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Barbosa, R.M.; Bartak, M.; Hensen, J.L.M.; Loomans, M.G.L.C.

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VENTILATIVE COOLING CONTROL STRATEGIES APPLIED TO PASSIVE HOUSE IN ORDER TO AVOID INDOOR OVERHEATING

Rebeca Barbosa[1], Martin Barták[1], Jan L. M. Hensen[1, 2], Marcel G. L. C. Loomans[2]
[1]Czech Technical University in Prague, Department of Environmental Engineering, Czech Republic
[2]Eindhoven University of Technology, Building Physics and Services, Netherlands

ABSTRACT

The increasing number of highly insulated and air tight buildings leads to the concern of indoor environment overheating. This research studies the possibility of applying natural ventilation as a way to avoid high temperatures indoors.

A monitored passive house was modelled in ESP-r and the impact of natural ventilation on indoor temperatures was simulated. The multi-zonal energy model was coupled with an airflow network and several control strategies were tested for the openings of the dwelling.

Thirteen control settings were simulated. They combined the cases of single-sided ventilation and cross ventilation for both night-time and day-time. The strategies also included the possibility to have the openings closed when the outdoor temperatures were within a specific range. The goal was to identify the most suitable control strategy to avoid overheating in the studied dwelling and to investigate the possibility of having indoor temperatures consistently lowered by the natural ventilation.

INTRODUCTION

After the Second World War, a large number of terraced dwellings has been built in the Netherlands. Current estimation indicates that there are still 650.000 terraced dwellings in the country dating from the period between 1966 and 1976. Due to the poorly insulated building shell, most of these houses had high energy consumption for space heating. In order to lower the energy consumption, some of them were renovated to achieve the Dutch passive house standard (Blok, 2013). However, the high-insulation and air tightness required for passive houses lead to the immediate concern about indoor overheating during warmer periods of the year (IEA EBC Annex 62).

It has been demonstrated that well planned passive houses can present a pleasant indoor environment even in warm summers as they feature an effective combination of shading devices with natural ventilation strategies (Mlakar, J.; Štrancar, J, 2011). However, the use of natural ventilation as a precise cooling technique still faces a number of challenges, such as prediction of cooling needed in a building, integration of ventilative cooling in energy performance calculations, recommendations of performance indicators, control strategies and solutions for a wide range of climates (IEA EBC Annex 62).

This work aims to give one step towards the predictive use of natural ventilation as a way of preventing highly insulated dwellings from overheating. For this purpose, one monitored renovated Dutch passive house was modelled in ESP-r.

MODEL DESCRIPTION

The studied dwelling was monitored for one year. Hourly values of temperature, humidity and CO_2 concentration were obtained for 3 rooms, together with the weather data that were measured in a climate station near the vicinity of the passive house. The house was modelled in ESP-r and the acquired climate data were incorporated to the software and used for the simulations.

The front façade of the dwelling is oriented to the south. The house is located in a row between two identical passive houses. The construction was modelled following the same U-values as the existing houses, where the roof, walls, ground and the windows have U-values 0.11 W/m²·K, 0.11 W/m²·K, 0.25 W/m²·K and 0.6 W/m²·K respectively. The house consists of three levels, represented in the ESP-r model by seven zones, see Figure 1.

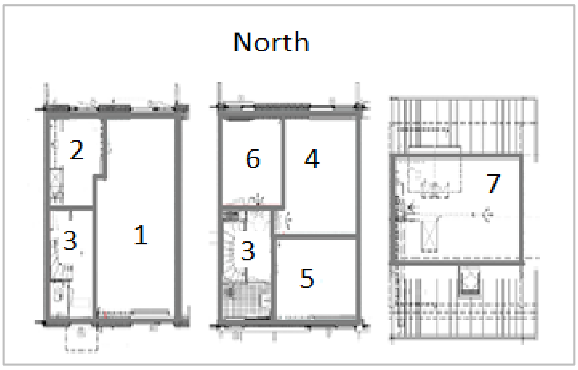

Figure 1. Plan of the modelled passive house, from left to right: ground floor, first floor, attic

The living room (zone 1) and kitchen (zone 2) are located on the ground floor of the house. The bedroom 1 (zone 4), bedroom 2 (zone 5) and bedroom 3 (zone 6) are located on the first floor. The hall, staircase and bathrooms on both floors are represented by a single zone (zone 3), which extends from the ground floor to the first floor. The attic (zone 7) is above the first floor.

