Impact of user behaviour on the heating season carbon footprint of naturally ventilated UK offices

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Abstract
The ability of office users to manually adjust windows and blinds in naturally ventilated spaces is seen as an important element in helping them to achieve a productive, comfortable workplace. This flexibility can however, potentially result in significant energy losses during the heating season if office users do not close windows at the end of the working day. This paper assesses the impact of such behaviour on a selection of office buildings at the University of Southampton through a series of Monday morning thermography surveys conducted between October 2007 and February 2008. It is shown that the additional heating load that results from poor user behaviour with the façade is typically around 10% of the annual space heating demand.

1 The Naturally Ventilated Office

Naturally ventilated office buildings enable users to have far more interaction with the façade than mechanically serviced spaces. Office users are provided with the possibility of changing their environment by adjusting a blind or opening a window which is generally believed to improve the user acceptance of spaces (Clements-Croome, 2000). However, this flexibility also increases the risk that the thermal comfort and energy performance of a building may be compromised by users.

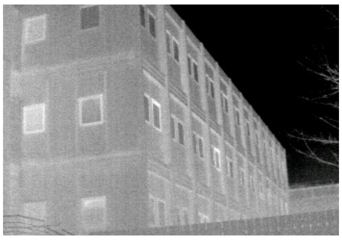
Previous work by the authors (James *et al*, 2006) focussed on the spring and autumn periods, looking at daytime user interaction with a façade through time lapse photography. This study showed; that for many office users; it is only when prompted by excessive solar gain or glare that interaction with the façade occurs. This can lead to a scenario of, for example, a window opening event late in the afternoon on South and West facing facades and the closing of windows when offices appear too cold the following morning. In effect, the user interaction is completely out of phase with what would be desired. This paper assesses the impact that user window opening can have on the carbon footprint of naturally ventilated offices during the winter heating season.

2 Legislation

Energy efficiency in buildings is currently a major topic in the UK with legislation driven by the European Commission having a significant impact. In England and Wales the interpretation of the EU 'Energy Performance in Buildings Directive' (EPBD) (EPC, 2000) came into effect in April 2006 as the new Part L of the Building Regulations 2000: Conservation of fuel and power (ODPM, 2006). A major change is that new or refurbished buildings must meet a target carbon dioxide emission rate (TER) as opposed to the previous elemental approach where components had to meet specific U-value requirements. Of perhaps more significance to this study is the emergence of energy performance certificates (EPC) as a result of the EPBD requirements. From October 2008 onwards all buildings larger than 1000 m² with public authority occupiers must have a display energy certificate (DEC) showing their annual operational energy consumption as well as an asset rating. This will include higher education buildings which are the focus of this paper. The DEC will use a colour banding scheme with an 'A' rating being the most energy efficient and 'G' the least (Arminas, 20008).

This study addresses the display energy certificate issue to some extent, in that it highlights the risk of a building dropping down a number of 'performance bands' through poor user interaction with a building's façade. It will clearly not be acceptable to many public authorities to have a building which is for example 'B' rated in terms of design, but 'D' rated in operation. This, in terms of public image, is far worse than a 'D' rated building performing to its design rating.

Table 1. Façade construction types of University test buildings and facade specification.

Thermographic Image	**Elevation detail**
	*B13 (South)* 1) 50 % glazed 2) 60 % openable 3) 30 % façade open Single glazed steel framed, bottom opening
	*B7 (South)* 1) 60 % glazed 2) 40 % openable 3) 24 % façade open. Single glazed steel framed, centre pivot vertical axis
	*B22 (North & South)* 1) 19 % glazed 2) 100 % openable 3) 19 % façade open. Double glazed, bottom opening
	*B4 (East & West)* 1) 45 % glazed 2) 36 % openable 3) 16 % façade open. Top window & single glazed steel framed, bottom opening
	*B2 (East)* 1) 50 % glazed 2) 50 % openable 3) 25 % façade open. Single glazed steel framed, bottom opening
	*B32 (East)* 1) 45 % glazed 2) 36 % openable 3) 16 % façade open. Double glazed, side pivot, vertical axis
	*B54 (East)* 1) 68 % glazed 2) 36 % openable 3) 16 % façade open. Single glazed, bottom opening

