Natural Ventilation and Thermal Behavior of Buildings

Extended Abstract

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ABSTRACT

Natural ventilation plays an important role on the thermal and energy performance of a building. The present study aims to analyze the natural ventilation conditions of a dwelling and its impacts on the thermal and energy performance using the EnergyPlus dynamic simulation software. Through this software, several multi-zone simulations were carried out under free-floating conditions (no HVAC systems), in the cooling season, and under controlled temperature conditions, in the heating season. In the cooling season, ventilation scenarios with windows opening in pre-set periods of time and existence or absence of fixed openings in the facades were analyzed. The analysis revealed that the ventilation schedule 18h-23h, corresponding to a period of occupation and activity in the dwelling, provides satisfactory results on the thermal and ventilation indicators. The existence of ventilation openings in the facades proved to be an important factor of temperature control by lowering the average indoor zone temperatures during the day. Cross-ventilation showed to be effective in dwelling ventilation during the periods of the day it occurs. In the heating season the chosen simulation alternatives were the existence or absence of fixed openings for room ventilation and their surface area. The results showed that the chimney effect plays an important role in the ventilation of the dwelling and that in general it outperforms the wind effect. The fixed openings on the facades were essential for the ventilation in this season and the sizing according to the existing standardization showed to be adequate for the expected performance of the dwelling.

1. Introduction

Sustainability is nowadays a major concern in all sectors of activity. The scarcity of non-renewable energy sources has been leading to a paradigm shift in society towards to an increasing adoption of clean energy sources and search for ways to reduce energy costs.

In buildings, this concern is also present, both in the construction and operation stages. In order to reduce energy costs in a sustainable manner, it is necessary to control several parameters related to the functionality and habitability of the buildings, such as thermal comfort, ventilation and lighting. Moreover, interactions between these parameters may take place. This can be exemplified through the interaction between the thermal behavior of buildings and natural ventilation.

Natural ventilation is important in order to maintain air quality and prevent undesirable condensations. However, it is necessary to keep ventilation levels to a minimum during the winter as the incoming air to the building is detrimental to thermal comfort in this season.

In the summer this issue is not critical and the ventilation can even be used to cool the rooms, especially at night time.

The interaction between natural ventilation and the thermal behavior of buildings was studied by several authors. It is important to highlight the studies for the cooling season on the potential of night ventilation for passively cooling buildings [1], on the control patterns of window opening for an optimized ventilation [2] and on the impact of different daytime periods in building ventilation [3]. Studies have also been carried out on the adoption of different window opening areas [4] and on the influence of the layout of windows, interior doors and building orientation on rooms ventilation degree [5].

Studies related to the heating season focuses mainly on ventilation due to temperature difference (by chimney effect), in which the existence and absence of wind [6] or wind direction variation [7] are compared.

This paper focuses on the study about the interaction of natural ventilation with the thermal and energy performance of a housing unit in the heating and cooling seasons. In the simulations for the cooling season, the study focuses on the influence of ventilation periods, the existence of openings in the facades and impact of cross-ventilation on rooms ventilation degree. In the simulations carried out for the heating season, the study focuses on the influence of the facade fixed openings on rooms ventilation, the existence or absence of fixed openings and the existence or absence of wind on rooms ventilation degree.

2. Natural Ventilation

In natural ventilation of buildings, the air flow through a building is caused by the pressures generated by wind on the building envelope (wind ventilation) and/or pressure differences generated by air density differences caused by indoors-outdoors temperature differences (ventilation by chimney effect). In this type of ventilation the admission of external air in the building is performed mainly through openings in the facades and by doors and windows. The openings in the facades can be fixed or adjustable, whereas the doors and windows can be operated manually or automatically by a building management system.

Wind ventilation can be distinguished between cross-ventilation and single-sided ventilation [8]. Cross-ventilation is generated by ventilation openings on opposite sides of an enclosed space. In order to have sufficient air flow, there must be a significant wind pressure difference between the inlet and outlet openings. Single-sided ventilation refers to the ventilation generated by openings placed on the same facade. The driving forces for single-sided ventilation are relatively smaller than for cross-ventilation and highly variable.

3. Methodology

For studying the natural ventilation features and their impacts on building thermal and energy performance, a housing unit was modeled and simulated through a dynamic simulation program - EnergyPlus - for the heating and cooling seasons.

