Characterising the use of windows in thermal simulation

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ABSTRACT

The use of windows is a key adaptive opportunity in naturally ventilated buildings especially in summer when the building is likely to be free-running. In these circumstances the use of windows can be on important key to occupants remaining comfortable, particularly in warm weather. This aspect of buildings is poorly covered in existing thermal simulations in which occupant behaviour is ignored or presented in a very basic fashion. This paper presents an approach to the simulation of window opening behaviour which has been developed from observations of occupant behaviour in UK offices. The paper presents examples of the use of the 'adaptive window-opening algorithm' which demonstrate the advantages of opening windows to comfort and the cost in terms of extra energy use. The paper suggests way in which the methodology can be extended to other controls and other climates.

1. INTRODUCTION

The opening of windows in Naturally Ventilated buildings is a key strategy occupants can use to improve their thermal comfort. The effect will be positive if mixing of indoor air with the outdoor air will improve conditions for comfort. The opening of a window can also increase air movement within the room and so allow the occupants to be comfortable at a higher temperature. Where conditions are particularly hot, windows and doors are often used together to increase the air movement by cross ventilation across the space. Other controls are also used: blinds are used to control the entry of solar radiation, fans to increase air movement and mechanical heating and cooling to change indoor air temperature.

The adaptive approach to thermal comfort understands such behaviours as part of the way in which people respond to the environment: *If a change occurs such as to produce discomfort people react in ways which tend to restore their comfort*. This *adaptive principle* understands comfort not so much as a result of a temperature or a particular set of conditions, but rather as the culmination of a series of actions which are designed to avoid *dis*comfort. The comfort is then in effect a measure of how successful those actions have been.

In this context the opening of windows is part of the means of achieving comfort. But such actions are not precise. Everyone does not open their window at one particular temperature.

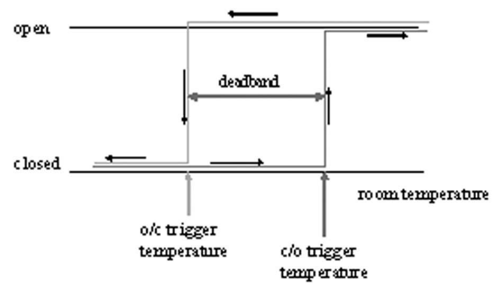


Figure 1. In the 'deadband' there is no need to close the window if it is open, or to open it if it is closed. The window status is indeterminate.

To take a simple example. Suppose there is a certain indoor condition at which a person opens the window because it has become too hot. There will be another, lower, temperature at which they will close it because it has become too cold. Between these two temperatures there will be what can be called a 'deadband' where the window may or may not be open, depending on the detailed history of the room and preferences of the occupant (Figure 1). In the adaptive theory the trigger will be a thermal one – the crossing of a comfort-discomfort threshold resulting in an action being taken to restore comfort. In reality such a threshold is not precise, even a single person will vary according to their state of adaptation and the recent thermal history. The result is that in any real case the 'sides' of the deadband take a sigmoid shape (figure 2).

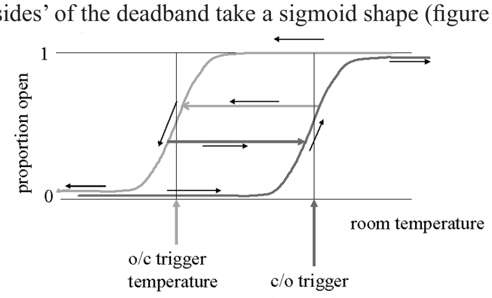


Figure 2. If the room cools before all have opened their window, those who have opened it have no need to close it, and those who

have not opened it have no need to do so. There is therefore a horizontal 'grain' within the deadband.

2. DEVELOPING THE ALGORITHM USING FIELD DATA

Data were collected in 25 offices in Aberdeen and Oxford UK during 1996-1997. These data included a record of indoor and outdoor temperatures, the comfort vote and clothing of the individual and the use of various controls, including windows, fans, blinds etc. Each subject recorded their comfort votes and window usage up to four times daily – early morning, late morning, early afternoon and late afternoon. The use of windows was recorded a '1' if the window was open and '0' if it was closed. Nearly 36,000 such 'datasets' were collected (Rijal et al 2007).