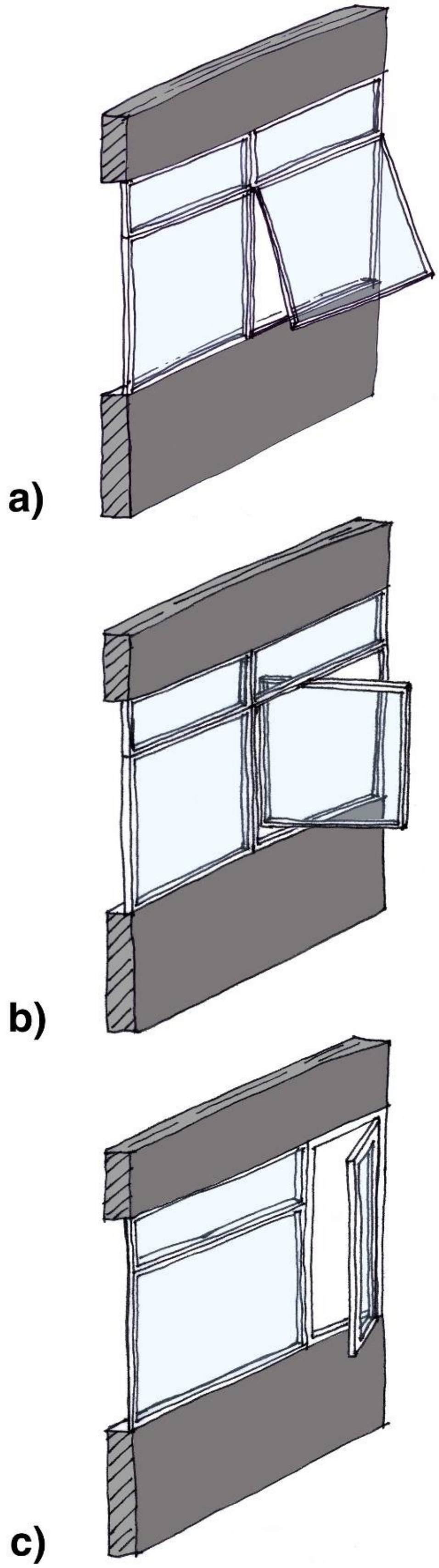


Fig. 1. Schematic representation of window opening types present on the investigated façades: (a) horizontal top pivot, (b) vertical, centre pivot, (c) vertical, side pivot.

3 Methodology and Experimental Approach

The study presented here is based on eight office buildings on Southampton University's main Highfield campus. Four of the study buildings were constructed pre 1970, one in the 1980's and three post 2003. Ten early Monday morning thermography surveys were undertaken between October 2007 and February 2008 to determine the level of office windows left open over the weekend and the resulting heat flux. The façades which were investigated within this study have a mix of glazing and window construction types as shown in Table 1. The air change as a result of windows being left open was calculated on the basis of observations conducted inside a dedicated test office. Figure 1 shows the three basic window opening types present on the investigated façades.

3.1 Airchange rate and window opening

The relationship between window opening, weather conditions (wind speed & ambient temperature) and the office air exchange rate was determined inside a dedicated test office using carbon dioxide as a tracer (B7 in Table 1). (Nabinger *et al*, 1994). Carbon dioxide levels were raised to between 900 and 1500 ppm by high occupancy before the 52m^3 test office was vacated and the windows set to the required opening position. The test office façade was similar to the central pivot type shown in Figure 1b. Figure 2 shows typical CO_2 concentration decay curves observed when the window was left closed and set to a specific aperture after vacating the room.

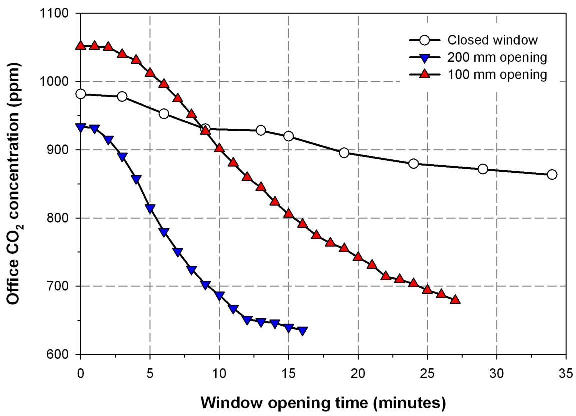


Fig. 2. Typical CO_2 profiles inside the test office as a function of window opening.

