A WINDOW OPENING ALGORITHM AND UK OFFICE TEMPERATURE: FIELD RESULTS AND THERMAL SIMULATION

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ABSTRACT

This investigation of the window opening data from extensive field surveys in UK office buildings investigates 1) how people control the indoor environment by opening windows, 2) the cooling potential of opening windows, and 3) the use of an "adaptive algorithm" for predicting window opening behaviour for thermal simulation in ESP-r. We found that the mean indoor and outdoor temperatures when the window was open were higher than when it was closed, but show that nonetheless there was a useful cooling effect from opening a window. The adaptive algorithm for window opening behaviour was then used in thermal simulation studies for some typical office designs. The thermal simulation results were in general agreement with the findings of the field surveys.

KEYWORDS

Thermal comfort; Adaptation; Behaviour; Building controls; Window; Algorithm; ESP-r

INTRODUCTION

Good building design is one of the important factors for energy saving. Another is how the occupants control the windows to achieve comfortable temperatures. Although adaptive thermal comfort models are already established (CIBSE 2006, CEN 2007), and relationships between indoor and outdoor conditions and the use of building controls have been described (e.g. by Nicol 2001, Nicol and Humphreys 2004), we still do not know exactly how to design naturally ventilated buildings to achieve comfortable thermal conditions. It is important to integrate into building design procedures occupant behaviour in relation to windows, for they are the most common thermal control device. If people feel too warm or too cool they often open or close windows to avoid discomfort. This is not only potentially useful for energy saving in summer, reducing the need for mechanical cooling or heating, but also provides a beneficial link with the outdoor environment. The way in which this occupant behaviour works is not yet fully understood, and so behaviour protocols for which there is little empirical support have sometimes been used (Rijal et al. 2007). Thus, the main objectives of this research are:

- To understand how people use windows to control the indoor environment .
- To use an algorithm for window opening behaviour, derived from the field data, for some appropriate thermal simulations.
- To evaluate the cooling effect of window opening, by means of field investigations and thermal simulation.

THE DATABASE

This investigation uses data from extensive thermal comfort surveys in Oxford and Aberdeen in the UK. Longitudinal (Abdnox-long) and transverse (Abdnox-trans) surveys were conducted in 15 office buildings (7 naturally ventilated (NV) and 2 air conditioned (AC) buildings in Oxford, 3 NV and 3 AC building in Aberdeen). The longitudinal surveys took place between March 1996 and September 1997. Data loggers recording the room temperature were placed in the working environment and the subjects were asked to record in a very brief questionnaire their thermal satisfaction and use of building controls. These responses were given 4 times a day (early morning, late morning, early afternoon and late afternoon). 35,764 sets of responses were collected from 219 subjects. The transverse surveys were conducted monthly during the period of the longitudinal surveys, researchers visiting each building with thermal instruments logging air temperature, globe temperature and humidity, and with a questionnaire which was administered verbally to each of the subjects. On each visit, one set of responses was recorded from each subject. A total of 4,997 sets were collected from 890 subjects. More details can be found in Rijal et al. (2007).

EXPLORING THE WINDOW DATA

The proportion of windows open was very low in the AC buildings, there being few openable windows, and so these buildings are excluded from further analysis. The proportion of windows open in NV buildings was, as expected, lowest in winter, highest in summer and intermediate in spring and autumn (Rijal et al. 2007).

