Building Simulation 2005

Ninth International IBPSA Conference
Montréal, Canada
August 15-18, 2005

A PRELIMINARY MODEL OF USER BEHAVIOUR REGARDING THE MANUAL CONTROL OF WINDOWS IN OFFICE BUILDINGS

Sebastian Herkel, Ulla Knapp and Jens Pfafferott
Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany
sebastian.herkel@ise.fraunhofer.de
www.ise.fraunhofer.de

ABSTRACT

This paper presents the results of a field study of manual control of windows which has been carried out in 21 individual offices within the Fraunhofer Institute's building in Freiburg, Germany, from July 2002 to July 2003. Window status, occupancy, room and outdoor climatic conditions were measured every minute. Previous research findings are validated and extended by the results of this field study. The analysis of user behaviour reveals a strong correlation between the percentage of open windows and the time of year, outdoor temperature and building occupancy patterns. Most window opening is connected with the arrival of a person. Based on the results, a preliminary user model is proposed to simulate and predict window status in office buildings with varying outdoor temperature and occupancy.

INTRODUCTION

As human well-being and productivity are strongly affected by the built environment, providing comfortable room conditions is a vital part of designing office buildings. Thermal comfort can surely be achieved with enhanced ventilation systems or air conditioning. However, in moderate climates a passive cooling concept using natural effects such as night ventilation with manually-controlled windows in combination with an exhaust fan and a high thermal inertia could in principle provide the same level of comfort with a substantially lower environmental impact. Thus the underlying question is how energy consumption and thermal comfort are affected by the use of manually-controlled windows.

Monitoring user behaviour reveals when and how people operate windows and identifies the influential variables. Based on the results, a user model is developed which can later be used either in building simulation to help designers decide which ventilation system to choose or as a model in a simulation based building energy management system (BEMS): E.g. simulations reveal whether manual window opening, which leaves the decision to open or close a window up to the occupant, can provide efficient night ventilation and can reduce overheating, or if windows require partial automation.

This paper reviews, validates and extends results from previous field studies on manual window control. Based on a literature review, a field study was carried out in 21 south-orientated offices within the Fraunhofer Institute's building in Freiburg, Germany. A brief literature review is presented in order to explain current knowledge. Based on the main conclusions from the literature, hypotheses are formulated and verified by analysing data recorded at the building. The percentage of open windows, opening hours and the frequency of opening or closing windows depends according to various papers on:

- *season*. In summer the percentage of open windows is higher than in winter. In summer the frequency of opening or closing windows is lower than in winter [IWU].
- *outdoor temperature*. The higher the outdoor temperature the more windows are open. Windows are opened more frequently as soon as the temperature exceeds a certain value. When reaching a certain outdoor temperature no more windows are opened[Raja et al., Nicol et al., Warren et al., Fritsch et al., IWU]
- *indoor temperature*. When indoor temperature exceeds a certain value, the percentage of open windows increases rapidly until a percentage of 100 is reached [Raja et al. and Warren et al.]
- *time of the day*. During the night, the percentage of completely open windows is around zero. The percentage of tilted open windows hardly varies between day and night [Warren et al.]
- *presence*. The use of windows mainly occurs when occupants arrive or leave their workspace. Open windows are mainly closed at the end of a working day [Warren et al.]

The results of the above mentioned studies can't be generally applied to any building, since building-specific variables like climate, culture, building structure, type of building (residential or office building) play an important role. Nevertheless they provide a good basis for formulating our own models which will later be reviewed. The relationship between wind velocity and solar radiation found in the literature is not yet evaluated and therefore not reviewed in this paper. This and the restriction on one building limits the generalisability of the presented model.

EXPERIMENTAL SET-UP

Building description, Ventilation and passive cooling concept

The field study was carried out in 21 south facing offices within the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany [Pfafferot et al. 2004]. As no active central or personal air-conditioning system IS installed in the offices, a passive cooling concept is implemented by reducing internal and external heat gains, providing thermal inertia and using night ventilation. The small and large windows in the façade are operated manually. A slit valve in the frame of the large windows provides a basic infiltration rate even when windows are closed. A ventilator at the end of the corridor supports the ventilation of the offices during working hours. In summer, during working hours the ventilator provides an air change of $1h^{-1}$, during night $4.5h^{-1}$. Occupants have to open windows and window flaps themselves to bring ventilation into effect and to achieve higher air change rates at night. Large windows should not be fully opened during absence due to security reasons.

