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THE IMPACT OF VENTILATION AND SHADING CONTROL ON THE RESULT OF SUMMER OVERHEATING SIMULATION

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Abstract

The most suitable methods for increasing the climate resistance of buildings on hot summer days are intensive ventilation and effective external shading. However, it is possible to discuss what kind of approach used, while simulating the control of these two elements in energy simulation programs, to make the result as much representative as possible. We created and compared three different control modes for this purpose. The basic mode represented models created from monitoring of habits of building users, while the second mode represented an automatic system based on sensory control. The third mode represented models that provide an early warning system against a series of hot days. They intervene in windows and blinds control for a several days in advance. The base mode using the schedules reached more than 2 °C higher maximum indoor air temperature than the two others in a direct comparison of these three systems by simulating a simple building. It also has been shown that with a relatively simple early warning system, it would be possible to replace an even more complex automatic system.

Keywords:

Built environment;
Simulation;
Thermal comfort;
Occupant behavior;
Ventilation.

1 Introduction

Building energy simulation programs (BES) are used for the so-called digital twinning [1], which is mainly about predicting energy consumption and thermal comfort conditions in old and new buildings [2] based on a digital building model. To successfully use this method, it is necessary to eliminate the discrepancy between the simulated results and reality. The main reason for the dissonance is not related to deterministic factors, such as the physical properties of the building envelope [3, 4]. The disagreement results mainly from the lack of a more accurate understanding of occupant behavior in buildings [5]. For example, occupants can open windows for various reasons. It is also possible to work with setting the thermostat, controlling external blinds, and so on. Typical schedules need to be created separately for each workday, Saturday, and Sunday [6]. Their behavior was represented in simplified and predefined schedules or fixed settings until recent years. That has led to deterministic and homogeneous results ignoring the stochastic nature, dynamics, and occupant behavior diversity. The human behavior model should roughly take the user's logic when opening windows and manipulating blinds into account. May-Ostendorp et al. [7] experimented with the Particle Swarm Optimization (PSO) algorithm. In simulating a common small office building with natural ventilation, they tried to develop an inductive method for generating an almost optimal window opening schedule. Coffey [8], in turn, simulated only one zone (unfurnished office) in EnergyPlus, using the Hooke-Jeeves method to optimize the percentage of shading by external blinds and ventilation. Lee and Malkawi [9] also explored the impact of occupant behaviors on building performance based on predicted mean vote (PMV) parameters. Hong et al. [10, 11] proposed a novel ontology to represent building occupant behaviors, which defines the schema and parameters for a standardized model.

The inductive approach can lead to increased operating costs or disruption of thermal comfort because schedules are not always optimized for local use, climatic conditions, orientation towards the

cardinal direction, building materials, and architectural form with glazing to the floor area ratio. In Fig. 1 it is seen how too low air temperature values are included in the statistics because of a simplified way of modeling ventilation through the number of exchanges. The additional ventilation, required on hot days, was simulated even during the colder period in the simplified models.

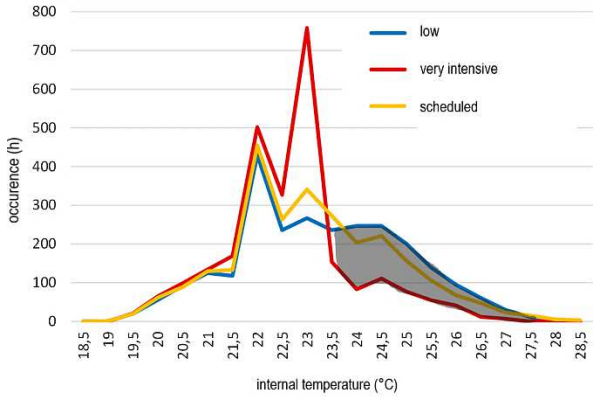


Fig. 1: The statistics of internal temperature from BPS simulation with various ventilation schemes.

It is important to understand these interactions to achieve the fulfillment of the designed parameters of the internal thermal environment. Recently, regression models of occupant behavior have been developed that are compatible with major energy simulation software. They are based on works such as Rijal et al. [12], which modeled the probability of window opening by occupants when deviating from the comfort zone by +/- 2K in terms of indoor and outdoor air operating temperatures. Or Haldi and Robinson [13], which integrated stochastic models of the Markov chain of the window opening and use of blinds by residents into the city simulation software City-Sim with connection to outdoor and indoor air temperature and outdoor and indoor lighting. These and other experiments led to make the Sub-Hourly Occupant Control module (SHOCC), which is designed for the ESP-r program [14]. A large group of researchers united under the Lawrence Berkeley National Laboratory is working to integrate occupant-based behavior prediction (obFMU) [15] into EnergyPlus using the Agent-Based Model (ABM) approach. That principle is used in various fields of science and industry, such as driving autonomous vehicles. Dziedzic et al. [16] designed an algorithm to simulate occupant movement in buildings using ABM with the in-situ observation of natural transitions of the building occupants. In another study, Chen et al. [17] applied their occupant behavior model to a small office building and visualized how the simulated occupants move and behave in the prototype building.

