Development of behavioural algorithms for thermal simulation of buildings – evaluating constraints on the operation of windows and fans

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ABSTRACT

Realistic knowledge of window-opening and fans use behaviour is needed for the thermal simulation of naturally ventilated buildings. If controls such as windows and fans were effective and easy to use, thermal discomfort could be largely avoided. In practice there may be constraints that hinder the use of such controls. In any thermal simulation these constraints need numerical values. In this paper, we explore the nature and extent of some of the constraints operating on the use of windows and fans, making numerical estimates of their magnitudes from extensive field databases.

1. INTRODUCTION

The basic principles of window opening behaviour and fan use are similar in different parts of the world. The temperature variation above and below the 'comfort temperature' is a useful metric on which to base algorithms describing the operation of windows and fans. However, people are not always free to open windows. It may be that the outdoor air quality is too poor, or that the environs of the building are too noisy or dusty. In such cases there is some degree of constraint acting on the opening of the window (Humphreys et al. 2008). If people open windows at all, it will not be until their thermal discomfort outweighs the inconveniences caused by opening them.

From the perspective of thermal modelling it is necessary to quantify such constraints if we are to predict whether the building will in practice afford a comfortable environment to its occupants. It is not to be expected that there will be a fixed level of constraint. The magnitude of a constraint will depend on the location of the building, as well as upon the design of the operating mechanisms of the controls. In this paper we quantify the constraints that are acting on the occupants of the buildings for which we have data. The resulting lists will show the extents of the constraints, and is a preliminary stage in the constructing of a table of typical values from which the building modeller can select those appropriate to the building being simulated.

We look first at the start-of-day settings of the controls. We then give the relations between the climate and the indoor comfort temperatures for our sets of data – from the UK, from Europe, and from Pakistan. We proceed to quantify the window opening behaviour and the fan use in relation to these comfort temperatures. If the temperatures in the buildings differ markedly from the comfort temperature, this may be an indication that some constraint is acting on the use of the controls. These constraints are quantified in terms of room temperature equivalents – that is to say by how much must the room temperature differ from the comfort temperature before the control is used? The procedure will be explained as the calculations are presented.

2. FIELD DATA-BASES

We have three main sets of data: the UK data, the European data (SCATs: Smart Controls and Thermal Comfort) and the Pakistan data.

The UK data were collected in Oxford and Aberdeen over a period of about a year, and the database has some 36,000 records from 15 buildings. The records include a comfort evaluation on the ASHRAE scale, a record of the use of fans and windows, a list of the clothing worn, and a note of the level of activity. There was a corresponding record of the room temperature, obtained from a data-logger at the work-station. Respondents provided information up to four times during the working day. The data are 'longitudinal' – that is to say the respondents provided repeated estimates over a period of time, varying from a few days to some months according to their willingness to continue. In all we have records from 219 respondents. A fuller description can be found in Raja et al. (2001) and Rijal et al. (2007).

The SCATs data were collected over a year-long period in a similar manner, in five European countries (France, Greece, Portugal, Sweden, UK). For this study we are using the data from the 'longitudinal' aspect of the project. This has over 28,000 records from respondents in 26 buildings. In all we have records from 127 respondents. A fuller description can be found in McCartney and Nicol (2002) and Rijal et al. (2008b).

The Pakistan data were collected in five cities (Islamabad, Karachi, Multan, Quetta, Saidu-Sherif) each in a different climatic zone of Pakistan. The research design was transverse. Each building was visited once a month for a year, and each month all available respondents gave replies to a questionnaire (Bedford scale), and thermal measurements were made at their work-stations. There are 7,105 records from 33 buildings, and 846 respondents in total. A fuller description can be found in Nicol et al. (1999) and Rijal et al. (2008a).

