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Development of Adaptive Algorithms for the Operation of Windows, Fans, and Doors to Predict Thermal Comfort and Energy Use in Pakistani Buildings

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ABSTRACT

This year-round field investigation of the use of building controls (windows, doors and fans) in 33 Pakistani offices and commercial buildings focuses on 1) how the occupants' behavior is related to thermal comfort, 2) how people modify the indoor environment and 3) how we can predict the occupants' behavior. We have found that the use of building controls depends on climate and season. The use of these controls has a cooling effect on the occupant through increasing the air movement or the ventilation. The behavioral model yields adaptive algorithms that can be applied in building thermal simulations to predict the effects of the occupants' behavior on energy-saving building design.

INTRODUCTION

The determination of ASHRAE that serious attention be given to the sustainability of buildings and their environmental engineering systems means that more attention will be focused in the future on naturally conditioned buildings. It will be increasingly necessary to understand and quantify the ways in which the occupants control these buildings, so that conflicts between user behavior and energy consumption can be avoided. It is with this need in mind that we offer this analysis of the behavior of office workers in Pakistan with regard to their use of operable windows and fans.

Various window opening models have been put forward in recent years, based on indoor or outdoor temperature (Warren and Parkins 1984, Fritsch et al. 1990, Nicol et al. 1999, Raja et al. 2001, Nicol and Humphreys 2004, Inkarojrit and Paliaga 2004, Yun and Steemers 2007, Herkel et al. 2008). Fritsch et al. (1990) proposed a model based on Markov chains for random window opening prediction. Pfafferott and Herkel (2007) used Monte-Carlo simulations to predict user behavior. Herkel et al. (2008) develop a window opening model based on outdoor temperature and occupancy levels. The way in which these occupant behaviors work is not yet fully understood and yet realistic patterns of occupant behavior are needed in building simulations (Rijal et al. 2007). It is also not known exactly how the indoor environment is modified when windows and doors are open or fans turned on (Rijal et al. 2007a, Nicol et al. 2007, Rijal et al. 2008). Most of this research has been conducted in European countries and occupant, and it would be useful to extend it to other climates, as behavior might differ according to climate and culture.

Pakistan has a wide range of climates including hot humid, hot dry, composite, temperate and even cold. Most Pakistani office buildings are naturally ventilated and use window and door opening as well as fans to achieve comfortable thermal conditions. People are well adapted to the local climate and their comfort temperatures differ according to region and season (Nicol et al. 1999). Even though an 'adaptive thermal comfort model' for Pakistan has already been established, we still do not know how we can best design naturally ventilated buildings to achieve comfortable thermal conditions. One of the key issues is to integrate observed occupant behavior in relation to building controls (windows, doors and fans) into building thermal simulation and hence into building design. A preliminary study of these actions was presented to ASHRAE in 2004 (Nicol and Humphreys 2004). This paper builds upon this earlier work, clarifying the control-nature of human behavior. The analysis uses the existing database to develop algorithms for the operation of windows, fans and doors to describe human control characteristics in these buildings.

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The aims of this paper are:

- to clarify and quantify occupant use of windows, doors and fans
- to evaluate the modification of the indoor thermal environment caused by this behavior
- to develop adaptive algorithms describing the use of windows, doors and fans
- to implement these adaptive algorithms in ESP-r and demonstrate some initial results

THE FIELD SURVEYS

Experimental Procedure

This investigation of the use of windows, doors and fans in offices and commercial buildings used transverse thermal comfort surveys conducted in 33 buildings (32 naturally ventilated (NV) and 1 air conditioned (AC) in 5 cities in different climatic zones of Pakistan (Islamabad, Karachi, Multan, Quetta and Saidu Sharif). The surveys were conducted monthly from Apr. 1995 to Aug. 1996 by researchers visiting each building with thermal measurement instruments and questionnaires which were administered verbally to each of the people (Nicol et al. 1999). On each visit, a single set of responses was recorded from each person and altogether 7,105 sets were collected from 846 people. The data about the use of building controls was recorded in binary form (windows closed = 0, windows open = 1, doors closed = 0, doors open = 1 and ceiling fans off = 0, ceiling fans on = 1). Indoor globe temperatures (T_g) were measured using an RS thermometer (212-095) whose probe was inserted in a black-painted table tennis ball (about 40 mm diameter). The globe temperature incorporates the effects of the air temperature and the mean radiant temperature, and approximates closely to the operative temperature. The air movement (V) was measured by a Whatman rotating vane anemometer. All measurements were made close to the respondent and at desk level (about 0.9 m above the floor level). The outdoor temperature (T_{out}) was taken from the meteorological data of each city.

The Buildings

In each city, five to eight buildings were selected and 10 to 30 individual subjects in each building took part in the survey. The buildings were of mixed usage, age and construction. Details are given in Appendix A. The offices have basic equipment such as typewriters[1] and telephones, contributing little to the thermal load. Not all the buildings have heaters available, and not all have coolers available. The type of cooler varies: evaporative local coolers, local room AC unit, central AC. In the only central-AC building in the sample the occupants never opened the windows during the time data were collected (Table 1, building 4.30). Fans were hardly ever used in this building and it is therefore excluded from further analysis. In seven of the NV buildings, the mean proportion of windows open was less then 0.10, window opening being inhibited perhaps by outdoor noise or air pollution,[2] and water coolers and fans are used. These buildings were also excluded from the analysis.

THE USE OF BUILDING CONTROLS

General Response to Temperatures

People use controls to try to improve their thermal and air quality environment. We assume that if occupants feel heat discomfort, they will use the controls with the aim of restoring their comfort by modifying the indoor temperature or the air movement. According to previous research, temperatures are the key variables explaining the use of controls (Rijal et al. 2007 & 2008). Thus it is expected that the use of fans and the opening of windows will increase with higher indoor temperatures.

The overall usage of controls for each decile[3] of indoor or outdoor temperature is shown in Figure 1. The mean number of samples for each decile is 490 for windows and 680 for fans or doors. The proportion of use of controls is higher with increasing indoor and outdoor temperatures. However, there is a clear difference in their use. The proportion of windows open continues to increase in higher indoor temperatures but it decreases in highest outdoor temperatures. The reason could be that occupants close the windows to prevent the hot air entering through them. The proportion of fans on increases from about 25°C (T_g) and 20°C (T_{out}) and continues to increase with higher temperatures. The proportion of doors open is about 0.50 even in low indoor and outdoor temperatures and it increases about to 0.80 at higher temperatures. So the proportion of doors open is less related to temperature. However, as we will discuss later, the opening of doors can be help provide cross ventilation.

Seasonal Differences

If the use of controls is related to temperature, then it will also be related to season. To clarify the seasonal differences of the use of controls, the survey data were classified into four seasons (winter: mid Nov. to Feb., spring: Mar. to Apr., summer: May to Sept. and autumn: Oct. to mid Nov.), according to Khan's classification (Khan 2006). Unfortunately, we do not have data from Karachi for autumn.

The proportion of controls in use is differs according to city and season (Figure 2). In most cities, the proportion of use of controls in summer is considerably higher than in winter.

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[1] In most offices the typewriters have since been replaced with computers and printers. However, the number of computers per room is still limited to one or two units in most offices. Heat gain from these would have a little impact on indoor environment.

[2] Unfortunately there are no records of local outdoor conditions (noise, fumes, dust, wind, or rain) at the times of interview.

[3] i.e., the data were divided into 10 groups of approximately equal numbers of observations in ascending order of temperature.

Table 1. Mean Proportion of Use of Controls

City	Building	No. of Observations	Windows Open	Fans On	Doors Open
Islamabad	1.10	240	0.62	0.76	0.63
	1.20	268	0.10	0.63	0.18
	1.30	327	0.67	0.74	0.91
	1.40	320	0.67	0.58	0.87
	1.50	214	0.24	0.59	0.71
Karachi	2.10	45	0.33	0.60	0.07
	2.20	52	0.54	0.60	0.92
	2.30	57	0.19	0.67	0.56
	2.40	42	0.86	0.50	0.88
	2.45	124	0.31	0.55	0.20
	2.50	125	0.94	0.55	1.00
	2.60	79	0.95	0.61	0.87
Multan	3.10[b]	266	0.00	0.67	0.08
	3.20[b]	219	0.06	0.68	0.16
	3.30	292	0.24	0.66	0.86
	3.40	260	0.36	0.69	0.91
	3.50[b]	219	0.06	0.50	0.93
	3.60	176	0.48	0.59	0.93
	3.70	222	0.29	0.55	0.92
Quetta	4.10	322	0.26	0.39	0.52
	4.20[b]	308	0.06	0.11	0.46
	4.30[a]	303	0.00	0.04	0.98
	4.40[b]	309	0.00	0.31	0.81
	4.50	308	0.19	0.24	0.65
	4.60	296	0.22	0.09	0.52
Saidu Sharif	5.10	80	0.50	0.61	1.00
	5.20[b]	300	0.02	0.14	0.49
	5.30	297	0.31	0.39	0.96
	5.40	296	0.38	0.46	0.91
	5.50	146	0.22	0.49	0.92
	5.60[b]	283	0.04	0.24	0.60
	5.70	240	0.37	0.47	1.00
	5.80	70	0.20	0.16	0.71
All NV		6,802	0.33	0.49	0.69
Windows open ≥ 0.10		4,898	0.42	—	—
All		7,105	0.32	0.48	0.70

[a] AC building

[b] NV buildings that have fewer than 0.10 windows open

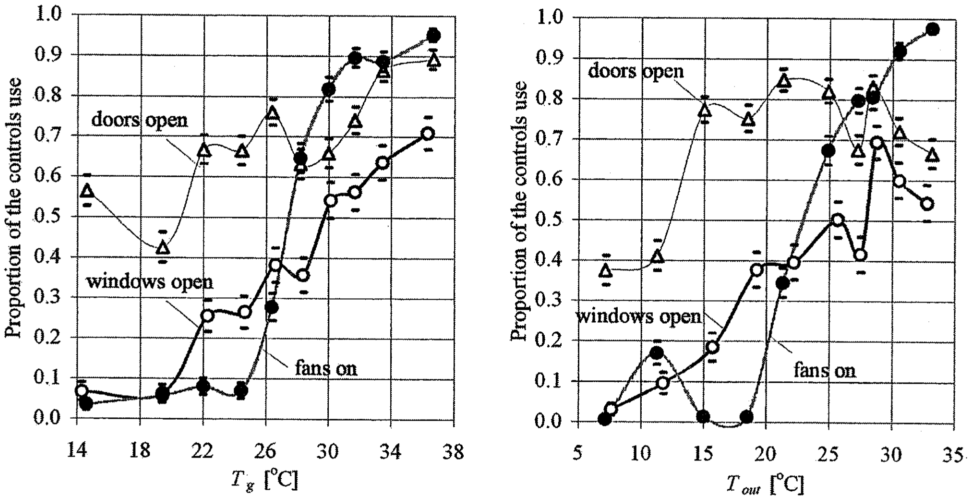

Figure 1 *Proportion of windows open, fans on and doors open with 95% confidence intervals at decile of indoor globe temperature* T_g *and outdoor air temperature* T_{out}.