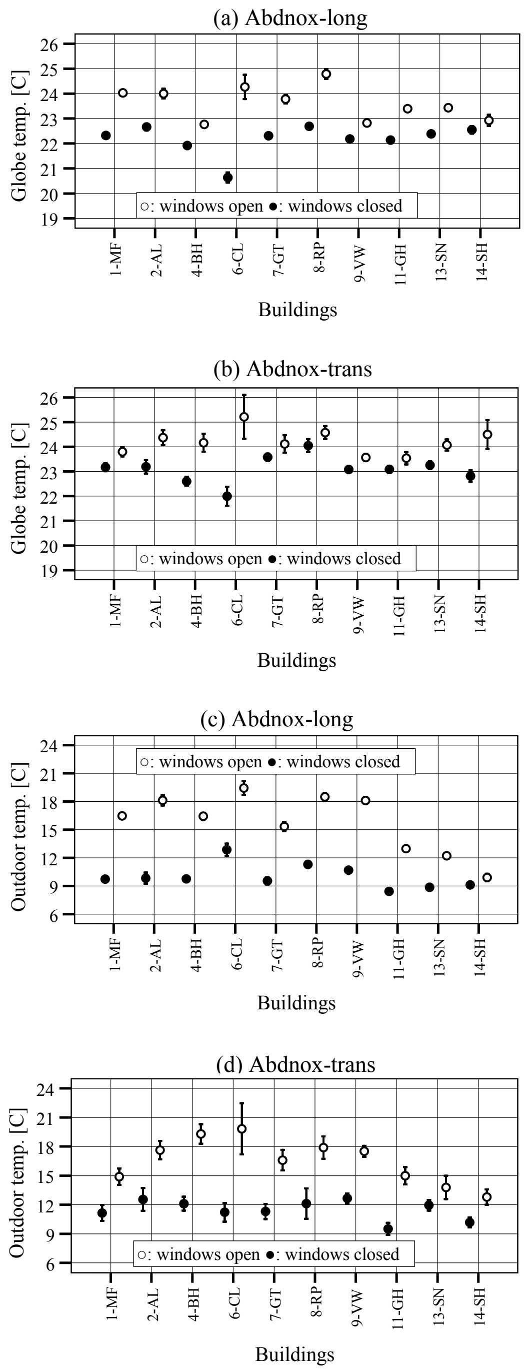

Figure 1 Comparison of mean globe temperature and outdoor air temperature with 95% confidence intervals for windows open (open symbols) and closed in longitudinal and transverse surveys

Table 1 Values of globe temperature and outdoor air temperature for windows open and closed in the longitudinal and transverse surveys

Temp. [°C]	Window	Abdnox-long					Abdnox-trans				
		N [-]	Min	Max	Mean	SD	N [-]	Min	Max	Mean	SD
T_g	closed (0)	13,702	8.8	30.6	22.2	1.8	2,296	18.1	28.6	23.1	1.4
	open (1)	8,784	15.6	33.5	23.4	2.0	1,156	16.7	29.5	24.0	1.6
T_{ao_i}	closed (0)	15,610	-6.4	30.8	9.7	5.5	2,308	-2.0	26.6	11.5	5.6
	open (1)	9,706	-2.4	30.7	15.6	5.9	1,122	-1.9	26.6	16.4	5.5

Temperatures for windows open and closed

The values of globe temperature (T_g) and outdoor air temperature (T_{ao_i}) for the windows open and for windows closed are shown in Figure 1 and Table 1. The mean values of T_g and T_{ao_i} with windows open for all buildings of longitudinal survey are 23.4 ^oC and 15.6 ^oC respectively. They are 1.2K and 5.9K respectively higher than with the windows closed. The results are consistent with people opening windows in response to increases in the indoor temperature, associated with raised outdoor temperatures. If the indoor temperature becomes too high while the outdoor temperature is low (e.g. with high solar gain on sunny winter days) the window will be opened, but generally only for a short period, because the room will quickly cool down again.

Even though the methods of investigation and the number of samples are different in the two surveys, the temperature associated with open windows is similar in both, as is that with closed windows (Table 1). In most of the buildings the temperature difference between all cases with the windows open and all case with windows closed is higher in Oxford than in Aberdeen (11-GH, 13-SN and 14-SH). These regional differences might be attributable to the difference in the climate between the two areas, which could also affect the occupants' window opening behaviour.

Range of temperatures at which windows are open and closed

To show the lower (⩽10%) and upper (⩾90%) temperature bounds for windows open and closed, the cumulative distributions of T_g and T_{ao_i} are shown in the Figure 2. The results are given in Table 2. The lower and upper bounds of T_g and T_{ao_i} with windows open are higher than with the window closed in the both surveys. It is interesting that there is little temperature difference between window open and closed at the lower and upper limit. The results show that people open windows over a wide range of both indoor and outdoor temperatures.

Effect of opening a window

In this analysis an open window is designated by "1" and a closed window by "0". To find from the longitudinal data the effect of opening a window, pairs of responses when a closed window was followed by an open window (01 pairs) were extracted, within the same day from the same subject. Although the subjects had been requested to make records 4 times in a day, some provided only 2 or 3. Consequently, some of the selected samples had 1 or 2 record gaps between them, but most were separated by about 2 hours.