Occupancy scenario

The exact number of people in the house and their behaviour is not known. The occupancy scenario was estimated on the basis of the measured levels of CO_2 in each room and the mass-balance equation for a contaminant in a ventilated room (Nový et al., 2000):

$$\dot{M}_C + \dot{V}_{\sup} \cdot c_{out} - \dot{V}_{ex} \cdot c = V \cdot \frac{dc}{dt} \tag{1}$$

where $\dot{M}_C$ (kg/s) is the mass flow of CO_2 released per person, $\dot{V}_{\sup}$ is the supply air flow (m^3/s), c_{out} (kg/m^3) is the concentration of CO_2 outdoors, $\dot{V}_{ex}$ is the exhaust air flow (m^3/s), c is the concentration of CO_2 indoors, V is the volume of the room and t (s) is time.

The measured data were available only for the living room and bedroom. This work targets on the analysis of corresponding zones. On average, the CO_2 concentrations in the living room and bedroom 1 were 735 ppm and 726 respectively. The living room was ventilated with 23 m^3/h of fresh air and the bedroom 1 with 13 m^3/h. The ventilation was assumed as balanced (supply equals to exhaust). The outdoor concentration of CO_2 was assumed to be 400 ppm and each occupant was assumed to be in resting, releasing 0,02 m^3/h of CO_2.

The application of equation (1) indicates that, in average, the living room is occupied by 2 people and the bedroom 1 by 1 person during the whole day. In order to be more realistic and take into account common occupancy behaviour, it was assumed that the house has 4 occupants: 4 people in the living room for 12 hours, 2 people in the bedroom 1 for 12 hours and 2 people in the bedrooms which were not considered in this study.

After including the occupancy distribution in the simulated model, preliminary simulations were performed in order to compare the monthly averaged measured temperatures with monthly averaged simulated indoor temperatures for August. The comparison was considered satisfactory, as both living room and bedroom 1 had a monthly averaged temperature of 25 °C for both simulated and measured temperatures.

The comparison of averaged temperatures does not provide a precise information, but it gives an estimation of internal heat gains, which should be sufficient for the purpose of this work. Comparison of measured and simulated indoor temperatures after including occupancy distribution is presented in Figure 2.

It is possible to notice that the measured temperatures present lower amplitude than the simulated ones in both zones, but especially in the living room. This can be explained by the fact that the simulation model does not include any sort of internal shading devices, which are likely to be used by occupants during the summer season. The impact of direct radiation on temperature oscillation is higher in the living room, since the external walls of this zone are almost fully glazed.

