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Understanding window behaviour in a mixed-mode buildings and the impact on energy performance

George M. Giakoumis[1*], Stephanie Gauthier[1], Patrick James[1], Leonidas Bourikas[1]

[1] University of Southampton, Faculty of Engineering & the Environment, Highfield Campus, Southampton, United Kingdom, gg7n14@soton.ac.uk

Abstract
Studies have shown that people feel more comfortable when they can control the environment in which they live and work. In a mixed-mode office building, this control is usually through openable windows, but window opening behaviour can have a significant impact on building energy performance. This monitoring study investigated window behaviours in a mixed-mode office building during the summer of 2016 in Southampton. Applying a mixed methods approach, 31 windows and 10 offices doors, movements were monitored using accelerometers. Concurrently indoor and outdoor environments were monitored and occupants' surveys undertaken. Results show a statistical relationship between window opening behaviour and indoor ambient and radiant temperature and CO_2 levels. The reasons for opening a window temperature and humidity as reported from the occupant's survey. Observed patterns of window opening behaviour did not match the building's design strategy as users acted differently from what BMS advised. This will have a substantial impact on energy performance in summer.

Keywords: Window behaviour, Energy performance gap, Mixed-mode buildings, Mixed-method approach, Longitudinal analysis

1. Introduction
Energy consumption, energy security and CO_2 emissions are major issues that the UK has to deal with. The government has a commitment to lower the carbon emissions by 80% from a 1990 baseline (DECC, 2015). UK's dwellings and commercial buildings are amongst the oldest building stock in Europe (Roberts, 2008). Buildings are significant consumers of environmental resources, particularly energy. When the actual energy consumption is higher than the predicted, it is called "energy performance gap"; one of the reasons has been identified as occupants' behaviour (Fabi et al., 2012, Agha-Hossein et al., 2013).

Currently, there is no standardised methods to monitor and to analyse how people use windows in commercial buildings. Furthermore, no specific standardisation for mixed mode (MM) buildings design regarding the best combination of operable windows and mechanical systems exists(Brager & Baker, 2008, Turner, 2008, Nicol & Humphreys, 2002, Brager, 2006). MM ventilation is based on the same principle as natural ventilation: energy efficiency; energy consumption is reduced by letting fresh air come into the building to refresh and circulate musty air (Nicol & Humphreys, 2002). Additionally, how people perceive thermal comfort inside their workspace, specifically in a mixed mode building, is a field of high interest. People trying to make their space comfortable may affect the energy performance of the building. Previous studies have highlighted a need for more sophisticated models of occupant control of windows (Borgeson, 2008). The research concerning the behaviour of users and how this affects the performance of buildings is emerging (Ackerly and Brager, 2013). Ackerly (2011), examined the variety of factors contributing to understanding the behaviour of building users who work in MM buildings; more specifically the impact of the operable windows on the performance gap.

Studies have shown a large difference between the actual and predicted energy consumption within buildings (Wilde, 2014, Menezes et al., 2012); which could be up to 2.5 times higher (Menezes et al., 2012). It is crucial to bridge the energy performance gap. First and foremost is the attainment of energy efficiency. The user's behaviour is linked to the energy performance of the building and therefore the energy demand within a building is related to window opening behaviour (Moghadam et al., 2015). Usually, the energy consumption depends on how people engage with the building management system and the building envelope. According to the statements above it is quite clear that the energy performance of buildings and the thermal comfort of building users are closely linked to indoor conditions.

The main aim of this paper is to identify the impact that windows use behaviour has on the energy performance of buildings, in particular, the energy performance gap between a building's design and operational performance. This study will focus on window behaviour in a mixed-mode building at the University of Southampton (Building 85, Life Sciences), the behaviour of the users as well as the impact that this behaviour has on the energy performance of the case study building. This paper will also contribute to an existing database by collecting and analysing qualitative and quantitative data and also developing an empirical model of window opening. This paper will be hinged on a longitudinal analysis of participants and their behaviours. The research question is formulated as: *"How to investigate windows behaviour in mixed-mode buildings and the impact on energy performance?".* To address this research question the paper is organised as follows. The data collection and analysis methods are described followed by an introduction of the the case study building. Results of the study are described, and then discussed.

2. Method

The mixed-method approach used in this study includes both qualitative and quantitative data, while the analysis includes both forms of data and also an integration of them (Creswell, 2011). Combining different methods is a useful technique for making a wide-ranging empirical model (Axinn and Pearce, 2006). A mixed-method approach it is a valid way to examine the relationship between social or technical influences, and occupants window behaviour (Birgit, 2016).