Another system that can help buildings and their occupants better overcome extremely hot day periods is the incorporation of a predictive control model (MPC) into the logic of opening windows and manipulating blinds [18]. Then the building cools down adequately during the colder weather period. The lower limit of acceptable summer thermal comfort parameters can be based on the standard ISO 7730:2005 [19] or the adaptive thermal comfort theory [20]. Several studies have looked at the response of building occupants to the temperature fluctuations of the indoor thermal environment that are needed to cool a building [21]. The simulation results using the predicted meteorological data have promise accuracy. The model could predict indoor air temperatures within 0.5 °C accuracies when the air-conditioned space was simulated in this way while a solar irradiance was predicted with a root mean square error (RMSE) of 15 % [22].For weather prediction, the model used forecasting information provided by local weather centers. As the information was insufficient for predicting hourly weather, interpolation and sky-conditions-based irradiance prediction model were proposed. The DOE-2 [23] has outdoor temperature prediction functions that can predict hourly outdoor temperatures using the minimum and maximum temperatures.

The question arises there which of the presented systems could be more effective in preventing thermal discomfort during hot summer days. Whether a complex (automatic to autonomous) sensory system for window control and blind adjustment or a slightly simpler system connected to the weather forecast. Or how big are the differences between them.

2 Description of the simulation model

A simple 2-zone model of a bungalow-type family house in the EnergyPlus energy simulation program was used. The first zone integrates all living rooms and the entrance hall and the second only

the bathroom. A view of the simulation model visualized using the Sketchup program is shown in Fig. 2. Each surface is color-coded. Instead of the roof, the attic ceiling was shown in brown. The architecture of the house is classic, its usable area of 117.9 m^2 ranks it among the average or rather smaller bungalows. Compared to other single-family projects, it gives medium results at risk of overheating [24]. The total window glazing area is only 10 % of the total floor area. That means this is not an example of modern solar architecture with large glazed areas.

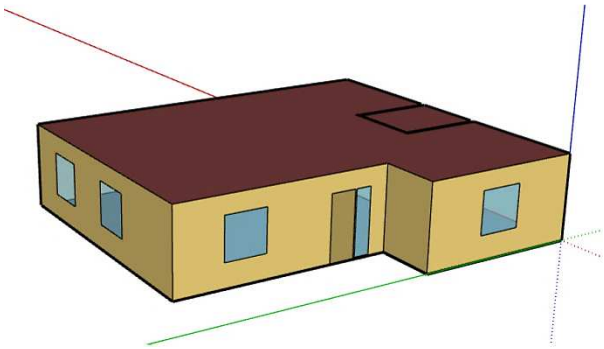


Fig. 2: 2-zone model of bungalow for EnergyPlus simulation program.

Two variants of the construction solution of the building walls were developed. The first variant is a masonry building, the second is a wooden building. The masonry building has perimeter walls and partitions made of aerated concrete blocks. The heat transfer coefficient (*U*-Factor) of the perimeter wall is 0.145 $W/m^2 \cdot K$, the ceiling to the attic 0.119 $W/m^2 \cdot K$, and the ground floor 0.293 $W/m^2 \cdot K$. It is clear from this that it can be classified as a low-energy building. The windows were considered with low-E triple glazing with a glass *U*-Factor value of 0.9 $W/m^2 \cdot K$ and a total solar heat gain coefficient (SHGC) of 0.51 (-). Most of the windows were to the west direction oriented.

The internal heat gains schedules correspond to the schedules previously published in previous works [25]. These were relatively higher values of profits (from people and facilities), which represented active living of the space by a family of 4 (2 adults and 2 children). The climate reference year of the IWEC database for Ostrava city in the Czech Republic was used. The air exchange model in the EnergyPlus program was divided into infiltration and ventilation. Infiltration was simulated using a constant air exchange number of 0.5 h^{-1}. Ventilation was variable and was part of the investigation below. A mass-flow network model that would take into account the effect of wind on ventilation intensity has not been simulated for simplicity. The neglect of the wind force can be justified by the fact, that during the summer heat period, the wind speed is usually low (except the time during the storm, which is followed by a noticeable cooling and reduced internal overheating risk). Active cooling using an air-conditioning unit was not considered in this simulation.

