therefore, operable windows are not the main means of controlling CO_2 levels. Furthermore, a number of classrooms and office spaces are located in the core spaces that have not direct access to external facades. Consequently, for benchmarking purpose and in accordance with the design intent, it is 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 Equation 1. An empirical equation was used to estimate power at part load, to allow for operational losses that lead to fan powers higher than what is predicted by the theoretical Cube Law (ASHRAE, 2007).

$$\begin{cases} Q = 0.5 \times Q_{100\%} & \text{if } O \leqslant 0.5 \\ Q = O \times Q_{100\%} & \text{if } O > 0.5 \end{cases} \tag{1}$$

$$P = 0.0013 + 0.1470 \times \left(\frac{Q}{Q_{100\%}}\right) + 0.9506 \times \left(\frac{Q}{Q_{100\%}}\right)^2 - 0.0998 \times \left(\frac{Q}{Q_{100\%}}\right)^3 \tag{2}$$

where, O: is Occupancy level (0–1), Q: flow rate (m^3/s), $Q_{100\%}$: flow rate at full load (m^3/s) and P: fraction of full-load fan power.

Fig. 6 shows how usage factor could be established for a typical school day. The occupancy profile used is the NCM standard profile for classrooms. This occupancy profile is a good approximation of occupancy patterns in schools and is broadly consistent with the post-occupancy observations in Buildings A and B. Fifty per cent occupancy level between 12:00 and 14:00 is well justified given the lunchtime break, and pupils spending time in atrium space or school courtyards.

To calculate the average usage factor for one year, night schools and extra-curricular activities should also be taken into account. The following equation was used to work out the benchmark usage factors listed in Table 4.

$$\mathit{Usage\ factor} = 1/n\sum_{i=1}^{i=n} 1/h_i \sum_{o=1}^{o=h_i}\left(\left(\frac{P_o}{P_{100\%}}\right)\right) \times \Delta t_o \tag{3}$$

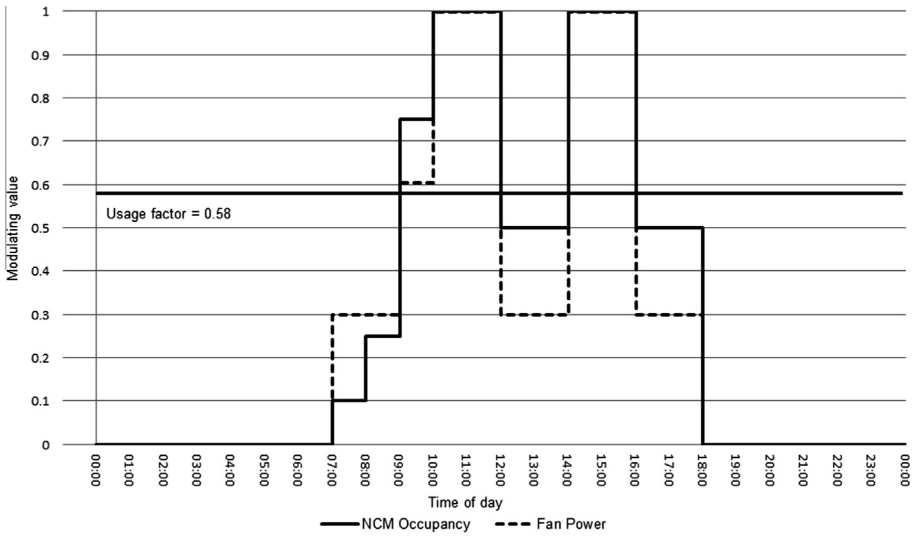

Fig. 6. Usage factor related to demand controlled ventilation for a typical school day.

where, Usage factor: is related to demand controlled ventilation, calculated for the whole year, D: Demand controlled ventilation rate (m^3/s), P: fan power (W), $P_{100\%}$: fan power at full load (W), t: time (h), h: number of operation hours per day and n: number of days with separate operating hours.

