UNIVERSITÀ DEGLI STUDI DI PADOVA
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IMPROVEMENT OF SUMMER COMFORT BY PASSIVE COOLING WITH INCREASED VENTILATION AND NIGHT COOLING

RELATORE: PROF. ROBERTO ZECCHIN

CORRELATORE PROF. BJARNE W. OLESEN

LAUREANDO: TOMMASO PELLEGRINI

MATRICOLA: 626289-IM

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PREFACE

The present Master Thesis is the result of a work carried out between February 2012 and September 2012 at the International Centre for Indoor Environment and Energy, Technical University of Denmark.

The extensive literature review conducted in the first stage of the project led to a better understanding of scopes and methodology.

The motivation for writing the Thesis was the realization that the warming of the climate is an ascertained problem and a reduction in the energy consumption is necessary to counteract the phenomenon. Buildings account for 40% of the worldwide energy consumption, then the adoption of passive cooling strategies, such as increased ventilation and night cooling, might be capable to reduce the CO_2 emission by 50% to 65%. The project then investigated, by means of dynamic simulations, potential and limitations of passive cooling techniques in four different climatic zones across Europe.

The report is divided in four main sections: the findings from recent studies, the climatic conditions and the methodology, the results, the discussion and conclusions are presented in the order. Three appendixes follow the main body: the wind analysis (Appendix A), the comfort categories (Appendix B) and the indoor air velocity and the temperature offset (Appendix C) are graphically presented.

Thanks are due to Prof. Bjarne W. Olesen and Peter Foldbjerg for advice and guidance during the entire project.

This study was sponsored by the SINO-DANISH research project "Activating the Building Construction for Building Environmental Control" under the Programme Commission for Sustainable Energy and Environment, the Danish Council for Strategic Research.

PREFAZIONE

La presente Tesi è il risultato di un lavoro di ricerca svoltosi tra febbraio e settembre 2012 presso l'International Centre for Indoor Environment and Energy della Technical University of Denmark.
L'esteso lavoro di revisione della letteratura condotto in una prima fase ha portato ad una miglior comprensione degli obiettivi e del metodo.
La motivazione che ci ha spinti a scrivere la Tesi è stata la constatazione che il riscaldamento globale rappresenta oggigiorno un problema inequivocabile e una riduzione del consumo energetico è necessario per arrestare il fenomeno. Gli edifici contribuiscono per il 40% al consumo globale di energia, pertanto l'adozione di tecniche di raffrescamento passive, quali il raffrescamento per ventilazione e il raffrescamento notturno, è in grado di ridurre potenzialmente l'emissione di CO_2 dal 50% al 65%.
Il progetto ha investigato, per mezzo di simulazioni dinamiche, le potenzialità e i limiti delle principali tecniche di raffrescamento passivo in quattro diverse zone climatiche in Europa.

La relazione di progetto è suddivisa in quattro sezioni principali, in ordine di elenco sono presentati: i risultati dei recenti lavori di ricerca svolti nei campi di interesse, le condizioni climatiche e la metodologia adottata, i risultati ottenuti e le conclusioni. Al corpo principale della tesi seguono tre appendici riportanti lo studio della ventosità dei siti (Appendice A), le categorie di comfort (Appendice B) e le velocità dell'aria con i corrispettivi offset di temperatura (Appendice C).

Si ringraziano il Prof. Bjarne W. Olesen e Peter Foldbjerg per il consiglio e la guida offerti durante lo svolgimento dell'intero progetto.

Lo studio è stato sponsorizzato all'interno del progetto di ricerca del SINO-DANISH CENTER (SDC) "Activating the Building Construction for Building Environmental Control", sotto la Programme Commission for Sustainable Energy and Environment, del Danish Council for Strategic Research.

TABLE OF CONTENTS

SUMMARY

In these last few decades there has been a growing concern for the warming of the climate global system. The unavoidable solution is the reduction of the energy consumption that would bring to a reduction in the CO_2 emission. Buildings account for a remarkable percentage (40%) of the global energy demand, thus a reduction of the energy absorption of buildings is essential.

The present study describes the potential improvement of summer comfort and reduction of energy consumption that can be achieved by adopting passive cooling solutions, such as daytime comfort ventilation with increased air velocities and night cooling, in domestic buildings. By means of the IDA ICE based software EIC Visualizer, the performances of ten ventilation and cooling strategies have been tested in four different climatic zones across Europe (Athens, Rome, Berlin and Copenhagen). Before testing the strategies potential and limitations with respect to the local climatic conditions, three parameters expected to have a relevant influence on the passive cooling performances (the night cooling threshold, the building orientation and the thermal mass) have been empirically optimized

Thermal comfort and indoor air quality (IAQ) have been evaluated according to the standard EN15251 for the summer period of the year only. The study revealed that thermal comfort can be achieved by passive means in all four locations. It was also found that, with the exception of Athens, the initially investigated combination of ventilative and night cooling is too aggressive, causing undercooling and increased energy consumption. A moderate strategy performed well without overheating and undercooling in Rome, Berlin and Copenhagen.

In general natural ventilation turned out to be capable to achieve a very good IAQ and a reduction in energy consumption in all locations, when compared with mechanical ventilation or mechanical cooling.

Hybrid solutions that combined active and passive cooling strategies were found to perform well in the Mediterranean climate (Athens and Rome), but should be avoided in Berlin and Copenhagen, especially if it is considered that in the two locations the benefits coming from a mechanical cooling system do not worth the installation cost.

To conclude the natural ventilation techniques were the only ones capable to achieve the trade-off between energy saving and indoor comfort. In particular:

- In a warm climate (Athens) the combination of ventilative cooling with increased air velocity and night cooling is necessary to achieve a good indoor environment. The passive cooling techniques allow a very high energy saving.
- In a moderate climate (Rome and Berlin) the daytime air velocity and the nighttime air flow rate have to be constrained to prevent the cold sensation due to both undercooling and draft. The energy saving is consistent for Rome, less relevant for Berlin.
- In a cold climate (Copenhagen) there is almost no need for cooling. The initially tested solutions turned out to over-perform and a change in the strategy was necessary. The night

cooling alone was found to be capable to meet the cooling load during the entire natural ventilation period. The ventilative cooling should be avoided and during daytime the windows should be opened only for airing the dwelling.

1. INTRODUCTION

1.1. Motivation

The 2007 report of the Intergovernmental Panel on Climate Change (IPCC) [1] stated that warming of the climate global system is an ascertained problem. For that reason in 2008 the European Union set the target of reducing by 20% the total energy consumption within 2020 [2]. According to the Promotion of European Passive Houses project (PEP) [3], buildings account for 40% of this total energy consumption and through the application of the Passive House concept a relevant reduction in the energetic consumption, quantifiable in a CO_2 emission reduction of about 50% to 65%, can be obtained.

The aim is to lower the energy consumption without affecting the thermal comfort or the indoor air quality (IAQ), and natural ventilation represents the most promising way to achieve such trade-off between indoor comfort and energy saving. The thermal comfort is function of different parameters and then it can be provided at a range of air temperature, acting on those parameters. When the air temperature increases the warm thermal sensation can be restored from warm to neutral by reducing the mean radiant temperature or by increasing the convective heat exchange between the body and the surrounding ambient [4]. The reduction of the radiant temperature is achieved by mean of the *night ventilation*: cold air is circulated through the building during night, the building structure is then cooled providing a thermal sink and a lower radiant temperature during the next day. The increase in the convective heat exchange is the basic idea of the *comfort ventilation*: thermal comfort is obtained by increasing the air velocity in the room through natural or mechanical ventilation. Of course this is just a general definition since, e.g., in the transition seasons, especially in the colder climates, also the comfort ventilation is capable to cool down the building structure when the outdoor temperature is lower than the indoor.

In the recent years there has been a growing interest in the IAQ issue and in its health effect as well. Comparative risk studies performed by the United States Environmental Protection Agency (EPA) [37] ranked IAQ as one of the 5 top environmental risks to the public health. Indoor pollution sources that release gases or particles into the air are the primary cause of indoor air quality problems in homes. Health effects from indoor air pollutants may be experienced soon after exposure or, possibly, years later. Immediate effects may show up after a single exposure. These include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. All these symptoms are commonly known as Sick Building Syndrome (SBS). Other health effects may show up either years after exposure has occurred or only after long or repeated periods of exposure. These effects, which include some respiratory diseases, heart diseases, and cancer, can be severely debilitating or fatal. There are three basic strategies to improve indoor air quality: (i) source control, (ii) air cleaners and (iii) improved ventilation. Usually the most effective way to improve indoor air quality is to eliminate individual sources of pollution or to reduce their emissions. But if on one hand the source control strategy is efficient, on the other hand it is also not always feasible since frequently the source of pollution is the occupant himself or the activities related to the everyday life. Air cleaners can represent a solution but they are generally not designed to remove gaseous pollutants. Probably the best approach to lower the concentration of pollutants in an indoor environment is to increase the amount of air entering from outdoor. Adequate ventilation can reduce indoor pollutant levels by bringing in enough outdoor air to dilute emissions from indoor sources and by carrying indoor air pollutants out of the home.

1.2. The project

The present project investigates the potential improvement of summer comfort and reduction of energy consumption that can be obtained applying both daytime comfort ventilation and night cooling in domestic buildings. By means of the IDA ICE based software EIC Visualizer, the response in terms of thermal comfort, indoor air quality (IAQ) and energy saving of a 1½-storey, single-family house (Figure 1) has been tested in four different climatic zones (the hot and dry climate of Athens, the warm and humid climate of Rome, the moderate climatic condition of Berlin and the cold climate of Copenhagen) across Europe.

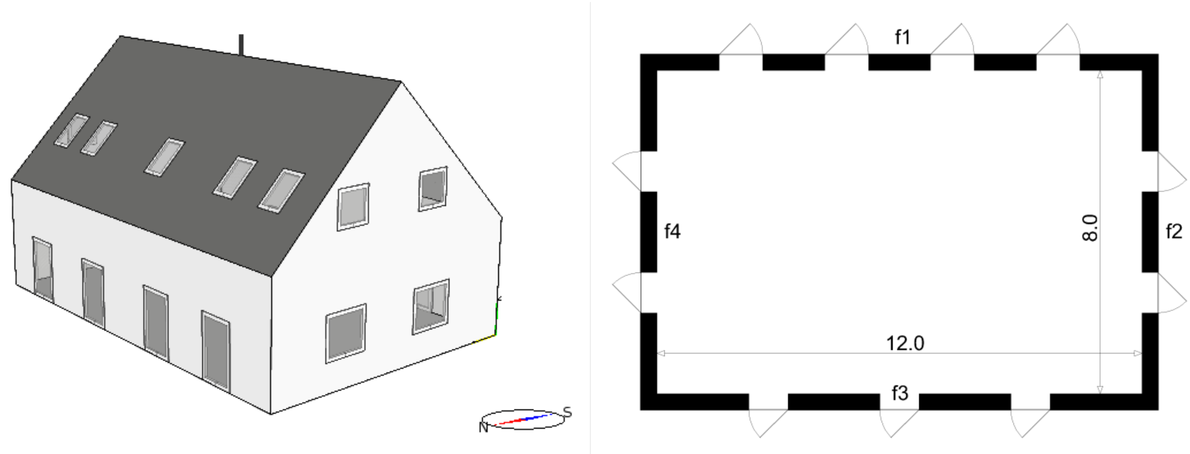


Figure 1 – Visual representation (left) and footprint (right) of the building selected for the investigation.

The testing procedure that has been followed can be divided into two steps.
Initially three sets of simulations have been run to empirically optimize the night cooling threshold, the building orientation, and the building thermal mass according to the local climatic condition and cooling requirements. All three the parameters are expected to influence the ventilation and cooling performance. In particular the night cooling threshold should allow the occupants to take full advantage of night ventilation without causing undercooling. The orientation has to be optimized with respect to solar radiation and wind direction. The thermal mass influences the night cooling efficiency since the phenomenon which night ventilation is based on is the storage of heat in the building mass during day and its removal during night.

On a second moment ten different ventilation and cooling strategies have been tested and the results have been compared to determine which one was the most promising in each location. The tested strategies are: four fully naturally ventilated building, with and without increased air velocities, two mechanically ventilated ones (one with mechanical cooling and one without) and four hybrid solutions that combined mechanical cooling with nighttime or nighttime and daytime ventilation.

2. LITERATURE REVIEW

In this first chapter, literature review and collections of data from earlier studies are reported. The earlier studies available in literature with the acceptance of the cooling effect by increased air velocity to compensate for increased temperature and night cooling, will support the founding of this work. On their bases the results will be established according different climatic regions and data with regard to thermal comfort, indoor air quality and potential for energy saving.

The effectiveness of increased air velocity and night cooling in reducing the energy consumption has been proved by means of both field surveys and dynamic simulations. In particular E. Gratia et al. [5] demonstrated, through simulations with TAS, how single-sided natural ventilation during daytime can reduce cooling needs by about 30%. The simulations were performed for a narrow office buildings in the oceanic climatic zone (the climatic data were referred to Uccle (BE)) with increased air velocities up to 0.8 m/s. J. T. Lin and Y. K. Chuah [6] evaluated the number of days for which natural cooling, hybrid ventilation and mechanical air conditioning are to be applied to satisfy the cooling requirement in subtropical region. Their analytical model predicted that natural ventilation can provide good thermal condition in subtropical regions, with exception for a small amount of days in the warmest season.

Furthermore CFD analyses [5], [7], [8] have been made to corroborate the deductions on the efficiency of passive cooling systems. But if it is true that the CFD models give extremely detailed results, it is also true that those results cannot be generalized and exported to other locations, thus giving little information about the real applicability of the modeled passive cooling system.

The potential reduction in the energy consumption by increasing the air movement to compensate for higher indoor temperature by mean of mechanical instead of natural ventilation has been investigated by S. Schiavon and A. K. Melikov [9] with the EnergyPlus software. They tested six cities, three indoor environment categories and three air velocities (0.2, 0.5, 0.8 m/s) and demonstrated that increased air velocity can improve the comfort as well as the occupants' health and productivity, and allows a cooling energy saving between 17% and 48% and a reduction of the maximum cooling power between 10% and 28%. They also reached the conclusion that traditional mechanical systems, such as ceiling fans, can hardly be considered an energy-saving solution due to their high energetic consumption. From this perspective natural ventilation with increased velocity remains the best option.