Data acquisition

The considered offices, each occupied by 2 or 3 people, are situated on 3 storeys. Conditions in the building such as indoor temperature and status of windows (open, closed, tilted open) are measured. Data over a period of 13 months – from 1 July 2002 to 31 July 2003 – was minutely recorded and stored from the following sensors:

- The status of 31 small and 34 large windows is measured every minute by read contacts. The small windows, which can be closed or tilted open, have one sensor on the inside of the window frame, and the large windows have two – one on the side and one on the bottom of the frame. Thus, it is possible to differentiate between tilted open and completely open.
- In each office a sensor for recording the indoor temperature is attached to the wall. As the air temperature near the wall is influenced by the wall, the PT-100 sensor acquires a temperature lying between the surface temperature of the wall and the air temperature, which is the operative room temperature.
- Occupancy is measured via an ultrasonic motion sensor attached to the monitor.
- A meteorological station is installed on the roof to acquire outdoor temperature and solar radiation. The data is updated every 10 seconds.

In the following, the paper differentiates between open and closed regarding the small windows and between open, tilted open and closed with regard to the large windows (see figure 1).

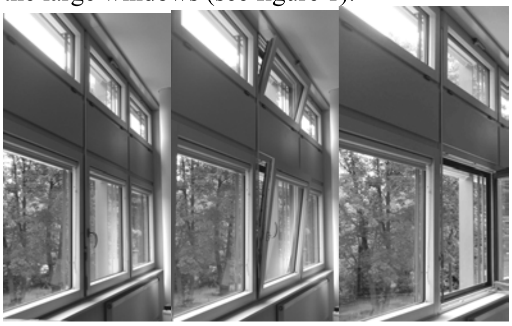

Figure 1 Small and large windows in the façade. Differentiation between: windows closed, small openings (small windows open, large windows tilted open) and large openings (large windows completely open).

RESULTS AND ANALYSIS OF MONITORED DATA

Correlations found in the literature and hypothesis based on these previous research findings are reviewed in the following. The results of the study will reveal whether the expected relationship between user behaviour and the season, outdoor temperature and indoor temperature is valid.

Seasonal effects

A large change in user behaviour between summer and winter is found in the monitored period as can be observed in Figure 2. Although the various curves of the percentage of open windows respond to the changing seasons with varying sensitivity, they follow the same general pattern.

- As expected, occupants tend to open fewer windows from the end of October until the end of March.
- In summer between 60 and 80 percent of *small windows* are open, whereas in winter the percentage decreases to 10 percent.
- *Tilted* opening of *large windows* follow the same pattern but deviate in value with about 40 percent in summer.
- During Summer, *large windows* are completely open during 20 percent of the working hours.
- A sudden decrease of the percentage of open windows is found in September/October and an increase in March/April, indicating that occupants respond to changing weather conditions in spring and autumn.

Outdoor temperature

When evaluating the time series, observations regarding the relationship between the user behaviour and the outdoor temperature can be made

(Figure 2). One can see, that the correlation between the percentage of open windows and the outdoor temperature is remarkable. The peaks of the percentage of open windows seem to correspond to those of the outdoor temperature. On the other hand, the outdoor temperature shows no sudden increase or decrease as observed in the percentage of open windows. The user behaviour changes with the change of the outdoor temperature, but comparing days with same daily mean outdoor temperatures in different seasons reveals that the percentage of open windows differs according to both temperature and time of year. It can be assumed, that the sudden decrease of open windows appears with the first cold day with an outdoor temperature below 10°C. Until that day, the outdoor temperature never fell below 15°C. This raises the question if the percentage of open windows is connected with the first cold and first warm day, which occupants may equate with the start of winter and summer.

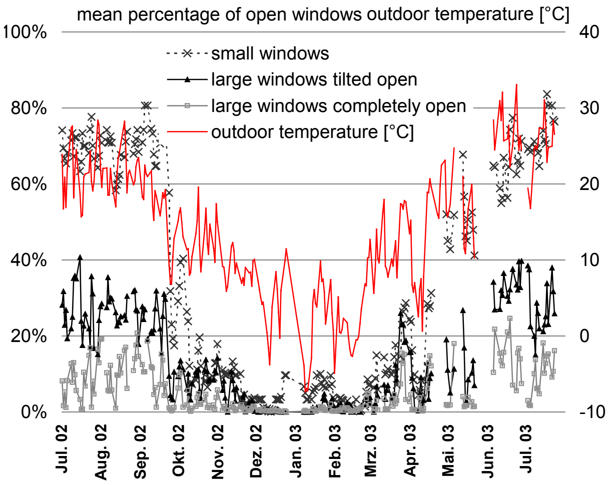

Figure 2 Mean percentage of open windows. Daily mean values. Data evaluation of working hours only (weekdays, 8am-6pm CET).