This study relied on surveying 78 participants who work in Building 85. A questionnaire survey collected information on the motivation for opening and closing windows, and influencing factors. 78 % was the response rate. This response rate is relatively large and represents almost half of the participants of each of the floors being studied. Participants were facilities managers, academics, secretaries, researchers, office workers and PhD students. In this survey, the questionnaires aim to record the reasons why an occupant interact with the environment (e.g., window). The number of accelerometers installed was 45. The sensors were mounted on the surface of the windows and the doors. Environmental loggers were placed inside the workspaces where they record CO_2, RH and ambient temperature. The data collection period was between the 1st April to the 1st August 2016 inclusive.

A longitudinal analysis was undertaken. The most challenging part of the data interpretation was to determine the state of a door or a window (open – close). Logistic regression was used to estimate the probability of an event having binary result (0-1) based upon predictor variables and coefficients; here the binary variable is the state of the windows and doors being closed or opened. The software which was used to run the analysis is R-studio. Furthermore, Levene.test, Anova and Turkeys' post hoc were some of the statistical functions used in the analysis.

3. Case study building

Building 85, is a mixed-mode ventilated building (Figure 1). The offices are all located on the south-east side at levels 2, 3, 4 and 6 (Figure 2). All the offices which are located at levels 3, 4 and 6 are divided into façade and internal zones. Levels 2 and 5 consist of internals zones only. The façades zones operate in a natural ventilation mode during the summer and mid-season. Natural ventilation in the office façade zones is achieved through low level manually operable windows and high-level motorised windows called "hoppers" (Figure 5) which are controlled by the Building Management System (BMS) to help provide draft-free ventilation and also allow a night cooling. Outside air enters the offices via these windows and exhausts via high-level motorised dampers at the top of the atrium (Figure 3). The supply of cold fresh air achieved through the low-level dampers and the extraction of air through the high-level zone dampers (Figure 5), which are fully modulating.

Figure 1: Building 85 at the University of Southampton

Figure 4: Level 2 windows

Figure 2: Building schematic

Figure 3: The atrium and the roof top dampers

Figure 5: Levels 4 and 6 windows and hoppers

The floors in which this study considers are the 2nd (ground) floor, 4th floor, 6th floor and also the atrium top roof. Level 2, is the floor where all the services of the building are located, it is an open plan room, with low level manually operable windows, without hoppers (Figure 2).

On floors 4 and 6, there are two sets of four identical offices, located in the front and at the back of the open plan. Offices, on floors 4 and 6 do not have any openable windows and they only run under the mechanical ventilation system of the building. The raised "top hat" section in the atrium roof is comprised of dampers on each face which could open or closed either automatically or manually. BMS's user interface is a traffic light system with wall beacon located on each floor.

4. Results

Having analysed the questionnaires results, the most frequently reported reason why occupants opened/closed windows was perceived internal temperature levels (warm or cold). Almost no occupants pay attention to the BMS's traffic lighting system. Moreover, people on 2nd floor reported to be very dissatisfied with the environmental conditions. As Figure 6 shows, an occupant on floor 2 (MM ventilated floor) opens a window at higher probability than an occupant on floor 4 or 6 (naturally ventilated floors). Due to the absence of hoppers on floor 2, there is no night time cooling as all the windows remain closed at night. Thus, by the time occupants arrive in the morning the indoor temperature level is higher than on floors 4 and 6 which leads them to open windows (Figure 8 & Figure 9). This is a potential reason why (according to Figure 6) the probability of a window state to be changed in floor 2 is higher from lower temperatures [22.5 °C] than on the other floors.

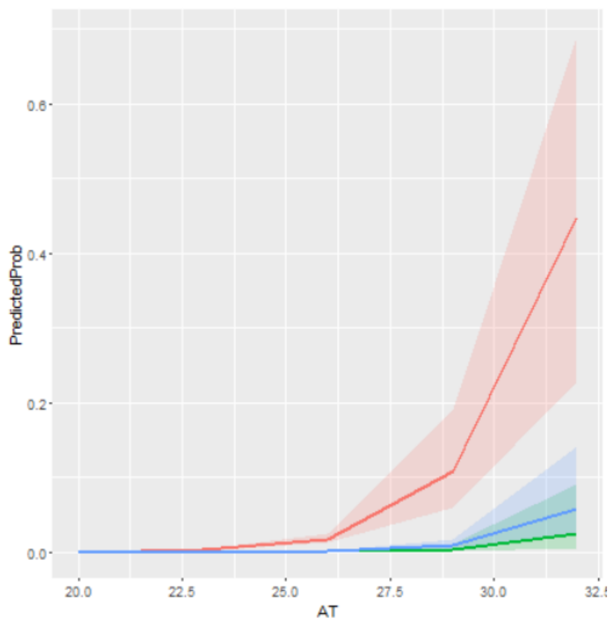

Figure 6: Predicted probabilities, and 95% confidence intervals, how temperature related to windows state on each floor (Red line is floor 2, green is floor 4 and blue is floor 6)

