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Towards a model of user behaviour regarding the manual control of windows in office buildings

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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, indoor 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.

1. 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: 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-oriented offices within the Fraunhofer Institute's building in Freiburg, Germany. A brief literature review is presented in order to explain current knowledge.

Using questionnaires, Raja et al. [1] studied the use of building controls in 15 naturally ventilated office buildings in Oxford and Aberdeen, UK during a summer period. The study focused on analysing the relationship of windows, doors, blinds, fans, etc. with indoor and outdoor temperatures and thermal comfort. It is reported, that proportion of open windows increases with an increase in indoor and outdoor temperature. Only few windows are open when the outdoor temperature is below 15 °C, whereas most windows are open when the temperature exceeds about 25 °C. The incidence of discomfort is strongly correlated with the use of windows, suggesting that this control is used in response to discomfort. Occupants who sit close to a window, and thus have

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greater access to controls, report less discomfort than those away from a window.

Nicol [2,3] did a survey on the use of simple controls—windows, lighting, blinds, heaters and fans—in naturally ventilated buildings in the UK, Sweden, France, Portugal, Greece and Pakistan. His intention was to make realistic assumptions about user behaviour that can later be used for simulations. He showed how the use of each control varies with outdoor temperature: Although considerable variations were found between different climates—the highest proportion of open windows was found in the UK, followed by the other European countries, then Pakistan—in all countries, occupants started to open windows at a temperature above 10 °C. As the temperature rises there is an increased probability that a window will be open. Nicol calculated the probability p for open windows as a function of outdoor temperature.

Warren et al. [4] conducted a study in five naturally ventilated office buildings in the UK over a period of 3 months during the heating season. The study describes the window-opening behaviour of occupants and its influencing variables: window opening was found to be strongly related to weather conditions. The main independent variable was outdoor temperature, accounting for 76 percent of the observed variance. Solar gain (8 percent) and wind speed (4 percent) had less important effects. Warren differentiated between small and large openings. The former were related less strongly to the weather, as windows were opened by a small amount to satisfy indoor air quality requirements. In contrast, large openings were strongly affected by outdoor temperature and solar gain. Windows were fully opened to give higher ventilation rates in order to control indoor temperature. The extent to which windows are used in the heating season to control indoor temperature depends upon a range of factors, including building characteristics such as glazed area and orientation, the type of heating system and its controls. A questionnaire showed that the opening of windows is evenly distributed throughout the day. However, most people close their windows at the end of the day than at any other time. This suggests that once opened, windows are rarely closed until the room is finally vacated at the end of the working day.

Fritsch et al. [5] took measurements in four office rooms in the LESO experimental office building over a complete heating season. They pointed out that existing simulations run with unoccupied buildings disregarding the important effect of user behaviour on the airflow rate by opening windows. Using Markov chains they developed a stochastic model which generates time series of window angles. The outdoor temperature was found to be the most important driving variable for window opening. However, the strong relationship between the window angle and the outdoor temperature in winter does not exist during the summer. For temperatures over 18 °C, the occurrence of open windows as well as the opening angle is reported as independent of the ambient temperature. Therefore, the model was seen to be valid only for the winter period. Windows are usually left in one position for a long period.

Ebel et al. [6] monitored the user behaviour of occupants of residential buildings (so-called "passive houses" with an energy consumption $<15\,\mathrm{kWh/m^2a}$) over a whole year. They measured the number of hours an individual window was open during the day. In winter windows were not open as long as during summer. A continuously decreasing of number of hours was observed during winter from November until January. Starting in February windows were kept open longer, suggesting that occupants begin to change their behaviour at the end of the heating season. Followed by solar radiation, the outdoor temperature had the strongest effect on the use of windows. From 8 °C upward, the open-window hours increased arithmetically until they reached a maximum at a temperature of 18 °C. At higher temperatures, the mean number of hours a window was open during the day tended to decrease slightly.

Based on the original Lightswitch model by Newsham et al. [7], Reinhart derived the Lightswitch2002 [8,9] algorithm to predict personal control of electric lighting systems and blinds. Key concepts include stochastic functionality, and dynamic responses to short-term changes in luminous conditions and occupancy patterns. By stochastic, it is meant that whenever a user is confronted with a control decision, e.g. to switch on the lighting or not, a stochastic process is initiated to determine the outcome of the decision. By dynamics, it is meant that instead of looking at an average day in a year or month, user occupancy, indoor illuminances and the resulting status of electric lighting systems and blinds are considered at regular time steps (e.g. 5 min) throughout the year. Reinhart introduced the use of different models to predict whether an occupant switches his or her lights on or not upon arrival, or whether the same occupant switches lights off or not upon departure.

Bourgeois [10] developed a method to integrate sub-hourly stochastic processes into building simulation adopting the above mentioned models of Nicol and Reinhart.

Based on the main conclusions from the literature, the following 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.
- *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.

- *Indoor temperature*: when indoor temperature exceeds a certain value, the percentage of open windows increases rapidly until a percentage of 100 is reached.
- *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.
- *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.

