S-Curves to Model and Visualise the Energy Performance Gap between Design and Reality – first steps to a practical tool

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Abstract
New and refurbished non-domestic buildings are failing to live up to their anticipated performance. Shortfalls show in excess energy consumption, high carbon dioxide emissions and other failings in quantitative and qualitative performance metrics. This paper describes the component parts of the performance gap using evidence from building performance evaluations. It introduces a way of visualising the consequences of decisions and actions that are known to compromise performance outcomes using a performance curve methodology (the S-curve) which plots performance, and the root causes of underperformance, from project inception to initial operation and beyond. The paper tests the hypothesis with two case studies. The authors conclude that use of S-Curves could visualise performance problems before they become chronic shortcomings, and could be useful for informing activities on Soft Landings (1) projects.

Keywords Performance gap, energy, Soft Landings, S-curve, visualisation

1.0 Introduction

Post-occupancy evaluations (POE) such as the PROBE (2,3) series of building investigations, government-funded building performance evaluations (BPE) such as the Low Carbon Buildings Performance (LCBP) research conducted by the Carbon Trust (4) and more recently by InnovateUK's 4-year BPE programme (5,6), reveal that new and refurbished buildings suffer from a range of performance shortfalls. These shortfalls are being summarised in the phrase 'the performance gap'.

Post-occupancy research has found energy performance shortfalls between a factor of two and three compared with design forecasts and/or performance benchmarks (7). Some projects can suffer a factor of five greater energy consumption compared with design ambitions (8). However, the tools available for setting more realistic predictions have not been available. Reference benchmarks themselves have come under question for their relevance, accuracy and usefulness (9).

The need for tools to enable building designers to understand better the component parts of a building's energy performance led to the publication of CIBSE *Technical Memorandum 54: 2013 Evaluating Operational Energy Performance of Buildings at the Design Stage* (10). This guide is primarily aimed at the designers and engineers, project managers, and asset managers. All of them play a part in determining the ultimate performance of new and refurbished buildings, and it is vital that performance issues are made visible to them.

The term 'performance' can mean diverse things to different project stakeholders. To a building client performance may be measured in staff retention and low absenteeism rates, while to a facilities manager it may be ease of management and maintenance. To an occupant it may be conditions of the internal environment and the quality of control they can exercise (11). There is no consensus on the definition of the term 'performance gap'. It all depends on the metrics chosen to represent performance. For example, there are moves to create performance metrics for occupant health and productivity (12).

Shortcomings in performance tend to be most apparent in buildings for which energy efficiency and low carbon dioxide emissions (among other sustainability targets) were a key objective. Such buildings tend to have higher ambitions for their subsequent performance and greater attention paid to target-setting. They are innovative in design, adopt multiple forms of low-energy technologies and controls, and overall tend to be technically more complex.

Calculations to set performance targets may be agreed while projects are still in their inception stage, and before the design has been detailed, and the building constructed, handed over, and brought into use. These notional calculations are motivated to a large degree by the requirement to demonstrate compliance with *Part L* of the *Building Regulations* (13). Calculations will therefore be based on design assumptions up to design stage E. The actual energy efficiencies of installed plant or hours of operation and occupants' equipment loads will usually only become known after Stage E when the design is signed-off.

Obtaining a true understanding of the performance gap requires analysis of all other building-related inputs, activities and responsibilities. This paper hypothesises that the key factors that lead to the emergence of a performance gap can be identified and verified using evidence from recent POE and BPE evaluations where the causes of underperformance have been recorded, along with the effects of attempts to mitigate or improve upon that performance. It concludes by proposing an approach by which the various factors can be visualised and tracked during a building project, and gives recommendations for further work.

2.0 Background

Part L2A of the *Building Regulations,* and the second tier documents, the *Approved Documents*, sets out energy performance requirements for new and existing non-domestic buildings in England and Wales (13). The cornerstone of these *Approved Documents* is a whole-building energy performance calculation method. Total carbon dioxide emissions of the regulated loads in a new building must be no greater than a notional building which has prescribed physical characteristics (e.g. U-values) and standardised operating conditions.

Regulated loads include energy required for space heating, cooling, domestic hot water, lighting and auxiliary energy use associated with fans and pumps. Loads not regulated by *Part L* (unregulated loads) include computers, servers, central and distributed catering equipment, and information and communications technologies (ICT) provided by the building user. In the absence of information from the client, designers will have to rely on their assumptions. So while designers are required to consider such loads up to Stage E, the effect of the real, actual loads on the building's total energy consumption may be significantly different. Those loads may also influence the actual performance of the building's regulated systems.

The *Part L Approved Documents* set out other requirements including limits for building fabric U-values, building services efficiencies and solar gain in different zones. Final calculation must be run after practical completion and the commissioning stage to ensure the as-built energy performance is consistent with what was envisaged at design stage. Furthermore, it is required to provide information and training to building users so that they can use their buildings efficiently.

There is no requirement to verify actual performance of a building when it reaches its steady operation post-handover in reference to the regulatory compliance calculations. The *Building Regulations* in England and Wales only focus on theoretical performance of regulated loads until practical completion.

It may be argued that compliance calculations only motivate developers to meet minimum energy efficiency requirements for building fabric and services. The calculations are not baselines for actual operation, especially as presumed operating conditions may significantly differ from actual operating conditions. Exclusion of equipment load from compliance calculations also poses difficulties in comparing actual and compliance energy performances.

In practice, the performance gap is not always explained solely by differences in operating conditions and equipment loads. Shortcomings in building procurement, construction processes, building commissioning and provision of information and training to building users are often not reflected in final compliance calculations. At each step the building's performance characteristics will rely less on calculations devised to achieve regulatory compliance, and more upon operational characteristics particular to each installed system (and the interactions between them).