The relationship between the percentage of open windows and the outdoor temperature is analysed in greater detail in Figure 3. Comparing the data of different windows with the Logit-function proposed by Nicol reveals a relationship between user behaviour and the outdoor temperature [Nicol 2001]. Nicol calculated the probability p for open windows as a function of outdoor temperature. As an algorithm he used the logit function:

$p = \exp(a + bx)/[1 + \exp(a + bx)]$ where a and b are constants and x is a variable – in this case the outdoor temperature. However, the values of single data points assigned to a certain temperature deviate widely. Tilted-open large windows show a strong statistical spread resulting in a low correlation coefficient of $r = 0.62$. The correlation of small windows ($r = 0.84$) and totally open large windows ($r = 0.77$) is slightly stronger. The small windows show a strong statistical spread between 10 and 20°C. The percentage of open windows ranges from 0 to 80. A strong accumulation of data points is found between 0 and 20 percent and between 60 and 80 percent. Data analysis shows that the lower accumulation is the percentage of open windows during the winter months, the upper accumulation during the summer months. Even if the temperature in different seasons is the same, people act differently. The behaviour on a cold summer day differs from a warm winter day. People respond to the season. Since one can expect summer temperatures to be higher than those during the winter, people will operate windows more frequently in the summer. At a temperature of 20°C the highest percentage of open windows is reached. At higher temperatures the percentage of open windows seems to decrease - as already mentioned by Warren et al. 0. However, it must be noted that the results referring to higher temperatures are observations specific to this study that cannot be generalised, since only few days with temperatures over 30°C were available.

Table 1

Parameter for Logit function to describe the mean percentage of open windows

CASE	A	B
Nicol	-2.31	0.34
ISE small windows	-2.99	0.16
ISE windows tilted open	-3.13	0.08
ISE windows completely open	-4.05	0.08

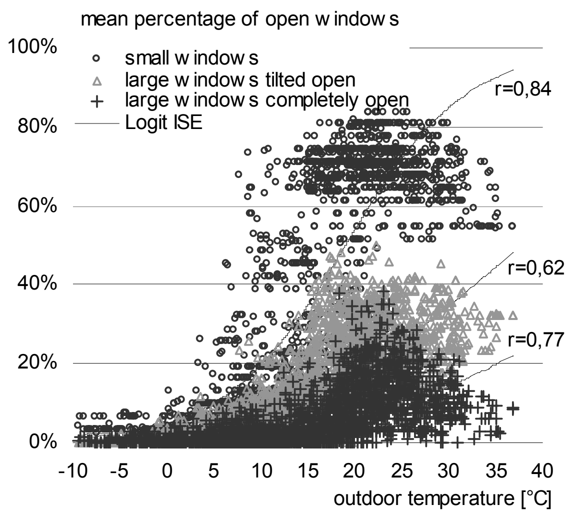

Figure 3 Correlation of the mean percentage of open windows to the outdoor temperature over 13 months. Hourly mean values. Data evaluation of working hours (weekdays, 8am – 6pm CET, occupied and unoccupied times).

Obviously, people prefer having small windows open at higher temperatures. Above a temperature of 20°C, 80 percent of small windows are open, whereas only 40 percent of large windows are tilted open and 20 percent completely open. As indoor temperature is strongly related with the outdoor temperature results concerning correlations to the opening status are not further discussed here.

Time of day

In previous sections, the percentage of open windows was evaluated in relation to changes in season as well as fluctuations in outdoor temperature. User behaviour was found to be strongly correlated with the season. Relationships between the user behaviour and the outdoor temperature exist, but the correlations are not as strong as expected. However, how does the occupant operate windows during the day? Which influencing variables make him open or close windows? In his section, the user behaviour is analysed at different times of day, with the aim to find behavioural patterns.