However, this is not true for windows and doors in Karachi. Karachi is located in a hot-humid sub-tropical climate zone close to the sea and there is less difference in temperature between summer and winter, and so it is still useful to open windows and doors in wintertime.

The difference from city to city is not wholly attributable to outdoor temperature differences (Figures 2 and 3). For example, the proportion of windows open in winter is higher in Islamabad than in Multan, even though the outdoor temperature is lower in Islamabad. The proportion of windows open in autumn is significantly higher than in spring, even though the outdoor temperature is similar in both season (Figures 2 and 3). This could be a seasonal hysteresis effect: people may be more accustomed to opening windows in autumn than in spring.

Order of Priority Among the Controls

Occupants might be expected to open the windows and doors as a first reaction. If this were not sufficient for comfort they might then use fans. We explore this hypothesis by relating the use of controls to the temperature (see Figure 1). When indoor or outdoor temperature is low, the proportional use of controls is highest for doors, medium for windows and lowest for the fans. However, it should be remembered that doors may be kept open for reasons other than thermal comfort. The order of priority for use of controls is doors, windows and then fans and they are used jointly when the temperature is high.

EFFECT OF THE CONTROLS ON THE THERMAL ENVIRONMENT

Temperatures and Air Movement

Occupants modify the indoor environment by using various controls. This modification may have both immediate and longer-term effects for the occupants. For example, when a window is opened occupants may feel cooler due to the immediate effect of increased air movement through the window, while in the longer-term, the indoor temperature of the whole room may decrease because of the influx of cooler air. It would also be expected that people use the controls over a wide range of temperature to improve their environment. For example, people may open the windows to cool the room down when they enter an office and leave them open for the whole day unless they feel cold discomfort. The occupants may make these decisions based on the outdoor condition that they experienced on the way to the office. Occasionally they may open the windows in winter for a short time to cool down an overheated office or to provide sufficient ventilation.

The means of indoor globe temperature, outdoor air temperature and air movement are higher with use of controls than without (Table 2). The use of controls is, however, a response to high temperature rather than its cause. The results confirm that people use the controls over a wide range of both indoor and outdoor temperatures. The use of controls is associated with increased air movement. Because of the high correlation between indoor temperature (T_g) and outdoor temperature (T_{out}) (Table 3), the results show a similar pattern of effects for T_g and for T_{out}. The temperature difference between doors open and closed is smaller than for the other controls. As expected, the correlation of air movement with 'fans on' is stronger than with 'windows open' or 'doors open'.

Figure 4 shows the relation between the use of controls and the air movement. The air movement increases with the increased with the use of controls (Figure 4). The results suggest that occupants are using the controls to achieve higher air movement for cooling. This can explain the previously

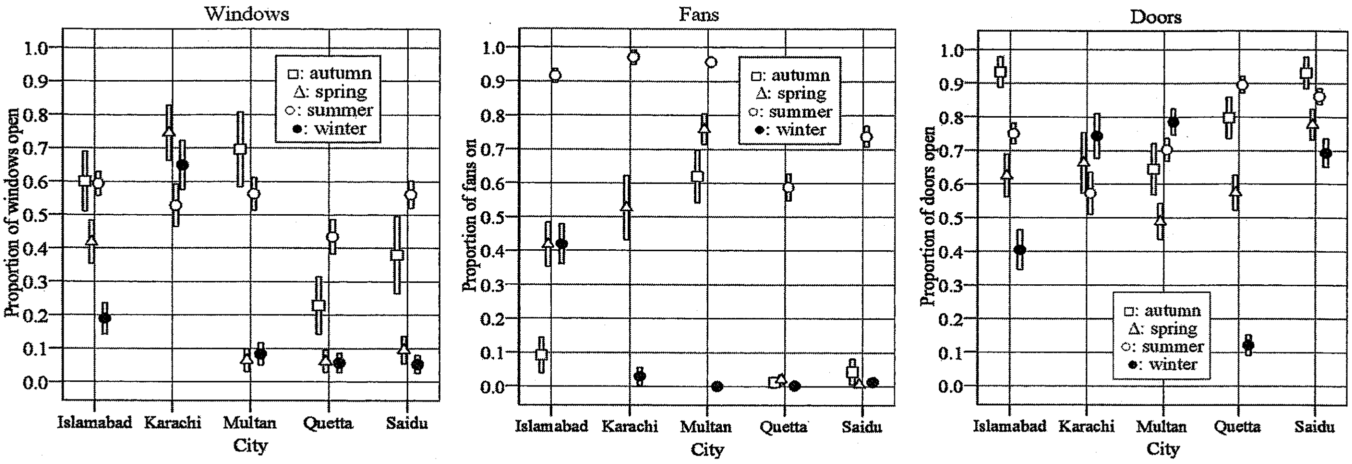

Figure 2 *Seasonal variation in the proportion of windows open, fans on and doors open, with 95% confidence intervals in each city.*

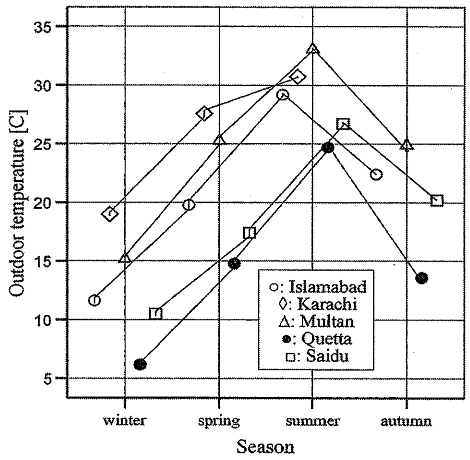

Figure 3 *Seasonal mean outdoor temperature in all NV buildings.*

Table 2. Values of T_g, T_{out}, and Air Movement (V) With and Without Use of Controls

Item	Status	Windows				Fans				Doors			
		n	Min	Max	Mean	*n*	Min	Max	Mean	*n*	Min	Max	Mean
T_g [°C]	closed	3,016	9.1	41.1	24.5	3,590	9.1	47.5	22.4	2,127	9.1	39.0	24.4
	open	1,882	11.5	41.0	30.2	3,212	13.2	46.6	31.4	4,675	9.3	47.5	27.7
T_{out} [°C]	closed	3,016	4.9	35.5	19.6	3,590	4.9	32.4	16.3	2,127	4.9	35.5	19.0
	open	1,882	9.9	35.5	26.3	3,212	8.2	35.5	27.9	4,675	4.9	35.5	23.0
V [m/s]	closed	3,016	0.10	3.80	0.23	3,590	0.10	2.25	0.12	2,127	0.10	3.80	0.22
	open	1,882	0.10	2.42	0.33	3,212	0.10	3.80	0.42	4,675	0.10	2.42	0.28

n = number of observations

mentioned finding that the temperature with use of controls is higher than without use of controls (a result similar to that of Brager et al. 2004 and Robinson and Haldi 2008).

Because the various controls are used together it is not clear from Figure 4 how much each affects the air movement. Their relative effects can be estimated by using multiple regression analysis. The following regression equation gives an indication of the relative effects of the controls on the air speed and it is clear from the regression coefficients that the air movement is dominated by the usage of the fans:

$$V = 0.007\ \mathrm{W} + 0.278\ \mathrm{F} + 0.046\ \mathrm{D} + 0.087\ (n = 4{,}898,\ r = 0.46) \quad (1)$$

where V is the air movement [m/s], the binary variables W, F and D are the use of windows, fans and doors thus for example if the window is closed W = 0 and if it is open W = 1. n is number of observations and r is correlation coefficient. The regression coefficients for F and D are statistically significant, while that for W is not. Thus switching on the fan raises the air speed by some 0.3m/s, while opening a door raises it by only some 0.05m/s, and the effect of opening a window is negligible. (It should be remembered that opening a window may increase the ventilation rate without much increasing the air speed in the body of the room).

Cross Ventilation

Cross ventilation is effective not only in increasing the air movement and air change rate but also in cooling down the indoor air, provided that it is cooler outdoors than in. It can be useful even if the occupants are positioned away from the windows in a large open plan office. In the UK, cross ventilation is associated with a decrease the indoor temperature in summer (Raja et al. 2001). We investigated the effect of cross ventilation in Pakistan, and it appears to be effective only in autumn. The reason could be that the outdoor temperature in summer is much higher in Pakistan when compared with UK temperatures. The indoor-outdoor temperature difference is also smaller in summer (average 2.9 K) than in autumn (5.9 K). Even though the outdoor temperature is similar in autumn and spring, cross ventilation is only effective in autumn. The lack of demonstrable effect in spring is puzzling, but we note that the proportion of window opening is then lower (see Figures 2 and 3).

