Building and Environment 50 (2012) 125–134

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Factors influencing the occupants' window opening behaviour in a naturally ventilated office building

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ARTICLE INFO

Article history:
Received 4 July 2011
Received in revised form
12 October 2011
Accepted 15 October 2011

Keywords:
Window
Occupant control
Temperature
Naturally ventilated building

ABSTRACT

Window opening behaviour has become of a specific concern when it comes to the adaptive comfort analysis and evaluation. A field study of occupants' window opening behaviour was carried out from Jan/05 to Apr/06 in a naturally ventilated office building in Sheffield's, UK climate conditions. Window positions were recorded daily on academic semester weekdays. A total of 1620 windows' positions in 329 days (16 months) were recorded. Outdoor and indoor physical parameters such as air temperature, relative humidity, wind speed etc. were collected at the same time. The results show that manual window control, as indicated by the proportion of windows opened, has a strong correlation with: outdoor air temperature, the season of year, time of a day and occupancy pattern. Window orientation is also considered as a relevant influencing factor. Moreover, the study tests a stochastic model to predict the probability of windows being open given the outdoor temperature with promising results. Also insights are reported about behaviour in non-office spaces in the building as a whole.

1. Introduction

With respect to the level of thermal comfort inside buildings, one of the main topics being discussed is the issue of 'adaptive comfort', which is a dynamic rather than a static situation [1]. Nicol and Humphreys [2] argue that people are not inert recipients of the environment, but interact with it in order to optimise their own conditions and use various means at their disposal to improve their comfort. They [3] also indicate that people with more opportunities to adapt themselves to the environment or the environment to their own requirements will be less likely to suffer discomfort. Recently, much work in this area has been devoted to establishing a series of reliable comfort indices for the desired indoor environment. This type of research involves observing the daily routines, practices and habits of building occupants in order to see how they modify and adjust windows, shading coverings, electrical lights, heater and fans etc. to achieve satisfactory built environments [4–7].

1.1. The literature on window opening behaviour

Among all the studies that reveal when and how people adopt environmental control strategies and identifies the influential variables, window opening behaviour has become of specific concern to a number of researchers. This is mainly because of the importance that windows play in the indoor environment and occupant comfort. The window performs a quite complicated multi-purpose function. A sensible and acceptable balance has to be achieved between many variables, such as heat input, natural light penetration, sound transmission and air movement, which mean people need to take an active role in the operation of windows and almost immediately experience the results of their actions. A selection of studies of window opening behaviour is summarised below.

Haldi and Robinson [8] investigate the influence of occupancy patterns, indoor temperature and outdoor climate parameters on window opening and closing behaviour. Fourteen south-facing cellular offices were involved for a period covering seven years. They develop and compare three different modelling methods for the prediction of actions on windows. Possible combinations in these approaches are tested and a hybrid model is selected for dynamic building stimulation purpose.

Yun and Steemers [9] conduct a field survey on window opening control by occupants in six offices at two buildings during the Summer. The monitoring data provide evidence that there is a statistically significant relationship between window opening behaviour patterns and indoor air temperature. Once a window state has been set up on an occupant's arrival it mainly stays the same until their departure. They also develop a time-dependent

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doi:10.1016/j.buildenv.2011.10.018

window opening behaviour model for building simulations, taking indoor temperature, time of day and the previous window state into consideration.

Herkel et al. [10] produce a field study of the manual control of windows which was carried out in twenty-one individual office rooms in Germany over a period of one year. They conclude that user behaviour reveals a strong correlation between the percentage of opened windows and the time of year, outdoor temperature and building occupancy patterns. Based on the results, a preliminary user model is proposed to simulate and predict window status in office buildings with varying outdoor temperatures and occupancy.

Rijal et al. [11] formulate a method for simulation of office buildings to include the effects of window opening behaviour on comfort and energy use based on field survey data collected over one-and-a-half years. Their findings confirm that the proportion of windows opened depends on indoor and outdoor conditions. They also quantify the likelihood that a window is open with the indoor and outdoor air temperature.

Fritsch et al. [12] report a study of four office rooms over a complete heating season. They reveal that the outside temperature acts as a driving variable for window opening or closing. However, the strong relationship found between the window angle and the outdoor temperature in Winter is not evident during the Summer. They also develop a model, using Markov chains to predict window operation but it is only valid for the Winter period.

Dubrul [13] works on inhabitant behaviour with respect to ventilation. He assesses the extent to which the actions of occupants can be modified in order to minimise energy use, yet maintain adequate indoor air quality. There is a multitude of factors influencing window opening and he structures them into five categories: dwelling fabric factors, life style, control strategies, socio–economic variables and weather factors. A strong correlation value is found between the percent of opened window and outside air temperature, while the wind speed is weakly related.

Warren and Perkins [14] provide a study in five naturally ventilated office buildings in the UK over a period of 3 months during the heating season. They find that window opening is strongly related to outdoor temperature, followed by solar gain and wind speed. Slight opening of windows is to satisfy indoor air quality requirements whereas wide opening of windows strongly corresponds to temperature. In addition, the glazed area, orientation, the type of heating system and its control all affect window control. They also reveal that once the window is opened, it is rarely closed until the room is finally vacated.

In addition to these individual studies, there have recently been two review papers concerning models of occupant control of windows. Borgeson and Brager [15] provide a summary of the origin, implementation, and applicability of the variety of models predicting occupant window control now emerging in the academic literature. Prays et al. [16] also review modular behavioural model for office buildings, including occupant's control of windows. They find that the model of Haldo and Robinson [8] stands out among several other behaviour models, because it is based on the largest dataset and the broadest measuring campaign.

1.2. Summary and focus for this study

The above studies are currently the most closely related to the present study. What they show is that various personal and environmental factors influencing the occupants' window control behaviour (open and close). From the literature, it can be anticipated that:

- Studies on manual window control will necessarily involve observing the daily routines, practices and habits of building rooms and the occupants who live (study, work) in them.
- Outdoor weather and indoor climate are likely to be important as factors influencing window opening behaviour. The impact of seasonal effects and time of day should also be taken into consideration.
- Window opening behaviour can be treated as a stochastic process where the probability is based on factors, such as weather conditions, indoor temperature, time of the day and occupancy features, etc. However, no clear consensus exists as to which factors should be used as input variables.
- An important application of window opening behaviour study is to formulate methods in the area of adaptive comfort research; the results can also be integrated into dynamic building simulations, using statistical algorithms that predict the probability of opening a window, given certain environmental conditions.

These studies also reveal missing dimensions in the research to date. Although the target of many studies is office buildings, they do not treat the 'building' as a whole but focus on just one, or several, individual office room(s) facing a particular orientation with one or two occupiers, so representing only one group of environmental and occupancy features.

