Proceedings of 7th Masters Conference: **People and Buildings**
London, UK, 22th September 2017
Network for Comfort and Energy Use in Buildings: http://www.nceub.org.uk

CLOSE THE ENERGY PERFORMANCE GAP, A WINDOW AT A TIME

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Abstract
This research aims to quantify occupants' window behaviour impact to the energy performance gap. Occupants' window behaviour poses a real challenge to energy demand control in mixed-mode buildings. A window being left open, may compromise the efficiency of the ventilation system. Applying a mixed-method approach, this study was carried out over the summer of 2017, in a mixed mode office building at the University of Southampton. Dry bulb temperature, radiant temperature, relative humidity, CO_2 and window movement were recorded. Concurrently a weekly questionnaire gathered environmental perception from 35 participants. Using TRNSYS, the results of the monitoring were compared to standard assumptions. Results indicate that windows activity plays a significant part in bridging the performance gap between design and actual energy consumption. Furthermore, the results of the questionnaires revealed participants' rationales for window opening and closing behaviours. Although this study comprises of a small sample in temperate climate, implications of this research addresses key issues for researchers investigating behaviour modelling and practitioners initiating building design.

Key Words: Mixed Mode Building, Occupants Behaviour, Energy Performance Gap, Dynamic Thermal Modelling

1. Introduction

UK Department of Energy & Climate Change vision is to provide secure, affordable and clean energy as the foundation for the UK's economic success (The Cabinet Office, 2015). In order to meet this vision, greenhouse gas emissions need to be reduced by at least 80% from the 1990 baseline (Parliament of the United Kingdom, 2008). The building sector has an important role to play as it is responsible for 37% of the UK greenhouse gas emissions (Committee on Climate Change, 2013). The total UK non-domestic floor area is expected to increase by 35% in 2020 with 60% of existing buildings still being in use (LCIC, 2012). The PROBE study (Post-occupancy Review of Buildings and their Engineering) presented results of 23 buildings' performance from 1995 to 2002 (Bordass, Leaman and Ruyssevelt, 2001). According to this study, the actual building energy consumption was two times higher than the predicted one. The discrepancy between the predicted energy performance and actual energy performance is commonly referred to as the performance gap.

The performance gap can lead to several issues (Zero Carbon Hub, 2014); it overestimates national carbon reduction and energy savings, energy bills are higher than expected and building occupants are unhappy despite the building's complying with the current UK building regulations. The energy performance gap can be attributed to three main stages (De Wilde, 2014); (1) building design, (2) construction and (3) operation. In these stages, assumptions over the future occupancy and use of the building are often inaccurate. In the construction process, the designed insulation and airtightness values sometimes are not achieved. Building commissioning and hand-over are also complicated processes that typically do not allow for full performance testing due to budget and time constraints. It is important to identify the different actors that contribute to performance gap and quantify their impact respectively. Occupants' behaviour affects the building energy use directly and indirectly by opening/closing the window, turning on/off equipment, turning on/off heating and air conditioning (AC) (Hong and Lin, 2012). The occupants' interaction with the building controls and in particular the windows is important to building modelling as the action of window opening is the most spontaneous and common action to achieve thermal comfort (Sorgato, Melo and Lamberts, 2016). Manual windows control is also increasing the energy consumption because of heat/cool waste and air pressure changes (Ackerly, Baker and Brager, 2011). The main focus in this study is to investigate window opening behaviours and analyse its contribution to the energy performance gap in a mixed-mode office building.