If we take actual data from buildings where occupants have been free to open or close windows and use logistic regression to analyse, for any given temperature, what mean proportion of windows are open we get the sort of graph shown in figure 3 which is for Aberdeen/Oxford offices. A different view is available if, instead of using each data point separately, we divide the data into small groups at a particular indoor temperature and find the proportion of windows open in each group. This will allow the 'shape' of the deadband area to be shown (Figure 4). The number of datasets used to calculate each point should be a balance between too large a number which will hide the basic shape of the area, and too small a number which will make the 'grain' of the graph too coarse. In figure 4 twenty –five datasets are used to generate each point.

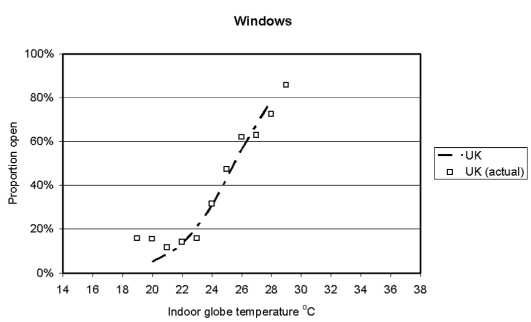


Figure 3. Mean proportion of windows open when the indoor temperature is as shown (From Nicol and Humphreys 2004)

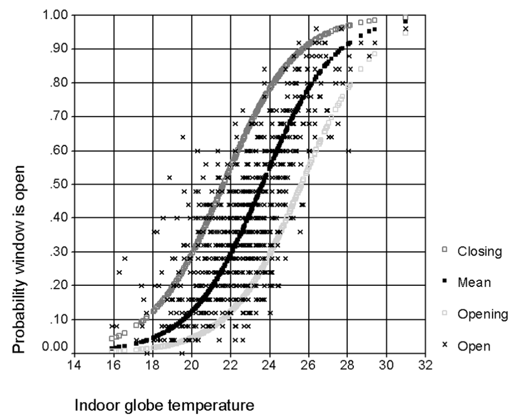


Figure 4. Showing the shape of the deadband for data collected in the UK. The two outer lines, based on logit regression, represent the upper and lower margins of the deadband and the central line the mean response. Each point represents the mean of 25 datasets at that indoor temperature. The deadband shown is 4K wide and contains 83% of the points, the right hand margin is the likelihood the window will be opened if closed, the left hand that it will not be closed, if open.

Figure 4 also shows some suggested limits for the deadband about 2K either side of the mean. This width for the deadband is based on comfort theory (Nicol and Humphreys 2007) and gives a dead-band width of ±2K. The slope of the lines is obtained by regressing operative temperature on the logit of the proportion of windows open.

2.1 The significance of the deadband

The existence of a 'deadband' is of great significance. An area in which there is no need for the window state to change ensures that the system is relatively stable. A model which suggested a particular indoor temperature at which windows are opened will be unstable, since the window opening can itself cause a drop in temperature resulting in a window closure, which will in turn cause a rise in temperature and a window opening and so on. A gradual increase in the probability of window opening as suggested by Nicol and Humphreys (2004) (figure 3) will reduce the instability but will still predict that a proportion of occupants will re-close the window fairly soon after opening it (as the room cools and the proportion of windows open falls).

Yun and Steemers (2007) made a study of window-opening behaviour in a small number of offices on Cambridge UK These data were collected in the summer and the winter months. They found that in the summer 61% of occupants opened their window on arrival and in winter only 2%. They also observed a total of only 5% of subjects actually opening or closing a window after setting an initial state on arrival.

In the Aberdeen/Oxford data throughout the year, 28% of subjects in NV buildings opened their windows all day and an additional 21% had their windows open at some time during the day. Looking at only the seasons covered in the Cambridge data, 59% of windows are open all day in the summer and a further 15% for part of the day, in winter the figures are 6% and 16% respectively. The major seasons for window adjustment were spring and autumn. In spring 23% were open all day and 28% part of the day, in autumn the figures were 14% and 27% respectively.

2.2 Developing an adaptive algorithm for window opening.
The above figures show that the relationship between people and their office windows is a dynamic one where, even in winter, there is an active use of windows. This raises questions for both comfort and energy use in buildings. A method for investigating both is to develop an algorithm for the use of window opening based on the analysis above which characterises the probability that the window is open. The likelihood that the window is open can be calculated on the basis of a logit formula obtained by logistic regression. The logit can be defined as

$$\text{Logit}(p) = \text{Log}\,\{p/(1-p)\} = aT + b \qquad (1)$$

Where p is the probability that the window is open, T is the temperature (indoor or outdoor) and a and b are the regression slope and the intercept.

