Performance Evaluation of Passive Cooling in a Multi-Zone Apartment Building Based on Natural Ventilation

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Abstract. In moderate climates, using natural ventilation systems could allow to save up to 60 % of the end energy for ventilation and air conditioning. Natural ventilation systems depend on pressure differences to move fresh air into buildings by wind effect and pressure effect. Night cooling can be achieved either by an increased air change rate. The higher air change rate can be realized by ventilators/ mechanical ventilation systems or by free convection. The main objective of this paper is to reduce the internal summer cooling load by increasing the natural cross ventilation between different zones in apartment buildings. The performance of natural ventilation is highly dependent on the external outdoor temperature. Over the last years, an increase in the outdoor temperature has been noticed and predicted to rise by the end of this century according to IPCC which puts into consideration the uncertainty of the climate. This paper investigates the performance of natural ventilation using building energy simulation tool 'DesignBuilder" to simulate a multi-zone apartment building in Belgium. The indoor thermal comfort is enhanced by determining an optimum set of input parameters such as the setpoint temperatures, the discharge coefficient of the night ventilation, and the opening areas in the building. Those parameters are optimized using current and future weather data to evaluate the evolution of natural ventilation system performance and indoor thermal comfort. The results show that proper use of natural ventilation can significantly reduce the overheating risk during a typical year and that the benefits of natural ventilation are not expected to vanish with global warming. It can be seen that, without natural ventilation, thermal comfort could be reached on average 53.7% of the time, while it could reach 66.2% of the time using single-sided ventilation and 78.8% with cross ventilation. However, during heatwaves, natural ventilation becomes inefficient and cannot guarantee the thermal comfort of the occupants all the time as the thermal comfort of occupants can only be achieved 51% of the time during heatwaves.

Keywords. natural ventilation, passive cooling, cooling demand, thermal comfort, heatwaves
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1. Introduction

The energy demand for space cooling is growing fast in the next decades and will be tripled by 2050, the increase in the cooling demand led to a significant increase in the sales of air-conditioning systems between 1990 and 2016 [1]. Therefore, there is an attention to the passive cooling techniques that reduce the need for air-conditioning systems by improving the internal environmental conditions with low or no energy consumption [2].

There is a growing interest in passive cooling techniques due to the energy and indoor air quality problems associated with mechanically ventilated systems. Natural Ventilation (NV) is one of the most promising passive cooling techniques used in buildings in different climates. NV helps to create healthy indoor environments for occupants and meet the EU targets to reduce CO_2 emissions by 2050.

Several studies analyzed the performance of NV in different climates. In the temperate climate, NV has a good potential for thermal comfort improvement that varies between 8% and 56% [3]. In the Mediterranean climate, it was predicted that cross NV during day and night resulted in up to 7 K temperature decrease in apartments [4]. In different climate zones in Australia, NV was investigated for a single-storey building, the results showed in hot humid summer, warm winter zone, the annual NV hours is 4728, while the least NV hours is in cool temperate zone [5].

However, the performance of NV under the climate change scenarios including the disruptive events of heatwaves is not appropriately addressed. This study focuses on the NV strategies performance under different future climate change scenarios in Belgium including summer heatwaves.

2. Methodology

The conceptual framework of the study is presented in Fig. 1. The first part of the framework introduces the literature review that has been conducted to identify the natural ventilation strategies and specify the performance indicators and the comfort models. The second part presents the case study as well as the weather data used in the framework.

