ZEMCH NETWORK

PERFORMANCE GAP? ENERGY, HEALTH AND COMFORT NEEDS IN BUILDINGS

Arman Hashemi[1], Minna Sunikka-Blank[2], Eugene Mohareb[3], Tatiana Vakhitova[4], Dimitra Dantsiou[2], Hui Ben[2] & Tania Sharmin[2]

[1] School of Environment and Technology, University of Brighton, UK, a.hashemi@brighton.ac.uk
[2] Department of Architecture, University of Cambridge, UK, mms45@cam.ac.uk
[3] School of the Built Environment, University of Reading, UK, e.mohareb@reading.ac.uk
[4] Granta Design Ltd., Cambridge, UK, tatiana.vakhitova@grantadesign.com

Abstract: Research on performance gap suggests that the actual energy consumption in buildings can be twice as much as expected. Energy models rely on predictive indicators and assumptions that are usually done at design stage, without acknowledging behavioural patterns of actual users. Moreover, in the context of performance gap, it is evident that energy efficiency is overemphasised while other key issues such as health and comfort of occupants, indoor air quality, noise levels etc. have been less stressed and discussed. This paper discusses the performance gap using surveys and physical measurements in a case study building at the University of Cambridge and reports findings of a research workshop with graduate students working on environmental performances of the built environment. The workshop addressed research issues related to energy, comfort and health, used as a method to understand the complexities of and trade-off between different aspects of sustainable buildings. According to the results, it is possible to balance energy, health and comfort needs in building projects. Lessons can be learned from the univer*sity's old and new* building projects to inform future research and policies.

Keywords: Performance Gap, Energy, Health, Thermal Comfort

1 Introduction

Buildings contributed to a substantial share of total UK energy demand in 2015, with domestic and non-domestic buildings making up 43% of the all energy consumption (Department of Energy & Climate Change 2016). Additionally, they accounted for 18% of the UK's greenhouse gas (GHG) emissions in 2015, with 75% of this share attributable to residences, 15% to commercial buildings and 10% to public sector buildings (Committee on Climate Change 2016). In particular, space heating was the largest energy end use, estimated to contribute up to 60% of total demand in households (2011) and 45% in commercial buildings (2009) (Palmer et al. 2013; DECC 2012). The successful long-term reduction of energy demand and related GHG emissions will require that high-performance buildings replace the existing energy-intensive building stock (Mohareb & Kennedy 2014). However, many modern high-performance building projects have produced an actual level of energy performance that does not match up with projections modelled during their design. This has come to be referred to as the "performance gap", which is a product of a number of technical and behavioural, described below.

The misalignment with design estimates and actual energy demand have been uncovered through an increase in use of post-occupancy evaluation, largely motivated by the surge in interest in certification of high-performance buildings. An early application of post-occupancy evaluations was in the UK PROBE study, which found energy performance was generally higher than anticipated (Bordass et al. 2001). The performance gap has appeared in various building end-use types and with a range of severity. A recent review stated found post-occupancy energy demand exceeded modelled values by 34% with a standard deviation of 55% for 64 non-domestic projects studied (van Dronkelaar et al. 2016). One case study office building assessed by the Carbon Trust (2011) demonstrated a nearly five-fold increase in energy demand relative to the energy performance certificate estimate. Even in Carbon Trust case studies where more detailed modelling was completed, there was a 16% increase in actual demand relative to modelled results. While performance occasionally improves upon predicted values, the Carbon Trust (2011) estimates that 75% of the variances are buildings where energy demand was higher than design specifications.

High-performance domestic buildings face similar issues in matching design specifications of energy demand. The Energy Saving Trust (2008) found that insulation measures in over 1500 UK domestic homes studied achieved a energy demand that was 50% less than what was expected, on average. Calì et al. (2016) examined a sample of recently-refurbished German multi-unit residential buildings and performance gap of up to 95% in the first year after retrofitting for one building. Further, Johnston et al. (2016) state the studies of new-build dwellings in the UK have demonstrated actual energy performance that were more than double predicted values.

This performance gap is not unique to the UK; a US analysis of LEED-certified buildings found an equal number of buildings performed worse than estimated versus those that performed better - indeed, some of these high performance buildings had greater energy demands than the energy code baseline (Turner & Frankel 2008). Similar underperformance has also been observed in New York City office buildings, with LEED-accredited office buildings often having higher energy use intensities than conventional office buildings (Scofield 2013).