This case study is a 2-room dwelling located on the first floor of a residential building, with the glazed spans located on two opposing facades oriented in the North and South directions (Figure 1). The remaining facades are oriented east and west and border two similar autonomous fractions which are assumed to have an indoor air temperature similar to that of the study model.

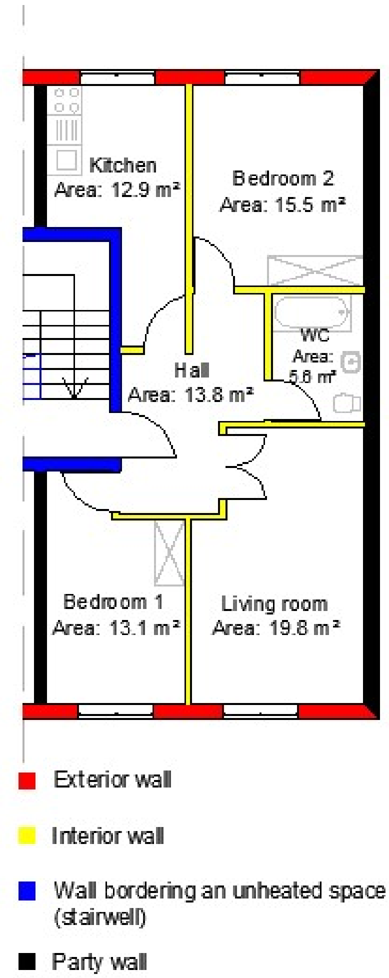

Figure 1 – Case study model

The model has two chimneys, located in the Kitchen and WC, with 12 m of height. They were sized according to the standard NP 1037-1 [9] and have cross-sectional areas of 400 cm^2 (20x20) and 225 cm^2 (15x15) for the Kitchen and WC ducts, respectively.

The fixed openings for ventilation in the facades are located in the main rooms (Bedroom 1, Bedroom 2 and Living room). Their sizing was performed according to the standard NP 1037-1 [9], which resulted in a section area of 55 cm^2 that was assigned to all fixed openings in the facades. The occupation period of the dwelling is restricted to the period 18h-7h. The period with the highest internal gains in the dwelling due to human occupation, equipment and lighting is the period 18h-23h.

3.1 EnergyPlus software

The EnergyPlus dynamic simulations software was used in order to carry out the simulations. This software allows to carry out simulations that simultaneously integrate the calculation of the thermal loads and the calculation of the building systems, using a nodal type multi-zone system. The program utilizes the concept of thermal zone, which is an air volume where the thermal conditions are homogeneous. Several thermal zones were used, one for each room of the model, on which hourly information on various parameters related to the study were obtained, such as the volume of air admitted/evacuated from the rooms and the internal rooms temperature. EnergyPlus does not allow for a prompt data input for the various zones of the study model, so Google SketchUp and the OpenStudio plug-in have been used to overcome this issue. To obtain the necessary information about the climatic conditions of the region where the model is located, the program uses a *Weather file* that depends on the geographic location that was chosen for the simulation. The simulations were performed using the file with climatic data for the city of Lisbon.

3.2 Ventilation strategy

The study model contemplates outside air intake openings and inside air evacuation zones with air paths created between each other in order to make air flow possible. The dwelling ventilation scheme is shown in Figure 2.

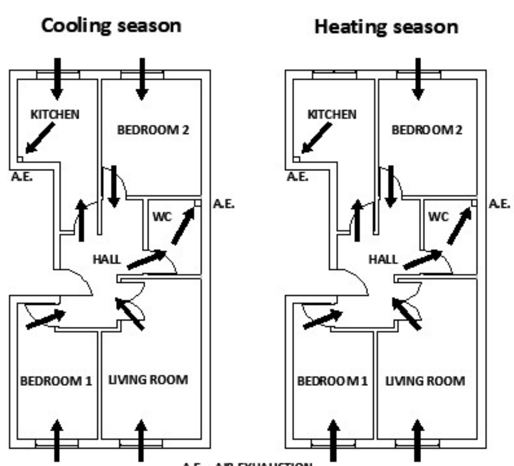

Figure 2 – Ventilation scheme of the model for the conventional cooling season (a) and conventional heating season (b)

