The influence of stochastic modeling of window actions on simulated summer comfort in office buildings

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Abstract

In this study, an attempt is made to define building design variables for a medium-sized office building with individual office cells in order to provide sufficient summer comfort without active cooling in a moderate climate.

Firstly, an approach to take realistic window-opening behavior into account is proposed based on observational data in literature. A stochastic model is defined for an active and a passive user, representing the variability between individuals.

The uncertainty in summer comfort due to the building use and occupant behavior is then assessed. The sensitivity of the simulated summer comfort proves to be substantial. A criterion for robustness of the building design for behavioral aspects is deduced from this analysis.

Finally, it is shown using the proposed criterion that for office cells with external shading where window-opening is allowed, satisfying summer comfort can be guaranteed independent of the building use if the glazing-to-wall-ratio does not exceed 60%.

Keywords: Window-opening, behavioral model, summer comfort, office building, adaptive theory

Introduction

In Belgium, which has a moderate climate, many existing small or middle-sized office buildings are not equipped with active cooling systems, but rely on window-opening for summer comfort [1]. In addition, there is a trend towards constructing low energy and even so-called passive office buildings. In these designs, it is attempted to combine minimized heating demands with passive cooling techniques ([2], [3]). Furthermore, it is now known that occupant satisfaction is higher in office buildings where the user can exercise some control over the environment than in fully air-conditioned offices ([4], [2]). Off course, this cannot be applied in every situation: window-opening or applying external shading is not always possible and manual control in landscape offices is often infeasible due to social interaction.

Meanwhile, the adaptive comfort theory has found its way to the building standards. The European standard EN15251, which provides boundary conditions for the design and the assessment of energy performance of buildings, allows for higher temperatures as a function of running mean outdoor temperature in buildings where the opening of windows is the primary means of regulating the thermal conditions in summer. This is a strong incentive for building designers to develop passive cooling concepts. However, when assessing the expected summer comfort at the design stage through building simulation, the manual control of windows is generally simplified to deterministic thresholds at which windows are assumed to be open ([5], [6]). The influence of the occupant can however be substantial [3].

During the past decades, several researchers have introduced behavioral window-opening models based on observational data for individual or 2-person offices ([7], [8], [9], [10], [11], [12]). Most of these models are Markov chains, with probabilities of transition depending on the physical conditions. There is disagreement between the authors on the selection of driving variables for actions on windows, though the recent publications seem to agree upon the inclusion of the indoor temperature, to explicitly implement the adaptive principle ([11], [12]). Additionally, these recent models include the occupancy state as a driving variable, because it was noticed that most of the actions occurred when the user was arriving at or leaving his office. Quasi all of the data were collected in office buildings without ventilation system, but the indoor air quality is not included as a driving variable in any study. Furthermore, no information on window opening angles was gathered. There is a clear lack of intercomparison and validation of all introduced models, preventing them to safely expand their applicability beyond the observed office building. Some of the models have already been coupled to building simulation software ([3], [10]).

In this study, the summer comfort of a middle-sized office building with varying building parameters will be calculated, taking into account a realistic pattern of window-opening based on the model of [12]. The requirements for the building design to provide sufficient comfort without active cooling for the Belgian climate can thus be identified. In addition, the uncertainty on this result due to occupant behavior will be assessed.

Building Model

The simulations are performed for the climate of Uccle, Belgium. The geometry of the office space is given in Fig. 1. The internal walls are assumed to be adiabatic, so heat losses or gains occur through the external façade only (though heat can be stored in the internal constructions). This façade faces south, representing the worst case scenario. The external wall is a masonry cavity wall; the floor is a heavyweight, concrete construction and the internal walls are lightweight, gypsum board walls. A basic hygienic ventilation rate of 1.2 ACH is supplied at outdoor temperature during office hours. Two levels of internal heat gains from appliances are considered: 5.4 W/m^2 and 16.1 W/m^2, respectively identified as low and moderate/high in [13].

The considered building variables and their ranges are the following:

- U-value of the opaque part of the external façade. This ranges from 0.6 W/m^{2}K (the legal maximum for new constructions in Flanders) to 0.15 Wm^{2}K (the Passive House Standard).
- Glazing-to-wall-ratio. This ranges from 21% to 71%.
- Glazing type. 6 glazing types were selected from manufacturer's data (see Table 1). Glazing with U-value higher than 1.1 W/m^{2}K is rarely placed in Belgian offices nowadays, so this is not considered. Types 1 to 5 represent the whole commercially

available spectrum of visual transmittance (in discrete steps) and associated g-value for double low-e glazing with a gas-filled cavity. Type 6 is a triple glazing.