One major problem associated with the natural ventilation is the estimation of the air velocity inside the building. As stated before the air motion increases the body's convective and evaporative heat loss, improving the thermal comfort. The physical processes that are involved in the natural ventilation are very complex. The air motion phenomenon is described by the Navier-Stokes equations combined with the equation describing the boundary conditions. Many studies have been made in the last years to develop methodologies capable to predict the air velocities induced by natural ventilation [10]. According to Ernest [11] the methods used to predict the air motion can be divided in five main groups:

- Researches based on a full scale investigation
- Researches based on a CFD method
- Methods based on data obtained from parametric wind tunnel studies
- Method making use of wind discharge coefficients
- Method based on direct measurements of the indoor air velocity in a scale model of the investigated building in a boundary layer wind tunnel

Givoni [10] was one of the firsts to propose a general correlation based on experimental data. According to his method the average indoor air velocity is:

$$V_i = 0.45(1 - e^{-3.48x})V_r$$

Where V_i is the indoor air velocity, x is the ratio between the opening area and the wall area where the opening is located and V_r is the reference external wind velocity. The correlation is valid for square floor plan with identical upwind and downwind openings located in opposite walls.
Melaragno [10] proposed values of the average and maximum indoor air velocity for two different ratios of the aperture width to the aperture of the wall by means of wind tunnel experiments. He also proposed values of the average indoor air velocity for cross-ventilation configuration without internal partition as a function of the inlets and the outlets. The results are obtained for aligned inlets and outlets and for wind perpendicular to the openings.
A prediction method based on test made on a scaled model in a wind tunnel is the CSTB methodology [10]. According to the methodology the air velocity can be expressed through the Global Ventilation Coefficient (C_G), defined as a ratio of the mean indoor velocity (V) of the air at 1.5 m height and the outdoor air velocity at the same height (V_{15}).

$$C_G = f(C_{site}, C_{orientation}, C_{Arch.Exter.}, C_{Aero.Inter})$$

The coefficient depends on:

- Characteristics of the site (C_{site})
- Orientation of the building with respect to the wind direction ($C_{orientation}$)
- Exterior characteristic of the building ($C_{Arch.\ Exter.}$)
- Interior architecture and aerodynamics of the building ($C_{Aero.\ Inter.}$)

Most researchers agree that the pressure distribution on the external façade of the building is the major driving force for wind-induced indoor air motion. Vickery et al. [12] concluded that wind pressure distribution can predict the air flow rate with accuracy of about 10% when the opening ratio is less than 23%, the openings are placed on opposite walls and the wind is not strongly inclined to the façade. Following this widely accepted theory Ernest [13] correlated the surface pressure data measured on a sealed building model with the air velocity data obtained from an identical model with open windows. He defined a non-dimensional air motion parameter (C_v), based on the velocity and turbulence measurements, and a non-dimensional surface pressure parameter (C_p), based on the pressure measurements. Then, using a stepwise multiple linear regression fitting routine, he established a correlation between the two:

$$C_V^2 = A\Delta C_P + BC_{P,i}cos\theta + CC_{P,o}cos\theta + Dcos\theta + E$$

Because of the procedure adopted by Ernest, the effect of momentum flow contributions and the influence of the effective wind incidence angle at the inlet are not taken into account. The author concluded that the value of the coefficients strongly depends on the building and windows geometry, but the form of the correlation equation is representative of the phenomenon observed.

The empirical correlations so far presented are simple, but they are based on the assumption of a homogenous distribution of the air velocity inside the room. On one hand such an approximation is clearly unrealistic, on the other hand, when judging the overall efficiency of natural ventilation, is convenient to refer to an average value. This is particularly true when a domestic building is considered: in a domestic building the occupants' position is not predictable because it can vary during the time and thus the air movement that the occupants are exposed to is an average value of the air velocity distribution in the zone potentially occupied.

Descalaki et al. [14] tried to determine the relationship between the air velocity at the opening and the bulk air flow rate measurements for a single sided naturally ventilated building, using the tracer gas decay technique. To analyze the correlation existing between air velocity and air flow rate a new coefficient (*k*) was defined as the ratio of the calculated and the measured air flow rate. This coefficient is representative of the alteration of the vertical air velocity profile along the horizontal axis, being the calculated air flow rate based on the vertical profile of the air velocity in the middle of the door, approximated by a polynomial expression. Then the impact of wind direction and speed, indoor-outdoor temperature difference and the relative impact of inertia and buoyancy forces on the coefficient *k* were investigated. From a qualitative point of view the analysis showed that:

- *wind direction:* the air velocity profile in the middle of the door is more representative of the average wind velocity profile when the wind component perpendicular to the opening increases
- *wind velocity:* the impact of the wind magnitude on the coefficient is evident, but the influence could not be properly investigated
- *indoor-outdoor temperature difference:* the *k* coefficient decreases with increasing temperature difference since the effect of the buoyancy forces is to make the air enter the room in a more homogeneous way

- *inertia and buoyancy forces:* as the Archimedes number (defined as the ratio between inertia and buoyancy forces) increases, the *k* coefficient decreases

Using an advanced experimental method based on Particle Image Velocity (PIV) Karava et al. [15] investigated the air velocity field in a naturally ventilated building with cross ventilation flow characteristic. They performed velocity field measurements on a scaled model using a boundary layer wind tunnel and a two-dimensional PIV technique. During the experiment they changed the openings area and disposition to evaluate the influence that those two parameters have on the air movement inside the building. The velocity field for some of the configurations is shown in Figure 2.The project leaded to some significant conclusions:

- higher air flow rates were found when symmetric openings, inlet in the upper part of the façade and an inlet to outlet ration smaller than 1 were used
- for all configuration two distinct flow regions can be observed: the main jet region and the recirculating region
- in all configuration the jet velocity initially increases as a vena contracta region, then decreases when it enters the low momentum fluid

The knowledge of the velocity field aims to facilitate the design process, particularly with respect to the openings position and area and with respect to the automation and optimization of the openings control.

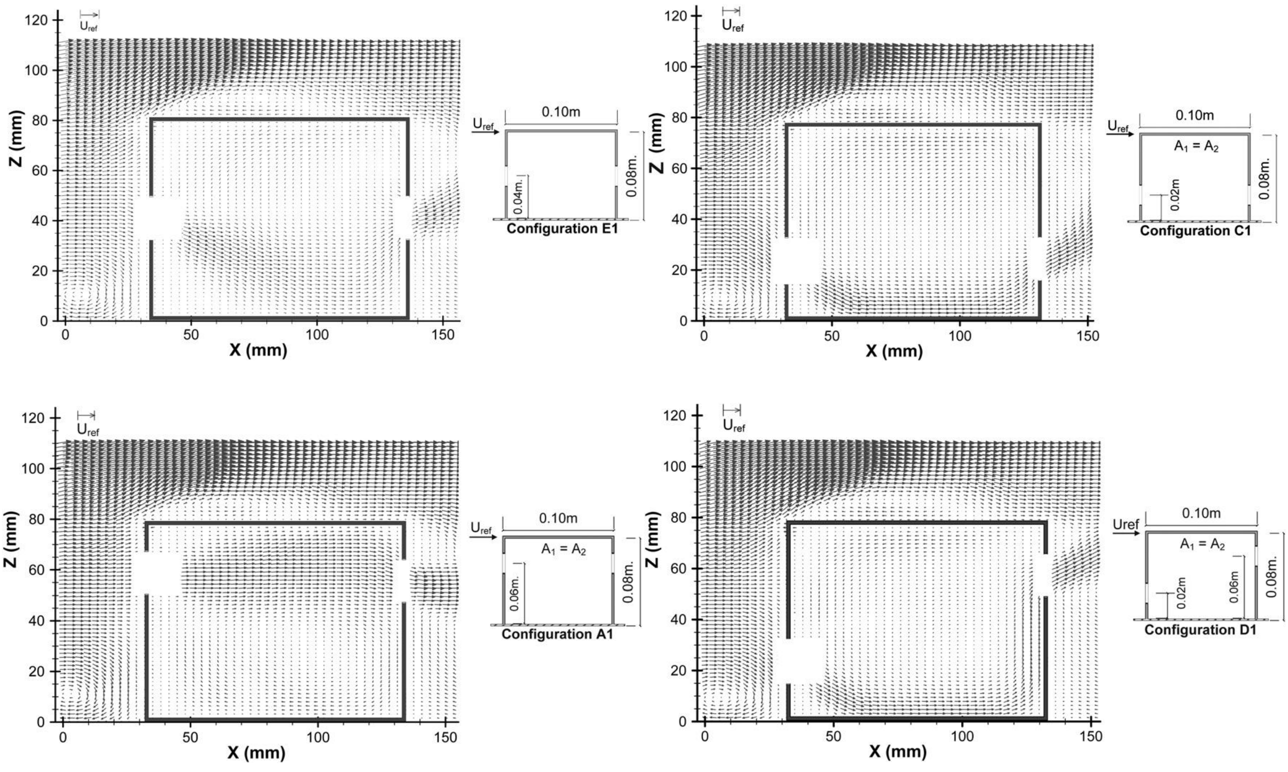


Figure 2 – main velocity vector fields for some of the configuration tested [15].

Thanks to the development of turbulence models more and more precise and the increase in the computers speed, computational fluid dynamics (CFD) probably represents nowadays the most cost effective and reliable method to investigate the air velocity in a building.
In an article published in 1996 [16] Awbi analyzed the air movement and the CO_2 distribution in naturally ventilated buildings located in a typical UK climate by means of the CFD software VORTEX. Two types of building were studied: an office room in an intermediate floor of a multi-store building and an atrium. For both the office and the atrium wind driven ventilation and buoyancy driven ventilation have been simulated. The main results obtained from the simulations are summarized in Table 1.

	Office room	
	Wind driven ventilation	Buoyancy driven ventilation
Air flow rate [m^3/s]	11.20	3.16
Mean air velocity [m/s]	0.47	0.14
Mean CO_2 concentration [ppm]	351.8	358.2
	Atrium	
	Wind driven ventilation	Buoyancy driven ventilation
Air flow rate [m^3/s]	9.60	12.99
Mean air velocity [m/s]	0.61	0.80
Mean CO_2 concentration [ppm]	395.2	389.5

Table 1 – Main results obtained from the simulation of both the office room and the atrium [16] (modified).

The CFD results have proven the wind driven and the buoyancy driven ventilations to be capable of achieving adequate thermal comfort and acceptable CO_2 level in the occupied zone in both the building typologies. A very detailed three dimensional investigation on the physical mechanism of the air movement inside a natural ventilated building is the one recently made by Bangalee et al [17] with the commercial software ANSYS ICEM CFD and the solver CFX. The authors used a *k-ε* turbulence model to simulate both cross and single-sided wind-driven ventilation and validated their results by comparing them with experimental data. The studied model is a full scale building of 4.5m x 4.5m x 3.25m (length x width x height) with 4 windows, 2 on the windward wall and two on the leeward wall. In order to properly simulate the actual environment a computational domain of 40.5m x 22.5m x 9.75m was chosen. In Figure 3 the model is schematically shown.

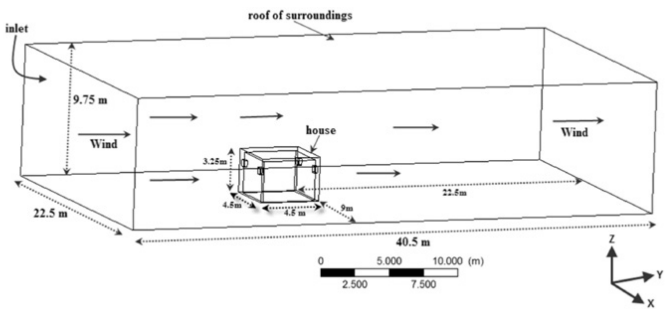


Figure 3 – Schematic view of the computational domain [17].

Three different configurations have been studied: (i) cross ventilation with two openings in windward and two openings in leeward wall, (ii) single-sided ventilation with two openings in windward wall, (iii) single-sided ventilation with two openings in leeward wall. The validation of the model has been performed by comparison of the simulation results with tabled data available in literature and very good agreement has been found. The main results obtained are:

- the air velocity inside the building has been proven to be higher in cross ventilation than in single sided ventilation case
- in single-sided ventilation the air flow is slightly higher in windward ventilation than in leeward ventilation case
- the mass flow rate through the windows and the indoor air velocity change linearly if the outdoor air velocity changes linearly

As mentioned before, and as stated by the same authors in the article, the results of the CFD analysis may not be satisfactory if any change in the boundary conditions (e. g. variation of the wind incidence angle, temperature variation, modification of the building design, etc.) takes place.
When simulations have to be run, the implementation of the human behavior is one of the most challenging aspects. It is ascertained that when the occupants can take actions that they feel can improve the thermal comfort of the environment, they are willing to undergo to objectively poorer thermal condition. Those actions are referred to as *adaptation* and the way of regarding thermal comfort as part of a self-regulating system is known as *adaptive model* (a detailed explanation of the adaptive model has been given by M. A. Humphreys and J. F. Nicol [18]). To integrate this model into building simulation software has been largely discussed in the latest years and it is still discussed. The main problem is the fact that the human behavior is stochastic, beside that not completely understood, while the software is optimized for deterministic processes. A number of field surveys has been conducted to discover the correlation that links the behavior with the parameters of the surrounding ambient (e.g. the indoor temperature) and interestingly there is no consensus between the authors about whether, e.g., indoor or outdoor temperature is dominant in influencing the behavior.

Author & Date	Inputs
Warren (1984)	outdoor temperature, season, noise, insulation, wind
Fritsch (1990)	outdoor temperature, current state
Inkarojrit and Paliaga (2004)	indoor temperature
Humphreys and Rijal (2008)	outdoor temperature, indoor temperature
Yun (2008)	indoor temperature, current state, time of day
Haldi (2008)	indoor temperature (for opening), outdoor temperature, time of day, current state, active/passive users
Pfafferot and Herkel (2008)	outdoor temperature (the indoor temperature is co-variant with the outdoor), time of day, current state, season

Table 2 – Summary of the existing models of occupant control of the windows [19] (modified).

An exhaustive overview of the existing models of occupant control of window is given by S. Borgeson and G. Brager [19], a summary is given in Table 2 (above).
What Borgeson and Breger suggest is to use a model as simple as possible, compatibly with the uncertainties that affect the data. They also state that, when predictable weather conditions are used, a simple schedule coupled with intuitions and common sense represents a good approximation of the human behavior.
What is interesting about the adaptive model is that the EN15251 [20] (the Standard that will be referred to in this project) allows more relaxed temperature limits to be applied to naturally ventilated buildings, when the space in question is equipped with operable windows easily accessible by occupants. In Figure 4 the upper and lower limits for the operative indoor temperature are shown as function of the outdoor running mean temperature for the three indoor environment categories. According to the EN15251 the temperature limits only apply to buildings used mainly for human occupancy and sedentary activities and only apply when the thermal conditions in the spaces are regulated primarily by the occupants through opening and closing of windows.

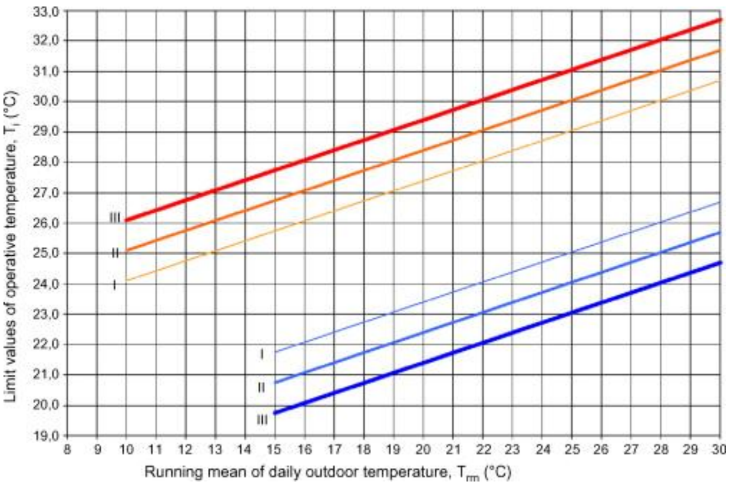


Figure 4 - Design values for the indoor operative temperature for buildings without mechanical cooling [20].

All the studies available in literature lead to the conclusion that natural ventilation and increased air movement succeed in lowering the energy demand without any reduction in the thermal comfort in moderate to cool climatic zones, but can hardly replace mechanical cooling in warmer climates. To avoid overheating in locations where the daytime outdoor temperature is too high (no value is here reported since there is not agreement between the authors), natural ventilation has to be combined with mechanical ventilation in what is commonly called mixed mode or hybrid system.
Hybrid systems switch between natural and mechanical ventilation, in order to minimize the energetic consumption while maintaining good thermal comfort and good indoor air quality. Hybrid systems have been widely investigated and are considered by many the most promising solution. The most challenging aspect of the hybrid ventilation is the control strategy [21]: what ventilation strategy should be chosen to optimize the energy efficiency, the indoor air quality and

the thermal comfort and what control parameters should be used is still under discussion. P. Foldbjerg et al. [22] studied the energy performance of two hybrid residential ventilation system, one manually controlled and the other automatically controlled in three different climates using the dynamic simulation software IES VE. They proved that there is a clear decrease in the total energy demand when hybrid ventilation is used, and this decrease is larger when an automatic intelligent control is put into action instead of a manual control (the reduction was in the range 2.7 – 4.7 kWh/m^2 for the intelligent control and in the range 1.3 – 1.7 kWh/m^2 for the manual control). The work of Foldbjerg confirms the results of an earlier study made by A. Martin [23]. In his article Martin asserts that manual control of a mixed mode system allows summer comfort conditions only when the cooling load is below approximately 25W/m^2, while the use of automatic control, making night ventilation feasible, extents the comfort conditions up to 40W/m^2 or more. Even if the comparison is not completely fair, the automatic control is proven better performing. Martin presents also a hybrid ventilation control strategy based on the indoor and outdoor temperatures.