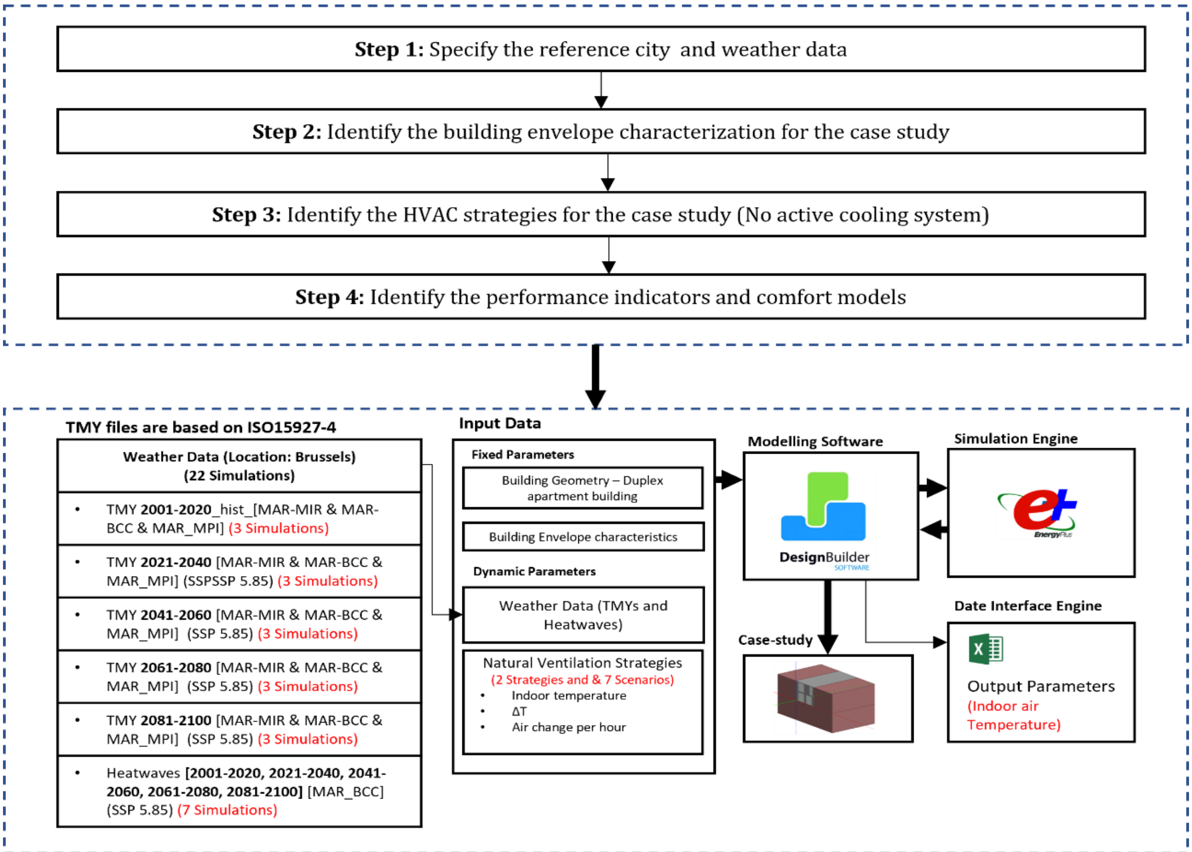

Fig. 1 – Conceptual framework of the study.

2.1 Building Model

This section gives the most important information about the geometry, envelope characteristics and operation features of the studied dwelling (see Tab. 1). Fig. 2 is an upper view of the studied duplex. The building has a North-South orientation and a large window-to-wall ratio (0.6) on the South façade. The dwelling has been divided into seven thermal zones, which have been defined depending on the zone usage, temperature setpoint and orientation.

The EPBD imposes energy performance standards for buildings. The building walls are compliant with the EPBD 2020 [6]. The glazing has been defined in the EPB file of the building as triple-glazing. The frame of the window, made of wood and aluminum, has a U-value of 0.9 $W/m^2{\cdot}K$, resulting in a net U-value of 0.6 $W/m^2{\cdot}K$, in compliance with the EPBD. The duplex is equipped with a balanced mechanical ventilation system with a heat recovery module of 85% efficiency and a by-pass system. The heating system is traditional with water radiators fed by a gas boiler. There is no mechanical cooling system.

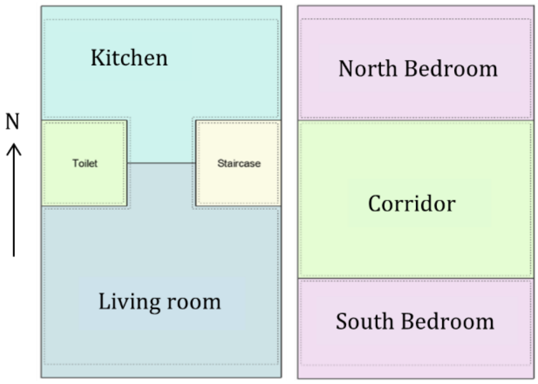

Fig. 2 – Upper view of the duplex.