- Shading device. The considered types are: (a) no shading device, (b) external fixed horizontal louvers. The latter is selected as a shading device, because it is assumed to have a minor influence on the air flows, as opposed to for example screens.

The combination of these variables results in 180 different building designs.

Behavioral Model

The model of [12] is selected for this research, because it is based on the largest dataset and the broadest measuring campaign. It is a Markov chain with probabilities of transition as a function of several physical variables and of the occupancy state.

In reality, there’s an important variability in user behavior that should be included in the uncertainty analysis. This is accomplished in this study by defining representative active and passive users [14]. As is stated in [15], the characteristic physical variable A_{50}, for which the probability of action is equal to 0.5, is a fair indicator to compare the individuals. Thus, it is proposed here to define *active* behavior as the 25th percentile and *passive* behavior as the 75th percentile of the set of individual A_{50}-values, where A is the most influential driving variable of the respective probability function. The functions resulting from this methodology are shown in Fig. 2. Since night ventilation is not considered in this study, it is assumed that the windows are closed at the last departure of the day.

From bivariate plots in [15] it can be deduced that people show consistent behavior at different occupancy states, e.g. users that show *active* opening behavior at arrival will also show this *active* behavior at intermediate times. However, people with *active* opening behavior will not necessarily show *active* closing behavior and vice versa. Therefore, two representative user patterns are defined, one with *active* opening and *passive* closing and one with *passive* opening and *active* closing. These two types will yield respectively the largest and the smallest net window opening times in building simulation.

As the behavioral model of window-opening depends on the occupancy state, it is necessary to implement a detailed stochastic occupancy model. Several models are available, but require mostly building specific inputs that cannot be supplied for this generic office building ([16], [17]). A simplified version of the model of [17], called the *Lightswitch* model, was already introduced in [18]. The probabilities of transition for 5 minute time steps are estimated from empirical data (Fig. 3).

To introduce some variability in the occupancy profiles, a parameter is introduced, accounting for the differences amongst office buildings. The probability of temporary absence is multiplied by a *parameter of mobility* M. This is the most important parameter, because it determines the number of vacant-to-occupied events per day, which influences the window-opening behavior. Based on findings in [17], [16] and [19], a spectrum for the parameter of mobility of 0.1 to 0.7, resulting in an average of 3 to 9 vacant-to-occupied events per day, is established.

Because the behavioral model is stochastic, it will generate different results every time it is run. However, in this research, only one run of the model for every building variant is done in order to limit the calculation time. For one building variant, the behavioral model was run 100 times, to see how large the deviations are. In terms of weighted exceeding hours (see further), the standard deviation due to the stochastic character of the behavioral model was limited to about 15% (Fig. 4).

Thermal and Lighting Model

The summer comfort calculations are performed with TRNSYS version 16 [20], a software package for dynamic building simulation, with a 1 hour time step. The installed lighting power is 11 W/m^2. The lighting is assumed to be switched on at full power at first arrival and switched off on last departure of the occupant. Additionally, an automated daylight dimming control is simulated, which results in lower heat gains. The light simulations are performed with the Daysim software [21]. Finally, the behavioral model is implemented in Matlab and is coupled in real-time to TRNSYS to be able to take possible window-opening as an adaptive action into account.

Air Flow Model

Only single-sided ventilation is considered. This is the most conservative option, resulting in the lowest air flows ([2]) and is therefore appropriate when assessing comfort. Because of this option, it is sufficient to model only one office cell. The air flows when the window is opened are estimated using EN15242:

$$q_{v,win} = 3.6 \cdot 500 A'_{ow} \sqrt{C_t + C_w V_{met}^2 + C_{st} H_{win} \left| \theta_i - \theta_e \right|} \qquad \text{(Eq. 1)}$$

Where the coefficients C_t (=0.01), C_w (=0.001) and C_{st} (=0.035) account for respectively the influence of wind turbulence, wind speed and stack effect. V_{met} is the meteorological wind speed at 10m height and H_{win} is the height of the window. A'_{ow} (m^2) is the equivalent open area of the window, depending on the opening angle α and the area of the window A_{ow}:

$$A'_{ow} = \left(2.6 \cdot 10^{-7} \alpha^3 - 1.19 \cdot 10^{-4} \alpha^2 + 1.86 \cdot 10^{-2} \alpha\right) A_{ow} \qquad \text{(Eq. 2)}$$

Two opening angles are considered, 10° and 90°.