In the conventional cooling season the outside air in the base model enters through the windows and the fixed openings for ventilation in the facades. The windows and openings are installed on the facade walls of Bedroom 1, Bedroom 2 and Living Room while there is only a window on the Kitchen facade wall. The Hall acts as a passageway for the air that comes from the main rooms (Room 1, Room 2 and Room) and is distributed to the Kitchen and to the WC. In the service rooms (Kitchen and WC) there are two ducts that perform air exhaustion.
In the conventional heating season, the outside air enters in the base model only through the fixed openings for ventilation in the facades.
The openings are placed on the facade walls of Bedroom 1, Bedroom 2 and Living room. As for the conventional cooling season, the Hall works as the passageway of air that comes from the main rooms (Bedroom 1, Bedroom 2 and Living room) and is distributed to the Kitchen and WC. Air exhaustion is performed in the service rooms (Kitchen and IS) through ducts.

3.3 Simulations plan

In the cooling season the opening of the windows of the rooms is conditioned by the value of the inside air temperature and outside air temperature. Five initial simulations are carried out in order to define the window opening area for the rest of the simulations. After defining the opening areas, two different groups of simulations are performed.
In the first group the simulations are performed with the presence of ventilation openings on the facades, while in the second group these openings are absent. Three simulations are performed for each group, differentiated by the windows opening schedule: 0h-7h, 18h-23h or 24h per day. For the first group there will be an extra simulation in which windows do not open at any hour of the day.
For the heating season two groups of simulations are performed: in the first group, the aforementioned fixed openings are placed on the exterior walls of the main rooms, while in the second group these openings are absent (this group has only one simulation).
The simulations carried out with openings in the exterior walls will be divided into two groups, distinct from each other only in terms of the *Weather File* used. One of the groups of simulations will be carried out with the original file for the city of Lisbon. The other group of simulations uses the same *Weather File*,

differing only in the fact that it has been assigned zero value to the wind speed for all hours of the simulation period. Each of the groups has five different simulations in which the area of fixed openings for ventilation in the exterior walls varies: 55 cm², 75 cm², 95 cm², 115 cm² and 135 cm².

4. Results

4.1 Cooling season

In the cooling season some indicators were used to compare the scenarios simulated. The first indicator is the *Average number of air changes per hour* (ACH) over a given time period. The second indicator, which is related to the first one, is the percentage of hours in a given time period for which the air changes per hour for a given room are above the design value (*Percentage of hours with the ACH number above the design value* - PHAD). The design values are defined by standard NP 1037-1 [9] as being equal to 1 ACH for the main rooms and 4 ACH for the service rooms. The third indicator refers to the building thermal characteristics. The standard REH [10] defines 25ºC as the internal comfort temperature, whereby the excess temperature in relation to this value is accounted at each hour of the day during the cooling season. The sum of the values for every hour leads to the concept of *Cooling degree-days*.

After performing an initial group of simulations, the percentage of window opening was set as 30% of the total glazing area for all windows in the cooling season.

4.1.1 Simulations performed using fixed openings for ventilation in the facades

The simulation results in terms of the abovementioned indicators are shown in Figures 3-5. The results show that the simulation performed with the permission of window opening during 24 hours per day provides the best results for all indicators, followed by the simulation with permission to open in the periods 18h-23h and 23h-7h, respectively. The simulation performed without the possibility of window opening provides the most unfavorable results for all the indicators, since the infiltration that occurs through the window frames does not allow satisfactory thermal and energy results.

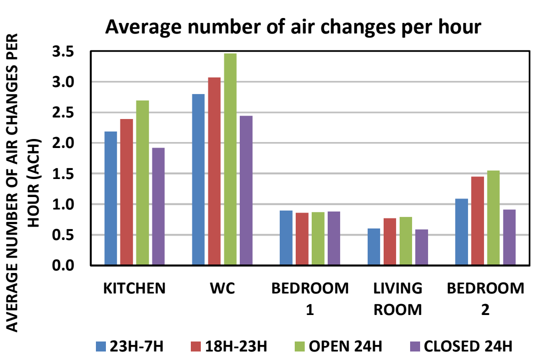

Figure 3 - Average ACH for the cooling season (simulations performed using fixed openings for ventilation in the facades)