A performance gap fundamentally implies higher energy consumption (and associated costs) than the occupant will have anticipated. In one case studied by the Carbon Trust

(2011), an additional £10/m^2 in unanticipated annual operating energy costs was observed by occupants in a particularly poor performing building. In pay-as-you-save energy retrofit schemes, the underperformance can be a burden on either the energy performance contractor or the building owner or occupant; where the realised savings do not match those that had been budgeted for, longer payback periods can result, as well as added costs and the potential for contractual disputes (van Dronkelaar et al. 2016).
A number of technical deficiencies with respect to materials and installation can lead to diminished energy performance relative to modelled projections. These include:

a) Calculations or simplifications in modelling software are inconsistent or not checked/revised throughout the delivery process (Sunikka-Blank & Galvin 2012; Carbon Trust 2011; De Wilde 2014; Schwartz & Raslan 2013).
b) Higher efficiency materials and equipment can provide lower than expected performance (Baker 2008; Rye & Scott 2012; De Wilde 2014).
c) Materials themselves may not be correctly installed per design specifications due to poor workmanship or inexperienced installers (Sunikka-Blank & Galvin 2012; Carbon Trust 2011; De Wilde 2014; van Dronkelaar et al. 2016).
d) Buildings may not have been commissioned properly upon completion (Carbon Trust 2011; De Wilde 2014).
e) Unregulated loads were not properly considered in the modelling process (Carbon Trust 2011).
f) Building designs themselves may be inherently flawed or design characteristics/goals poorly communicated (De Wilde 2014).
g) Poor communication between landlord (involved during the design process) and future occupants with respect to optimal building operation (Robinson et al. 2016)
h) Split incentive to fulfil energy performance between the building owner and tenant (Robinson et al. 2016)
i) Occupant behaviour is markedly different from design estimates (De Wilde 2014; Menezes et al. 2012; Haldi & Robinson 2008; Calì et al. 2016).

The complexity involved in building construction and occupant behaviour leads to a number of solutions that should be considered in effectively addressing the performance gap. In one German case study, Calì et al. (2016) found that through careful post-occupancy monitoring was able to remedy building performance issues related to technical issues with heat pumps and wide variation in occupant behaviour. As well, Johnston et al. (2016) were able to match expected energy demand through the careful quality control systems inherent in the PassivHaus certification process applied in their cases.

With respect to non-domestic buildings, Fedoruk et al. (2015) suggest that, in the case of a showcase high performance building on the University of British Columbia campus (Centre for Interactive Research on Sustainability), the performance gap was mostly attributable to issues outside of shortcomings in installed building components. They go on to state that it could have been reduced through building energy monitoring, improved integration between designers and builders (such as through design charrettes; Mollaoglu-Korkmaz et al. 2013), and expanding current boundaries of energy analysis beyond the building itself. Robinson et al. (2016) suggest a mandatory post-construction review (per BREEAM for New Construction's 2014 guidelines) and the 'soft landings' approach of continual post-occupancy communication between designers, owners, and occupants (directed by the CIBSE TM54) can contribute to a better match between anticipated and actual demand. From a legislative perspective, a regulatory framework to govern energy underperformance in buildings (van Dronkelaar et al. 2016). The authors also note the need for better monitoring for data collection, as well as more training that targets energy-related technical and communication skills in the building sector (construction and operation). Finally, Tuohy & Murphy (2014) suggest that through reshaping the aims of BIM to include actual building performance, providing ratings/awards based on actual performance, and the adoption of a more robust feedback systems in the design process, greater accountability can be realised with respect to actual energy demand.

It is evident from the above that the importance of energy consumption in buildings is well represented in the literature, while other important issues such as health and wellbeing of occupants, indoor air quality, thermal comfort, noise levels etc. require further study. It is in this context that this paper sets out to investigate performance gap to collectively address the abovementioned issues in buildings. To this end, a workshop was organised to study energy, health and comfort needs in a case study building at the University of Cambridge. The workshop was a continuation of EU Marie Curie FP7 project 'Uni-metrics' on sustainable campuses. The workshop mainly aimed to a) develop a common understanding of research problems in energy efficiency, comfort and health in buildings; b) identify knowledge gaps; and c) gain understanding from research projects that have addressed performance gap, comfort and health in buildings.

2 Energy use in University of Cambridge

The University of Cambridge has a total floor area of 642,000m^2, over 330 buildings and 150 departments and institutions. The capital building programme is £60M/pa (plus £15M for equipment). There are 18,900 students and 9,800 staff studying and working at the university. In 2013-2014 the University spent £16 million on energy. The University spends £1,825 every hour (or around £30 every minute) on energy. Figure 1 shows the top 30 users of electricity in the campus (Environment and Energy Office 2016).