This calculation method is simplified, but as was shown in [22], the resulting air flows comply well with air flows calculated with a more sophisticated nodal network. It is therefore decided to use this simplified equation in the building simulations, since this effects in much smaller computational times.

Summer comfort criteria

The summer comfort of the different building designs is assessed according to the degree hours criteria of the European standard EN15251. In this method, the comfort is considered insufficient if the weighted sum of hours at which the indoor temperature exceeds the limit value is more than 5% of the occupied time, i.e. about 100 hours on a yearly basis. The weighing factor is the difference between the occurring temperature and the limit value. The latter depends on the running mean outdoor temperature (Fig. 5).

Thus, in contrast to [3], the interest of this analysis does not lie in detailed temperature profiles, but rather in aggregated seasonal performance.

Results and Discussion

Different behavioral patterns are simulated for every building design. The level of internal heat gains from appliances, lighting control, occupant mobility, window-opening user type and opening angles are considered here as behavioral variables. For each variable, two more extreme values were chosen, resulting in 32 patterns.

In Fig. 6, the results are shown for a sample of the building designs, ordered according to the mean of the weighted exceeding hours for the 32 patterns. The graph shows the mean value, 25th and 75th percentile in the boxes, while the whiskers show the 10th and 90th percentile.

It is clear that on the one hand, for about half of the designs the simulated summer comfort is independent of the behavioral patterns, either because there are no problems or because there are certain problems to provide satisfying comfort. However, for another part of the building designs, the summer comfort is not guaranteed and is dependent on the occupant behavior. In Fig. 7, this is shown in detail. This raises the question about the necessary robustness of designs for user behavior. Should the building suffice even in the worst case scenario? When considering the rather conservative upper value of the internal heat gains and the fact that a possible correlation between 'activity' of window-opening and individual sensitivity for high temperatures is neglected, this might be too strict. It is therefore proposed for this research that a building satisfies if the 75th percentile of the results for simulations with different behavioral patterns is lower than 100 weighted exceeding hours.

In Fig. 8, the 75th percentile of the weighted exceeding hours is compared for different window-opening patterns for a selection of buildings. This graph indicates that applying a deterministic threshold temperature at which the windows are opened underestimates the potential summer discomfort. Using a deterministic threshold in building simulation appears to be comparable to assuming an *active* window-opening behavior, which is a too optimistic boundary condition for comfort calculations, as this is only representative for minor part of the building occupants.

In this last paragraph the building designs that can provide satisfying summer comfort without active cooling are identified. The higher established criterion for robustness for building use and occupant behavior is applied, i.e. only buildings where 75% of the behavioral profiles result in less than 100 weighted exceeding hours annually are retained.

Some conclusions can be drawn from Fig. 9. Firstly, respective comparison between the graphs for U-value of the opaque façade of 0.6 W/m^{2}K and 0.15 W/m^{2}K, and the graphs for glazing 5 and 6 -with comparable g-values but different U-values, see Table 1- learns that thermal insulation of the envelope has a negligible influence on the performance of the building in summer conditions.

Secondly, it is possible to achieve good summer comfort without active cooling in a building without solar shading, but only for small glazing-to-wall-ratios (lower than 40%) and glazing with low g-values (lower than 0.40).

Finally, unless for very large glazing-to-wall-ratios (higher than 60%), it is possible to design the individual office cells of an office building in a moderate climate without active cooling, if external solar shading is applied and window-opening by the occupant as an adaptive measure is allowed.

Conclusions

In this study, an attempt has been made to define building design variables for a medium-sized office building with individual office cells in order to provide sufficient summer comfort without active cooling in a moderate climate.

Firstly, an approach to take realistic window-opening behavior into account was proposed based on observational data in literature. A stochastic model, which explicitly includes the adaptive principle, has been defined for an active and a passive user, representing the variability between individuals.

The uncertainty in summer comfort due to the building use and occupant behavior was then assessed, by applying different levels of internal gains, occupancy variability, varying lighting control, *active* and *passive* window users and different window opening angles. The sensitivity of the simulated summer comfort proved to be substantial. A criterion for robustness of the building design for behavioral aspects was deduced from this analysis. The uncertainty on the induced air flow through window-opening was not taken into account.

Finally, it was shown using the proposed criterion that for office cells with external shading where window-opening is allowed, satisfying summer comfort can be guaranteed independent of the building use if the glazing-to-wall-ratio does not exceed 60%. It is also possible without external shading device, but only for small glazing-to-wall-ratios and low g-value glazing.

