DEVELOPMENT OF AN ADAPTIVE WINDOW OPENING ALGORITHM TO PREDICT THE THERMAL COMFORT, ENERGY USE AND OVERHEATING IN BUILDINGS

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ABSTRACT

This investigation of the window opening data from extensive field surveys in UK office buildings demonstrates: 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. It was found that when the window was open the mean indoor and outdoor temperatures were higher than when 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. The adaptive algorithm is shown to provide insights not available using non adaptive simulation methods and can assist in achieving more comfortable, lower energy buildings while avoiding overheating.

KEYWORDS

Adaptive thermal comfort, Building control, window opening algorithm.

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INTRODUCTION

Good building design is one of the important factors for energy saving; another is how occupants control windows to achieve comfortable indoor conditions. Although adaptive thermal comfort models are established (ASHRAE 2004, CIBSE 2006, CEN 2007), and relationships between indoor and outdoor conditions and the use of building controls have been described (e.g. Nicol 2001, Nicol and Humphreys 2004), there remains uncertainty in how to design naturally ventilated buildings that achieve comfortable thermal conditions. It is important to integrate into building design procedures occupant behaviour in relation to windows as they are the most common thermal control device. When people feel too warm or too cool they often open or close windows to alleviate their discomfort. This is not only potentially useful for energy saving in summer, reducing the need for mechanical cooling, but also provides a beneficial link with the outdoor environment. The basis of this occupant behaviour is not yet fully understood, and so behaviour protocols for which there is little empirical support have sometimes been employed (Rijal et al. 2007).

In the UK building regulations, domestic dwellings now require a summer overheating calculation to be carried out using a standard methodology (BRE 2005), while the guidance for non domestic dwellings for summer overheating has recently been revised with the issue of CIBSE TM37 2006. The guidelines on how to achieve compliance, set static thresholds and take no explicit account of outside daily or hourly temperature variations, or actual building ventilation paths and their interaction with the external climate. Other guidelines for building overheating performance do account for climate variations and permit dynamic simulation but specify fixed values for the number or percentage of occupied hours allowed above a specified temperature (CIBSE 2006).

Adaptive comfort temperatures are now a well established concept (Nicol and Humphreys 2007) in which indoor comfortable temperatures vary with the running mean outdoor temperature. The adaptive behaviour applies to free running naturally ventilated buildings where the occupants have opportunities for adapting by, for example, adjusting clothing, posture, windows, blinds or fans. Adaptive comfort temperatures are now included in CIBSE (2006) and ASHRAE (2004) guidelines and most recently the CEN standard EN15251 (Olesen 2007). To make studies of occupant adaptive comfort possible using dynamic simulation at the building design stage, adaptive temperature algorithms must be implemented into the program codes.

In an adaptive building, performance is dependent on how the building responds to internal and external variations in climate and on how and when the occupants respond to these variations (i.e. what adaptive actions they take and under what conditions they take them) and on how these actions alter the building's state. In order to model the performance of naturally ventilated buildings it is essential to be able to model the occupant behaviour. Among the most common adaptive actions in a naturally ventilated building is the adjustment of window position.

Historically many window opening models have been put forward 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. 2007). Fritsch et al. (1990) proposed a model based on Markow chains for random window opening prediction. Pfafferott and Herkel (2007) used Monte-Carlo simulations to predict user behaviour. Herkel et al. (2007) develop a window opening algorithm based on outdoor temperature and occupancy levels.

Rijal et al. (2007) evolved the Humphreys window opening algorithm based on adaptive comfort criteria in conjunction with indoor and outdoor temperatures and demonstrated its application within the ESP-r simulation program. The combination of the adaptive comfort temperature together with the modelling of comfort driven occupant adaptive behaviour was shown to be important in achieving accurate representation of comfort and energy performance in a naturally ventilated building. ESP-r was chosen as the simulation modelling 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 behavioural 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 modelling and coupling of behavioural algorithms such as Lightswitch 2002 across many ESP-r domains. Anecdotally, an additional driver of window opening is air freshness, which may also be modelled using ESP-r's embedded contaminant modelling and CFD capabilities.

Naturally ventilated or hybrid ventilated buildings are common. The quantification of the comfort and energy use performance of these buildings is however an area under development. The importance of good understanding and good practice in this area is being heightened by increasing outdoor temperatures and the increased focus on reductions in building energy use within a number of countries. It is important to understand and model correctly the behaviour of occupants in buildings and how this behaviour affects energy use and comfort. It is similarly important to understand how a building's design affects occupant comfort, occupant behaviour and, ultimately, the energy used in the operation of the building.

This paper reviews the implementation of the EN15251 adaptive comfort criteria and the Humphreys window opening behavioural algorithm in ESP-r and demonstrates their application to an analysis of summer overheating for an office in the UK. The effect of several building design options is then investigated and the use of the Humphreys adaptive model compared to the use of proportional window opening above a static threshold temperature for a number of building design options. Thus, the main objectives of this research are (Rijal et al. 2007a, Tuohy et al. 2007):

- To understand how people use windows to control the indoor environment.
- To use an algorithm for window opening behaviour, derived from field data, for some appropriate thermal simulations.
- To evaluate the cooling effect of window opening, by means of field investigations and thermal simulation.
- To analyze the impact on summer overheating of window opening behaviour for a variety of building design options.
- To compare the adaptive behavioural approach with non adaptive approaches.

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 buildings 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 occupants were asked to record in a brief questionnaire their thermal satisfaction and use of building controls. These responses were gathered 4 times daily (early morning, late morning, early afternoon and late afternoon). 35,764 sets of responses were collected from 219 people. 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, backed by a questionnaire. On each visit, one set of responses was recorded from each person. A total of 4,997 sets were collected from 890 people. Further 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).

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 cases 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^{o}C and 15.6^{o}C respectively. They are 1.2 K and 5.9 K 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 cases, 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.

Near Here: Figure 1 and Table 1.

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 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 indoor and outdoor temperatures.

Near Here: Figure 2 and Table 2.

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 person. Although the people 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.

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). As the value of the outdoor temperature can not be influenced by the action of opening the window, the window opening must be in responses to the higher temperatures. This suggests that the general result of opening the window was to limit any 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.

Near Here: Figure 3 and Table 3.