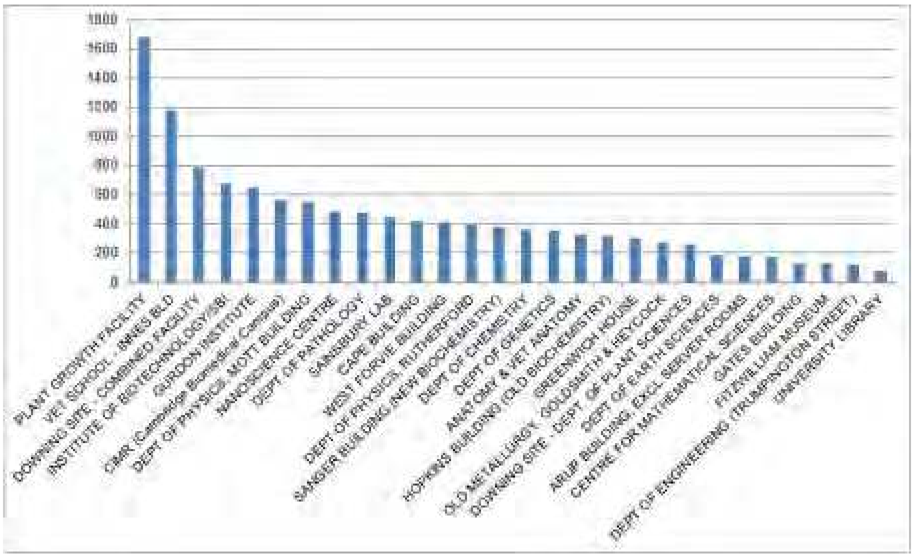

Figure 5: Top 30 users of electricity, ranked by usage per kWh/m2 (Environment and Energy Office 2016)

The actual energy consumption can be twice as much as expected. The University of Cambridge has also observed performance gap issues; for example, regulated electricity and gas consumptions for Sainsbury Lab at the university are around 130% and 284% of the design estimates, respectively. Solar photovoltaic (PV) panels have provided energy as predicted, but only equivalent to 50% of the 10% reduction required by the Merton Rule. High occupancy rates outside core office hours have been reported as a major issue affecting energy performance. Thermal comfort is also an issue, as accounts of high temperatures have been noted in some offices. More individual controls over the environment has been suggested as a solution to improve thermal comfort (Lee 2014; Khatami et al. 2014). According to the university's policies on thermal comfort, air conditioning should only be allowed for specific academic needs assuming that "occupants will moderate their own comfort by dressing appropriately for their preference" (University of Cambridge 2016).

3 The Case Study

The selected case study was the Faculty of History in Cambridge (Figure 2). The design of James Stirling was selected based on an architectural competition in 1962. From the beginning, there were concerns about the building's environmental performance 'the building would be subject to solar heat to a fairly large extent' (EMBS files 1963). The building was funded by the Universities Grants Committee (UGC), which meant that the funds had to be spent within a certain time frame and there was pressure to reduce the number of design iterations. The project was well funded; the contract price was £104/m^2 which amounts to £2440/m^2 at current prices. The design accommodates the history faculty, with an L-shaped stacked block of 6 levels enclosing a large fan-shaped glazed central space that houses the library. Early in construction, a poor relationship was reported amongst all parties, along with time / cost overruns and leaks were noted during the handover of the building. Due to neighbours' complaints an adjustment and reorientation of the building was made. After two decades of contending with construction and thermal comfort issues, demolition was considered in 1985 but the building was conserved and "grade II" listed in 2000 (Figure 2).

Figure 6: Faculty of History

Main reason for poor thermal comfort and high energy use is that 75% of the envelope above the plinth is standard industrial glazing, along with the giant stepped-pyramid skylight of the library (Figure 3). The glazed, double-skin roof in the library was meant to acts as a light diffusing layer where the inner layer was obscured to prevent glare and to give shadowless light in the reading area. This was also designed to insulate the cavity between the two skins so that all the louvres in the vertical steps would be closed in winter and opened in the summer to enable ventilation through the stack effect. Artificial light sources in the cavity and the roof provide an 'overhead spectacle'; however, the library space and office spaces are prone to overheating in summer (and draught in winter). The noisy extract fans in the library were never used and small air-conditioning units have been placed in the administrative corridors. Offices have draughty glass louvres for ventilation, along with secondary glazing and venetian blinds that have been installed in later renovations. It was predicted as early as 1968 that “controls will be fouled up through mismanagement by the humanities-oriented occupants who are below the average in mechanical literacy and competence, while the occupants will take verbal revenge on the architects - whereas revenge should be on UGC and their budgets that are too ‘skimpy’ to permit decent environmental installations or idiot-proof control systems” (Banham 1968).