The results of the above-mentioned studies cannot be generally applied to any building, as variables like climate, culture, building structure, space typology (e.g. residential or office building) play an important role. In literature driving forces for user–window interaction like noise level and indoor air quality were reported either as not recorded or as evaluated by questionnaires, which indicate the impoatance of these factors but does not contribute to formulate behavioural models. Nevertheless, previous work provides a good basis for formulating our own models which will later be reviewed. The restriction on one building limits the generalisability of the presented model.

2. Experimental set-up

2.1. 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 [11]. As no active central or personal air-conditioning system is installed in the offices, thermal comfort conditions are insured by implementing a passive cooling concept: internal and external heat gain reduction, thermal inertia and 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, the ventilator provides an air change of $1\,h^{-1}$ during working hours and $4.5\,h^{-1}$ at night. 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 outside working hours due to security reasons.

2.2. Data acquisition

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

- 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 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 Fig. 1).
- 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, a 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 recorded (IN/OUT) via an ultrasonic motion sensor attached to the monitor.
- A meteorological station is installed on the roof to acquire outdoor temperature and solar radiation every 10 s.

Fig. 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).

3. Results and analysis of monitored data

3.1. Correlation of window status and indoor/outdoor conditions

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

The correlation between the different weather records, hour of day, presence and window status as defined by Pearson is given in Fig. 2. The highest correlation can be found between indoor and ambient temperature with $r = 0.84$. The correlation between window status and ambient temperature is highest followed by indoor temperature. The correlation for large tilted window is lower ($r = 0.63$) compared to small window open ($r = 0.81$) and large window fully open ($r = 0.79$). The correlation for irradiation (r0.5) and wind patterns is small ($r < 0.2$) compared to the temperatures mentioned before.

3.2. Seasonal effects

A large change in user behaviour between summer and winter is found in the monitored period as can be observed in Fig. 3. 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.
- 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.
- 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.

3.3. Outdoor temperature

The relationship between the user behaviour and the outdoor temperature can be seen by analysing time-series data (Fig. 3). A correlation between the percentage of open windows and the outdoor temperature is shown to be significant ($p < 0.001$). Although the peaks in the percentage of open windows loosely correspond to those of