Regarding the operation of the building, it is assumed that the occupants are four adults each emitting 100 W. For lighting, it is good practice to consider a consumption of 6 W/m^2, according to norm NBN EN 15193 [7]. The energy consumption linked to electric appliances is assumed to be 3 W/m^2. Some operation/occupancy schedules can be applied to that energy consumption. They can be found in standard ISO 17772 [8].

Tab. 1 – General characteristics of the case study.

General information		Envelope	
Building location	Liège, BE (50°37'57" N 5°34'47"E)	Walls	
Building type	Residential	U-value [W/m²]	
Nb storeys	9	External wall	0.152
Case study	4-person family duplex	Internal wall	0.452
Floor	8-9	Adjacent wall	0.198
Orientation	South	Roofing	0.081
Surface	173 m²	Floor/ceiling	0.132
WWR	0.6	Windows	
Infiltration rate	0.6 ach at 50 Pa	U-value [W/m²]	0.6
Ventilation rate	3.6 m³/h/m²	Solar factor [-]	0.5

2.2 Weather Data

This study uses MAR regional atmospheric model, MAR is a three-dimensional atmospheric model coupled to a one-dimensional transfer scheme between the surface, vegetation, and atmosphere [9]. Since MAR is a regional model, it must be forced at its lateral boundaries (temperature, wind, and specific humidity) by a global model by the reanalysis of the ERA5 which represents the closest climate to reality, and then by 3 Earth System Models (ESMs) from CMIP6 database namely BCC-CSM2-MR (MAR-BCC), MPIESM.1.2 (MAR-MPI), and MIROC6 (MAR-MIR) [10].

These ESMs forced MAR simulations can be used to anticipate future periods. MAR simulations are able to represent the current climate and its interannual variability with success, except MAR-MIR which significantly overestimates temperature and solar radiation in summer. MAR-MPI can be considered as the coldest MAR simulation and MAR-BCC is the ensemble mean of all the MAR simulations [10]. MAR Model runs at 5 km spatial resolution over the Belgian territory as shown in Fig. 3.

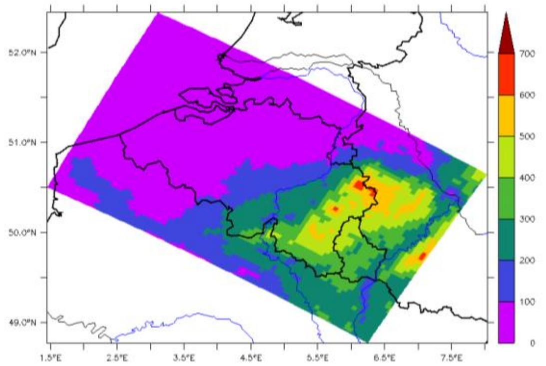

Fig. 3 – Topography (in meters above sea level) of the MAR domain representing Belgian territory [11].

In the framework of this study, data sets of the Typical Meteorological Years (TMY) are used for the 3 MAR-Simulations for the Shared Socioeconomic Pathway (SSP5.85) [12]. There are 3 main scenarios, SSP2-4.5, SSP3-7.0, and SSP5-8.5, which are respectively increasingly warming for 2100, this study used SSP5.85. In addition to that, TMY for historical scenarios based on MAR-BCC simulation is used as a reference TMY for the period (2001-2020).