2. Study design

The review of methods for closing the performance gap, concluded that "*building performance evaluation requires a mixed approach, certain application require quantitative measurements, forensic investigation, qualitative insights or a combination of all the above*" (National Measurement Network, 2012). A mixed approach could provide a comprehensive understanding of the research problem. A combination of quantitative and qualitative methods was applied in this study. Data collection included three types of questionnaires (initial, weekly and feedback) and monitored environmental conditions. Occupants' initial and weekly thermal comfort questionnaires were based on ISO 7730 and ISO 10551 with questions on temperature and air velocity perception (how do you feel right now?), affective evaluation (how do you find it? e.g. comfortable) and preference (how would you prefer to be? e.g. warmer cooler). Environmental monitoring included measurements of air temperature (Ta), relative humidity (RH), radiant temperature (Tr), carbon dioxide levels and window movement. Window state was monitored using 3-axes accelerometers installed on the windows' panes. The 3-axes accelerometer logged acceleration changes (12.5 samples per second) in x, y, and z-axis. Observations from CO_2 data loggers (1 minute sampling rate) were used to identify the actual occupancy profiles and ventilation rates. Radiant temperature (5 minutes sampling rate) was used to evaluate the occupants' thermal environment and to analyse the relationship between the indoor temperature, thermal comfort and window opening behaviour.

The analysis of CO_2 concentration gives valuable insights into building ventilation rates and indoor air quality (Persily, 1996). Fresh air supply by opening the window is a typical way to manage CO_2 concentration. Air change rates can be estimated by applying CO_2 dispersion rate and the difference between the inside and outside CO_2 concentrations (Calver *et al.*, 2005). In this study, CO_2 measurements were used to assess the indoor air quality and to estimate the air change rates used in ventilation profiles for the simulation of the heating load. The difference between air change rates in the standards and the actual air change rates measured in the office may be one of the reasons for the discrepancy in cooling and heating loads between design and actual building energy performance. Two models with different ventilation rate and schedule were developed for the case study office. These two models were used as input to thermal dynamic simulations in TRNSYS to estimate the office annual heating loads.

2.1 Case Study

The study was conducted in Building 85 Life Science in University of Southampton during the summer of 2017, starting in June and finishing in August. The average temperature during project was 19.4^{0}C with the highest measurement (36^{0}C) between 2 and 3 pm on the 20th of June. The lowest measurement was 10.4^{0}C, recorded between 5 and 6am on the 6th of June. The study was conducted in a mixed-mode office orientated South-East, with no external shading nor over-shading from trees or other buildings. The open-plan office is on level 2, has an area of approximately 240 m^2 area and is occupied by 35 to 40 people.

2.2 Environmental Conditions

Indoor environmental conditions were monitored, and included dry-bulb temperature (Ta), radiant temperature (Tr), relative humidity (RH) and CO_2 concentration (CO_2). External environmental conditions were from CIBSE Test Reference Year and Weather Underground (Station: Church Lane, Southampton). Results shows slight differences in Ta within the office, see figure 1. Mean Ta between the five sensors varied between 24 and 22.5^{o}C. There was a significant difference between the five dataset (p-value<0.05).

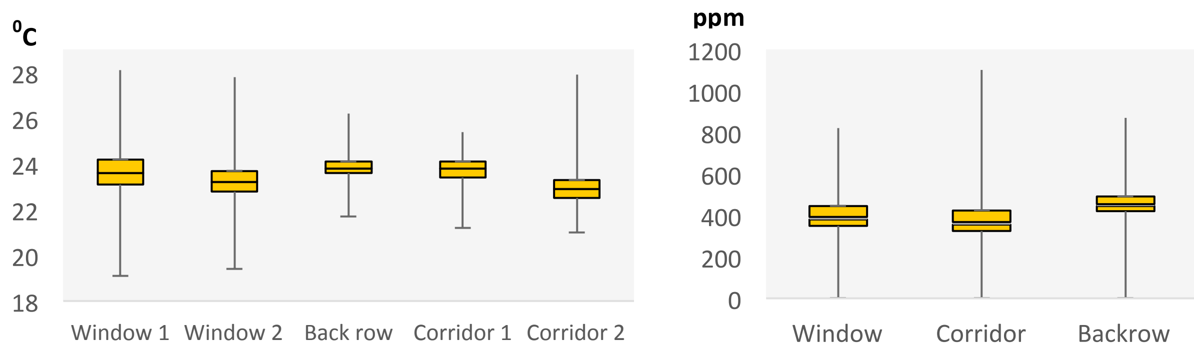

Figure 1 Indoor temperature (left) and CO_2 concentration (right)