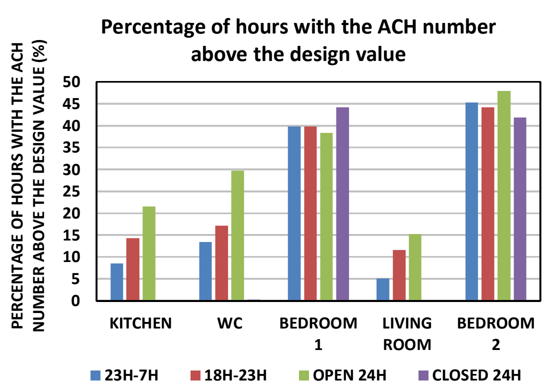

Figure 4 – PHAD for the cooling season (simulations performed using fixed openings for ventilation in the facades)

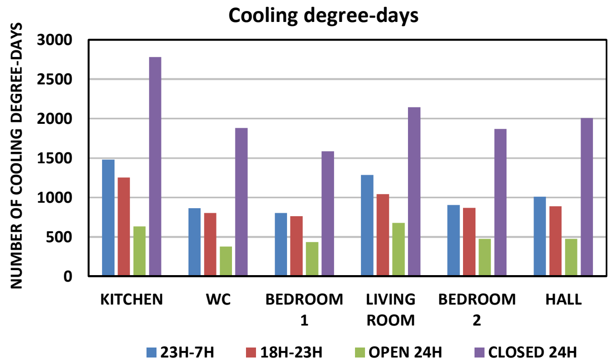

Figure 5 – *Cooling degree-days* for the cooling season (simulations performed using fixed openings for ventilation in the facades)

4.1.2 Simulations performed without using fixed openings for ventilation in the facades

Figures 6-8 show the results for the simulations performed without using fixed openings for ventilation in the facades. In this case, the simulation in which window opening is allowed during 24 hours per day provides the best results for the indicators described above. In this specific case, the *Percentage of hours with the ACH number above the design value* (PHAD) for the ventilation period 23h-7h is higher than that of the simulation 18h-23h, while the *Average number of air changes per hour* from is higher for the ventilation period 18h-23h. The number of hours where window opening is allowed is lower for the simulation with ventilation period 18h-23h than for the simulation with ventilation period 23h-7h, which explains why the PHAD indicator is higher for the latter one.

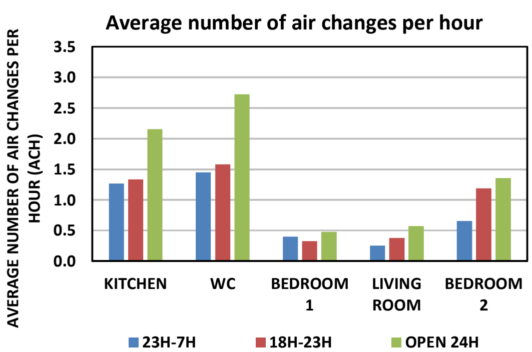

Figure 6 - Average ACH for the cooling season (simulations performed without using fixed openings for ventilation in the facades)

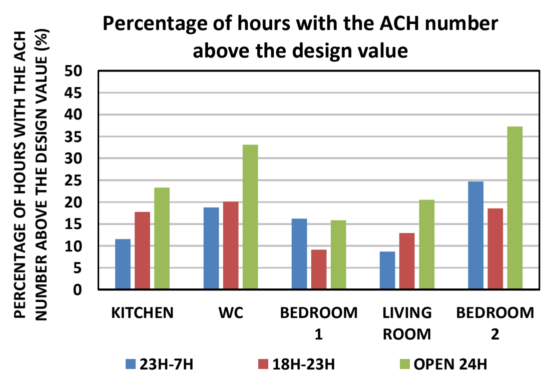

Figure 7 - PHAD for the cooling season (simulations performed without using fixed openings for ventilation in the facades)