To clarify the cooling effect of cross ventilation in autumn, a regression analysis of T_g and T_{out} is conducted with cross ventilation (both window and door open) vs. single sided or no ventilation (only one open or both closed) (Figure 5).

Table 3. Correlation Coefficients of Raw Data

Controls	No. of Observations	T_g:T_{out}	T_g: *control*	T_{out}: *control*	*V: control*
Windows open	4,898	0.90	0.43	0.41	0.17
Fans on	6,802	0.88	0.69	0.70	0.49
Doors open	6,802	0.88	0.24	0.23	0.10

Note: all correlation coefficients are significant (p<0.001).

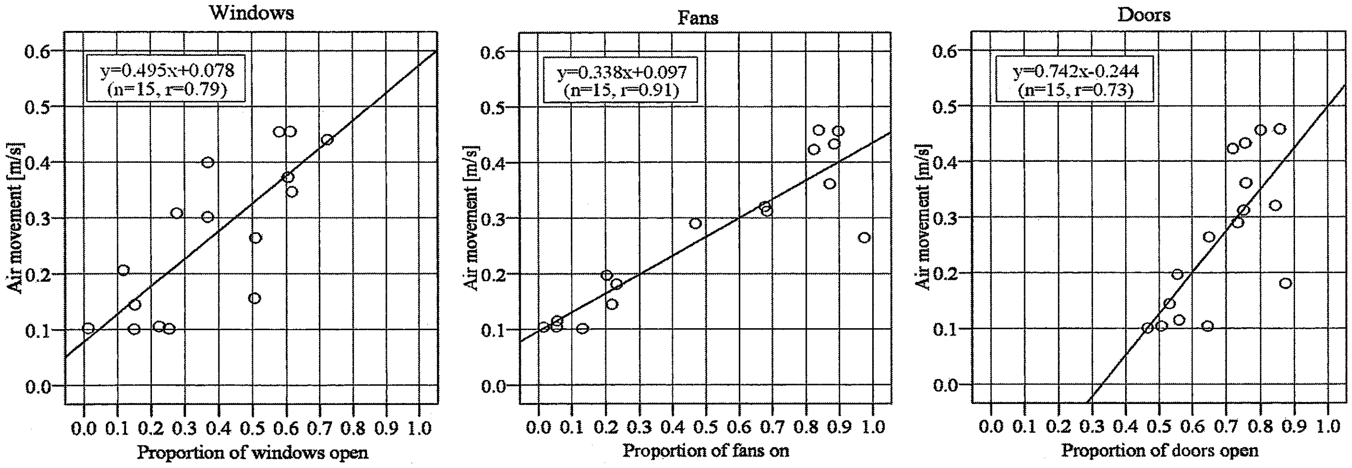

Figure 4 *Relation between the use of controls and air movement. Each point represents the investigated monthly mean value. The anemometer was insensitive below 0.1 m/s, so any readings below this level have been set to 0.1 m/s. Monthly mean values are adopted for analysis because comfort temperature is related with monthly mean outdoor temperature (Humphreys 1978). n is number of monthly mean observations and r is correlation coefficient. All regression coefficients are significant (p<0.001).*

The indoor temperature of the rooms with cross ventilation is 1.1 K lower than outdoor temperature for those without cross ventilation. This result is similar to UK data (Raja et al. 2001).

Prediction of the Use of Controls: Logistic Regression Analysis

Binary data are most appropriately analyzed by means of logistic regression. In logistic regression the probability of an action occurring, say a window being opened, is related to the variable causing it, say an increase in the indoor temperature. Logistic regression need not be confined to a single predictor-variable, so we may predict the probability that a window will be open from both the indoor temperature and the outdoor temperature. Multiple logistic regressions were performed to predict the occupants' use of windows, fans and doors (Table 4). The regression coefficients for the fans are higher than for the windows or doors. These high regression coefficients indicate that fans come into use over a rather narrow range of temperature, when compared with windows or doors. The regression coefficient of the T_g is also higher than the T_{out}. This indicates that the occupants are using the building controls as a response to the indoor temperature more than to the outdoor temperature. The prediction accuracy of the fans on is higher than the windows or doors open (Figure 6). (The statistical package SPSS Version 14 was used for calculation.)

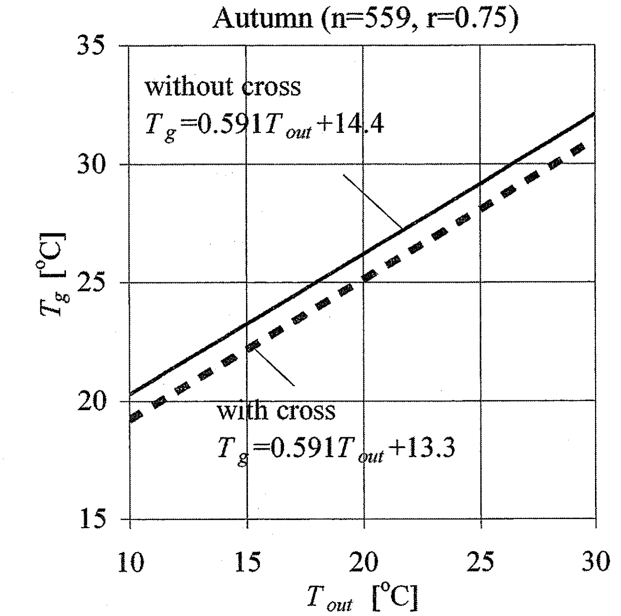

Figure 5 *Effect of the cross ventilation in autumn in all NV buildings. n is number of observations and r is correlation coefficient. Both regression coefficients are significant (p<0.001).*

Table 4. Multiple Logistic Regression Equations

Controls	No. of Observations	Equation	R^2
Windows open	4,898	$\text{logit}(p) = 0.140T_g + 0.032T_{out} - 5.06$	0.19
Fans on	6,802	$\text{logit}(p) = 0.240T_g + 0.159T_{out} - 10.39$	0.50
Doors open	6,802	$\text{logit}(p) = 0.060T_g + 0.019{*}T_{out} - 1.17$	0.06

logit(p) = log{p/(1−p)}
p = probability that window is open or fan is on or door is open
R^2 = Cox and Snell R square
Note: All regression coefficients are significant (p<0.001, *0.007).

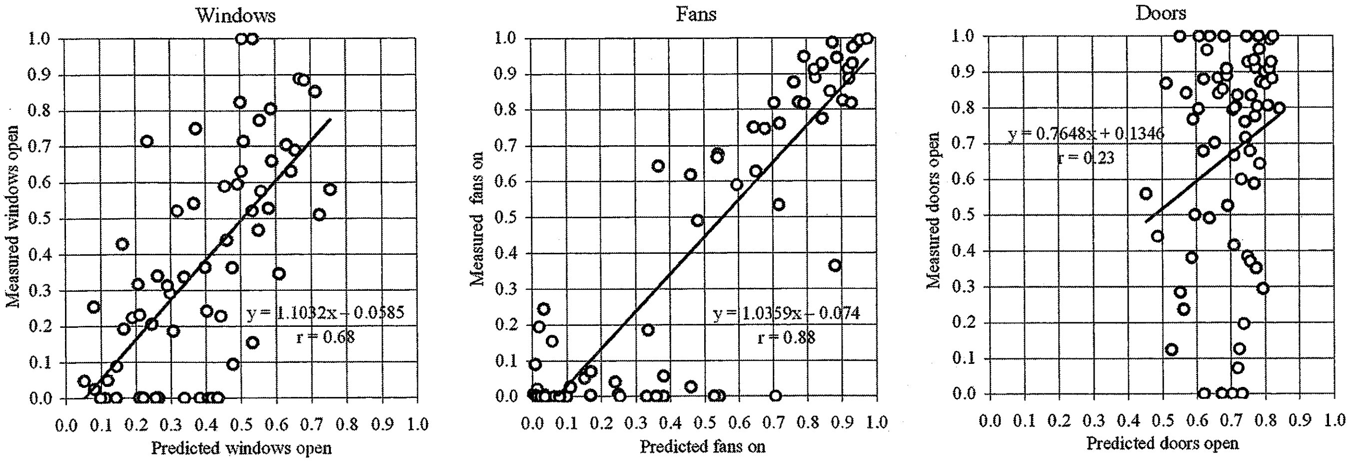

Figure 6 *Relation between the measured and predicted values. Each point represents the decile of outdoor temperature for*

ADAPTIVE ALGORITHMS FOR BUILDING CONTROLS

The Causative Role of the Indoor Temperature

While both the indoor and the outdoor temperatures are useful statistical predictor-variables for the use of the building controls, it seems likely that in terms of causation it is the *indoor* temperature that matters. For example, if the indoor temperature caused the person to become too warm they would open a window, but how long the window would remain open would be likely to depend on the outdoor temperature. So while it is true that the likelihood of the use of controls is increased at higher indoor and outdoor temperature it is probable that it is the *indoor* temperature that prompts the use of the controls, and the analysis now proceeds on this assumption.

Logistic regression equations for the use of controls, based on the indoor temperature, in all buildings, are shown in Table 5. The relationship between the probability of use (p) of the control and the indoor temperature (T_g) is of the form

$$\mathrm{logit}(p) = \log\{p/(1-p)\} = bT_g + c \qquad (2)$$

where

$$p = e^{(bT_g+c)}/\{1+e^{(bT_g+c)}\} \qquad (3)$$

and where b is the regression coefficient for T_g, and c the constant in the regression equation. The regression coefficient for the fans is higher than for the windows or for the doors, for both indoor temperatures.

The logistic regression equation predicting the probability of use of controls against the room temperature, although giving an unbiased statistical prediction of the use of the controls, does not adequately reflect the underlying behavior-pattern of the occupants as they open and close their windows. That is to say, if a person had opened a window because he or she became too warm, it would not be necessary to close it again unless the person were to become too cold. This closing action would occur at a lower temperature than that at which the window was opened. Such a 'deadband' is essential to the modelling of the human behavior, and in any algorithm used in thermal simulation it also avoids the risk of instability.