Extremely interesting is the result obtained by Deuble and de Dear [24]. In their paper they provide evidence that the adaptive comfort model is applicable in mixed mode buildings during times of natural ventilation, and not only to fully naturally ventilated buildings as the EN15251 prescribes. In Figure 5 the observed AMV and the PMV are plotted against the indoor operative temperature. It can be seen that when the building is mechanically ventilated (AC mode) the AMV conforms the PMV (Figure 5a), thus the PMV-PPD model adequately describes the thermal comfort.

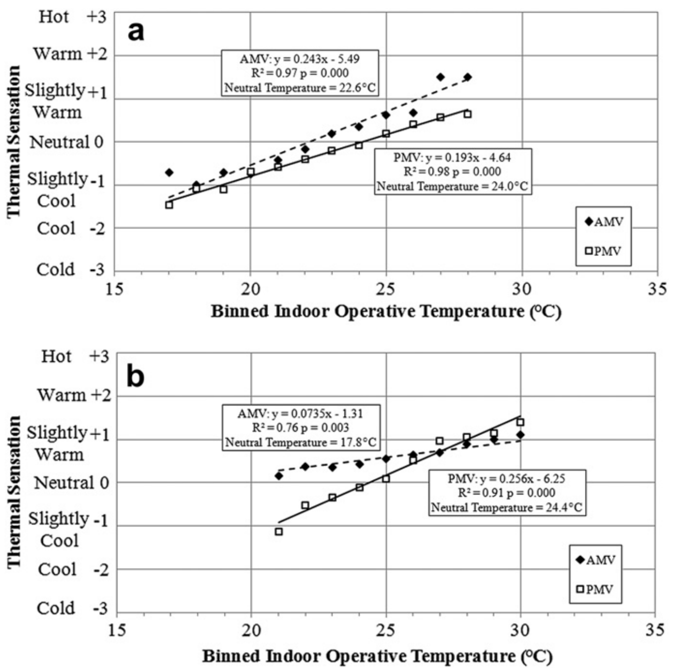


Figure 5 – Average observed (AMV) and Predicted (PMV) thermal sensation votes plotted against the binned indoor operative temperature for AC mode (Figure 5a) and NV mode (Figure 5b) [24].

On the other hand when the building is naturally ventilated (NV mode) there is a discrepancy between the observed comfort condition (AMV) and the predicted comfort condition (PMV) (Figure 5b), hence the PMV-PPD model fails to predict the comfort conditions when the hybrid system is in NV mode. According to the authors this is the evidence that the occupants must have been accommodating the higher temperatures through a series of adaptive opportunities that affected their thermal perception. This breakthrough makes room for further reduction in the energy consumption when hybrid systems are used to maintain the thermal comfort.

Hybrid ventilation is widely used and appreciated because of its capability of integrating the advantages of both natural and mechanical ventilation, but it is not the only way to improve the thermal comfort in climates where the simple natural ventilation is not sufficient. Architectural solutions such as solar chimneys and wind catchers have been proved to be effective in increasing the ventilation rate, and thus the thermal comfort, without any impact on the energy consumption, in both residential and office buildings. In solar chimneys the solar radiation is used to increase the air temperature inside the chimney and as the temperature raises the density drops. The drop in the density causes the air to move upward and to be expelled from the top of the chimney. The expelled air has to be replaced by fresh air which, before entering the chimney, flow through the building and provides an increase in the natural ventilation flow rate. In other words solar chimneys enhance the buoyancy ventilation by collecting the solar gain in an absorber. A solar chimney is typically formed by an absorber wall, an air gap and a glass cover designed to maximize the solar gain. In Figure 6 a schematic diagram of a solar chimney is shown.

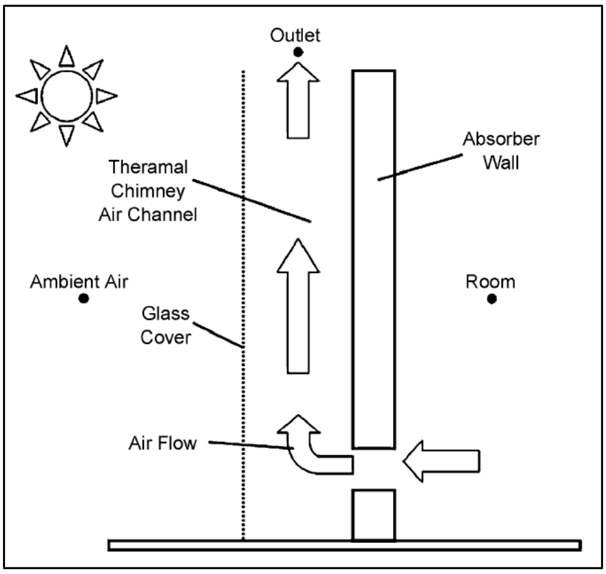


Figure 6 – Schematic diagram of a solar chimney [25].

The benefits of solar chimney are attested by Lee and Strand [25] who modeled an algorithm to describe the working principle of a solar chimney, implemented it in EnergyPlus software and used it to test the influence of the parameters on the chimney efficiency and the potential energy impact under three different climatic conditions in the U.S. The analysis of the sensitivity of the system performance to the individual parameters showed that:

- The ventilation rate increases when the chimney height is increased: the longer is the chimney, the larger is the heat exchange area between the absorber wall and the air, and thus the larger is the heat transfer.

- As the solar absorptance is increased the ventilation rate is enhanced as a consequence of the increased wall surface temperature.
- As the glass solar transmittance increases also the ventilation rate is increased since more solar radiation can be absorbed by the wall.
- The ventilation rate is slightly reduced when the air gap width increases, but the impact of the air gap width on the chimney performance is almost negligible when compared with the impact of the other parameters.

To test the potential energy saving and comfort improvement that can be obtained with a solar chimney two identical buildings, one with and one without solar chimney, were simulated for a whole year period. The three selected locations were Spokane, Phoenix and Minneapolis, and the results showed that a significant amount of energy can be saved by using a solar chimney in all three cities: a cooling energy reduction of 20.4%, 18.9% and 13.1% was achieved respectively. The authors evaluated also the potential heating load reduction and found out that only 4.7%, 2.5% and 4.7% of the heating energy can be saved, thus demonstrating that solar chimneys have a greater potential for cooling than for heating. In addition climatic conditions were found to strongly influence the overall performance, indicating that the weather of a location must be taken into account when deciding whether or not a thermal chimney should be used.
More recently Zhai et al. [26] made an extensive review of the applications of solar chimneys in buildings. They asserted that for improving natural ventilation effect, solar chimneys have to be integrated with other technologies and summarized the characteristic of those integrated configuration. The applications of solar chimneys can be divided in the following categories:

- *Application based on roofs of buildings:* buildings with gable roofs can be designed for integration with solar chimneys to form the roof solar collector. With this roof solar collector it is possible to induce natural ventilation and to reduce the fraction of solar flux absorbed by the dwelling. A 10% improvement in the performances can be obtained changing the configuration from a single pass to a double pass roof solar collector.
- *As of solar chimney based on walls of buildings:* A wall solar collector, known also as Trombe wall, is a vertical channel attached to the exterior surface of the building. The air flow that derives from the temperature difference generated by the solar radiation can be used for ventilation or heating of the building. The standard configuration has two main drawbacks: important heat losses during cold and cloudy days, considerable and undesired inputs during summer. Thus more complex and efficient solutions, such as the composite Trombe designed by Zalewski et al., have been proposed. Because of their large surface area per unit of volume, porous structures could play an important role in improving the efficiency of solar walls. Macias et al. incorporated a solar wall in a high thermal mass building to create a passive night cooling system. The chimney was orientated to west and collected the solar gain during the afternoon reaching temperatures up to 50°C. While collecting the chimney was kept closed and was open during the night, when the

temperature dropped down to 20°C. The large temperature difference between the air inside the chimney and the fresh outdoor air caused a flow that ran through the flat cooling down the thermal mass without having to open the windows.

- *Integrated configuration based on solar chimneys:* according with some authors a single solar chimney is generally not enough to induce sufficient ventilation. A two part chimney formed by a roof solar collector and a vertical stack has then been proposed. The integrated configuration was found to be more efficient thanks to a higher temperature difference.
- *Integrated renewable energy system based on solar chimneys:* the performance of a solar chimney can be improved by coupling the increased ventilation with a precooling (or preheating) system. Different solutions have been proposed, the ones that have been proved to be more efficient are: precooled air by using the sanitary area of the building, earth to air heat exchanger and direct or indirect evaporative systems.
- *Integration of active solar systems with solar chimney:* solar chimneys have been implemented with PV panels: the electricity produced was used to enhance the ventilation by means of a DC electrical fan installed in the air gap. The system was reliable and cheap and capable of improving the thermal comfort both because of the enhanced ventilation and because of the reduction of the solar gain absorbed by the building structure thanks to the shielding offered by the PV panels. In Zhai's design the ventilation was enhanced by a solar hot water system. The solar collectors were used to supply heating in winter, cooling in summer and hot water during the transition seasons.

Also Khanal and Lei [27] presented an overview of solar chimney research that has taken place in the last decades. The main parameters that influence the solar chimneys' ventilation performance are: the aspect ratio, the ventilation height, the aperture area, the absorber material and the tilt angle. They reported the most relevant results obtained in previous projects conducted on full size models, scaled models and controlled indoor environment and got to the conclusion that solar chimneys have great potential for both diurnal and nocturnal ventilation. According to their survey there is not agreement between authors on whether the air gap is a relevant parameter or not in determining the ventilation performances and the optimum tilt angle strongly depend on the latitude, but an optimum value is reasonable to be in the range 40° - 60°. They observed that solar chimneys are evidently an excellent passive ventilation system, but the contradictory claims indicate the necessity of further research and investigation.

Wind catcher is an architectural feature mounted on the roof of a building which looks like a tower and brings fresh air from outside. This cooling system has been used for centuries in the hot and arid climates, especially in the Persian Gulf region. Wind catchers present some advantages, but have been drastically ignored in modern building and some academicians have argued on the possibility to utilize them because allow insects and dust to easily enter the building and present almost zero volumetric flow rate control.

The possible configurations and utilizations of the wind catchers and their advantages and disadvantages have been reviewed by Saadatian et al. [28]. Wind catchers can be divided into three main categories:

- *Vernacular wind catchers:* those are the typical wind catchers historically used in the Arabs dwelling for centuries. They have various shapes and height ranging from 5 to 34 m and are typically opened during the summer season and closed during the winter one. The height is a symbol of the dignity, richness and social position of the householder, beside that an increase in the height allows the wind catcher to capture faster wind with les dust.
- *Modern wind catchers:* new technologies allowed the implementation in the wind catchers of sophisticated controlling option such as dampers, sensors and adjustable ventilator. Those wind catchers have been recently introduced to building industry and allow the automatic control of temperature, humidity, air flow and CO_2 level.
- *Super modern wind catchers:* coming from the implementation of highly advanced technologies and architectural features, the super modern wind catchers are buildings with an almost zero energy demand. Some examples are the "Wind Catcher Tower Concept", a 125 floors tower designed in an aerodynamic form that can absorb the wind power and use it to produce electrical energy and the Council House 2 (CH2) in Melbourne, which saves up to 80% of energy needs.

Some of the features that influence the performance of a wind catcher are then evaluated. The number of openings is an essential parameter, from previous studies it is clear how increasing the number of openings the induced ventilation decreases, on the other hand also the sensitivity to the wind inclination angle decreases as well. Thus in locations where there is no prevailing wind the number of openings should be increased. Also the shape has a relevant impact on the performance. Not only the external shape, but also the internal partition is important. The role of the partition is not only to divide the wind catchers to smaller shaft to increase the buoyancy effect, but also to satisfy the structural needs. Based on CFD simulation it has been found out that a squared shape has higher performance than a circular one since the sharp edges impose a stronger flow separation and thus a higher pressure difference. Also integrated wind catchers with curved roof have been proven to be very efficient in increasing the air flow distribution.
Dampers and egg grilles allow to better control the air flow, but reduce the ventilation, even in the fully open position.
Wind catchers use different technologies and different physical principles to operate. They generally depend on wind to operate, but even in calm weather can bring thermal comfort by inducing air circulation for effect of buoyancy (e. g. in the commercial wind catcher Monodraught ABS550 a temperature difference of 10°C amplifies the air movement when the wind speed is less than 2 m/s). The buoyancy affect has been amplified by installing a heat source inside the wind catcher and the performance has been found improved, particularly at low wind speed. The best performance has been obtained with the implementation of wind catcher and evaporative cooling

technology. This technique can reduce the temperature up to 10°C in hot and arid climates, but it is not feasible in humid ones. Hybrid systems have also been developed. The combination of wind catchers with active heating and cooling systems and the implementation of a performing control logic leaded to acceptable comfort condition and IAQ both in summer and winter.
Finally the wind catchers' configuration is discussed. The studies available in literature showed that the most efficient inclination angle is 90°, while 60° have been found to maximize the short-circuit phenomenon. The louver is necessary element to prevent the penetration of the rainwater in the building, but can represent an obstruction to the wind. Louver angles between 10° and 45° have been tested within a CFD model by Hungs and his colleagues. The results showed that a louver angle of 35° has the maximum efficiency. An investigation of the effect of the windows positioning in relation to the wind catcher efficiency have been made by a group of scholars in Hong Kong. They set four combination forms: (i)no buoyancy and no windows, (ii) buoyancy but no windows, (iii) buoyancy and windward windows, (iiii) buoyancy and leeward windows. They discovered that positioning the windows windward amplify the short-circuit, while the leeward positioning generate a negative pressure on the leeward side, increasing the air flow from outside to inside. Several studies available in literature investigated the potential of combining wind catchers and sola chimneys. Kalantar conducted a simulation study and revealed that such a combination can lower the air temperature up to 15°C. Similarly a research made by the Indian Institute of Technology found out that for a wind speed of 1.0 m/s an integrated solar chimney can double the air flow (from 0.75 kg/s of a simple wind catcher to 1.4 kg/s of the combined configuration).
While natural ventilation with increased air velocity can maintain thermal comfort providing direct cooling of the occupants, night ventilation removes the heat from the structural mass of the building during nighttime, it is then considered an indirect cooling system. As reported by Givoni [29] the main aspects that influence the night ventilation are the diurnal temperature range and the building thermal mass. A large diurnal temperature range means a large indoor-outdoor temperature difference during night that leads to both a strong driving force (indeed a higher temperature difference means a higher pressure difference) and a considerable cooling capacity. In particular Shaviv et al. determined the existence of a linear dependency between the maximum daytime indoor temperature and the temperature swing from day to night when night ventilation techniques are used [30]. The thermal mass acts as a heat sink, thus the higher the thermal mass, the higher the heat that can be stored in it during daytime and removed during night (indeed a low-mass building, even if ventilated at night, cannot retain enough cold to appreciably lower the temperature during daytime). In addition, if the building has a high thermal mass the increase in the air temperature during the occupancy hours is slow, and a slow heating means that the inside temperature peak is shifted to the late hours of the day, when the outside air temperature is already low, thus allowing a more efficient comfort ventilation.
According to Santamouris, night ventilation is not free from limitations [31]. Moisture condensation is a serious problem, particularly in warm and humid climates, and a window left opened during night can represent a security issue. In residential buildings night cooling is

associated with pollution and acoustic problems as well as problems of privacy when it is realized by mean of natural ventilation techniques. Due to this practical problems night ventilation is currently not widely used. Nonetheless recent researches have shown that night ventilation is probably the most efficient technique to improve thermal comfort in free floating buildings and to reduce the cooling load, and thus the energy consumption, in air conditioned buildings. Figure 7 shows the annual numbers of overheating hours as a function of the night ventilation air flow rate and for three different values of the comfort temperature for a free floating building in Athens. The strong increase in the thermal comfort that can be achieved with night ventilation is evident. The decrease in the next day peak indoor temperature is up to 3°C and the expected reduction in the number of overheating hours varies between 39.3% (for a comfort temperature of 25°C and an air flow rate of 10 ach) and 95.7% (for a comfort temperature of 29°C and an air flow rate of 30 ach). Figure 8 shows the cooling load for the same building when it operates in A/C mode and it is clear how night ventilation decreases the energy consumption. The expected energy saving is between 48% and 94% for a set-point temperature of 25°C and 10 ach, and for a 29°C set-point and 30 ach respectively. Both figures show that an increase in the air flow rate over 10 ach grants a negligible improvement in the effectiveness of night ventilation. This phenomenon is enhanced when the comfort temperature is increased.