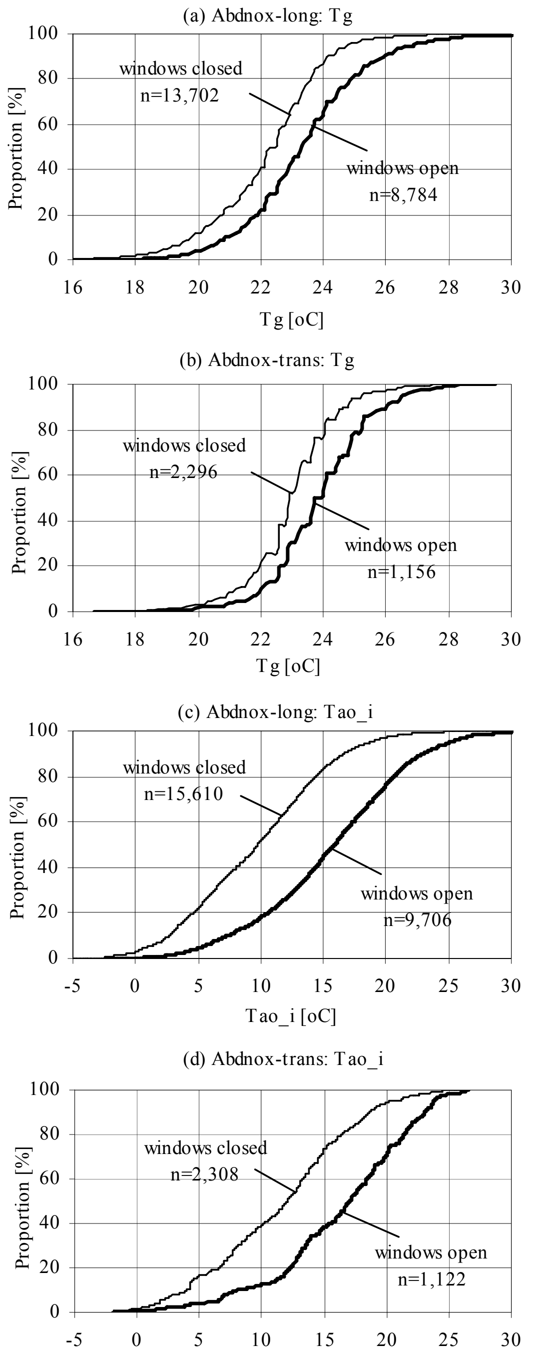

Figure 2 Cumulative distributions of globe temperature and outdoor air temperature for NV buildings when windows are open and closed.

Table 2 Globe temperatures and outdoor air temperatures for percentile points when windows are open and closed.

Temp. [°C]	Window	Abdnox-long				Abdnox-trans			
		N [-]	Cumulative value			N [-]	Cumulative value		
			10%	50%	90%		10%	50%	90%
T_g	closed (0)	13,702	19.8	22.4	24.3	2,296	21.4	22.9	24.8
	open (1)	8,784	20.9	23.3	26.0	1,156	21.9	23.8	26.1
T_{ao_i}	closed (0)	15,610	2.7	9.8	16.6	2,308	4.1	12.0	18.7
	open (1)	9,706	7.3	15.9	23.0	1,122	8.2	17.1	23.1

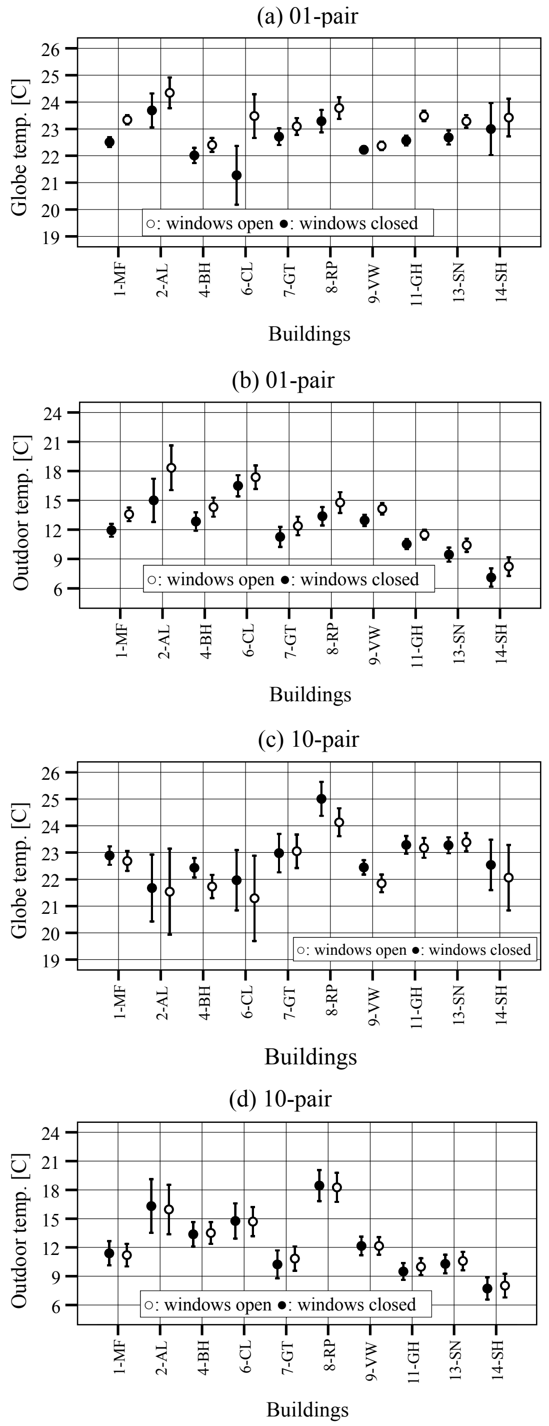

Figure 3 Comparison of mean globe temperature and outdoor air temperature with 95% confidence intervals for windows open (open symbols) and closed at adjacent times in the longitudinal survey