Figure 7: Glazed, double-skin roof of the library

The building got mixed reviews from the beginning. Brogan (1968) accused Stirling of ‘complete disdain’ for the users of their buildings and being ‘not so much undemocratic as anti-democratic: structural fascists”. On the other hand, Banham who is an acknowledged architectural critique in Britain commented in Architectural Review (1968) that ‘the result, respectful to Cambridge at a more fundamental level of what Cambridge actually does, presents a startling critique of buildings that have tried to be respectful to Cambridge at the superficial level…the sad things is that Cambridge opinion will eventually accept it as part of the ‘Cambridge traditions’ and then no one will have the guts to pull it down when the useful life for which it was designed has come to an end”.

4 Physical Measurement

Physical measurements were carried out during February-August to evaluate indoor conditions and thermal comfort as well as the energy consumption in the case study building. Data loggers were installed on five different floors of the building to assess the conditions in various areas including in the main library, as well as corridors and office buildings. Table 1 shows the annual electricity consumptions of the case study building between 2005 and 2014. According to the results, the annual energy consumption over the period between 2005-2014 has remained nearly constant, averaging 216,549 kWh per annum, or 49.3 kWh/m^2 (for a total floor area of 4393m^2).

Table 14: Electricity Consumption during 2005-2014 (University of Cambridge)

Year	2005 - 06	2006 - 07	2007 - 08	2008 - 09	2009 - 10	2010 - 11	2011 - 12	2012 - 13	2013 - 14
Annual energy consumption (kWh)	223,287	222,608	226,760	214,548	222,726	209,891	215,046	212,868	201,278

Figure 4 and Figure 5 show the internal temperatures and relative humanity as well as the external temperatures during one year in different areas of the building. According to the results, the building has been thermally uncomfortable in almost all areas. The internal temperature in many areas has reached 35 ℃; the indoor temperature in the rooms/offices between July and August has frequently been over 30 ℃. The temperature in the main library on the ground floor has also fluctuated greatly and in many cases has exceeded 30 ℃. Meanwhile, CIBSE Guide A 2015 recommends average summer operative temperatures of 24-25 ℃ for libraries and 22-25 ℃ offices, respectively (CIBSE 2015).

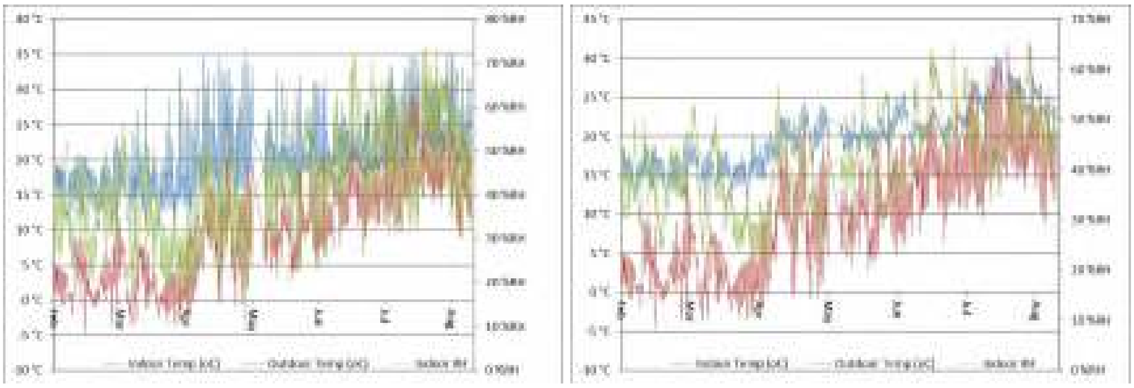

Figure 8: Ground Floor Library (Left); 1st Floor Library (Right) (University of Cambridge)

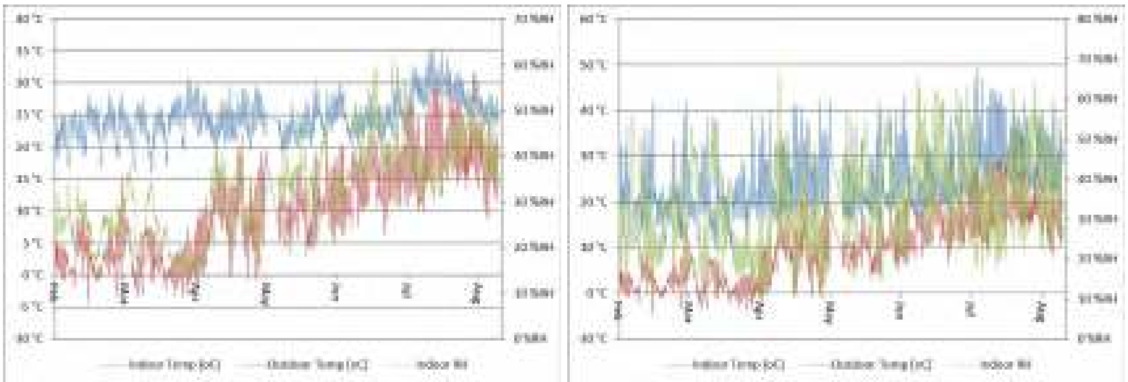

Figure 9: Room on the 4th floor (Left); 6th Floor Corridor (Right) (University of Cambridge)