This same aspect has been investigated by Santamouris and Asimakopoulos [32]. The two authors simulated a single-zone building of 400 m^2 located in Athens and calculated the impact of night ventilation on the daytime indoor air temperature for different values of the air flow rate (5, 10, 15, 20, 25 and 30 ach). Their results showed that for ventilation rates up to 10 ach the daytime indoor temperature is significantly reduced, while for greater air change rates no further reduction is observed. Thus 10 ach seems to be a reasonable upper limit for the nighttime ventilation.

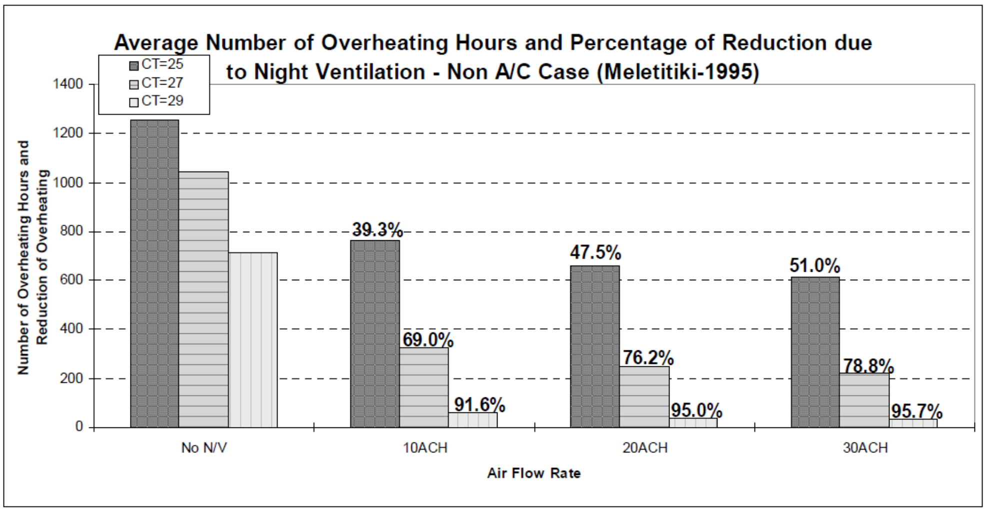


Figure 7 – Average overheating hours and reduction because of the use of night ventilation in a free floating building in Athens [31].

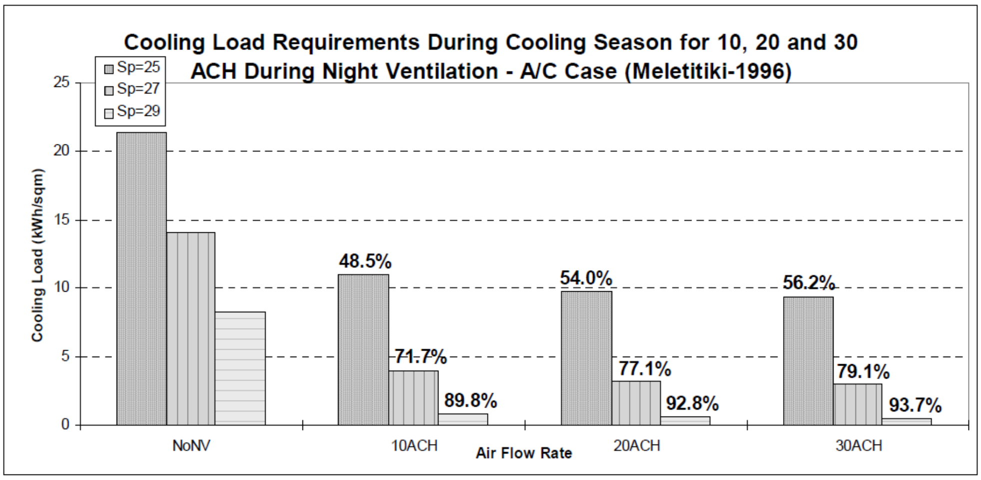


Figure 8 – Cooling load reduction because of the use of night ventilation in an air conditioned building in Athens [31].

Similarly Shaviv et al. tested the effect of the air flow rate on the night cooling strategy in the hot-humid climate of Israel [30]. They considered four levels of night ventilation: 2 ach (mere infiltration), 5 ach, 20 ach and 30 ach and pointed out how the temperature reduction is vanishing towards the value of 30 ach, therefore corroborating the result of Santamouris.

The impact of the air flow rate on the night ventilation strategy has been tested by Böllinger and Roth [33] as well. They carried out simulations for a room of 23.4m^2 located in Frankfurt/Main with different air flow rates (3 or 6 ach). For an air flow rate of 3 ach the temperature threshold (28°C) is reached at a specific load of about 35W/m^2, while for 6 ach the specific load rises up to 41W/m^2. According to their experience, higher air exchange rates allow only slightly higher loads, and since the difference between 3 ach and 6 ach is quite small they recommend an air flow rate of 3 ach. The results obtained by Böllinger significantly differ from the results of both Santamouris and Shaviv. A reasonable explanation can be given if the climatic conditions are considered. Athens and Jerusalem are in a hot climatic zone and presents a limited diurnal thermal swing (that means that the temperature difference between day and night is limited), thus on one hand the heat stored in the building structure during daytime is high and, on the other hand, the cooling effect is limited. For those reasons a considerably high ventilation rate is necessary. Frankfurt/Main has a temperate climate and a wide temperature range between day and night, thus a lot lower air exchange rate is required to remove the heat from the building mass. This conclusion is proven correct by Santamouris et al. who proved that the higher is the cooling load, the higher is the specific utilisability of the energy stored during the night for increasing flow rate [34]. In particular an increase of the flow rate from 2 to 30 ach yearly contributes 7.3 and 19.4 additional kWh/m^2 for buildings having a cooling load of 30 and 80 kWh/m^2 respectively. The results are reported in Figure 9 where the energy contribution of the night ventilation is presented as a function of cooling load and flow rate. It can be seen how the tilt angle of the regression line increases for higher flow rate. However, the specific contribution of night ventilation per unit of air flow decreases with increasing flow rate. In particular for 2, 5, 10, 20 and 30 ach the energy contribution of night ventilation per unit of air change is 3.3, 2.5, 1.8, 1.2 and 0.7 kWh/m^2 per year. This explains why increasing the air changes over a reasonable limit gives negligible improvement of the night ventilation performance.

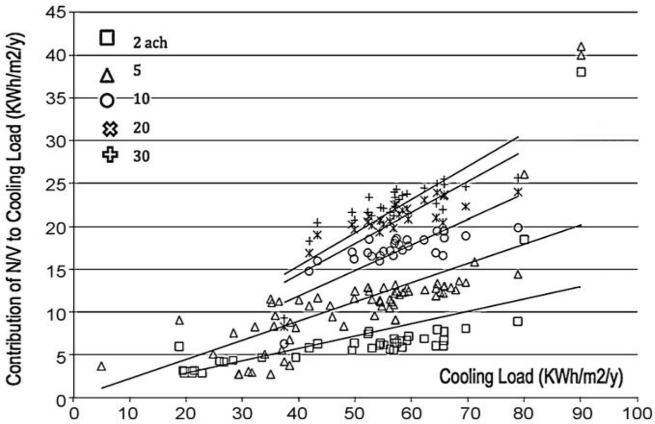


Figure 9 – Energy contribution of the night ventilation as a function of the initial cooling load for different flow rates (2, 5, 10, 20, 30 ach) [34].

A higher air flow rate requires either a larger opening area or an extraction fan to increase the outdoor-to-indoor pressure difference, and they both mean a higher initial investment. For this reason it is advisable to evaluate the maximum reasonable air flow rate with respect to the climatic zone to avoid an unnecessary increase in the building cost.

Böllinger and Shaviv focused their works also on the thermal mass of the building. Shaviv observed that a light structure behaves like a heat trap, leading to indoor temperatures even higher than the outside temperature. He also proved that increasing the heaviness of the building structure the performance of night ventilation is improved, but this improvement is less and less significant when the structure becomes too heavy. Böllinger asserted that the minimum thermal mass of the building should be at least 800 kg per m^2 floor area and thus that most of the conventional non-residential building are not adequate for night ventilation, having a mass of about 400 to 600 kg/m^2.

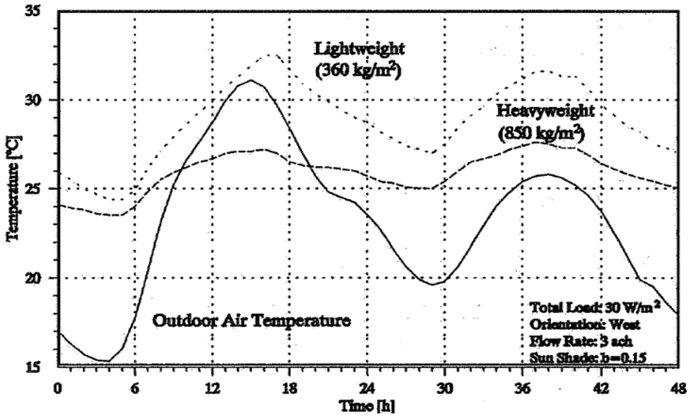


Figure 10 – Indoor daytime temperature as function of the building thermal mass [33].

The results of Böllinger are shown in Figure 10 (above) where the behaviour of a lightweight structure (360 kg/m^2) is compared to the behaviour of a heavyweight structure (850 kg/m^2).
When night ventilation is in use, the building influences the performances not only through its thermal mass, but also through its very shape since the shape determines the interaction between the structure and the surrounding environment. The driving force of natural ventilation can come either from the stack effect or from the external wind. The stack effect is the movement of air in and out the building driven by buoyancy. Buoyancy occurs due to a pressure difference induced by a temperature gradient between inside and outside: the greater the temperature difference, the greater the pressure difference and then the greater the driving force. The height of the building is an essential parameter in determining the magnitude of the stack effect. The wind induced ventilation is the circulation of air in the building by mean of the wind force. When the wind driven ventilation is established, both the shape and the location of the building are critical: the shape with relation to the prevailing wind speed and direction, the location in connection to the alterations that the topography can cause to the wind profile. Rennie and Parand showed that an office in a rural or coastal location can almost always rely on wind cooling, while an office in a city cannot [35]. Most likely the two driving forces coexist and the mutual effect can be both of enhancing or opposing each other.
E. Gratia et al. studied how to optimize the natural ventilation in a narrow office building and compared the effect of the wind driven to the effect of the buoyancy driven ventilation [5]. The buoyancy driven ventilation was obtained considering the building shielded from wind so that the air movement was generated only by the indoor-to-outdoor temperature difference. In this case single-sided ventilation was obtained. The wind driven ventilation has been studied for two different orientations of the building: wind direction parallel or perpendicular to the windows. When wind is the driving force, a cross ventilation is set up. The results show that during night, cross ventilation is almost as efficient as single-sided ventilation, both reducing the cooling needs by about 40%. This is probably due to the fact that the outside temperature is rather low and the ventilation period is relatively long, thus the heat is removed from the building mass, no matter which ventilation technique is adopted.
As pointed out by Gratia, as well as by other authors, also the window shape plays an important role in determining the ventilation pattern and thus affecting the coupling of the thermal mass and the air flow. The result is a considerable influence of the window shape on the heat removal capacity of the night ventilation. In particular a tall window uses the stack effect better than a short one, for single-sided ventilation it is then better to dispose of two openings, one at the bottom and one at the top. To create a cross ventilation the opening levels must be at different height at each side of the building.
A more accurate investigation of the window shape effect on the night cooling has been conducted by Lissen et al. [36]. They determined, through a series of CFD analyses, the flow pattern for the most common typologies of opening.
The results are summarized in Figure 11, where the opening typologies (on the left) and the correspondent performances (on the right) are shown.

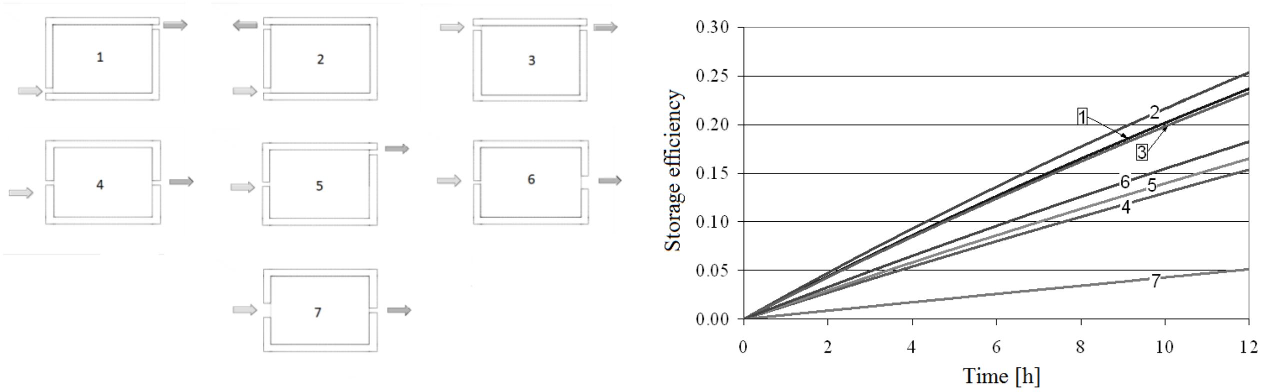


Figure 11 – Most common typologies of opening and relative storage efficiencies [36] (modified).

It has been found that when the openings are facing each other a short circuit is present. The solution that allows the most efficient contact between the wall and the primary flow rate (the *primary* air flow rate is defined as the air flow that moves from the inlet to the outlet, in opposition with the *secondary* air flow rate, that is the amount of air recirculated inside the room) is the number 2: two openings, one at the bottom and one at the top, provides a good stack ventilation. The finding agrees with the window shaping suggestion given by Gratia.

What is also interesting to evaluate is the potential improvement in the indoor air quality (IAQ) that can derive from the use of daytime natural ventilation and night cooling. In his review of ventilation and air quality [38] Liddament says that, when the weather conditions dictate the need for refrigerative cooling, the ventilation rate should not outsize the flow rate necessary to meet optimum health need since excessive ventilation causes a loss of conditioned air and then an unnecessary energy consumption. On the other hand natural ventilation without refrigerative cooling requires high air flow rate to preserve the thermal comfort, thus achieving also a high IAQ level. It is also true that the studies of Limb and Kukadia documented that the concentration of external pollutants in monitored buildings followed the daily external variation, good outdoor air quality is then essential for effective ventilation. For that reason in highly polluted urban environment a HVAC system with filtration of the outdoor air can perform better in terms of IAQ than natural ventilation. This is generally not true for a domestic building where the air conditioning system does not introduce fresh air from outdoor. In such a situation it is highly probable that natural ventilation can provide a good air quality level while an air conditioner cannot.

