# CHARACTERISING OCCUPANT BEHAVIOUR IN BUILDINGS: TOWARDS A STOCHASTIC MODEL OF OCCUPANT USE OF WINDOWS, LIGHTS, BLINDS HEATERS AND FANS.

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## ABSTRACT

This paper presents the results of surveys of the use of simple controls – windows, lighting, window blinds, heaters and fans by occupants of naturally ventilated buildings. The surveys were conducted in the UK, Pakistan and throughout Europe. The data are analysed to show how the use of each control varies with outdoor temperature. The paper discusses the application of such results to the simulation of occupied buildings.

## INTRODUCTION

The thermal simulation of occupied buildings requires assumptions to be made about the behaviour of the occupants. In particular assumptions must be made about the use of building controls such as windows, blinds, heaters or fans which can be adjusted by building occupants. These assumptions are usually made on the basis of best practice, or in an experimental way to test the effect of different behaviour patterns. They are not based on the actual behaviour of building occupants and therefore are of limited applicability when used to predict the behaviour of buildings in use. In real buildings the indoor temperature at a given outdoor temperature is a distribution rather than a single value (figure 1): the use which occupants make of controls is an element of that distribution.

Some recent studies of thermal comfort in buildings have recorded the use of building controls in the vicinity of subjects as part of the information collected. Patterns of behaviour relating to the ways use is made of controls by building occupants have emerged from these studies and are reported in this paper. The use of controls is clearly influenced by physical conditions, but their use tends to be governed by a stochastic rather than a precise relationship. Thus there is not a precise temperature at which everyone opens a window, but as the temperature rises there is an increased probability that they will have done so (Nicol et al 1999, Raja et al 1998). It has been suggested by Nicol and Raja (1997) that temperatures in buildings should be calculated "both as an expected temperature and as a probabilistic variation about it" in order to judge whether a building will provide an acceptable environment. This supports an approach which models occupant behaviour as a stochastic process. Both the indoor environment and the energy use can then be modelled as a distribution rather than as an assumed discrete value.

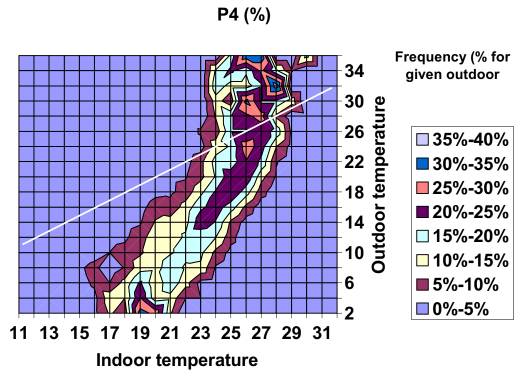


*Figure 1. Frequency distribution of indoor temperatures for a given outdoor temperature in a Building in Portugal. The diagonal line indicates equality between indoor and outdoor temperature*

## THE SURVEYS

A number of databases are now available from which an estimation of the use of controls can be made. The principal database results from field studies of subjective comfort in offices in five European countries - Sweden, UK, France, Portugal and Greece (Nicol & Sykes 1998 McCarthy and Nicol 2001). The database includes the comfort responses of the subjects, records of the indoor thermal environment (air and globe temperatures, humidity and air speed) and the outdoor temperature and humidity. In addition observations were made of the subjects clothing, activity and of the use of various controls (windows, doors, lighting, fans, heaters and, where applicable, air conditioning). The database comprises some 4,655 full records from subjects in 25 buildings of which 11 were naturally ventilated (NV) (1,649 records). Similar databases of some 5,000 results (3,600 NV) wholly from the UK (see McCartney *et al* 1998) and 7,000 from Pakistan (Nicol *et al* 1999) are compared with the European data.

This paper reports on some probability algorithms relating occupant behaviour to outdoor temperature. The paper suggests ways in which this information could be used to inform simulation of occupied buildings. The international nature of the data means that estimates can be made of the extent to which climate and culture are a factor in the relationship

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## METHOD OF ANALYSIS

The data collected about the use of controls in these studies is essentially binary – window open or closed, blind up or down etc. The likelihood that any particular control is being used can be said to depend on the thermal environment and in particular the temperature. Thus as the indoor or outdoor, temperature increases the likelihood that a window is opened – or a fan switched on – increases. One powerful method of analysing such processes is probit analysis (Finney 1964).