Figure 1 shows that the highest temperature was recorded near the façade area, as there may be incident solar gain. Yet the back row and corridor area were on average warmer than the façade. This may be due to window opening behaviour. Furthermore, the variability in Ta is greater near the façade due to solar gain and window opening behaviour. Figure 1 shows that mean CO_2 in the back row is highest (489 ppm), which is 90 ppm more than in the corridor. This may be due to the position of the ventilation extract. However, the highest concentration level (1101 ppm) and the largest variability occurred in the corridor area where occupancy is higher but variable as it is a transitional space. Although CO_2 remained below 1500ppm, many occupants from the back row area have raised concerns about the air quality and the extract damper's noise.

2.3 Window State and dynamic thermal modelling

The four windows in the office have varied percentage of window opening, as shown in Figure 2. Window C has the highest activity state, with 13 activities (opened and closed actions) from the 2nd of June to 8th of August 2017.

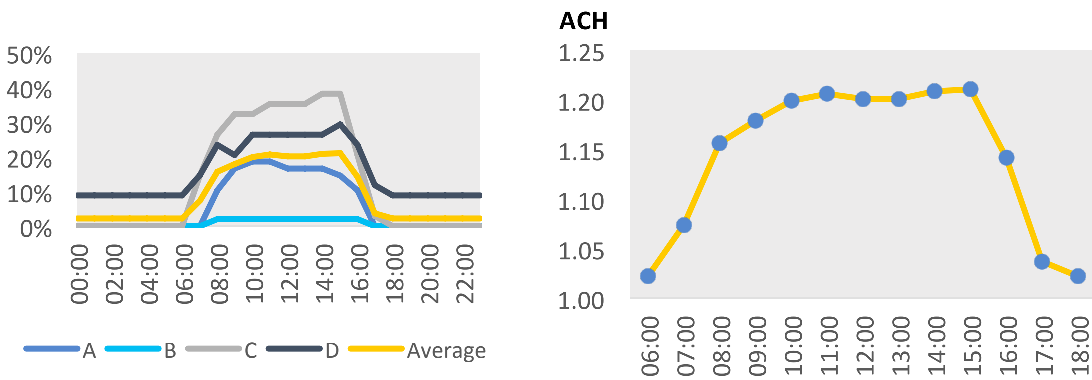

Figure 2 Opening percentage for the four windows (A to D) (left) and estimated ventilation rate schedule (right)

The numbers of activities were translated into probability of window opening behaviour for each hour of the day, only considering weekdays. Figure 2 shows that windows were likely to be opened between 10:00 am to 15:00 pm with average percentage of opening of 20%. The infiltration rate and ventilation rate were estimated using CO_2 decay (Calver *et al.*, 2005). The results of these tests enabled air change rate to be estimated when windows were opened (2.5 ACH) and when windows were closed (1.5 ACH). From these results and the window opening daily profile, air change rates were estimated through the course of the day, see Figure 2. This was used as an input to TRNSYS actual model.