3. RESULTS AND DISCUSSIONS

3.1 Start of day settings

When people enter the office at the start of the working-day they are likely to assess the environmental conditions in their office and make any adjustment requisite for comfort. For example they may raise or lower blinds, set fans running, open windows, and choose whether or not to keep on a jacket. These initial adjustments are likely to remain unchanged for the day unless discomfort of some kind occurs, whereupon further adjustments would be made. One method to predict the start-of-day settings is logistic regression (for an example of its application to controls see: Nicol & Humphreys 2004). The relationship between the probability of use (p) of the control, and the predictor variable, which may be for example the indoor globe temperature T_g, is of the form:

$$\text{logit}(p) = bT_g + c \qquad (1)$$

where the logit of p is defined as log $\{p/(1-p)\}$. b is the regression coefficient for T_g, and c the constant in the regression equation. At the start of the day the probability of the window being open or the fan being on (or both) may be estimated for our data in this way. The following equations give the approximate probability that the window will be open and the fan on as a result of these start-of-day decisions.

European data

$$\text{logit}(P_w)=0.448T_g-10.3 \ (R^2=0.28) \qquad (2)$$

$$\text{logit}(P_f)=0.374T_g-10.6 \ (R^2=0.12) \qquad (3)$$

Pakistan data

$$\text{logit}(P_w)=-0.73 \qquad (4)$$

$$\text{logit}(P_f)=0.335T_g-8.6 \ (R^2=0.40) \qquad (5)$$

P_w is the probability that window would be open, and P_f the probability that fan would be on for the free running mode. All regression coefficients are significant ($p<0.001$). In logistic regression equation, the Cox & Snell R square is used. For Pakistan the logistic regression for the window opening was unreliable, and thus a constant value (mean logit) was used (equation 4).

3.2 The comfort temperatures

Once these initial settings have been made, whether further adjustments occur is likely to depend on how different the room temperature is from the comfort temperature – the temperature at which the average occupant is in thermal neutrality. The comfort temperature is related to the outdoor temperature. From each set of data we estimated the relation between the comfort temperature and the running mean of the outdoor temperature (McCartney and Nicol 2002). The following equations enable the temperature most likely to be thermally neutral in the building to be estimated from the recent history of the daily mean outdoor temperature.

For the UK and Europe

$T_{comf}=0.33T_{rm}+18.8$ ($T_{rm}>10^{o}$C) (6)

$T_{comf}=0.09T_{rm}+22.6$ ($T_{rm}\leq 10^{o}$C) (7)

T_{rm} is the running mean outdoor temperature. T_{comf} was estimated by Griffiths' method, assuming a regression coefficient 0.5 votes/K (Griffiths 1990, Nicol et al. 1994, Rijal et al. 2008a). Equation 6 is for the 'free-running' mode – no heating or cooling in operation. Equation 7 applies when the heating is in operation. The changeover was found to occur at about 10^{o}C outdoor running mean temperature. When the running mean of the outdoor temperature is below 10 ^{o}C equation 6 applies; if it is above 10 ^{o}C then equation 7 applies.

Different equations were needed for Pakistan. Also the use of ceiling fans was normal in Pakistan, and turning on the fan increases the comfort temperature, so separate relations apply according to whether the fan was on or off. For Pakistan:

$T_{comf}=0.526T_{rm}+14.7$ ($T_{rm}>10^{o}$C) (8)

$T_{comf}=-0.132T_{rm}+21.1$ ($T_{rm}\leq 10^{o}$C) (9)

$T_{comf}=0.408T_{rm}+16.6$ (fan off) (10)

$T_{comf}=0.480T_{rm}+16.6$ (fan on) (11)

3.3 Probability of window opening and fan use in relation to the comfort temperature

To investigate further the manner of variation of the probability that the window will be open or the fan on it is helpful to group the data. To obtain these 'binned' data-points the data were sorted by building and then by the temperature departure from the comfort temperature (Δt) and split into groups of 25 records in order of increasing Δt. These probabilities were plotted as scatter diagrams (Figure 1). As expected from the underlying model (Humphreys et al. 2008), the horizontal scatter of the resulting points was far greater than could be attributed to the binomial error in the probabilities, showing the presence of a substantial 'deadband' between the action of opening a window and of closing it. A similar logic applies to the use of the fans. This dynamic human behaviour gives a 'horizontal grain' to the data. We wished to establish a curve representing the centres (in terms of Δt) of the bands of observations. To obtain this central curve we regressed Δt on the logit of probability of the use of the controls. The equation was calculated, and its regression gradient adjusted to make allowance for the binomial error in the predictor variable (the logits) arising from the sample size of only 25 grouped data. (For details of the procedure see Rijal et al. 2008 & 2008a) The resulting curves are superimposed on the scatter-plots and their equations are found in Table 1.