This observation is confirmed by the field survey conducted by Wong and Huang [39]. They focused on 3 residential dwellings in Singapore and carried out measurements of the IAQ in the bedrooms during night. 58 bedrooms were equipped with air conditioners, the remaining 105 used natural ventilation during night. In the analysis two parameters were considered as representative of the air quality level: one objective, the CO2 level, and one subjective, the SBS incidence. The authors discovered that the CO2 level of those bedrooms utilizing AC systems were consistently higher than those using night ventilation. In particular for those AC without fresh air intake the carbon dioxide level reached 1600 ppm, a level consistently higher than the threshold suggested by the standards (1000 ppm) [20]. On the other hand the measurements of the particulate level in the bedrooms showed that when night ventilation is used the level is higher, ranging from 40 to 80 µg/m^3, than the level in air conditioned bedrooms, found to be between 40 and 70 µg/m^3. However in both cases the particulate level was below the recommended threshold (150 µg/m^3). Also the IAQ perception, investigated through a questionnaire survey, showed a preference of the occupants for the naturally ventilated bedrooms. The percentage of respondents in naturally ventilated homes who reported no symptoms was 48%, consistently higher than the 18% of respondents who reported no SBS symptoms in the AC houses. Finally the two authors compared the thermal comfort perception. They found an extremely high PPD in the air conditioned scenarios and a substantially lower PPD in the natural ventilated houses. The results are though questionable since the survey was conducted with 22°C set point for the air conditioners and in some cases the indoor temperature was found to drop down to 19.8°C, thus the thermal dissatisfaction in the AC solutions was caused by extreme undercooling.

Takemasa and Moser [40] introduced the concept of Occupant Contaminant Inhalation (OCI), defined as the kilograms of each contaminant inhaled by persons ever present in the building during its operational life, for long term assessment of the IAQ. Using the long term evaluation model the authors investigated a part of a normal office space in Tokyo equipped with different ventilation strategy and reached the conclusion that natural ventilation is effective in saving energy and improving the IAQ, but can lead to poor thermal environment if the ventilation strategy is not appropriate. Mechanical ventilation has large energy consumption but ensures a good thermal environment. Hybrid ventilation reduces the energy demand and improves the IAQ without compromising the thermal comfort.

From this literature review one can infer that comfort ventilation and night ventilation have been widely investigated and compared under different control strategies and climatic conditions. What has not been properly investigated yet is the possibility to enhance the benefits of night ventilation by taking advantage of the higher comfort temperature allowed when the building operates under free floating conditions and with increased air velocities. As stated before the larger the temperature gap between inside and outside during nighttime, the more performing is the night ventilation, thus, if daytime comfort can be achieved at a higher temperature level, the night cooling is expected to be more effective. Vice versa the daytime comfort ventilation can be optimized by the combination with the night ventilation. As mentioned before the increase in the indoor temperature is slowed down by the cold stored in the building during night, thus the indoor temperature peak is shifted to the late hours of the day, when the outside temperature is lower. In this way the comfort ventilation is required to be effective when the weather condition allows it to be effective. The aim of this project is then to evaluate under which climatic conditions the synergetic effect of increased air velocity during the occupancy period and night cooling exists and if it can ensure adequate thermal comfort, lowering the energetic consumption.

3. CLIMATIC DATA

The main purpose of the project is to test the efficiency of both daytime increased velocity and night ventilation under various climatic conditions, to determine how the local weather can constrain or enhance the passive cooling of a domestic building. From this point of view the four cities (Athens, Rome, Berlin and Copenhagen) have been selected with the intent of being representative of four different climatic zones. According to the Köppen-Geiger climate classification system [41], both Athens and Rome have a Mediterranean climate, Berlin has a humid-continental climate and Copenhagen is in the oceanic climate zone. In Figure 12 the average high temperature and the average low temperature are shown, and in Figure 13 the day-to-night temperature swing during the cooling season (May 1st to September 30th).

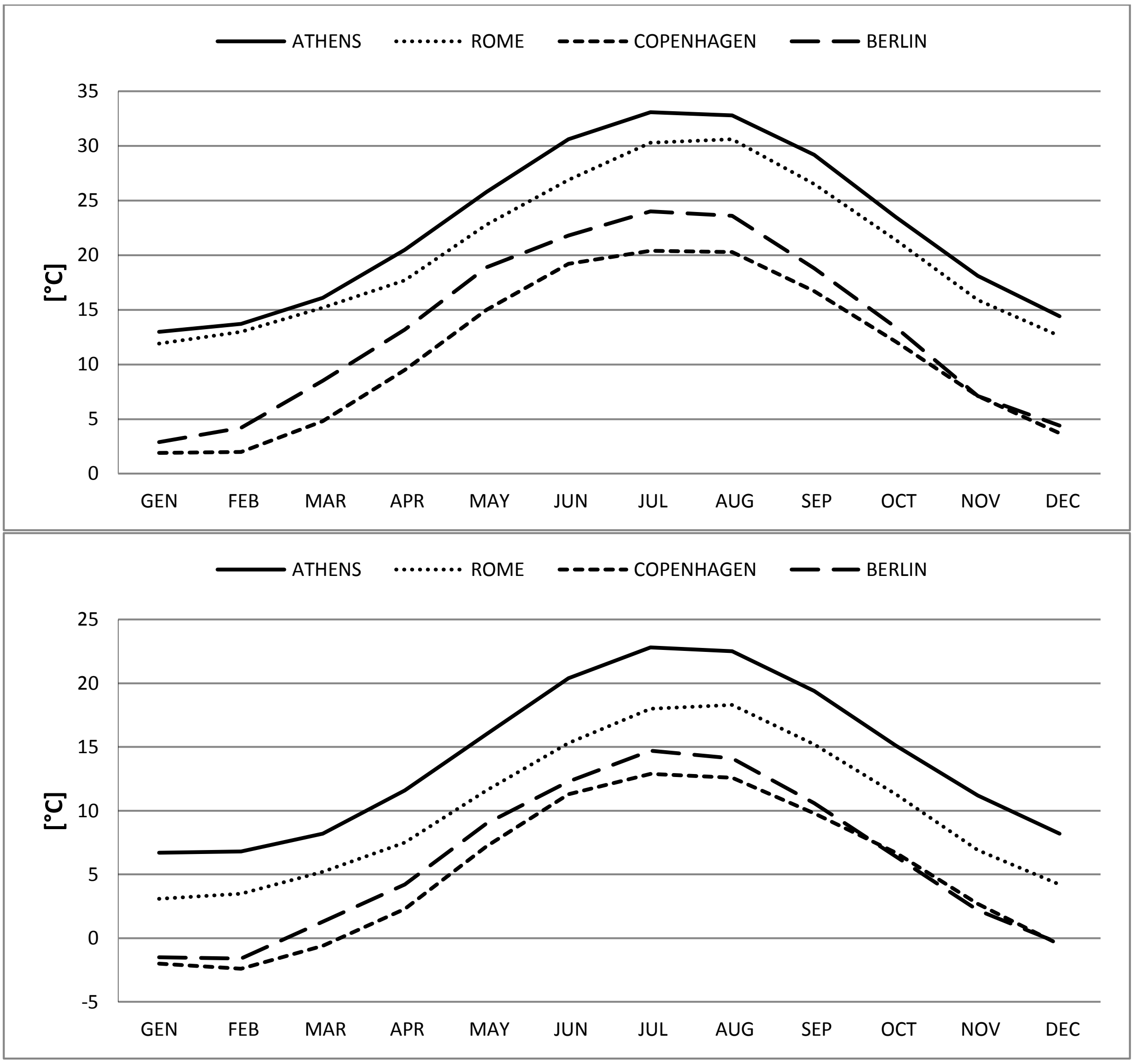


Figure 12 – Average high temperature (top) and average low temperature (bottom) for the four selected cities.

The climatic data are monthly averaged and have been obtined from the National Observatory of Athens (Athens), The Rome-Fiumicino Airport (Rome), the World Meteorological Organization (Berlin) and the Danmarks Meteorologiske Institute (Copenhagen).

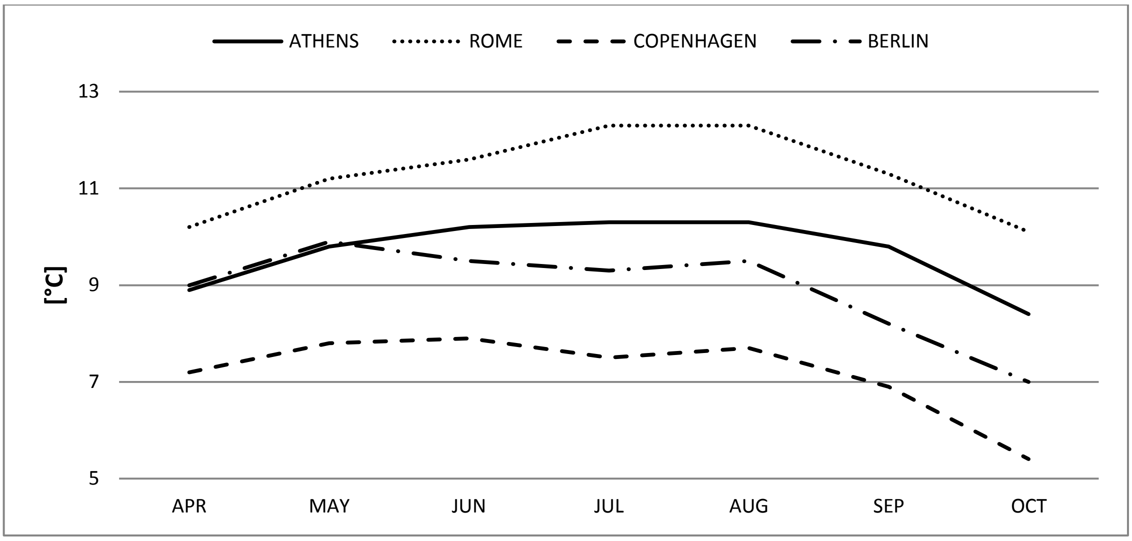


Figure 13 – Temperature gradient between day and night for the four selected cities

Both Athens and Rome present high cooling loads in the summer season, therefore the possibility to achieve thermal comfort using passive cooling systems can potentially lead to a remarkable energy saving. The most interesting characteristic of Rome is the fact that during daytime the temperatures are high (up to 30,6°C in August) and the temperature gradient between day and night is high as well (over 12°C in July and August). For this reason the location is particularly suitable, according to various studies [31], [43], [44], for night ventilation. On the other hand Athens has even higher temperatures, but a lower temperature gradient between day and night (around 10°C). Furthermore in the hottest period even during night the temperature is higher than 17°C, value that has been identified by Pollet and Renson [45] as the upper limit for night ventilation to be effective when daytime outdoor temperature rises above 25°C. Night ventilation is then expected to be less efficient than in Rome and it is questionable whether night ventilation and increased air velocities will be enough to ensure thermal comfort in the occupancy period. On the other hand Berlin and Copenhagen present a climate respectively moderate and cold, then the energy demand during the cooling season is low and the passive cooling strategies will probably provide good thermal comfort. Nonetheless recent studies have proved that, due to the ever increasing thermal insulation of buildings, the internal gain plays a more and more relevant role in the cooling load. Thus even in cold climates there is a cooling requirement during the warmest days.

Other than the indoor - outdoor temperature difference, the air flow rate through the openings is driven by the wind velocity and direction with regards to the building orientation. The analysis of the wind in the four selected locations has been made using the data contained in the ASHRAE's International Weather for Energy Calculations (IWEC) database that gives an hourly – based wind intensity along two directions (WindX is the component from East to West and WindY is the component from North to South). For every city the wind characteristics have been evaluated only for the cooling season (for now considered to go from May to September), when there is potentially demand for increased ventilation. For each month the data have been grouped along eight main directions (N, NE, E, SE, S, SW, W, NW), and for every direction an average speed and *frequency* (the frequency is defined as the percentage of time during which the wind blows from a given direction) have been calculated as arithmetic mean of the wind velocities included in an angle of ±22.5° with respect to the considered main direction. In the following the results are presented. August has been chosen as representative of the summer period.

In Figure 14 the results for the city of Athens are shown. The highest main wind velocity is from East (4.4 m/s) and North (4.0 m/s) and for most of the time the wind blows from North (35.1%). Then the existence of a prevailing wind over Athens can be deducted. The analysis also showed that for 22.7% of the time the wind velocity is 0, the stillness is concentrated in May (29.6%) and July (27.4%).

In Figure 15 the results for the city of Rome are shown. The highest main wind velocities are from South/East (5.6 m/s) and West (4.5 m/s). There seems not to be a predominant wind direction, but two peaks are present: for 15.5% of the time the wind blows from North and for 22.6% of the time it blows from West. The analysis also showed that for 14.4% of the time the wind velocity is 0, the stillness is concentrated in June (24.4%).

In Figure 16 the results for the city of Berlin are shown. Both the second highest mean velocity and the main frequency are from West (3.7 m/s and 30.9% respectively). As in Athens, also in Berlin it seems there is a prevailing wind. The analysis showed that for only 2.6% of the time the wind velocity is 0. Even if the wind is not strong compared with the other location it is constantly blowing.

In Figure 17 the results for the city of Copenhagen are shown. The wind speed is very high with a maximum of 5.5 m/s from South – East and presents peaks in the frequency from West (23.0%) and South (19.1%). The analysis showed that the wind is almost constantly blowing during all the five months: on a total amount of 3672 hours the air is still for 4 hours only (0.1% of the time). Copenhagen is then the windiest location among the four studied for both wind intensity and frequency.

A complete visualization of the wind characteristics is in APPENDIX A.

The wind profile obviously changes from month to month in all the locations, but August can be considered representative of the main characteristics, thus some considerations can be made on the above presented data. Not all locations present a prevailing wind, nonetheless they all show some preferential direction, phenomenon that results interesting when the building is designed to work in a cross ventilation configuration (and this is the case). Both Athens and Rome have an average wind speed that seems sufficiently high to grant enough ventilation during the cooling season, but, as can be seen from Appendix A, in some period the wind velocity drastically decreases and even stops, reducing the cooling potential of natural ventilation. In particular in Athens the air is still for 27.4% of the time in July, while in Rome the critical period is August with still air for 23.0% of the time. On the other hand the wind availability is absolutely not a constraint of the cooling potential in Berlin and Copenhagen.

Once again Athens is the location where the weather condition can cause the natural ventilation to fail in achieving thermal comfort.

The four locations represent then an exhaustive survey of the possible climatic conditions throughout Europe. It will then be possible to investigate the potential of increased air velocity and night ventilation with respect to the various climatic zones.