Acknowledgments

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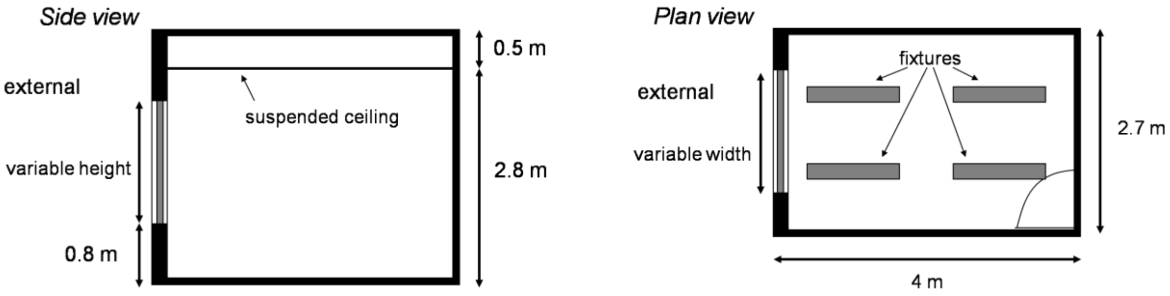
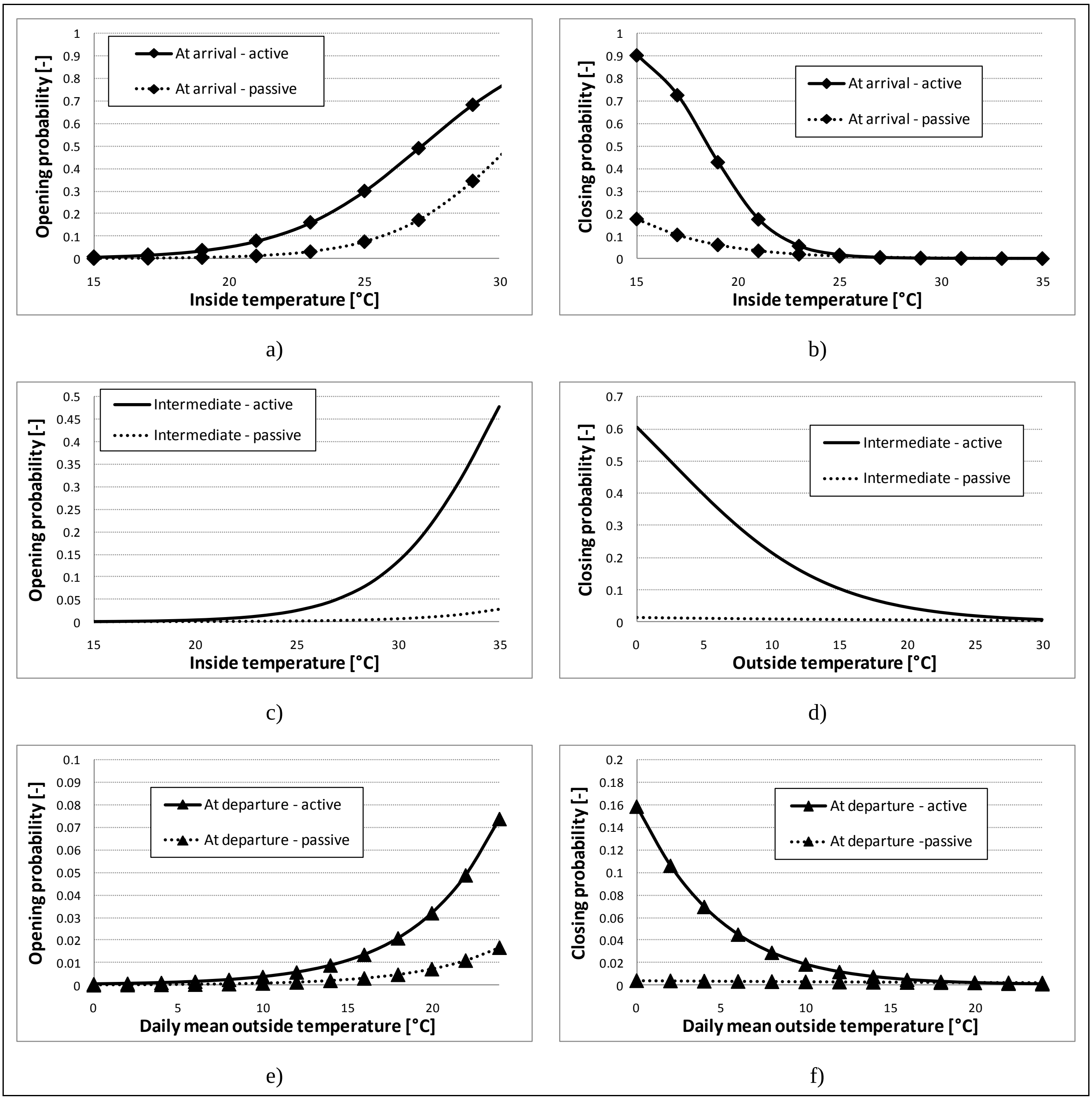