So what starts out as a fluid set of design concepts will gradually solidify, possibly in a different form to what was originally envisaged. Their actual operational characteristics will gradually emerge, but not necessarily in a form visible to the project team. Opportunities to influence operational characteristics may occur at project gateways and decision thresholds. For such opportunities to be seized a change in a performance characteristic will not only need to be visible and communicated to all relevant parties, but also appreciated by the client and project team as something worthwhile addressing. If it is neither visible nor addressed, the opportunity to intervene will be lost. Aspects of the building's operational under-performance will become ingrained, unnoticed and unappreciated by the project team.

As the authority and responsibility shifts from design to construction, priorities will change. For example, the progression from design to construction will often coincide with a shift in emphasis from design quality to an emphasis on time and cost. The degree to which quality is traded against time and cost pressures (in severe cases, involving a sacrifice of quality) will put pressure on the performance outcomes. Again, if performance-related decisions and the consequences of those decisions are not visible, they are unlikely to be acted upon, and the opportunity to intervene to redress any conflict between design intention and performance outcome will be missed.

This suggests that better mechanisms are needed to make the invisible, visible, and for it to be in a form that all members of the project team – clients included – can understand and appreciate. This is the motivation behind the S-curve concept.

S-shaped curves generally represent a growth mode subjected to limitations that, over time, slow down the growth and strive towards a maximum value. They are especially applicable to transitional modes where rapid changes happen within a system in a relatively short period of time before the system reaches its steady state operation (14).

These conditions make S-Curve modelling a viable option to analyse the evolution of building energy performance throughout a construction project and into building operation, when the end-users operational profile and the quality of fine-tuning reaches a steady-state, ultimately confined by physical factors such as building size, number of occupants and hours of operation.

3.0 Methodology

3.1 S-curve conceptual framework

The description of the steps that lead to shortfalls in building performance are, of necessity, simplified. To identify the key factors that influence the performance gap, from inception to building operation, the authors created a timeline that charts performance expectations and the consequences of activities and decisions against a notional benchmark for a building procured with high performance as a client objective (Figure 1).

The sine-wave curves in the diagram depict performance trajectories for four buildings that have started out with ambitions for sustainable low energy performance that are better than, for example, a minimum compliance standard or a median energy benchmark (15)

The vertical axis represents +3 to -3 on a performance scale. As explained earlier, performance could be defined in many different ways – quantitatively (such as energy consumption) or qualitatively (such as occupant satisfaction). For the purposes of this exercise, the performance midpoint is statutory compliance with the energy requirements in *Part L* of the *Building Regulations*, but it could be any performance metric. (Note that a best practice line might be at -1, if one regards *Part L* purely as a statutory minimum.)

To illustrate the broad concept, Figure 1 contains four idealised S-curve scenarios that represent performance ambitions and outcomes over time.

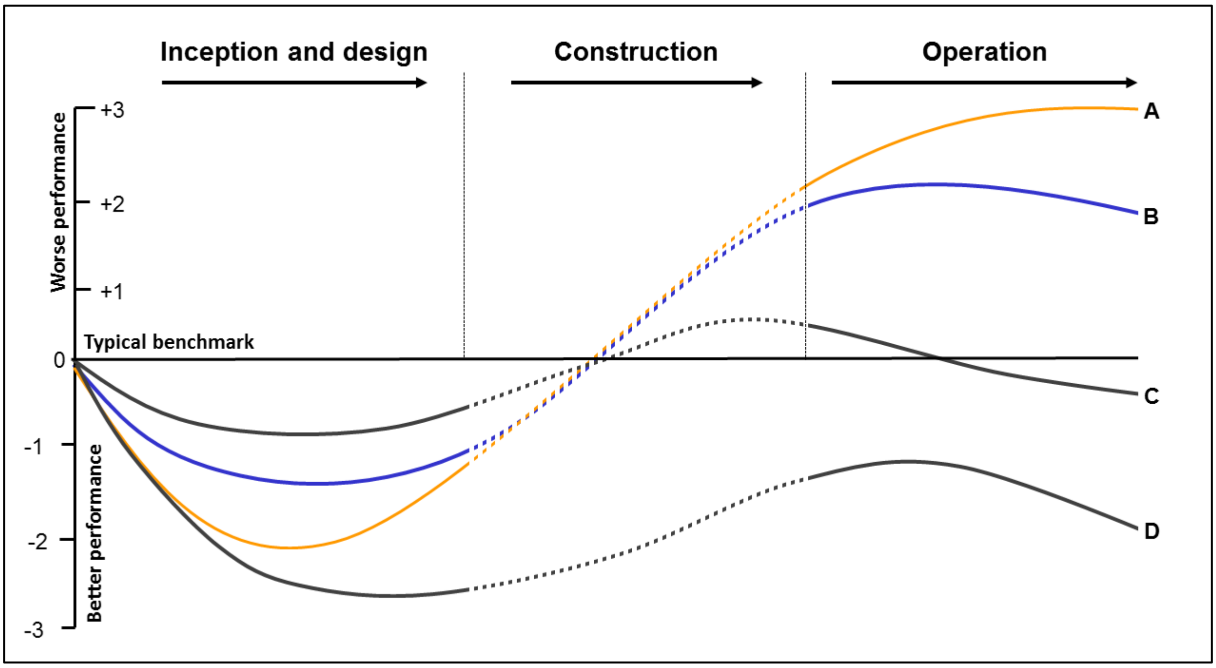

Figure 1: Four scenarios illustrating suspected fluctuations in building performance against a -3 to +3 scale for performance. The hatched lines of the construction phase illustrate the area of greatest uncertainty as to the actions and events that confound design expectations. Not that while the as-built EPC is meant to reflect and take into account construction-related factors (such as airtightness test results), many decisions and actions that affect building performance go wholly unrecorded.