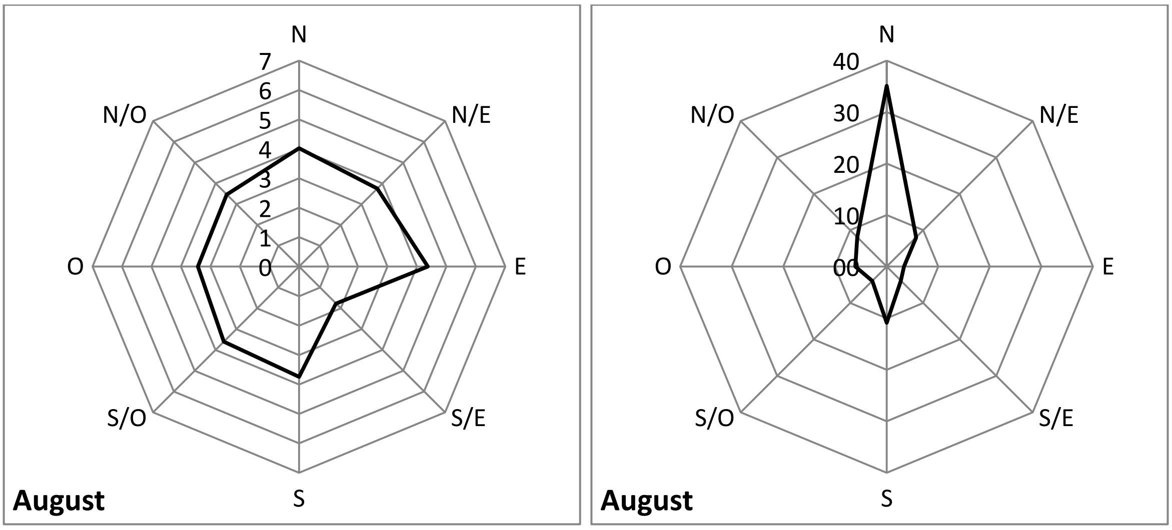


Figure 14 – Average wind velocity (left) and frequency (right) in Athens during August.

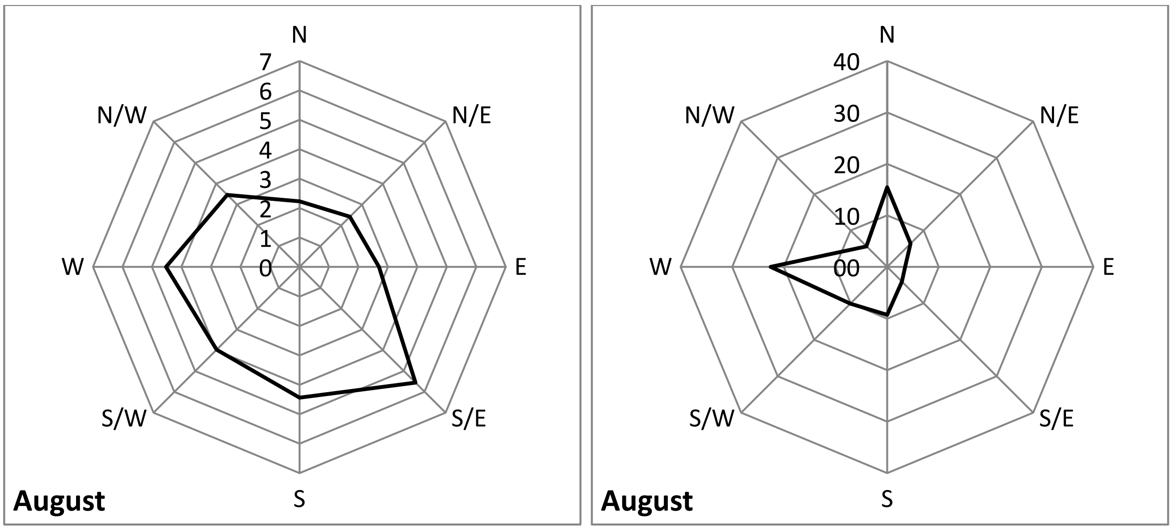


Figure 15 – Average wind velocity (left) and frequency (right) in Rome during August.

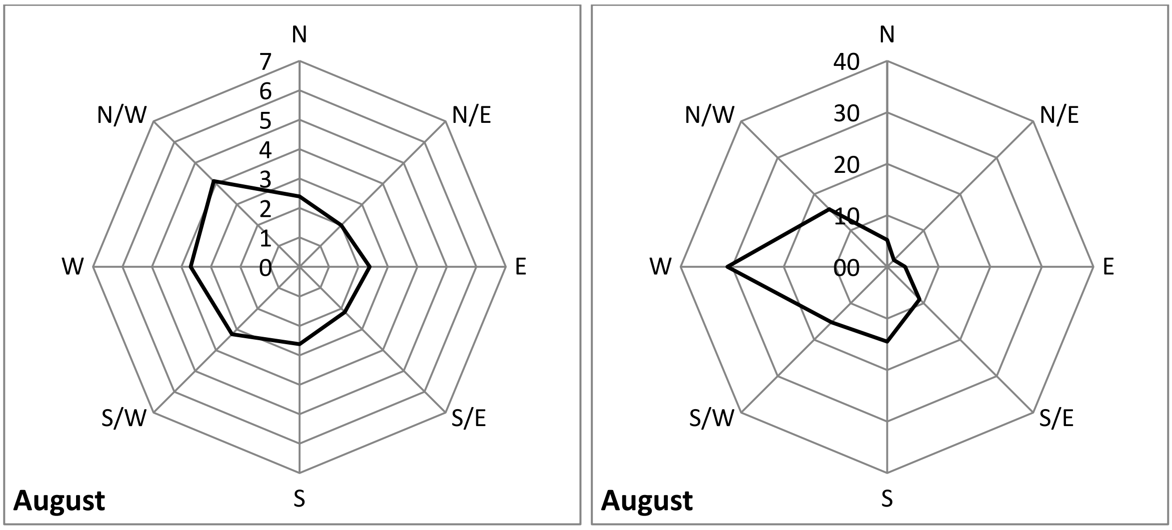


Figure 16 – Average wind velocity (left) and frequency (right) in Berlin during August.

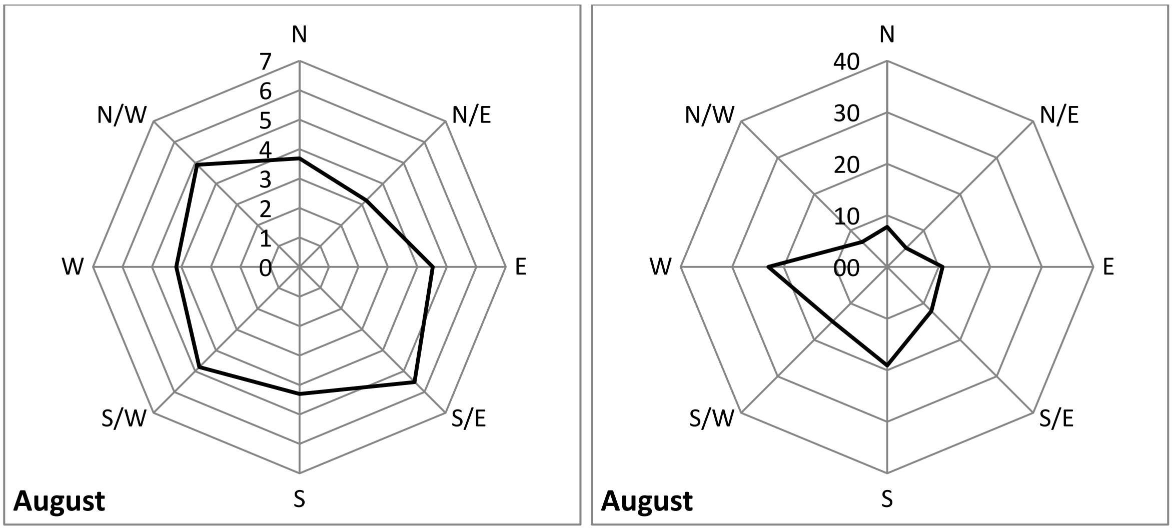


Figure 17 – Average wind velocity (left) and frequency (right) in Copenhagen during August.

4. MODEL AND METHODOLOGY

4.1. Building and occupants

The building is a 1½-storey, single-family house (Figure 1) originally designed for the proposal for an energy rating system of windows [47]. It is very simplified in most of its characteristics, but has been designed to optimize the performance of passive cooling strategies and to minimize the energy consumption. In particular the windows size and distribution aims to reduce the electric consumption for artificial lighting and to increase the cooling potential of natural ventilation techniques. The presence of windows facing each other favors the cross ventilation, that has been proven to be particularly efficient.

The building presents no internal partition at all (the entire house is a big single room), this simplifications might seem rough, but since the purpose of this project is not a precise evaluation of the energetic performance of a realistic building, but the comparative evaluation of passive and active cooling strategies in different climatic zone, such a model is detailed enough. The house has an internal length of 12 m, an internal width of 8 m, an internal floor area of 175 m^2 and a roof slope of 45°. The building tightness allows a leakage of 0.15 ach, corresponding to 0.071 l/s per square meter of external surface, at a 50 Pa pressure difference. The dissipations caused by the presence of thermal bridges are:

- Joint between an internal slab and an external wall: 0.0116 W/K/m
- Joint between an internal wall and an external wall: 0.01 W/K/m
- Joint between two external walls: 0.06 W/K/m
- External windows perimeter: 0.02 W/K/m
- External doors perimeter: 0.02 W/K/m
- Joint between the roof and an external wall: 0.07 W/K/m
- Joint between an external slab and an external wall: 0.08 W/K/m
- Joint between a balcony floor and an external wall: 0.084 W/K/m

The walls, floor and roof stratigraphy is:

- Wall (from inside to outside):
  - 0.01 m of internal plastering with a heat conductivity of 0.7 W/(m K), a density of 1400 kg/m^3 and a specific heat of 850 J/(kg K)
  - a concrete layer with a heat conductivity of 1.7 W/(m K), a density of 2300 kg/m^3 and a specific heat of 1000 J/(kg K)
  - 0.1 m of mineral wool with a heat conductivity of 0.04 W/(m K), a density of 30 kg/m^3 and a specific heat of 850 J/(kg K)

    - 0.1 m of outer layer with a heat conductivity of 0.99 W/(m K), a density of 1800 kg/m^3 and a specific heat of 850 J/(kg K)
- Floor (from top to bottom, where top in internal):
    - 0.01 m of stone with a heat conductivity of 3 W/(m K), a density of 2700 kg/m^3 and a specific heat of 880 J/(kg K)
    - a concrete layer with the same parameters of the one used for the walls
    - 0.1 m of insulation layer with a heat conductivity of 0.04 W/(m K), a density of 50 kg/m^3 and a specific heat of 850 J/(kg K)
    - 0.1 m of concrete with a heat conductivity of 2.1 W/(m K), a density of 2400 kg/m^3 and a specific heat of 850 J/(kg K)
    - 0.02 m of acoustic board with a heat conductivity of 0.06 W/(m K), a density of 400 kg/m^3 and a specific heat of 840 J/(kg K)
- Roof (from top to bottom, where top is external):
    - 0.01m of external layer with a heat conductivity of 0.23 W/(m K), a density of 1500 kg/m^3 and a specific heat of 1300 J/(kg K)
    - 0.16 m of insulation with a heat conductivity of 0.04 W/(m K), a density of 50 kg/m^3 and a specific heat of 850 J/(kg K)
    - a concrete layer with the same parameters of the one used for walls and floor

The thickness of the concrete layer has not been specified yet since it is the results of the thermal mass optimization.

A family of four people lives in the house. During weekdays (from Monday to Friday) they leave the house at 8:00 in the morning and they go back at 17:00, during the weekends they spend in the house 24 h/day. The occupants' clothing and activity levels have been set equal to 0.5 ± 0.2 clo (the clothing level is automatically adjusted between limits to obtain the best comfort) and 1.2 met (corresponding to 70 W/m^2 of body surface) respectively. For each occupant there is a consumption of hot water of 40 l/day. Also the electrical consumption for lighting is connected with the presence of the occupants in the building. An installed electrical lighting power of 4 W/m^2 has been assumed, but the percentage of lighting turned on simultaneously is 75% (that means a maximum lighting power of 525 W). The lights are turned on only when there are occupants inside the building and when the average daylight level is below 50 lux, if one of the two condition is not satisfied the lights are off.

The electrical consumption for the equipement has been set equal to 4 W/m^2 of floor area, the equipement is always on during the occupancy time.

4.2. Windows and doors

To achieve a potential for sufficient natural ventilation and good daylight conditions requires a large windows area; the building has then a 30.4 m^2 glazed surface (corresponding to 17% of the internal floor area). Five types of windows are used:

- Type 1 is an openable façade door with a glass width of 0.97 m and a glass length of 1.7 m, for a total glazed surface of 1.65 m^2.
- Type 2 is an openable façade door with a glass width of 1.08 m and a glass length of 1.8 m, for a total glazed surface of 1.9 m^2.
- Type 3 is an openable façade window with a glass width of 1.31 m and a glass length of 1.21 m, for a total glazed surface of 1.59 m^2.
- Type 4 is openable façade window with a glass width of 1.0 m and a glass length of 1.0 m, for a total glazed surface of 1.0 m^2.
- Type 5 is an openable pivoting roof window with a glass width of 0.78 m and a glass length of 1.178 m, for a total glazed surface of 0.92 m^2.

All the windows are openable for natural ventilation and are equipped with the same glazing and solar shading. The glass is a 2 pane with the following properties:

- Solar heat gain coefficient (g): 0.6
- Solar transmittance (T): 0.54
- Visible solar transmittance (T_{vis}): 0.77
- U-value: 1.471 W/(m^2K)
- Internal emissivity: 0.837
- External emissivity: 0.837

The sunshade is external and presents the following characteristics:

- Multiplier for the solar heat gain factor: 0.1
- Multiplier for the solar transmittance: 0.05
- Multiplier for the U-value: 0.90

The windows distribution is shown in Figure 1. On façade 1 (f1 in Figure 1) there are four type 2 windows for a total glazed surface of 7.6 m^2 (24% of the façade opaque surface), on façade 2 (f2) and façade 4 (f4) there are two type 3 windows at the bottom and two type 4 windows at the top for a total glazed surface of 5.18 m^2 (14% of the façade opaque surface). Façade 3 (f3) has three type 1 windows for a total glazed surface of 4.95 m^2 (14% of the façade opaque surface). Roof 1 is equipped with five type 4 windows and has a total glazed surface of 4.6 m^2 (7% of the slope opaque surface) and the three type 4 windows on roof 2 has a total glazed surface of 2.76 m^2 (4% of the slope opaque surface).
The control strategy for the window opening is intended to simulate human behaviour and is illustrated in Figure 18.
During daytime there are two conditions determining the window opening: the indoor air temperature has to be above the selected threshold (24°C in the example in Figure 18) and the outdoor air temperature can be maximum 2°C higher than the indoor. This last condition prevents the building from being heated further when the outdoor temperature is warmer than the

indoors. If one of the conditions is not satisfied (i.e. the indoor air temperature is below 24°C or the outdoor air temperature is more than 2°C above the indoor) the windows are closed. The controller is based on a PI logic, which means that the windows will start opening 1 – 2°C before the threshold is reached. Also the windows will not open all at once, but the opening area is modulated to maintain the set point value. To prevent the daytime ventilation from being used during night, a condition on the night occupancy schedule has been put: if according to the schedule it is nighttime (from 22:00 to 7:00) then the output from the PI controller is multiplied with 0, otherwise it is multiplied with 1. As already stated the controller aims to simulate the human behavior, then only when the building is occupied the daytime comfort ventilation is adopted. This condition is applied by multiplying the controller output with the occupancy schedule.