Fig. 1 Office geometry



a) b)

c) d)

e) f)

Fig. 2 Probabilities of transition as a function of the main physical stimulus for different occupancy states for active and passive users. a) no rain, previous absence over 8h and outdoor temperature 15°C b) outdoor temperature 20°C c) no rain, ongoing presence of 2h and outdoor temperature 15°C d) indoor temperature 20°C e) following absence over 8h f) following absence under 8h and indoor temperature 20°C

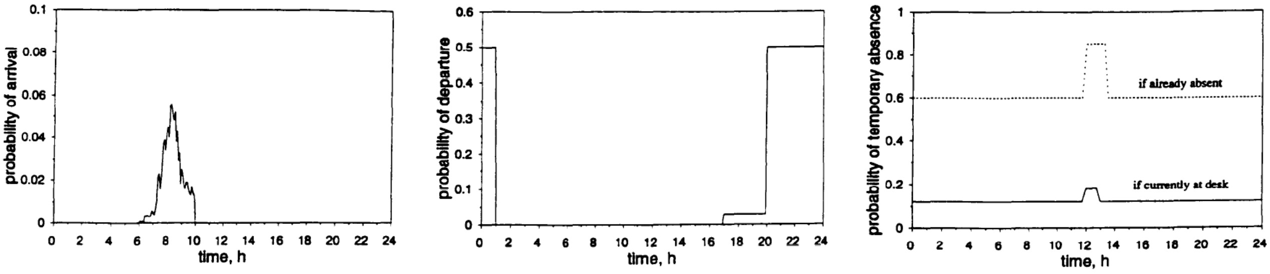


Fig. 3 Probabilities of transition, from [18]

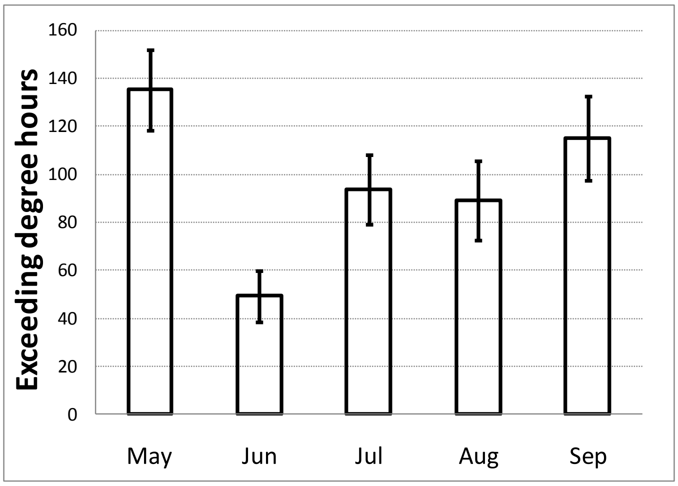


Fig. 4 Average and standard deviations of monthly weighted exceeding hours for 100 runs of the same building with the stochastic behavioral model

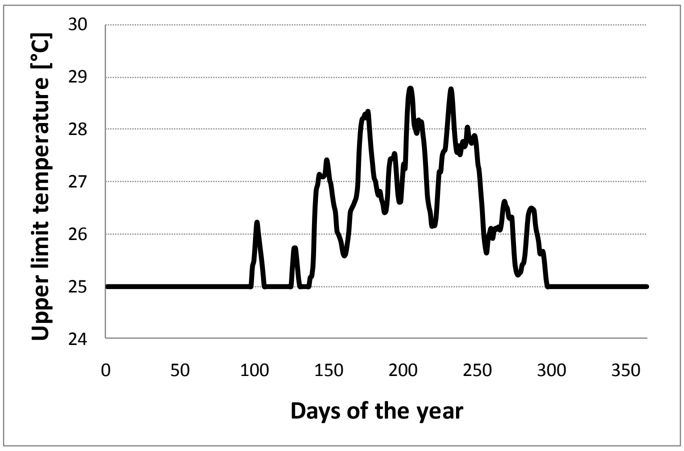


Fig. 5 Upper limit temperature for the climate of Uccle, for class II according to EN15251