Percentage of open windows

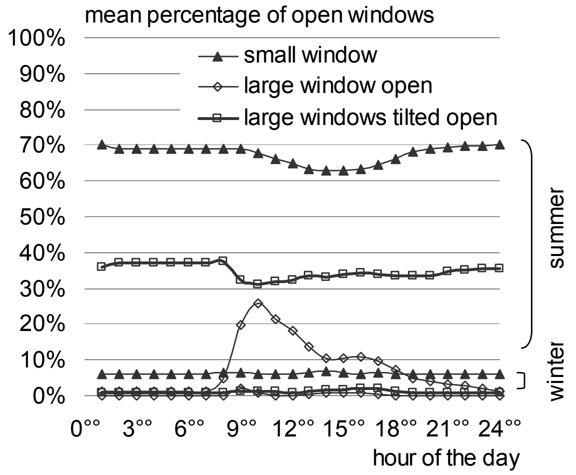

Figure 4 Typical courses of the day. Monthly mean values for each hour of a day (0 to 23). Data evaluation of weekdays 0am – 11pm CET

Figure 4 shows the typical course of the day (using monthly averages) during the considered period of time. An hourly average is calculated from the values collected from each individual window. Therefore, the results do not correspond to individual but to general user behaviour. There might be occupants operating windows in a different way than the data suggests. During working hours between 8 am and 6 pm all types of windows change status. The two types of small openings – the *small* and *large tilted-open windows* – show the same general pattern. In summer, the percentage of open windows varies on the average between 5 and 10 percent during the day. A closing during day time might be due to noise reduction. In winter, only little changes occur between day and night. The *small windows* don't show typical patterns during the course of the day: Windows appear to be either open all the time or closed all the time. The highest percentage of open windows is found with small windows, though there are the least changes. This suggests that occupants operate small windows unsteadily, deciding monthly whether they should be open or not. Regarding the *tilted-open windows*, an increase of open windows can be recognised between noon and 6pm. The percentage of *completely open windows* shows most changes over the day as it influences indoor comfort heavily. In summer, most window openings take place on the beginning of the working day and a few during the afternoon between 2pm and 5pm. In winter, the same pattern is found, but the percentages are much lower. The windows are closed at night. As the percentage of open windows changes mostly in the morning at 8am, after noon at 1pm and in the evening at 6pm, it can be assumed that operating windows strongly relates to the presence of people: arrival, lunch break and leaving of the office at the end of the working day.

Length of time windows were open

The average length of time windows belonging to a certain window type were open is shown in Figure 5.

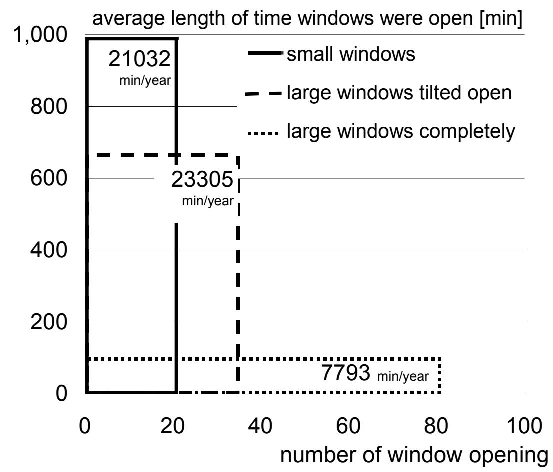

Figure 5 Mean values of the length of time windows were open. A curve is generated by calculating the average of all curves belonging to the same window type . The x-axis shows the average of how often a window was opened during the considered period of time and the y-axis shows the average of how long the window was open. The areas represent the average length of time windows of a certain window type were open during 13 months.

Small openings, i.e. small and tilted-open windows, are opened less frequently but remain open for a few days on average, whereas large openings, i.e. completely open windows, are opened more frequently, but are generally closed after less than a working day:

- The longest average length of time that small windows were open is about 10.000 minutes (approx. 7 days), for tilted open windows 6.000 minutes (approx. 4 days) and for completely open windows 800 minutes (approx. 13 hours). The average time of 13 hours indicates that a few times, probably during hot periods, windows were completely open for longer than one working day.

- The number of times a window was open follows an opposite trend. On average, large windows are completely opened 150 times, tilted 110 times and small windows are opened 95 times.
- Multiplying the average length of time a window was open by the average number of window opening yields the total number of hours a window was open during the 13 months:

On average, a small window was open 350 hours, a large window was tilted-open 388 hours and completely open 130 hours.