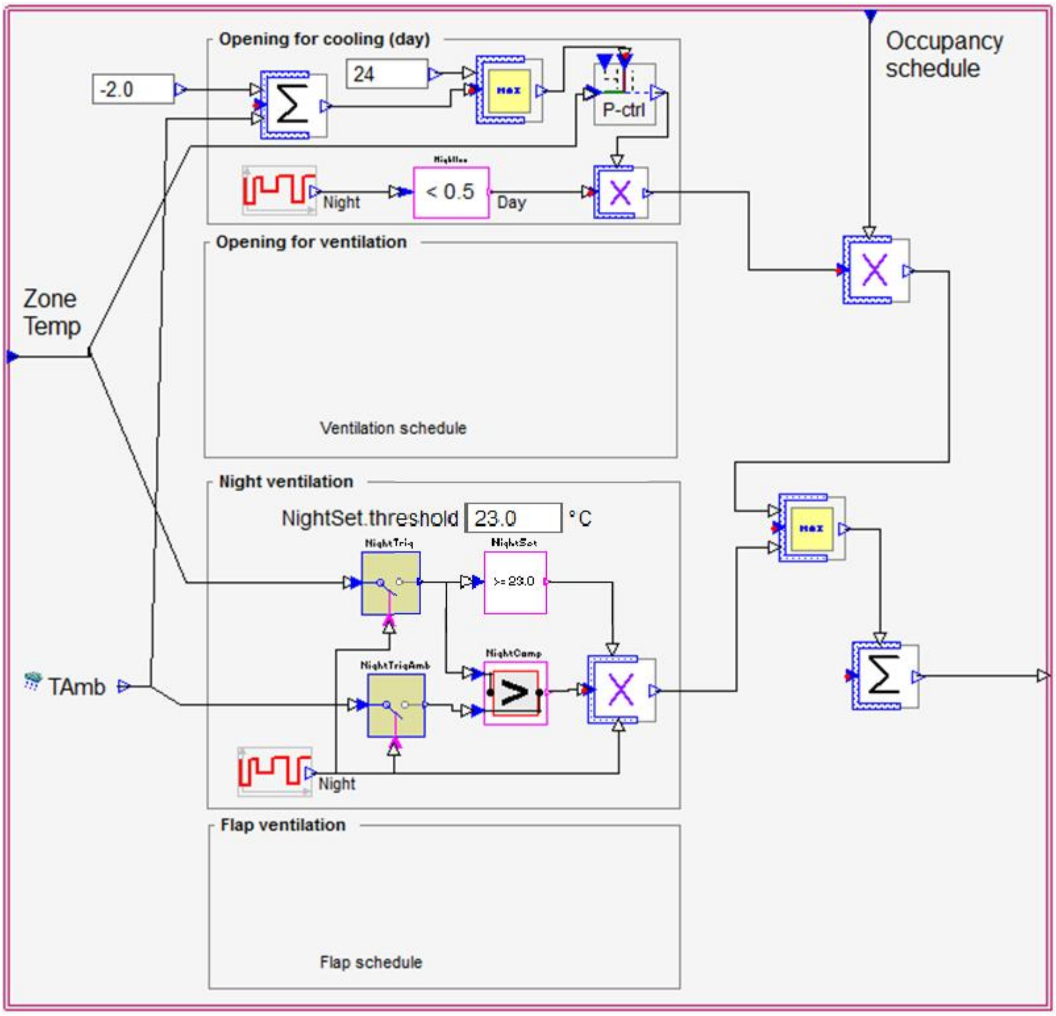


Figure 18 – Control strategy for the window opening (screen dump from IDA ICE).

To better understand how the controller operates, in Figure 19 the windows opening is shown for a three days period from June 11th to June 13th. In the following all the considerations are corroborated by comparisons between the various scenarios on a three days period. The graphs used to show the phenomena are divided into three zones: blue is nighttime (between 22:00 and 7:00), red is when the building is not occupied (from 8:00 to 17:00 during weekdays), and white is daytime occupancy time.

The first day the 2°C difference between outdoor and indoor air temperature is not respected between 12:00 and 15:00, then the windows are closed, between 15:00 and 19:00 the outdoor air temperature decreases and the windows are opened proportionally to the temperature difference. The third day both the conditions are fully satisfied until 19:00, when the indoor air temperature reaches the 24°C threshold, then the windows are progressively closed.

The control strategy just described can be looked at as a basic one, some changes have been made in the case studies to obtain the different ventilation strategies.

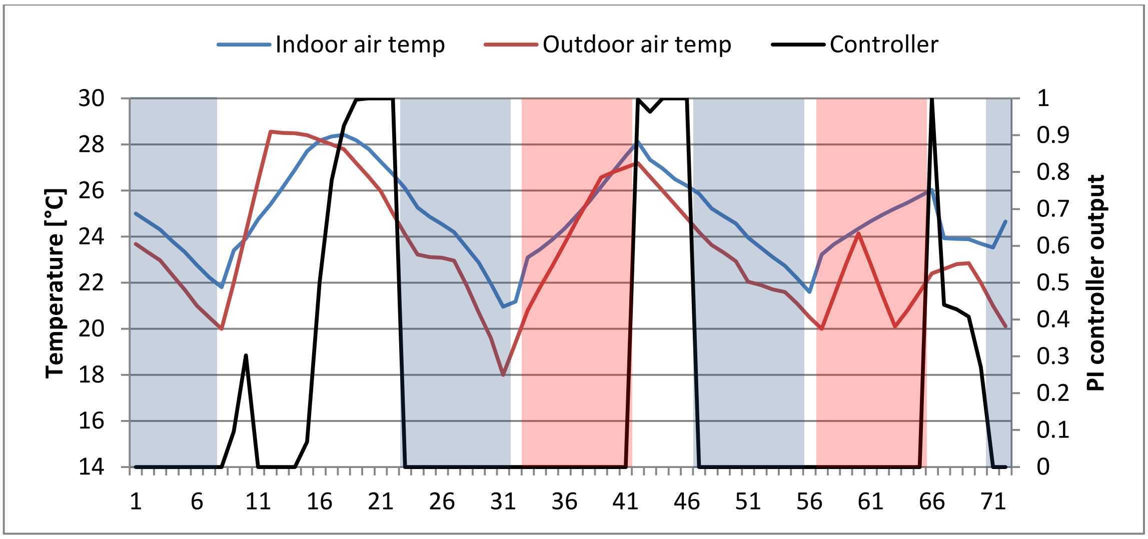


Figure 19 – PI controller for the daytime ventilation on a three days period.

During nighttime the windows are opened if two conditions are satisfied: the indoor air temperature has to be above the selected threshold (23°C in the example in Figure 18), the indoor air temperature has to be higher than the outdoor. Both the conditions are tested at 22:00, when the occupants go to sleep and, if satisfied, the windows are opened and kept open for the entire night. In other words the samplers record both the indoor air temperature (Zone Temp) and the outdoor air temperature (TAmb) at 22:00 and use them as condition for the windows opening for the entire nighttime. This is because recent studies showed that the occupants do not wake up during the night to close the windows even if the temperature drops causing undercooling and the presence of a thermostat that automatically controls the windows opening is not very frequent in domestic buildings. During night the windows are either completely open or closed, there is no modulation of the opening area. Again, the night schedule is used to obtain a 0 as output from the night ventilation controller during the day.

The shading system is based on a PI controller as well (Figure 20): when the indoor air temperature rises up to the selected set point (23°C in Figure 20) the sunshades are operated in order to maintain such temperature by modulating the solar radiation that enters the building through the glazed surface. A natural ventilation extraction duct has been added to the building (it is visible on the top of the roof in Figure 1). The duct has a diameter of 0.15 m and a length of 0.588 m, it is always open and it is used to increase the natural ventilation by stack effect.

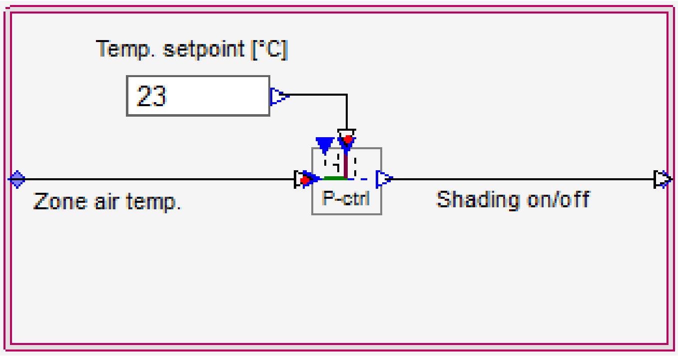


Figure 20 – Control strategy for the sunshade (screen dump from IDA ICE).

4.3. *Mechanical ventilation*

The building is equipped with a mechanical ventilation system. The air handling unit (AHU) is shown in Figure 21 and it is formed by an external supply grid, a supply pipe and a supply fan. After the fan the system is connected to the internal supply grid, placed at the floor level. The internal extraction grid is 2.5 m from the ground and is connected through a pipe to the extraction fan. The air supplied from the mechanical system is directly taken from the outside and is not processed before the introduction in the building (the cooling coil efficiency is set to 0). The fans are controlled according to the occupancy schedule or, as we will see later on, according to occupancy schedule and windows opening. Both the fans produce a pressure rise of 200 Pa, have an efficiency of 0.8 and are assumed to cause no increase in the processed air temperature. It has been assumed that every grid introduces a pressure loss of 5.0 Pa.

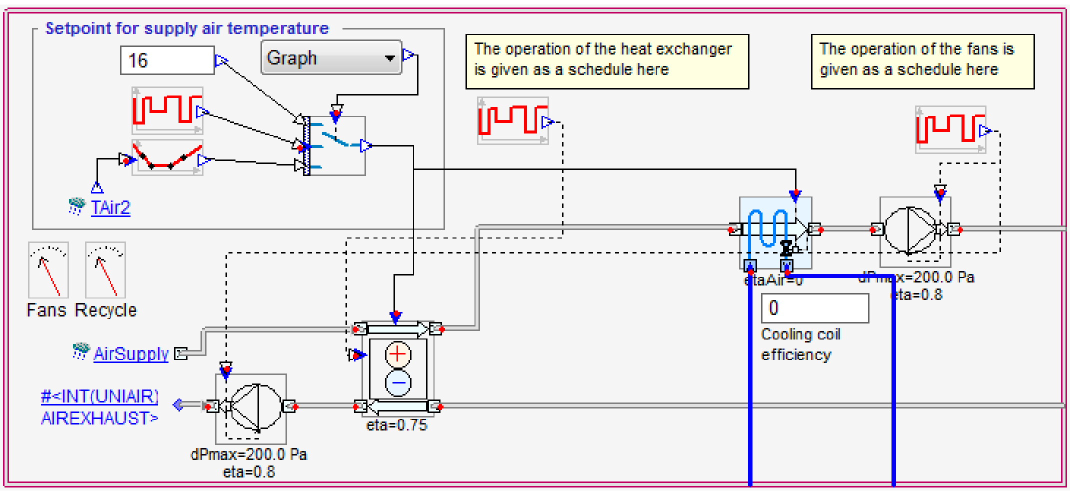


Figure 21 – Air handling unit (screen dump from IDA ICE).

A very important observation is now necessary. In Figure 21 a heat exchanger with a 0.75 efficiency connects the inlet and the outlet pipes to provide some heat recovery and to reduce the energy consumption both for heating and for cooling, when a cooling system is used. As a matter of fact the heat exchanger turned out to be the cause of the failure of some of the tested configurations and no solution has been found other than to remove the heat exchanger itself from those configurations. We are aware that nowadays the heat recovery is a widely used and energy efficient solution, but this technical hitch forced us not to use it.

4.4. Heating and cooling system

One of the simplifications mentioned before concern the heating and cooling system. that have been assumed to be an ideal heater and an ideal cooler respectively. The ideal heater has a maximum power, included the emission losses, of 17500 W, a generation efficiency of 0.9 and an emission efficiency of 1.0. The distribution losses have been assumed to be equal to 1% of the heat delivered by the plant. The ideal cooler has a maximum power, included the emission losses, of 35000 W, a COP of 2.4 and an emission efficiency of 1.0. The distribution losses have been set equal to 0.10 W/m^2 of floor area. In all the simulation the heating set point has been set to 21°C and the cooling one (for the scenarios equipped with a cooling system) has been set to 24.5°C.

4.5. Methodology

The software: the simulations have been run with the software Energy and Indoor Climate Visualizer (EIC Visualizer) from the VELUX Company. EIC Visualizer is based on the commercial software IDA Indoor Climate and Energy 4 (IDA ICE), a dynamic multizone simulation application developed by the Swedish company EQUA Simulation AB, that has been tested several times against different validation schemes (the validation reports can be found in the VELUX webpage http://eic.velux.com/EIC_Visualizer/About/Validation.aspx). The main strength of the software is the use of a general-purpose variable time step solver, which allows to identify the exact moment when a change (e.g. opening or closing of the windows) occurs.

All the simulations have been run for a yearlong period, but the evaluation of the indoor environment (i.e. thermal comfort and IAQ) has been made for the *natural ventilation period*, which is defined as the period of the year that starts the day during which natural ventilation is used for the first time (i.e. the conditions for the window opening are met for the first time since the beginning of the year), and ends the last day of application of natural ventilation (i.e. the conditions for the window opening will never be met again for the rest of the year).

It is in fact during the natural ventilation period that the passive cooling strategies such as comfort ventilation, night cooling and solar shading are used to preserve thermal comfort and air quality without causing any energy consumption. Only the energy consumption is referred to the entire year. This should not compromise the results since the amount of energy used to heat the building during winter does not change when changing scenario (the thermostat set point of the heating system is the same in all configurations).

Thermal comfort: the thermal discomfort occurs when the indoor environment does not meet the requirements of the human body. Basically six main parameters influence this environment: the occupants activity, the clothing, the air movement, the mean radiant temperature, the air temperature and the relative humidity. Beside the physical environmental parameters just mentioned also the occupants expectations have a strong influence on the perceived thermal comfort. For this reason the standard EN15251 prescribes two different models to identify the comfort ranges: for building equipped with a mechanical cooling system the upper and lower limits of the three categories are given as static values (non-adaptive model). In particular for residential buildings and sedentary activity (~ 1.2 met) the standard prescribes the thresholds shown in Table 3.

Category	Minimum for heating (~ 1.0 clo)	Maximum for cooling (~ 0.5 clo)
I	21.0°C	25.5°C
II	20.0°C	26.0°C
III	18.0°C	27.0°C

Table 3 – Thresholds for the comfort categories prescribed by the standard EN15251 non-adaptive model.

For buildings without a mechanical cooling system the standard prescribes the use of an adaptive model based on the assunption that the people will freely adapt to the thermal condition inside the dwelling by adjusting the clothing, operating the windows, regulating the activity level, etc. As consequence of this adaptation the thermal comfort can be achieved in warm climates by using natural ventilation (providing air movement and, if the outdoor temperature is lower than the indoor, free cooling), solar shading (limiting the solar radiation that enters the building through the glazed surface) and a proper building design, with a relevant reduction in the energy consumption. According to this adaptive model the upper and lower limits for each category are given as function of the outdoor running mean temperature as shown in Table 4.

Category	Lower limit	Upper limit
I	$\theta_i = 0.33\theta_{rm} + 18.8 + 2$	$\theta_i = 0.33\theta_{rm} + 18.8 - 2$
II	$\theta_i = 0.33\theta_{rm} + 18.8 + 3$	$\theta_i = 0.33\theta_{rm} + 18.8 - 3$
III	$\theta_i = 0.33\theta_{rm} + 18.8 + 4$	$\theta_i = 0.33\theta_{rm} + 18.8 - 4$

Table 4 – Thresholds for the comfort categories prescribed by the standard EN15251 adaptive model.

Where θ_{rm} is the running mean outdoor temperature, defined as:

$$\theta_{rm} = (1-\alpha)\theta_{ed-1} + \alpha \cdot \theta_{rm-1}$$

The upper and lower limits for each category are shown in APPENDIX B for both the adaptive and non-adaptive models.

In addition the standard EN15251 prescribes the temperature offset that can be obtained by means of increased air velocities under summer comfort condition. When the indoor air speed is above 0.2 m/s it grants an increase in the heat transfer from the skin, thus allowing an increase in the upper limits of the comfort categories. To calculate the temperature offset from the graph presented in the standard, four easy-to-identify points ((0.2;0), (0.3;1), (0.9;2.75) and (1.2;3.3)) have been chosen and connected with a logarithmic trendline, the equation describing such trendline has then been used to calculate the temperature offset, known the air velocities. Both the trendline and the equation are reported in Figure 22.