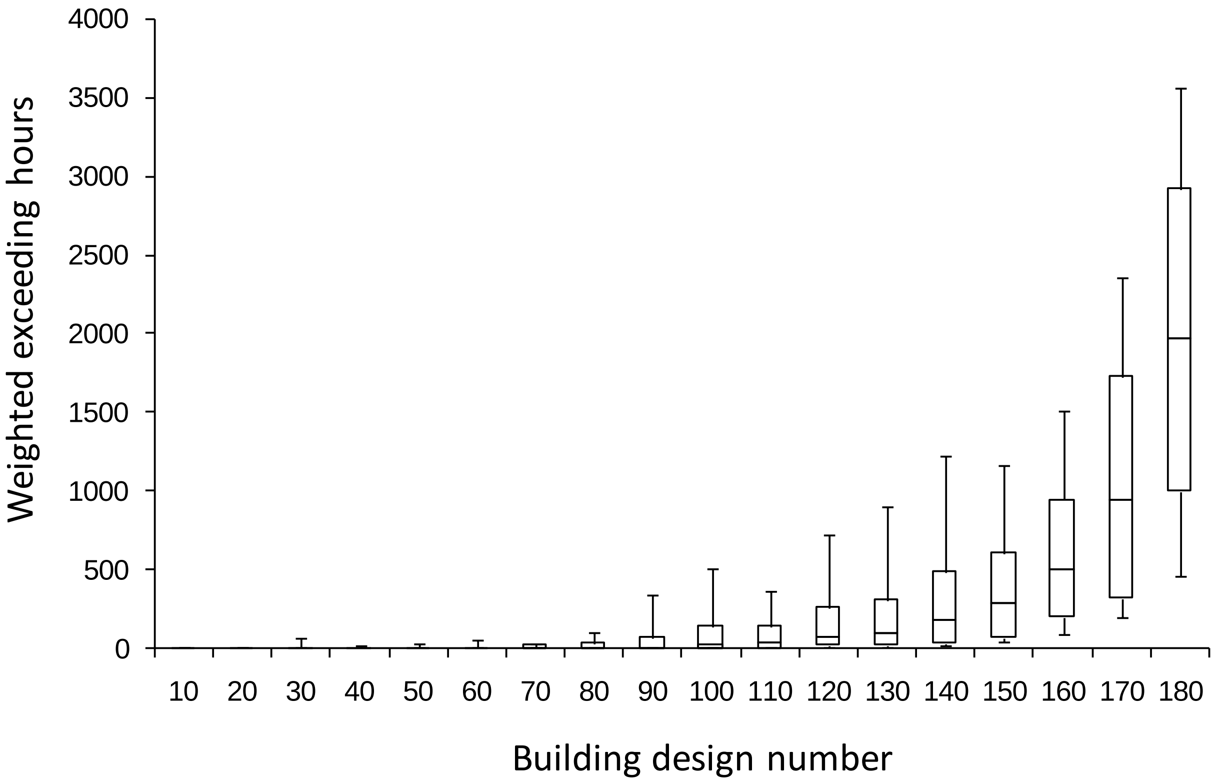


Fig. 6 Uncertainty on simulated summer comfort due to behavioral patterns for a selection of 18 over the whole range of designs