The deadband cannot be revealed by inspecting the binary data. To demonstrate its presence it is necessary to group the data. To obtain these 'binned' datapoints the data were sorted by building and then by indoor temperature and split into groups of 25 records in order of increasing room temperature. The probability of use of controls in each 'bin' is plotted on a scatter diagram against the indoor temperature at the time (Figure 7). The scatter of the points is far greater than can be attributed to the binomial error in the probabilities, showing the presence of a substantial deadband. The envelope of the points therefore indicates the width of the temperature deadband.

The dynamic of the human behavior gives a 'horizontal structure' to the data. That is to say, within the deadband a change of room temperature does not provoke a corresponding change in window opening. For example, if the room temperature were to rise such that 50% of the windows were open, and then the temperature were to fall, the window opening would remain at around 50% until the temperature had fallen sufficiently to demand further closure of windows. It follows that the regression equation of the room temperature on the logit of use of controls becomes the more appropriate description of the data, rather than the logistic regression curve. This 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. (The presence of error in the predictor variable of a regression has the effect of depressing the regression coefficient. The correction procedure is given in Table 6. Each batch of 25 has an error variance that depends on the sample size and the value of its logit. The mean of this variance is used to make the correction. For a full discussion of the errors on regression see for example Cheng and Van Ness, 1999.)

The visual 'fit' of the regression line for 'windows open' is significantly improved by making due allowance for a deadband in the analysis (the adjusted regression equation Figure 7). For the fans on, it is interesting to note that the difference between the adjusted regression line and the original logistic regression line is small. This would be expected, because the act of switching on a fan raises the threshold temperature at which people would feel too cool, thus narrowing the deadband for this action. For the doors, the two regressions are very different, suggesting that the opening of doors is not primarily related to thermal control, and so it may be more appropriate to use the logistic regression line to predict the likelihood of a door being open in the simulation, rather than attribute a deadband to the door opening and closing behavior.

Table 5. Logistic Regression Equations

Controls	No. of Observations	T_g, °C	R^2
Windows open	4,898	$\mathrm{logit}(p) = 0.176T_g - 5.33$	0.19
Fans on	6,802	$\mathrm{logit}(p) = 0.426T_g - 11.78$	0.48
Doors open	6,802	$\mathrm{logit}(p) = 0.081T_g - 1.34$	0.06

$\mathrm{logit}(p) = \log\{p/(1-p)\}$
p = probability that window is open or fan is on or door is open
R^2 = Cox and Snell R square
Note: All regression coefficients are significant ($p<0.001$).

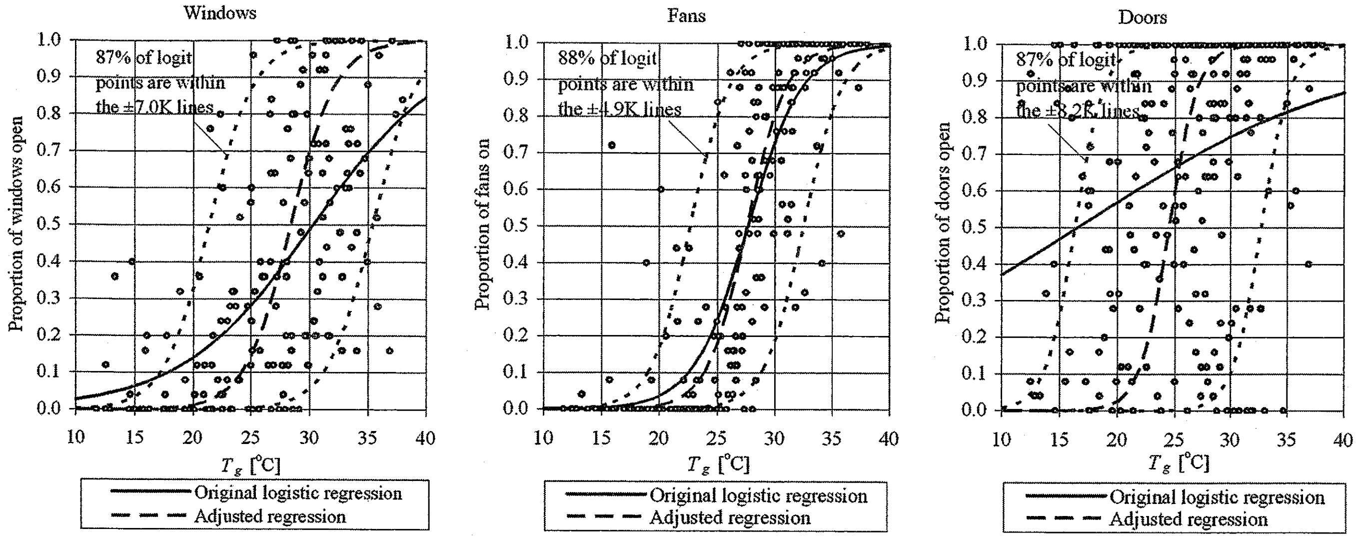

Figure 7 *Deadband of the windows open, fans on and doors open. (The 'original logistic regression' line is the simple logistic regression. The 'adjusted regression' line results from regressing the temperature on the logits of the grouped observations and adjusting the result for the binomial error of the groups, as shown in Table 6.)*

Table 6. Symbols and Values of Parameters Used to Calculate the Adjusted Regression Equations, Based on the Records Grouped in 25 Observations

Parameter: Symbol	Windows	Fans	Doors
Globe temperature: T_g	—	—	—
Logit of use of controls: logit	—	—	—
Regression coefficient of T_g on logit: b	1.637	1.481	1.077
Variance of logit: var(logit)	2.252	3.053	2.891
Covariance of logit and T_g: cov(logit, T_g)	3.687	4.521	3.114
Number of observations in each group: n	25	25	25
Proportion of use of controls: p	0~1	0~1	0~1
Mean variance of logit error: var(logit error)	0.3183	0.3627	0.3645
Mean logit: logit$_m$	−0.4346	0.1293	0.3634
Mean globe temperature: T_{gm}	27.6	27.8	25.0
Residual of T_g	4.69509	3.27331	5.46958

Note: Steps in obtaining the adjusted equation

Description	Windows	Fans	Doors
Equation for regression coefficient	b = cov(logit, T_g)/var(logit)		
Therefore, the equation for covariance	cov (logit, T_g) = b×var(logit)		
Equation for logit error	var(logit error) = 1/{np(1−p)}		
Adjusted value of b	b = cov(logit, T_g)/{var(logit) − var(logit error)}		
The adjusted equation	T_g = 1.906logit+c	T_g = 1.681logit+c	T_g = 1.232logit+c
Therefore, the equation for logit	logit = 0.525T_g+c	logit = 0.595T_g+c	logit = 0.812T_g+c
The equation must pass through the T_{gm} and logit$_m$	c = logit$_m$ − 0.525T_{gm}	c = logit$_m$ − 0.595T_{gm}	c = logit$_m$ − 0.812T_{gm}
The centre line of the deadband	logit = 0.525T_g − 14.9	logit = 0.595T_g − 16.4	logit = 0.812T_g − 19.9
The width of deadband	±1.5SD×Residual of T_g		
The equations for deadband margins	logit = 0.525(T_g±7.0) − 14.9	logit = 0.595(T_g±4.9) − 16.4	logit = 0.812(T_g±8.2) − 19.9
The proportion of use of controls	p = e$^{(\text{logit})}$/{1+e$^{(\text{logit})}$}		

The width of the deadband is taken as 1.5 standard deviations[4] of the distribution of residual temperature about the adjusted regression line. In Figure 7, this assumption includes about 87% of the observations (Values '0' and '1' are excluded as their logits are -∞ and +∞ and have zero weight.) The width of the deadband for windows is wider than had been found from UK data (Rijal et al. 2007), possibly because Pakistan has higher regional and seasonal differences in comfort temperatures (Nicol et al. 1999) compared with UK (CIBSE 2006). The width of this deadband thus includes a portion attributable to the seasonal shift in the comfort temperature, which itself includes a component attributable to the use of fans. The fundamental or basic deadband can be estimated approximately by subtracting this seasonal shift, and is approximately 4 K. This value accords well with estimations of the width of the comfort zone (Nicol and Humphreys 2007) from comfort surveys. By relating them to the comfort temperature, the equations of the margins of the deadband (see Table 6) can be written as follows:

$$\text{Windows open: } \mathrm{logit}(P_w) = 0.525\{T_g - T_{comf} + (S_w - 0.5)\, WD\} \quad (4)$$

$$\text{Fans on: } \mathrm{logit}(P_f) = 0.595\{T_g - T_{comf} + (S_f - 0.5)\, FD\} \quad (5)$$

The $S_w = 0$ and $S_w = 1$ are the initial state of windows, closed or open. The $S_f = 0$ and $S_f = 1$ are the initial state of fans, off and on. So, for example, equation 4 with S_w set to zero gives the conditional probability that the window will change from closed to open. With S_w set to 1 it gives the conditional probability that the window will change from open to closed. T_g is the room globe temperature. In simulation, it will be represented by operative temperature (T_{op}). $WD = FD = 4$ K (± 2 K) is the basic deadband (difference in room temperature) between feeling so warm as to wish to open the window or switch the fan on, and feeling so cool as to wish to close the window or switch the fan off. This value is taken from a wide range of UK and European data analysis (CIBSE 2006, Nicol and Humphreys 2007, Rijal et al. 2007). This fundamental deadband is assumed to be the same for the use of the fan as for the windows, but it must be remembered that switching the fan on raises the comfort temperature by some two degrees (Nicol and Humphreys 2004, Nicol 2004).