Building occupancy

Results in the previous section suggested a connection between the use of windows and the presence of occupants. The assumption will be reviewed in detail in this section. The charts presented so far have described the state of windows, differentiating between open and closed. In the following analysis, the event of opening or closing a window, i.e. the moment a change occurs, is considered.

Frequency at which windows are opened or closed

While the highest percentage of open windows was found in summer, as shown in Figure 4, the highest frequency of opening and closing windows occurs in autumn and spring, since weather conditions change most often during these seasons. Comparing different window types reveals that windows are completely opened more often than tilted opened. The small windows are opened or closed least frequently.

These observations are verified by Figure 6, which shows the typical daily behaviour.

- The curves belonging to the *small windows* and *tilted-open windows* are quite similar. Occupants tend to open and close windows most frequently in the morning and in the afternoon.
- Analysing data from *completely open windows* throughout 13 months, the pattern of morning and afternoon opening and closing becomes even clearer: In the morning, most changes of the window position occur, with a maximum at about 9am when occupants arrive at their workplace. Though lower in value, another peak occurs after lunchtime. When comparing the openings and closings of windows, it appears that both curves are almost identical in winter, indicating that windows are closed shortly after being opened in order to prevent droughts.

In summer, a time displacement exists between opening and closing a window, indicating that windows are opened longer than in winter. The second peak in summer is not as high as in winter. Concerning the closing of windows in summer, peaks are found in the morning and in the afternoon. Obviously, there are two cases during the summer: Either windows are closed shortly after being opened, or windows are left completely open throughout the day. In figure 6 it can be observed, that the small windows are usually opened twice a day, whereas the large windows show a large peak in the morning that decreases throughout the day. The trend is reversed when considering the times at which windows are more frequently closed.

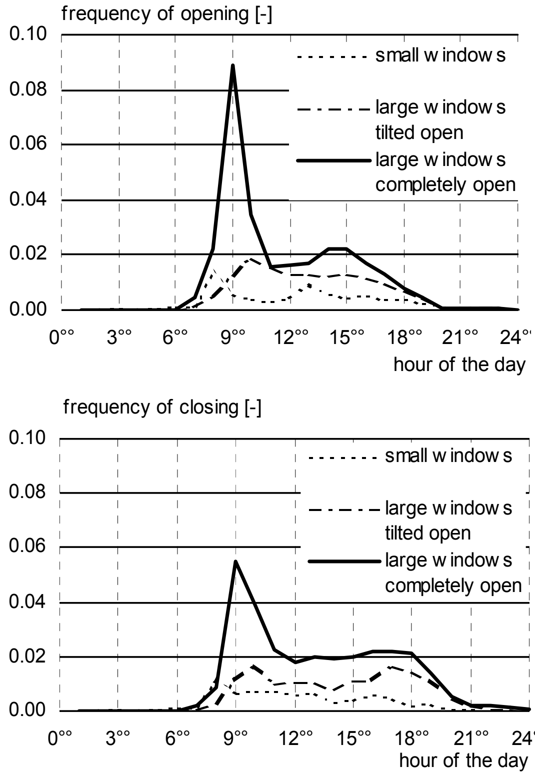

Figure 6 Typical daily trends averaged over all months of the considered period of time. Mean number of openings or closings per hour. Data evaluation of working hours (weekdays, 8am-6pm CET). Independent of arrival and departure.

Arrival / Departure / intermediate

In the following, the events of opening and closing a window will be analysed in relation to occupancy, differentiating between events that occur when a person arrives, is already present or leaves the office. Therefore, each individual window and the occupancy of each person in the corresponding office is considered. If a window is opened or closed, the occupancy of each person in the office is observed 15 minutes before and 15 minutes after opening or closing a window in order to filter short time occupancy. Four different cases can appear:

- Window opening or closing *at arrival.:* The occupant arrives between 0 and 15 minutes before a window is opened or closed.
- Window opening or closing *at departure.*: The occupant leaves the office within 15 minutes after a window is opened or closed.

- *Intermediate* window opening or closing: Two cases can appear: First the occupant is present 15 minutes before and 15 minutes after a window is opened or closed. Second the occupant is present only for a short time. The window is opened or closed exactly between arrival and departure.

Window opening or closing when *absent* are neglectable as this occur only if there is either a measurement error or the person is out of reach of the sensor.