4.4. Lessons learned from the case studies

The case study buildings were constructed after inception of the EPBD, and in accordance with the Building Regulations 2006. The NCM calculated performance of three schools, adjusted for equipment and miscellaneous loads not regulated under the EPBD, is comparable to the 10th percentile of the secondary schools in England and Wales. The calculated performance for Building A is comparable to the 25th percentile of secondary schools, which indicates, even if the design intents were met, this building would be less energy efficient than other buildings in the sample. However, actual energy performance of Building A is significantly worse than the calculated performance. Such discrepancy between measured and calculated performance raises the question whether NCM calculations under standardised operating conditions could be a basis for building benchmarking. The building physics models developed for the schools with the worst and best performances in the sample confirm that the bulk of the discrepancy between measured performance and adjusted NCM calculations could be attributed to the procurement and operational issues identified in post-occupancy studies. Therefore, where actual operating conditions are typical of the building type, standardised NCM calculations for a building could be adjusted and used for benchmarking.

There is huge discrepancy between auxiliary energy in the Building Regulations compliance calculations and the measured auxiliary energy in Building A. Table 2 listed some of the identified root causes for this discrepancy. A bottom up analysis quantified the effects of the issues related to the ventilation component of auxiliary energy in a systematic way. Fig. 7 is an illustration of the results of this analysis and shows how small deviations from individual benchmarks could be compounded and result in a measured performance that is almost ten times the aggregate benchmark.

It is also notable that issues such as increase in ventilation rate, the operating schedule and the failure of demand-controlled strategy have also had adverse impact on heating energy use, which is the other energy end-use with a poor measured performance in Building A.

Building B, on the other hand, is a good example of a low energy mechanical ventilation system. Although the supply fan is oversized and less efficient than the design intent, the inverters are enabled and linked to the CO_2 sensors installed in teaching spaces. This led to a low usage factor for the system and thereby low energy use.

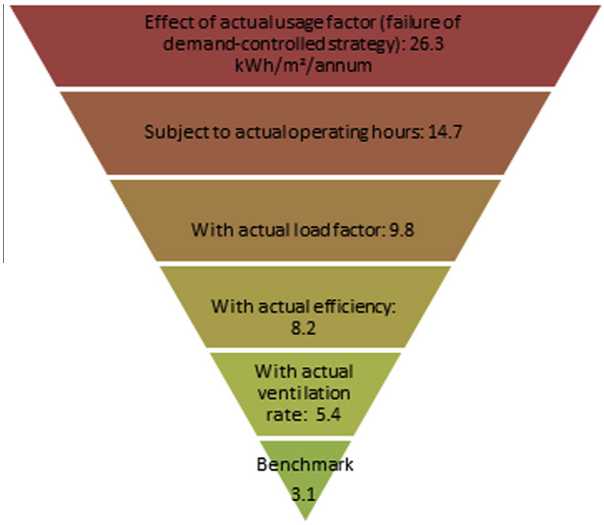

Fig. 7. Evolution of ventilation energy from benchmark to measured performance and the effects of contributing factors: Building A.

4.5. Reflection on the bottom-up methods

Table 5 provides a summary of the benefits and limitations of the bottom-up methods for energy benchmarking.

The building physics method is the only energy benchmarking method that takes into account full geometry, building services and operating conditions. This can help set accurate baselines and benchmarks for energy performance depending on the type of operating conditions defined in the model. However, the quality of input data, calculation engine, and the experience of the user are critical factors in deriving good quality benchmarks. It is necessary to cross check the outcome of this method with top-down methods to ensure the results are reasonable.

The aggregated end-use method is generally useful for system level benchmarking. However, the following methodological issues may hinder the tools developed based on CIBSE TM22 in projecting total energy performance of buildings with reasonable accuracy:

- All versions of TM22 developed so far are for electrical end-use analysis only. The tools developed based on this method allow users to record non-electric end-uses if they are available from sub-meters or estimated by other means. The tool itself, however, does not offer a bottom-up analysis for fossil fuel based end-uses.
- As for Heating, Ventilation, and Air Conditioning (HVAC) equipment, the method is mainly reliant on supply side information (e.g. installed capacities). These systems are often oversized and, therefore, it would be difficult to estimate the absorbed power of the equipment without an evaluation of building demand taking into account building thermal characteristics and climatic conditions. The method does not take into account these aspects of energy performance assessment.

Table 5
Benefits and limitations of the bottom-up methods for energy benchmarking.