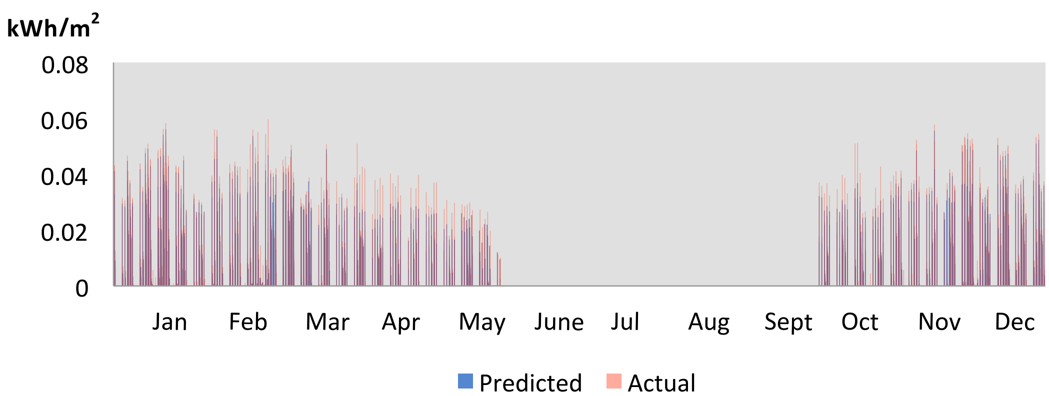

Figure 3 Predicted and actual annual heating loads.

Building fabric thermal properties, building systems, occupancy schedule and air change rate were input to the TRNSYS models. According to CIBSE (2015) the minimum air change rate is 1.6 ACH, considering 40 occupants and a volume of 720 m^3. The room's air change rate accounts for the infiltration, the background ventilation from the floor diffuser and window opening. This estimation of air change rate were used as input to TRNSYS predicted model. Building energy performance was simulated for one year. The heating system during the summer period was assumed to be off. The heating load throughout the year was simulated using input from standard ACH and monitored ACH. The standard ACH resulted in the 'predicted' model, while the monitored ACH resulted in the 'actual' model, see Figure 3. The actual model has higher heating demand (26.8 kWh/m^2) than the predicted model (22.9

kWh/m^2). The actual model incorporates the actual windows opening behaviour, which accounts for around 17% of the annual heating load. This percentage is slightly lower than the finding of Bourikas et al (2016) at 19%. This may be due to different type of occupants (office worker vs. students) and the easiness in operating the windows. In this study, one of the windows remained closed as files and books obstructed it.

2.4 Window opening behaviour

In addition to monitoring window opening behaviour, occupants' indoor comfort was studied using weekly questionnaire. 35 people took part and 105 surveys were collected from 25th July to 30th August 2017. Results are shown in Figure 4.

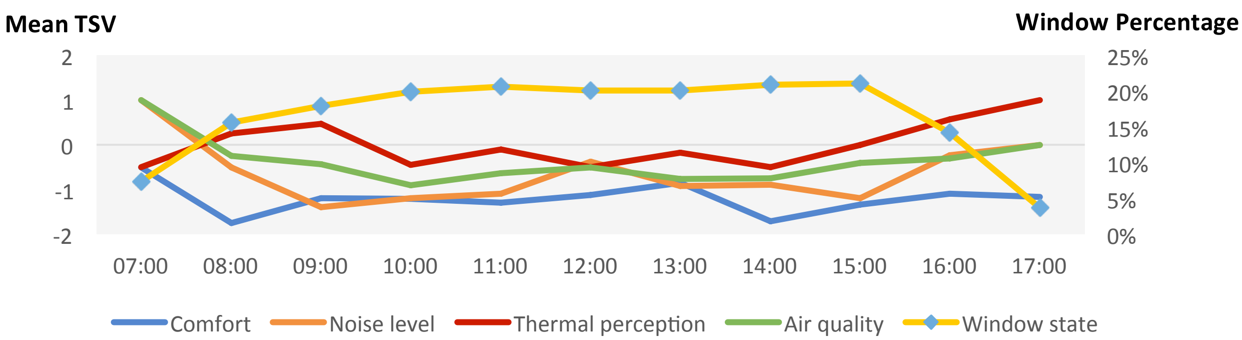

Figure 4 Mean vote for thermal sensation including thermal preference, noise level and air quality and probability of window activity.

The strongest relationship was between 'feeling comfort' and perceived air quality (R^2=0.54). Results of the initial and weekly questionnaires reveal that around 70% of the occupants think that the air movement in the office was lower than what it should be. When asked '*Which reason(s) lead you to open windows in your office?*' the most frequently reported reason was 'felling stuffy' (33% of the responses). In summary, occupant's fresh air perception is a key reason for windows opening behaviour, more than thermal sensation, and may lead to an increase in annual heating loads.