Table 3 Values of globe temperature and outdoor air temperature for windows open and closed (01-pair and 10-pair) in longitudinal surveys

Temp. [°C]	Window	01-pairs					10-pairs				
		N [-]	Min	Max	Mean	SD	N [-]	Min	Max	Mean	SD
T_g	closed (0)	1,316	12.6	28.6	22.5	1.6	487	17.7	28.4	23.0	1.6
	open (1)	1,316	17.8	31.4	23.1	1.6	487	15.6	27.8	22.7	1.8
T_{ao_i}	closed (0)	1,469	-2.4	25.9	11.6	5.2	580	0.1	30.5	11.5	5.5
	open (1)	1,469	-0.8	28.4	12.8	5.4	580	-1.1	30.7	11.6	5.3

The number of paired samples is 1,316 for T_g. The mean T_g and T_{ao_i} for the windows open is higher than for the windows closed (Figure 3 (a), (b) and Table 3). This suggests that the general result of opening the window was to limit subsequent rise in room temperature that would have occurred had the window remained closed, rather than to cool the room. As well as window opening affecting the indoor temperature, there may also be an air movement or fresh air advantage.

Effect of closing a window

To find the effect of closing a window, open-closed (10) pairs of responses were selected. Again they were from records adjacent in time, within the same day, and from the same subject. The number of the selected samples for this condition is small (n = 487 for T_g) because people rarely closed windows in the offices once they were open, probably because during the day both indoor and outdoor temperatures were generally rising. When the windows were closed, in most of the buildings T_g increased and T_{ao_i} decreased (Figure 3 (c), (d) and Table 3). It seems that people were likely to close windows when the outdoor temperature was falling. The results suggest that windows are closed to effect an increase in the indoor temperature, or to limit its fall, by shutting off the effect of falling outdoor temperatures.

The cooling effect of open windows

To investigate the cooling effect of having the windows open, the globe temperatures for weekdays and weekends are compared. The sequences Friday to Monday inclusive, in Aug., Sep. and May-Jun., were chosen. In each period, the outdoor temperature profiles were similar and the heating was off. The selected subjects for analysis are 15 people from 5 different buildings in Oxford. The analysis is for the office hours (9:00 to 17:00). It is assumed that all windows were closed during the weekend. During the weekdays the proportion of windows open was always high in these periods, so the windows were taken to be open. The globe temperature had been recorded at 15 or 30 minute intervals.

The internal heat gain (from occupancy, lights, equipment) are small at the weekend, and the indoor air movement is low. There are no air-movement records from the Aberdeen and Oxford data, but in the SCATs data (McCartney and Nicol 2002), a European project of similar design, the mean air velocity with windows open in NV buildings was 0.06 m/s higher than with the windows closed (P<0.001). This difference can be shown to be equivalent to a reduction of about 0.6 K (see e.g. Humphreys and Nicol 1995) in the globe temperature, and it is subtracted from the globe temperatures in the weekdays. The mean temperature rise due to the internal heat gain is estimated from the difference between the adaptive windows open algorithm and windows closed of 13:30 to 17:30 (Rijal et al. 2007). This is equivalent to 1.7 K and it is added to the globe temperatures at the weekend. This process gives an indication of what the indoor temperature would have been on the weekdays had the windows not been opened. The results are shown in Figures 4 and 5.

The temperature difference between the windows open and closed is small in a heavyweight building (9-VW). Overall, the mean globe temperature when windows were open (weekday) was 2.2 K lower than when the windows were closed (weekend). The results show that if occupants had not opened their windows on the weekdays, the indoor temperature would have continued to rise. Thus opening the windows had a significant cooling effect.