Bottom-up methods	Benefits	Limitations
Building physics method (e.g. ASHRAE 90.1, EPBD/NCM)	The only method that takes into account detail geometry of a building, building fabric, and fixed building services.	Where all energy end-uses are not included and operating conditions are not necessarily similar to expected operation (as in EPBD/NCM), adjusting and interpreting the outcomes of building physics models could be challenging.
	The method could yield accurate projections of energy performance if good quality input data is provided.	If operating conditions of a building are significantly different from standardised operating conditions, using EPBD/NCM calculations for benchmarking could be misleading.
	Valuable tool to analyse the root causes of performance issues.	Many parameters are involved; good quality data and experienced thermal modellers are required to get accurate results. The process is also more time consuming than other benchmarking methods.
Aggregated end-use (CIBSE TM22)	Helps identify and separate the contributing factors to energy use.	It is not a ‘whole-building’ benchmarking tool.
	It is well structured and easy to understand.	Does not take into account building fabric and thermal characteristics.
	Valuable tool for end-use energy diagnostics.	It is dependent on usage and load factors that are difficult to establish without systemic evaluation of building demand.

- Usage factors are also often related to building demand. It is not clear from TM22 (CIBSE, 2006) how these factors could be established with reasonable accuracy for different end-uses without systematic evaluation of building’s demand.

A number of techniques are available to overcome some of these problems for an existing building for which good quality data are available. For example, half-hourly electrical demand profiles and monthly electricity bills could be used to estimate loads with strong seasonal variation such as cooling loads, assuming the effects of other loads are also recognised and taken into account (Field et al., 1997). Actual absorbed powers of fixed building services and equipment could also be measured for existing buildings. However, given the above mentioned methodological issues, it is perhaps optimistic to expect good quality projections of energy performance at design stage using this method.

4.6. Complementary approach to benchmarking

A possible combination of the top-down and bottom-up approaches to benchmarking would be to use simple statistical analysis embedded in the DEC scheme to compare a building’s energy performance *to* other peer buildings and use bottom-up methods to compare operational performance of the building *with* its whole-building or end-use performance yardsticks. Where bottom-up methods are based on expected operating conditions, the energy performance yardsticks are effective baselines for energy performance and the measured performance could be directly compared with the theoretical performance. On the other hand, where bottom-up methods are based on standardised conditions and subject to energy efficiency limits, the energy performance yardsticks could be used as benchmarks for energy performance. The measured performance must be close to the benchmark if a building’s use is typical of the building type, building completion is consistent with the design intents, and the building’s operation is efficient. However, as the operating conditions are not identical, some discrepancies from benchmark are expected. The extent of these discrepancies is determined by how intelligently the building is managed outside standardised operating conditions.

5. Conclusions

The Building Regulations compliance calculations performed for four secondary schools constructed post-2006 in England yield performance levels that, when adjusted for equipment and miscellaneous non-regulated loads, are comparable with the 10th or 25th percentile of the national building stock. Furthermore, a significant part of the discrepancy between the actual performance and adjusted compliance calculations of the worst and best performers among these schools was quantitatively attributed to specific procurement and operational issues. It can therefore be concluded that the Building Regulations compliance calculation is a good proxy for efficient building procurement and operation so far as the building’s operating conditions are not too dissimilar to the building type defined in the Building Regulations.

Adopting the tree diagram approach of CIBSE TM22, the contributing factors to fan energy use were identified and the effects of inefficiencies associated with these factors on aggregated performance were analysed. It was demonstrated how small deviations from system benchmarks could be compounded and lead to a measured performance that is almost tenfold the aggregated benchmark with further repercussions for heating energy.

The following key conclusions could be drawn from this comparative study of benchmarking methods (Part 1 and Part 2):

- Display Energy Certificates (DECs) have proved successful in collecting measured energy performance data for public buildings and could help update the existing benchmarks. At building level, they can motivate building users to improve their buildings and save energy. Rolling out DECs to private sector could accelerate the quest for energy efficiency, provide annual feedback about actual performance of the nation's non-domestic building stock, and help develop robust benchmarks for all sectors.
- Complex top-down methods such as regression analysis and artificial neural networks explore relations between building parameters, system characteristics and energy use. They account for some aspects of a building's context that are often not included in simple methods. These methods also have the potential to produce projections of energy performance at early stages of design, to inform designers and various stakeholders. Platforms such as CarbonBuzz can help collate the extensive information required to make best use of these methods in the future.
- The EPBD/NCM calculations could be used for energy benchmarking subject to adjustments for non-regulated loads and applicability of standardised conditions to the building context. However, the process is complex and may not be practical for all buildings. The on-going debate about performance gap and new developments in energy efficiency finance makes it imperative to move from regulatory frameworks to total performance assessment under real conditions. Energy yardsticks derived from this method could be used as baselines for energy performance. ASHRAE 90.1 provides a framework for this type of assessment.
- The extent of performance issues uncovered in post-occupancy studies point to the necessity of measurement and verification of performance after building completion. For a building to achieve its full potential, a concerted action from designers, contractors and building users is required after building handover. More emphasis on performance in-use is required to ensure buildings are fine-tuned after completion and a performance level close to the baseline is achieved.