3. Conclusion

Applying a mixed method approach, this study has identifying the contribution of window opening behaviour to the energy performance gap in a mixed-mode office. Ventilation rate and heating load were estimated using dynamic thermal modelling and in-situ monitoring. Results show that window opening behaviour increased heading load by 17%. Participants' surveys uncovered the reasons behind the window opening activity. The occupants reported poor indoor air quality, with more than half of the participants finding the air movement low. In this study, one window was obstructed; future research may review access to window as a contributor to heating and cooling loads. In this study, there was little variability in occupants' activity profiles; future researches may review how this may have an effect on the energy performance gap. Although this was a small-scale study the findings could still be beneficial to various parties. For the government, it would help in analysing national carbon reduction and energy saving plan. For the building owners and occupants, energy bill might be lower while comfort is increased. For planners, designers and house builders, it would be an opportunity to improve the accuracy of predicted energy performance, which could impact on reputation credibility and business.

References

Ackerly, K., Baker, L. and Brager, G. (2011) 'WINDOW USE IN MIXED-MODE BUILDINGS: A LITERATURE REVIEW'.

Bordass, B., Leaman, A. and Ruyssevelt, P. (2001) 'Assessing building performance in use 5: conclusions and implications', *Building Research & Information*, 29(2), pp. 144–157. doi: 10.1080/09613210010008054.

Bourikas, L. and S, G. (2016) 'Camera based window opening estimation in a naturally ventilated office', *Camera-based window-opening estimation in a naturally ventilated office*.

Calver, A. *et al.* (2005) 'Simple methods to measure air exchange rates and detect leaks in display and storage enclosures', *14th triennial meeting, The Hague, 12-16 September 2005: preprints (ICOM Committee for Conservation)*, (1989), pp. 597–609.

Committee on Climate Change (2013) '2013 Progress Report to Parliament', (June), p. 253. doi: 10.1002/yd.20054.

CIBSE (2015) *Environmental design*. CIBSE Guide A.

Hong, T. and Lin, H. (2012) 'Occupant Behavior : Impact on Energy Use of Private Offices', *Asim IBSPA Asia Conference*, (January).

ISO 2001. Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales. BS EN ISO 10551:2001

ISO 2005. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. BS EN ISO 7730:2005

Low Carbon Innovation Coordination (CIC) (2012) 'New low carbon TINA reports', pp. 12–14.

National Measurement Network (2012) 'The Building Performance Gap – closing it through better measurement', (December). Available at: www.npl.co.uk/measurement-network.

Parliament of the United Kingdom (2008) 'Climate Change Act 2008', *HM Government*, pp. 1–103. doi: 10.1136/bmj.39469.569815.47.

Persily, A. K. (1996) 'The relationship between indoor air qualiti and carbon dioxide.pdf', *Indoor Air '96: The 7th International Conference on Indoor Air Quality and Climate*, pp. 961–966.

Sorgato, M. J., Melo, A. P. and Lamberts, R. (2016) 'The effect of window opening ventilation control on residential building energy consumption', *Energy and Buildings*. doi: 10.1016/j.enbuild.2016.09.059.

The Cabinet Office (2015) *Cabinet Office single departmental plan: 2015 to 2020*. Available at: https://www.gov.uk/government/publications/cabinet-office-single-departmental-plan-2015-to-2020/cabinet-office-single-departmental-plan-2015-to-2020.

De Wilde, P. (2014) 'The gap between predicted and measured energy performance of buildings: A framework for investigation', *Automation in Construction*. doi: 10.1016/j.autcon.2014.02.009.

Zero Carbon Hub (2014) 'Closing the Gap Between Design and As-built Performance - Interim Progress Report', (July), p. 44. doi: 10.1136/bmj.a1770.