A multiple regression equation can be calculated in terms of both indoor and outdoor temperature. From the Aberdeen/Oxford data the relationship can be calculated:

$$\text{Logit}\,(p) = 0.171T_{op} + 0.166T_{out} - 6.43 \qquad (2)$$

Where T_{op} is the operative temperature (often taken as equal to the measured globe temperature) and T_{out} is the instantaneous outdoor temperature. This formula shows that the probability that the window is open is affected by both how hot it is in the room and the outdoor temperature. If the outdoor temperature is low, the window may be opened to relieve overheating but it is likely to be shut more quickly. Thus the likelihood it is open at any one time will be reduced. Eqn. 2 can be used to determine the initial setting of the window at the start of the day. We can use the formulae presented in CIBSE Guide A (CIBSE 2006) (similar to those presented for freerunning buildings in CEN Standard 15251 (CEN 2007)) to calculate the comfort temperature from the outdoor running mean temperature:

$$\text{If } T_{rm} > 10,\ T_{comf} = 0.33\ T_{rm} + 18.8 \qquad (3)$$

$$\text{If } T_{rm} > 10,\ T_{comf} = 0.09\ T_{rm} + 22.6 \qquad (4)$$

Where T_{rm} is the exponentially-weighted running mean temperature (for a definition see CIBSE (2006)) and T_{comf} is the comfort temperature for that day. If T_{rm} is less than 10°C then inspection of the data suggest that the building will be running in heated mode and eqn. 4 should be used, if greater it will be free running and eqn. 3 will apply.

Now if T_{op}, the indoor operative temperature is greater than $T_{comf} + 2$ then if the window is closed there will be a motivation to open it, if the window is open and the temperature is less than $T_{comf} - 2$ there is a motivation to close it. If the indoor operative temperature is calculated at the start of the day (assuming, say, that the windows have been closed at night) then using the criteria shown above we can estimate whether there is the desire for a change in the window state. Using a random number generator we can then make a decision whether the window should be opened (closed) based on the likelihood the window is open according to the indoor operative and the outdoor air temperature

A more detailed description of the 'Humphreys' window-opening algorithm can be found in Rijal et al 2007.

3. APPLYING THE ALGORITHM IN BUILDING SIMULATION

An algorithm of the type described above can be embedded in a simulation program so that the opening of windows can be properly accounted for. The Humphreys algorithm has been embedded in the ESP-r simulation tool (Clarke 2001) and the implications for comfort and energy use in an office building have been explored.

First the implications for occupant comfort were explored. The comfort of occupants with openable windows was compared with those without in a representative cellular office in Northern UK. The definition of overheating was that of CIBSE: that the indoor temperature should not exceed 28°C for more than 1% of occupied hours (CIBSE: 2006). The percentage of occupied hours predicted to be in excess of 28°C are shown in figure 5

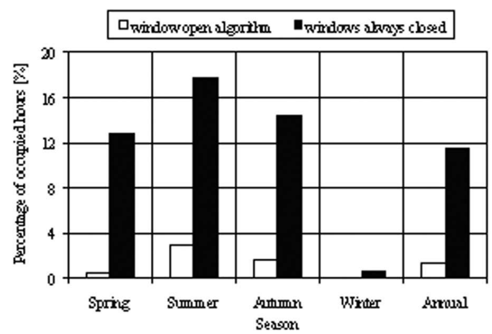


Figure 5. Percentage of occupied hours in which the indoor temperature exceeds 28oC with and without the window opening according to the algorithm (source Rijal et al)

The 'exceedance hours' where the temperatures is above 28°C are in excess of CIBSE 1% guidance even with opening windows in summer and autumn. The exceedance for the room with non-opening windows is always higher.

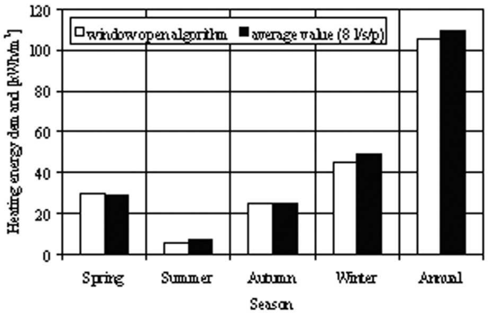
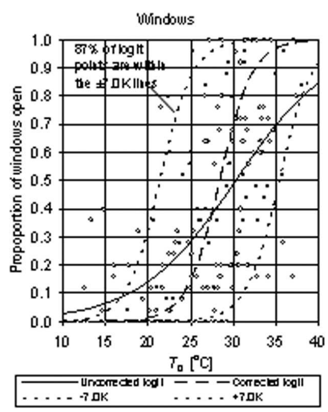
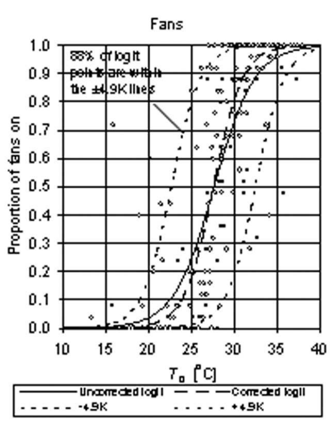