Recent developments in the field aim to address some of the issues discussed in this paper and could be subjected to future investigation. The introduction of CIBSE TM54 is a

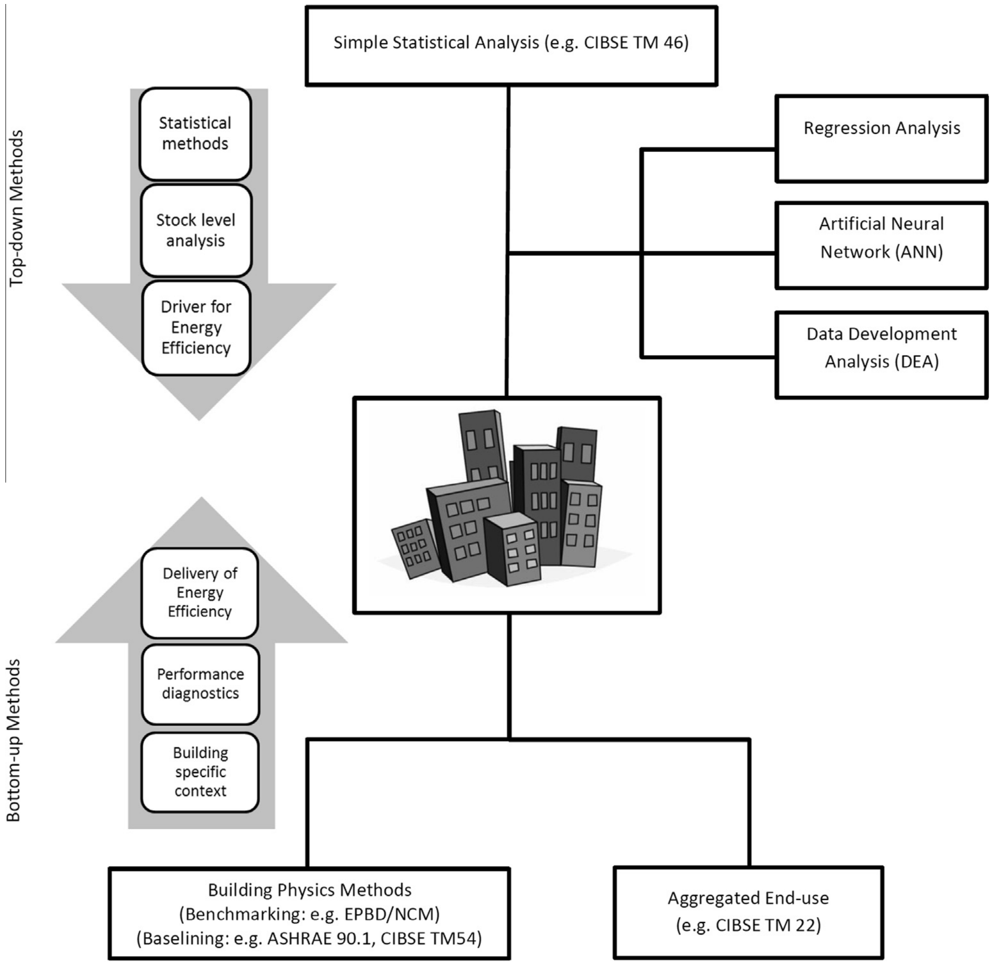

Fig. 8. Illustration of top-down and bottom-up approaches to energy benchmarking for buildings.

timely response to the urgent need for baselining energy performance in the context of the United Kingdom (CIBSE, 2013). As for performance in use, the Education Funding Agency has set out energy measurement and verification requirements for the new Priority School Building Programme (EFA, 2012).

Fig. 8 provides an illustrative summary of the methods discussed in Part 1 and Part 2.

The top-down and bottom-up approaches to benchmarking complement each other and provide a toolbox for performance analysis. The top-down methods benchmark a building against a representative sample of other buildings and therefore could be a driver for energy efficiency. The bottom-up methods, on the other hand, benchmark a building against its own theoretical performance and could be invaluable for system diagnostics and performance improvement.

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