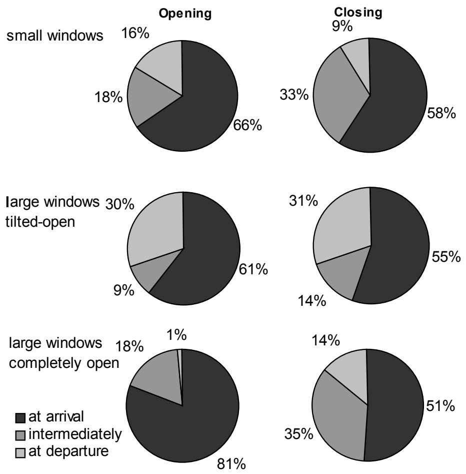

Figure 7 Window opening and closing of different window types. Percentage differentiation between window opening and closing at arrival, at departure and intermediate window opening and closing.

Figure 7 reveals the relationship between window opening/closing and building occupancy: Obviously, most *window openings* are associated with the arrival of a person. At arrival, 66 percent of small windows are opened, 61 percent of large windows are tilted and 81 percent of large windows are completely opened. The second highest number of openings (concerning small windows and completely open large windows) occur intermediately, accounting for 18 percent of all openings in both cases. Only 1 to 16 percent of window openings are found at departure. The tilting large windows follows an opposite trend. 30 percent of window openings take place at departure, whereas only 9 percent of window openings take place intermediately. The same trend occurs with *window closing*. At first, it seems amazing that many windows are closed when a person arrives. However, this can be explained by windows which are opened only for a short time. If windows are opened at arrival and closed within 15 minutes, the closing still occurs at arrival. One can see that most windows which are completely opened at arrival are closed shortly after (closing at arrival, i. e. within 15 minutes). The same appears with small and tilted-open large windows. However, since the small windows and tilted- open large windows remain open for a few days on average, the openings at arrival probably relate to other arrivals rather than closings. A more detailed analysis show, that the relation between window opening at arrival, intermediately and at departure is almost the same in winter and summer, though the number of window openings and closings is lower in winter.

DEVELOPING A USER MODEL

The analysis of the user behaviour shows a strong relationship between window opening and closing and the season. The study reveals that occupancy is another important driving variable. Entering and leaving the office is often connected with opening or closing a window. These relationships will be considered when a user model is developed.

- The outdoor temperature, which is strongly related with the season, is taken as an input variable instead of the season, since it is more convenient as an input variable. A future and more sophisticated model should take both into account, seasonal effects and outdoor temperature.
- The user occupancy depending on the time of the day is considered as another input variable.

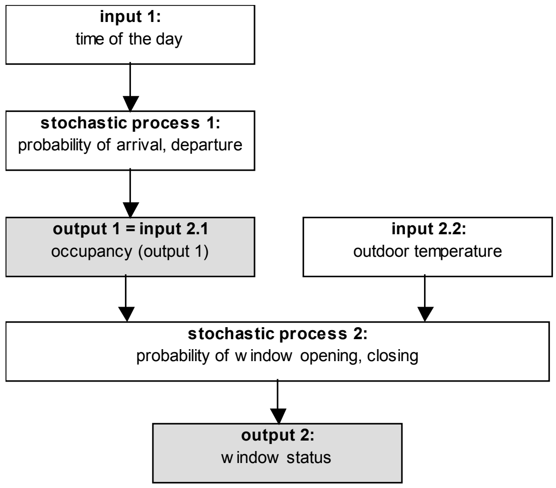

Figure 8 Scheme of the two stochastic processes used to predict the window status.

Based on these results, a user model is developed which simulates the user behaviour and predicts the window status in relation to the outdoor temperature and the occupancy. As can be seen in Figure 8, two stochastic processes are needed in order to predict the window status. First, the occupancy is determined in relation to the time of the day. Using the occupancy determined in the first stochastic process and the outdoor temperature as inputs, the window status is then predicted in a second stochastic process.

Occupancy model and probability

Based on the model for occupancy developed by Reinhart and Newsham, two random numbers of a rectangular distribution between 0 and 1 are generated to determine the time when an occupant is entering or leaving the office. The first random number is compared with the cumulated probability of arrival. The probability function of the occupancy is received by assigning the relative frequencies of arrival to each time unit. As windows are only opened or closed when a person is present, in the following only the time between the first arrival and the last departure is considered. Breaks in between, i. e. the short absence of a person, for example during the lunch break, are determined by another probability function which is generated by subtracting the cumulated probability of arrival from the cumulated probability of departure.