Orientation can affect solar heat, daylight, air movement, especially in a naturally ventilated building. Thus, occupants may have very different thermal experiences, even when they are in the same building, which will potentially result in different control behaviour. Furthermore, many of the field surveys cover only a short period, e.g. a few months of a (non)heating season. Time of year variations in behaviour is often not taken into account.

In addition, offices themselves only represent one occupancy feature: users who stay continuously for long periods, with fixed seating with low density space use. However, there are large areas in the office building representing different occupancy patterns, such as meeting/social and service spaces. These have been excluded from the above studies, but in reality, they should not be separated and ignored as these areas are part of the building as well.

This study is therefore focused on building on the previous studies and making a contribution to the identified gaps. The aim is to review and investigate which driving factors influence the occupants' window opening behaviour, as reflected by the proportion of windows opened. In particular correlations will be investigated with:

(1) outdoor weather stimulus, such as temperature, wind speed, rainfall etc.
(2) seasonal change
(3) outdoor temperature with one additional variable taken into consideration: window orientation
(4) indoor temperature
(5) time of day
(6) occupancy pattern

These research questions are investigated and verified by daily observations of a naturally ventilated office building (rather than just a number of office rooms) in Sheffield, UK over 16 months. The study firstly reviews and extends the results from previous concerned studies. Then based on the results, a stochastic model is tested for its potential to predict the probability of windows being opened. The assumptions, which underlie this approach, are (1) the window (open/closed) position will be changed in response to the occupants' discomfort condition [11,18]; and (2) the window is usually left in one position for a long period time until the discomfort happens again [9,14]. The study's result on a survey of occupants' satisfaction in this building has been presented in another paper [17].

2. Method of study

2.1. Climate and weather during the data collection

The investigated building is located at Sheffield, which is a major city of the north of England, UK. The climate of the UK has generally warm summers, cool winters and plentiful precipitation, rather than seasonal extremes of hot and cold. Generally, Sheffield has mild to cool winters and warm to very warm summers with moderate variation in air temperature throughout the year.

During the survey time from Jan/05 to Apr/06, the average monthly temperature was 9.2 °C. Feb/05 was recorded as the lowest (3.9 °C) while Jul/05 was the highest average temperature (17.0 °C) and a mini heat wave from the 9th lasting for 5 days. The relative humidity was always high with a similar pattern and value, monthly changing in the range from 70 to 88%. The wind speed and direction were displayed with a high degree of reliability. 50% of time the wind speed was within 4 m/s from the southwest. But winds with higher wind speeds mainly came from the west. The monthly value of rainfall was 59.7 mm from 18.7 mm in Jan/06–113.1 mm in Oct/05.

2.2. Building description

The investigated building is a freestanding high-rise office with 78 m height. Each floor from 1st to 19th has a similar plan pattern of which can be divided into three layers. The centre part is the core with lifts, staircases and toilets. The transition part is a 1500 mm-width corridor connecting the centre core and each room on the floor. The offices are located around the perimeter of the building, along with other purpose rooms, such as seminars, meetings and store etc. These rooms (from 1st to 18th floor) are centrally heated by perimeter convective heaters, mounted at floor level on exterior walls under each window and naturally ventilated by means of vertically sliding upper sash windows at each bay between the columns. All users in this building are asked to make sure every window is closed if they are the last one who leave a room, anytime.

All investigated windows have a same height (2450 mm) and shape (rectangular). Windows towards south/north are 50 mm wider than those towards the east/west (920 mm). With the exception of the sealed windows at each corner, the size of opening aperture is variable, allowing for a maximum 500 mm opening. In addition, because of the high-rise feature, natural ventilation not only can come from the prevailing wind pressure from the outside, but also the stack effect from lift shafts and service ducts from the inside. Only the passive zones from the 1st to the 18th floors are considered in this study. The building contains all kinds of function rooms due to its huge mass. Roughly, there are four types of rooms in terms of their occupancy features following the time budget of their established pattern. Fig. 1 shows the breakdown of total areas between these four kinds of rooms. Total number of investigated windows is also presented in round brackets.

- Offices for academic staff, clerk, technician and research student etc;
- Communication areas such as seminar rooms, lecture theatres for teaching, training and/or meeting;

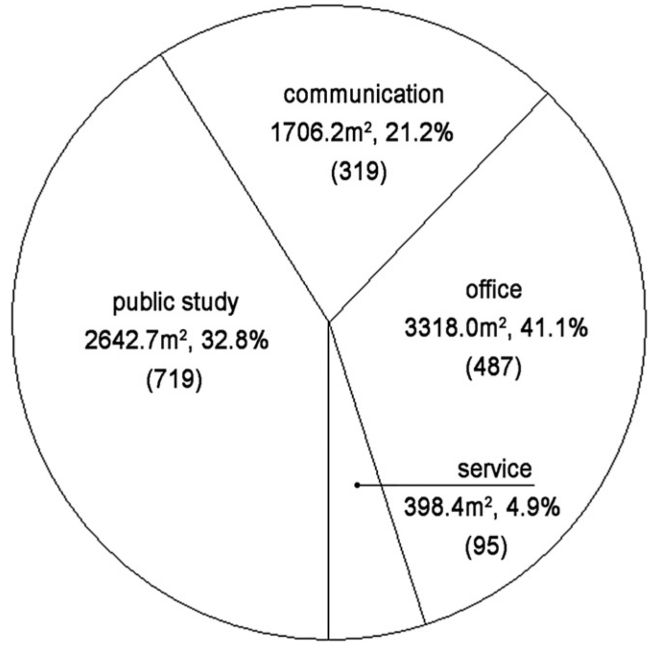

Fig. 1. Breakdown of different occupation rooms.

- Public study areas such as pc labs, libraries, studios and workspaces;
- Other service rooms for resting, assembling, copying and printing, and storage etc.

All rooms (333 total numbers of rooms) under investigation were assigned with a unique identification number. The basic information about each room, like the floor, room number, function, size and so on, were also recorded and associated with the identification number. Similarly, all the windows were assigned a unique identification number from 1 to 1764. These windows were also assigned to the rooms as well.

2.3. Data acquisition

The previous works provides a solid basis for what this study proposing to examine and how the research methodology can be refined. They use different methods to record the window positions and measure climates inside and outside the building. The works of Rijal et al. [11] and Warren and Parkins [14] are good examples of how a field survey can be conducted. In this study, the survey was carried out over a period of 16 months. Each façade of the building was photographed from the beginning of Jan/05 to the end of Apr/06, twice per day (morning and afternoon) on academic semester weekdays (sometimes once if an interruption happened caused by building maintenance etc.). At the same time, hourly weather conditions, such as temperature, RH, wind direction/speed and rainfall etc. were collected from a local weather station located 250 m west of the investigated building.