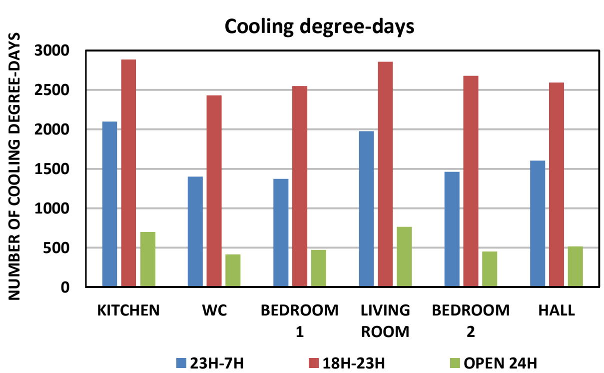

Figure 8 - *Cooling degree-days* for the cooling season (simulations performed without using fixed openings for ventilation in the facades)

4.1.3 Influence of fixed openings for ventilation in the facades

When comparing the simulations with windows opening allowed in the period 18h-23h, it is noticed that the simulations without openings in the facades generally have higher values of ACH, since the rooms internal temperature increases due to the absence of ventilation in the remaining periods of the day. This originates a greater need for windows opening in this period (as the window opening control depends on the internal temperature) and also an increase in the ventilation by chimney effect (due to the greater temperature difference between inside and outside air). When comparing the simulations for the window opening period 11h-7h the results show that there is no clear advantage of any of the simulations.
In the simulations carried out with fixed openings in the facades there is a continuing ventilation of the rooms, which causes a decrease of their internal temperature and leads to a smaller number of hours in which the windows are opened.

4.1.4 Cross-ventilation

By analyzing the average number of ACH and the percentage of hours per day in which there is air exhaustion through the windows (Table 1 and Table 2) it is noticed that this occurs mostly in the North-South direction.
The number of hours that the windows are open is greater in the simulation with ventilation period 23h-7h than in the simulation 18h-23h. The lower wind intensity for the simulation with windows opening allowed in the period 23h-7h causes windows to be opened for a greater number of hours, which leads internal temperatures to drop below 25°C. When comparing Tables 1 and 2 with Table 3, it is found that the air is mostly evacuated through the chimneys during the cooling season. However, cross-ventilation shows greater effectiveness, as the number of hours in which it occurs is substantially lower than the number of hours in which there is ventilation through the chimneys.

Table 1- Percentage of hours in which there is air evacuation through windows and chimneys, relative to the period of the day in which the opening of windows in the cooling season is allowed

	Air evacuation through windows				Air evacuation through chimneys	
	North to South		South to North			
	Bedroom 1	Living room	Bedroom 2	Kitchen	Kitchen	WC
18h-23h	79%	83%	18%	19%	99%	84%
23h-7h	76%	75%	19%	19%	99%	69%
24h per day	13%	22%	3%	4%	99%	85%

Table 2 - Average number of hours per day in which there is air evacuation through open windows in the total period of the cooling season

	Air evacuation through windows (h)				Air evacuation through chimneys (h)	
	North to South		South to North			
	Bedroom 1	Living room	Bedroom 2	Kitchen	Kitchen	WC
18h-23h	4.7	5.0	1.1	1.1	23.9	20.0
23h-7h	6.1	6.0	1.5	1.5	23.8	16.6
24h per day	3.0	5.2	0.7	1.0	23.9	20.4

Table 3 - Percentage of the evacuated air volume relatively to the total volume evacuated in the cooling season, through windows and chimneys

	Air evacuation through windows				Air evacuation through chimneys		Total evacuated volume (m^3)
	North to South		South to North				
	Bedroom 1	Living room	Bedroom 2	Kitchen	Kitchen	WC	
18h-23h	21%	26%	2%	3%	32%	16%	120
23h-7h	8%	9%	1%	1%	54%	27%	66
24h per day	15%	20%	2%	2%	39%	22%	154

4.2 Heating season

Four indicators will be used to characterize the simulation results in the heating season. The first two indicators are similar to those used for the cooling season: the *Average number of air changes per hour* and the *Percentage of hours with the ACH number above the design value.* The third indicator used is the *Heating energy needs* required to maintain the dwelling temperature above the minimum limit of 18°C for each room throughout the heating season. The fourth indicator is the percentage of hours in which the air changes for each room are above a minimum value of 0.6 ACH [11] (*Percentage of hours with the ACH number above the minimum value* - PHAM).