3 Description of the window and blind control systems

Different approaches to predicting the use of windows and blinds were considered in the three test modes: base, sensory and maximum. The characteristics describing the logic of using windows and blinds in these individual modes are documented in Table 1.

Table 1: Tested modes of the window and blind control.

	Windows opening behavior	**External blinds adjustments**
Base mode M0	scheduled	pulled out for full 24 hours
Sensor mode M1	ventilation if the indoor air temperature > 22 °C and at the same time the outdoor air temperature < 25 °C	pulled out (lamella angle 45 °) if indoor air temperature > 24 °C or incident solar radiation > 300 W/m^2
Maximal mode M2	according to command ventilation if indoor air temperature > 22 °C and at the same time the outdoor air temperature < 20 °C	According to command continuously retracted (lamella angle 15 °)

The first mode was the base mode and could be called a reference mode, marked as M0. In this case, any special action was not taken into account. The blinds remained pulled out 24 hours a day. The windows open according to a schedule that has been compiled based on statistics on the manipulation of people with windows. This schedule does not take into account the dependence of the

window opening on the outside and inside temperature described above. Uniform behavior of residents is expected, who wish to ventilate intensively in the morning after waking up from 9:00 to 12:00 AM and a little longer in the evening after returning to the house from 7:00 to 12:00 PM. With intensive ventilation, one medium-size window was assumed to be wide open, which was simply modeled in the simulation as ventilation with air exchange n = 5.0 h^{-1}. Such a ventilation timetable is common but is not ideal from the summer overheating point of view. The entering of warm outside air will further increase the temperature of the indoor air.

During the second mode called sensor (marked as M1), windows and blinds are manipulated based on the results of measuring the air temperature in the interior and exterior, or measurements of incident solar radiation respectively. The blinds were controlled with relatively simple logic. The external blinds come to the closed position (at an angle of 45°) if the room air temperature rises above 24 °C or the value of the incident solar radiation is more than 300 W/m^2. The window in the room, which provides intensive ventilation, also opens and closes based on two sensors: the average indoor air temperature sensor and the outdoor air temperature sensor. Ventilation modeled by air exchange n = 5.0 h^{-1} was performed according to this logic when the average indoor air temperature was higher than 22°C and at the same time, the outdoor air temperature was lower than 25 °C. In this way, ventilation with hot outside air was avoided, as well as excessive pre-cooling of the interior below the temperature ensuring thermal comfort in the summer.

The last mode, called maximum (marked as M2), represents the case where maximum measures go in advance based on an early meteorological warning system against extreme weather. This means that solar heat gains were limited to the minimum by setting the external blinds in the entire living area of the house. Blinds were in the closed position for the whole 24 hours a day (at a 15° angle). Also, intensive ventilation with a wide-open window was limited to the time when the outside air temperature was below 20 °C.

4 The test results

In the IWEC test reference year for Ostrava, the appropriate period for testing summer overheating was from July, 28 to August, 6. As can be seen from Fig. 3 there was a sequence of consecutive hot days during this period, preceded by cold weather with varying intensity of sunlight. Higher values of diffuse radiation indicate cloudy or partly cloudy weather. During this cold period, the building can be cooled and prepared for the subsequent sunny weather and high air temperatures. The maximum outdoor air temperature of 32.5 °C was in the climatic year on August, 4 at 4:00 PM. The next day it was no longer higher, but the intensity of the incident direct sunlight was the same and exceeds 700 W/m^2. According to calendar days, August, 5 was Saturday. The highest internal heat gains were expected on Saturday because of the full occupancy and specific family house operation.

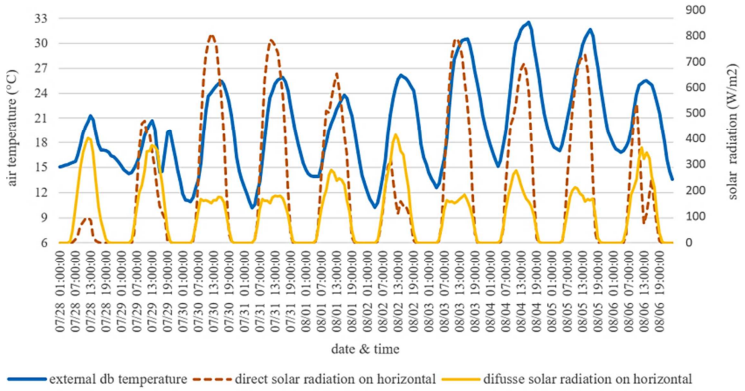


Fig. 3: Outside boundary conditions from Ostrava IWEC test reference year.