The equation for Pakistan comfort temperature (T_{comf}) for the day is:

Free running mode (heating = off, AC = off): $T_{rm} > 10$ °C

$$\text{Fans off: } T_{comf} = 0.408 T_{rm} + 16.6 \ (n = 2{,}769,\ r = 0.69) \quad (6)$$

$$\text{Fans on: } T_{comf} = 0.480 T_{rm} + 16.6 \ (n = 2{,}810,\ r = 0.71) \quad (7)$$

Cooling mode (heating = off, AC = on): $T_{rm} > 28.1$ °C

$$T_{comf} = 0.416 T_{rm} + 16.5 \ (n = 489,\ r = 0.62) \quad (8)$$

Heating mode (heating = on, AC = off): $T_{rm} \leq 10$ °C

$$T_{comf} = 0.156 T_{rm} + 19.1 \ (n = 701,\ r = 0.22) \quad (9)$$

All the equations are statistically highly significant ($p < 0.001$). n is number of observations and r is correlation coefficient. T_{rm} is the exponentially weighted running mean outdoor temperature for the day (CIBSE 2006). The T_{comf} was calculated from the data using the Griffiths method (see appendix A2) (Griffiths 1990, Nicol et al. 1994). The comfort temperature incorporates the effect of the fans on the warmth sensation – it is the comfort temperature for the expected extent of fan use at that room temperature.

SIMULATION

Adaptive Behavior in Dynamic Simulation

ESP-r was chosen as the simulation modeling code for this work as its Open Source nature supports dissemination and adoption of the methods in other software tools. ESP-r already offers several behavioral models such as the Hunt model (Hunt 1979) for the switching of office lighting, the stochastic Lightswitch 2002 algorithm developed by Reinhart (2004) to predict dynamic personal response and control of lights and blinds as well as Newsham et al.'s (1995) original Lightswitch model. Bourgois et al. (2006) developed the SHOCC module to enable sub-hourly occupancy modeling and coupling of behavioral algorithms such as Lightswitch 2002 across many ESP-r domains. Rijal et al. (2007) developed the Humphreys window opening algorithm for the UK based on adaptive comfort criteria in conjunction with indoor and outdoor temperatures and demonstrated its application within ESP-r simulation. The Humphreys algorithm combines adaptive comfort with adaptive behavior and was shown to be important in achieving accurate representation of comfort and energy performance in naturally ventilated buildings in the UK. This paper describes the implementation of the adaptive algorithms for occupant comfort in the Pakistan context and occupant adaptive behaviors such as the use of fans, windows, doors, heating and mechanical cooling.

Implementation of the Adaptive Algorithms in ESP-r

The algorithms representing occupant operation of windows, fans and doors have been incorporated within ESP-r. The window and door algorithms are implemented as control functions operating on the appropriate components within the airflow network while the operation of fans is represented as a change in the perceived occupant comfort and an increase in equipment heat gains due to the fan motor. The implementation of the algorithms is illustrated in Figure 8 and Table 7 and discussed in some detail below. The frequency at which the

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[4] The choice of 1.5 standard deviations is a matter of judgement and is open to debate and possible revision in the light of experience. The aim is to delineate the margins of the deadband while remembering that some datapoints would be expected by chance to fall outside the band.

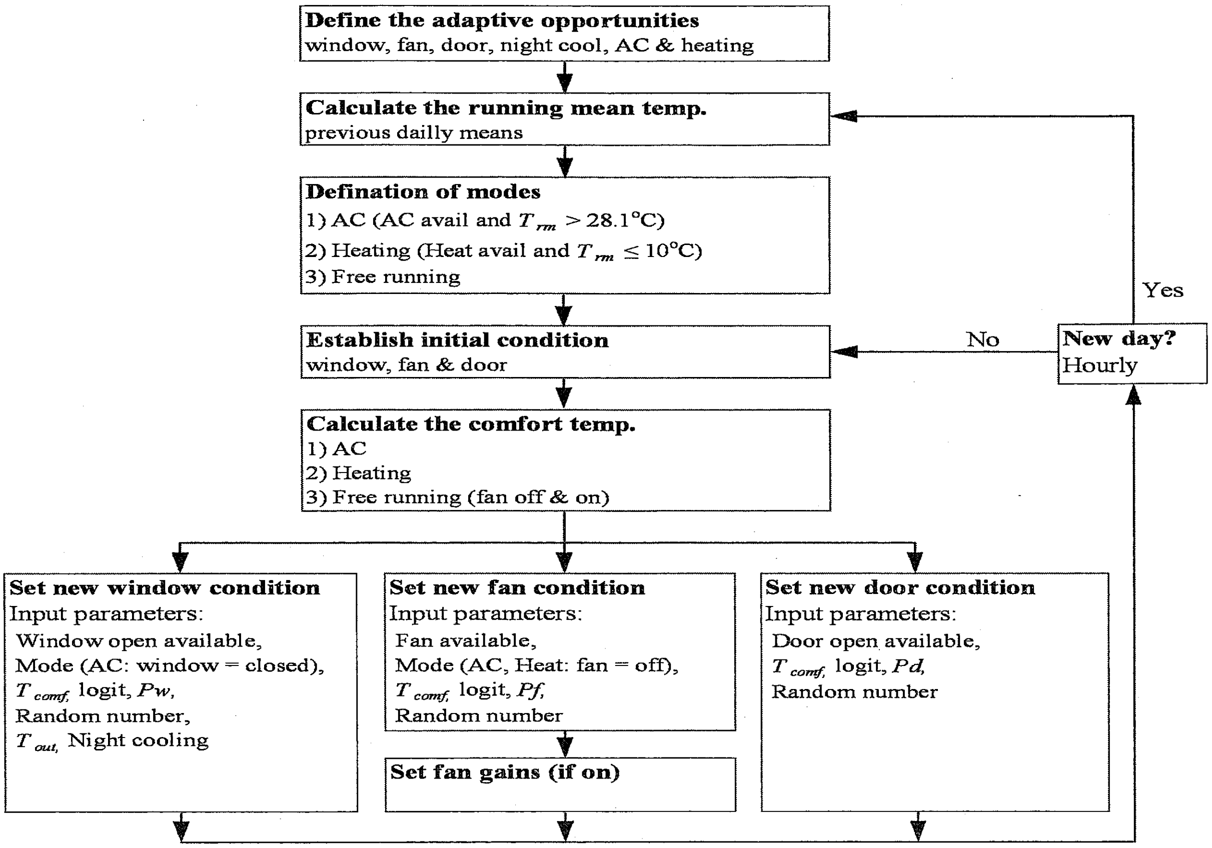

Figure 8 *Flow chart of the adaptive algorithms.*

Table 7. Steps in the Implementation of the Adaptive Algorithm in ESP-r

Function	No.	Parameter	Symbol	Sample	Derivation or Source
Define adaptive opportunities and other parameters such as fan energy use when control period specified.	1	Running mean response to T_{out}	α	const	Default $\alpha = 0.8$ (0.01 to 0.99 allowed range)
	2	Window open possible?	*Wposs*	const	Yes or No (if noise, pollution, privacy or security issue)
	3	Ceiling fan available for use?	*Fposs*	const	Yes or No (if no fan fitted)
	4	Door open possible?	*Dposs*	const	Yes or No (if noise, pollution, privacy or security issue)
	5	Window available for night cooling?	*NCposs*	const	Only set Yes if night / weekend period and NV allowed: No if day or NC not available (security issue)
	6	Air conditioning system available?	*ACavail*	const	Yes or No
	7	Heating system available?	*Havail*	const	Yes or No
	8	Power rating of fan	*PWRfan*	const	$PWRfan = 5$ W/m^2 (normalise for floor area)
	9	Deadband for window open	*WD*	const	$WD = 4$
	10	Deadband for fan on	*FD*	const	$FD = 4$

Table 7. Steps in the Implementation of the Adaptive Algorithm in ESP-r ***(continued)***