4.2.1 Simulation performed without using fixed openings for ventilation in the facades

For the simulation performed without fixed openings in the facade, the results show that there is only a residual ventilation of the rooms, originated by the air infiltration through the window frames (Figure 9). This causes PHAD and PHAM to be zero and the energy needs to be low (120 kWh).

4.2.2 Simulations using fixed openings for ventilation and wind speed as per Weather File

In this group of simulations the *Average number of air changes per hour* increases linearly with the increase of the fixed openings area in the facades. This value gets closer to the design values for opening areas greater than 75 cm^2 in most of the rooms (Figure 10).
The PHAD values are low in the simulations for the fixed openings area of 55 cm^2 and in general the main rooms provide better results for this indicator than the service rooms (Figure 11). The PHAM indicator provides good results for all rooms, with percentage values greater than 70% (Figure 12). The *Heating energy needs* naturally increase as the areas of fixed openings increase (Figure 13).

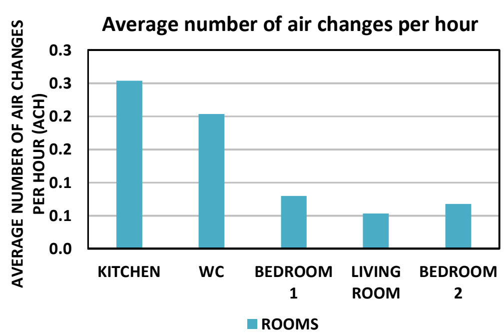

Figure 9 – Average number of ACH in the period of the heating season, for a simulation performed without using fixed openings in the facades

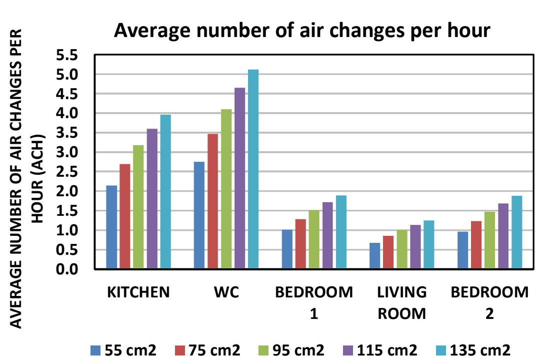

Figure 10 - Average number of ACH in the heating season for the simulations performed using the wind speed according to the *Weather file*

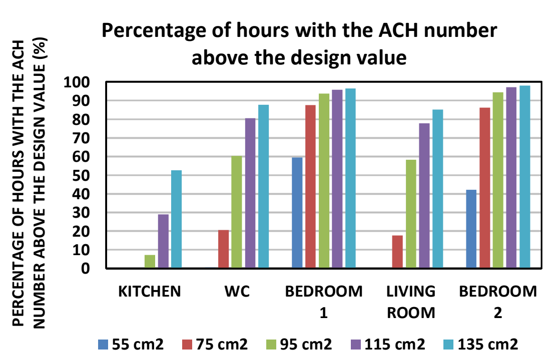

Figure 11 - PHAD in the heating season for the simulations performed using the wind speed according to the *Weather file*

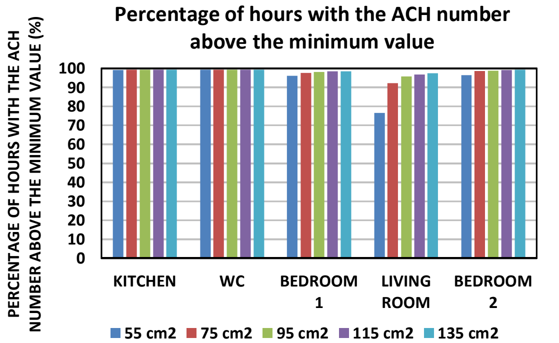

Figure 12 - PHAM in the heating season for the simulations performed using the wind speed according to the *Weather file*

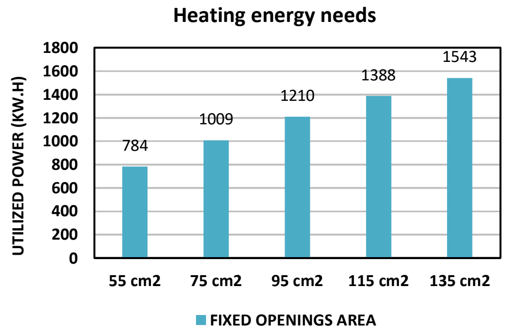

Figure 13 – *Heating energy needs* for the simulations performed using the wind speed according to the *Weather file*, in the heating season

