Modelling window-opening and the use of other building controls

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ABSTRACT

People who become too warm or too cool will adjust their clothing or reset building controls (windows, blinds, fans, thermostats) with the aim of restoring comfort or reducing discomfort, if they are free to do so. However, the trigger-temperatures for warm and cold discomfort depend on (among other things) the clothing and the fan setting. The trigger-temperatures differ from person to person and from time to time. If several controls are available, people will first use those that are user-friendly, effective and without undesirable consequences. These various considerations are built into a flexible model of behaviour that is capable of wide application.

1. INTRODUCTION

How occupants exercise control over their indoor environment is a topic of current research (see e.g. Yun & Steemers, 2007, Robinson & Haldi 2007). The Thermal Comfort Unit at Oxford Brookes University with colleagues from the University of Strathclyde have been developing algorithms describing occupant behaviour and implementing them in the thermal simulation package ESP-r (see e.g. Rijal et. al. 2007). For reliable simulation of naturally ventilated buildings a realistic model of human behaviour is needed, and its parameters must be supplied by studies of people in everyday life. This paper develops such a model. The procedure is to construct a simple model, and then increase its realism until it usefully portrays daily life. The model is based on thermal comfort, is initially applied to window opening and then extended to cover the use of other controls. including ceiling fans and the choice of clothing.

2. MODELLING THE RESPONSE

2.1 The consistent occupant

Given the opportunity, people commonly avoid discomfort, and among the actions they take are the opening and closing of windows. The assumptions for the simplest case are: the occupant's thermal-comfort perception is consistent; the occupant is free to open or close the window; the window is easy to operate; opening the window cools the room; there is no non-thermal reason to open or close the window.

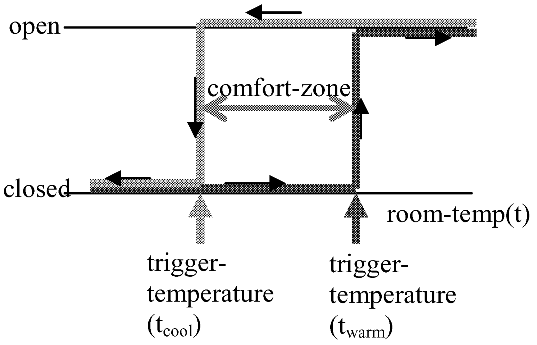

Figure 1: Window opening and closing behaviour of a perfectly consistent person

A consistent person would always become uncomfortably warm at the same room-temperature (t_{warm}), and always uncomfortably cool at the same (lower) room-temperature (t_{cool}) (Figure 1). We call these the 'trigger-temperatures', for at these temperatures the occupant would take action to restore comfort. Between the two trigger-temperatures is the comfort-zone, and the temperature at its centre may be taken to be the optimum room-temperature - the or 'comfort-temperature' (t_{comf}).

If the room-temperature is above the warm trigger-temperature t_{warm} the occupant will always be uncomfortably warm and so the window will always be open. If the room temperature is below the cool trigger-temperature t_{cool} the occupant will always be uncomfortably cool and the window always closed. Between the two trigger-temperatures the person will be comfortable, and the window might be either open or closed; for if it were open there would be no need to close it, while if it were closed there would be no need to open it. So the status of the window is indefinite, and depends on the sequential variation of the room-temperature.

2.2 Introducing human variability

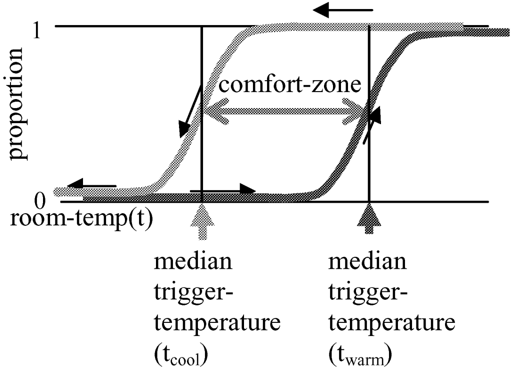

Figure 2: Window opening and closing behaviour with human variability

People are not identical in their thermal requirements. They have different comfort-temperatures, and therefore different trigger-temperatures.