The situation has been considerably worse in the corridors on the 6th floor (Figure 6) as the temperature has reached nearly 50 ℃ which is an indicator of severe, and potentially dangerous, thermal comfort conditions for the occupants. Extremely high indoor temperatures in the building necessitated the use of air conditioning units particularly on the higher floors. According to Figure 5, occupants also experience extremely low temperatures (between 10 ℃ and 15 ℃) during winter. Such conditions indicate high heating and cooling requirements in the case study building during both winter and summer. Yet, considering benchmarks, the average electricity consumption of 49.5 kWh/m^2 is rather low. A possible explanation for this may be the seasonal use of the building by the occupants.

Figure 10: Excessive glazing and solar heat gain contribute to overheating

5 The workshop

The participants (Figure 7) were provided with the above information on the current performance of building including the physical measurements. The participants also visited the case study building and spoke with occupants and facilities mangers to identify and evaluate the current conditions, as well as the problems of the building.

Figure 11: The workshop

Three themes were identified as the core subjects which needed to be investigated while developing solutions:

A. Energy: e.g., lighting, equipment, building envelope, renewable energy etc.
B. Architecture: e.g., interior/exterior, extension, partitions, retrofit, demolition
C. Comfort and Health: e.g., thermal comfort, indoor air quality, noise, glare, ventilation.

5.1 Summary of proposals and findings

Group A followed an approach divided in three sections: a) identification of problems; b) proposed energy efficiency measures; c) cost/time/benefit assessment of proposed measures. After the walkthrough inside the case study building (History Faculty), the group discussed the elements that could lead into inefficient energy use. The following issues were raised:

- Building users unable to understand and operate the building’s passive features (glass louvre ventilators, venetian blinds).
- Air conditioners placed in corridors as an additional way of heating/cooling indicating the inefficiency of the existing heating/cooling system.

- Lights left on in corridors and library while the building was almost unoccupied.
- Window blinds that were meant to prevent overheating to obstruct daylight.
- Extract fans of the existing mechanical ventilation system deactivated due to noise.

In terms of the proposed efficiency measures, the group emphasised the need to respect the building’s aesthetic quality through discrete material interventions while focusing on educating the users on the proper use of its passive features and systems. The following efficiency measures were proposed as solutions to improve the energy performance of the building:

a) Fritted glass for the outer layer of the double-glass envelope that assists with the building’s natural ventilation scheme, daylighting and weather shielding. The pattern of the fritted glass will be specially designed for the building to enhance its aesthetic value and diffuse light as it enters the building, reducing glare as well as solar gain.
b) Behavioural nudging from an interactive ‘building wizard’ accessible through the building’s Wi-Fi.
c) Building user guide to be provided during staff inductions and along with guidance on the proper use of the building’s passive and active systems and controls.
d) HVAC with heat recovery system to replace the existing noisy ventilation system.
e) PV panels in southern-facing façade to provide electricity for light-emitting diode (LED) lighting.
f) Reprogramming of movement lighting sensors in shorter time intervals.
g) Carpeting the library for noise reduction.
h) Thermal buffer zone in the entrance to prevent heat loss.

The practical aspects related to the implementation of the proposed interventions (cost, benefit, timeframe) were presented in a comparative graph. The different measures were plotted based on their cost (high, medium, low), the timeframe of their implementation and their impact on energy efficiency and comfort (small, medium, high) (Figure 9).