Figure 6. Energy use in a naturally ventilated building with occupant-controlled windows compared with a constant ventilation rate of 8 litres per second per person (Source Rijal et al 2007)

The adaptive algorithm can also be used to show how occupant behaviour will affect the energy use of buildings. A simple comparison was made between energy use with opening windows (assumed to be used adaptively) and with constant ventilation rate of 8 litres per second per person. The results are shown in Figure 6. Note that the adaptive algorithm predicts a slightly lower annual energy use.





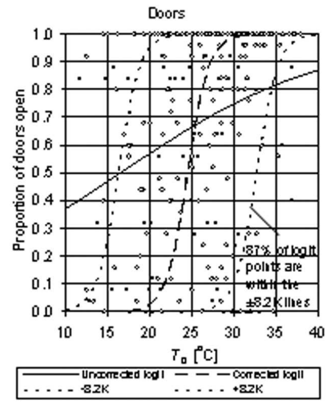


Figure 7. Deadband diagrams for use of windows, fans and doors for Pakistan (source Rijal et al 2007a)

Since the adaptive behaviour of occupants is motivated by the avoidance of discomfort, it is to be expected that a more comfortable environment will require less window use. This effect is predicted by simulations using the adaptive algorithm in Rijal et al (2007). They show that adding an external shading device will reduce window use and discomfort but will increase energy use because of additional use of lighting. Adding thermal mass as well as shading will improve comfort further and reduce overall energy.

4. DEVELOPMENTS OF THE BASIC WINDOW ALGORITHM

The adaptive algorithm for window opening described above is available in ESP-r, an open-source simulation tool. As presented above it applies only to windows and to the UK context. A number of developments have taken place which will broaden its applicability and usefulness.

4.1 Extension to other climates

As well as the UK (Aberdeen/Oxford) data, two similar sets of data are available. The first is data from 5 European countries collected as part of the SCATs project (Nicol and McCartney: 2001) and the second is from a survey in 5 cities in Pakistan (Nicol et al 1999) with a range of climates. These databases can also been used to provide window-opening algorithms.

The scatter diagram for window opening probability against indoor temperature for Pakistan is given in the first graph in Fig. 7. The deadband is centred on a different temperature and the horizontal scatter of points is wider than for the equivalent graph for UK shown in Fig 4. The slope of the lines in Figs 4 and 7 is comparable. The difference in the central temperature at which there is a 50% probability that windows are open (23.5°C in

UK and 30°C in Pakistan) can be explained in adaptive comfort theory. The deadband is centred on the comfort temperature. As the comfort temperature changes with climate and season the deadband will shift. So the width of the deadband is related to the range of environments which occur in the database. The Pakistani subjects are adapted to a larger range of temperatures than those on the UK.

These hypotheses can be tested by analysing the window opening in terms of the difference between the operative temperature and the comfort temperature. This method, used by Nicol and Humphreys (2007) to explore overheating, assumes that the motivation to make a change is related to the difference between the comfort temperature (variously defined) and the actual temperature which the occupants are experiencing. Using this measure of indoor temperature the width of the deadband is reduced from 7.0K (Figure 7:1) to 2.6 K (Figure 8). This width is similar to that obtained from other surveys (e.g. SCATs data) and suggests there is an underlying curve for all climates which is offset by the prevailing climate. This adaptive element in the data means that a model can potentially be developed which can be used in all climates.

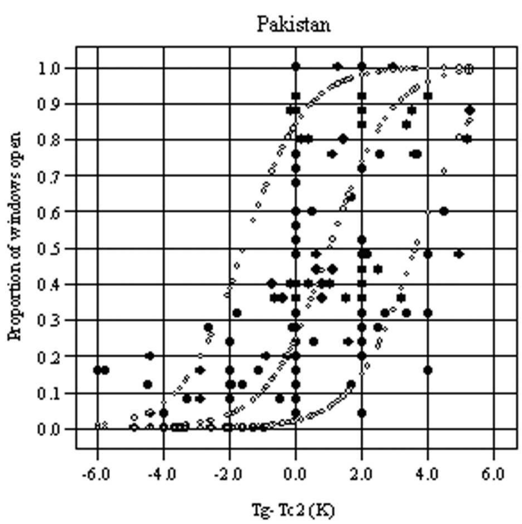


Figure 8. The graph of window use from Pakistan in terms of the difference between operative temperature and comfort temperature. The width of the deadband is reduced from 7.0K (figure 7:1) to 2.6K suggesting that the original width had an adaptive element to it