The surveyor also visited the building to specify the purpose of rooms and how many occupants were in them. Those who have a fixed working space (room) were reached as a potential respondent one by one by the surveyor with measurement instruments and questionnaires distributed to each of them. Totally 235 respondents were collected. The questionnaires included their response to the thermal environment at the survey moment, overall evaluation of the working place and their normal (un)occupied period. When they filled in the questionnaire, major physical parameters of indoor environmental information were measured, such as temp and RH. The respondent's personal information such as age, gender, clothing and basic information about the room they stay in were also recorded (188 were regarded valid). After that, a short interview was carried out with the aim of identifying complex feelings and beliefs of their working environment. This questionnaire lasted 5 months from Dec/05 to Apr/06.

After the cessation of the information collection period, the editing of data gathered was conducted and methods of statistical analysis were followed. A total of 1620 windows' position in 329 days (16 months) was obtained. The position information of all windows was recorded through the photos that have been taken. The resulting a clear contrast between transparencies and glazed part in each window, when slid down enabled those windows that were open to be identified. Four situations are considered: 'open', 'closed', 'fixed' and 'n/a' due to varied reasons that cannot be identified clearly (e.g. glare). The 'fixed' and 'n/a' records were omitted because these are beyond the scope of this study. It has to be mentioned the recording of window position did not follow exactly same procedure as some previous studies [10,12,14] (big and small windows, slightly and completely open) because of two reasons. One is that all investigated windows have a similar size with same way for manual control. The other reason is that, all manual control can be looked as 'slightly open'. None of windows were ever completely opened by occupants, at least during the field survey period, as it could easily cause strong draught and noise due to the building's high-rise nature.

3. Results and analysis

The results from the observation are set out below. The analysis is consistent with an order of research questions, which are raised in the 'Introduction' (1.2) to this paper.

3.1. Correlation of outdoor weather stimulus and proportion of windows opened

Statistically, correlation indicates the strength and direction of a linear relationship between two or more random variables or observed data value. According to previous studies, it is widely applied to validate and analyse the relationship between the window opening behaviour and influencing variables that affect occupant control. In this study, it is also used to reveal whether the outdoor weather conditions influence occupants' window opening behaviour, which is reflected by the proportion of windows opened. Some basic values, such as descriptive statistics and correlation as defined by Pearson are given in Table 1.

It can be seen that the outdoor air temperature has the strongest correlation (0.724) with the proportion of windows opened: more windows are likely to be opened when the outdoor temperature is higher, which is consistent with many previous studies [2,6,8,10–12]. The correlation with sunshine hours, solar radiation is similar, but less strong to that with outdoor temperature (0.543 and 0.344). Relative humidity (RH) and wind speed, in this case were also found significant linked, negatively: the higher the RH and/or wind speed, less windows are likely to be opened. This may be explained by the fact that to open the windows under high RH or wind speed may result in uncomfortable humidity and drafts for occupants in the room. All the weather stimuli mentioned above carry statistically high significance ($p < 0.01$). The correlation with rainfall, however, is not statistically significant and its R^2 value is small (0.025), when compared with other outdoor weather variables.

Table 1
Correlation between the proportion of windows opened and outdoor weather conditions.

Outdoor weather condition	Descriptive statistics		Correlation with the proportion of windows opened		
	Mean	Std. deviation	Pearson correlation	Sig. (2-tailed)	Covariance
Air temperature (°C)	10.667	5.524	0.724[a]	0.000	18.739
Wind speed (m/s)	7.502	2.984	−0.280[a]	0.000	−3.906
Rainfall (mm)	0.654	2.152	−0.025	0.589	−0.252
Sunshine hours (h)	1.726	1.778	0.386[a]	0.000	3.214
Solar radiation (W/m^2)	141.456	114.504	0.549[a]	0.000	1059.107
Relative humidity (%)	70.511	12.561	−0.401[a]	0.000	−23.609

[a] Correlation is significant at the 0.01 level (2-tailed).

3.2. Seasonal effects

Fig. 2 presents a distinct link between total number of opened windows and the outdoor temperature from Jan/05 to Apr/06. Usually the windows are in the 'closed' position no matter what the season is, only when required are they intermittently opened by occupants. On average, around 100 windows were opened monthly, accounting for 6.2% of total operable windows (1620). Although this represents a small figure for the whole building, the daily variation responds to the changing weather and follows a noticeable and consistent pattern. The peaks in the total of opened windows are strictly related to those of the outside temperatures. The daily drop or hike corresponds to every shift in temperature. In Winter, when the outdoor temperature is low, there is a low proportion of windows opened, which is reasonable as it is suggested that the indoor temperature can be maintained at a comfortable level using the central heating system without introducing cold air from the outside. The total windows opened reaches its highest during the Summer. Also the figure shows the two variations happening simultaneously with almost no time lag, which demonstrates the impact that the short-term fluctuations of outside air temperature have on the indoor environment of the building, is triggering the window adjustments made by occupants. Moreover, the point accumulation from Jan to Apr in 06 shares a similar pattern to that of year 05. This indicates a kind of building 'life style' in which occupant behaviour in this case is periodically repeated in correlation with the time of the year.

3.3. Outdoor air temperature

The relationship between total opened windows ratio and the outdoor temperature is analysed in greater detail in Fig. 3. Compared to the previous work done [14,15], there is no noticeable upper accumulation when the temperature is high since Sheffield has less days with average daytime temperature over 20 °C than those cases in the other climate areas. A strong accumulation of data points is found below 10 °C, which means most windows are remained closed when the temperature is below 10 °C. From 10 to 15 °C, the impact of temperature on window opening control becomes evident. A strong statistical spread is found from 15 °C and at a temperature of 25 °C, the highest value is reached. The maximum value is 27.9% ($N = 1620$) when the temperature is 25.3 °C.