Carbon dioxide concentration in a vacated office space is related to the fresh air infiltration rate and the office volume as shown in equation 1:

$$C = C_i e^{-nt} + C_0 (1 - e^{-nt}) \qquad (1)$$
$$C - C_0 = e^{-nt}(C_i - C_0)$$
$$ln[(C - C_0) / (C_i - C_0)] = -nt$$

Where, C, is the CO_2 concentration in the office at time t, C_0, is the outdoor CO_2 concentration, C_i, is the initial CO_2 concentration in the office, $n(s) = Q_0 / V (s)$, is the air change rate, Q_0, outdoor supply rate (m^3/s), V, is the room volume (m^3) and t, is the time duration (s).

Figure 3 shows the observed relationship between window opening (defined as horizontal distance between bottom of the window frame and the window sill) and the air change rate per hour for the test office as determined by the CO_2 measurements. A first order linear fit to the data is shown, the scatter is as a result of the variation in wind pressure on the façade during the tests. For example, data points located above the trend line correspond to tests undertaken during conditions windier than the average wind speed for the dataset. The impact of variation in outdoor CO_2 concentration was seen to be small in comparison.

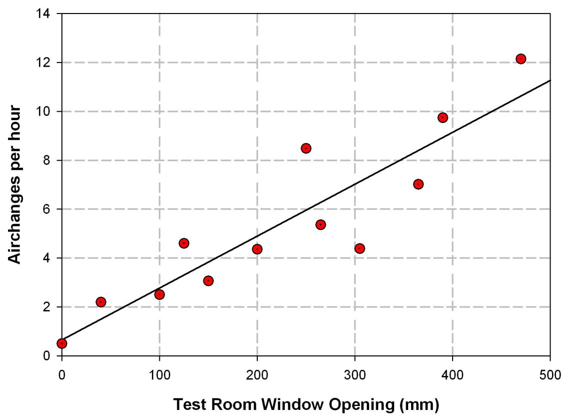


Fig. 3. Window opening - air change rate relationship in the test office (B7, 52m^3 vol).

The y-axis intercept of the trend line gives the infiltration rate (i.e. baseline air tightness) of the test building at 0.7 ac/hr which corresponds well to literature values given for leaky façades of older buildings (CIBSE, 2006). This value must be offset from any window opening heat loss calculation as it represents the baseline air exchange rate.

3.2 Window opening assessment of test façades

A high resolution thermography camera (Infratech VarioCAM 1280 x 960 pixels, 7.5 to 14 μm range) was used for the façade assessment of the eight study buildings. Figure 4 shows a typical image of a case study façade (Table 1, B13 South) on one of the ten Monday morning surveys. A number of windows have been left open over the weekend with some of them being in an almost fully open state.

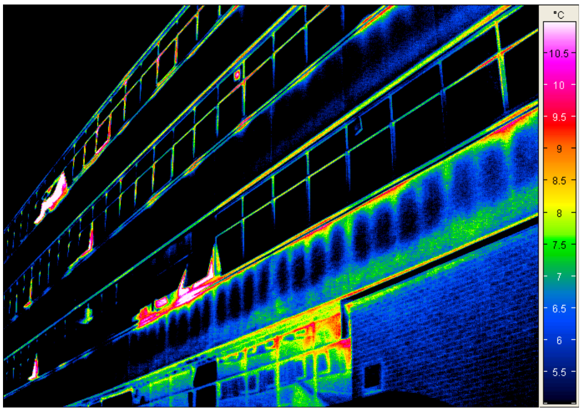


Fig. 4. Thermography image of the South facing façade of a 1960's office building (B13) at the University of Southampton. Monday morning before 7 am, February 2008.

It was found that the status of the case study façades on a Monday morning was influenced by the weather conditions on the previous Friday afternoon. If the Friday was sunny, the low sun probably caused problems of excessive solar gain, leading many office users to open their windows to provide ventilation and cooling. There was however, 'no driver' to remind users to close their windows at the end of the day. This created the undesirable scenario of an open façade during the heating season with night time ambient temperatures as low as 0 °C. Window opening behaviour across the working week was inferred from the Monday morning studies. A weather station on the campus has been used to relate environmental conditions (temperature, humidity, windspeed & irradiance) to façade conditions. This enabled prediction of the degree to which windows were left open overnight during the heating season (October to March inclusive) based on the measured meteorological conditions. The weather profile of the Fridays prior to the Monday thermography surveys was fairly typical of the entire heating season with a mix of both wet and dry days.

3.3 Estimating heat loss from window openings

The night time (out of working hours) heat loss from an office space can be estimated based on the ambient-office space temperature gradient and the air exchange rate as shown in (2) below.

$$\textit{Heat loss} = Q_0 \rho \, C \, \Delta T \qquad (2)$$

Where, ΔT, temperature between ambient and office space, ρ, density of air (kg/m^3), C, specific heat capacity of air (J/kg °C), Air change rate, $n(s) = Q_0 / V\,(s)$, Q_0, outdoor supply rate (m^3/s) and V, is the room volume (m^3).