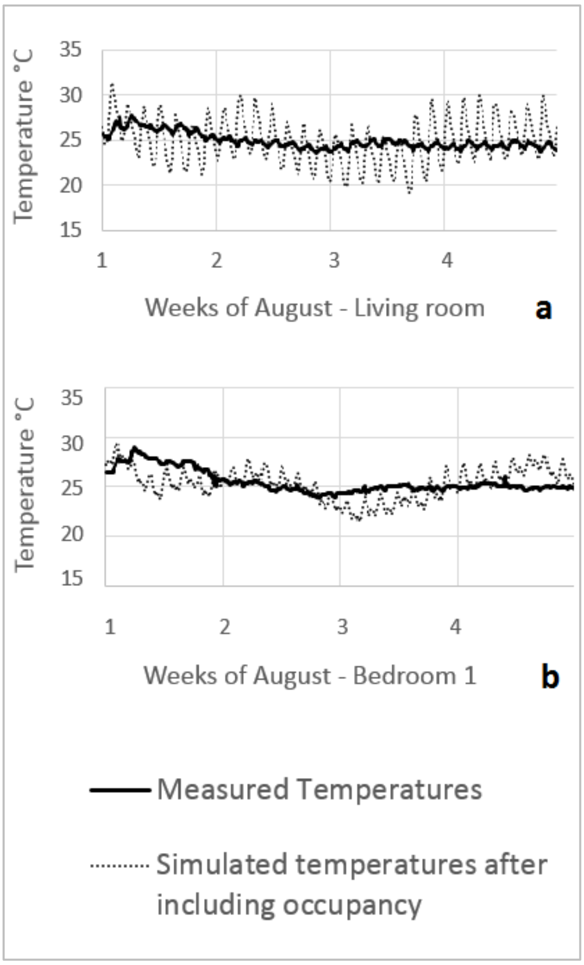

Figure 2: Measured and simulated temperatures after including occupancy distribution for a: Living room, b: bedroom 1

The position of temperature sensors may be another reason for the amplitude difference. The simulated model assumes the temperature sensor to be located in the middle of the room. However, the measurement equipment are placed at internal walls, thus being directly affected by wall temperatures.

AIRFLOW NETWORK

The simulated model includes an airflow network consisting of 15 nodes, 14 components and 14 connections, see Figure 3. The openings are represented by components type 130 and 110 (Hensen, 1991).

Components 130 are connecting internal nodes to external nodes. They allow bidirectional flow and they are convenient for modelling large openings. Component 130 requires the two connected pressure-nodes to be in the same height.

Components 110 are interconnecting internal nodes. They simulate an opening with discharge coefficient equal to 0.65. The interconnected pressure-nodes can be in different heights, which is the case of the hall pressure-node (zone 3), which is connected with zones on different floors.

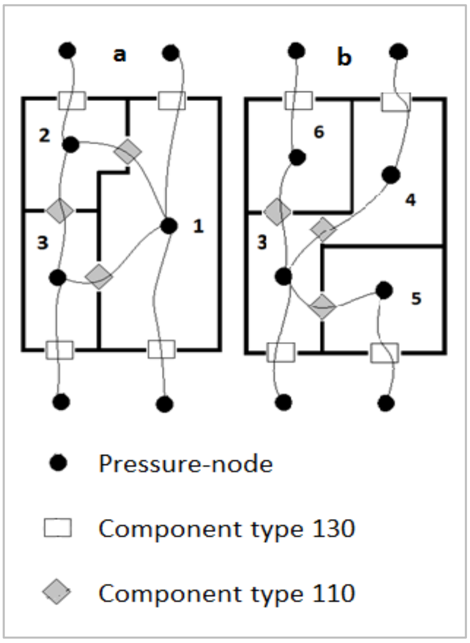

Figure 3: Scheme of the airflow network of the studied passive house

CONTROL STRATEGIES

The numerical model of the house was used to test thirteen control strategies for the openings of the dwelling, in order to identify best settings to avoid indoor overheating. The simulation period was the whole August. This month was chosen because it reflects the weather conditions of the middle of the summer, when buildings are more susceptible to overheating, see Figure 4 for air temperature distribution.

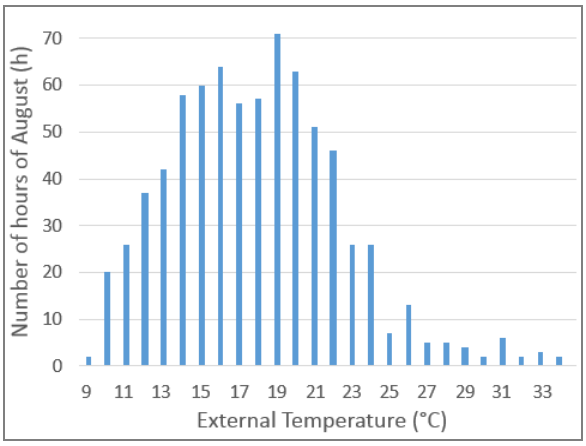

Figure 4: Histogram of external air temperatures during the month of August

The first step was to choose one representative zone to test the control strategies, as it would not be effective to set the simulations and process the data for 7 zones and 13 control strategies. The living room (zone 1) was selected as it has two openings facing the outdoor environment. Thus, the living room allowed the possibility to test both single-sided and double-sided ventilation. Also the measured data were obtained for this zone so the results of the simulation could be compared with them.