4.2.3 Simulations using fixed openings for ventilation and zero wind speed

As it was shown in section 4.2.2, the *Average number of air changes per hour* also increases linearly with the increase of the area of fixed openings in the facades for this group of simulations. However, this value gets close to the design values only for fixed opening areas greater than 95 cm^2 in most of the rooms (Figure 14). The PHAD indicator shows low values for the opening areas in this group of simulations (Figure 15). For service rooms, the percentages of this indicator are highly low, especially for the Kitchen.

In the main rooms the PHAD value is higher, reaching acceptable values for opening areas over 75 cm^2. The results for the PAHM indicator are high in general, but are lower than the values reached by the previous simulation group (Figure 16).

The *Heating energy needs* indicator provides values lower than those reached in the previous simulation group, although they also increase linearly with the increase of the openings area (Figure 17).

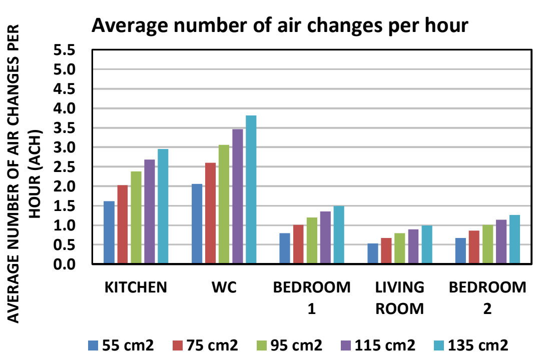

Figure 14 - Average number of ACH in the heating season for the simulations performed using zero wind speed

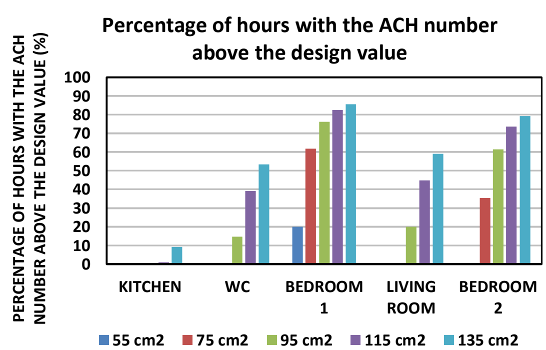

Figure 15 - PHAD in the heating season for the simulations performed using zero wind speed

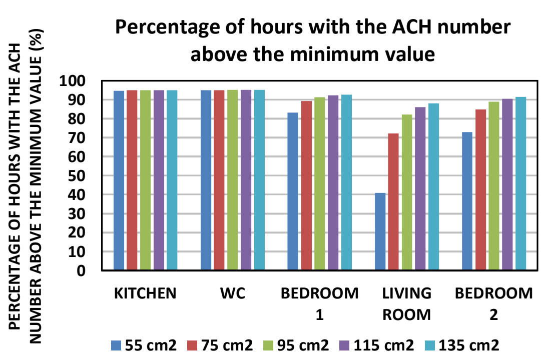

Figure 16 - PHAM in the heating season for the simulations performed using zero wind speed

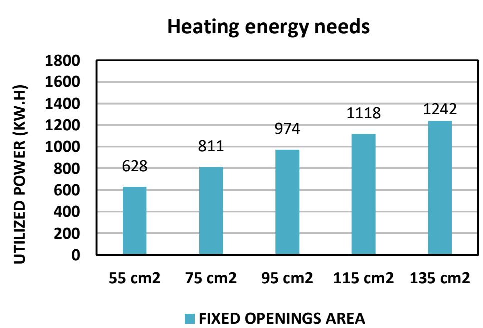

Figure 17- *Heating energy needs* for the simulations performed using zero wind speed, in the heating season

4.2.4 Influence of wind effect and chimney effect on room ventilation on the heating season

As observed in sections 4.2.2 and 4.2.3, the simulations performed using wind velocity as per the *Weather file* show better results for all the indicators when compared with the simulations performed using zero wind speed. However, as it can be seen in Table 4, the difference in terms of average ACH is not significant. The rooms have differences of less than 35%, with the only exception being the case of Bedroom 2. This room is oriented according to the main wind direction, which causes an ACH difference of almost 50% between the two simulation groups, which is insufficient for wind ventilation to overcome ventilation due to the chimney effect for the heating season period.