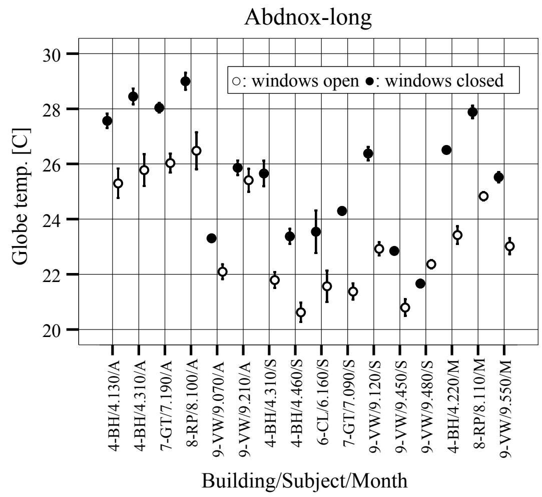

Figure 4 Comparison of mean globe temperatures with 95% confidence intervals *in the buildings when windows are open (weekdays: open symbols) and closed (weekends) in longitudinal survey, after adjustment for air movement and heat gains. A: Aug. (16th to 19th, 1996), S: Sept. (13th to 16th, 1996) M: May-Jun (30th to 2nd, 1997).*

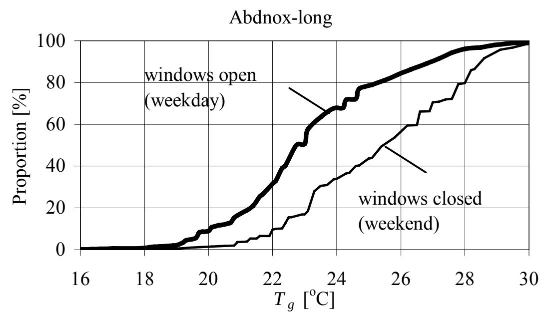

Figure 5 Cumulative distribution of the globe temperature during weekdays (windows open) and weekends (windows closed) in longitudinal survey, after adjustment for air movement and heat gains.

These findings are compared with the T_g for the windows open and closed for each subject in the weekday and weekend and month (Figure 6). To give the approximate picture, the monthly mean temperature when the windows are open and closed for Aug., Sep. and May are selected for comparison. The reason for this selection is that most of windows are open in the selected weekdays, and so we cannot compare with temperatures when windows are closed. At first, we tried to compare only the selected subjects of weekend and weekend, however, 1/3 of these subjects always open the windows in these months and give more points in the monthly mean temperature, other subjects are also included in the analysis. The temperatures for windows open and for windows closed are highly correlated in both cases (Figure 6). The two lines are almost parallel to each other and temperature difference between them is about 3 K. Most of monthly mean temperatures for windows open are on the hotter side of the diagonal line of the figure, while most of the weekday mean temperatures for windows open are on the cooler side. In the monthly mean temperatures for windows open and closed, the cooling effect of the windows open had not been clear. However, this comparison of T_g for windows open and closed in the weekday and weekend clearly shows the cooling potential of open windows.

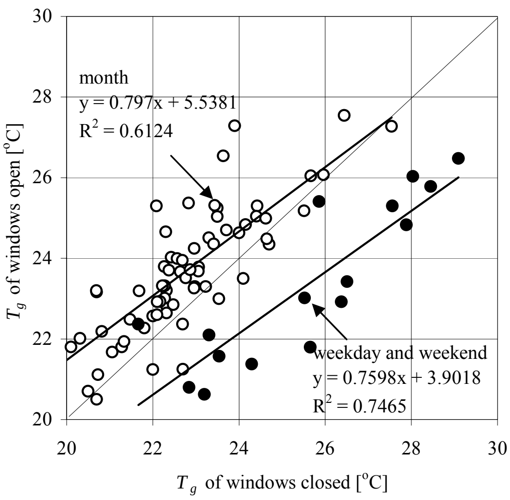

Figure 6 Comparison of T_g for the windows open and closed for each subject in weekday and weekend and month.

Window opening algorithm

In a previous paper we described the construction of a practical algorithm for incorporation into ESP-r (Rijal et al. 2007). Logistic multiple regression analysis was used to construct an equation to predict the probability of the window being open from a knowledge of the indoor and outdoor temperatures at the time. The operational form of this algorithm is shown in the Rijal et al. (2007).

We noted in that paper that there is necessarily a "deadband" of indoor temperature between the opening of a window to avoid overheating and its subsequent closure to avoid cold discomfort, should the room temperature fall. The logic of the use of windows to control personal thermal comfort is similar to that of the way people adjust their clothing insulation for comfort, and is described by Humphreys (1973).

The present data do not enable a direct visualisation of the width of this deadband, because of the binary nature of the data. To provide such a visualisation and thence to estimate the width of the deadband it is necessary to group the data into "bins" in which the window opening can be expressed as a proportion between zero and unity.