The living room has 4 openings: 2 internal and 2 external. Both internal openings were considered to be closed, i.e. without any flow mass, for all 13 cases. The control strategies were only simulated for the external openings of the zone: 1 garden door facing north (area 2,1 m^2) and 1 window facing south (maximum opening area assumed to be 1,4 m^2).

The simulated control strategies are numbered from one to thirteen. The first eight settings represent single-sided ventilation and the last five settings represent double-sided ventilation; see tables 1 and 2.

Table 1

Control strategies simulated in the living room for single-sided ventilation case

single-sided ventilation: door always closed		
	Window	**Control Condition**
1	Fully opened	Always
2	Half opened	Always
3	Fully opened	When Tout < 30 °C. Otherwise closed
4	Half opened	When Tout < 30 °C. Otherwise closed
5	Fully opened	When Tout < 25 °C. Otherwise closed
6	Half opened	When Tout < 25 °C. Otherwise closed
7	Fully opened	When Tout is between 15 °C and 30 °C. Otherwise closed
8	Fully opened	From 9 PM to 7 AM. Otherwise closed

Table 2

Control strategies simulated in the living room for double-sided ventilation case

double-sided ventilation			
	Window	**Door**	**Control Condition**
9	Fully opened	Opened	Always
10	Fully opened	Opened	When Tout < 30 °C. Otherwise closed
11	Fully opened	Opened	When Tout < 25 °C. Otherwise closed
12	Fully opened	Opened	When Tout is between 15 °C and 30 °C. Otherwise closed
13	Fully opened	Opened	From 9 PM to 7 AM Otherwise closed

RESULTS AND DISCUSSION

The numerical models were simulated at first using control strategies 1 to 8. The results were evaluated in order to identify the best performing strategies to avoid indoor overheating among the single-sided ventilation cases. Then the simulations were performed using the control strategies 9 to 13, in order to compare the first results with the ones obtained for double-sided ventilation – see Figure 5.

Single-sided ventilation: Control strategies 1 to 8 in the living room

The results obtained for single-sided ventilation cases in the living room indicate that the most comfortable indoor temperatures are achieved when the windows are kept fully opened all the time (control 1), or closed only when external temperatures rise above 25 °C (control 5) or 30 °C (control 3). The temperature distributions for these three cases are very similar. It is possible to notice that the control strategy 5 presents slightly higher percentage of hours above 28 °C and smaller percentage of hours between 19 °C and 25 °C.

The control strategies 1, 3 and 5 are identical to the strategies 2, 4 and 6, except for the dimension of the opening. The first three cases considers the window to be fully opened, while the last three cases assumes the window to be only half-opened. This difference in the size of the opening affects the temperature inside the living room. When the window is fully opened, the number of hours in which the indoor temperatures are within the comfort zone is higher. On the other hand, when the window is partially closed, the living room tends to overheat more, with higher number of hours with temperature above 28 °C.

The control strategy 7, which keeps the window fully opened only when external temperatures are in the range 15 to 30 °C proves to be the most efficient strategy, among the eight here presented, to avoid unpleasantly cold temperatures inside the living room. However this strategy seems to be not effective for keeping the room within the range of comfortable temperatures. It provides the second lowest percentage of hours between 19 °C and 25 °C.