- **Scenario A:** A building that has started out with ambitions to be low or zero carbon. Actual performance remains 3 – 5 times higher than prediction for the first three years.
- **Scenario B**: A building that has more modest performance targets but nonetheless better than the statutory minimum. Initial poor performance has been mitigated by technical interventions, seasonal commissioning and refining of system setpoints.
- **Scenario C** A simpler building than Scenario A and B, and more modest energy ambitions. Diligent and effective management has brought performance nearer to original targets.
- **Scenario D** A small building with minimal servicing and possibly a fabric-first approach to its architecture. Premises management may be diligent, but the building is mostly free-running with low fuel and maintenance needs.

Figure 2 itemises the S-curve in the form of histograms. Scenario B is used to define specific elements of the S-curve. Even though problems may be less acute than Scenario A, more can be said about the building's initial in-use management activities.

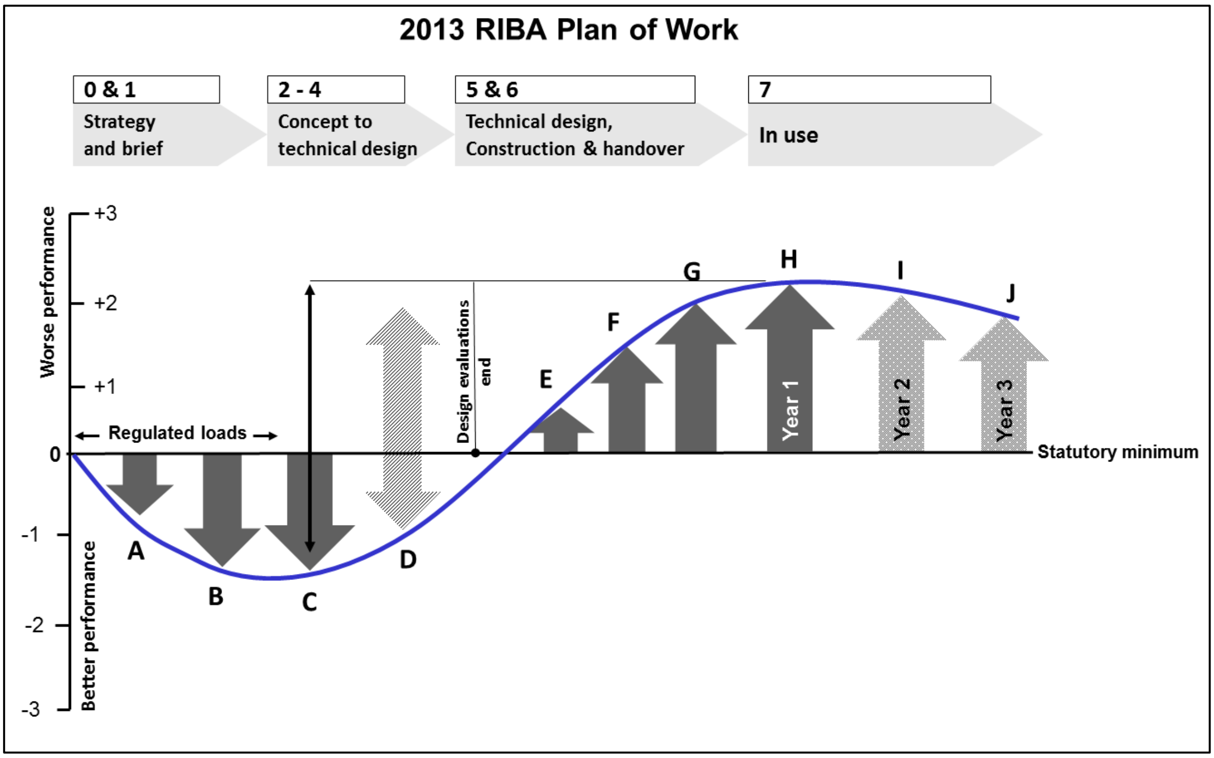

Figure 2: A simplified breakdown of the lifecycle of S-curve scenario B in the form of histograms. These are effectively dots on the generic S-curve depicting the changing fortunes of building performance, from estimations made at the project inception stage through to actual operational performance 36 months post-handover. Year 1 includes defects warranties. Years 2-3 reflect a Soft Landings approach to aftercare (1).

Stage A represents a client that requires the building's performance to be in excess of the norm (or better than the regulatory minimum). It would typically represent a client's desire for a low energy building, such as an A-rated design EPC, augmented by a requirement of a high BREEAM rating, such as 'Very Good' or 'Excellent'. The actual targets would arguably be notional, as the client's requirements and the design brief have yet to be developed.

Stages A to C are often well-documented, as are stages H to J where data from post-occupancy studies are available. For this reason the authors are confident that the extremes of the S-curve are defensible, particularly for cases where performance outcomes are higher between a factor of three to five compared with design ambitions. Stage B is where the professional design team is developing concepts and testing options. Simulation modelling will be used to assess potential energy and carbon dioxide savings from passive measures, such as high levels of insulation and fabric airtightness, and active measures such as free cooling, heat recovery, and daylighting. Modelling may still be simplified, as many details of the building will not be known.

Stage C represents a stage where more consideration is given to the potential offset from on-site low and zero-carbon technologies, such as solar, wind and biomass. Their contribution will be estimated using simplified modelling and from calculations made in spreadsheet-based programs, either by design team experts or by appointed specialists. Payback periods will be calculated to identify which technologies or techniques show the best return on investment. The energy estimates may be driven to exemplary levels, often motivated by criteria in environmental rating schemes.

From Stages A to C, designers will only be required to consider regulated loads covered by *Part L* of the *Building Regulations*, and will use notional values for non-regulated loads (as discussed in section 2.0 Background). Some repeat clients such as banks may know their unregulated loads, others, as in speculative developments, may not.