4.2 Use of other controls

There are controls other than windows which are commonly used in offices to change the indoor climate to avoid discomfort. Notable among these are fans, used to create air movement to offset high temperatures, and internal doors which are often used in conjunction with windows to create cross ventilation and increase the cooling effect of windows.

The middle graph in Figure 7 shows how the use of fans conforms to a similar pattern to the use of windows. The data are from Pakistan, where the supply and use of fans in summer to offset high temperatures is almost universal. The central curve for window- and fan- use are almost identical suggesting that these two adaptive aids are used a roughly the same temperature.

Blinds or curtains are sometimes used to reduce radiant temperature in offices on sunny days. Sutter et al (2006) have provided evidence that the driver for blind use is external illuminance rather than temperature.

Similar curves can be formed for the use of heating, though this is best done using outdoor temperature as the driving factor. The sigmoid curve for heaters is relatively narrow with the 50% temperature at about 10oC outdoor temperature (see eqns 3 and 4 above)

4.3 New approaches

The approach to developing an algorithm for window opening which is outlined above relies on existing results from thermal comfort studies, assuming that the width of the deadband is related to discomfort. The data can be analysed from a purely statistical point of view, and this will essentially be a behavioural result rather than one based on theory. Similar results are obtained.

5. CONCLUSIONS

This paper presents some preliminary results from a stochastic analysis of control use by office workers in the UK and beyond

- The proportion of windows which are open can be modelled in terms of adaptive theory suggesting that the desire on the part of occupants to avoid discomfort is the motivation to change the window setting (open-to-closed or closed-to-open).
- There is a dead-band of temperatures in which there is no motivation to open or close windows so that the proportion open or closed remains constant.
- An adaptive algorithm has been developed to allow a building simulation to mimic the behaviour of real building occupants.
- Simulation with the algorithm suggests that occupants are largely successful in achieving their comfort aims, though there may be some cost in terms of energy use
- The algorithm is based on adaptive theory and will be applicable to a wide range of climates
- The algorithm can be developed to describe occupant use of fans and other controls

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REFERENCES

CEN (2007) Standard EN15251 *Indoor environmental parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics* CEN, Brussels

CIBSE (2006) Chapter 1, *Environmental criteria for design, Environmental Design:* CIBSE Guide A London, Chartered Institution of Building Services Engineers

J.A. Clarke, JA. (2001) Energy Simulation in Building Design, Butterworth-Heinemann, Oxford, 2001.

Nicol, J.F. and Humphreys, M.A. (2004) A Stochastic Approach to Thermal Comfort, Occupant Behaviour and Energy Use in Buildings *ASHRAE Transactions 110(2)* pp554-568

Nicol, J.F. and Humphreys, M.A. (2007) Maximum temperatures in European office buildings to avoid heat discomfort. *Solar Energy 81 (3)* 295–304

Nicol, F. and McCartney, K. (2001) *Final report (Public) Smart Controls and Thermal Comfort (SCATs) Project (Contract JOE3-CT97-0066)*, Oxford, Oxford Brookes University.

Nicol, J.F., Raja, I.A., Allaudin A. and Jamy, G.N. (1999) Climatic variations in comfort temperatures: the Pakistan projects. Energy and Buildings 30 (3) pp261-279

Rijal, H, Tuohy, P, Humphreys, M.A. Nicol, F., Samuel, A. and Clarke, J. (2007) Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings, *Energy and Buildings 39(7)*823-836

Rijal, HB, Nicol, JF, Humphreys, MA and Raja, IA (2007a) Use of windows, fans and doors to control the indoor environment in Pakistan, developing a behavioural model for use in simulations, Proceedings of Environmentally sustainable development conference ESDEV2007, Abbotabad, Pakistan.

Sutter, Y., Dumortier, D. and Fontoynont M. (2006) The use of shading systems in VDU task offices: A pilot study, *Energy and Buildings*, *Volume 38 (7)*, *780-789*

Yun, G.Y. and Steemers, K. (2007), "User behaviour of window control in offices during summer and winter", Renewables in a changing climate: Innovation in the built environment, CISBAT international conference 2007, Lausanne, Switzerland