All of the studied buildings, with the exception of B22, have high capacity wet radiator heating systems installed. These are all coupled to a central network supplied by a large combined heat and power plant on the main campus. Figure 5 shows a typical profile for the ambient and the office temperature of an office inside one of the case study buildings for a week in December 2007 (B7 in Table 1). The office space is maintained at a minimum of ~22 °C throughout the week with a night time ambient of between 0 and 8 °C (Figure 5.).

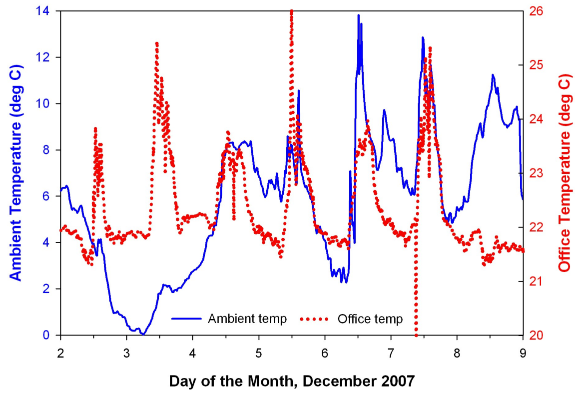


Fig. 5. Ambient and dry bulb temperature inside one office in building B7, 02-09 Dec 2007.

4 Results

4.1 Monday morning window opening status

Figure 6 shows the recorded façade condition of five of the case study building façades during the surveys. The percentage of the glazed area which was left open is shown for each of the buildings. The open area is defined as the ratio of the total window area and the area created between the outer edge of the window and the façade plane. For example, for the case of a bottom opening horizontal top pivot window (see Fig. 1a.), the horizontal area created at the sill level by the opening of the window is compared to its total area. This means that, if all the glazing in a façade consisted of top pivot, openable windows, which were opened to an angle of 45 degrees, the open area would be 71% (1/√2).

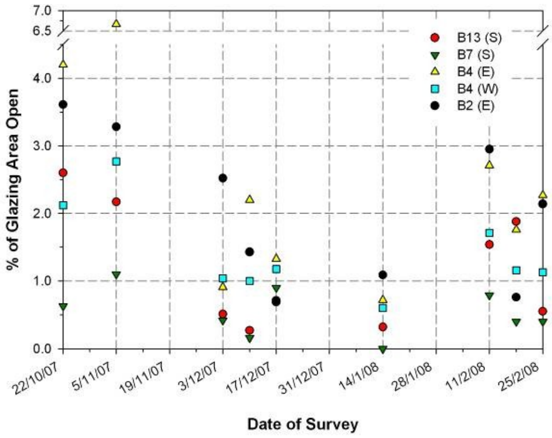


Fig. 6. Façade opening status of five case study façades during Monday thermography surveys.

As can be seen in Figure 6 the percentage of open façade area over the weekend appears in different clusters and variances between the individual buildings for different days. This was identified to be related to the Friday afternoon weather conditions the week before. However, the position of individual buildings within the sample appears to be relatively consistent in relation to the other buildings even though the maximum openable area is relatively similar (Table 1). This was found to be related to the type of window opening mechanism. The B7 building (Green triangles in Fig. 6.) has central pivot windows which create strong drafts in offices when there is air pressure on the façade and will allow water into the building if it rains. On Fridays, where it rained prior to a Monday thermography survey the B7 building façade was almost completely sealed (see 14/01/08 in Figure 6 for example). Office users in this building are aware of these limitations and it is reflected in the small level of window opening variation compared with for example the B13 building (Red dots in Fig. 6.) which has horizontal top pivot windows.

4.2 Impact of open windows on space heating

To estimate the impact of the increased air flow of open windows on the heating demand of the case study buildings assumptions based on the Southampton weather dataset, building floorplans and the thermography surveys have been made in respect of equation 1.