Establish temperatures and running mean outdoor temperature.	11	Indoor air temp.	T_{ai}	1/h	Available at each timestep (variable)
	12	Indoor operative temp.	T_{op}	1/h	Available at each timestep (50% mrt, 50% T_{ai})
	13	Outdoor air temp.	T_{out}	1/h	Interpolated from climate file (hourly data in file)
	14	Daily mean outdoor air temp.	T_{odm}	1/day	Calculated from 24 hourly data points per day
	15	Running mean outdoor air temp.	T_{rm}	1/day	$T_{rm}(\text{init}) = (1-\alpha)\{T_{odm-1} + \alpha T_{odm-2} + \alpha^2 T_{odm-3} \cdots\}$ Initial value calculated from previous 20 days daily mean then $T_{rm} = (1-\alpha)T_{odm-1} + \alpha T_{rm-1}$
Selection of mode	16	Determine mode	*Mode*	1/day	if *ACavail* = Yes and T_{rm}>28.1°C then *Mode* = AC if *Havail* = Yes and $T_{rm} \leq$ 10°C then *Mode* = Heating else *Mode* = Free running
Status of window, fan and door	17	Status of window (0 = closed)	*Sw*	1/h	Initial values set to 0. Then set by previous timestep.
	18	Status of fan (0 = off)	*Sf*	1/h	Initial values set to 0. Then set by previous timestep.
	19	Status of door (0 = closed)	*Sd*	1/h	Initial values set to 0. Then set by previous timestep.
Determine comfort temp. from mode and previous fan status.	20	Determine comfort temperature	T_{comf}	1/day 1/day 1/h 1/h	if *Mode* = AC, $T_{comf} = 0.416T_{rm}+16.5$ if *Mode* = Heating, $T_{comf} = 0.156T_{rm}+19.1$ if *Mode* = Free running (includes NC) if *Sf* = 0, $T_{comf} = 0.408T_{rm}+16.6$ (without fan effect) if *Sf* = 1, $T_{comf} = 0.480T_{rm}+16.6$ (with fan effect)
Window status (Free running or Heating)	21	Free running or heating?	*Mode*	1/day	if *Mode* = Heating or Free running
	22	Logit function for window	*FuncW*	1/h	$FuncW = \text{logit}(Pw) = 0.525\{T_{op} - T_{comf} + (Sw - 0.5)*WD\}$
	23	Probability for window open	*Pw*	1/h	if *Wposs* = Yes, $Pw = \exp^{(FuncW)}/\{1+\exp^{(FuncW)}\}$, else $Pw = 0$
	24	Random number between 0 and 1	*Rn*	1/h	Generated from Fortran RNG.
	25	Window opening effectiveness	*Weff*	1/h	if $T_{rm} > 28.1$ and $T_{out} < T_{ai} + 5$, *Weff* = Yes, else *Weff* = No
	26	Window status (0 = closed, 1 = open)	*Sw*	1/h	if *Pw*>*Rn* then window open (*Sw* = 1) if *Rn* ≥ *Pw* then window closed (*Sw* = 0)
	27	If 5°C hotter outside: close window?		1/h	If *Sw* = 1 and *Weff* = No then *Sw* = 0 (window closed)
	28	Night cooling mode, open if T_{rm} met	*NC*	1/h	If *NCposs* = Yes and T_{rm} > 28.1°C then *Sw* = 1
Window status (AC)	29	AC?	*Mode*	1/day	if *Mode* = AC, *Sw* = 0 (windows closed if AC mode)
Fan status (free running)	30	Free running?	*Mode*	1/day	if *Mode* = Free running
	31	Logit function for fan	*FuncF*	1/h	$FuncF = \text{logit}(Pf) = 0.595\{T_{op} - T_{comf} + (Sf - 0.5)*FD\}$
	32	Probability for fan on	*Pf*	1/h	if *Fposs* = Yes and T_{rm}>23.6°C $Pf = \exp^{(FuncF)}/\{1+\exp^{(FuncF)}\}$, else $Pf = 0$
	33	Random number between 0 and 1	*Rn*	1/h	Generated from Fortran RNG.
	34	Fan status (0 = off, 1 = on)	*Sf*	1/h	if *Pf*>*Rn* then fan on (*Sf* = 1) if *Rn* ≥ *Pf* then fan off (*Sf* = 0)
Fan status (Heating or AC)	35	AC?	*Mode*	1/day	if *Mode* = AC, *Sf* = 1 (fans on if AC mode)
	36	Heating?	*Mode*	1/day	if *Mode* = Heating, *Sf* = 0 (fans off if heating mode)
Fan heat gains	37	Additional heat gains for fan	*Gfan*	1/h	*Gfan* = *PWRfan***Sf* (Added to thermal calculations)
Door status (all modes)	38	Logit function for door	*FuncD*	1/h	$FuncD = \text{logit}(Pd) = 0.081T_{op} - 1.34$
	39	Probability for door open	*Pd*	1/h	if *Dposs* = Yes, $Pd = \exp^{(FuncD)}/\{1+\exp^{(FuncD)}\}$, else $Pd = 0$
	40	Random number between 0 and 1	*Rn*	1/h	Generated from Fortran RNG.
	41	Door status (0 = closed, 1 = open)	*Sd*	1/h	if *Pd*>*Rn* then door open (*Sd* = 1) if *Rn*≥*Pd* then door closed (*Sd* = 0)

adaptive algorithm is run is set to hourly at present but could be varied in future.

There may be issues such as security, pollution or privacy which do not allow window or door opening in a given situation, similarly there may be no electric fan, heating or air conditioning available to the occupant. The simulation code is configured to capture the available adaptive opportunities as inputs; this allows the simulation to align with a specific building context. The code is extendable to allow the addition of further adaptive actions such as shutter, blind and light use in future.

Daily values for running mean outdoor temperature are calculated as described in CIBSE Guide A (CIBSE 2007) and the CEN Standard EN15251 (Olesen 2007) from the climate data and the response factor α (the response factor can be user input, a default value of 0.8 is suggested).

The equation used to determine the comfort temperature depends on the mode of the building which is defined to be either 'Free-running', 'Heating' or 'AC'. The particular mode of building operation for a given day is selected based on the availability of the adaptive mechanism and the running mean outdoor temperature (T_{rm}). Present data suggest that where heating is available the heating is more likely to be on than off when the running mean outdoor temperature (T_{rm}) is less than 10°C. If heating is available and running mean outdoor temperature less than 10°C then the building is in 'Heating' mode. Similarly, data suggests that where air conditioning is available it is more likely to be on than off when the running mean outdoor temperature (T_{rm}) is greater than 28.1°C. If cooling (AC) is available and running mean outdoor temperature greater than 28.1°C then the building is in 'AC' mode. If the building is not in 'Heating' or 'AC' modes then it is in 'Free running' mode. The simulation code also allows for occupant use of windows for night cooling, the trigger for night cooling has also been set to a running mean outdoor temperature (T_{rm}) of greater than 28.1°C.

The occupant comfort temperature (T_{comf}) is then determined based on the mode of operation and the fan condition (on or off). This comfort temperature is then used in determining occupant comfort conditions and occupant adaptive actions (windows, doors and fans)[5].

Analysis of the survey data indicated that fans were more likely to be off than on when the running mean outdoor temperature is less than 23.6°C. If the building is in 'Free running' mode, a fan is available, and the running mean outdoor temperature (T_{rm}) is greater than 23.6°C then the probability of fan use is calculated by equation 5 and compared to a random number to determine the fan status for the current time-step (The comparison with the random number represents the stochastic nature of occupant behavior). If the building is in 'Heating' mode the fan is set to off and if the building is in 'AC' mode the fan is set to on. Where the fan is on then the gains associated with its electricity use are added into the thermal calculations within the simulation.

If the building is in 'Free running' or 'Heating' modes and window opening is possible then the probability of window use is also calculated (using equation 4) and window status determined using comparison to a new random number. In periods where cooling is desired (i.e. T_{rm} is greater than 28.1°C) if the outdoor temperature is more than 5K above the indoor temperature (i.e. window opening is not effective at improving comfort: the value of 5K is a provisional judgement.) then the windows are set to 'closed'. If the building is in 'AC' mode then the windows are assumed to be closed. Night cooling can be applied in free running mode only and leads to the windows being open out-with occupied hours when the running mean outdoor temperature is greater than 28.1°C for that day.

Where door opening is possible the probability of door open is calculated (door open equation in Table 5) and compared to a new random number to determine door status. Door opening at present is set to be independent of mode.

If the building is in air conditioning or heating mode a cooling or heating set-point is imposed through the normal simulation heating controls.

It should be noted that normal practice in simulation was applied in this work including running of an extended pre-simulation period in advance of commencement of the simulation proper in order to allow the effect of imposed initial values of parameters to become extinct.

Simulation Results Including the Adaptive Algorithms

In order to demonstrate the algorithms in dynamic simulation a representative cellular office within an office building was simulated for the Karachi climate. The cellular office faces south, has a 22.5 m^2 floor area (Figure 9) and is located on a middle floor within a larger open plan office. The external walls construction is of un-insulated concrete, the area of the window is 3.9 m^2. The window is well shaded. The office is assumed to be occupied during weekday office hours (8:00 ~ 18:00). Heat gains from equipment, occupants and lighting are applied (90W sensible occupant gains during occupied hours, 50W equipment gains during occupied and unoccupied hours, 3 W/m^2 lighting gains during occupied hours). Outside of occupied hours, it is assumed that all the windows remain closed except when night cooling is activated. Only background infiltration is allowed when the window is closed.

Figure 10 (a) shows the office performance for a simplified case on a hot summer's day where the occupants are free to open windows and turn on ceiling fans (35W fans) but the door opening is not an allowed adaptation (i.e. *Dposs* set to 'No' as would be the case where a noise, security or privacy issue prevents the door being left open continuously), there is no air conditioning (*ACavail* set to 'No') and there is no oppor-

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[5] These comfort-temperatures are conceptually similar to those given in the adaptive section of ASHRAE Standard 55-2004, in the CIBSE Guide A, and in CEN 15521. However, the relations we use here were derived from survey data from Pakistan (Nicol et al. 1999).

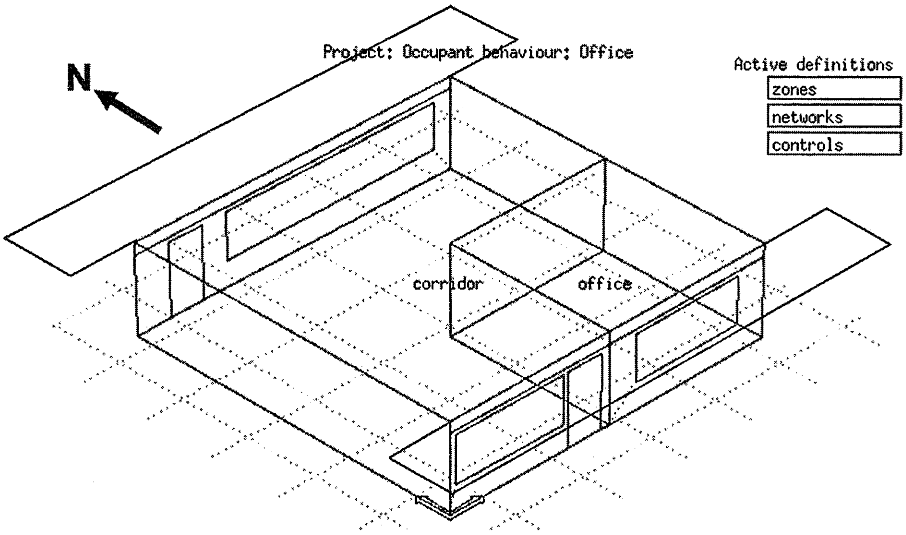

Figure 9 *Representation of the cellular office (labeled 'office') located within the larger open plan office area (labeled 'corridor'). The office window faces south. The external shades of 1.7m width were provided above the windows level of building.*