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 person. The number of 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 August, September and May-June, were chosen. In each period, the outdoor temperature profiles were similar and the heating was off. For the analysis 15 people were selected from 5 buildings in Oxford. The analysis is for office hours (9:00 to 17:00). It is assumed that all windows were closed during the weekend. During weekdays the proportion of windows open was always high in these periods, so the windows were taken to be open. The globe temperature was recorded at 15 or 30 minute intervals.

The internal heat gains (from occupancy, lights and 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 (Humphreys and Nicol 1995) in the globe temperature, and this amount 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 this amount is added to the globe temperatures at the weekend. This process gives an indication of what the indoor temperature would have been during 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 cases is small in a heavyweight building (9-VW in Figure 4). 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 windows during weekdays, the indoor temperature would have continued to rise. Thus, opening windows had a significant cooling effect. This can explain the previous finding that the comfort temperature with use of controls is higher than without use of controls (Brager et al. 2004 and Robinson and Haldi 2007).

A further illustration might be helpful. Figure 6 compares T_g for the windows open (Fridays and Mondays) and closed (Saturdays and Sundays) cases for each person. Each point represents one person for the selected days during that month. The temperatures for windows open and closed are highly correlated. Most of the temperatures for windows open are on the cooler side of the figure. This comparison of T_g for windows open and closed clearly shows the cooling potential of open windows.

Near Here: Figures 4, 5 & 6

Development of window opening algorithm

A previous paper 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 windows being opened from a knowledge of the indoor and outdoor temperatures at the time. This paper noted 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 hence 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 therefore 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, 84% of the data points are within ±2 K of the central line and so a 4 K zone was adopted as the width of the deadband. (This is close to ±1.5 standard deviations of the horizontal scatter of the points, a conventional estimate for the 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.

Near Here: Figure 7 and Table 4.

THERMAL SIMULATION

Implementation of window opening algorithm in ESP-r

A separate paper has described how the Humphreys algorithm (Appendix 1) for window opening was derived from analysis of extensive survey data (Rijal et al. 2007) and its implementation in the ESP-r dynamic simulation software. In this work a behavioural algorithm for window opening, developed from field survey data has been implemented in ESP-r. The algorithm is in alignment with the CEN standard for adaptive thermal comfort. The comfort temperature was calculated from exponentially weighted running mean outdoor temperature for a day (T_{rm}) (CIBSE 2006).

For $T_{rm}>10^{o}C$: $$T_{comf} = 0.33\ T_{rm} + 18.8 \quad (1)$$

For $T_{rm} \leq 10^{o}C$: $$T_{comf} = 0.09\ T_{rm} + 22.6 \quad (2)$$

Multiple logistic regression analysis of windows open on both indoor globe temperature T_g and outdoor air temperature T_{ao_i} gave rise to an equation for use to predicted window opening (Rijal et al. 2007):

$$\log(p/1-p)=0.171T_g+0.166T_{ao\ i}-6.4 \quad (3)$$

A comfort zone of ±2 K about the comfort temperature is used to represent the range of internal conditions under which the occupant is likely to be comfortable (Nicol and Humphreys 2007).

The office model

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 (Figure 8). The construction of the external wall, floor and ceiling is shown in Figure 9. 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 when the window is closed.

The heat gain from equipment is the same for weekdays and weekends. The heat gain from occupants and lighting is applied only during weekdays (Table 5). The office has south facing windows, occupant gains are set at 90 W during occupied hours, lighting gains at 90 W during occupied hours and equipment gains at a constant 50 W. The combination of solar, occupant and equipment gains gives a value of 36.6 W/m^2 using the TM37 calculation method (CIBSE TM37 2006). This is within the 30 to 40 W/m^2 range where natural ventilation is thought to be effective and just above the current UK building regulation threshold of 35 W/m^2 .

The cooling effects of window opening were simulated for four cases with 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 cases A and B.) Glazing is of a standard double glazing type as used in the 1990s. The internal walls are plasterboard partitions.

For simulation, Gatwick climate data were used to evaluate the cooling effect of opening windows while Dundee climate climate data were used for to evaluate summer overheating because these data are located in a similar climate zone to Oxford and Aberdeen. The outdoor temperatures and solar gains are similar over the four investigated days (Figure 10). 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 simulations is 1 hour.

Near Here: Figures 8, 9 and Table 5.

Cooling effect of opening windows

To investigate the cooling effect of window opening, the thermal environment on weekdays and weekends is predicted using ESP-r. For the unshaded office, the indoor temperatures are high, triggering window opening early and delivering up to 500 W of cooling power (Figure 10 and Table 6). For the unshaded office, the indoor temperatures are higher during weekends because the loss of cooling power is larger than the reduction in occupant and lighting gains. For the shaded office, the indoor temperature is generally cooler (Figure 11 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. 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 because windows are closed. Thus, the temperature during weekdays is similar to the weekend in the shaded office. The difference between weekday and weekend operative temperatures can be explained partly by looking at a simple 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 mentioned above, there may also be 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 10 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 window opening behaviour is highly important for the cooling of NV buildings.

Near Here: Figures 10, 11 and Table 6 & 7.

Summer overheating

The model was run through annual simulations with the Humphreys adaptive algorithm controlling the window opening. Detailed results of time, temperature and energy flows for a summer's day are shown in Figure 12. In this case the window is opened at noon when the operative temperature is close to 26^{o}C. The outdoor temperature peaks at 23^{o}C at 14:00 while the indoor operative temperature peaks at 27^{o}C around 16:00.

It is common in the study of the summer performance of naturally ventilated buildings to assume that windows will begin to be opened in the summer when the indoor operative temperature reaches some threshold and then opened proportionally until fully open when some higher threshold is reached. In this analysis, this approach is termed 'proportional' and is contrasted with the 'adaptive' approach of the Humphreys algorithm. This proportional opening behaviour is illustrated in Figure 13, which shows windows beginning to open at 20^{o}C and becoming fully open at 21^{o}C for the same baseline office. The windows are open earlier for this assumption than for the Humphreys algorithm (Figure 12). The thresholds chosen here are towards the low end but within the range commonly used to demonstrate the capability of a building in the UK to achieve an overheating specification.

Comparing the proportional approach to the adaptive behavioural algorithm over the summer period shows significant differences as illustrated in Figure 14 and Figure 15. The proportional approach gives lower peak temperatures and much lower temperature exceedances.

For this example, the proportional approach gives a more optimistic prediction than the Humphreys algorithm. The difference appears to be that in the proportional case the window opening occurs before a discomfort triggered window opening event occurs. The Humphreys algorithm, which is survey based and building and climate specific, is more likely to represent actual behaviour than an arbitrary threshold that, in the absence of established criteria, would be likely to be set at the most advantageous value.