The hatched arrow of Stage D contains the greatest amount of uncertainty about the points at which performance outcomes diverge from the design ambitions. Design estimations will be poorly informed unless the unregulated loads are counted. Furthermore, unregulated loads will be creeping under the radar, along with the client's intended hours of use and their control and management policies. Unless the design team asks enough questions, or performs a range of risk assessments and sensitivity analysis on their calculations, the actual loads in the building could be significantly different to the calculations made to reach statutory compliance. The design may still be 'deemed to comply', but the hidden reality may be somewhat different. The actual hours of use will only be known closer to handover, and often only when the user has taken occupation. In any case, energy performance calculations are rarely updated beyond Stage E.

Between Stage D and E of the S-curve, design calculations will be submitted for *Part L* compliance purposes, and the design Energy Performance Certification (EPC). Unless the client pays for continued modelling and estimating, the design energy performance will be fixed. There is usually no instruction or fee provision for the design team – whose design may in any case be a contractual deliverable at this point – to refine the energy performance analysis.

Stage E represents the point at which a main contractor is appointed and the design is detailed. Risk assessments and sensitivity analysis by the professional design team may have stopped, and the contractor and either the novated designer (or the contractor's design team) will be refining the design for build-ability and to meet budgetary constraints.

At Stage F, value engineering decisions may change the design. Product substitution may occur (possibly with design team sanction, but not always) which may result in cheaper/less efficient installations.

While the client/end user may know more about their operational requirements at this point, such as hours of use and intensities of use, this information may not be sought by the project team. The subtleties of the design – for example control strategies – may be left to a controls contractor and other suppliers of specialist packages such as motorised windows or renewables. Consequently, the evolution of the strategic design into a summation of individual system performances may change the building's performance outcomes. Without sensitivity analysis it will not be possible to visualise it, let alone account for it. Specialist consultants may be aware of their individual systems, but they may not have an holistic appreciation, as the case studies in Section 3.2 demonstrate.

Stage G represents shortcomings in commissioning, training and handover, as identified in POE (4). Buildings were found not to be operationally ready at handover. Operation and maintenance manuals were often inaccurate and/or incomplete, as were the as-built record drawings.

Stage H represents the period of initial building operation. The end-user's operating hours may emerge higher than the design estimations, and occupancy densities may also be higher or lower, thereby affecting the operation of heating and cooling systems (which, due to rushed commissioning and possibly perfunctory training and familiarisation, may perform sub-optimally). More time may be spent on resolving defects rather than fine-tuning systems.

Stage H also represents the 12-month defects period. It is usually here that under-performance against targets is first noticed and reported, presuming that the various means of measuring performance are themselves operating correctly. Many energy sub-metering systems were found by the Carbon Trust to be dysfunctional (4).

In the absence of diligent and effective facilities management, the ongoing performance of the building is unlikely to change significantly, as initial shortcomings will become chronic failings (as per Scenario A). However, Stages I and J represent a case where some effort has been made to improve performance.

It is hypothesised that it is highly unlikely that the performance would match the level envisaged by the original designers at Stages A-C due to omissions from the calculations and lack of refinement through sensitivity analysis.

Having defined the S-curve components and the factors that contribute to its shape, the authors studied available evidence to determine whether the theoretical shape of the curve reflects the reality.

3.2 Testing the hypothesis

Evidence was collated from two educational buildings studied by the authors under the InnovateUK's BPE programme.

Table 1 provides some background information about these buildings to give context to the energy performance data subsequently presented in this paper.

The energy sub-metering in the case studies enables disaggregation of energy by end-use. Both buildings follow England and Wales secondary schools' calendar with some extracurricular activities. Occupancy profiles recorded during post-occupancy study were used for CIBSE *TM54* analysis.

Table 1: Background information about case study buildings

Building	**Type**	**Location**	**Gross area**	**Pupils**	**External envelope**	**HVAC and lighting strategy**
Building 1	Secondary School	East London	14,600 m^2	2000	Average U-Value: 0.51 W/m^2K; Tested air permeability: 4.36 $m^3/(m^2.h)$	Natural ventilation in most spaces. GSHPs backed-up by gas-fired boilers for heating. High efficacy fluorescent lighting (mainly T5 & CFL)
Building 2	Academy	North West England	10,400 m^2	11,150	Average U value: 0.48 W/m^2K; Tested air permeability: 9.0 $m^3/(m^2.h)$	Mechanical ventilation, GSHP backed-up by gas-fired boilers for heating. High efficacy fluorescent lighting (mainly T5 & CFL)

Figure 3: Cross ventilation strategy in Building 1 – operable windows (left), plenum air intake (middle) and the motorised vents on the corridor side (right).

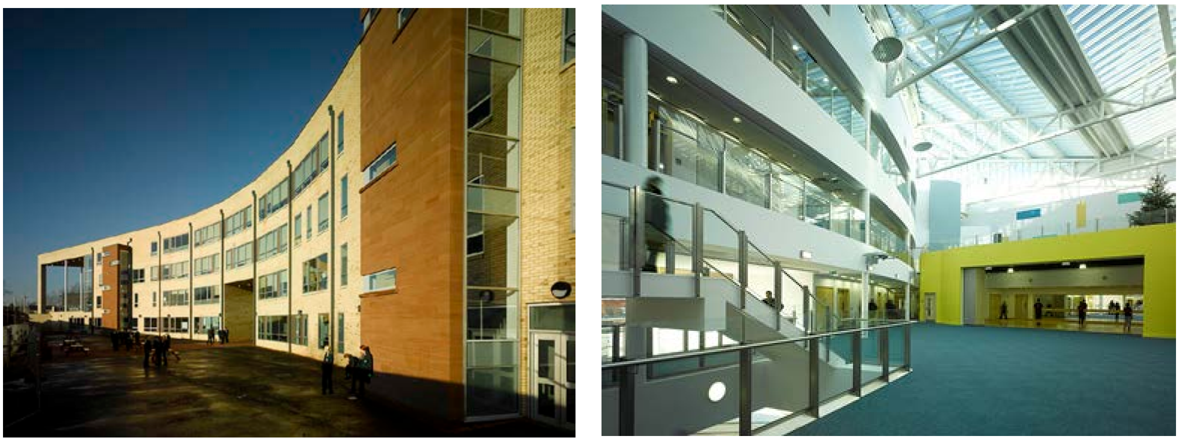

Figure 4: Building 2 south façade (left); atrium space (right)