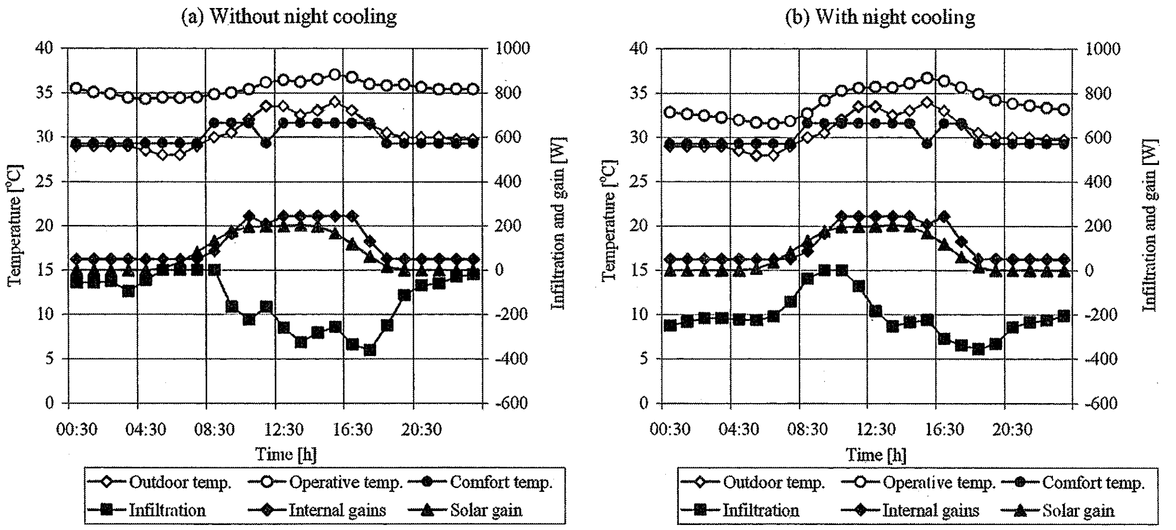

Figure 10 *Temperatures and energy flows for a summer day with and without night cooling. The lines represent the outdoor air temperature, the indoor operative temperature (open symbols), the comfort temperature (varies with fan use) and the energy flows from the convective cooling by the incoming air, the heat gains from occupants, equipment and lights and the incoming solar heating absorbed in the surfaces of the office. The night cooling is indicated by the cooling due to infiltration of around 200W overnight.*

tunity for night cooling (*NCposs* set to 'No'). For this hot day the windows are open and the fans are on for most of the day (window opening is indicated in the figure by the cooling due to air infiltration, fan use is indicated by the increase in gains and comfort temperature). Figure 10 (b) shows the same situation but where night cooling is allowed (cooling through air infiltration through open window during both occupied and unoccupied hours).

Annual simulations were run to investigate the performance of the algorithm across a range of indoor and outdoor conditions. Figures 11 (a) and (b) show the predicted probability of fan and window use for the office (without night cooling) plotted against indoor operative temperature (T_{op}) and outdoor temperature (T_{out}) respectively. It can be seen that reasonable correspondence was found with the survey data (see Figure 1). The window and fan opening frequency for the

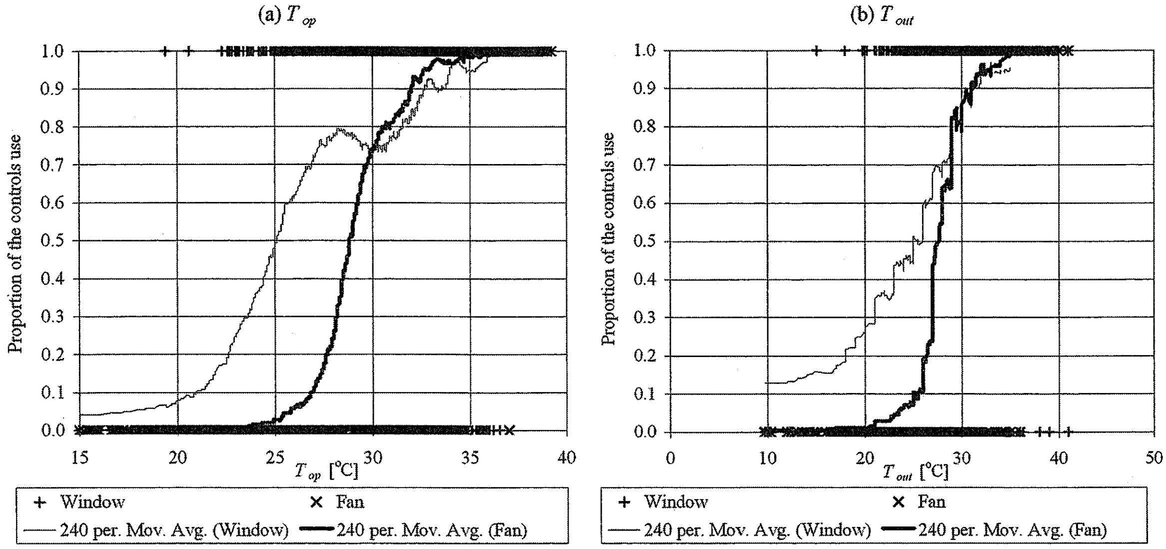

Figure 11 *The predicted probability of window and fan use plotted against (a) indoor operative temperature (T_{op}) and (b) outdoor temperature (T_{out}).*

same office model was analyzed by season (Figure 12). Again correspondence with survey data is reasonable given the fact that the simulation was based on a single building, building to building variation across the survey data was high, the available climate data was not for the survey timeframe and the survey data did not capture simulation input data such as gains and geometry.

To clearly illustrate the operation of the algorithm, the data presented here has been taken from application in a single throw deterministic-like mode. In future applications to real building design, the algorithm will be deployed within a structured multiple simulation methodology that accounts for the stochastic nature of the algorithm and variations/uncertainties in input parameters (e.g. gains, climate) in order to produce outputs representing realistic distributions of occupant comfort, adaptive behavior and energy use. The approach is intended to be extended and integrated with other adaptive behaviors such as lighting and moveable shading use, heating and cooling controls adjustment etc.

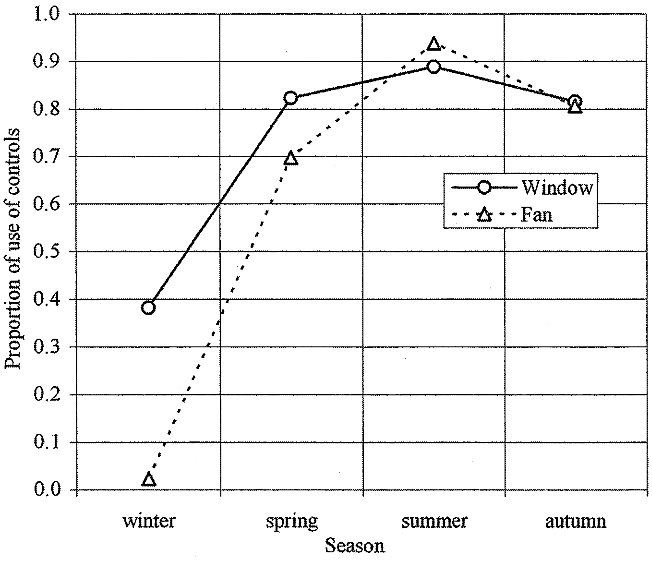

Figure 12 *Proportion of the predicted windows open and fans on.*

DISCUSSION

The above example of the use of the algorithm is a simple case for illustrative purposes. The algorithm has been written in a manner that enables modification of its coefficients and constants in the light of further experience and more experimental data. For example the width of the deadband could be subject to modification in the light of experience, as could the various cut-off points for the use of fans and the for the switch between modes of building operation. In some buildings the fans were decommisioned in winter by having their blades wrapped in paper to keep them clean, and recommissioned for the summer. This would, if the practice were widespread, give a winter constraint on the use of the fans, but unfortunately sufficient information is lacking. Nevertheless it is clear that the application of an algorithm that simulates the actual behavior of the occupants is possible, and is likely to produce more realistic estimates of indoor temperatures and potential energy use than would be obtained by making arbitrary assumptions about human behavior. This is highly important for decisions about the necessity of providing cooling, and hence contributes to the design of buildings that use little energy yet are considered comfortable by the occupants.

Because the behavioral algorithms are expressed in terms of the adaptive comfort temperatures as derived from appropriate field studies, such as now are provided in ASHRAE Standard 55-2004 and it CEN Standard EN 15251, it is likely that the behavioral algorithms will apply to a good approximation to a wide variety of climates worldwide. A possible exception is the hot humid climate. We had such data from Karachi only, and our analysis has taken no account of humidity. Further data are therefore needed from such climates to confirm or disconfirm the algorithms. The algorithms were derived from offices and commercial buildings. It remains to be seen how well they might apply to other types of occupancy. Of these domestic buildings are particularly important, in view of the large amount of energy use in this sector.

The use of realistic behavioral algorithms such as derived in this paper will help the building thermal simulations to predict energy consumption, and hence help the designer and the services engineer in the design, construction and operation of energy efficient naturally conditioned buildings.

CONCLUSION

The use of building controls (windows, doors and fans) in relation to the thermal environment has been analyzed to understand and predict the occupants' behavior in offices and commercial buildings in Pakistan. The following results were obtained:

a. The proportion of use of controls varies according to the city (climate) and season. In summer, the proportion of fans on is considerably higher than the proportion of windows open.
b. The controls are generally used when the mean globe temperatures (T_g), outdoor air temperature (T_{out}) are high, and their use results in increased air movement. The results show that the use of controls is effective for cooling by creating increased air movement.
c. In autumn, effective cross ventilation reduces indoor globe temperature by about 1 K.
d. The centre line of the deadband equations are derived from the logistic regression analysis.
Windows open: $\text{logit}\,\{p/(1-p)\} = 0.525T_g - 14.9$
Fans on: $\text{logit}\,\{p/(1-p)\} = 0.595T_g - 16.4$
e. These adaptive algorithms can be applied in building simulations to predict occupant behavior and energy use in buildings.
f. The basic deadband for window opening and fan using can be estimated by subtracting the seasonal shift in comfort temperature, and is approximately 4 K.
g. The adaptive algorithms have been implemented within the ESP-r software to allow incorporation within dynamic simulation. This will enable occupant comfort and adaptive behavior to be comprehended in building design in the future so that more comfortable and energy efficient buildings can be achieved.