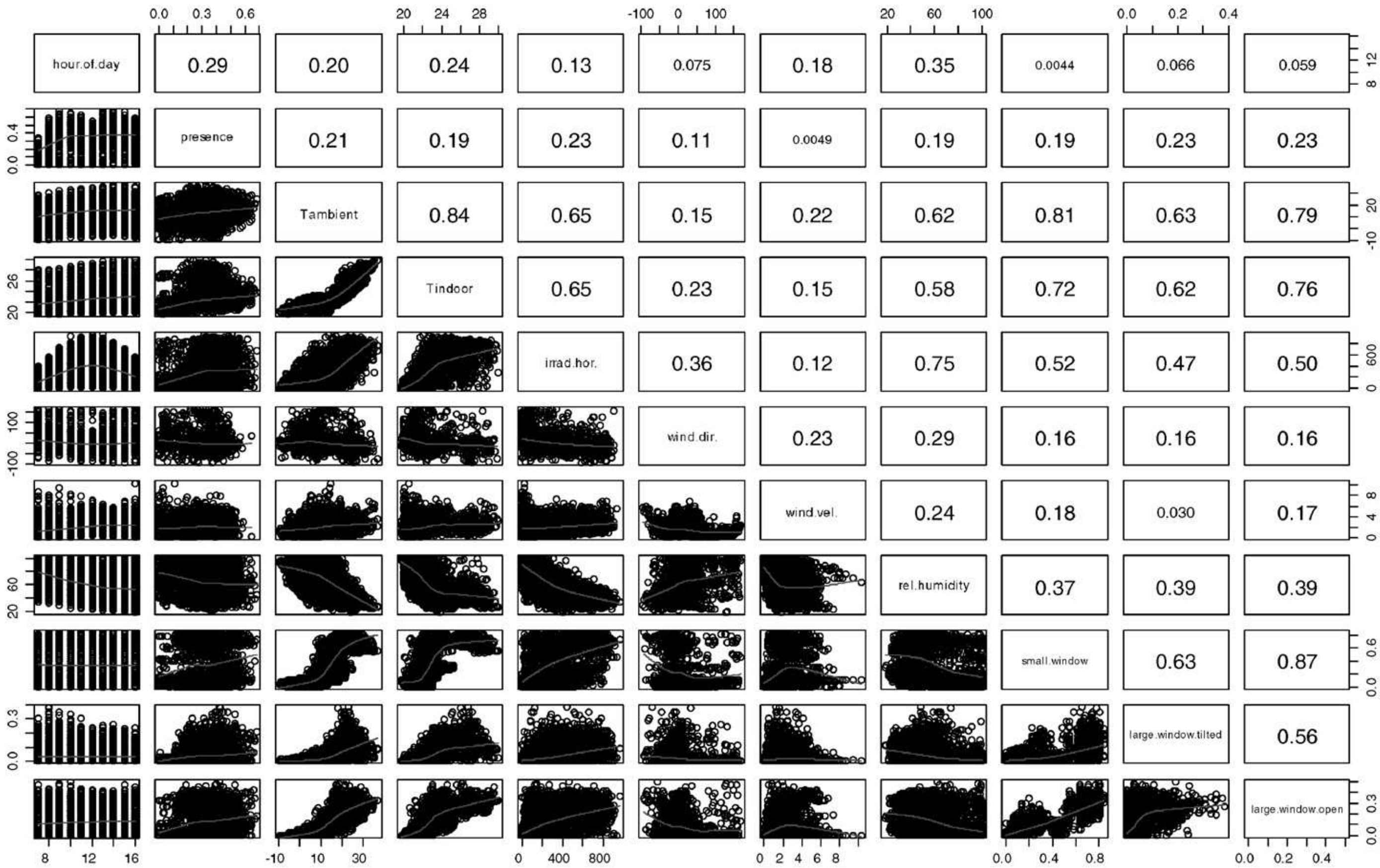


Fig. 2. Correlation between different climatic parameters, hour of day, presence and the hourly mean value of opening status of the monitored windows. Data base is weekdays between 7° and 17°. The correlation coefficient according to Pearson is given in the upper field.

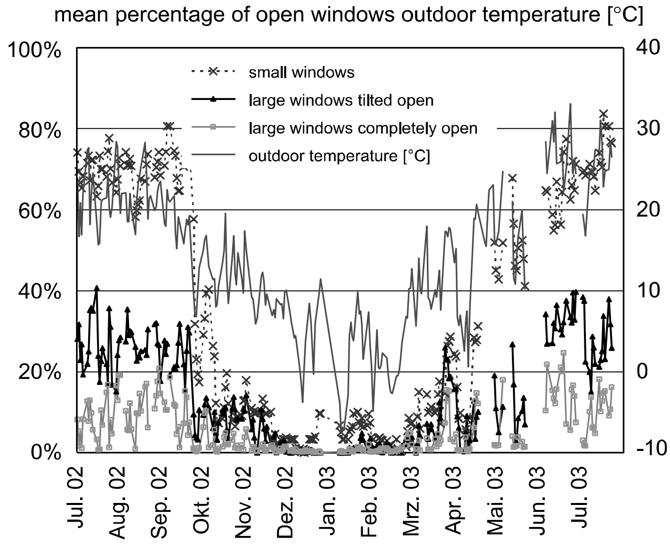


Fig. 3. Mean percentage of open windows. Daily mean values. Data evaluation of working hours only (weekdays, 8 am–6 pm CET).

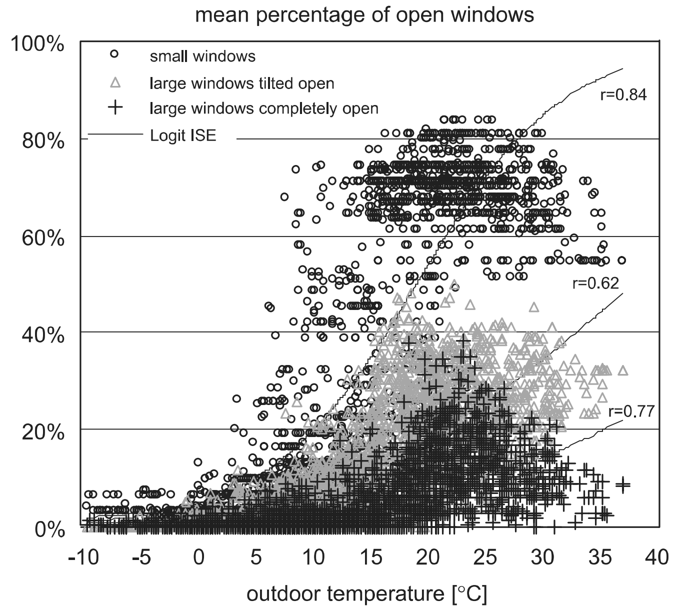


Fig. 4. Correlation of the mean percentage of open windows to the outdoor temperature over 13 months. Hourly mean values. Data evaluation of working hours (weekdays, 8 am–6 pm CET, occupied and unoccupied times).

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

outdoor temperature, the sudden seasonal drop—or hike—in the percentage of open windows does not correspond to any sharp shift in outdoor temperatures. User behaviour changes along with variations in outdoor temperature, yet a comparison of days with equal mean outdoor temperatures—yet during different seasons—reveals that the percentage of open windows differs according to both temperature and time of year. It is observed 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.

The relationship between the percentage of open windows and the outdoor temperature is analysed in greater detail in Fig. 4. Comparing the data of different windows with the Logit -function proposed by Nicol [2001] reveals a relationship between user behaviour and outdoor temperature, where the probability p for open windows is calculated as a function of outdoor temperature. Nicol expressed this relationship with the following 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. The parameters a and b of the logit function for the three evaluated states of the windows are given in Table 1, using hourly weekday data from 7° to 17° and using a least-squares fit.