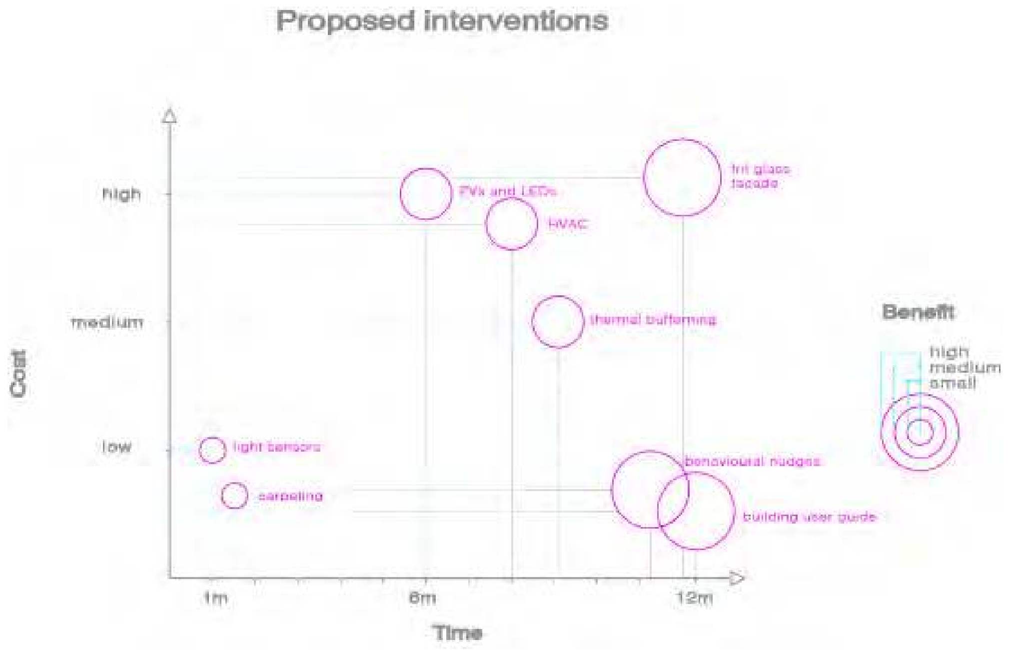

Figure 12: Proposed interventions for the refurbishment of the History Faculty at the University of Cambridge based on the cost, implementation timeframe and benefit

In terms of comfort and energy efficiency, the replacement of the outer layer of the building’s glass envelope with fritted glass and the behavioural nudges were the interventions with a higher expected impact. The new façade intends to give a creative and delicate aesthetic touch, enhancing the identity and popularity of the building however, this is anticipated to be a costly intervention. The interactive ‘building wizard’ would be less costly but needs constant update and monitoring. The case where the two measures are combined is seen as the optimal intervention in the existing context.

Group B explored three discrete options for a fundamental shift in the building's operation. These options focused on changes in end use, energy demand/supply systems, and building services systems. The discretisation of these options was understood to be purely theoretical, as components of the three options would likely be considered in any planned building upgrade. However, for the sake of the workshop exercise, it was pursued in the interest of a deeper understanding of the value of each approach.

The options were assessed using four main criteria, which included six sub criteria: cost (capital and operating), time required for implementation, user impacts (during transformation and post transformation), and aesthetic impacts (heritage and public perception). While the intention of most of these criteria are self-evident, the aesthetic impacts require further explanation. The "heritage" component relates to the preservation of the original architectural value of the building, especially in conforming with its Grade II listed building status. The "public perception" aesthetic feature was based on the assumption that the general public does not view the current modernist design favourably and would welcome an upgrading of the exterior of the building. A summary of the evaluation of the three options is provided in Table 2.

Table 15: Proposed changes to the Faculty of History building to address its poor thermal performance.

Proposed Change	**Cost**		**Time**	**User Impact**		**Aesthetic**		**Sum**
	Capital Cost	Operating Cost		Mid-Transform.	Post-Transform.	Heritage	Public Perception	
User	4	3	4	1	4	3	2	21
Energy Demand/Supply	1	4	1	2	4	2	4	18
Building Services	2	2	2	3	2	4	2	17

The first option for transforming the building assessed the problems surrounding the building's primary end uses as a library and for faculty office space. Given the problems with overheating in the summer and difficulties maintaining a sufficiently warm temperature in the winter, the conversion of the building to a more compatible end-use, such as botanical research lab, seemed worthy of consideration. The ample solar access and the inhospitableness for humans lead to this suggestion. This would also be a relatively low cost solution, requiring an exchange of users from the poorly conditioned Sainsbury Lab for botanical studies, for example. The time requirement would likely be low, and the heritage value could be retained. Mid-transformation impacts and public perceptions scored low, but it was projected that user satisfaction would be very high after the relocation.

The second option involved a substantial investment in low-carbon technologies for the building. While the library's skylight structure would be retained, it would be covered with PV panels. The natural lighting would be reduced substantially and the interior of the glazing would be fitted with special LED panels that could be used to project images of the sky or any other suitable visuals that would be pleasing to the library occupants. The PV panels would supply electricity to meet demand within the building, with any excess production being converted to heat for a borehole thermal energy storage network located on the Sedgwick site. The building envelope would also be upgraded to meet high performance standards and reduce heating/cooling demand.