Using the proportional approach in this way could lead to the assumption that the lightweight unshaded office performance would prove acceptable. However, the Humphreys algorithm identifies that the risk of overheating in the no shade or shaded office would be significant. Moving ahead with a design based on the proportional approach would result in a significant risk that occupants would experience discomfort leading to the need for remedial measures such as fans, air conditioning or glazing replacement.

The integration of the algorithm and the adaptive comfort criteria within the dynamic simulation tool allows comfort and behaviour in a given situation to be modelled as well as the effect of behaviour for any given situation. In this case the window opening behaviour is implemented within a dynamic thermal model. This means that occupant behaviour will influence ventilation in a dynamic manner allowing design modifications to be made in response to issues found.

Near Here: Figures 12, 13, 14 & 15

Further application of the algorithm

The algorithm was shown previously by the authors to give window opening results across all 4 seasons similar to those extracted from survey data (Rijal et al. 2007). The impact of the window open behaviour as represented by the algorithm on annual heating energy use was also shown to be more sensitive to changes in building parameters than a standard non adaptive approach. The building design and operational drivers of commonly observed behaviours (such as having windows open while the heating is on in winter season) can begin to be comprehended at an early stage in the design process . The algorithm generally suggests that more comfortable buildings tend to be more energy efficient (less heating energy waste in winter, lower risk of AC in summer).

It is suggested that an adaptive algorithm will better represent human control of windows and allow a more accurate assessment of human thermal comfort conditions and building performance, including summer overheating and annual energy use. The algorithm embedded in simulation software will assist in the design of more comfortable and energy efficient buildings. In order to illustrate the operation of the algorithm the data presented in this paper has been taken from the application of the algorithm in a single throw deterministic-like mode. In future applications to real building design, the algorithm should 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 energy use and occupant comfort. The approach is intended to be extended and integrated with adaptive behaviours such as lighting and shading use, heating and cooling controls adjustment, use of fans and doors etc.

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 wide.

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

The method of calculating the 'deadband' for window opening is explained. A similar method can be used in other data analysis situations, such as the use of fans (Rijal et al. 2007b, Nicol et al. 2007).

The cooling effect of the window opening was verified by thermal simulation, using an adaptive algorithm for window opening behaviour derived from field investigations. The simulation results are compatible with 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. Thus, window opening is useful to mitigate summer overheating. An adaptive algorithm for window opening behaviour can be used in building simulation to help design buildings that achieve thermal comfort and energy saving.

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

Temp. [^oC]	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

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

Temp. [^oC]	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

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

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	1.33
Variance of logit	var(logit)	1.062
Covariance of T_g and logit	cov(T_g, logit)	1.412
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	-	1.36836

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=1.713logit+c (5)

so logit=0.584T_g+c (6)

The equation must pass through the group means of T_g and the logit, thus c=logit$_m$−0.584T_{gm} (7)

The centre line of the deadband:

logit=0.584T_g−13.8 (8)

the width of deadband is taken as ±1.5SD×Residual of T_g (9)

So the equations for deadband margins are:

logit=0.584(T_g±2.1) −13.8 (10)

but p=e$^{(\text{logit})}$/{1+e$^{(\text{logit})}$} so the curves may now be drawn (11)

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

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

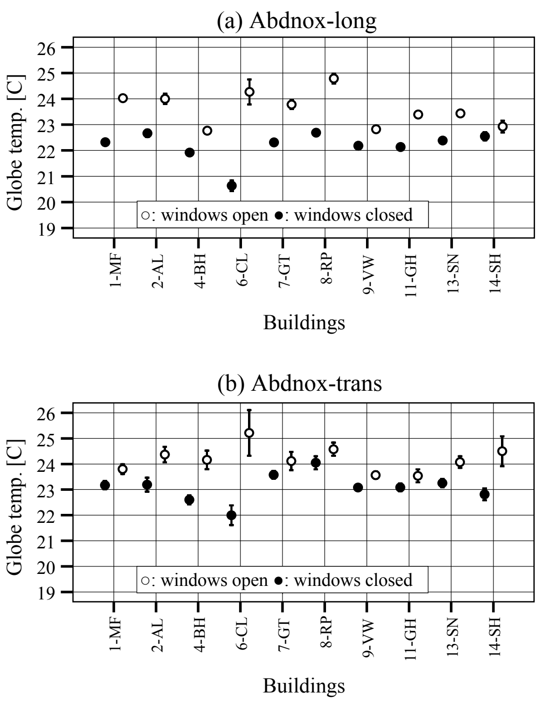
Case	Operative temperature [°C]								Weekday−Weekend [K]			
	Weekday				Weekend							
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
A	21.2	31.2	28.1	2.7	23.3	33.3	29.7	3.4	-2.1	-2.1	-1.7	-0.7
A’	22.7	31.8	29.0	2.4	24.9	34.9	31.3	3.5	-2.2	-3.1	-2.3	-1.1
B	22.3	30.4	27.9	2.1	24.5	31.6	29.0	2.3	-2.2	-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



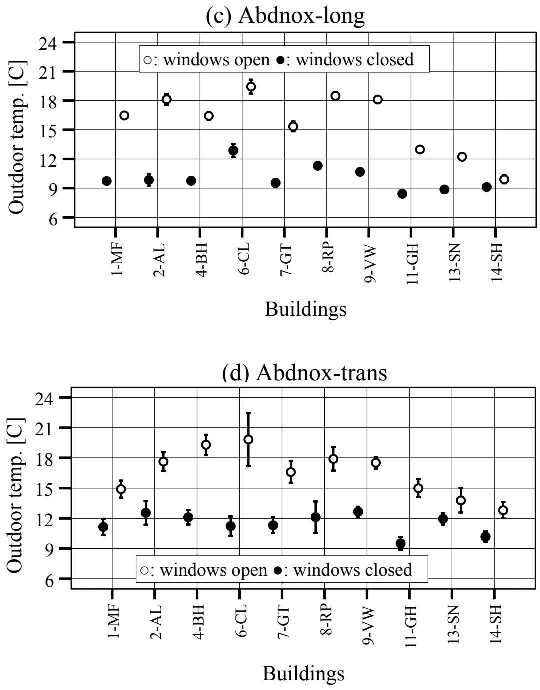


Figure 1 Comparison of mean globe temperature and outdoor air temperature with 95% confidence intervals for windows open (open symbols) and closed in longitudinal and transverse surveys.