In order 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 proportion of windows open in the longitudinal survey is plotted as a scatter diagram against the indoor temperature at the time of voting (Figure 7). Each point shows the proportion of windows open at a particular room temperature. The logistic regression line, predicting the probability of a window being open against the room temperature, although giving an unbiased statistical prediction of the window opening, does not adequately represent the structure of the scatterplot, for the scatter of the points is far greater than can be attributed to the binomial error in the probabilities. This inadequacy is attributable to the dynamic of the window opening: a proportion of the windows are opened in response to a rising room temperature. Only if the room cools enough to cause discomfort need more windows again be closed. The proportion open will therefore remain much the same so long as the room temperature remains within the deadband. The envelope of the points therfore indicates the width of the temperature deadband.

This dynamic gives a horizontal structure to the data, so that the regression equation of the room temperature on the logit of the window opening becomes the more appropriate description of the data, rather than the logistic regression curve. This equation was calculated, and the regression gradient adjusted to make allowance for the binomial error in the predictor variable (the logits) arising from the sample size of only 25. (For a treatment of regression with measurement errors see Cheng and Van Ness 1999). The symbols of the equations and the values of the parameters are given in the Table 4, together with a note on the calculation of the adjustment, since the method is not commonly used and may be unfamiliar.

In Figure 7, 83% of the data points are within ±2 K of the central line and we have adopted this 4 K zone as the width of the deadband. (This is very close to ±1.5 standard deviations of the horizontal scatter of the points, a conventional estimate for range.) The decision to include some 80% of the points is a matter of judgment, and may need to be modified in the light of further experience.

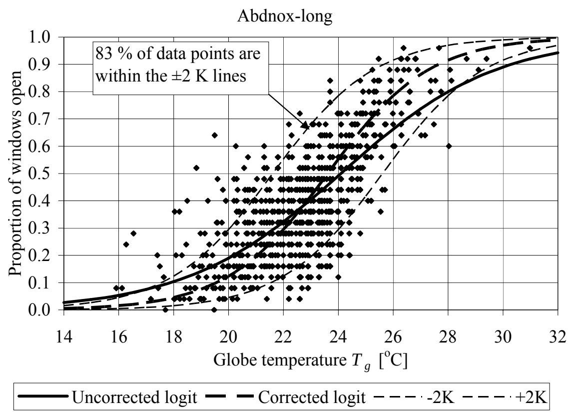

Figure 7 Logistic regression curve for windows open as a function of globe temperature in all NV buildings in longitudinal surveys, and the adjusted lines showing the margins of the deadband.

Table 4 Symbols and values of parameters used to calculate the adjusted regression equation, based on the records grouped in 25s

Parameter	Symbol	Value
Globe temperature	T_g	-
Logit of the windows open	logit	-
Regression coefficient of T_g on logit	b	1.432
Variance of logit	var(logit)	1.062
Covariance of T_g and logit	cov(T_g, logit)	1.521
Number of sample size	n	25
Proportion of windows open	p	0~1
Mean variance of logit error	var(logit error)	0.2378
Mean logit	logit_m	-0.5303
Mean globe temperature	T_{gm}	22.7
Residual of T_g	-	1.27048

Notes: Steps in obtaining the adjusted equation:
b=cov(T_g, logit)/var(logit) (1)
hence cov (T_g, logit)=b×var(logit) (2)
and var(logit error)= 1/{np(1−p)} (3)

Adjusted value of b:
b=cov(T_g, logit)/{var(logit) −var(logit error)} (4)
hence T_g=1.845logit+c (5)
so logit=0.542T_g+c (6)

The equation must pass through the group means of T_g and the logit, thus c=logit_m−0.542T_{gm} (7)

The centre line of the deadband:
logit=0.542T_g−12.8 (8)
the width of deadband is taken as ±1.5SD×Residual of T_g (9)
So the equations for deadband margins are:
logit=0.542(T_g±1.91) −12.8 (10)
but p=$e^{(\text{logit})}$/1+$e^{(\text{logit})}$ so the curves may now be drawn (11)

THERMAL SIMULATION

In this section we explore the application of the window opening algorithm to the thermal simulation of an office building using ESP-r, and see whether using the algorithm yields results compatible with the survey data.

Cooling effect of opening windows

The chosen baseline cellular office faces south and is constructed to represent a typical 1990's office with a 22.5 m^2 floor area within a thermally lightweight building (Rijal et al. 2007). The construction of the external wall, floor and ceiling is shown in the Figure 8.

To investigate the cooling effect of window opening, the thermal environment on weekdays and weekends is investigated using ESP-r. Climate data from Gatwick are used in the simulation because it is located in a similar climatic zone to Oxford. The outdoor temperature and solar gain are similar on the four investigated days (Figure 9). Running mean outdoor temperatures were calculated using 26 previous days of climate data, and the full simulations were run over a start up period of 6 days prior to the weekend period of interest. The time step of the simulation is 1 hour.