Consider an office block occupied by numerous people, each in a cellular office with an openable window. Suppose it is cold, and no windows are open. If the indoor temperature gradually rises, the proportion of occupants becoming too warm would increase. These people would open their window. This is represented by the ascending curve on the right of figure 2. It is the proportion of people who are warmer than they would like to be, and so have opened the window. The curve isrepresents the conditional probability that the window would be opened, had it been closed. Now suppose it is hot and all the windows are open. If the indoor temperature then gradually cools, the proportion of windows open at first remains unchanged, and then, as people begin to feel uncomfortably cool, it will fall steadily from unity to zero. This is the descending curve on the left. It is the conditional probability that the window, being open, would remain so.

The temperature-displacement between the curves is the width of the comfort-zone for the median occupant, and the centre of the zone at the 0.5 probability level is the median occupant's comfort-temperature. The points where the curves cross the 0.5 probability level are the trigger-temperatures for the median occupant.

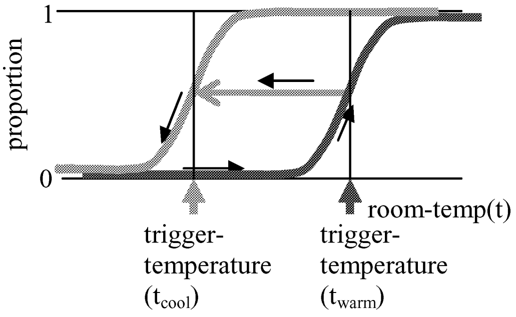

Figure 3: Showing the proportion of windows open when the direction of temperature change reverses. Note the 'horizontal grain' within the loop.

What happens if the room-temperature varies in a less regular manner? Let the room-temperature gradually rise from a cold start until the proportion of windows open has risen (on the right-hand curve) till it was, say, 0.5 (Figure 3). If the room-temperature were then to fall, the proportion of the windows open would remain unchanged, for those who had already opened them would not need to close them, and those who had not yet opened them would have no need to do so. However, when the falling temperature reached the value for the 0.5 level on the left-hand curve, the proportion would then fall according to that curve. This argument applies to any chosen proportion of windows open, so the proportion open has a strong tendency to stay the same when the direction of temperature-change reverses. This imparts a horizontal ‘grain’ to the data that needs to be incorporated in the statistical analysis of any survey results. Rising and falling room-temperatures of differing extents over many days will result in spot observations of the proportion of windows open eventually ‘filling in’ the entire zone between the two curves[1].

2.3 The single occupant: random variation

Consider a single occupant who does not respond consistently to the thermal environment. The comfort-temperature varies from time to time, and the trigger-temperatures vary in sympathy. A figure similar to figure 3 may therefore be drawn for a single occupant. The vertical axis would be the *probability* that the window would be open. Thermal comfort research has found that the usual extent of the variation within a person from time to time is only a little less than the extent of variation among diverse people at a particular time, so the figure for the median occupant would be much the same as for a representative group.

2.4 Extending the model to include other control actions

It is important to notice that the trigger-temperatures, corresponding as they do to the onset of thermal discomfort, apply to *any control action that could be freely used*, s. uchThe ascontrols might include adjusting blinds, thermostats, fans orand clothing. Some of these actions – removing a garment or switching on a fan – changeaffect the comfort-temperature. Consider the median occupant who has a fanusing a fan as the control. . It will be switched on when the warm trigger-temperature is reached. But because the fan increases the air speed, the comfort-temperature is raised by two or three degrees, and so ares are both the trigger-temperatures (Figure 4). If the room were then to cool down, the fan would be turned off when the person became too cool. This would occur at the *new* ‘too cool’ trigger-temperature, two or three degrees higher than the original one. The band in which the fan might be either on or off would therefore be narrower than the comfort-zone by an amount equal to the change in the comfort-temperature. Identical considerations apply to the removal of a layer of clothing.

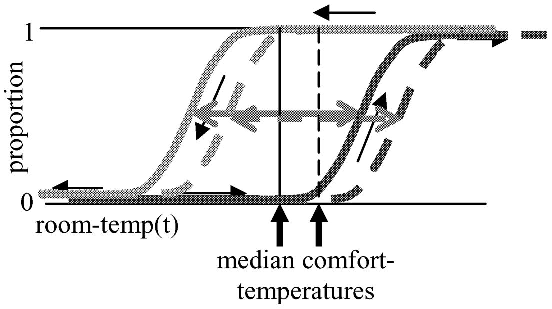

Figure 4: The effect of a fan. The dotted lines apply when the fan is on. Switching on the fan raises the comfort-temperature, and hence shifts the entire figure a few degrees to the right. The figure also applies to removing a layer of clothing.