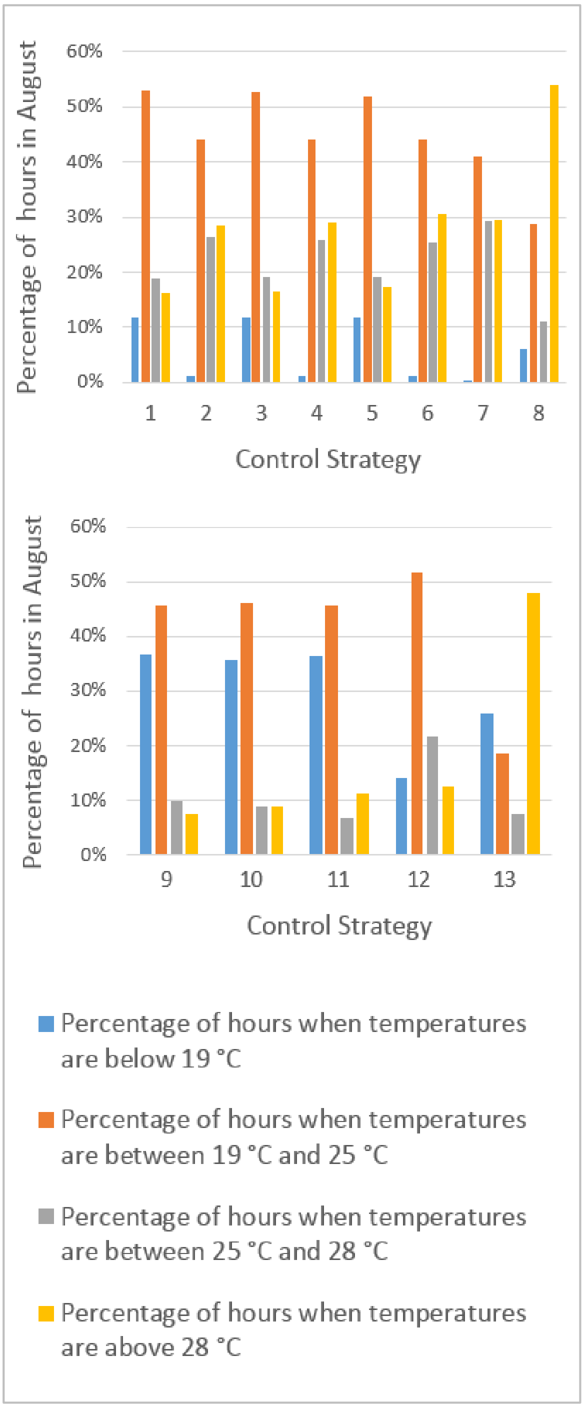

Figure 5: Simulated temperatures in living room a: single-sided ventilation; b: double-sided ventilation

The worst performance has the control strategy 8, when the windows are closed during day-time and opened during night-time. The studied climate should have a good potential for night-cooling, as the temperatures during the night are considerably lower than during the day. However, the use of night-cooling seems to be an inefficient way to avoid overheating in this case study, as the temperature inside the living room rises above 28 °C in more than 50% of the time.

The poor efficiency of night-cooling ventilation can be explained by the fact that the external air temperatures are rarely above 28 °C in the analysed case (see Figure 4), thus a good decision would be to keep the windows opened even during day-time. Moreover, the internal heat gains and the energy from solar radiation accumulate in the room over the day when the windows are kept closed, causing an increase of temperature indoors.

The night-cooling might be a powerful strategy to avoid indoor overheating when the external air temperatures reach higher levels for longer periods than in the current case. In such events, it might be preferable to keep the windows closed during most part of the day and prevent the heat transfer into the internal environment.

Double-sided ventilation: Control strategies 9 to 13 in the living room

The control strategies 9, 10, 11, 12 and 13 considered the possibility to open the door connecting the living room to the external environment. The control of the door follows the same control strategy as set for the window. Based on the results obtained from the simulations with single-sided ventilation strategies, the possibility of opening only half of the window was not considered, as it performed worse than the fully opened window, for all the tested cases. Aside of this, the same control strategies as for the single-sided ventilation were tested.

The analysis of the temperature for double-sided ventilation in the living room shows similar trends as the analysis of the single-sided ventilation cases. By applying the control strategies 9 and 10, the temperatures in the living room only raised above 28 °C during less than 10 % of the month of August.