Window status model and probability

In order to predict the position of a window, a flow-chart is formulated, as shown in Figure 10. Data sets collected from the windows at each time step pass through the flow-chart and indicate the window status of each different type of window. To answer the question if the window is open at any given time, the result of the flow-chart from the previous time step is used. All arrivals are considered to determine the probability of opening or closing a window. Arrivals when the window is open and arrivals when the window is closed must be differentiated. The probability that a window is opened at arrival is determined by dividing the number of arrivals when the window is closed by the number of arrivals when the window is opened. The probability that the window stays closed can be calculated by subtracting the previous calculated probability from 1. The probability that a window is closed at arrival is calculated in the same manner. As the probabilities of opening or closing a window at the first arrival on a working day is much higher than at intermediate arrivals (i.e. entering the office after a short break), the probabilities are calculated separately for first arrivals and intermediate arrivals. The same steps are taken regarding the probabilities at departure. Again, it is differentiated between last departures of the days and departures in between. Plotting the probability against the time results in a probability function, as shown in Figure 9. The same steps are taken when calculating the probability that a window will be opened or closed when the occupant is already present or leaving the office.

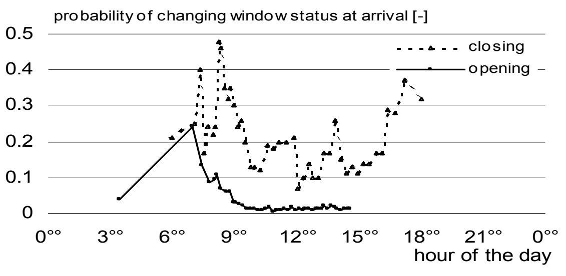

Figure 9 Probability function for changing of window status as function of time of day (large window e.g.)

Simulation result

When simulating the window status the probability of opening and closing a window is needed for each time step in relation to the outdoor temperature. The relationship between the probability p and the outdoor temperature t_o - is described by the quadratic equation $p = a \cdot t_o^2 + b \cdot t_o + c$, whereas a and b and c are constants determined for each probability function (arrival, intermediate and leaving x 3 window types = 9 sets of a,b,c). E.g. for large window completely opened at arrival is P = 5E-06t2 + 0.0002t + 0.0005.

A random number is generated for each time step and compared with the probability calculated in relation to the outdoor temperature and occupancy (first arrival, intermediate arrival, intermediate, intermediate departure, last departure). If the random number is lower than the probability or equal, the window status is changed, i.e. the window is opened or closed depending on the previous window status.

In Figure 11 the simulated data, converted into the mean percentage of open windows during the course of a day, are compared with the measured typical course of the day of open windows. The simulation results show that the window status can be simulated by taking the occupancy and outdoor temperature as inputs, but can surely be optimised.

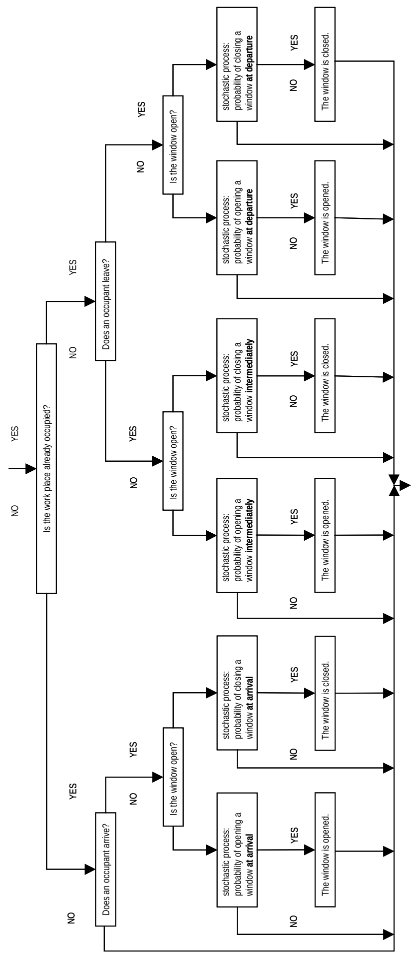

Figure 10 Flow-Chart of the user model.