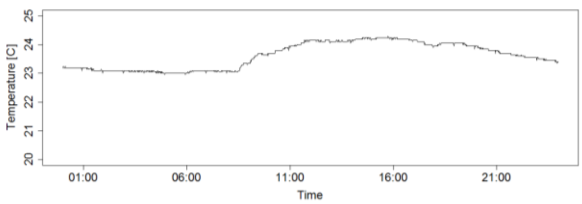

Figure 7: An example 24-hour period temperature profile in Level 2, justify the absence of overnight cooling

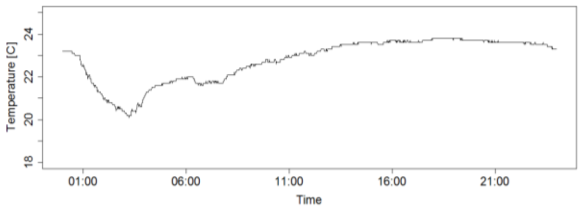

Figure 8: An example 24-hour period temperature profile in Level 4, justify the overnight cooling

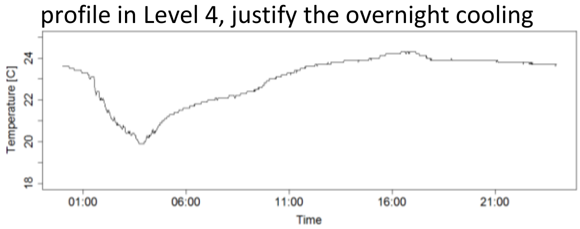

Figure 9: An example 24-hour period temperature profile in Level 6, justify the overnight cooling

To estimate the impact that an opened window has on the energy performance of the building, the airchange per hour rate of offices with open windows was estimated. The wind speed was monitored while the window was fully (11 degrees) and semi opened (5.5 degrees). The air changes per hours was estimated as 3.56 and 0.83. To follow number of visit to the building, it was observed that the traffic light system guidance was not follow. In particular during warm day ($T_{External} > T_{Internal}$), it was observed that occupants opened windows. Over the studied period of -15.48 cooling degree days, the impact of window opening was estimated as - 53.65 [kWh/m^2] and -12.50 [kWh/m^2] thermal, when the window was fully opened and semi-opened respectively. For a typical cooling system with a Coefficient of Performance (CoP) of 3.0, this would correspond to 18 - 4 [kWh/m^2] electrical.

This research gathered different types of data, which may be summarised as follows: (1) Subjective and quantitative data from the questionnaires and (2) Objective and quantitative data from the building monitoring sensors. These findings will contribute to how MM buildings, should be designed to meet the needs of the occupants and also how some variables affect occupants comfort. Logistic regression analysis was applied with the binary dependent variable as the state of windows and doors and the independent variables as the environmental factors. The following equations were developed:

-In mixed mode ventilated space, the change of a window's state could be estimated by the following equation:

- State = -17.80 + 0.23 * AT + 0.01 * RH + 0.012 * CO_2

-In a naturally ventilated space, the change of a window's state could be estimated by the following equation:

- State = - 30.156 + 0.635 * AT - 0.007 * RH + 0.018 * CO_2

-In mechanically ventilated offices, the change of door's state could be estimated by the following equation:

- State = - 8.305 + 0.16 * AT

Where,

- State is the Open / Close position
- AT is the Ambient Temperature
- RH is the Relative Humidity
- CO_2 is the CO_2 concentration in the office space

5. Conclusion

The limitations of this study could be divided into two categories, internal and external validity. As the comfort survey with the questionnaires was undertaken only once, the reported behaviours may not have been the actual responses to thermal comfort. During the study the participants were not asked to rate their thermal sensations which may have as a result to introduce bias in the study. Moreover, the study focusing on monitoring windows only at the east façade and not windows with different orientation.

Furthermore, two empirical studies were undertaken, first a pilot study (15th April – 23rd June), and then a main study (23rd June – 1st August). Both studies addressed using mixed-method framework including data collection and longitudinal analysis methods. Future works may apply the same procedure on a bigger sample and also to a different building. The participants who took part in this study were related to the University, and for this reason they may have similar attitudes and routines. This may have included bias in the results. The study was during summer, yet a similar framework may be applied during the winter. Finally, the examined building was located in the South of England. Other studies may be carried out in different regions.

As reviewed in the literature review, the current standards suggest environmental targets and benchmarks for the design of naturally ventilated and mechanically ventilated buildings. These findings will contribute to how mixed mode buildings, should be designed to meet the needs of the occupants and also how some variables affect occupants comfort.

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