This approach was deemed to require high up-front investment, be disruptive to occupants during the construction phase, take the greatest time to complete and negatively affect the heritage value of the building. The participants agreed that loss of the heritage aesthetic would be an increasingly unavoidable issue in meeting the necessary improvements of building stock performance towards the University’s 2050 GHG reduction goals. The energy supply and demand improvements were expected to perform well in post-construction operating costs and user satisfaction, as well as public perception of its updated facade.

The final option that was assessed was the improved building services approach which focused on automation and highly-sensitive occupant detection systems. This option envisioned automated building service controls, coupled with redesigned heating and ventilation systems that serviced zones on the scale of individual offices. These zones would be equipped with motion, CO_2, and humidity sensors, with highly-structured user feedback systems, enabling fine-tuning of controls of the building services. This approach was projected to be costly in both construction and operation, with the latter requiring frequent servicing of the advanced control systems and heating/ventilation network. As well, while the installation of such a scheme might be less invasive to users during its installation, it was expected to require more work in keeping the user feedback system 'tuned' and take a long time to install. The heritage value of the building would be retained, but this approach would not improve public perception as no externally-visible upgrades would be included.

Ultimately the group felt that a focus on changing the end user would score the best if all criteria were weighted equally. However, the weighting of the criteria would depend on the goals and constraints. As well, each option had merits and a more integrated implementation of these could remedy the detriments of each of the others.

6 Conclusions

This paper discussed the performance gap using surveys and physical measurements in a case study building at the University of Cambridge. Overheating was identified as the major issue contributing to thermal discomfort and high energy consumptions in the case study building. Various design, operation and management solutions, such as lighting and ventilations strategies, user controls, renewable energy as well as options such as complete change of use etc., were suggested by the workshop participants to improve the conditions in the building.

According to the results of the paper, there is a need to challenge narrowly focused perceptions of energy efficiency. When it comes to performance gap, health and comfort should be considered alongside the energy efficiency. Indeed, health and wellbeing of occupants should be the main driver rather than energy efficiency in building. Substantial savings could be achieved by fixing the technical problems, disaggregating consumption data and encouraging behavioural changes of end-users. Moreover, there exists a need to understand actual occupancy patterns, user requirements and social norms in the workplace in order to effectively address and improve both energy performance and comfort in buildings. In this respect, although technical deficiencies and information gaps play an important role, all stakeholders including clients, designers, builders, policy- and decision-makers need to understand potential trade-offs between aesthetic, comfort and energy values to close the gap.

Acknowledgements

The workshop was a continuation of EU Marie Curie FP7 project ‘Uni-metrics’ on sustainable campuses. Special thanks to Arup, Faculty of History and the Environment and Energy Team at University of Cambridge for providing information and access to the case study building.

References

BAKER, P., 2008. In situe U-Value Measurements in Traditional Buildings - Preliminary Results

BANHAM, R., 1968. History Faculty Cambridge. Architectural Review. 1968, November. pp. 329-332.

BORDASS, B., COHEN, R., STANDEVEN, M., & LEAMAN, A., 2001. “Assessing Building Performance in Use 3: Energy Performance of the Probe Buildings.” Building Research & Information 29 (2): 114–28. doi:10.1080/09613210010008036.

CALÌ, D., TANJA, O., RITA, S., & DIRK MÜLLER. 2016. “Energy Performance Gap in Refurbished German Dwellings: Lesson Learned from a Field Test.” Energy and Buildings 127. Elsevier B.V.: pp. 1146–58. doi:10.1016/j.enbuild.2016.05.020.

CARBON TRUST, 2011. Closing the Gap - Lessons learned on realising the potential of low carbon building design, Available at: http://dare.uva.nl/aup/nl/record/172826.

CIBSE, 2015, Guide A: Environmental Design, Chartered Institution of Building Services Engineers (CIBSE), London, UK.

COMMITTEE ON CLIMATE CHANGE, 2016. Meeting Carbon Budgets - 2016 Progress Report to Parliament, London, UK. Available at: https://documents.theccc.org.uk/wp-content/uploads/2016/06/2016-CCC-Progress-Report.pdf.

DECC, 2012. The Future of Heating: A strategic framework for low carbon heat in the UK, London, UK. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48574/4805-future-heating-strategic-framework.pdf.

DEPARTMENT OF ENERGY & CLIMATE CHANGE, 2016. Energy Consumption in the UK, London, UK. Available at: http://www.thestar.com.my/news/nation/2016/03/21/schools-in-kedah-and-perlis-to-close-on-tuesday-and-wednesday-due-to-heatwave/.

DE WILDE, P., 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction, 41, pp.40–49.