The heat gain from equipment is the same for weekdays and the weekends. The heat gain of from occupants and lighting is applied only in the weekday (Table 5).

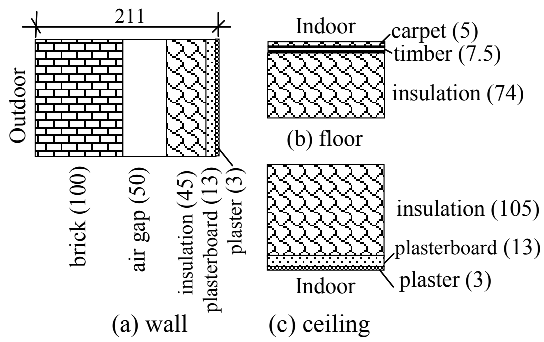

Figure 8 Construction of the wall, floor and ceiling. The thickness of the materials is shown in the millimeters.

Table 5 Schedule of the internal gains

Items	Internal gain of weekday/weekend [W]		
	0:00~9:00	9:00~17:00	17:00~24:00
occupant	0/0	90/0	0/0
light	0/0	90/0	0/0
low heat gain equipment	50/50	50/50	50/50
high heat gain equipment	150/150	150/150	150/150

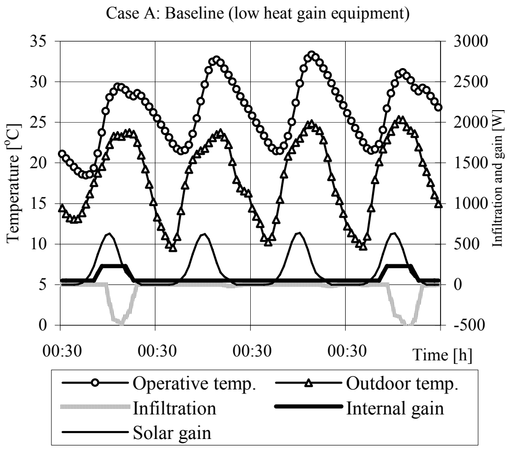

Figure 9 Temperatures and energy flows for weekday and weekend (July 19 Friday ~ July 22 Monday, 1991, Gatwick, UK). The lines represent the outdoor air temperature, the indoor operative temperature (with symbols) and the energy flows from the convective cooling by the incoming air, the heat gains from occupants, lights and equipment and the incoming direct solar heating absorbed in the indoor surfaces of the office.

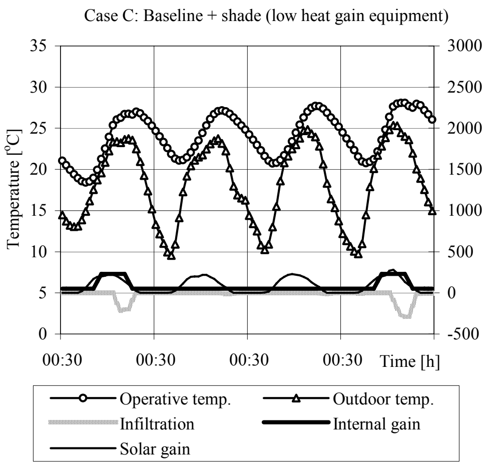

Figure 10 Temperatures and energy flows for the same period as for Figure 9 but with case C.

The cooling effects of window opening were simulated for four different building constructions: A) baseline, B) baseline + high thermal mass (plasterboard is replaced by 100 mm concrete ceiling), C) baseline + external shade (1.25 m projection from the wall) and D) baseline + high thermal mass + external shade. They were simulated with low (50 W) and high (150 W) heat-gain equipment. (Most of the investigated buildings in the surveys were similar to the cases A and B. But, a north facing office would be more like a shaded south facing office.) Glazing is of a standard double glazing type as used in the 1990s. The internal walls are plasterboard partitions.

Table 6 Operative temperature in the office hour (9:30 ~ 17:30) of weekday and weekend

Case	Operative temperature [°C]								Weekday−Weekend [K]			
	Weekday				Weekend							
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
A	21.2	31.2	28.1	2.7	23.3	33.3	29.7	3.4	-2.1	-2.1	-1.7	-0.7
A'	22.7	31.8	29.0	2.4	24.9	34.9	31.3	3.5	-2.2	-3.1	-2.3	-1.1
B	22.3	30.4	27.9	2.1	24.5	31.6	29.0	2.3	-2.2	-1.2	-1.2	-0.2
B'	23.7	31.2	28.7	1.9	25.9	33.1	30.5	2.3	-2.2	-1.9	-1.8	-0.4
C	20.0	28.1	25.3	2.5	21.7	27.7	25.1	2.0	-1.7	0.4	0.2	0.5
C'	21.5	28.8	26.3	2.2	23.3	29.3	26.6	2.0	-1.8	-0.5	-0.3	0.1
D	21.2	27.4	25.2	1.8	22.8	26.5	25.0	1.3	-1.6	0.9	0.2	0.5
D'	22.6	28.3	26.4	1.6	24.3	28.1	26.5	1.3	-1.6	0.1	-0.2	0.2