Probit analysis assumes that the likelihood of an event happening increases as the 'intensity' of the stimulus (in this case temperature) increases. In the method used in this study the probability p of an event having happened is defined according to the Logit model

$$\text{Log}\{p/(1-p)\} = a + bx \qquad (1)$$

Where a and b are constants and x is a variable (in this case a thermal index). The values of a and b are determined by calculating the Logit function at each value of the index x from the total number of cases and the number in which the particular event has occurred (window opened, blind down etc). A weighted regression analysis of the Logit against the values of x is then performed to give estimates of the values of the constants a and b[1].

Once the values of the constants are known a curve can be constructed linking the index x and the probability of the particular event using equation 2 which is derived from equation 1 above

$$p = e^{(a+bx)}/(1+e^{(a+bx)}) \qquad (2)$$

The method has been most widely used in analysing the effectiveness of insecticides with increasing concentration. It has often been used in thermal comfort studies to investigate the changing incidence of discomfort with increases in temperature or some other environmental index (see e.g. Webb 1964, Fanger 1970 and many subsequent studies). Figure 2 uses probits to analyse of some data about the changing probability that people will use fans as the outdoor temperature rises (see also figure 7).

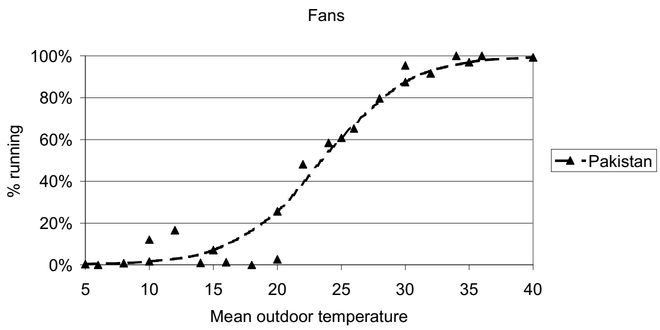


*Figure 2. Use of probit analysis to illustrate how the proportion of people who use fans changes with outdoor temperature. With increasing temperature, the proportion of people who use fans increases (points). The probit line represents the best-fit line to the points using the curve in equation (1).*

## ANALYSING THE USE OF CONTROLS USING PROBITS

Probit analysis has been applied to the use of controls by Nicol *et al* (1999) in the analysis of data about controls from the different climates in Pakistan. This study uses the results of that study to compare to results from a range of European climates.

The controls whose use has been analysed here are the opening of windows, the use of lighting, the drawing of window blinds or curtains, the use of heating and the use of fans. The results of the analysis are displayed in Figures 3-7 below. These analyse the use of these controls against outdoor temperature rather than indoor temperature. In most cases the correlation with indoor temperature is similar to that with outdoor temperature ($T_o$). In the case of general heating the correlation is higher with $T_o$ than with $T_i$. The reason for using $T_o$ in the analysis of the use of controls is that the outdoor temperature is a part of the input of any simulation, whereas the indoor temperature is an output. The relationship between the use of controls and the outdoor temperature is therefore more useful. Table 1 shows the values of the constants a and b used in equation 2 to calculate the curves.

[1] Commonly used statistical packages such as SPSS can be used to calculate the vales of a and b.

*Table 1. Values of the constants a and b in equations 1 and 2 calculated from each of the three databases.*

| | | Intercept a | Slope b |
|---|---|---|---|
| windows open | Pakistan | -3.73 ±.06 | 0.118±.004 |
| | UK | -2.65±.11 | 0.169±.009 |
| | Europe | -2.31±.16 | 0.104±.010 |
| General lighting on | Pakistan | 0.69±.08 | 0.036±.004 |
| | UK | 2.08±.11 | -0.049±.009 |
| | Europe | 2.47±.18 | -0.058±.011 |
| Blinds or curtains drawn | Pakistan | - | - |
| | UK | -1.08±.09 | 0.022±.007 |
| | Europe | -0.30±.12 | 0.005±.008 |
| General heating on | Pakistan | 2.73±.14 | -0.345±.012 |
| | UK | 5.28±.19 | -0.514±.017 |
| | Europe | 2.72±.18 | -0.322±.017 |
| Fans running | Pakistan | -7.09±.17 | 0.301±.007 |
| | UK | -5.37±.26 | 0.220±.017 |
| | Europe | -3.80±.25 | 0.110±.014 |