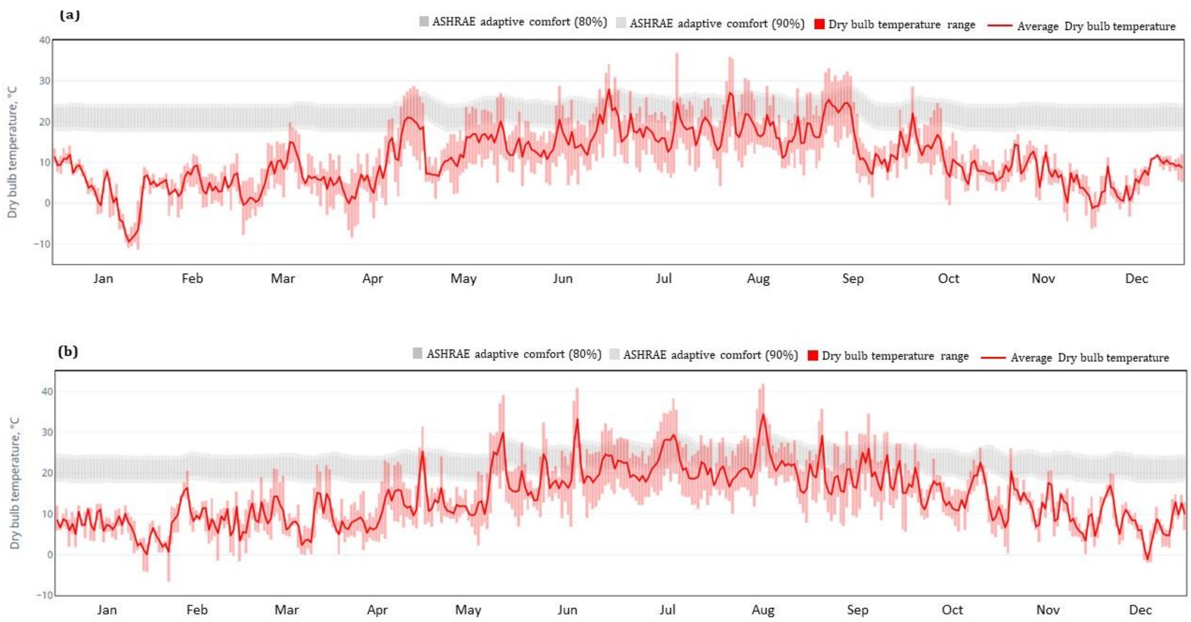

Fig. 4 – Evolution of monthly outdoor temperature with the adaptive comfort model for two periods (a) TMY 2001-2020 and (b) TMY 2081-2100.

Fig. 4 shows the evolution of the monthly outdoor temperature between the reference period and the period 2081-2100. It can be seen that, there is a significant increase in the temperature range during the periods, especially in the summer months by 3.4 K.

In addition to the TMYs, this paper also studies the performance of natural ventilation during heatwaves in the summer period. Belgium has two definitions for the heatwaves, the retrospective heatwave is defined according to the Royal Meteorological Institute as a period of 5 consecutive days with a maximum daily temperature of 25°C or more (summer days) and with a 3 day period of 30°C or higher [13], while the prospective heatwave is defined as a period of 3 consecutive days with a minimum temperature of 18.2°C or higher (average for the 3 days) and a maximum temperature of 29.6°C or higher [14].

However, this paper followed a different definition of heatwaves which is considering the local climate of each region, based on the statistical definition of a heatwave by Ouzeau et al. [15], they defined the heatwave events and classified them according to three criteria of the heatwave (the duration, the highest temperature and the intensity).

- The duration is specified according to the duration of the heatwave which is calculated by the number of consecutive days of the heatwave.
- The highest temperature is detected based on the maximal daily mean temperature reached during the period of the heatwave event.
- The intensity is calculated by the cumulative difference between the outdoor temperature and the temperature threshold (Sdeb) of 23°C for the whole duration of the event, divided by the difference between Sdeb and Spic (26°C).

2.3 Passive Cooling Concept

A passive cooling concept based on natural ventilation is applied to cool the apartment. A series of cooling simulations were conducted using DesignBuilder simulation tool to investigate the impact of climate change on the potential of natural ventilation in Belgium.

The control strategy of the natural ventilation in this study is based on the minimum indoor temperature, the temperature difference between the indoor and outdoor temperature (ΔT) and the occupancy schedule in the different scenarios. Single-sided ventilation and cross ventilation strategies are studied using the TMYs for the different MAR simulations in the kitchen zone. Single-sided ventilation occurs when the fresh air exits the room in the same direction it had entered. Cross-ventilation occurs when there are pressure differences between one side of the building and the other, the airflow path goes from one side of the building and exits from the other side after rotating around the openings and windows [16]. The airflow path for single-sided ventilation and cross ventilation is illustrated in Fig. 5. Natural ventilation is assumed to be triggered by the opening of the windows and there is no obstacle to cross-ventilation as there is no physical separation between the kitchen and the living room.