The selected building is naturally ventilated. No regard is paid to the natural variation that exists in those rooms with respect to how these rooms are heated. As a result of rooms with less direct solar radiation are thus often colder than those that receive more. Therefore, window orientation in this case, is considered to be an issue of primary importance in influencing the user operation behaviour

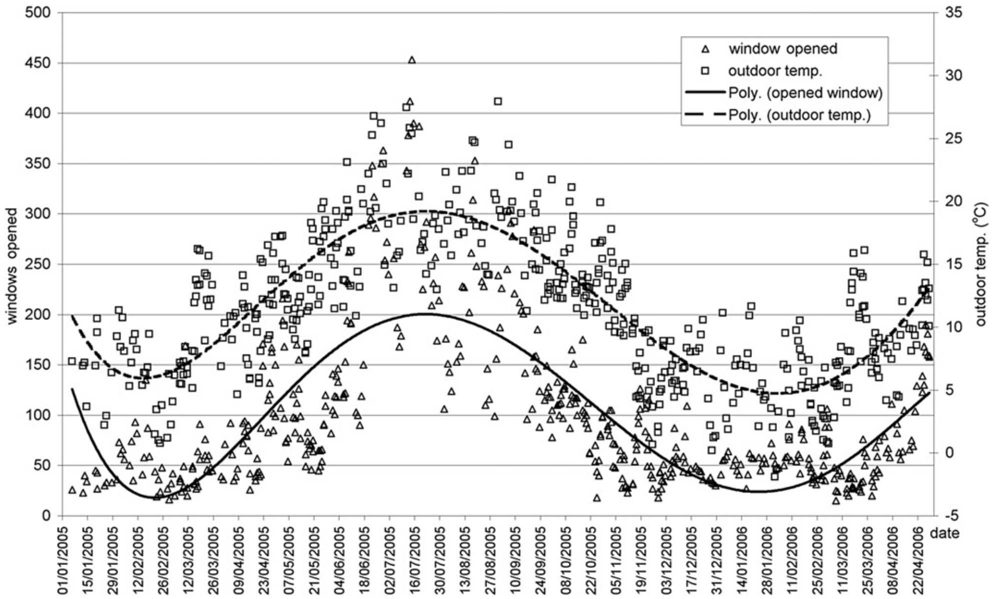

Fig. 2. Total number of windows opened and outdoor temperature from Jan/05 to Apr/06.

mainly with regard to solar radiation. It has to be mentioned that because the building's long axis is tilted 18°, the orientation of the building façade and window has to be more precisely described as being rotated 18° anti-clockwise. For example, the orientation of the South façade is actually 18° east of south.

Fig. 4 gives the comparisons of the mean percentage of opened windows to the outdoor temperature based on the window orientation. The points of the values from four orientated rooms in this case are kept in the low accumulation (around 3%), especially when the temperature is low. However, the distribution of data points exhibits a discernable difference between four orientations. The percentage values of south facade deviate widely. It shows the biggest fluctuation (29.9%) and the highest average during the survey time with a figure of 7.3%. This is to be expected as the rooms towards the south receive the most solar radiation of all the different room orientations. The rooms heat up quickly, especially during the summer time. Without air conditioning, natural ventilation to increase the air movement is the main option occupants have when it comes to eliminating the discomfort that arises from high temperatures.

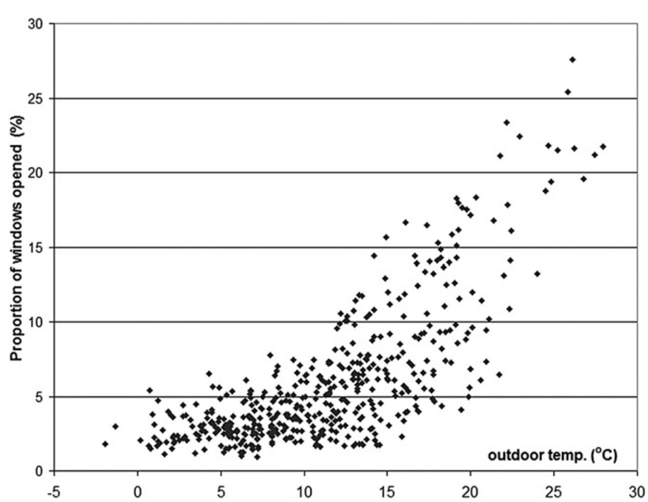

Fig. 3. The relationship between the proportion of windows opened and outdoor temperature.

The values for the East and West share a similar distribution and the fluctuations from maximum to minimum are much the same: 24.7 and 24.6% with the average value just around 1% less than for the south with 6.3 and 5.6% respectively. But the data points of the East spread more than those of the West all the time. This is perhaps due to the prevailing wind, especially winds with high speeds (more than 4 m/s). It comes from the West most of the time and may result in the lower opened windows value. In this case, the high-rise feature of this building strengthens the negative impact of wind speed on the operation of windows. The occupants of the West rooms may experience a high frequency of discomfort from draughts, which influences their preference not to have the window opened. As a result, it is expected to see that the West and East ratios are close but that the former is a little lower (0.7% difference).

The North rooms do not receive direct solar radiation for most of the time, which means that the occupants' desire for higher levels of air movement due to overheating is not as frequent as the case for other room orientations. Therefore, it turns out that the ratio for the North has the smallest maximum value (21.7%) and the lowest average ratio of opened windows (3.6%). Not until the outside temperature exceeds 12 °C does the spread of the value points start increasing.

'Probit analysis' is used in order to have a deep insight into the relationship between the opened window and temperature. It is a type of regression applied to analyse binomial response variables with only two outcomes, which is a powerful method of analysing window opening behaviour processes [7,19]. This method has often been used in thermal comfort studies to investigate the changing incidence of discomfort with increases in environmental index. In this study, probits is used to analyse data about the changing probability p for windows that people will open them as the outdoor temperature rises. p stands for the probability that windows will be opened, while x stands the temperature (°C). The relation is expressed from the equation below where a and b are constants, which refer to intercept and regression coefficient:

$$p = \exp(a + bx)/[1 + \exp(a + bx)]$$

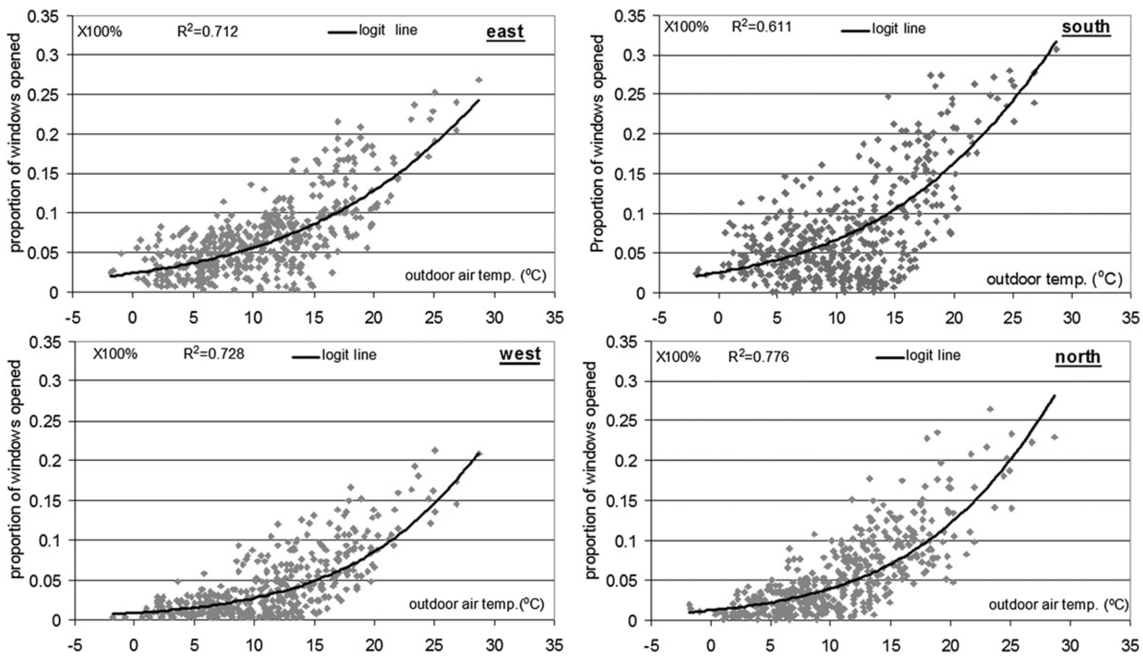

Fig. 4. The relationship between the proportion of windows opened and outdoor temperature (four orientations).

Table 2 not only shows the values of the parameters *a* and *b* in this study but also compares results with a range of cases studies by other researchers, using the same method (algorithm). All the equations from this study in Table 2 show statistically high significance ($p < 0.001$). Climate conditions and building features are main reasons that cause the differences of *a* and *b* values between each case study. They play the substantial role in the overall built environment, which affects occupant sensation and comfort; further their respond to their comfort conditions: manual control, including window opening behaviour.

The regression lines in Fig. 4 are drawn based on the calculated *a* and *b* values in Table 2. All of them have the same rising pattern with air temperature. The smaller the value of an intercept (*a* value), the lower the start point of the logit line located. While the smaller the *b* value is (regression coefficient), the earlier the dramatic increase happens. The logit lines imply that some of occupants are more active in interacting with a window (open and close) while some of them more passively adjust a window according to the variation of the outdoor temperature. For example, the windows towards the west has the smallest *a* and biggest *b* value, which indicates that occupants will open a window with a lower probability here when compared to those at other side of the building under a given outdoor temperature. The prevailing wind direction is southwest and wind with high speed is from west. Therefore its windward face results in a negative impact when it comes to the window operation.

Table 2
Parameters calculated to describe the probability of windows opened (outdoor temperature).

Ref.	Case location	a	b
[5]	Lausanne, Switzerland	−1.12	0.05
[7]	Pakistan	−3.73	0.12
	UK	−2.65	0.17
	Europe	−2.31	0.10
[10]	Freiburg, Germany – small window	−2.99	0.16
	Freiburg, Germany – windows titled open	−3.13	0.08
	Freiburg, Germany – windows completely open	−4.05	0.08
[11]	Oxford & Aberdeen, UK – each building	−3.80 ~ −2.09	0.16
	Oxford & Aberdeen, UK – all building	−2.92	0.16
	Sheffield, UK – east windows	−3.72	0.09
	Sheffield, UK – south windows	−3.64	0.10
	Sheffield, UK – west windows	−4.77	0.12
	Sheffield, UK – north windows	−4.38	0.12
	Sheffield, UK – all windows	−4.01	0.10

3.4. Indoor temperature

Different studies tend to show that there is a very high correlation between indoor and outdoor temperature during the non-heating season in a naturally ventilated building [20]. Therefore, when modelling the window opening behaviour, instead of using indoor temperature as an input, which is regarded as a calculated result with less accuracy, the outdoor temperature is chosen in most circumstances as a driving force to influence the occupant control [7,8,10]. However, there are studies arguing that the occupant behaviour is a response to the specific environment where they are accommodated. They recommend using the indoor temperature as a more coherent and intrinsic factor for the use of windows [9]. Rajal et al. [11] subsequently developed a more refined model, taking both indoor and outdoor temperature into consideration.

There are two reasons to measure the indoor physical parameters, besides the purpose of indoor environmental evaluation of this selected building [19], Firstly, to see whether it has a correlation with outdoor temperature. This measurement work is done during the heating seasons from Dec/05 to Apr/06 to determine whether indoor or outdoor thermal stimulus has a potential to account for window opening behaviour. In this case, the link between indoor and outdoor temperature is weak as shown in Fig. 5. The outside is cold and humid with an air temperature of 10.8 °C and RH 71.1% (average). Because the central heating is always switched on, there is no strong correlation between the outside and inside temperature (0.0006). However, it is interesting to see the correlation values are strengthened when the indoor temperature is grouped into orientations of the room where these are measured. Although the central heating maintains the thermal comfort up to a certain level, the 'passive' heating source (outdoor environment)

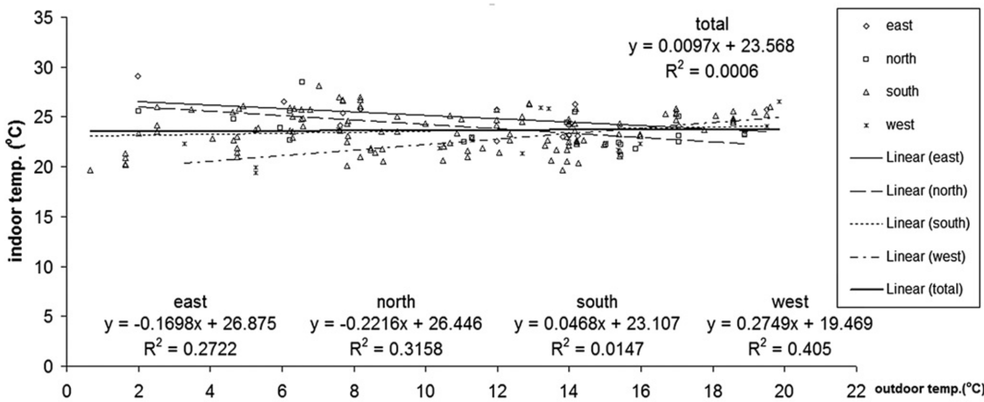

Fig. 5. Indoor temperature for a given outdoor temperature in this selected building from Dec/05 to Apr/06 (heating months).

still affects the thermal environment of this building. The fact that extreme situations, with maximum temperature in the room towards the South while the minimum is towards the North on the same day shows that orientation is an issue that causes great temperature variation. This result is confirmed in the non-heating season at Yun and Steemers' study [9] as well.

The second reason for indoor measurement is to see whether the temperature has a noticeable distribution pattern between each room. In this building, the variation between each room is so varied that the measurement data in several rooms will result in lack of accuracy because they cannot represent an overall situation. As the study target is the whole building, it is not practical and accessible to put the thermometer in every room (333). Therefore, it seems more reasonable to take the outdoor temperature and building orientation into account (instead of indoor temperature) as the factors influencing window opening behaviour in this case. The advantage is that the outdoor temperature, building orientation are both independent variables while the indoor temperature is a dependent one.