Table 4 - Comparison of the average ACH between the simulations with wind speed according to the *Weather file* and the simulations with zero wind speed, for different areas of openings in the facade

	Fixed openings area														
	55 cm^2			75 cm^2			95 cm^2			115 cm^2			135 cm^2		
	w/o wind	w/ wind	comp	w/o wind	w/ wind	comp	w/o wind	w/ wind	comp	w/o wind	w/ wind	comp	w/o wind	w/ wind	comp
Kitchen	1.61	2.14	32%	2.02	2.69	33%	2.38	3.18	34%	2.69	3.60	34%	2.95	3.96	34%
WC	2.07	2.75	33%	2.60	3.47	34%	3.06	4.10	34%	3.47	4.65	34%	3.81	5.12	34%
Bedroom 1	0.80	1.02	27%	1.01	1.29	27%	1.19	1.52	27%	1.35	1.72	27%	1.49	1.89	27%
Living room	0.53	0.67	27%	0.67	0.85	27%	0.79	1.01	27%	0.90	1.14	27%	0.99	1.25	26%
Bedroom 2	0.68	0.96	42%	0.85	1.23	44%	1.01	1.47	46%	1.15	1.69	47%	1.26	1.88	49%

5. Conclusions

Through this study it was possible to analyze the natural ventilation conditions and their impacts on the thermal and energy performance of a dwelling, under free-floating conditions and controlled temperature conditions.

In the cooling season the simulation that provided the best results for all the indicators was the one in which is allowed to open windows 24h per day. When comparing the simulations with ventilation periods 18h-23h and 23h-7h, it was concluded that the first shows better results for almost all indicators. Although the window opening is possible in a greater number of hours in the simulation 23h-7h, the higher wind speed in the period 18h-23h and the accumulation of external heat gains (solar radiation, heat conduction through construction) and internal heat gains during the day favors ACH increase and thus the interior temperature decrease in this simulation.

Two groups of simulations were also performed with, respectively, the use and non-use of fixed openings for ventilation in the facades and the results compared. The simulation results show that the existence of ventilation openings provides better results for the indicators *Average number of air changes per hour* and *Cooling degree-days*, since the openings help to renew the air in the periods when the windows are not open, also helping the control of the indoor temperature by keeping the *Cooling degree-days* number at a lower value.

The study of cross-ventilation for the group of simulations in which there are no openings in the facades showed that cross-ventilation produces better results in relation to the evacuated air volume than ventilation through chimneys. The average number of hours of windows opening is between 12-25% of the total number of hours of the day and the contribution of cross-ventilation to the internal air evacuation exceeds 50% of the total volume of air evacuated for the cooling season period.

However, the simulation in which there is possibility of windows opening in the period 23h-7h is the exception to this conclusion. Although this simulation has the highest number of hours of cross-ventilation (about 25% of the total number of hours), it is not possible to evacuate a large quantity of air due to the low outside air velocity during this period.

In the heating season it was noticed that the chimney effect in general outperforms the wind effect. All rooms have PHAM of more than 70% for the simulation performed with zero wind speed (with the exception of the Living room, which is the room that has the highest volume), which means that the chimney effect works well for the Mediterranean climate that is typical of

Portugal. The wind speed and direction play a secondary role in the number of *Air changes per hour* of the rooms. However, its action causes an increase in the ACH value which raises it to values close to the design values in each compartment, when added to the ACH number due to the chimney effect.

The area of the fixed openings for ventilation in the facades plays an important role in the thermal and energy performance of the dwelling in this period. The *Average number of air changes per hour* increases by 25% as the area of the fixed openings is increased by 20 cm^2, from the initial value of 55 cm^2 to the maximum value of 135 cm^2, which leads energy consumption to increase by the same proportion (around 25%)

The opening area of 55cm^2 shows good results in terms of ACH, since although the ACH of the Living room and Kitchen does not reach the design value, the minimum value of ACH is reached in most of the hours for the heating season.

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