Next we wished to know the width of the bands of observations in Figure 1, and chose to adopt the convention that the range of a set of data may be taken as three times the standard deviation. The dotted lines on the figure thus show the conventional margins of the bands of data. The bands include some 86% of the observations. For the windows the right hand margin can be shown to represent the probability that the window setting will change from closed to open, while the left marginal curve applies to closure from the open position.

3.4 Comparing the centre-lines of the bands

Inspection of the centre-lines on Figure 1 shows that they are quite similar in shape, and theoretical considerations had suggested that they should be parallel (Humphreys et al. 2008), so we decided to choose a representative regression gradient (0.8/K) for their underlying regression equations, forcing each through the joint means of their respective data-sets. Thus, the regression gradient for window opening and fan use is taken to be 0.8 for Δt (Table 1).

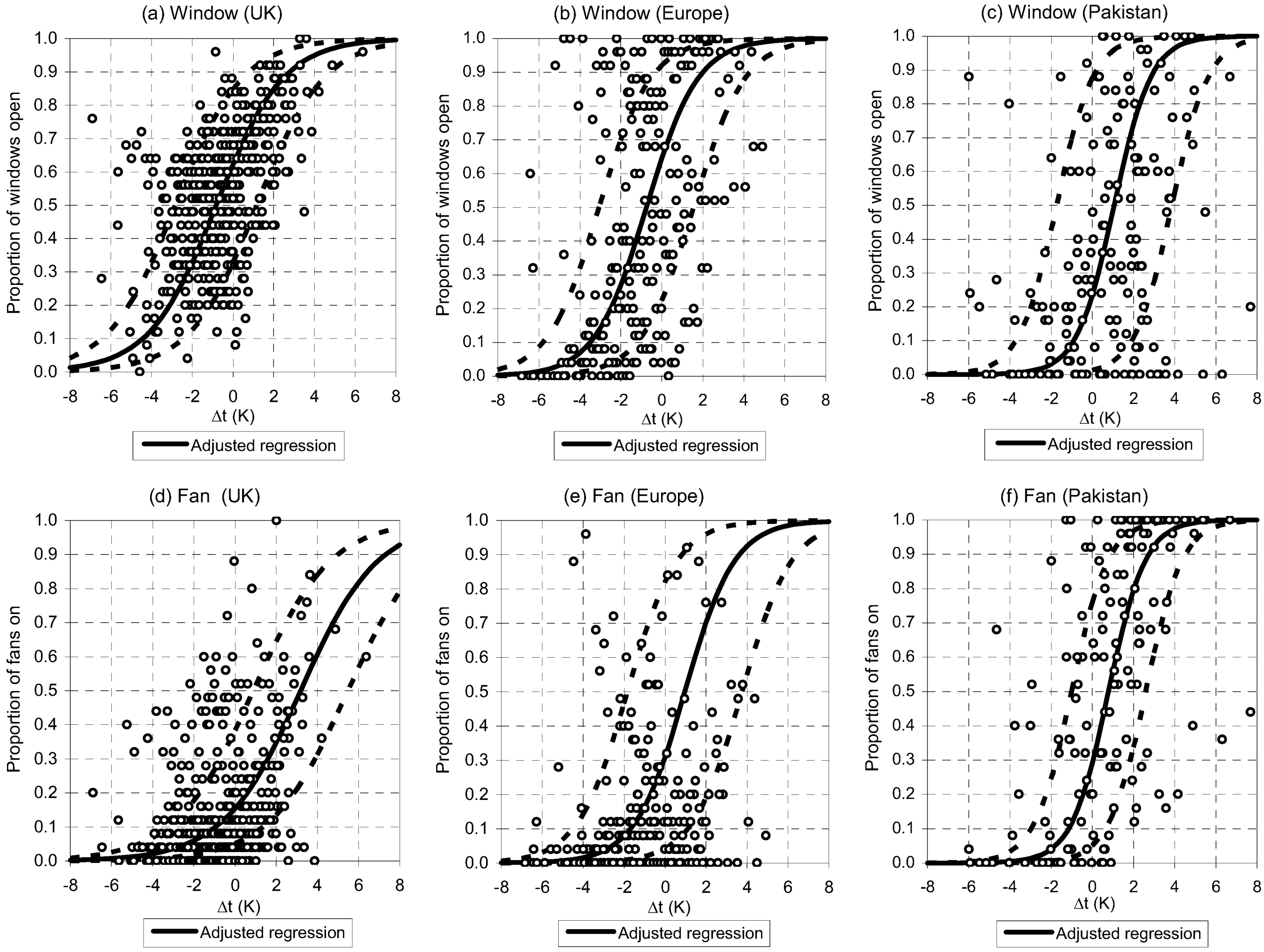

Figure 1: The central curves indicating window opening and fan use, together with the estimated margins of the band, set at ±1.5 K standard deviations of the scatter about the central curves.

Table 1: Calculation method of the regression coefficient for algorithms.

Data	Windows open		Fans on	
	Equation	*WD*	Equation	*FD*
UK	logit=0.609Δt+0.5	2.0	logit=0.533Δt-1.7	2.3
Europe	logit=0.801Δt+0.6	2.3	logit=0.829Δt-0.8	2.8
Pakistan	logit=1.125Δt-1.2	2.8	logit=1.133Δt-0.9	1.8
Mean regression coefficient	0.845		0.832	
Mean regression coefficient		0.8		

WD & FD: Window and fan 'deadband'

3.5 Algorithm for occupant behaviour

Windows opening (closed to open)

$\text{logit}(P_w)=0.8\,(T_g-T_{comf}-C_{wo})$ (12)

Windows closing (open to closed)

$\text{logit}(P_w)=0.8\,(T_g-T_{comf}+C_{wc})$ (13)

Fans on (off to on)

$\text{logit}(P_f)=0.8\,(T_g-T_{comf}-C_{fo})$ (14)

Fans off (on to off)

$\text{logit}(P_f)=0.8\,(T_g-T_{comf}+C_{fc})$ (15)

Where, C_{wo} and C_{wc} are the constraints for windows open and closed, C_{fo} and C_{fc} are the constraints for fan on and off (Table 2).