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. 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.

Observation show that 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.

3.4. Indoor temperature

The indoor temperature is strongly related with the outdoor temperature as shown in Fig. 5. At outdoor temperatures below 15 °C, i.e. in winter, the statistical spread is small. The indoor temperature remains between 20 and 23 °C, as the heating system maintains consistent room conditions. In summer, however, the influence of the outdoor temperature becomes visible. When outdoor temperatures exceed 15 °C, both the indoor temperature and the statistical spread (difference between the maximum and minimum indoor temperature belonging to a certain outdoor temperature) increase.

In general, the increase of indoor temperature results from different factors such as outdoor temperature, solar radiation and internal loads. As internal loads are assumed to be almost constant in summer and winter, the relevant driving variables for the increase of indoor temperature are supposed to be higher temperatures and solar gain caused by higher solar radiation in summer.

Open windows can have a strong effect on the indoor temperature on warm summer days if the outdoor temperature exceeds the indoor temperature. As only a few days with outdoor temperatures higher than the indoor temperature exist during the considered 13 months, a higher indoor temperature does not result from an increasing percentage of open windows.

A possible reason for the increasing indoor temperature could be that the passive cooling concept is realised by thermal inertia and night ventilation. If the stored heat is not dissipated during the night, the thermal inertia of walls does not help provide comfortable indoor temperatures. Since the outdoor temperature does not fall under 15 °C during the nights of hot summer months, an efficient night ventilation cannot be guaranteed. Walls can only store a finite amount of heat. If this limit is exceeded, the indoor temperature increases constantly until nights become cooler again.

Fig. 6 presents the relationship between the percentage of open windows and the indoor temperature. The figure is very similar to Fig. 4, since there exists a strong correlation between indoor and outdoor temperature.

Between 20 and 25 °C, the percentage of open windows ranges from 0 to 80 percent. Between 25 and 27 °C, the percentage of open windows stays almost constant. At temperatures higher than 27 °C, people tend to open small windows less. However, this observation cannot be generalised as only a few hot days were measured.

The correlation of the percentage of open windows to the indoor temperature is smaller than the correlation to the outdoor temperature. The data belonging to outdoor temperatures between –10 and 15 °C, i.e. a range of 25°, is compressed to an indoor temperature range of 3°, which means the indoor temperature varies between 20 and 23 °C. The same happens at higher outdoor temperatures, but the

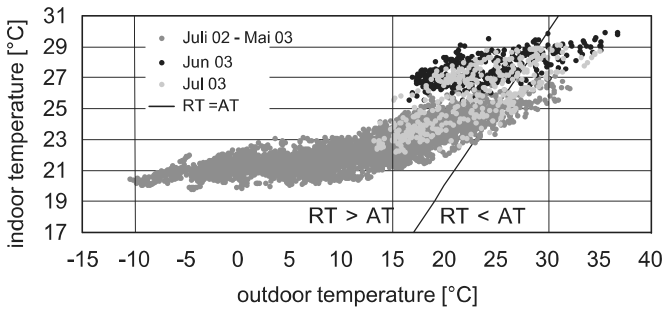


Fig. 5. Relationship between indoor and outdoor temperature during the period of 13 months. Hourly mean values.

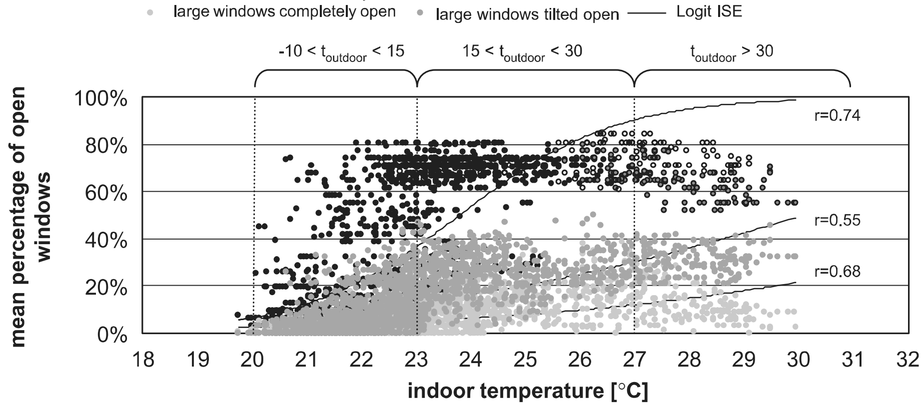


Fig. 6. Correlation of the mean percentage of open windows to the indoor temperature over the period of 13 months (July 2002–July 2003). Hourly mean values. Data evaluation of working hours (weekdays, 8 am–6 pm CET).

indoor range is not as compressed, since no heating system maintains a constant indoor temperature. The best fit with the logit function is found with the small windows, having a correlation coefficient of $r = 0.74$, followed by the completely open large windows ($r = 0.68$) and the tilted-open windows ($r = 0.55$).

3.5. 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/her open or close windows? In his section, user behaviour is analysed at different times of day, with the aim of establishing behavioural patterns.