The control strategy 12 considers the window and the door to be opened when external temperatures are in the range 15 to 30 °C. This strategy performs better than the same control applied to the widow in the case of the single-sided ventilation. It keeps the temperatures in the living room between 19 °C and 25 °C for more than 50 % of the time. However, the use of control 12 still causes the temperature in the living room to be above 25 °C for almost 35 % of the time, while it is less than 20 % when strategies 9 and 10 are applied.

Similar to the results obtained for the single-sided ventilation case, the night-cooling ventilation is still the worst strategy among the ones studies for this case. When the openings are closed during day-time and opened during night-time, the living room achieves temperatures higher than 28 °C for almost 50 % of the time. The temperatures are between 19 °C and 25 °C for less than 20 % of August.

Control strategies 9 and 10 applied to all the openings of the house

The analysis of the 13 control strategies tested for the living room indicates that the most comfortable temperature – respectively the least overheated indoor environment – should be achieved when the door and window are kept constantly opened (control 9) or closed only when the external temperature rises above 30 °C (control 10). Therefore, these two strategies were selected and applied to all the openings of the studied passive house, except to the entrance door. The opening that gives access to the dwelling was assumed to be closed in all the cases.

In this work, the simulation model coupled with airflow network did not include the presence of the ventilation system installed in the real house. The ventilation system was neglected as the goal was to evaluate the possibility of avoiding overheating in the house by sole opening and closing windows and doors, without adding any extra mechanical devices. The mechanical ventilation system was considered in a separate simulation. The simulated results of control strategies 9 and 10 applied to all the openings of the house were compared with the case in which the openings are kept closed and the dwelling is only mechanically ventilated – see Figure 6.

The Figure 6 indicates almost identical results for both control strategies 9 and 10. However, the use of strategy 10 causes indoor temperatures to achieve higher peaks, especially during the first week of August, when external temperatures reaches 30 °C.

Among the three simulated cases presented in the Figure 6, the use of control strategy 9 causes indoor temperature to be above 25 °C for about 50 hours in both living room and bedroom 1. This number rises for more than 250 hours when the dwelling is exclusively ventilated by the mechanical ventilation system. On the other hand, the indoor temperature achieves a peak of 35 °C in both zones when the openings are kept constantly and fully opened (control 9) while the peak temperature in the living room and bedroom 1 lowers to 31 °C and 30 °C respectively in the case of mechanical ventilation.

During 85% of August, the lowest simulated temperatures are achieved by keeping the doors and windows opened. However, when external temperatures are high, keeping the windows constantly opened means bringing the unpleasant external conditions inside the house. On the other hand, closing the openings when the external temperature rises above 30 °C (control 10) causes the indoor temperatures to be even higher, because the internal heat gains accumulate over an already overheated room.