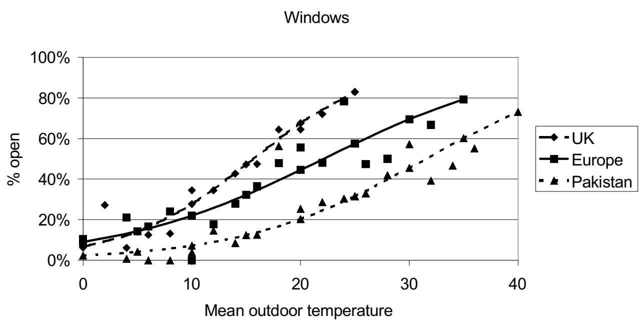


*Figure 3. Proportion of windows open at different outdoor temperatures*

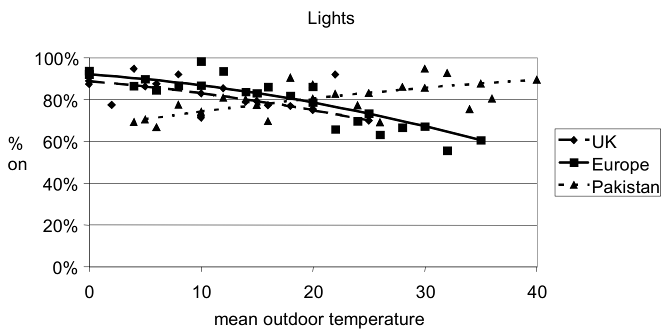


*Figure 4. Proportion of general lights on at different outdoor temperatures*

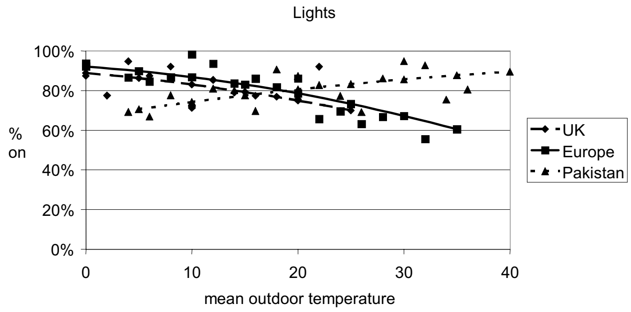


*Figure 5. Proportion of blinds or curtains windows drawn at different outdoor temperatures*

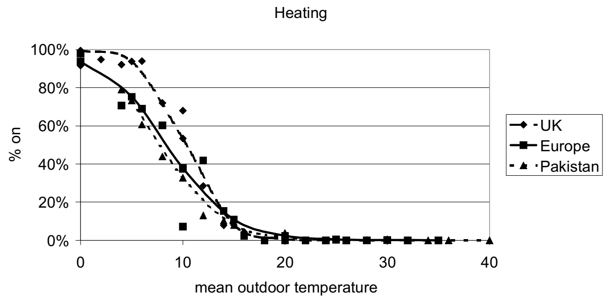


*Figure 6. Proportion of general heating in use at different outdoor temperatures*

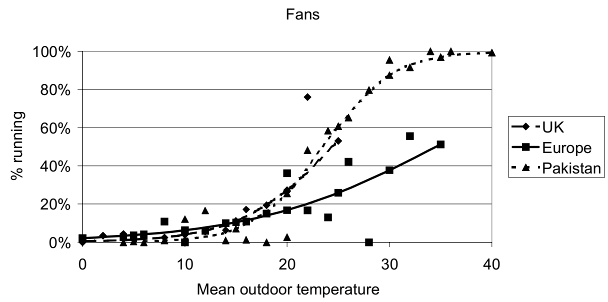


*Figure 7. Proportion of fans running at different outdoor temperatures*

## DISCUSSION OF THE RESULTS

It should be noted that the results are governed by an adaptive principle: *If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort* (Humphreys and Nicol 1998). This principle has been found to apply in surveys of comfort and behaviour in buildings and suggests a feed-back mechanism between the environment and the actions of building occupants. This can be used to explain the order which exists in the data presented.