3.5.1. Percentage of open windows

Fig. 7 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 suggest. 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, few changes occur between day and night. The *small windows* donot 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 6 pm. 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 2 and 5 pm. 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 8 am, after noon at 1 pm and in the evening at 6 pm, 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.

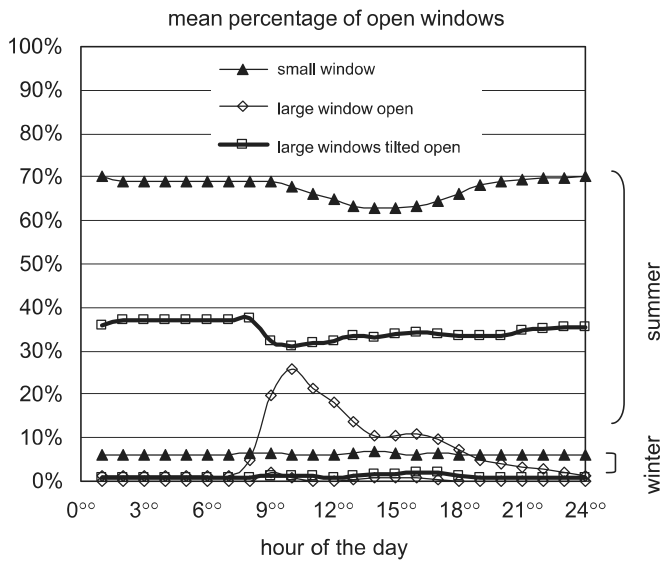


Fig. 7. Typical courses of the day. Monthly mean values for each hour of a day (0–23). Data evaluation of weekdays 0 am–11 pm CET.

3.5.2. Length of time windows were open

The average length of time windows belonging to a certain window type were open is shown in Fig. 8.

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 min (approximately 7 days), for tilted-open windows 6,000 min (approximately 4 days) and for completely open windows 800 min (approximately 13 h). The average time of 13 h 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 h, a large window was tilted-open 388 h and completely open 130 h.

3.6. 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

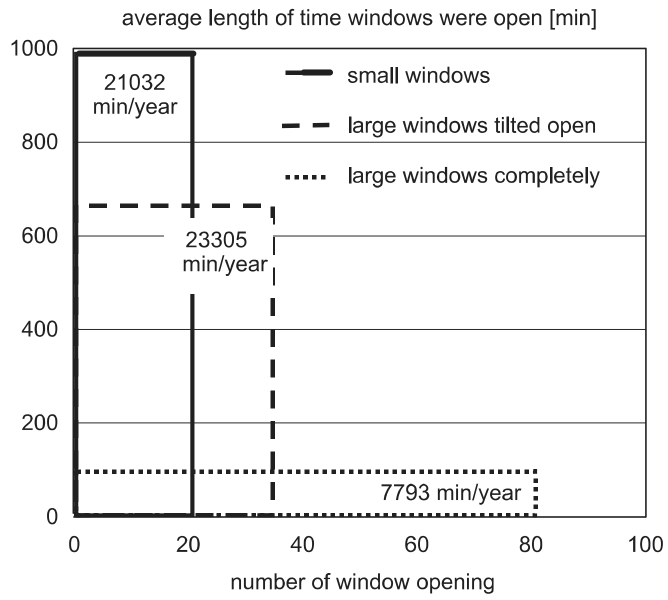
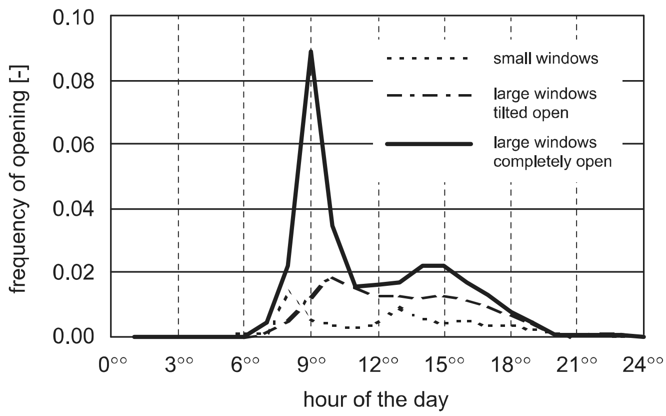


Fig. 8. Mean values of the length of time windows were open. A curve is generated by calculating the average of all curves belonging to the same window type. x-axis shows the average of how often a window was opened during the considered period of time and y-axis shows the average of how long the window was open. The areas represent the average length of time windows of a certain window type were open during 13 months.