During heatwaves, different scenarios have been conducted by adapting the parameters of the natural ventilation control strategy. The maximum admissible airflow rate has also been changed. The characteristics of the considered scenarios are described in Tab. 3.

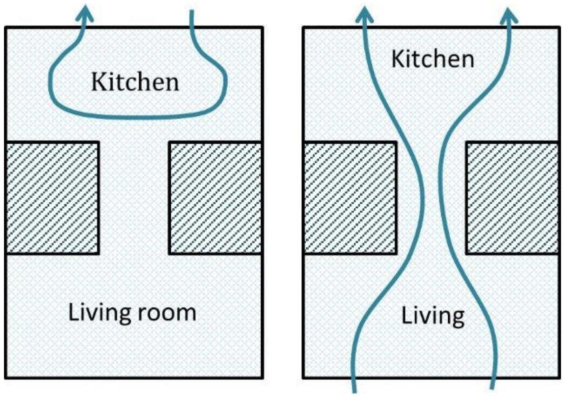

Fig. 5 – Illustration of the single-sided and cross-ventilation strategies in the studied building.

The minimum indoor temperature corresponds to the indoor temperature above which windows can be open. ΔT is the temperature difference between the indoor and the outdoor temperature. The windows can only be open if $T_{in} - T_{out} > \Delta T$. The schedule defines the periods during which the windows can be open. In the end, the windows are open only if all the previous conditions are satisfied.

Due to the unavailability of monitoring data, the performance evaluation of the different NV strategies and the different scenarios are analyzed in a comparative method.

2.4 Comfort Evaluation

In this study, the adaptive comfort model is used to determine the overheating risk in the dwelling and the efficiency of passive cooling. The adaptive comfort theory states that the comfort temperature range can be broadened because the occupants can adapt their behavior depending on the outdoor conditions. The adaptive comfort model is described in norm EN 15251 [17]. In a naturally ventilated building without any air-conditioning, the occupants feel more connected to the outdoor environment and can bear higher temperatures in summer. The maximum comfort temperature adaptive can be expressed by a relationship depending on the mean outdoor temperature:

$$T_{confort,max} = 0.33\, T_{rm} + 21.8$$

where T_{rm} is the running mean outdoor temperature during the previous seven days. For the adaptive comfort theory to be applicable, there should be neither a heating nor a cooling system in operation and window opening and closing should be of primary importance as a means of regulating thermal conditions in the space. They should also be able to adapt their clothing to indoor and outdoor conditions.

3. Results

The results of the simulations are shown in Fig. 6. The most interesting room to study regarding natural ventilation is the kitchen. The graph shows the evolution of time during which thermal comfort is reached in the kitchen with global warming. By the end of the century, the average indoor temperature is expected to increase by 3 to 3.7 K depending on the considered MAR simulation, which results in thermal comfort degradation.

The percentage of time during which the indoor temperature remains below the maximum comfort temperature drops from 53% to 43.6% over the century. Single-sided ventilation results in an average indoor temperature decrease by 2.5 K and an increase of 12.5% in thermal comfort achievement. Cross ventilation allows for a further reduction of 1.8 K on average and a 12% increase in thermal comfort achievement.

The 3 different heatwaves are studied: The most intense heatwave (HI), the maximum temperature (HT) and the longest duration (LD) of the heatwave. The characteristics of the studied heatwaves are shown in Tab. 2. As expected, by 2100, heatwaves will last longer (around 20 days vs 5 nowadays) with a significant temperature increase (15% of time above 40°C in the period 2081-2100 vs 0% in the period 2001-2020).

Fig. 7 shows the temperature profile of an average day during heatwaves throughout the century. Some natural ventilation strategies are studied and compared in Fig. 8 for a heatwave between 19/06/2015 and 24/06/2015. It can be directly seen that natural ventilation has a positive impact on indoor temperature. In particular, the use of natural ventilation also during the night allows for a reduction of 6 K.