Fig. 4 shows the impact of the selected mode of the window opening and set of blinds on the intensity of ventilation and solar heat gains in the selected period of the climate year from 28 July to 6 August. See the differences in a direct comparison here. When we look at ventilation courses, most ventilation was at the M1 sensor mode. In this mode, ventilation by automatic window opening takes place from approximately 10:00 AM to 2:00 PM and from 5:00 PM to 9:00 PM, while on hot days, the ventilation time was shorted or extended into the night. The temperature averaged day algorithm allows automatic intensive ventilation without a break throughout the day August, 1. There is no

intensive ventilation on cold days with too low outside temperatures. An exchange called infiltration was enough.

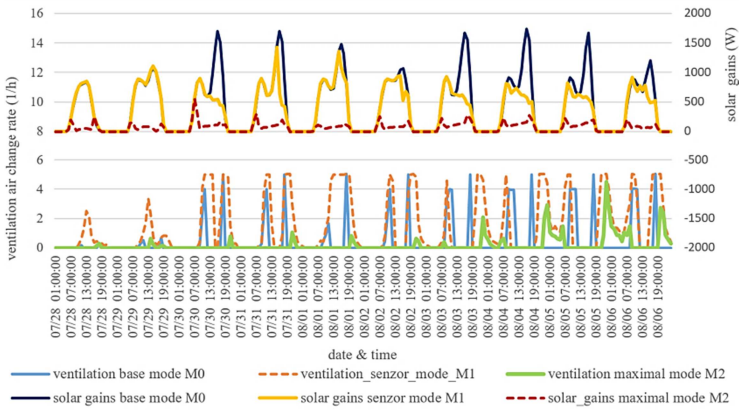


Fig. 4: Courses of ventilation and solar gains before and during the hot period.

It was almost not intensely ventilated at all with the maximal mode M2. Windows did not open wide. Only on days with the highest outdoor air temperature was it slightly ventilated at night. Of course, even in this mode, as in all three, a hygienically necessary amount of air was provided with an n = 0.5 h^{-1} exchange, referred as infiltration. Intensive ventilation in the basic mode M0 according to the schedule was not as frequent as in the automatic mode M1. The difference in ventilation was the biggest during the transition from colder to hot weather. In addition, it was often ventilated at inconvenient times when the outside air temperature was higher than the indoor air temperature and then the indoor environment was heated by ventilation.

Looking at the differences in solar heat gains, they were the largest between the M0 and M2 modes. The highest values of solar heat gains were with the M0 mode in the afternoon (more than 1700 W). That was because the windows had a prevailing west orientation. On colder days and in the morning, the automatic blind control in M1 mode left the blinds unattended. Based on exceeding the threshold value of the indoor air temperature they were retracted on a hot afternoon. Precisely due to the higher threshold value 24 °C, the solar heat gains in the M1 sensor mode were relatively high compared to the M2 mode. Not only that, but higher gain also results from setting the blinds at a 45° angle in M1 mode compared to setting at 15° in the M2 mode. The total transmittance of sunlight through closed blinds was different in each mode. That was reflected in a higher increase in the average indoor air temperature during sunny days, as can be seen in Fig. 5. Although the temperature profiles during the colder cloudy weather period were almost identical. With the onset of sunny warm days, the daily temperature rise was already higher in the M1 sensory mode than in the M2 mode. At night, the temperatures were equalized at a stable 22 °C every day, even with the intensive ventilation help. The average indoor air temperature had a different course in the base mode M0. The indoor environment in the residential zone cooled down less during the colder cloudy weather period due to the time-limited intensive ventilation time. Indoor air temperatures were approximately 1.5 °C higher at all times than in the other two cases. The difference increases during hot days. The highest indoor air temperature of 29.0 °C was simulated for a masonry construction system on the day following the day with the maximum outdoor air temperature August, 5 at 5:00 PM.

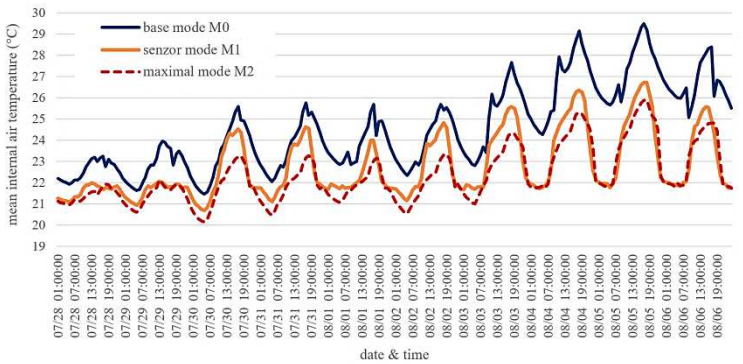


Fig. 5: Internal air temperature trends as BPS simulation results with masonry walls.