In simulation, T_g will be represented by the operative temperature (T_{op}). This algorithm can be implemented in simulation in the same way as for our earlier algorithms (Rijal et al. 2007 & 2008a).

3.6 Quantification of the constraints

We are now able to estimate the constraints acting on the use of the controls. To illustrate this process, consider Figure 1 (a). The dotted curve for the action of opening the window cuts the 0.5 probability level at a temperature some 1.5K above the comfort temperature, while the corresponding closure occurs some 3K below the comfort temperature. Compared with the ideal, we may say there is a constraint of about 1.5K on opening the window, but a 'negative constraint' of some 3K on closing it. That is to say, in this illustration there is some incentive to keep the windows open. Now, from the comfort point of view, people normally tolerate departures of some 2K from the comfort temperature before desiring to take remedial action. So the picture emerges that people opened their windows a little before their discomfort would have suggested they would have done so, and closed them a little after their discomfort would have suggested they would. When calculating the constraints for the fans, an allowance is made for the shift of comfort temperature caused by the use of the fan.

How we reckon the sign of a constraint is a matter of convention. We have adopted the convention that a positive constraint indicates that the action is for some reason difficult, for example the windows may not be opened until the room temperature is higher than expected, or not closed until the room temperature has fallen to below the comfort temperature. This pair of constraints would occur if, for example, a window mechanism were difficult to operate. An example of a negative constraint would be some non-thermal incentive to open the window – perhaps a desire to improve air quality.

Table 2 shows the constraints we have estimated for each of the buildings in our data. We have reckoned all constraints from the relevant comfort temperature, but it should be remembered that only constraints of more than 2K are likely to be of practical importance.