3.5. Time of day

When occupants arrive at the building, all windows are in the 'closed' position. Only when they feel 'discomfort', are the windows opened by users, which correlates robustly with a desire for better air quality or a higher ventilation rate in order to cool the internal temperature. This can happen at arrival or during the work anytime. However, once a window is opened, it is usually left in its position for a long period unless occupants feel 'discomfort' again and then close it. Another 'closing' reason is that it is a 'rule' all windows are closed when vacating a room (Fig. 6). In a very rare situation, 1–5 windows are left open in some public study spaces overnight. Consequently, the proportion of windows opened normally starts from (nearly) zero at the beginning of the working time and then ends to zero again after that on a daily basis without seasonal differences. In this building, the users customize their own work schedule to fit their personal needs and goals. Their alternatives consist of two components: flexible bands and core hours. The highest occupancy density happens in core hours, while the dramatic change happens in the flexible band, which is also consistent with the variation of proportion windows open: more windows are opened when more users are in occupation (Fig. 7). The peak value at mid afternoon is slightly higher than at mid morning probably because it is generally hotter in the afternoon than in the morning in Sheffield's climatic conditions.

3.6. Occupancy pattern

Offices make of the biggest part this investigated building (Fig. 1). In these rooms, occupants normally have fixed study/work places permanently. Besides a large number of floating occupants, people are in this building for different purposes, such as working, studying, teaching, training and meeting etc. Their movement is quite mobile within the building from one room to another: taking or giving lectures, meetings, copying files, visiting other colleagues or simply having a break. This behaviour pattern is discussed in the Page et al.'s study [21]. They confirm that the state of presence (absent and present) in an office is intermittent in terms of probability of presence, mobility and periods of long absence etc.

As no sensor was installed in each room during the field work; records of the occupant's specific arrival, departure or absence were not available. However, there is no doubt that in an office building, some of the spaces are heavily used while some are not. To study an office building, those spaces, other than offices themselves, cannot be ignored as they take a considerable amount of space of the building (58.6% in this case).

Fig. 8 reveals an interesting finding. No matter in which season, occupants who are in the communication area (e.g. rooms for seminar, teaching and/or meeting) are the most active in operating

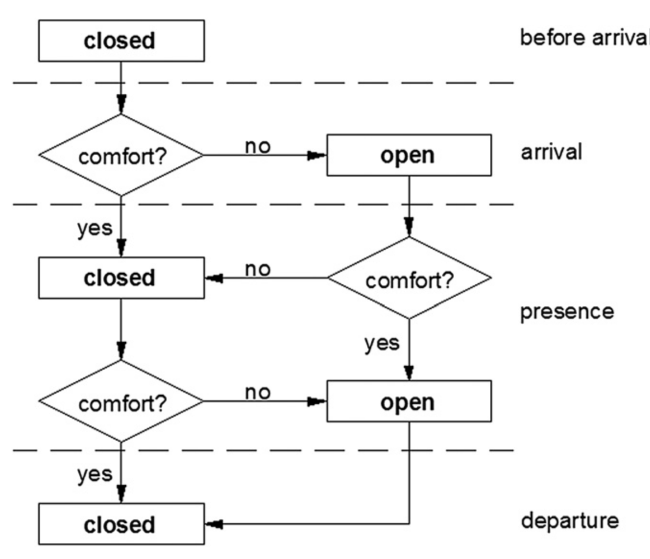

Fig. 6. A flow chart of the window condition on a daily base.

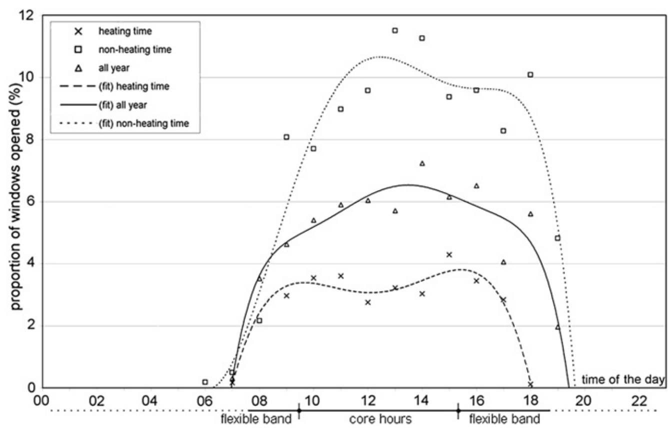

Fig. 7. Mean percentage of windows opened on a daily base.

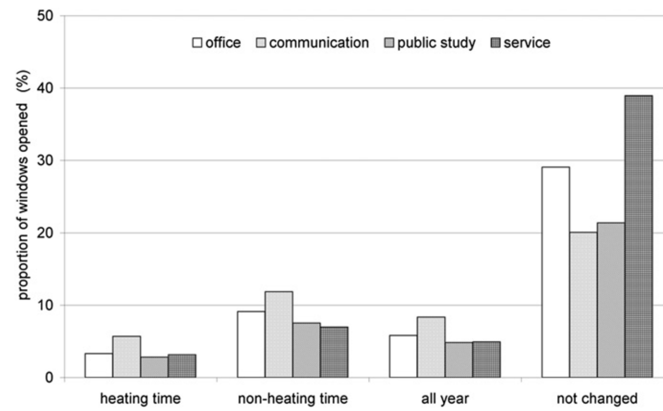

Fig. 8. Four occupancy patterns and the proportion of windows opened.

windows among those at other spaces. When these rooms are occupied, they normally have a relatively high user density. This may explain why more windows are opened here than in others rooms. The consequence of high density is that related metabolic heat gains from the occupants are quite significant. The impact of these people is considerable and their heat output contributes greatly to the raising of internal air temperatures. People in such situations can easily feel uncomfortably stuffy. Thus a high level of ventilation may be required even though the total period of occupation might last for less than a few hours. This requirement is strengthened when the outside temperature is high. The office is occupied continuously for a long time with low density. When ventilation is desired, opening the door is usually the first priority option as it is convenient and quick. Only when privacy, fire door requirements and/or noise etc. are factored in can window opening be seen as an alternative. In contrast, occupants in public study and service rooms usually stay intermittently and for a short period; so the requirement for ventilation is not as great as in other rooms. Therefore, only a small proportion of windows are kept open all time.

The result also reveals a significant variation when it comes to how many windows were recorded 'closed' all the time, at least during the survey period. The highest is noted for service rooms (38.9%) and office rooms (29.1%). Both represent a specific occupancy feature: low density. In these rooms, it is not necessary to use all but just a few specific windows for occupants to adjust the indoor environment. Only when the density becomes high are more windows involved in decreasing the room temperature and/or increasing the ventilation rate.