2.5 Use of controls in the presence of constraints

If the various controls were equally effective and easy to use, they would all be equally likely to be used. In practice which control the occupant uses depends on its ease of use, its effectiveness, and the likelihood of undesirable consequences. Thus opening a window is less likely if it is difficult, ineffective, causes papers to be disturbed, or allows rain, noise, dust or pollution into the room.

A universally applicable ‘hierarchy’ of use of the various controls is not to be expected,

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[1] The model is analogous to the hysteresis loop of a magnetic material, and to the method of deriving thermal comfort data from the clothing behaviour of schoolchildren (Humphreys 1973) and to Hunt’s model for the switching of lights in offices (Hunt, 1979).

since it would depend on their design, the outdoor environment and onthe social circumstancesconstraints (such as dress codes.) affecting the occupants.

Such circumstances may impose constraints on the occupants' adaptation to their thermal environment, and a constraint may lead to discomfort. The *circumstance* of having a dress-code for the workplace introduces a restriction or *constraint* on the occupants' choice of clothing (see Humphreys & Nicol, 1998). Whether this constraint would lead to thermal discomfort would depend whether the required clothing was suitable to the room-temperature. From the viewpoint of our model, the question would be "how much discomfort would a person tolerate before breaking the dress-code?" This can be expressed as a temperature difference. An example may help to clarify this statement. During research into school-children's summertime comfort we found a school where the girls did not like their summer-uniform dress. As a result they tended to wear the warmer winter dress, and tolerated some three degrees of heat-stress before they adopted the summer uniform. Thus the constraint on their behaviour (due to fashion) could be translated into a temperature-difference of some three degrees (Humphreys, 1973).

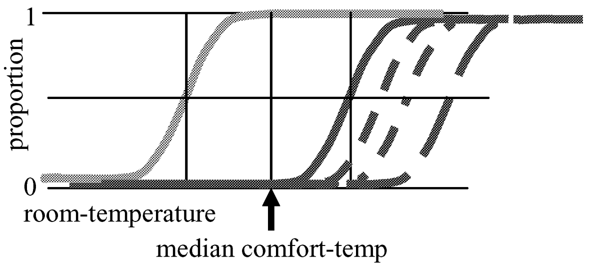

Figure 5: The effect of constraints on the use of controls to avoid warmth discomfort. The solid lines are for zero constraint. The dotted lines are for controls having varying degrees of constraint to their application, and therefore differing probabilities of being chosen at any particular room-temperature. For simplicity only the actions to avoid excessive warmth are shown.

Constraints need not be symmetrical in their action, as some examples will show. If the clothing insulation were already minimal there would be a high constraint on removing a garment but not on adding one. If a window were difficult to open but easy to close, there would be a constraint on opening but not on closing. If the constraint on opening a window arose from traffic noise, there would be an incentive to close the window before it had become necessary for avoiding cold discomfort. A constraint may also vary with time of day – traffic noise and fumes mightay be a problem only during rush hours.

If each control were associated with a different degree of constraint, each would have a response-curve displaced by a different amount from the trigger-temperature (Figure 5). The displacements could vary from zero (no constraint) to indefinitely large (total constraint), and be either positive or negative. At a particular room-temperature each of the controls would therefore have a different probability of being used. More than one control action could occur - if an office were very hot when people arrived at work, opening the window and turning on the fan would both be highly probable actions.

For the comfort of the occupant, there should be sufficient effective controls having minimum constraint. Thus if window opening were constrained by the location of the building additional low constraint effective controls would need to be provided. Energy could be conserved by applying constraints to control-actions that resulted in high energy consumption, provided there were other effective controls that were free from constraint.

This system of constraints is very flexible and could (for example) be used to allow some accessible secure window-openings to have a lower constraint than other windows. It could be extended to allow constraints that depended on parameters such as occupancy, or degree of over-heating on previous days, which could be useful in the context of window opening on arrival or window-opening for night-time cooling.

In this way constraints could represent behaviour based on factors other than thermal comfort. Window opening on arrival could depend on factors such as air quality or high internal temperatures on preceding days. Applying a negative constraint at the appropriate time-step could model such behaviour.