In each of the figures 3-7 the calculated probit line is given for each of the three surveys. In addition points are shown for comparison which represent the actual proportion using the given control at two degree intervals of outdoor temperature – in effect the points from which the probit lines have been calculated.

Window opening
The occupants of naturally ventilated buildings can open their windows for two main reasons: to improve indoor air quality or to help improve comfort by reducing indoor temperature and encouraging air movement. Figure 3 shows the changing proportion of subjects reporting their windows open at different outdoor temperatures illustrating a strong correlation between window opening and temperature.

There is clearly a difference between the results from the three surveys. The proportion of open windows in European offices is generally lower than in the UK alone at any given temperature. A country-specific analysis of the European data confirms that UK office workers tend to open windows more frequently than their counterparts in other European countries. The Pakistani subjects on the other hand seem to use windows less. This may be because fewer of them have control over a window (note that the proportion with windows open never rises above about 55%) or it may be that in the hot dry conditions of Pakistan the opening of a window has little advantage and may even increase indoor temperatures.

It is noticeable that in all three surveys the proportion of windows open tends to increase significantly as the outdoor temperature rises above 10°C. 50% of European offices have their windows open at 22°C rising to 80% at 33°C.

Use of lighting
The probit lines for UK and European surveys both show a gradual fall in lighting use with increasing temperature. This behaviour is consistent with the greater likelihood that lights are on in the darker winter months. The most striking finding of this analysis is that some 60% of European offices are using lights even in the hottest weather. In Pakistan there is a contrary effect: the number of offices with lights on increases with the outdoor temperature. Again the effect is weak, but it is consistent with the tendency in hot dry countries to close shutters or blinds against the sun and high outdoor temperature in hot weather, necessitating the use of lights. Unfortunately data on the use of sun controls was not collected in Pakistan, so this hypothesis cannot be confirmed.

Use of blinds or curtains
Blinds or curtains can be used by building occupants to control glare from windows, but indoor controls do little to ameliorate high indoor temperature. There is some evidence that occupants are more likely to use these controls in hotter weather, but the effect is small and barely significant statistically. It is possible that the solar intensity would be a better indicator than outdoor temperature for predicting the use of this control.

Use of heating
The variable in this case is the use of general heating in the buildings. Few subjects use auxiliary heating except in the case of Pakistan, where a general heating system is less usual. There is a strong negative relationship between the use of heating and outdoor temperature and the probit lines for the three surveys are almost congruent. Significant use of heating begins at an outdoor temperature of 15°C and reaches about half of all buildings at 10°C. When the outdoor temperature has dropped to 5°C almost all buildings are heated.

Fans
Fans are used primarily to offset the effects of high temperature. It has been estimated that the effect of higher air movement is the equivalent of a drop in indoor temperature of up to 4°C (Nicol 1973). At the same time the effect of fans on the indoor temperature will be minimal – restricted to an increase in convective heat transfer, and a minor increase in the heat load. The use of fans is therefore significant not so much in the effect it will have on the indoor temperature but in the comfort of occupants.

The working of the adaptive principle is constrained by the availability of the means to exert control on the environment. The absence of a fan will be such a constraint. The relatively low use of fans by the subjects in the European survey (figure 7) may be caused in many cases by the absence of the necessary fan. Two populations in these data that have relatively good access to fans are those in Greece and in Pakistan. Figure 8 shows the European probits separately by country. It suggests that there is a difference between countries in the availability of fans. The probit for Greece is similar to that for Pakistan shown in Figure 7. The UK probit in Figure 7 follows that for Pakistan but stops short at 25°C – effectively the upper limit for outdoor temperatures in the UK. This suggests that in the surveyed buildings, UK workers generally have fans – and use them – if they are needed.