The described indoor air temperature and intensive ventilation results were also the same for simulating the variant with a light construction system (wooden constructions) in Fig. 6. However, with this design variant, the maximum indoor air temperatures were higher 0.3 - 0.5 °C depending on the control mode.

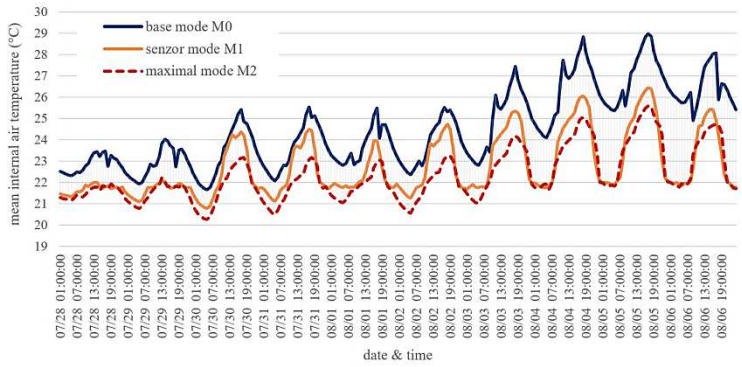


Fig. 6: Internal air temperature trends as BPS simulation results with lightweight walls.

5 Conclusion and discussion

There is no need to discuss whether or not to use external blinds and intensive natural ventilation by opening windows. Those are the two most effective tools for increasing the climate resilience of buildings on hot summer days. However, it is possible to discuss which approach must be chosen when simulating the control of these two elements in energy simulation programs, so that the results have the greatest possible informative value. For this purpose, three control modes were compared. The base mode M0 represented models created from occupants monitoring, while the M1 mode represented an automatic system based on sensory control. The latest M2 model represented models that provide an early warning system against a series of hot days and intervene in a relatively simple but effective window and blinds control. With the help of the early warning system, for example, it is possible to prohibit the handling of blinds. Occupants can leave them closed for several days before the hot weather period. A direct comparison of these three systems on the simulation of the current low-energy bungalow-type family house showed that:

- The worst scenario of summer interior overheating can be expected with regulation based on an unsuitable schedule of intensive ventilation by opening windows and without closing the blinds during sunny days. The simulation model used in this basic mode M0 was achieved by the simulation of more than 2.0 °C higher maximum air temperature than the others. If the simulation aimed to verify the worst thermal comfort conditions in the proposed building during relatively usual operation, this was an appropriate approach. The sensitivity of the simulation model to the considered wall material was low. It gave a difference in air temperature up to 0.5 °C.
- The other two modes M1 and M2 based on automatic control and an early warning system did not differ significantly in the results. Although the control system in mode M1 gave slightly higher temperatures in the simulation (by a maximum of 0.8 °C). This was a logical consequence of the fact that the blinds did not retract to the fully closed position, but only to a 45° angle. Higher solar gains subsequently overheated the interior more, but the automatic ventilation system was able to cool the room back to a comfortable temperature every evening. The functionality of the sensor system was the same when simulating a building made of light-weight building materials (wooden construction). Also, the adaptive algorithm could be incorporated for the window opening set-point temperature [26].
- The best result was achieved in M2 mode with an early warning system and subsequent closing of the blinds and prohibiting the window opening (except for the hygienically necessary amount of fresh air). Avoiding the blinds to open at the beginning of the hot period played a critical role in how the interior temperature was looking in the next hours and days. With this relatively simple system, it is possible to replace a more complex automatic regulation system of the windows and blinds opening and closing. However, closing the blinds completely for a few days can cause some visual discomfort at the time of occupancy. Pulling the blinds to an angle of 45° was allowed outward vision and visual contact with the environment. That was no longer possible when the blinds were closed to an angle of 15°. Therefore, this approach cannot be applied universally and requires further investigation.

From a comparison of the results for masonry and light-weight wall construction, it was clear that in the case of appropriate ventilation control and effective external shading, the difference based on the materials used in a low-energy house was insignificant. Mainly with a small window to floor area ratio. The weather conditions in the IWEC test reference year were obtained from measurements during the 80 s and 90 s. It is due to climate change relatively long ago. For further climate adaptability investigation, it would be necessary to create a new test reference year from measurements in the University of Zilina area [27].

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