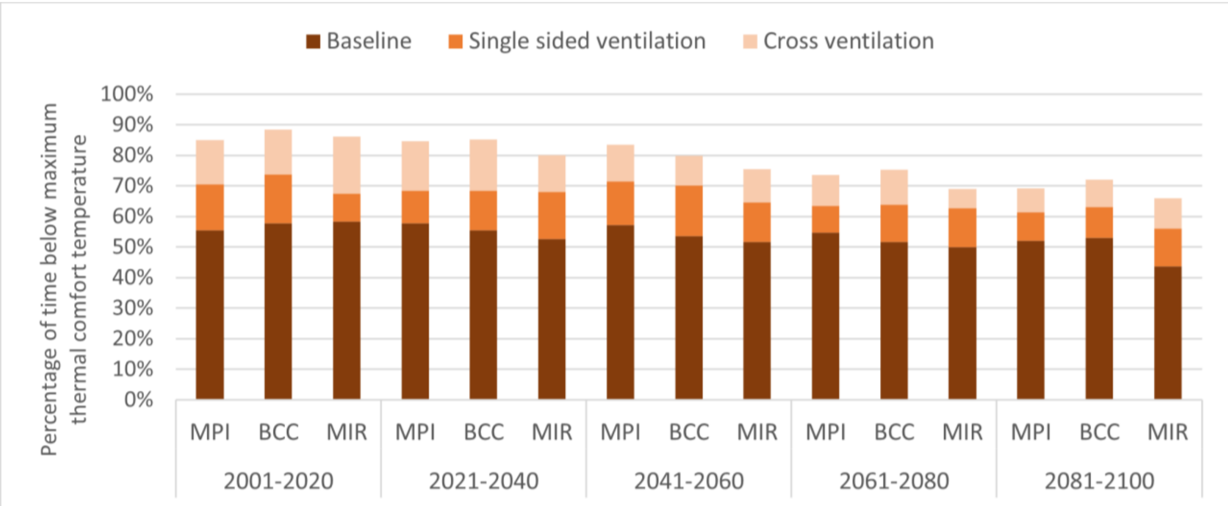

Fig. 6 – Percentage of thermal comfort time during the cooling period depending on the climate scenario and the adopted natural ventilation strategy.

Tab. 2 – Main characteristics of the studied heatwaves.

Period **Type of heatwave**	**2001-20** **HI**	**2021-40** **HI & HT**	**2021-40** **LD**	**2040-60** **HI**	**2061-80** **HI**	**2081-100** **HI**
Number of days of the heatwave	5	7	8	26	21	19
Percentage of time above						
25°C	83%	70%	60%	60%	76%	80%
30°C	57%	50%	34%	34%	47%	55%
35°C	29%	21%	13%	8%	19%	30%
40°C	0%	9%	0%	0%	1%	14%
Maximum temperature	39.8	43.6	37.4	38.0	41.6	44.4
Minimum temperature	14.9	14.1	14.9	14.8	15.4	17.1

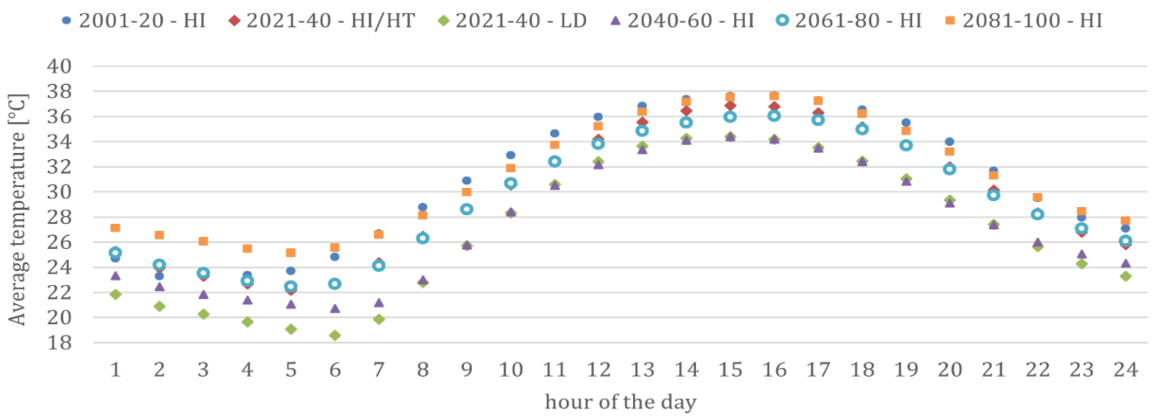

Fig. 7 – Evolution with global warming of an average day during the different heatwaves.