4. Discussion

Results from this field survey illustrate the factors influencing occupant window opening behaviour. Generally, the main motivating force for manual control of window opening is strongly related to the outdoor air temperature. In other words, the higher the outdoor temperature, the more likely windows are to be opened by occupants. The correlation (R^2) between these two is higher than 0.7, which is consistent with many other adaptive comfort studies [2,6,8,10–12]. Other weather stimulus, such as RH and wind speed also affect the window opening behaviour up to a certain level. In this study, the impact of wind speed has a higher correlation than some of other studies [5,10,14], which may be explained by its high-rise feature. Wind picks up speed when its travel is unhindered. Therefore the higher the building is, the more likely the wind movement becomes strong and cause heat loss and noise.

The literature indicates a much higher proportion of windows opened than this study. The main reason is that their study target is individual offices rather than building as a whole. In this building, only a small portion of windows (6.2%) is operated by occupants, while most of the windows are closed no matter what the climate/weather condition is. However, the variation in the use of windows responds to the seasons and follows a clear pattern. It reaches its highest figures in Summer and drops to its lowest in Winter, which is periodically repeated in correlation with seasons of the year. This result is consistent with another field study, which also lasted over a year [10].

There is an argument in the literature as to whether indoor or outdoor temperature should be used as the independent variable in the analysis of control on windows. Besides the fact that indoor and outdoor temperature tend to co-vary in a naturally ventilated building, especially in the non-heating season, the outdoor air temperature is chosen in this study mainly for two reasons. Firstly, although there is no significant correlation between indoor and outdoor temperature during the heating season, further data filtering in terms of different orientation strengthens the correspondence with outdoor temperature. This implies that in this naturally ventilated building, the outdoor air temperature still has a definable effect on indoor temperature even during the heating seasons. Secondly, the individual occupant of this building is found to be quite sensitive to short-term fluctuations of outdoor air temperature that make differences to the internal environment of the building and cause adjustment. The impact is direct with almost no time lag.

Nevertheless, this study still considers the difference of indoor environment between spaces (rooms) to be one of the factors influencing occupant window behaviour, based on a more

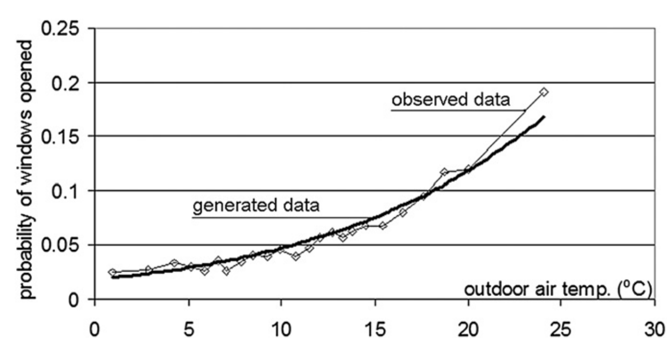

Fig. 9. Comparison of results from the field work and stochastic model.

Table 3
Insights from results about main study interests.

Study interests		Aspirations from the literature	Findings from this study
Factors influencing the window opening control	Outdoor weather stimulus	Air temperature, wind speed, RH, solar radiation are correlated significantly.	It is consistent with the literature. The impact of wind speed is more significant in this case than previous studies. 'Sunshine hours' is also correlated significantly.
	Outdoor temp.	The impact is significant with the correlation value around 0.7.	It is consistent with the literature ($r^2 = 0.724$).
	Indoor temp.	The impact is significant especially at non-heating seasons.	It is not shown statistically significant due to the measurement is at the heating season. Users will not open window even it is hot inside when the outdoor temp. is low.
	Seasonal effects	Different control behaviour exists across seasons. User responds differently between Winter and Summer even the outdoor temp. is same.	It is consistent with the literature. A building 'life style' is also presented that the user behaviour is periodically repeated in correlation with the season of the year.[a]
	Time of day	User behaviour is very different when they first arrive and depart the room, according to their preferred spatial configuration.	It may indicate that users open the windows at their first arrivals, although there is no accurate record to support, while they do close the windows when they leave the building.
	Window orientation	Its impact is expected although there is no field evidence to support.	It produces distinctly different control responses mainly regard to solar radiation and prevailing wind direction.[a]
	Occupancy pattern	It is discussed similarly with the 'time of day'. Also when the room is occupied, the window is usually left in one position until the discomfort happens.	High occupancy density is likely to cause more windows opened due to a general desire for fresh air. Also, only a small proportion of windows operated actively in an office building (not just individual office rooms).[a]
Method	Field study	Observation is based on real people's life in r eal offices (buildings). The environmental factors and presence status are measured and recorded.	Observation, measurement and survey are carried out in an office building. Accurate presence/absence data, however are not available.
	Stochastic model	Window operation is treated as a stochastic process. Variety of models is developed to predict the users' window control behaviour.	Probit analysis is used and tested. Although only one driving variable is considered (outdoor temp.), the algorithm gives a promising result to those measurement with a high correlation.[a]
	Indoor or outdoor temp. as an model input	No clear consensus is reached whether indoor or outdoor temp. should be used as an input variable.	Outdoor temp. is used. The variations happen simultaneously with almost no time lag, which demonstrate that occupants open the windows as a response to the short-term fluctuations of outdoor air temp.[a]

[a] Findings that may particularly contribute to the concerned study area.

independent feature: window (room) orientation, which has been proved by many research that affect the built environment very much. Although the correlation (Fig. 4), regression coefficient and intercept value (Table 2) are calculated with a small difference between window (room) orientations, the orientation does affect the amplitude of the variation, even when the outdoor temperature is low. This is mainly with regard to solar radiation and prevailing wind direction. Both factors affect the occupants' comfort perception and control behaviour: sometimes positive (e.g. appropriate heating gain and air movement), while sometimes negative (e.g. overheating or heat loss due to the air infiltration).

Furthermore, although probit analysis is rather simple, it is commonly applied in the literature to further quantify the relationship between the outdoor temperature and window opening behaviour. A stochastic model, which was proposed by Nicol [7] is developed to describe the probability of window opening. In this naturally ventilated office building, the equation can be calculated as:

$$p = \exp(-4.01 + 0.10x)/[1 + \exp(-4.01 + 0.10x)]$$

Fig. 9 compares the data observed from field survey and generated by this stochastic model. The algorithm gives similar results to those measurement with a strong correlation ($r^2 = 0.831$), which implies that the window status can be predicted by taking the outdoor temperature as an input variable in this stochastic model promisingly, although it is rather preliminary in terms of predication and stimulation with only one driving variable considered. For certain, many other factors that influence the window opening behaviour could be integrated into the model for still greater accuracy. Previous window control studies have, for example, allowed for: occupancy status [8,10], time of the day [9,10], indoor temperature [9], individual behaviour [8] and its impact on energy consumption [2,11].