The following data from both buildings was used to derive curves that track the changes in recorded energy performance throughout the life-cycle of the projects:

- For Building 1: energy projections included in the planning application. For Building 2: detailed energy calculations at RIBA Stage D based on expected operating conditions
- *Building Regulations* compliance calculations for both buildings (BRUKL reports) based on standardised operating conditions
- The EPC certificates and XML source files that include the default equipment load used for the *Building Regulations* and EPC calculations to estimate heating/cooling loads. This default equipment load was added to the regulated load as a proxy for equipment load at design stages.
- Actual equipment loads were established using a combination of functional sub-meters and outputs from energy analysis using the CIBSE *TM22 Energy Assessment and Reporting Method* (16).
- As the original thermal models were not available, thermal models were developed based on as-built documents and post-occupancy studies to evaluate the effects of actual operating conditions and equipment load. The CIBSE *TM54* protocol (10) and the IES Apache simulation tools were used for this purpose.

- The Target Emissions Rate (TER) was extracted for each building from the respective *Building Regulations* compliance report and all performances were compared relative to this target.
- Where there was evidence of procurement issues that had not been included in *Building Regulations* compliance calculations, these were incorporated in the *TM54* model.
- Actual energy consumption for each fuel was sourced for up to three years from Display Energy Certificates, utility bills, and directly from meters.

Both projects followed the RIBA *Plan of Work*. However, energy performance was not calculated at every stage. Some energy performance calculations were not available to the authors, which is therefore a limitation.

While the effect of actual occupant density and occupancy hours were taken into account, the operating conditions that stem from poor building management were not accommodated in the *TM54* model. For example, schedules of operations for HVAC systems were restricted to core hours and any possible out-of-hours activity in specific zones. Similarly, no allowance was made for whole-building heating during half-term breaks and school holidays.

As the metric used for whole-building performance in England and Wales is carbon dioxide emissions, all energy figures were converted to this metric and normalised by building size and assessment period. For consistency, the same carbon dioxide emission conversion factors used in design stages were applied to the in-use energy use.

The histograms for both buildings show the evolution of energy performance throughout each project's life-cycle. A list of procurement-related and building management issues for each building during building performance evaluation was compiled to give context to the measurements

4.0 Results

The following figures show how energy performance evolved from early stages of construction until 2-3 years after practical completion. Note that that some energy calculations before building completion include equipment loads and some do not. This is reflected in explanation given below each energy bar.

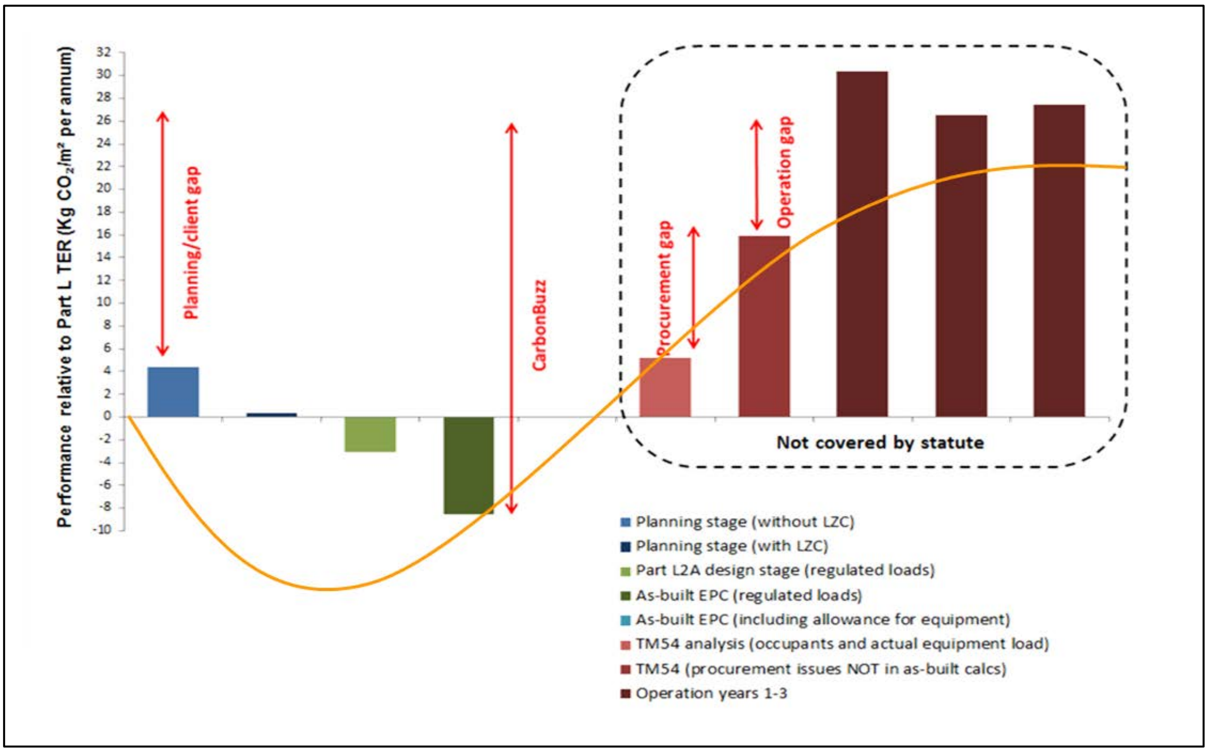

Figure 5: Energy performance measurements for Building 1. The data points are overlain on the worst-case (Type A) S-Curve purely for comparison. (Note: planning stage calculations included equipment loads).