The enhancement of the ventilation flow rate during the night also has a positive effect on the indoor temperature. During the night, the temperature can even fall to 25°C. However, during the day, it is impossible to reach an indoor temperature below 30°C. Tab. 3 also shows the percentage of time during which thermal comfort is reached. The minimal thermal comfort temperature has been calculated with the adaptive comfort theory. When the airflow rate is at its highest, thermal comfort is reached only half of the time, and mostly during the night.

Tab. 3 – Description of the parameters used for the natural ventilation strategies and calculation of the percentage of time during the heatwaves during which thermal comfort is reached.

	Min T_{in}	ΔT	Schedule	Max airflow rate (ach)	Thermal comfort
Scenario 1	23	2	Day	5	0%
Scenario 2	23	2	Night	5	2.5%
Scenario 3	23	2	24/7	5	5.0%
Scenario 4	23	0	24/7	5	5.0%
Scenario 5	23	0	24/7	10	21.7%
Scenario 6	23	0	24/7	20	44.2%
Scenario 7	23	0	24/7	40	51.7%

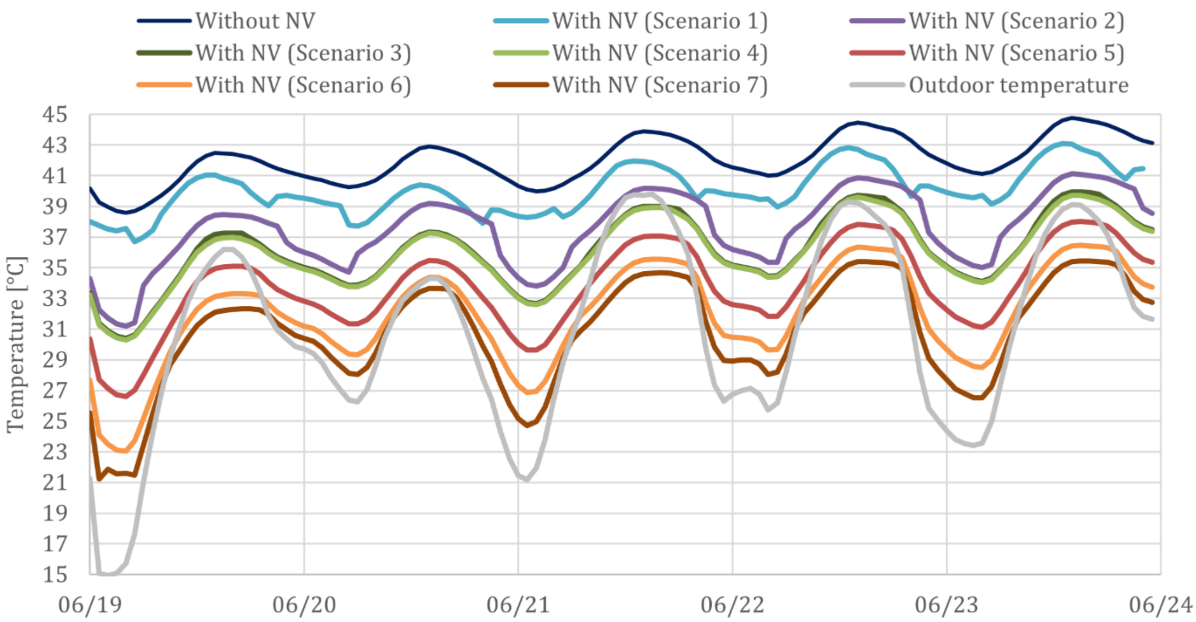

Fig. 8 – Evolution of the indoor temperature in the living room during a heatwave depending on the different natural ventilation strategies.