In terms of daily control, the window status has to be kept at 'closed' position before and after the working time; in this case, the effects of the previous window state on the subsequent window state is not as important as those cases with night ventilation [9,12]. Only when required are they intermittently opened, encouraging air movement on a hot day. The dramatic change happens in the flexible occupancy band in the morning, which may indicate that occupants open the windows on their first arrival, although there is no accurate record to support this finding. However, this study shows that when the occupancy density is high, more windows will be opened even if it is intermittent, of short duration and composed of floating users.

5. Conclusion

This paper presents the results from field work measurements to characterize occupants' window opening behaviour in an office building in Sheffield's, UK climate conditions. These are summarised in Table 3. In particular, the following results are addressed and believed to be a contribution to the concerned study area.

- In this office building, only a small portion of windows (6.2%) is operated by occupants, while most of the windows are closed no matter what the climate/weather condition is.
- A building 'life style' is presented that the user behaviour is periodically repeated in correlation with the season of the year.
- The window orientation produces distinctly different control responses due to the solar radiation and prevailing wind direction.
- When the research target is an office building, non-office spaces should not be ignored as these areas are part of the building. High occupancy density is likely to cause more windows opened due to a general desire for fresh air, even if it is intermittent with floating users.
- Although only one driving variable considered (outdoor temperature), the algorithm (probit analysis) gives a promising result to the measurement with a high correlation.
- The outdoor temperature can be an independent variable in a model input. The variations happen simultaneously with almost no time lag, which demonstrate that occupants open the window as a response to the short-term fluctuations of air temperature.

It is anticipated that the results obtained from the investigation will be useful in answering some essential questions concerning user response in the built environmental control, specifically related to a whole building perspective. Future studies can be identified and deserve more attention in the area of the many motivating forces behind manual window control, such as wind speed, solar radiation, noise level, spatial configuration etc. The study of these aspects could lead to a more comprehensive understanding of occupant control behaviour. The application of such results also can be used in the building simulation of ventilation and energy consumption. Also, this study is limited to the very building itself. Further studies of buildings with varied location, climate, building structure and function are also to be desired.

The limitation and weaknesses of this study are unavoidable. The basis of this one building case study cannot represent the targeted building type or be applied to any other buildings type. In addition, accurate everyday monitoring of occupation and absence in the investigated rooms during the observation period was not practical or accessible. This is especially important when considering the operation behaviour of the window – whether the space is occupied or empty and how long it lasts. Therefore, the variation analysis of manual control cannot conclude that the changes in window status mainly occurred on arrival, which has been proved by many other previous studies as a function to affect the window opening behaviour patterns. Also, as a crucial part of the building design, spatial and/or intermediate conditions have profound effects on occupants' perception and behaviour. Therefore, when it is subtracted from its immediate context, the data collected and the results analysed in this study may have been over-simplified in some way.

Despite this, clarity has been added to the prediction of window use by occupants from a whole building perspective. This provides data at a level of detail that should enable improved models of building performance to be created.

References

[1] Brager G, Dear R. Thermal adaptation in the built environment: a literature review. Energy and Buildings February 1998;27(Issue 1):83–96.

[2] Nicol J, Humphreys MA. Stochastic approach to thermal comfort-occupant behaviour and energy use in buildings. ASHRAE Transactions 2004;110(2): 554–68.

[3] Nicol J, Humphreys M. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Building 2002;34:563–72.

[4] Indraganti M. Adaptive use of natural ventilation for thermal comfort in Indian apartments. Building and Environment 2010;45:1490–507.

[5] Haldi F, Robinson D. On the behaviour and adaptation of office occupants. Building and Environment 2008;43:2163–77.

[6] Andersen R, Toftum J, Andersen K, Olesen B. Survey of occupant behaviour and control of indoor environment in Danish dwellings. Energy and Buildings 2009;41:11–6.

[7] Nicol J. Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans. In: Proceedings of the seventh international IBPSA conference; 2001. p. 1073–8.

[8] Haldi F, Robinson D. Interactions with window openings by office occupants. Building and Environment 2009;44:2378–95.

[9] Yun G, Steemers K. Time-dependent occupant behaviour models of window control in summer. Building and Environment 2008;43:1471–82.

[10] Herkel S, Knapp U, Pfafferott J. Towards a model of user behaviour regarding the manual control of windows in office buildings. Building and Environment 2008;43:588–600.

[11] Rijal H, Tuohy P, Humphreys M, Nicol J, Samuel A, Clarke J. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. Energy and Buildings 2007;39:823–36.

[12] Fritsch R, Kohler A, Nygard-Ferguson M, Scartezzini L. A stochastic model of user behaviour regarding ventilation. Building and Environment 1990;25: 173–81.

[13] Dubrul C. Inhabitant behaviour with respect to ventilation – a summary report of IEA Annex VIII Technical notes AIVC 23. Bracknell, United Kingdom: Air Infiltration Centre; 1988.

[14] Warren P, Parkins L. Window-opening behaviour in office buildings. ASHRAE Transactions 1984;90(1B):1056–76.

[15] Borgeson S, Brager G. Occupant control of windows: accounting for human behavior in building simulation. Berkeley: Center for the Built Environment (CBE), University of California; October 2008.

[16] Parys W, Saelens D, Hens H. Coupling of dynamic building simulation with stochastic modelling of occupant behaviour in offices – a review-based integrated methodology. Journal of Building Performance Simulation; 2011:1–20. doi:10.1080/19401493.2010.524711.

[17] Zhang Y, Altan H. A comparison of the occupant comfort in a conventional high-rise office block and a contemporary environmentally-concerned building. Building and Environment 2011;46:535–45.

[18] Humphreys M, Nicol J. Understanding the adaptive approach to thermal comfort. ASHRAE Transactions 1998;104(1):991–1004.

[19] Schweiker M, Haldi F, Shukuya M, Robinson D. Verification of stochastic models of window opening behaviour for residential buildings. Journal of Building Performance Simulation; 2011:1–20. doi:10.1080/19401493.2011.567422. iFirst article.

[20] Humphreys M, Nicol J. Outdoor temperature and indoor thermal comfort: raising the precision of the relationship for the 1998 ASHRAE database of field studies. ASHRAE Transactions 2000;206(2):485–92.

[21] Page J, Robinson D, Morel N, Scartezzini J. A generalised stochastic model for the simulation of occupant presence. Energy and Buildings 2008;40: 83–98.