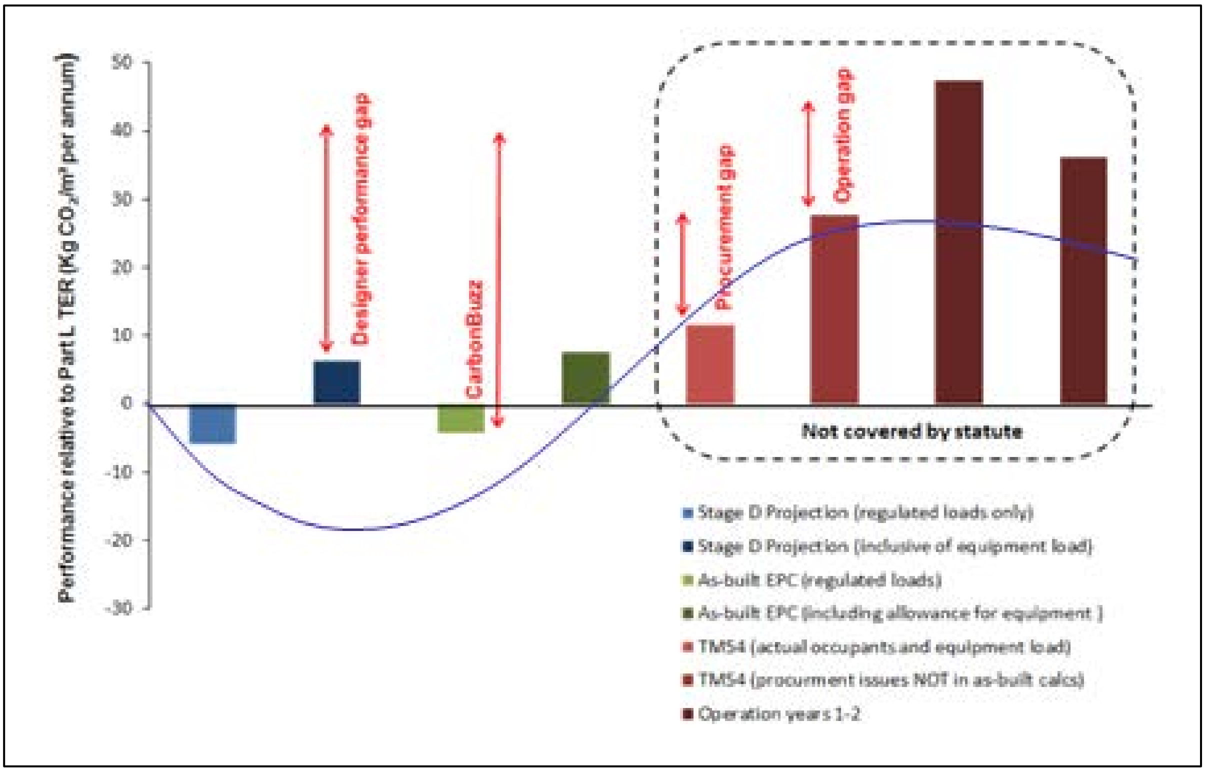

Figure 6: The energy performance S-Curve for Building 2. The data points are overlain on a histogram representation of the Type B S-Curve purely for illustration.

Table 2 explains how major procurement shortcomings, not reflected in statutory compliance calculations and usually unrecorded outside of BPE research, became compounded by operational issues.

Table 2: Examples of procurement and operational issues identified in the case study buildings.

Project stage	Building A	Building B
Preparation	Natural ventilation and low carbon technology were among the main determinants of expected performance.	Site noise levels triggered mechanical ventilation. No evidence that the risks of this strategy for energy performance were effectively assessed and managed.
Design	Ground Source Heat Pumps specified. Heat meters specified to measure heating and cooling contribution of heat pumps. No electricity meter specified to measure the electricity use of the heat pumps. HVAC zoning designed to enable users to hydraulically isolate zones not used during out-of-hours activities; measure not effectively implemented in later stages.	Demand-controlled ventilation adopted to save energy. No details specified in the energy model. *Building Regulations* limits for specific fan power used in the energy model. Actual fan power not calculated.
Pre-construction	Motorised vents critical for effective cross-ventilation. Cladding sub-contractor procured vents and motors. No evidence of an effective plan to flag up the significance of the vents, nor protect the integrity of the design intent from any downsides of value engineering.	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.
Construction	Motorised vents designed to respond to carbon dioxide concentrations in classrooms and summer temperature control settings. In practice, all motorised vents are controlled by carbon dioxide sensors only. No evidence that hydraulic isolation of HVAC zones was included in commissioning. Commissioning confirms that actual fan power is 40% higher than design target. No corrective action taken.	No evidence of carbon dioxide sensors in classrooms or extract ductwork to modulate supply and extract fans. An automated control option was not installed. Final compliance calculations assumed an effective demand-controlled ventilation strategy. Commissioning results revealed actual fan powers higher than statutory limits.
In-use	BPE studies identified malfunctioning motorised vents stuck open in winter. Open doors and malfunctioning motorised vents led the maintenance contractor to increase the set point of the low temperature heating to 80ºC to overcome excessive heat loss. The GSHPs are not operational at this temperature, so back-up boilers take the lead. GSHP heating is less than 3%; significantly lower than design intent. Two-port valves installed for hydraulic isolation of HVAC zones are not effective and zones isolated by the BMS are unnecessarily heated.	POE revealed that fan inverters are not correctly set up, and provide 100% fresh air regardless of actual demand. No functional demand-controlled strategy. Fan powers higher than allowed in the *Building Regulations*. Problems are compounded by the ventilation schedule setup in the BMS whereby air handling plant provides full fresh air to the whole building during out-of-hours use and weekends, with severe implications for ventilation energy and space heating.