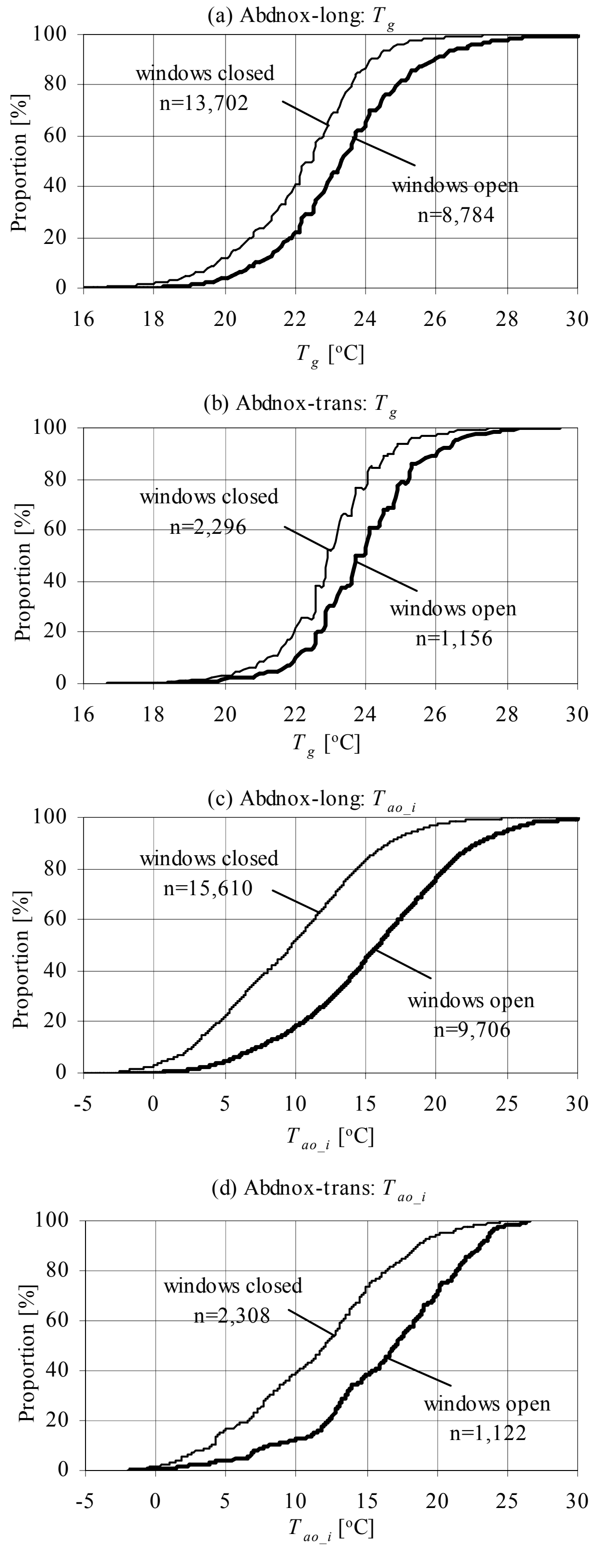


Figure 2 Cumulative distributions of globe temperature and outdoor air temperature for NV buildings when windows are open and closed.

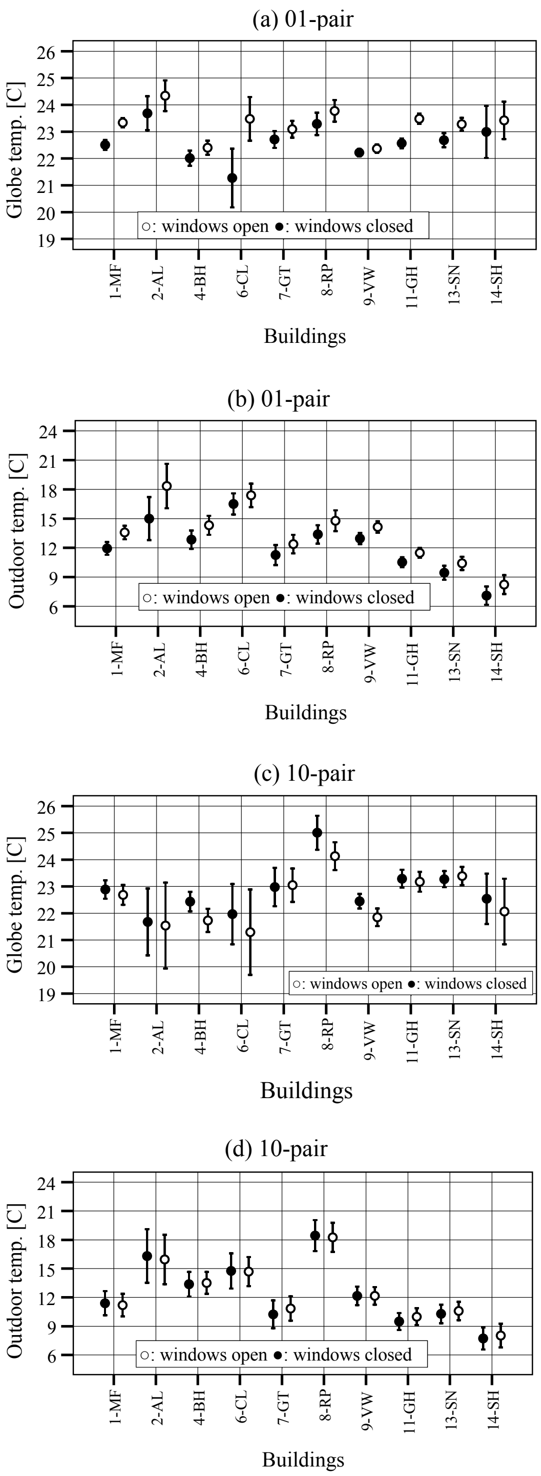


Figure 3 Comparison of mean globe temperature and outdoor air temperature with 95% confidence intervals for windows open (open symbols) and closed at adjacent times in the longitudinal survey.