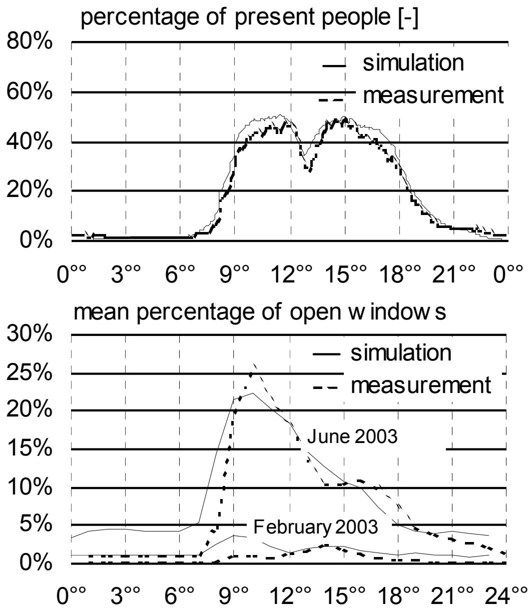

Figure 11Comparison of measurements and simulation of occupancy and window status

CONCLUSION

The relationships between the user behaviour and the season, the outdoor temperature, the course of the day and user occupancy are analysed in a new field study carried out in 21 offices. Based on these results, a preliminary user model is developed using the time of the day as an input to generate the occupancy (occupant arrives, leaves, is present) through a stochastic process. Depending on the occupancy and outdoor temperature, another input variable, the window status is predicted.

The percentages of open windows and frequency with which windows are opened or closed strongly correlate with the season. In summer the percentage of open windows is much higher than in winter. A sudden increase and decrease of the percentage of open windows is found in spring and autumn, indicating a change in the user behaviour presumably resulting from the first cold/warm day during the year As the highest percentage of open windows is found in summer, this results in a small number of window openings and closings. In winter, the length of time a window is open is short, but the percentage of open windows is small. The highest frequency in changing the window opening status is observed in spring and autumn probably because weather conditions are changing. When reaching a certain temperature, the measured percentage of open windows increases strongly until a maximum is reached. However, a percentage of 100 percent, as found in previous studies, is never reached, indicating that some windows are rarely, if ever, opened. The percentage of open small windows and tilted-open large windows varies only slightly between day and night, whereas completely open windows show big differences. During the night no windows are completely open. Analysis of the user behaviour during the course of a day show that windows are opened and closed more frequently in the morning, at lunchtime and in the evening. Analysing the arrival and departure of the occupant in detail reveals that most window openings and closings take place at arrival. Departure is the second most likely time to manipulate window status. The developed stochastic model to predict the window status shows promising results in representing user behaviour in building simulation. Uncertainty assessment can be done regarding the robustness of natural ventilation strategies using windows und thus enhance simulation quality. However, further work has to be done regarding the general validity of the derived probability functions and extensions to other variables as incident radiation, wind and indoor temperatures.

ACKNOWLEDGMENT

This work was funded by the German ministry of Economics and Labor under reference O3350006X. Special thanks to S. Oexle and A. Gerber, FH Biberach for setting up the data acquisition.

REFERENCES

Raya, I. A., Nicol, J. F., McCartney, K. J., Humphreys, M. A. (2001) “Thermal comfort: use of controls in naturally ventilated buildings“ Energy and Buildings, 33 (3), 235-244.

Nicol, J. F. (2001) “Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans“ Proceedings of the seventh international IBPSA conference, Rio, 1073-1078.

Warren, P. R., Parkins, L. M. (1984) “Window-opening behaviour in office buildings” ASHRAE Transactions, 90 (1B), 1056-1076.

Fritsch, R., Kohler, A., Nygard-Ferguson, M., Scartezzini, J.-L. (1990) “A stochastic model of user behaviour regarding ventilation” Building and Environment, 25, 173-181.

IWU, Institut für Wohnen und Umwelt (2003) „Wohnen in Passiv- und Niedrigenergiehäusern – Eine vergleichende Analyse der ‚Siedlung Lummerlund‘ in Wiesbaden-Dotzheim“

Reinhart, C. F. (2001) “Daylight Availability and Manual Lighting Control in Office Buildings – Simulation Studies and Analysis of Measurement“, IRB Verlag.

Pfafferott J., Herkel S., Jäschke M. (2003) “Design of passive cooling by night ventilation: evaluation of a parametric modeland building simulation with measurements”. Energy and Buildings 35

Newsham G. R., (1995). Lightswitch: A stochastic model for predicting office lighting energy consumption. Proc. Right Light Three, 3rd European Conference on Energy Efficient Lighting, Newcastle, UK , 59-66.