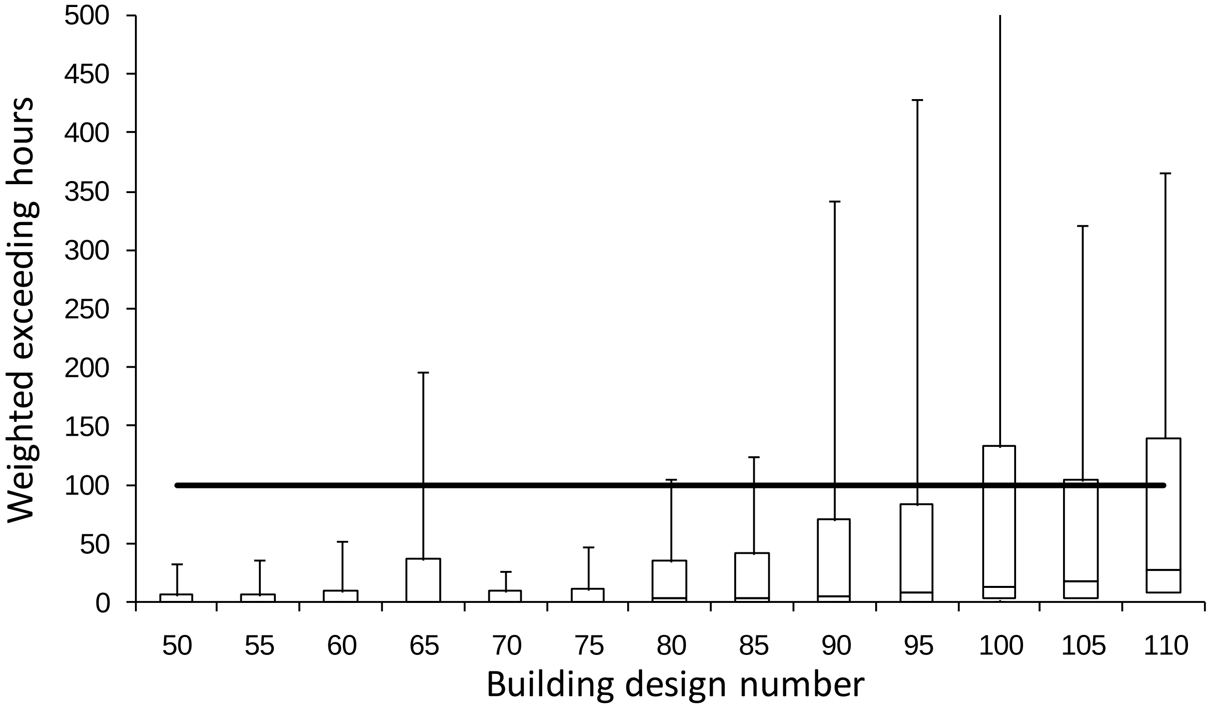


Fig. 7 Uncertainty on simulated summer comfort due to behavioral patterns for a selection of 13 building designs