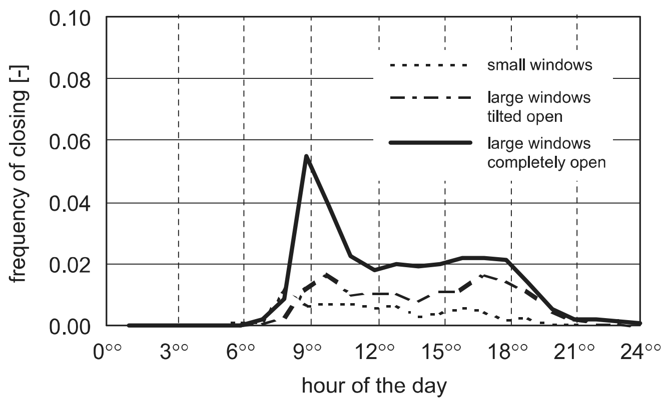


Fig. 9. Typical daily trends averaged over all months of the considered period of time. Mean number of openings or closings per hour. Data evaluation of working hours (weekdays, 8 am–6 pm CET). Independent of arrival and departure.

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.

3.6.1. Frequency at which windows are opened or closed

While the highest percentage of open windows was found in summer, as shown in Fig. 7, 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 frequently than tilted opened, while small windows are opened or closed least frequently.

These observations are verified by Fig. 9, 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: most changes of the window position occur in the morning, with a maximum at about 9 am 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, possibly in order to prevent draughts.
- 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 Fig. 9 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.

3.6.2. 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 min before and 15 min after opening or

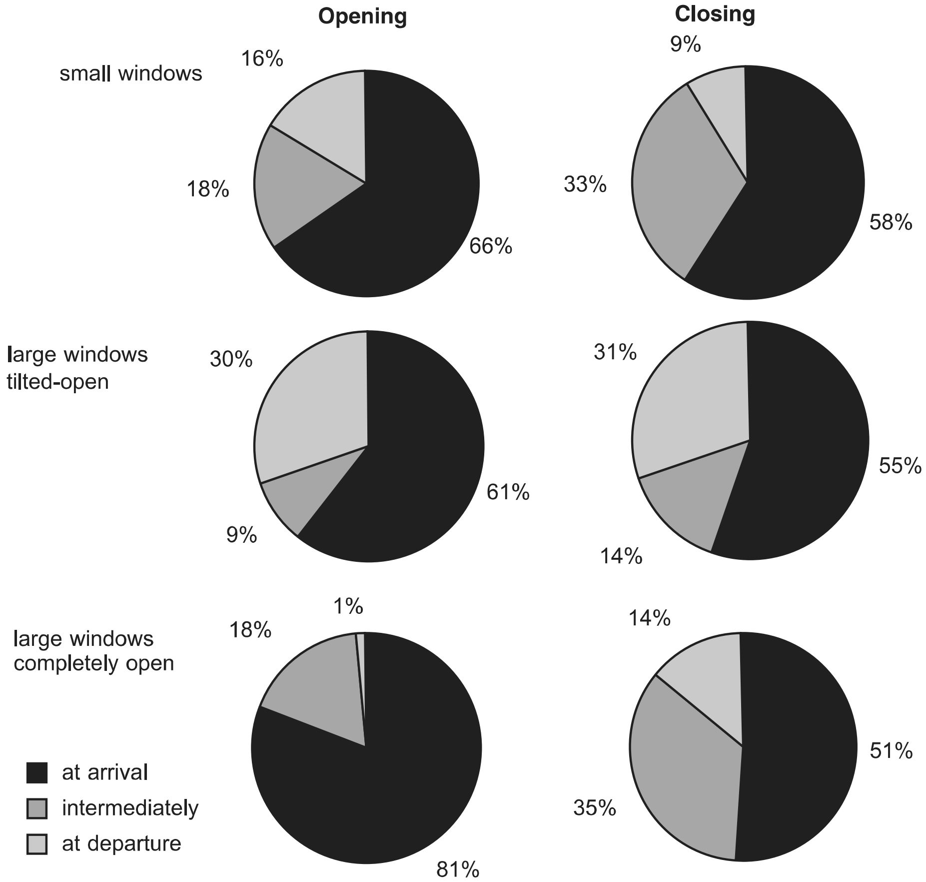


Fig. 10. Window opening and closing of different window types. Percentage differentiation between window opening and closing at arrival, at departure and intermediate window opening and closing.

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 min before a window is opened or closed.
- Window opening or closing *at departure.*: the occupant leaves the office within 15 min after a window is opened or closed.
- *Intermediate* window opening or closing: two cases can appear: First the occupant is present 15 min before and 15 min 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 occurs only if there is either a measurement error or the person is out of reach of the sensor.

Fig. 10 reveals the relationship between window opening/closing and building occupancy: Most *window openings* can be 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 1–16 percent of window openings are found at departure. The tilting large windows follows an opposite trend. About 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*. It may seem odd at first 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 min, 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 min). 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 shows, 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.

4. Developing a user model

The analysis of the user behaviour shows a strong relationship between window opening and closing and the season. However, what is season by meaning of quantifiable conditions? From the recorded data, it can be derived that "winter" behaviour starts with a first drop of the daily mean of the outdoor temperature below 10 °C, while "summer" behaviour starts with a first exceeding of 15 °C by the ambient daily mean temperature. So switching in seasonal behaviour could be reflected in a model by observing such drops and exceeds of the running dalily mean of the ambient temperature. Nevertheless, this observation is based only on one season in one building and therefore not yet used in the model.