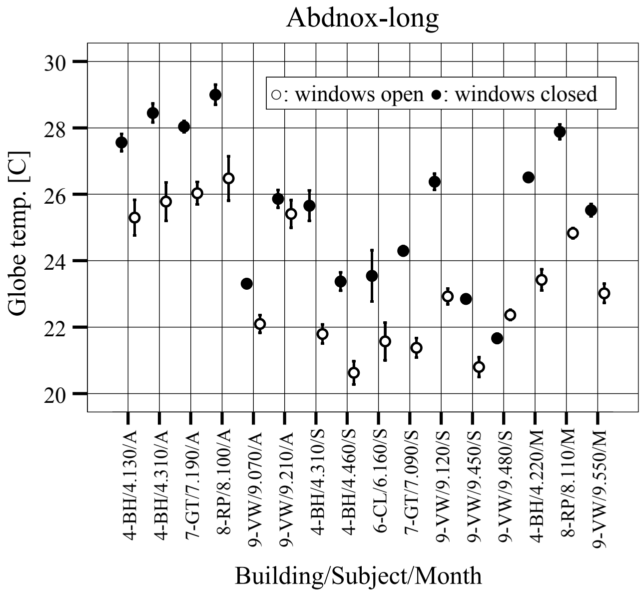


Figure 4 Comparison of mean globe temperatures with 95% confidence intervals *in the buildings when windows are open (weekdays: open symbols) and closed (weekends) in longitudinal survey, after adjustment for air movement and heat gains. A: Aug. (16th to 19th, 1996), S: Sept. (13th to 16th, 1996) M: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

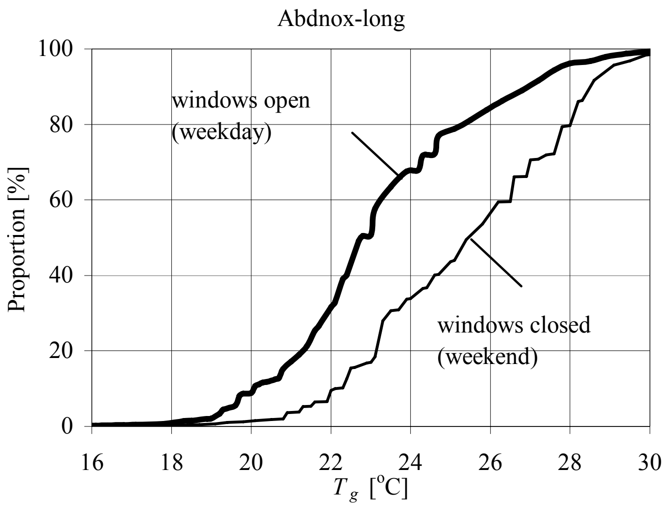


Figure 5 Cumulative distribution of the globe temperature during weekdays (windows open) and weekends (windows closed) in longitudinal survey, after adjustment for air movement and heat gains.

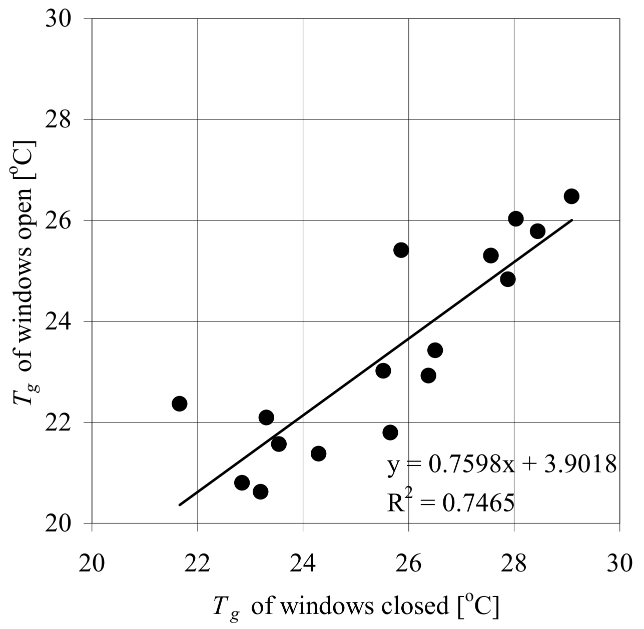


Figure 6 Comparison of T_g for the windows open and closed for each person in weekday and weekend.

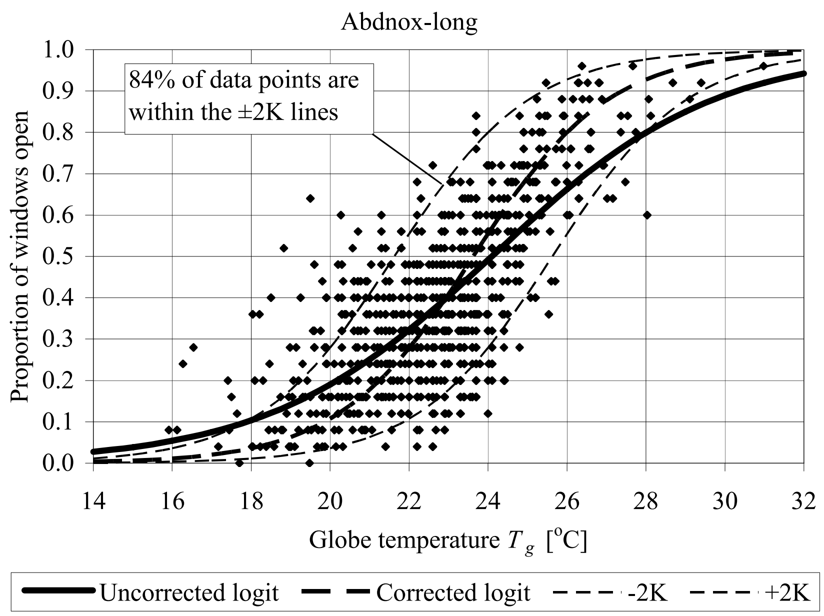


Figure 7 Logistic regression curve for windows open as a function of globe temperature in all NV buildings in longitudinal surveys, and the adjusted lines showing the margins of the deadband.