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APPENDIX A1— DESCRIPTIONS OF INVESTIGATED BUILDINGS

Table A.1. Descriptions of Investigated Buildings

Building	Building Age (years)	No. of Floors	Construction		Thickness (mm)		Facade	Cooling/ heating	Description
			Walls	Roof	Walls	Roof			
(1) Islamabad (Longitude: 74.90°, Latitude: 33.72°, Altitude: 507m)									
1.10	10	2	Bricks	Concrete	225	150	E	FR	Open surrounding, mix of grass and paving. Small overhangs over windows.
1.20	20	5	Bricks	Concrete	225	150	N	RC	A row of offices blocks, with roads on front and rear. Large box louvers around windows.
1.30	10	1	Bricks	Concrete	225	150	W	FR	Verandas in front of major windows. Open surroundings, mix of grass and paving.
1.40	25	2	Bricks	Concrete	225	150	N	FR	Surrounded by roads and commercial buildings. Small overhangs on windows.
1.50	5	2	Bricks	Concrete	225	150	E	FR	RCC framed structure. Open surroundings, mix of grass and paving. Small overhangs on windows.
(2) Karachi (Longitude: 67.13°, Latitude: 24.90°, Altitude: 21m)									
2.10	25	9	Bricks	Concrete	150	150	N	RC	Concrete framed structure. Located in residential and commercial area. Blinds and prism glass shading.
2.20	70	1	Concrete	Concrete	450	225	-	FR	Walls fixed with translucent glass. Main road on the front, garden and open area.

Table A.1. Descriptions of Investigated Buildings *(continued)*

2.30	35	1	C blocks	Concrete	450	225	-	RC	Concrete frame structure. Densely populated area. Some plantation and landscaping.
2.40	10	3	Bricks/ Blocks	Concrete	180	180	E	FR	Shading: sunbreakers & curtains. Densely populated, landscaped.
2.45	10	2	Bricks/ Blocks	Concrete	180	180	W	RC	Big hall, sunbreakers & curtains. In densely populated & landscaping.
2.50	10	3	C blocks	Concrete	450	225	-	FR	Corridors & court yard. In densely populated area.
2.60	-	5	Bricks	Concrete	225	225	NW	FR	Concrete frame structure, in residential & commercial area.
(3) Multan (Longitude: 71.43°, Latitude: 30.20°, Altitude: 122m)									
3.10	1	1	Stone/ C block	Concrete	300	150	NW	EC	Large windows shaded with curtains. In commercial area, roads on two sides.
3.20	25	2	Stone/ C block	Concrete	300	150	SE	EC	Large windows with curtains. In commercial area, roads on two sides.
3.30	35	1	Stone/ C block	Concrete	300	150	NE	FR	Court yard planted with trees, flowers.
3.40	30	1	Stone/ C block	Concrete	300	150	E/W	FR	Double storey buildings on three sides.
3.50	100	1	Bricks/ Mud	Brick/ Mud	750	-	EW	FR	Heavy old building Well planted compound.
3.60	20	1	Stone/ C block	Concrete	300	150	N/S	FR	Open compound on three sides, planted with trees.
3.70	30	2	Bricks/ block	Concrete	225	150	N/S	FR	Open agriculture land on two sides.
(4) Quetta (Longitude: 66.95°, Latitude: 30.18°, Altitude: 1,672m)									
4.10 (Block-a)	100	1	Stone/ Brick	Al- sheets	450	-	E	H	Lawn, gardens at front. Heavy weight, high ceiling, tilted roof.
4.10 (Block-b)	100	1	Stone/ Brick	Al- sheets	300	-	S	H	Low ceiling small offices, 1.5m wide veranda.
4.10 (Block-c)	30	1	Stone/ Brick	Al- sheets	225	-	S	RC/H	Light weight, wooden partition, veranda.
4.20	5	3	Bricks	Concrete	250	150	W	H	A single row block of offices and shops, veranda, open land rear.
4.30	4	3	Bricks/ Block	Concrete	350	150	W	AC	Air-conditioned, chip- board ceiling, in commercial area.
4.40	50	1	Bricks	Concrete	350	150	E/S	RC/H	Shopping centre, with central concrete court yard, hardboard ceiling.
4.50	50	1	Stone/ Brick	Concrete	250-350	150	E/W	H	Open space at front and rear, hardboard ceiling
4.60	5-25	2	Bricks	Concrete	250	150	E/W	H	Blocks having offices and halls on two sides with a central passage, open area planted with trees and gardens.
(5) Saidu Sharif (Longitude: 72.35°, Latitude: 34.73°, Altitude: 961m)									
5.10	3	1	Bricks	Concrete	250	150	NE	H	L-shaped block, central court yard, flowers and trees. 1.5m wide veranda.
5.20	15	2	Bricks	Concrete	250	150	E	RC/H	Open area all around with some plantation. Plastered and cream painted.
5.30	15	1	Bricks	Concrete	250	150	E	H	L-shaped with low ceiling veranda, and court yard. Ventilators above veranda.

Table A.1. Descriptions of Investigated Buildings *(continued)*

5.40	15	1	Bricks	Concrete	250	150	W	H	Low roof veranda, extended roof shade ventilators.
5.50	10	3	Bricks	Concrete	250	150	S	H	Ground floor office, 1st & 2nd floor residence. Low veranda, small court yard, trees & plants.
5.60	30	3	Bricks	Concrete	250	150	S	RC/H	In a busy commercial area. Each floor has a hall and side room offices.
5.70	18	1	Bricks	Concrete	250	150	W	H	Big central hall with partitions. High ceiling.
5.80	25	3	Bricks	Concrete	250	150	NE	H	A block, located in a commercial area, surrounding by roads, 1st floor shopping centre, 2nd & 3rd floor Water and Power Development Authorities offices.

C = concrete
Al = aluminium
— = unknown
N = north
S = south
E = east
W = west
FR = free running (no heating or cooling [only fans])
RC = room cooler in summer
EC = evaporative cooler in summer
H = heating in winter (FR in summer)
RC/H: room cooler in summer and heating in winter
AC = air conditioned

APPENDIX A2— DESCRIPTION OF GRIFFITHS' METHOD OF ESTIMATING A COMFORT-TEMPERATURE

Griffiths suggested a way in which the comfort temperature can be calculated from a small sample of data (Griffiths 1990). He has stated that "correcting the physical measurements of operative temperature for each subjective report of warmth made by our informants, it is possible to estimate the temperature which they would require to feel neither cool nor warm". To estimate the comfort temperature, he has assumed the 0.44 regression slope for 9-point thermal sensation scale which is based on 0.33 regression slope of 7-point ASHRAE scale (0.44 = 0.33×8/6). By assuming the regression coefficient, individual comfort vote (C) is predicted by indoor globe temperature (T_g).

$$C = a^*T_g + d \qquad (A.1)$$

where a* is the assumed value of regression coefficient and 'd' is intercept. The comfort temperature (T_c) can be estimated by

$$4 = a^*T_c + d \qquad (A.2)$$

where '4' is 'neutral' vote in 7-point ASHRAE scale. By eliminating 'd' of Equations A.1 and A.2, we get

$$T_c = T_g + (4 - C) / a^* \qquad (A.3)$$

The Griffiths' method has modified to use the centroid of the data (Nicol et al. 1994). The centroid is the position of the mean comfort vote (C_m) and mean temperature (T_{gm}), and all regression lines will pass through it. Equation A.3 can be rewritten as follows:

$$T_c = T_{gm} + (4 - C_m) / a^* \qquad (A.4)$$

The choice of an appropriate value for the gradient is difficult. We have assumed a gradient of 0.5 votes/K (Nicol et al. 1999). This value is somewhat higher than the usually assumed value of around 0.33votes/K. It arises from an analysis of the SCATs database (Nicol and Humphreys 2007) and the de Dear database (de Dear 1998) which gave a value of 0.4 votes/K (Humphreys et al. 2005). We have adjusted this slightly upward to allow for an effect of random error in the globe temperature. The precise value chosen makes little difference to the neutral temperatures unless the mean comfort vote departs excessively from neutral.

The application of Equations A.3 and A.4 is shown in Figure A.1. Griffiths' method can be applied where the calculation of comfort temperature by regression analysis is unreliable especially for small variation in comfort votes and temperatures.

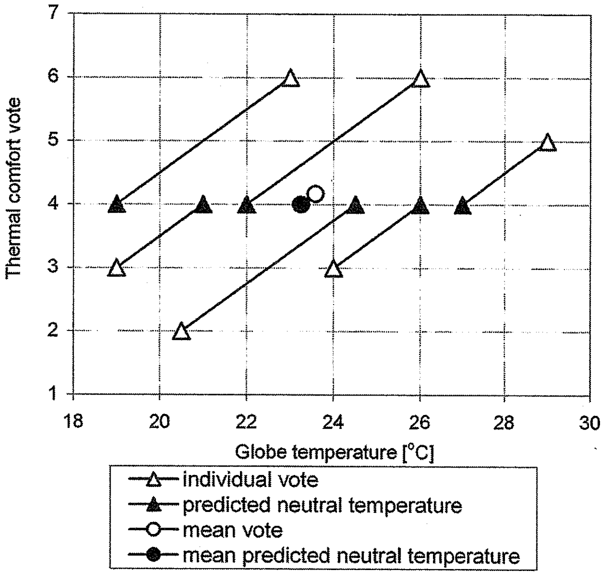

Figure A.1 *The prediction of the comfort temperature (neutral temperature) from individual vote and mean vote (ASHRAE 7-point scale) by assuming a gradient of 0.5 votes/K.*