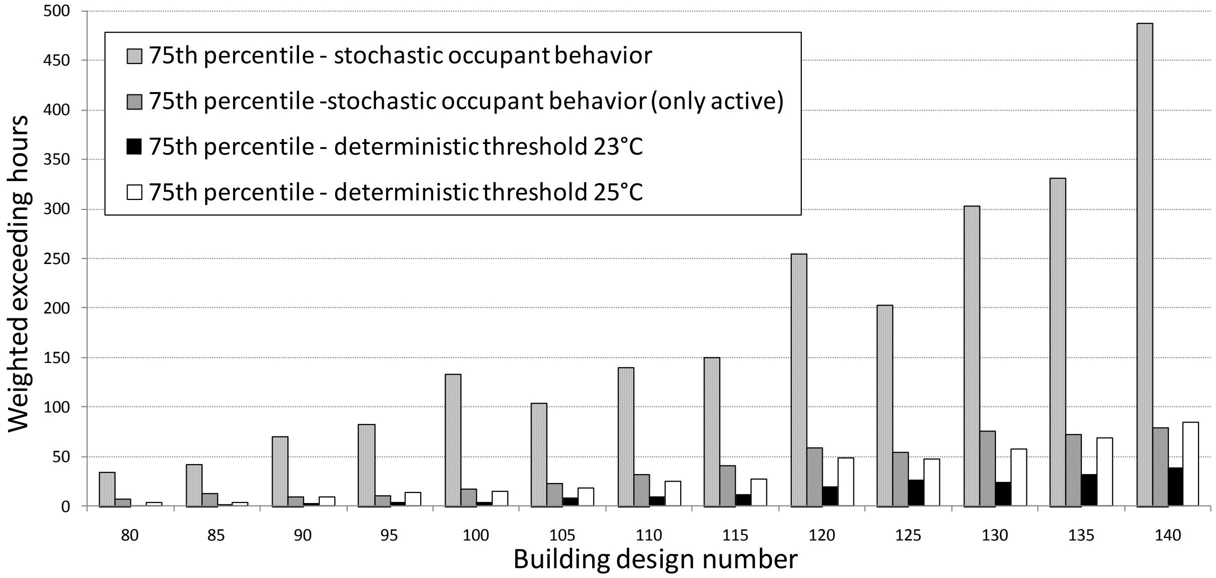
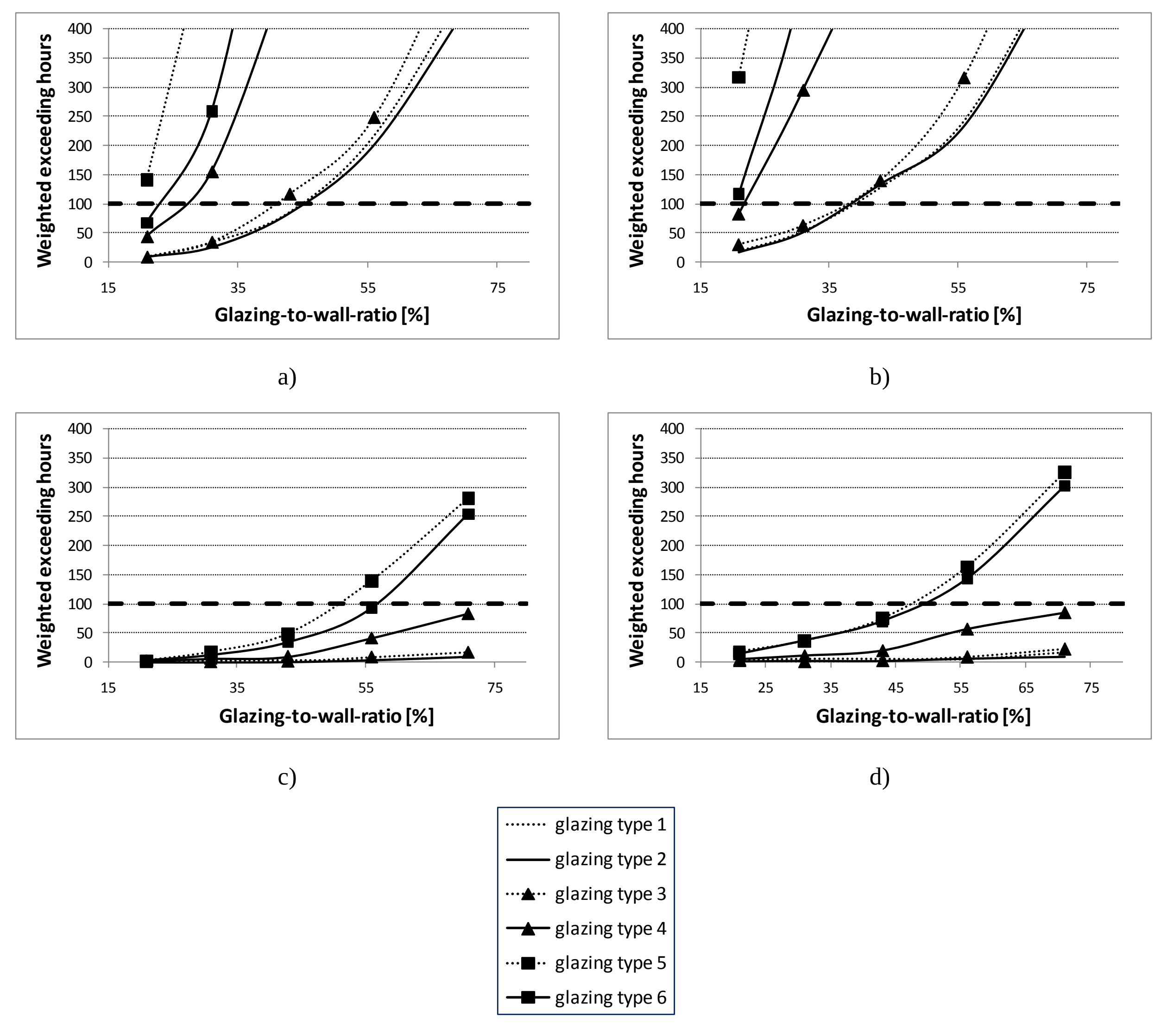


Fig. 8 Sensitivity of the simulated summer comfort to applied window-opening pattern



a) b) c) d)

Fig. 9 75th percentile of simulated summer comfort for varying glazing-to-wall-ratio and glazing type. a) No shading device, U_{opaque} = 0.6 W/m^{2}K b) No shading device, U_{opaque} = 0.2 W/m^{2}K c) External horizontal slats, U_{opaque} = 0.6 W/m^{2}K d) External horizontal slats, U_{opaque} = 0.2 W/m^{2}K

Table 1 Various glazing types

Nr.	Visual Transmittance [-]	g-value [-]	U-value [W/m^{2}K]
1	0.36	0.26	1.1
2	0.48	0.29	1.1
3	0.61	0.35	1.1
4	0.59	0.44	1.1
5	0.77	0.59	1.1
6	0.72	0.48	0.8