2.6 Systematic variation of comfort-temperature

We have already incorporated into the model random variations of the comfort-temperature, and noticed that some controls alter the median comfort-temperature. We now consider the effect of gradual systematic variations of comfort-temperature, such as may result from the cycle of the seasons.

The median comfort-temperature is the 'anchor' of the model, and the control-response arises from the departure of the room-temperature from this central anchor-point. So if the median comfort-temperature undergoes a systematic change, the effect is to shift the whole figure to the right or to the left according to the size and direction of this temperature change.

For example, in naturally ventilated offices studied in Pakistan the median comfort-temperature had a seasonal variation of some 10K (Nicol et. al. 1999). The empirical observations of the proportion of windows open therefore lay between the curve for the onset of cold discomfort in winter, with winter clothing, and the curve for the onset of warm discomfort in summer, with light summer clothing. In order to apply the model to thermal simulation it is therefore necessary to estimate the current comfort-temperature.

The probable comfort-temperature can be estimated from the prevailing outdoor temperature together with knowledge of the mode of operation of the building (heated, cooled, free-running) (see Humphreys, 1978, deDear & Brager, 1998). ASHRAE Standard 55-2004 (Fig 5.3 in the Standard) relates the preferred indoor operative temperature to the monthly mean of the outdoor temperature. The CIBSE Guide provides lines relating the preferred indoor operative temperature to an exponentially-weighted running-mean of the outdoor temperature (CIBSE 2006). Similar lines are found in European Standard EN 15251:2007 (CEN 2007).

The seasonal change in comfort temperature in these standards incorporates average seasonal variations in clothing and in air speed. There is scope for adaptation beyond these values, subject to the constraints that may apply, as occupants wear lighter or heavier clothing, and have less or more air movement.

3. APPLICATION TO BUILDING THERMAL SIMULATION

The model described is transparent and easy to translate into algorithmic form for use in the thermal simulation of a room. The curves provide the modeller with the conditional probabilities of use for each of the several controls. The modeller can therefore set up statistical decision-rules for the use of these controls, and so estimate the effect of realistic user-control on energy use and indoor temperature. The parameters needed to quantify the model are:

1. The standard deviation of individual differences in comfort temperature
2. The difference between the upper and lower median trigger temperatures
3. The current median comfort temperature assuming still air
4. The change in comfort temperature from elevated air speed or removal of a garment
5. A table of the constraints operating on each of the controls (expressed in degrees)

The first four can be supplied from current knowledge with reasonable precision. Work continues on the quantification of the constraints, and some examples are given in our other paper to this conference.

4. DISCUSSION

Our fundamental conviction is that thermal simulation of buildings requires a realistic representation of occupant behaviour – behaviour that is sensitive to the occupants' comfort and to the available adaptive opportunities. This necessitates the study of people in real buildings; it is not sufficient to assume schedules of behaviour that lack an empirical support.

Our modelling of control-behaviour has been evolving over a period of years. First we described peoples' use of their controls by regression or probit analysis of empirical field data on indoor and outdoor temperature (Raja et. al. 2001, Nicol & Humphreys 2004). More recently we have employed a mixed model, using logistic regression together with a 'deadband' derived from field study data (e.g. Rijal et. al. 2007, 2008). The deadband took into account the comfort-zone of an occupant.

In the present paper we have explained the derivation of a logical behavioural model whose parameters are to be supplied from empirical field investigations. For an example of the quantification of some of these parameters see Rijal et al 2008. We have not used the outdoor temperature in this model except insofar as it enables an estimation of the probable indoor comfort-temperature. The outdoor temperature has its effect via the thermal behaviour of the building envelope, rather than being used as a direct statistical predictor of occupant control behaviour.

A new feature of this model is its ability to handle the use of several occupant controls simultaneously, by introducing to the model the concept of differing constraints acting upon their probable use. The concept of constraint is a flexible addition, useful for extending the scope of simulation algorithms.

The merit of a logical model over a simple empirical model is that refinements can be added without disturbing its form. For example, aFor example, we speak of 'room-temperature'. It is an easy matter to replace this with, say Effective Temperature (ET*) or some other desired thermal environment index. Again, as improvedd methods of estimatesing of comfort temperatures become available they can be easily incorporated. We believe the model realistically portrays the behavioural dynamic of occupant control, while allowing refinement when its parameters are more precisely knownevaluated. We plan to implement the model using the simulation package ESDV.

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