Table 2: Constraints of each building

Data	Building	Constraints (K)			
		Windows		Fans*	
		closed	open	off†	on
UK	1-MF	2.7	1.3	0.5	6.1
	2-AL	3.0	1.0	0.9	5.7
	4-BH	3.5	0.5	4.0	2.6
	6-CL	2.4	1.6	1.4	5.2
	7-GT	2.2	1.8	0.6	6.0
	8-RP	1.2	2.8	0.0	6.6
	9-VW	4.0	0.0	1.3	5.3
	11-GH	2.2	1.8	-0.2	6.8
	13-SN	2.8	1.2	1.9	4.7
	14-SH	1.8	2.2	3.1	3.5
Europe	F1	4.2	0.4	1.3	6.3
	F5	1.9	2.7	5.9	1.7
	G4	5.5	-0.9	6.1	1.5
	P2	1.5	3.1	3.0	4.6
	P3	-0.6	5.2	-0.4	8.0
	P5	2.8	1.8	4.0	3.6
	U3	4.8	-0.2	2.4	5.2
	U7	4.8	-0.2	3.9	3.7
	Max	5.5	5.2	6.1	8.0
	Mean	2.8	1.5	2.2	4.8
Pakistan	1.10	4.2	1.4	5.7	-0.1
	1.20	0.7	4.9	1.5	4.1
	1.30	1.9	3.7	3.3	2.3
	1.40	1.3	4.3	1.5	4.1
	1.50	0.9	4.7	3.2	2.4
	2.20	0.7	4.9	0.9	4.7
	2.40	3.4	2.2	1.8	3.8
	2.45	1.4	4.2	-	-
	2.50	4.9	0.7	2.4	3.2
	2.60	2.2	3.4	1.6	4.0
	3.10	-	-	2.1	3.5
	3.20	-	-	1.8	3.8
	3.30	0.7	4.9	3.0	2.6
	3.40	1.4	4.2	3.6	2.0
	3.50	0.1	5.5	0.8	4.8
	3.60	1.8	3.8	3.0	2.6
	3.70	2.0	3.6	1.5	4.1
	4.10	0.6	5.0	3.0	2.6
	4.20	-1.9	7.5	-2.1	7.7
	4.40	-	-	-1.5	7.1
	4.50	0.6	5.0	0.7	4.9
	4.60	1.5	4.1	0.9	4.7
	5.10	3.0	2.6	5.7	-0.1
	5.20	2.4	3.2	-0.4	6.0
	5.30	3.1	2.5	3.4	2.2
	5.40	4.7	0.9	4.6	1.0
	5.50	2.0	3.6	5.1	0.5
	5.60	2.6	3.0	1.1	4.5
	5.70	2.5	3.1	4.0	1.6
	5.80	4.1	1.5	-	-
	Max	4.9	7.5	5.7	7.7
	Mean	2.0	3.6	2.2	3.4
Overall mean		2.3	2.8	2.2	3.9

*: In Pakistan, T_{comf} were calculated by fan off equation, †: 2 K is added to adjust the comfort temperature, -: none.

Inspection of the table shows a considerable variation from building to building, as would be expected. The constraints may relate to various factors (e.g. outdoor noise and air pollution) but further field investigation is required to explain them. The mean constraint for Europe of 1.5K on window opening shows a slight tendency to open windows before required to avoid discomfort (2K), while the mean constraint for Pakistan of 3.6K indicates some degree of reluctance to open windows. The presence in the table of some large values for the constraints, both for fans and for windows, indicates that the action is unlikely to be taken in that building unless discomfort is severe. We recall that a constraint of 2K is normal and unlikely to cause discomfort, while constraints of around 5K would indicate a problem with the use of that control, while a constraint of around 8K would render the control of little use for controlling the thermal environment.

4. CONCLUDING DISCUSSION

The analysis presented shows that, when reckoned from the appropriate comfort temperature, the window opening behaviour and the fan use is reasonably consistent across our databases, whether from Europe or from Pakistan.

Opening or closing windows or switching fans on or off are actions that can be subject to various constraints. We have suggested a way of handling such constraints, and have quantified the constraints operating in our sample of buildings. They give some idea of the magnitudes of constraint likely to be encountered, and range from negligible to large.

We emphasise that this study has many uncertainties – the data were not designed to be put to the use that we have made of them. Field studies dedicated to quantifying the constraints and relating them to the circumstance of culture, building design, and environmental setting will be required for more accurate work.

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