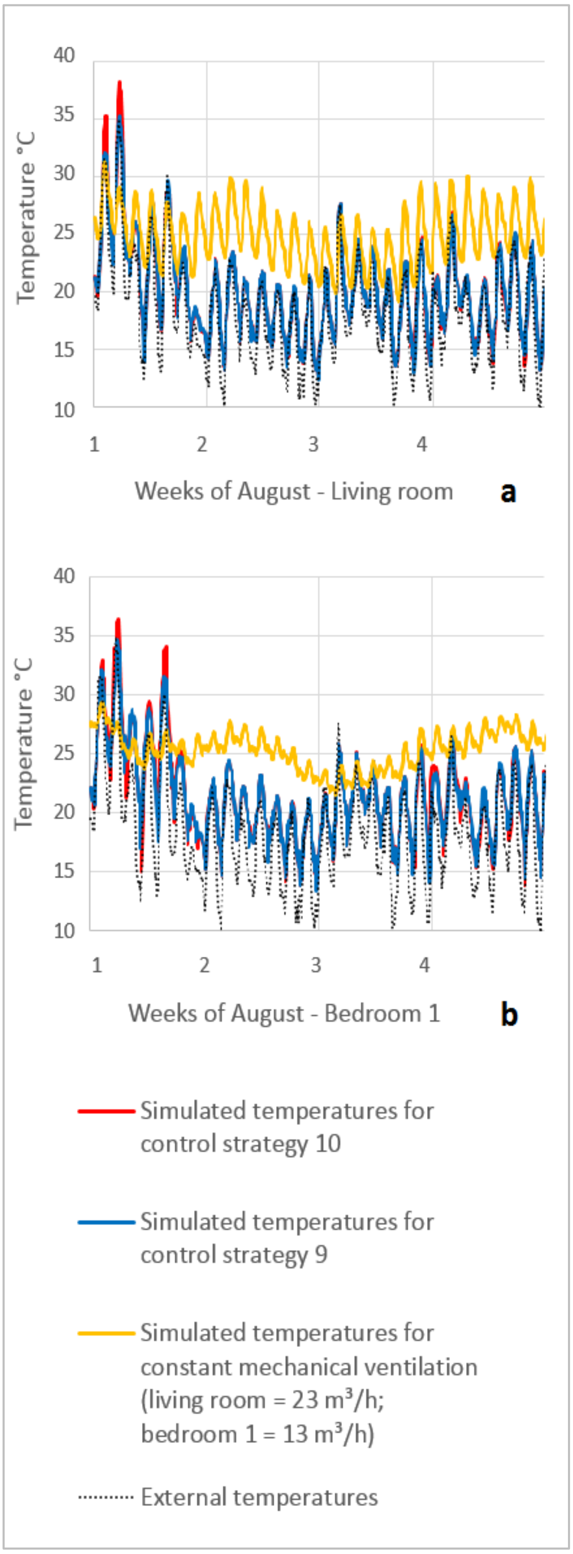

Figure 6: External and Simulated temperatures a: living room, b: bedroom 1.

The mechanical ventilation system performs better than the control strategy 9 for about 20 hours in the living room and 60 hours in the room 1. This difference can be explained by the position of the openings in each zone. In the living room, there are 2 openings to the exterior and they are in opposite walls, easily enabling cross-ventilation. There are also 2 openings in the bedroom 1, but only one window that connects to the external environment. The second opening is a door that connects the bedroom 1 with the hall. The door and the window are in adjacent walls, thus being more difficult to achieve cross-ventilation.

If the external temperatures are going to be high (about 30 °C) in the forthcoming hours, it is preferable to keep the windows closed through the whole period, even while the external temperature is still under comfortable levels. Otherwise, closing the windows only when the external air is too warm leads to even higher indoor overheating.

In this context, predictive control might play a key-role to avoid indoor overheating. If the occupants know in advance that the future hours or days are going to be warm, they might already choose to keep the windows closed.

CONCLUSION

This work studied the possibility of avoiding indoor overheating in a monitored passive house in the Netherlands. The living room was tested for both single-sided and double-sided ventilation cases.

The best performance was achieved by double-sided ventilation when the openings were kept fully opened all the time (control 9). By applying such strategy, the temperatures in the living room raised above 28 °C during less than 10 % of the month of August.

The night-cooling ventilation was the less efficient strategy among the ones studied in this work. When the openings were closed during day-time and opened during night-time, the living room achieved temperatures higher than 28 °C for almost 50 % of August.

The weather plays an important role when deciding which control strategy to apply to the openings of a passive house. The weather data used in this study provides a considerable cooling potential during the whole August, with air temperatures rarely above the value of 28 °C. In such cases, keeping the dwelling constantly ventilated seems to be an efficient way to avoid indoor overheating. However, in climates where external air temperatures achieve values higher than 30 °C for longer periods, the night-cooling might be the most suitable strategy to keep the temperatures inside the house closer to comfortable levels. In this context, predictive control may be a powerful technique to improve indoor environment. If the weather forecast indicates that forthcoming days will be too warm, the occupants might decide in advance to keep the windows closed and prevent uncomfortable temperatures inside the house when the warm period strikes.

ACKNOWLEDGEMENT

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