Figure 7: A number of motorised vents stuck open in winter in Building A which compromised the operation of the heating system.

Figure 8: Building B ductwork installation with high aspect ratio and sharp bends (left). Dirty air filters further reduce the efficiency of the ventilation system (respective pressure drops shown in right).

5.0 Discussion

Figures 5 and 6 and the details in Table 2 show that the performance gap between theoretical energy calculations and actual energy use are symptoms of deeper systemic failures in building procurement, and not merely differences in equipment loadings or variances in operating conditions. The problems identified in the two examples are also not unusual, and represent similar failings identified in other post-occupancy evaluations, particularly those run under InnovateUK BPE programme.

The authors believe that the fragmented nature of the construction process, and the pressures on time and budget experienced by project teams in the latter stages of a project, make it difficult to focus on performance outcomes. Building control officers are also unable to identify nascent problems without the right skills, evidence, and time to do so. In unravelling procurement and operational issues in the case study buildings, authors have had the benefit of hindsight, unprecedented access to buildings and their documentation, feedback and insights from project teams and the luxury of time within the realm of a research project that is not available to construction professionals. Nonetheless, the problems do not alter the fact that the existing regulatory framework is not delivering the anticipated environmental benefits. It is therefore necessary to go beyond practical completion to acheive high performance outcomes.

The *Soft Landings Framework* (1) was devised to provide a process that clients and project teams can use to focus more on operational outcomes. Soft Landings describes a process of graduated handover and a professional period of aftercare to enable construction teams to focus on improving performance outcomes up to three years post-handover. However, soft landings are predicated on good take-offs. Hence it is crucial to devise appropriate processes and tools to ensure design is continually informed by feedback from building performance investigations, and by regular reality-checking, from design through to performance-in-use, to inform the corrective measures.

The problem remains that there is no consensus on the precise meaning of the term ‘performance gap’. There is no agreement on the points of measurement, and as a consequence little understanding of the division of responsibilities needed to close it, either during the project as the gap is growing, or once the gap has appeared and the building is in operation.

Figure 9 illustrates the nature of the problem. A performance gap could be measured between a variety of different points, the selection of which would determine the magnitude of the gap. The largest gap tends to be between the design predictions and the initial period of operation, which may be why the blame for the performance gap is pinned on designers. Poor design may be at fault, but it may be small compared to failings in activities and/or subsequent facilities management. The client is ultimately responsible for ensuring that their requirements remain valid as the building design evolves. They may be largely responsible for the appointment and skills of the building’s managers and maintainers. Therefore, they shoulder responsibility for a part of the performance gap that cannot be delegated.

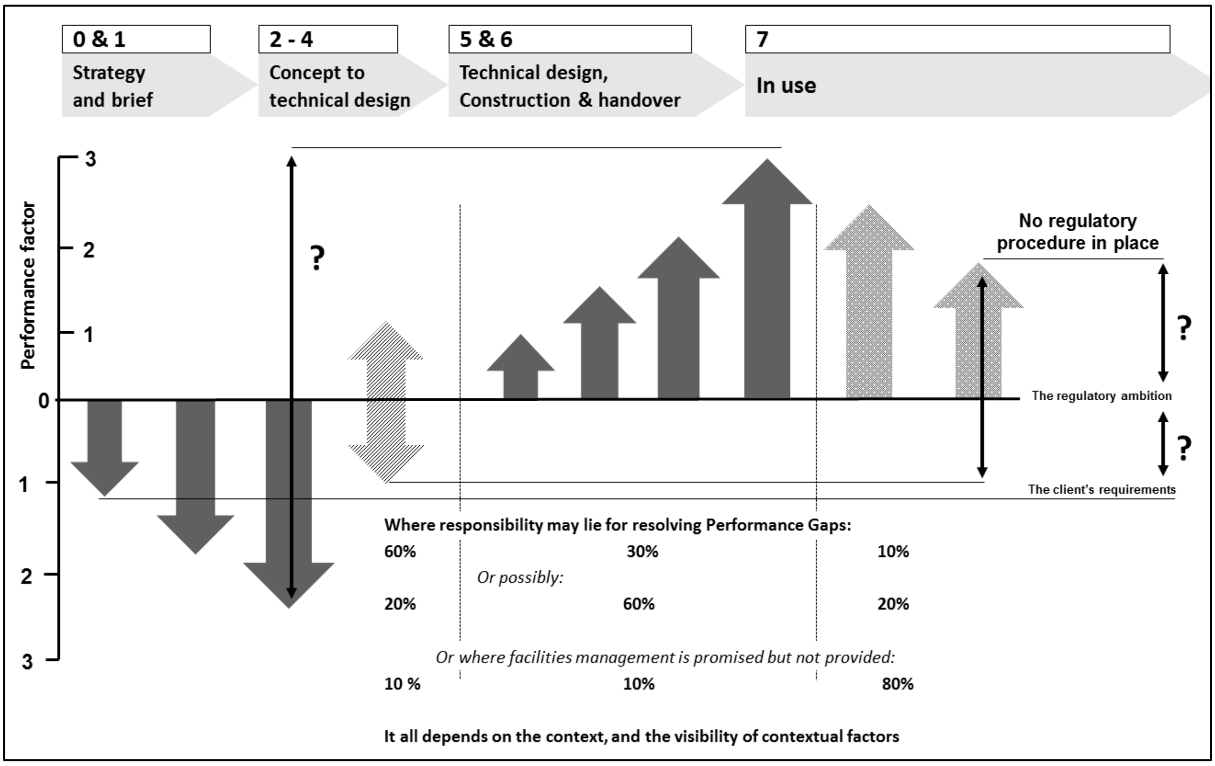

Figure 9: The responsibility for building performance shortfalls depends on the availability of information and data at various points during the procurement cycle as decribed in section 3. The histograms represent datapoints on an S-curve, and are an amalgamation of over-ambitious targets and deficiencies in construction and commissioning that compromise performance. Interventions by facilities managers and perhaps a Soft Landings aftercare team can reduce the performance gap, but cannot undo earlier actions and decisions. The percentage responsibility between designers, constructors and premises management is highly context-dependent and will lie on a spectrum.