ENERGY SAVING TRUST, 2008. Disaggregation of the Energy Savings Achieved from Insulation in EESoP 3 and the Energy Efficiency Commitment

EMBS FILES, 1963. History Faculty building documents from the archives of the Estate Management and Building Services (EMBS), University of Cambridge.

Environment and Energy Office, University of Cambridge, 2016. http://www.environment.admin.cam.ac.uk/resource-bank/facts-figures (accessed 29 Aug 2016)

FEDORUK, L.E., COLE, R.J., ROBINSON J.B., & CAYUELA A.. 2015. "Learning from Failure: Understanding the Anticipated–achieved Building Energy Performance Gap." Building Research & Information IN PRESS (August): 1–15. doi:10.1080/09613218.2015.1036227.

HALDI, F. & Robinson, D., 2008. On the behaviour and adaptation of office occupants. Building and Environment, 43(12), pp.2163–2177.

JOHNSTON, D., FARMER, D., BROOKE-PEAT, M., & MILES-SHENTON, D., 2014. Bridging the domestic building fabric performance gap. Building Research & Information, 44(2), pp.147–159. doi:10.1080/09613218.2014.979093.

Khatami, N., Hashemi, A., Cook, M. & Firth, S., 2014. Effects of manual and automatic natural ventilation control strategies on thermal comfort, indoor air quality and energy consumption, Mass Customisation and Sustainability in Housing, ZEMCH 2014 international conference, 4th-6th June 2014, Londrina, Brazil, pp. 210-222.

LEE, S.M., 2014. Energy Performance Analysis of the Sainsbury Laboratory, Fourth Year Undergraduate Project, Department of Engineering, University of Cambridge, Cambridge.

MENEZES, A.C., CRIPPS, A., BOUCHLAGHEM, D., & BUSWELL, R., 2012. "Predicted vs. Actual Energy Performance of Non-Domestic Buildings: Using Post-Occupancy Evaluation Data to Reduce the Performance Gap." Applied Energy 97, pp.355–364. Elsevier Ltd: 355–64. doi:10.1016/j.apenergy.2011.11.075.

MOHAREB, E. A. & KENNEDY, C.A., 2014. Scenarios of technology adoption towards low-carbon cities. Energy Policy, 66, pp.685–693. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421513010938 [Accessed October 19, 2014].

MOLLAOGLU-KORKMAZ, S., SWARUP, L. & RILEY, D., 2013. Delivering sustainable, high-performance buildings: Influence of project delivery methods on integration and project outcomes. Journal of Management in Engineering, 29(1), pp.71–78. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84872731494&partnerID=40&md5=3507ce155f7262cb45800c19e2de079a.

PALMER, J., COOPER, I., TILLSON, A., POPE, P., ARMITAGE, P., HUGHES, M., & GODOY-SHIMIZU, D., 2013. "Housing Energy Fact File." London, UK. https://www.gov.uk/government/statistics/united-kingdom-housing-energy-fact-file-2013

ROBINSON, J., FOXON, T. & TAYLOR, P., 2016. Performance Gap Analysis Case Study of a Non-Domestic Building. Proceedings of the ICE - Engineering Sustainability, 169(ES1), pp.31–38.

RYE, C. & SCOTT, C., 2012. The SPAB Research Report 1: U-Value Report,

SCHWARTZ, Y. & RASLAN, R., 2013. Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study. Energy and Buildings, 62, pp.350–359. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.03.022.

SCOFIELD, J.H., 2013. Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings. Energy and Buildings, 67, pp.517–524. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.08.032.

SUNIKKA-BLANK, M. & GALVIN, R., 2012. Introducing the prebound effect: the gap between performance and actual energy consumption. Building Research & Information, 40(3), pp.260–273. Available at: http://www.tandfonline.com/doi/abs/10.1080/09613218.2012.690952.

TUOHY, P.G. & MURPHY, G.B., 2014. Closing the gap in building performance: learning from BIM benchmark industries. Architectural Science Review, 58(1), pp.47–56. Available at: http://www.tandfonline.com/doi/abs/10.1080/00038628.2014.975780.

TURNER, C. & FRANKEL, M., 2008. Energy performance of LEED for new construction buildings, Vancouver, WA: New Buildings Institute. Available at: http://www.usgbc.org/Docs/Archive/General/Docs3930.pdf.

University of Cambridge, 2016. Policy on Thermal Comfort, http://www.environment.admin.cam.ac.uk/files/uoc_thermal_comfort_policy-webv2.pdf (accessed 29 Aug 2016)

VAN DRONKELAAR, C., MARK, D., CATALINA, S., & DEJAN M. 2016. “A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings.” Frontiers in Mechanical Engineering 1 (January): pp. 1–14. doi:10.3389/fmech.2015.00017.