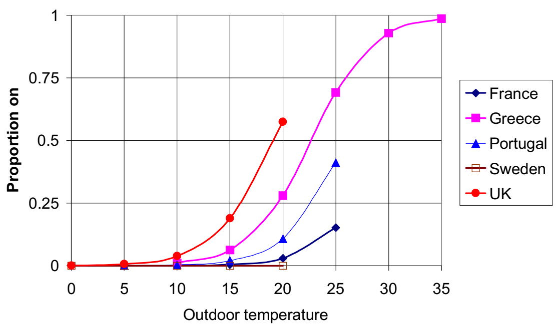


*Figure 8. Probit lines for fans running in different European countries.*

The analysis suggests therefore that *if fans are provided* the use of fans will follow the pattern given by the Pakistan/Greece probit curves. This suggests that 20% of building occupants use fans at 18°C, 50% at 23°C and 80% at 28°C. At outdoor temperatures above 30°C the use of fans is almost universal, below 15°C it is almost unknown.

## APPLYING THE RESULTS TO SIMULATIONS

The use of these results to inform simulations assumes that the aim is to suggest a distribution of indoor temperatures rather than an exact value. Each of the controls investigated affects the indoor temperature to a greater or lesser degree. This model of the use of controls gives an assessment of the probability that a particular control is being used.

If the indoor temperature resulting from a particular outdoor temperature was calculated both with and without windows open, for instance, the likelihood of each scenario can be estimated from figure 3 or from equation 2 using the relevant values of a and b from Table 1. Other considerations obviously need to be considered – in this example the distribution of wind speed and direction. The result will be the sort of distribution of indoor temperatures resulting from given outdoor temperatures which is pictured in Figure 1.

Clearly a great deal of work and analysis will be needed to transform the charts presented in this paper into a workable simulation tool. The full analysis will require that other factors – such as solar intensity or wind speed – are also treated as stochastic processes and that their effect on temperature is understood in the same way.

Air movement indoors is another important consideration in characterising the indoor environment. This is highly dependent on both the opening of windows and the use of fans. Together the temperature and the air movement are the most important considerations for indoor comfort.

As Nicol and Raja (1997) comment the development of a stochastic approach to indoor temperature and air movement in occupied buildings will help to make building simulation useful to those who wish to design acceptable comfortable buildings for the future.

The results reported are limited to a small number of surveys conducted by the Thermal Comfort Unit of the Oxford Centre for Sustainable development in which the use of such controls was recorded. Other data are available in which such behaviour is recorded, but which were not available to the author at the time of writing. For instance a number of the individual surveys collected together to form the ASHRAE database (deDear 1998) included such data. Unfortunately this information was not included in the database. Further verification needs to be undertaken using such data before the results can be fully accepted.

## CONCLUSIONS

This paper presents results which enable the probability that occupants of naturally ventilated buildings will use a variety of controls to be calculated as a function of outdoor temperature. This should help occupied buildings to be successfully simulated.

A convenient algorithm for the increasing use of controls is the logit function which can be used to calculate the probability of use (p) to be calculated according to the algorithm:

$$p = e^{(a+b.To)}/(1+e^{(a+b.To)}) \qquad (3)$$

Where a and b are constants and $T_o$ is the outdoor temperature. Derived values for a and b are given in Table 1.

This paper does not seek to provide answers to the problems which arise in characterising occupied naturally ventilated buildings but rather to present some methodologies and results which may be useful to those who are concerned with these problems

The results presented are from large and wide-ranging databases from a variety of climates and cultures in Europe and Pakistan. Although considerable variations were found between climatic groups, there were also some remarkable congruencies. In particular

- the outdoor temperature at which occupants start to open windows for ventilation is similar in all climates but window use is more common in Europe than Pakistan

- there is a high incidence (70-90%) of lighting use in all offices and it is little affected by outdoor temperature
- the use of blinds or curtains is about 40-45% and is almost independent of outdoor temperature in European offices
- the dependence of heating use in buildings on outdoor temperature is independent of climatic context about 50% using heating at 10$^o$C rising to 100% at 5$^o$C
- the use of fans starts at an outdoor temperature of about 15$^o$C and increases to 100% at about 30$^o$C where fans are available.

## SYMBOLS USED

a, b: Constants used in the calculation of p

p: the probability that a particular control is in use

r: correlation coefficient

$T_i$: Indoor temperature

$T_o$: Outdoor air temperature

x: a variable or index against which the variation of p is measured


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