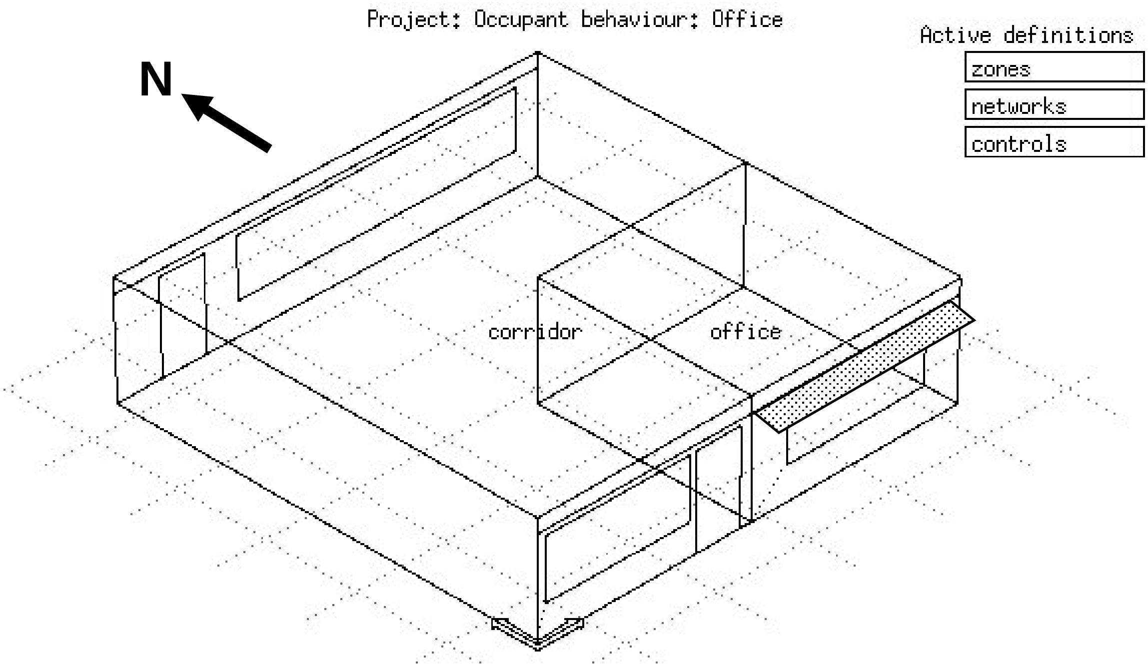


Figure 8 Representation of the cellular office (labelled 'office') located within the larger open plan office area (labelled 'corridor'). The office window faces south (Note that the cellular office showing the external shade above the office window for case C).

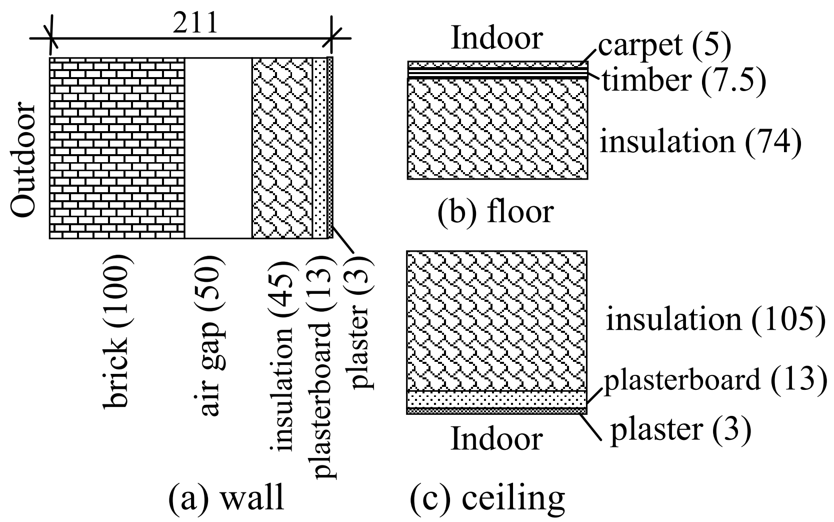


Figure 9 Construction of the wall, floor and ceiling for baseline case (A). The thickness of the materials is shown in the millimeters.

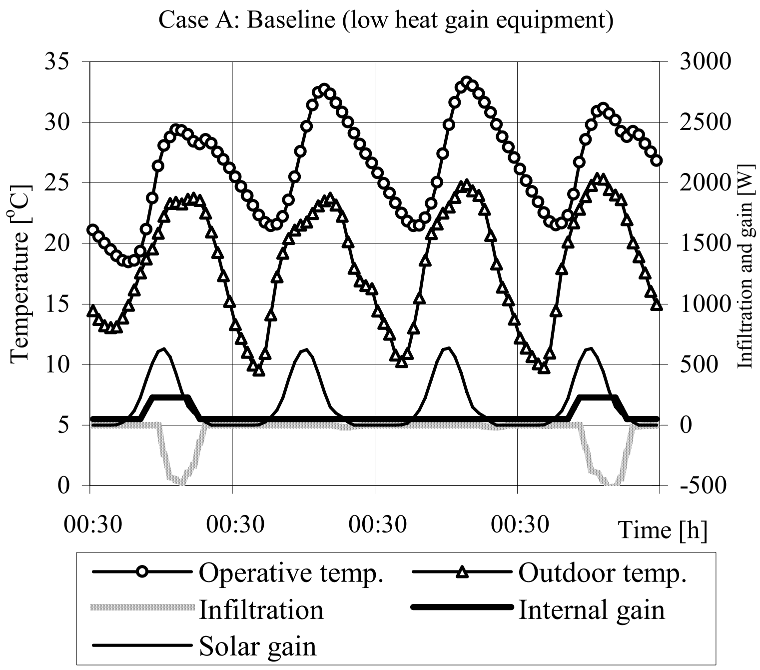


Figure 10 Temperatures and energy flows for weekday and weekend (July 19 Friday ~ July 22 Monday, 1991, Gatwick, UK). The lines represent the outdoor air temperature, the indoor operative temperature (with symbols) and the energy flows from the convective cooling by the incoming air, the heat gains from occupants, lights and equipment and the incoming direct solar heating absorbed in the indoor surfaces of the office.