4. Discussion

Two natural ventilation strategies have been studied. The graph of Fig. 6 highlights the indoor temperature decrease due to the natural ventilation strategy. Those two strategies are well-known in the field of natural ventilation: single-sided ventilation and cross ventilation. Cross ventilation is the most efficient technique regarding natural ventilation, especially if the building is oriented according to the main wind direction. From this graph, it can be deduced that, for the whole cooling period, the potential of natural ventilation is not expected to vanish with global warming.

It is also interesting to study the evolution of the potential of natural ventilation during heatwaves. With global warming, heatwaves in Europe are expected to become more frequent, more intense and to last longer. Some present and future heatwaves have also been analyzed using MAR-BCC simulation. Globally the temperature profile is similar for all heatwaves (Fig. 7) but by 2100, the temperature decrease during the night will be lower, threatening the benefits of night ventilation. The main principle of night ventilation is to take advantage of the cooler outdoor air during the night to release the heat stored all day long within the walls, "resetting" the thermal inertia of the building. With global warming, it is thus expected that the potential of night ventilation will be reduced due to warmer nights. The potential of natural ventilation is also jeopardized by the longer duration of the heatwaves.

Natural ventilation on its own is thus not sufficient to reach thermal comfort in the living room. Aflaki et al. [18] suggested that natural ventilation should always be coupled to heat avoidance complementary techniques to increase its potential. The orientation of the building is also of primary importance. Eastern and western windows receive twice as much irradiation as north-south elevation. However, it is also recommended that the building should be oriented according to the prevailing wind direction, which could lead to a contradiction.

It also possible to study the evolution of the prevailing wind direction to see if the building design should also take climate change into consideration. Fig. 9 shows that the wind direction profile of Brussels remains similar all along the century. Wind mainly has a South orientation which matches the recommendations linked to solar gain avoidance. In Belgium, new constructions should preferably have a north-south orientation.

5. Conclusion

This paper studied the potential of natural ventilation in Belgium to reduce the internal cooling loads during summer period through different natural ventilation strategies (single-sided ventilation and cross ventilation).

The simulations are conducted by DesignBuilder and using MAR regional atmospheric model. The results compared between the two aforementioned natural ventilation strategies and the impact on the indoor air temperature. The results show that without natural ventilation thermal comfort could be reached on average 53.7% of the time, while it could reach 66.2% of time using single-sided ventilation and 78.8% with cross ventilation. The paper also discussed the effect of adapting the operating schedule and airflow rate during heatwaves on the indoor temperature in the different scenarios. The ventilation strategies proved that natural ventilation only is not sufficient to satisfy the thermal comfort of occupants for more than 51% of the time during heatwaves.

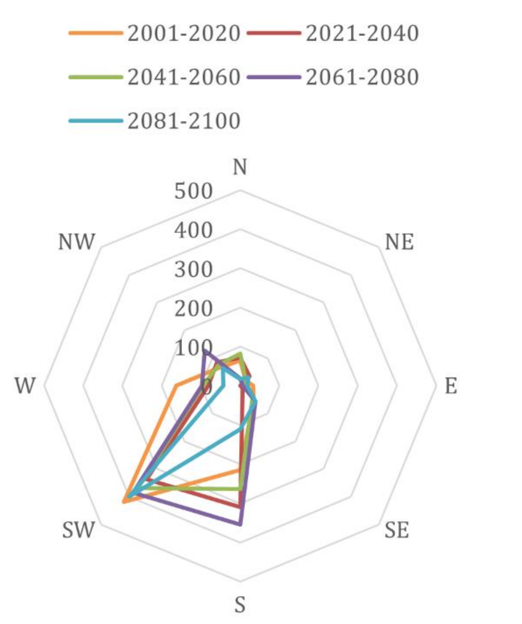

Fig. 9 – Wind diagram showing the number of hours during which wind blows in each direction at a speed higher than 3.5m/s. The number of hours is counted only during the cooling period to emphasize the potential of natural ventilation.

6. Acknowledgment

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