A, A': Baseline
B, B': Baseline + high thermal mass
C, C': Baseline + shade
D, D': Baseline + high thermal mass + shade
A ~ D: Low heat gain equipment (50 W)
A' ~ D': High heat gain equipment (150 W)

Table 7 24hr average heat flows due to solar / casual gains and infiltration losses for the same cases as in Table 6.

Case	Average gains / losses of 24 hour [W]								Weekday−Weekend [W]			
	Weekday				Weekend							
	Sol	Inf	Cas	Total	Sol	Inf	Cas	Total	Sol	Inf	Cas	Total
A	174	-117	110	167	174	-2	50	222	0	-115	60	-55
A'	174	-145	210	240	174	-3	150	321	0	-142	60	-82
B	174	-92	110	193	174	-2	50	222	0	-90	60	-29
B'	174	-125	209	258	174	-2	150	321	0	-123	59	-62
C	91	-45	110	156	88	-2	50	136	4	-43	60	20
C'	91	-70	210	232	88	-2	150	236	4	-67	60	-4
D	91	-32	110	169	88	-1	50	136	4	-31	60	33
D'	91	-54	210	247	88	-2	150	236	4	-52	60	11

Sol: Solar gain, Inf: Infiltration losses,
Cas: Occupant, lighting and equipment gain

The area of the windows is 3.9 m^2. The adaptive window opening algorithm is applied in the weekday office hours (9:00 ~ 17:00). Outside these hours, it is assumed that all the windows remain closed, and were closed all day at the weekend. Only trickle ventilation is allowed for when the window is closed.

For the unshaded office, the indoor temperatures are high, triggering window opening early and delivering up to 500 W of cooling energy (Figure 9 and Table 6). For the unshaded office the indoor temperatures are higher in the weekends because the loss of cooling energy is larger than the reduction in occupant and lighting gains. For the shaded office, the indoor temperature is generally cooler (Figure 10 and Table 6). When windows are opened there is less cooling energy because of the smaller indoor-outdoor temperature difference. The window opening also occurs much later and overall delivers less cooling energy. For the shaded office the effect at the weekend is that the reduction in heat gain from occupants and lighting is similar in magnitude to the loss of cooling energy because windows are shut, and they cancel out each other. Thus, the temperature of weekday is similar to the weekend in the shaded office. The difference between weekday and weekend operative temperatures can be explained partly by looking energy balance (Table 7). In general when there are higher average total gains (-losses) then indoor temperatures will tend to be higher.

The cooling effect of the open windows is higher in the lightweight building (case A) compared with the heavyweight building (case B). Having windows open is also effective in decreasing the indoor temperature when the internal gain is high. As we mentioned above, there may be also an air movement or fresh air advantage. For cases A, A', B and B', the minimum, maximum, mean and SD of operative temperature of the weekday is lower than at the weekend (Figure 9 and Table 6). The results show that having the windows open is not only useful for reducing the mean indoor temperature but also useful for reduce the minimum and maximum temperature in summer. The simulation results are well matched to the finding of the field investigation. It can be said from the simulation that the windows open is highly important for the cooling of NV buildings.

CONCLUSIONS

The window opening data from the field surveys showed the following principal features.

1) The mean T_g and T_{ao_i} when the window is open are higher than when the window is closed. This suggests that people are opening the window in response to increases in the indoor and outdoor temperature, and that this effect conceals the cooling effect of window opening on room temperature.

2) The lower (⩽10%) and upper (⩾90%) limit of the cumulative T_g and T_{ao_i} when windows are open is higher than for when they are closed. The temperature range over which windows are opened is very wide.

3) The measured T_g of the weekdays (windows open) is lower than for the weekends (windows closed). The results show that the window opening had a significant cooling effect.

The method of calculating the "deadband" for window opening is explained. (A similar method might be used in other data analysis situations, such as the use of fans).

The cooling effect of the window opening was verified by thermal simulation, using an adaptive algorithm for window opening behaviour derived from the field investigations. The simulation results are compatible with the field observations and show that window opening is effective for cooling, by controlling the internal and external heat gains in summer, and by increasing indoor air movement. An adaptive algorithm for window opening behaviour can be used in building simulation to help in designing buildings which achieve thermal comfort and energy saving.

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