- Average nighttime ambient temp = 6 °C
- Average nighttime office temp = 21 °C
- Office vol. per openable window, V = 50 m^3
- Heat capacity of office air, C = 1.0 kJ/kg °C
- Density of office air, ρ = 1.25 kg/m^3 (10 °C)
- Heating season 6 months, October to March
- Nighttime duration, 16 hours per day

The experimental results showed that under average wind conditions an opening area of 1 m^2 inside an office of 50 m³ corresponded to an air change rate of 14.6 ac/h (see Figure 3.). If this window opening level had been retained for the test office every night over the entire heating season, this would have corresponded to an estimated night time heat loss from the open window of 11,100 kWh. The average night time open window area over the case study building sample was calculated from the Monday morning surveys to be 1.3 ± 0.3 m^2 per 100 m^2 of glazed area. The additional heat loss due to night time window opening is therefore 1.3 x 11,100 kWh per 100m^2 of glazed façade (i.e. 144 kWh/m^2 glazed façade).

To put this into perspective, it is useful to consider the heat loss that would have occurred through a non-openable window with a U-value of 1.0 W/m^2K. This corresponds to a high quality, double glazed unit with twin low-e coatings. (Single glazing has a U-value of ~ 6.0 W/m^2K, standard low-e double glazing ~ 1.7 W/ m^2K.) Over the heating season, the energy loss through such a glazing unit would be:

Energy lost per m^2 glazing = time (hours) *x* temp gradient *x* U-value = 44 kWh per m^2.

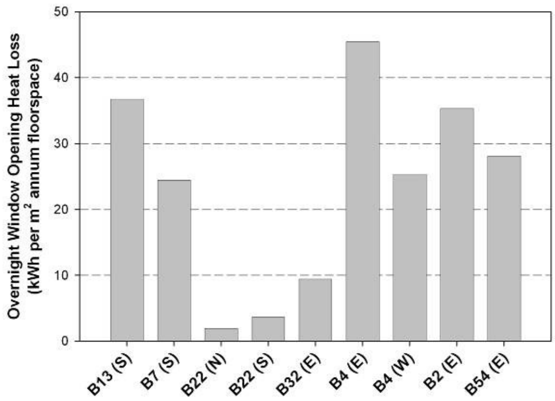


Fig. 7. Overnight window opening energy loss during the heating season for 9 case study façades, University of Southampton.

The heat loss effect during the night time over the building sample is therefore equivalent to an increase of the glazing of 3.3 W/m^2K for the entire investigated façade area. Figure 7 shows the estimated heat loss due to windows left open over night per m^2 of office floor space for the case study building sample. The average annual heating demand of all buildings at the University is typically around 200 kWh/m^2. The average heat loss associated with windows open during the night time was 23 kWh per m^2 annum, which represents about 10% of the University's annual floorspace heating demand.

As can be seen in Figure 7 the heat losses of B22 and B32 do not match to the rest of the building sample. Building B22 is an open plan, temporary building with air conditioning and electrical space heating. A user survey conducted in January 2008 inside this building highlighted that many users felt the building to be cold in the morning. The reasons for this are probably diverse, ranging from the electric heating system and the user setting of the heating system to leaks in the building fabric. However, anticipation of cold morning temperatures is believed to have had a major influence on the drive to close windows in the evening. In addition, both B22 and B32 are the only buildings in the sample with easily accessible window openings at a comfortable height and without window sill. Furthermore, B32 only has a small number of openable windows as it contains large mechanically ventilated areas, which is not representative for the University's building stock.

4.3 Impact of open windows on display energy certificates

The average heat loss associated with avoidable night time window opening is 23 kWh per m^2 -this corresponds to a carbon emission of ~ 6kg CO_2 per m^2 for gas based heating. The impact on a building's rating based on the benchmarking system to be applied in England and Wales is not easy to readily quantify. It is anticipated that it could represent the width of perhaps half of a performance band and so would readily downgrade the rating of a building asset.

5 Conclusions

The study has highlighted that the actions of a few users can compromise the carbon footprint of an entire building. For newer naturally ventilated buildings in particular, which have better air tightness and high levels of insulation, user behaviour becomes increasingly important as it can potentially create a wide disparity between the 'designed' and 'operational' performance. The increase in heating demand across the studied building portfolio which mainly included naturally ventilated buildings with single glazing constructed prior to 1990, is estimated at 10%. Mechanically controlled buildings (B32) with a low amount of openable windows as well as buildings with poor heating system (B22) were observed to have less window opening related heat losses in terms of absolute values. The type of window opening can have an important influence on user interaction with the façade. Central pivot windows in particular cannot be left open unattended, as rain ingress into the building may result. Whilst this can be viewed as desirable in the winter period considered in this study it causes problems during the summer period where office users are reluctant to leave the façade open overnight – in effect, night purging potential is somewhat compromised unless the weather conditions are very settled.

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