One of the benefits of the S-Curves is that they could be used to communicate a perceived performance gap as the project progresses. If applied within a shared visualisation tool, and regularly informed by actions, decisions and activities on a construction project, an S-Curve would provide clients and project managers with an opportunity to have a pluralistic view of building performance as it emerges, and therefore the chance to act before problems become ingrained and irremediable.

The authors recognise limitations. While case study examples fit the S-curve well, there is no guarantee that the amplitude of a curve applied to a building project will subscribe such a smooth trajectory as predicted by the model. Modest ambitions at design could still result in massive under-performance during the early in-use phase, leading to a distorted (atypical) curve. Similarly, ambitious targets will not necessarily lead to equally massive under-achievement. The best that can be said is that buildings that have been studied in POE tend to subscribe to a sine-wave to a lesser or greater degree. In any case, what matters is not the curve itself, but real-time identification of the decisions and actions that operate to pull it in one direction or another.

6.0 Conclusions

Using energy calculations at every stage of construction projects along with measured energy use in early stages of post-occupancy provide an insight into evolution of energy performance. S-shaped curves describe the transitional nature of energy performance as important decisions are taken, changes made in the project and product specifications, and the building is completed and handed over and brought into use. S-Curves therefore have the potential to be used as a common platform to communicate different types of building performances among various stakeholders, transparently and effectively.

The two case-study examples show that the S-Curve model of building performance is consistent with known building performance issues. A number of procurement issues have also been identified and traced to the design stages. Although more research is required to test the relationship between design targets and operational outcomes, the authors believe that the S-Curves approach - as itemised in the histograms with the available evidence- has the potential to be a useful tool in visualising many aspects of the performance gap.

The specific procurement and operational issues identified in the case studies suggests that a checklist approach could be used (perhaps within a simple simulation model) to enable project teams to plot the performances of known factors against a generic S-Curve, modified with contextual information. The authors further postulate that a modelled S-curve trajectory could be created, with progress against that trajectory linked to performance risk management activities (perhaps in the form of a performance risk register, as used on Soft Landings projects). The register and trajectory could be maintained throughout a project to ensure performance-critical issues are spotted, managed and recorded, using performance inputs and actions (Table 3). Table 3 identifies risks for particular performance measures, and describes responses for following project stages. This could be used for recording and acting on risks at project gateways, with the result that the trajectory would ascribe a shallower curve. Lack of action would visualise the likely performance gap.

Case study data overlain on S-Curves suggests that radical action is required from policy makers to cover the whole transitional period until buildings reach their steady-state operation. This may mean statutory compliance moving from an early stage of design to a period after the building has been in operation. The continuing failure to take into account building construction and the initial period of operation will result in inceasingly ambitious building performance targets not being achieved in practice.

In order for clients and project teams to understand the performance gap better, the authors believe it will be necessary to record and visualise the consequences of project decisions and actions. An S-curve model could help make divergence of performance issues more visible and identify where responsibilities truly lie. It would satisfy a principle espoused by the *Soft Landings Framework*: it is better to work together to deal with the performance gap as it emerges, rather than ignore it and argue about it when it’s too late.

Table 3: Example risk register for mechanical ventilation system in Building B, based on the performance risk register developed for Soft Landings (17).

Element	Risk	RACSI	State	Soft Landings actions			
				Design	Construction	Pre-handover	Aftercare
Specific fan power at full load	Shortcomings in system procurement might lead to SFPs much higher than design intent. This would compromise building's energy efficiency.	RB JS TC CM JB		Designers to check air flow rates, total system pressure loss and fan specification to ensure the SFP used in energy calculations is achievable.	Designers to revisit the pressure loss calculations to allow for deviations from design specification such as the installed AHU spec & tight ductwork bends, air leakage, etc.	Contractor to compare the commissioning SFP with the design intent and the value used in the Building Regulations calculations; identify the root causes for any discrepancy and address the issues.	Contractor to ensure the panel and bag filters are cleaned or replaced regularly to maintain low operational SFP.
Fan inverter	If control settings are not correct, demand-controlled ventilation and energy efficiency can be compromised.	RB JS JB CM TC		Designers to set minimum air flow rate at 30% of full load air flow; demand-controlled-ventilation triggered by CO_2 sensors; commissioning plan to cover the whole range .	Designers to ensure the demand-controlled ventilation is installed as designed; commissioning to confirm fan inverters are enabled across the full range & control settings checked.	Contractor to review the commissioning results and address any shortcoming in system installation and control strategy.	Contractor to carry out random check of the operation of fans and inverter status from BMS & AHUs to ensure system is responsive to occupancy patterns.
Mechanical ventilation schedule	Mechanical ventilation in this building is installed to provide fresh air and NOT heating. Therefore, the ventilation schedule should closely follow occupancy pattern. Prolonged use of ventilation system(e.g. during building preheating period) must be avoided to achieve energy performance targets.	RB TC TC CM JB		Designers to allow for 'expected' schedule of operation in energy calculations in addition to NCM standardised schedules.	Designers to update the energy calculations if client has a more clear idea about their 'expected' operating conditions as they approach building completion and get ready to move in. Review the implications for energy performance and advise accordingly.	Contractor to ensure the ventilation schedule reflects actual demand and follows occupancy pattern; the mechanical ventilation is installed to provide fresh air to occupants and must not be used to provide background heating when the building is not occupied.	Contractor to carry out regular check of the ventilation schedule and provision of training to occupants to respond to any specific out-of-hours demand by taking advantage of HVAC zoning.

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