The field study indicates that indoor temperature can be used for modelling in the same way as ambient temperature which is chosen as model input. Indoor temperature is not used for two reasons—first indoor air temperature as a calculated variable in building simulation is of less accuracy as ambient temperature, second the additional information about user behaviour is small due to the high correlation between indoor and ambient temperature.

The study reveals that occupancy is another important driving variable. Entering and leaving the office is often connected with opening or closing a window.

So the following relationships are considered in developing a user model.

- outdoor temperature,
- user occupancy depending on the time of the day is considered as another input variable.

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 Fig. 11, two stochastic processes are needed in order to predict the window status. First, occupancy is determined in relation to the time of the day. Using occupancy determined in the first stochastic process and outdoor temperature as inputs, the window status is then predicted in a second stochastic process.

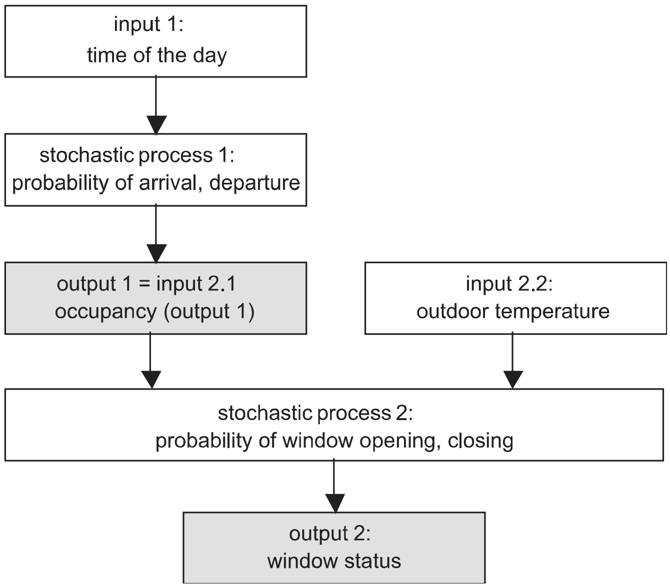


Fig. 11. Scheme of the two stochastic processes used to predict the window status.

4.1. 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.

4.2. Window status model and probability

In order to predict the position of a window, a flow chart is formulated, as shown in Fig. 13. 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, daily "final" versus "intermediate" departures are differentiated. Plotting the probability against time results in a probability function, as shown in Fig. 12. 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 (See also Fig. 13).

4.3. 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_0 is described by the quadratic equation $p = at_0^2 + bt_0 + c$, whereas a, b and c are constants determined for each probability function (arrival, intermediate and leaving $\times$ 3 window types = 9 sets of a, b, c). E.g. for small window opened at arrival is

$$P = 5E - 06^{*}t^2 + 0.0002^{*}t + 0.0005 \pm 0.003$$

with a correlation of $r = 0.77$. The probability function was derived by grouping the 4103 arrival events into classes of 100 and fitting with a least-squares fit (Fig. 14).

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 Fig. 15 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.

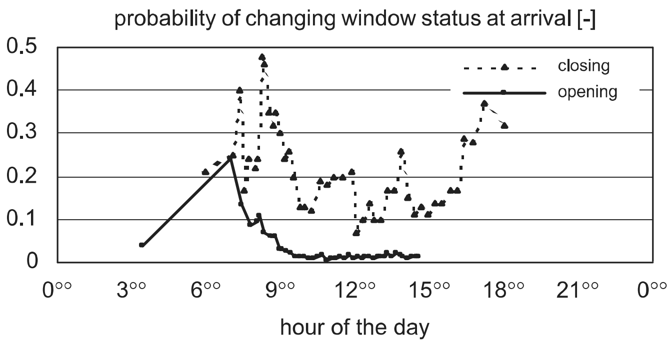


Fig. 12. Probability function for changing of window status as a function of time of day (large window e.g.).

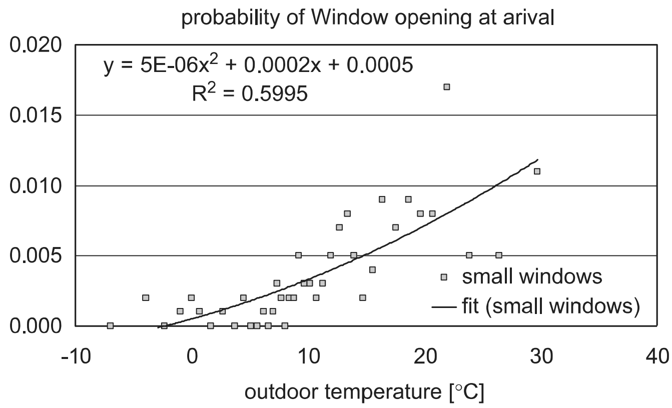


Fig. 14. Probability of opening at arrival for small windows as a function of the ambient temperature. Points represent the probability of 100 events.