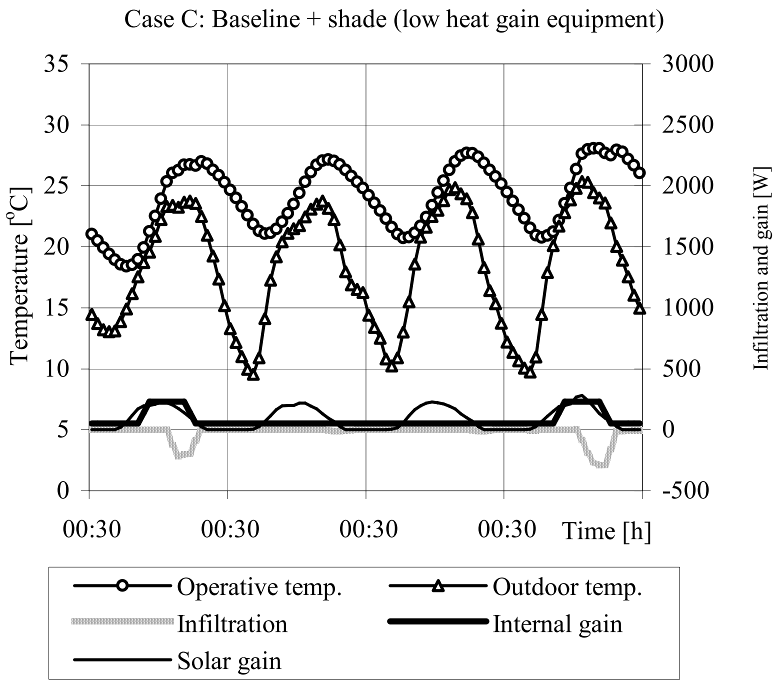


Figure 11 Temperatures and energy flows for the same period as for Figure 10 but with case C (with external shade).

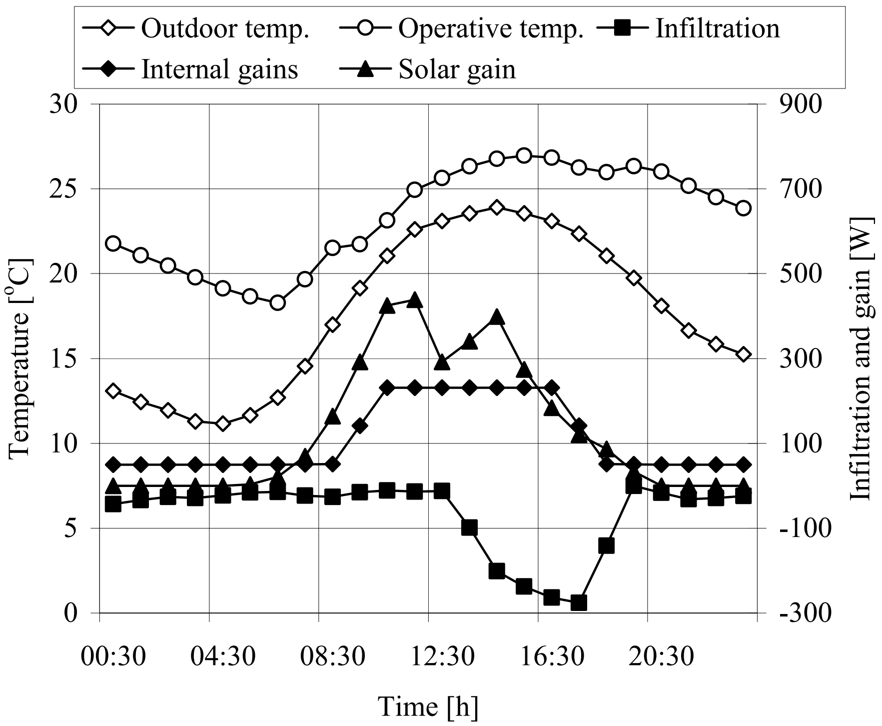


Figure 12 Temperature, heat gains and ventilation losses for a summer day modeled using the Humphreys algorithm (Case A).

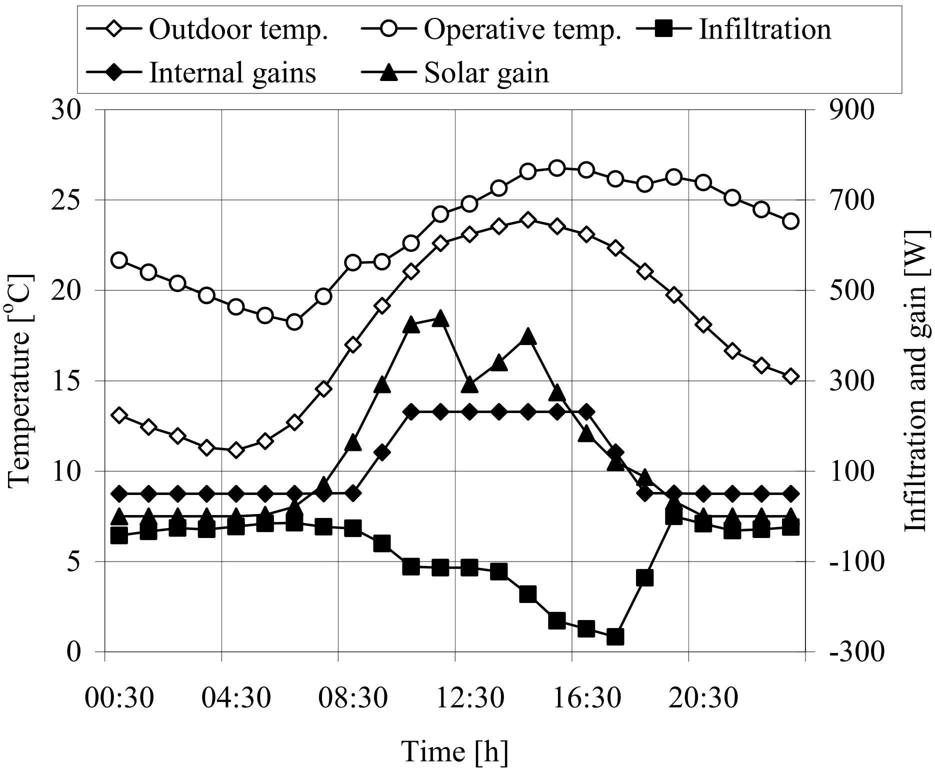


Figure 13 Temperatures, gains and losses for a summer day with window opening behavior modeled using a temperature threshold with proportional opening (Case A).

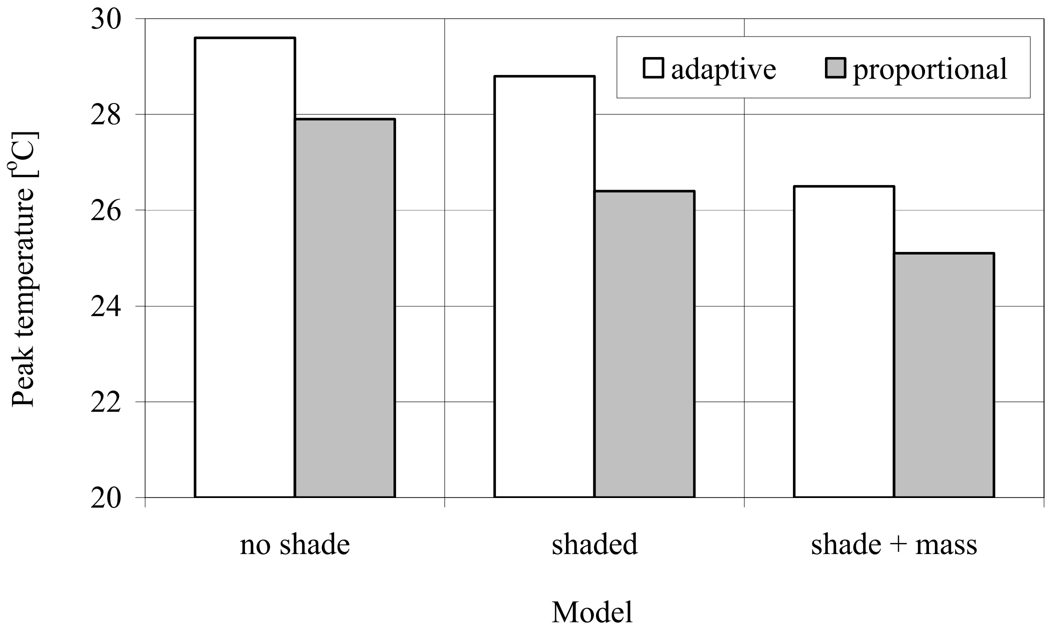


Figure 14 Peak operative temperatures for the summer season modeled using the Humphreys algorithm (adaptive) and the threshold method (proportional) (no shade=baseline (Case A)).

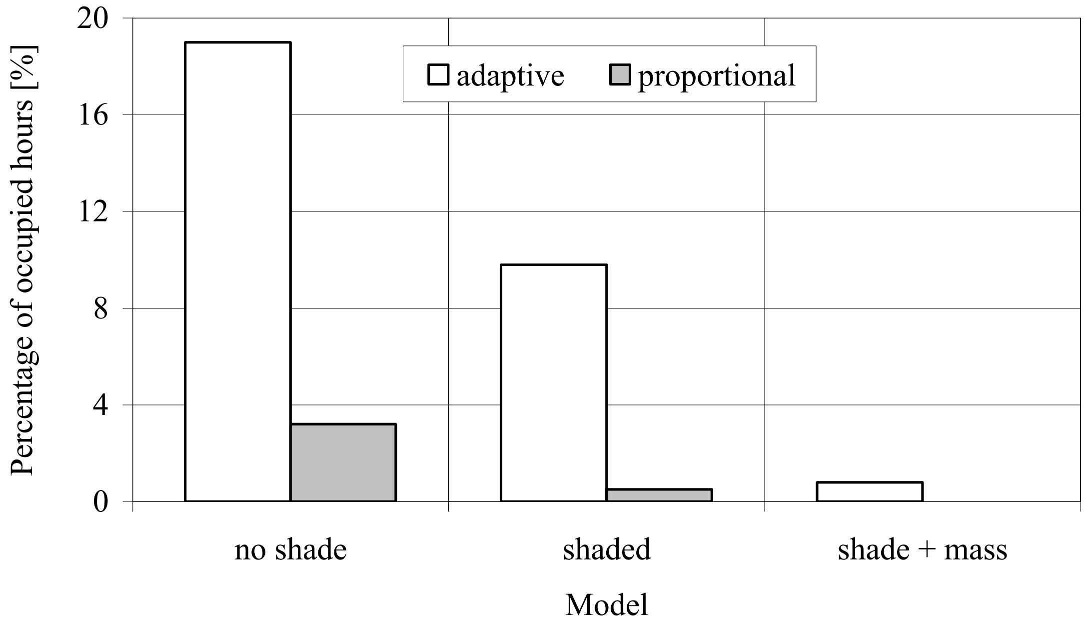


Figure 15 Percentage of occupied hours with operative temperatures over 26^{o}C for adaptive and the threshold (proportional) window open algorithms (no shade=baseline (Case A)).

Appendix 1 Steps in the implementation of the 'Humphreys' adaptive window open algorithm in ESP-r (Rijal et al. 2007).

No.	Window algorithm parameter	Symbol	Sample	Derivation or source
1	Outdoor air temp.	T_{out}	1/h	Interpolated from climate file (hourly data in file)
2	Daily mean outdoor air temp.	T_{odm}	1/day	Calculated from 24 hourly data points per day
3	Running mean outdoor air temp. (CEN)	T_{rm}	1/day	T_{rm}(init) = $(1-\alpha)\{T_{odm-1} + \alpha T_{odm-2} + \alpha^2 T_{odm-3}\ldots\}$ Initial value calculated from previous 20 days daily mean then $T_{rm} = (1-\alpha)T_{odm-1} + \alpha T_{rm-1}$
4	Running mean response to T_{out}	α	Const	Default α = 0.8 (0.01 to 0.99 allowed range)
5	Comfort temp.	T_{comf}	1/day	If $T_{rm}>10$, $T_{comf} = 0.33T_{rm} + 18.8$ (CEN standard) If $T_{rm}\leq 10$, $T_{comf} = 0.09T_{rm} + 22.6$
6	Indoor air temp.	T_{ai}	1/h	Available at each timestep (variable)
7	Indoor operative temp.	T_{op}	1/h	Available at each timestep (50% mrt, 50% T_{ai})
8	Comfort	Comf	1/h	Comf = 'yes' if abs $(T_{op}-T_{comf})\leq 2$K Comf = 'hot' if $(T_{op}-T_{comf})>2$K Comf = 'cold' if $(T_{op}-T_{comf})<-2$K
9	Logit function	Func	1/h	Func = Logit(Pw) = $0.171T_{op} + 0.166T_{out} - 6.43$
10	Probability function for window open	Pw	1/h	Pw = $\exp^{(Func)}/\{1+\exp^{(Func)}\}$
11	Random number between 0 and 1	Rn	1/h	Generated from fortran RNG

12	Window status (0=closed, 1=open)	iwin	1/h	If Comf = 'hot' and window closed (w = 0) then
				if $Pw>Rn$ then window open (w = 1)
				If Comf = 'cold' and window open (w = 1) then
				if $Rn>Pw$ then window closed (w = 0)