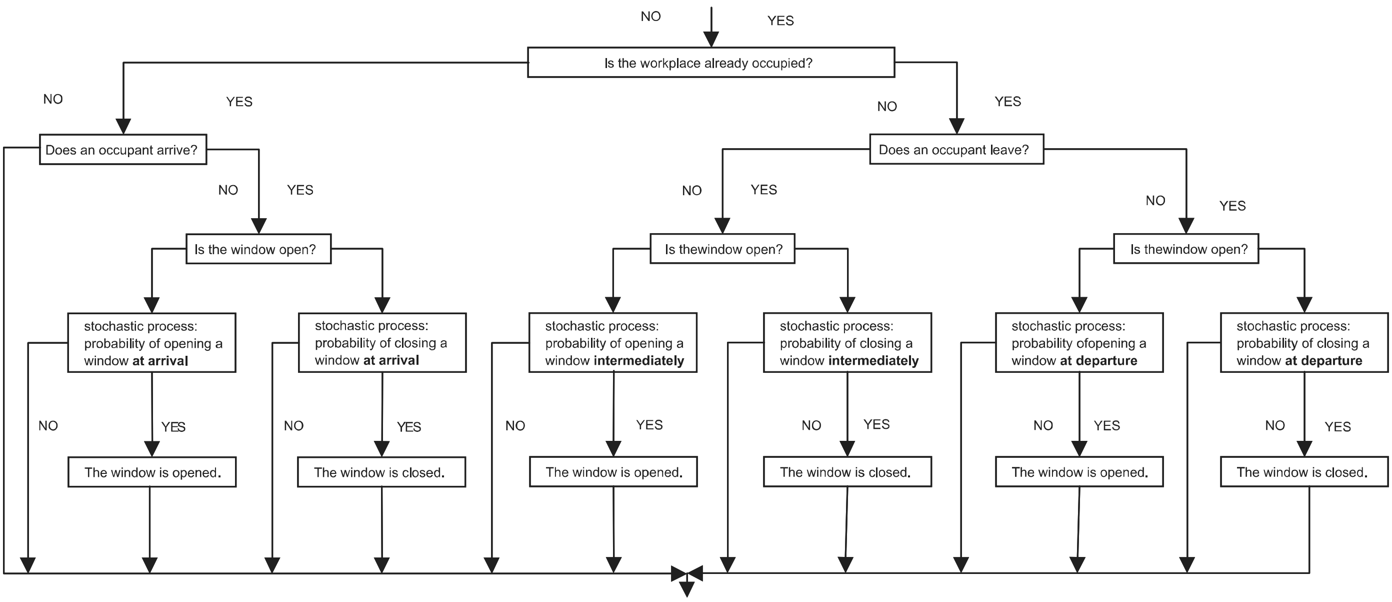


Fig. 13. Flow chart of the user model.

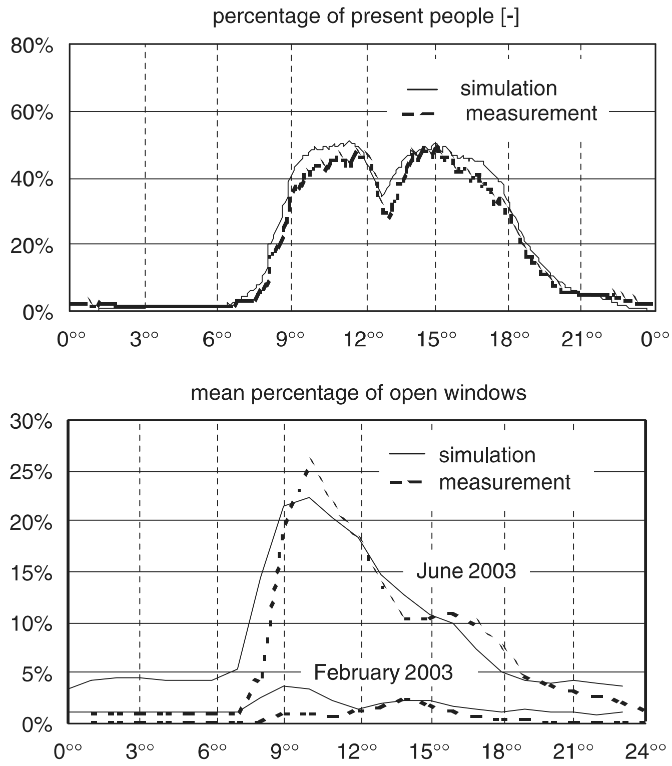


Fig. 15. Comparison of measurements and simulation of occupancy and window status.

5. Conclusion

The relationships between user behaviour and the season, the indoor and 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 sharply. When reaching a certain temperature, the measured percentage of open windows increases strongly until a maximum is reached. However, 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. At night no windows are completely open. Analysis of the user behaviour during the course of a day shows 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 and 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. Future field studies should include recording of noise level and indoor air quality, the latter could be easily applied as input variable in a model. In order to enhance the validity and generalisability of behavioural model buildings with different HVAC concepts an space typologies should be analysed.

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