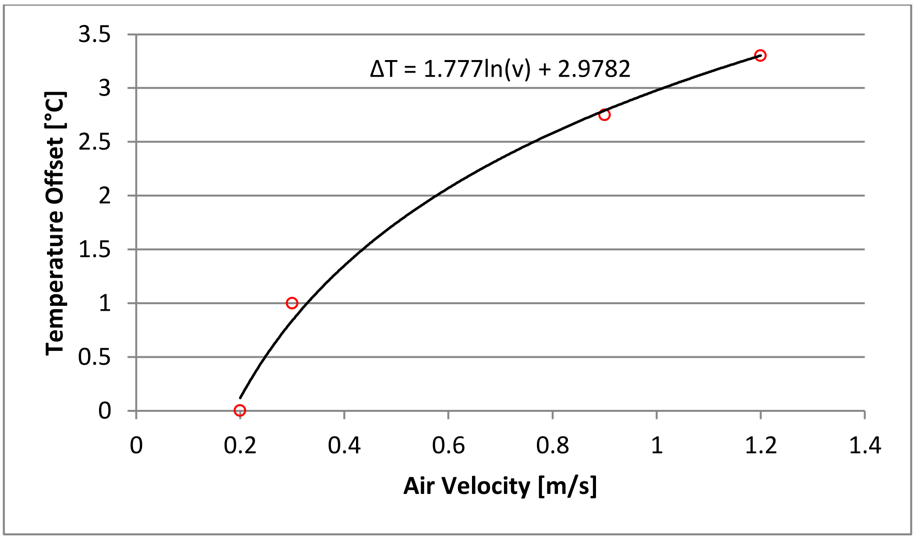


Figure 22 – Air speed required to offset increased temperatures.

The *perceived operative temperature* is the value of temperature used for the comparison with the comfort ranges prescribed by the standard and represents an attempt to provide a number corresponding to the temperature actually experienced by the body. It is calculated as sum of operative temperature (that takes into account the air temperature and the mean radiant temperature) and temperature offset caused by the air velocity inside the occupied zone.

<u>Energy consumption</u>: to reduce the energy consumption without compromising the comfort is the basic scope of the investigation. The evaluation of the energy consumption of the various scenarios takes into account three contributions: the energy consumption of the heating, cooling and ventilation systems. To sum the contribution of every system the consumption must be expressed in terms of primary energy use, thus a coefficient of 2.5 has been assumed for the electric consumption of fans and cooling system, while a coefficient of 1.0 has been chosen for the heating systems. It is better to remind here that the energy consumption is the only parameter among the ones considered which is referred to the entire year and not to the ventilation period only.

IAQ: Indoor air contains many particles and gasses. Some of this particles enter the building from outdoor (e.g. pollen, traffic, etc.), but most of the pollutants come from indoor sources like electrical equipment, building material, furniture and occupants (CO_2 from breathing, tobacco smoke, products for the personal care etc.). Since the people spend 55% of the time inside their houses [49] it is important to provide an adequate amount of fresh air from outdoor to prevent the symptoms due to a bad indoor air quality. As stated before, the parameter chosen as representative of the IAQ is the CO_2 level during the occupancy time. The outdoor air contains approximately 350 - 400 ppm, because of the human presence the indoor level is usually higher. The standard EN15251 prescribe three levels of CO_2 concentration:

- Category I: 350 ppm above the outdoor level
- Category II: 500 ppm above the outdoor level
- Category III: 800 ppm above the outdoor level

According to the same standard the air flow rate of the mechanical ventilation system has then been determined as sum of two contributions:

- 4 l/s/person (Category III building) to compensate for the pollution from the occupants
- 0.2 l/s/m^2 (Very low polluting building) to compensate for the building emission of pollutants

The total mechanical air flow rate has then been calculated as equal to 0.29 l/s/m^2. In addition an infiltration rate of 0.15 ach for an outdoor-to-indoor pressure difference of 50 Pa (0.12 l/s/m^2) has been assumed. The combination of the two ventilation rates gives an air flow rate of approximately 0.41 l/s/m^2, granted during the occupancy time.
The outdoor CO_2 level has been assumed equal to 350 ppm.

Indoor air velocity: the indoor air velocity is one of the fundamental aspects of the project. According to the standards (EN15251, EN ISO 7730) an air velocity above 0.2 m/s is capable to reduce the temperature experienced by the body by increasing the heat removed by convection from the skin. In all simulations the mechanical ventilation system is assumed not to provide increased air speed. The indoor air velocities are increased only by natural means, as consequence both controlling and calculating such velocities has been quite challenging and required some assumptions. The software calculates the opening air flows at top (the air flow rate at the upper part of the window), the opening air flows at bottom (the air flow rate at the lower part of the window) and the windows opening width. The increased air velocities have been calculated only for the comfort ventilation and not for the night cooling strategy so first of all the daytime air flow rate has been isolated. Since the building is always in a cross ventilated configuration (in Figure 23 an example is given and it possible to see both the cross ventilation configuration and the separated air flows at top and air flows at bottom of every window), an excel sheet has been created where, for the single windows, the inflow has been separated by the outflow and the correspondent window opening has been calculated from the opening width and the window geometry. The calculation of the window opening is based on the assumption that the air flows only through the cross section normal to the wall surface. The inflow has then been divided into two contributions according to the direction, axial or transversal, with respect to the building footprint. For each direction two values of air velocity have been calculated: one on the windows threshold and one on the building cross section. Averaging the threshold air velocity and the cross-section air velocity the two components, namely axial indoor air velocity and transversal indoor air velocity, of the indoor air velocity have been obtained. Finally, averaging[1] those two components, an approximation of the indoor air velocity value has been obtained. The procedure just described has been adopted to determine the air velocity, and from it the temperature offset, hour by hour.

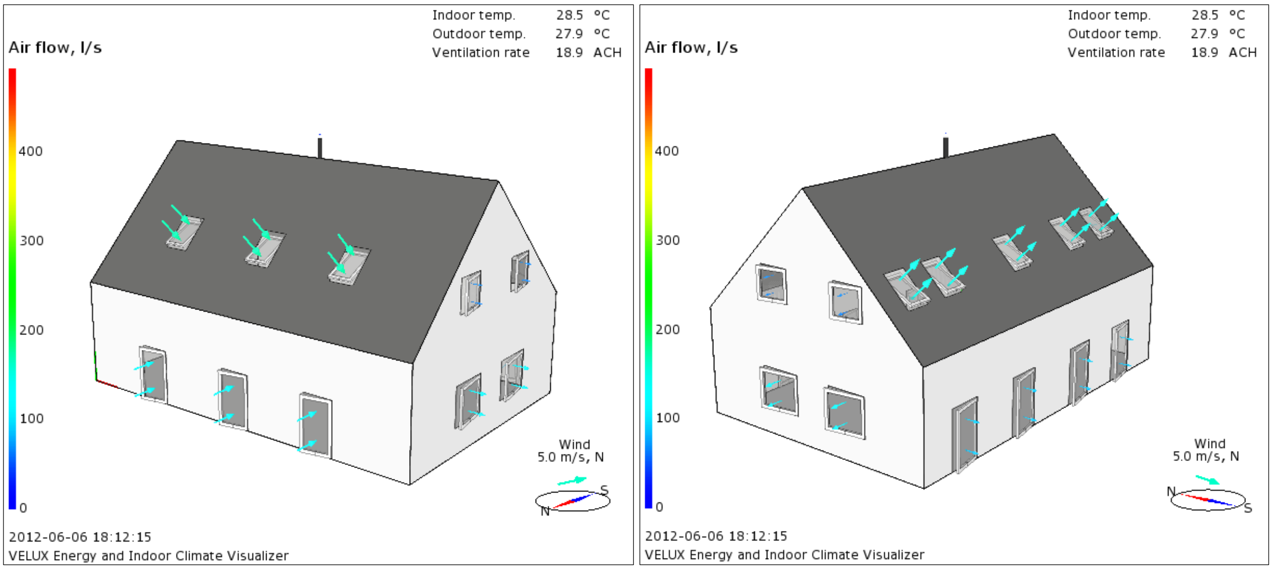


Figure 23 – Example of cross ventilation configuration (screen dump from EIC Visualizer).

__The simulations__: for the selected locations two sets of simulations have been run.

In the first set the night ventilation threshold, the orientation and the thermal mass has been empirically optimized with respect to the energy consumption and to the thermal comfort. These three parameters are expected to have a strong influence on the building´s comfort, air quality and energetic characteristics. In particular the temperature threshold determines the discomfort caused by the undercooling or overheating of the dwelling, on the orientation the indoor air velocity induced by the natural ventilation and the solar gain depend. The thermal mass has an impact on the night ventilation performance, determining the amount of heat that can be stored in the building mass during the day and removed from it during the night.

[1] The temperature offset has been calculated referring to the velocity-offset curve valid when the mean air temperature is equal to the mean radiant temperature. In our case the mean radiant temperature is lower than the mean air temperature for most of the time, then, for the same air velocity, the offset prescribed by the standard is lower. To compensate for it, the two contribution have been averaged and not summed as vectors.

The model used for this preliminary analysis relies on natural ventilation only. During daytime the windows are opened to provide ventilative cooling proportionally to the indoor-outdoor temperature difference, and only when the indoor temperature is above the selected threshold. When the indoor temperature is below this threshold we assumed that the occupants manually operate the windows according to their ventilation needs. Such manual control has been simulated by imposing an infiltration rate of 0.3 ach. No cooling system is present since the idea is to optimize the night ventilation for a free running building.
On a second moment ten scenarios that rely on different cooling and ventilation strategies have been simulated and their performances have been compared to determine whether or not the passive cooling strategies are capable to ensure an adequate thermal comfort and IAQ, lowering the energy consumption. The ten scenarios are:

- *N_02_H* is a scenario that relies on natural ventilation without increased air velocities and without a mechanical cooling system.
- *N_02_H_A* to prevent the night undercooling of the dwelling the system used in the N_02_H configuration has been integrated with a controller that modulates the opening area during night. The controller has a proportional logic: when the indoor air temperature is above the chosen threshold the windows are fully opened, when the temperature is in the modulating range the window opening is proportional to the indoor air temperature, if the temperature drops below the lower limit of the range the windows are closed.
- *N_02_HC* is the first scenario equipped with a mechanical cooling system. When during daytime the indoor air temperature rises above the set point the windows are closed and the mechanical cooling is switched on.
- *N_I_H* is similar to the first mentioned scenario. The difference is the daytime average air velocity, now all the windows can be opened to provide comfort ventilation.
- *N_I_H_A* also the scenario with increased air velocity has been equipped with an automatic control system for the night cooling. The control logic is the same described for the N_02_H_A scenario.
- *N_I_HC* is a configuration with increased air velocities, mechanical heating and mechanical cooling systems.
- *M_H* is a ventilation strategy based on mechanical ventilation and heating only. It can be seen as a reference case to evaluate the performance of the other scenarios.
- *M_HC* is a fully mechanical (mechanical ventilation, heating and cooling) scenario.
- *M_HC_N* is a model built to test if the night ventilation is capable to reduce the energy consumption and hopefully to increase the thermal comfort and the IAQ when combined with a fully mechanical system.
- *M_HC_N_A* is the last studied case. Also in the night ventilated, fully mechanical configuration a proportional controller has been integrated in the system to prevent the undercooling during night.

Table 5 allows a direct comparison between the scenarios.

Case studies	Ventilative cooling	Night cooling	Mechanical ventilation	Mechanical cooling
N_02_H	Non-increased air velocities	Open all night from 22:00 to 7:00	When windows are closed	Not equipped with a mechanical cooling system
N_02_H_A	Non-increased air velocities	Modulated according to comfort requirements	When windows are closed	Not equipped with a mechanical cooling system
N_02_HC	Non-increased air velocities	Open all night from 22:00 to 7:00	When windows are closed	Daytime: when the temperature is above the set point. Nighttime: when the temperature is above the set point and the windows are closed
N_I_H	Increased air velocities	Open all night from 22:00 to 7:00	When windows are closed	Not equipped with a mechanical cooling system
N_I_H_A	Increased air velocities	Modulated according to comfort requirements	When windows are closed	Not equipped with a mechanical cooling system
N_I_HC	Increased air velocities	Open all night from 22:00 to 7:00	When windows are closed	Daytime: when the temperature is above the set point. Nighttime: when the temperature is above the set point and the windows are closed
M_HC	Never used	Never used	During the entire year	When the temperature is above the set point
M_HC_N	Never used	Open all night from 22:00 to 7:00	When windows are closed	Daytime: when the temperature is above the st point. Nighttime: when the temperature is above the set point and the windows are closed
M_HC_N_A	Never used	Modulated according to comfort requirements	When windows are closed	Daytime: when the temperature is above the set point. Nighttime: when the temperature is above the set point and the windows are closed

Table 5 – Case studies

The results: the final results of the analysis are the *individual signatures* of the buildings. In a 3D graph IAQ, energy consumption and thermal comfort have been correlated.
The data used to plot the individual signature are:

- *IAQ*: being all the studied solutions capable to ensure a fully category II building, the parameter chosen as representative of the IAQ is the percentage of time in category I according to the EN15251.
- *Energy consumption*: the specific energy consumption on the entire simulated period (one year) has been used. The contributions considered for the calculation are the specific energy demand for ventilation, heating and cooling. Other contributions (e.g. hot water, lighting, etc.) have not been taken into account because they do not directly influence the thermal comfort and the IAQ.

- *Thermal comfort*: the evaluation of the thermal comfort has been carried on according to the standard EN15251, the adaptive model has been used to evaluate the thermal performance of the five configurations without mechanical cooling system, while the non-adaptive model has been used for the five configurations equipped with a cooling system. Also the graphs show the thermal comfort evaluation in accordance with the adaptive model prescribed by the ASHRAE55: the percentage of time in category A is represented along with the percentage of time in category II for the buildings that do not rely on mechanical cooling to achieve the thermal comfort in summer.

This representation allows a straight comparison between the scenarios and provides a visual way to identify which of the solution performs the best.

5. ROME

The results obtained from the ten scenarios for the city of Rome are discussed in this chapter. The analysis revealed that, in a climate zone such as the Mediterranean one, natural ventilation is capable to ensure good thermal comfort and high IAQ, along with a remarkable reduction of the energy consumption. However the combination of increased air velocities and night cooling turned out to be too aggressive and to cause undercooling in the dwelling, thus a constraint to the air flow rate was necessary to obtain a good environment.
For the city of Rome and with the chosen thresholds the natural ventilation period starts on April 7th and finishes on October 25th.

5.1. Preliminary simulations

Temperature threshold for night ventilation

The thermal threshold for the night ventilation strategy is the minimum indoor air temperature at which night ventilation is applied. When the indoor air temperature exceeds such threshold it is assumed that the occupants will open the windows during nighttime to allow the removal of the heat stored in the building mass during the day. A threshold too low can cause undercooling during night and can potentially lead to an increase in the energy consumption if the undercooling is so severe to require the heating system to run in order to reestablish thermal comfort. On the other hand, if the temperature threshold is too high it can prevent the occupants from taking full advantage of the night cooling strategy during the transitional seasons, thus causing overheating. For such reasons a preliminary set of simulations has been run to identify this optimum temperature level.
For the weather condition of Rome the tested threshold are 23.0°C, 23.5°C, 24.0°C, 24.5°C, 25.0°C, 25.5°C and the results have been compared with a reference case that does not uses night ventilation at all (namely NoNight).
The threshold used to decide whether to open or not the windows during daytime has been set to 24°C. Such value is not the result of an optimization process, but it is a decision based on the commonsense and on the assumptions found in papers describing similar projects.
The results relative to the thermal comfort during the ventilation period have been evaluated according to the adaptive model prescribed by the standard EN15251 and are shown in Figure 24.
Thermal comfort increases when the night threshold is increased and the solution that grants the best thermal environment is the one which does not use night ventilation at all. In Figure 25 undercooling and overheating are separately analyzed and it appears clear how the discomfort is caused by the nighttime undercooling of the dwelling.

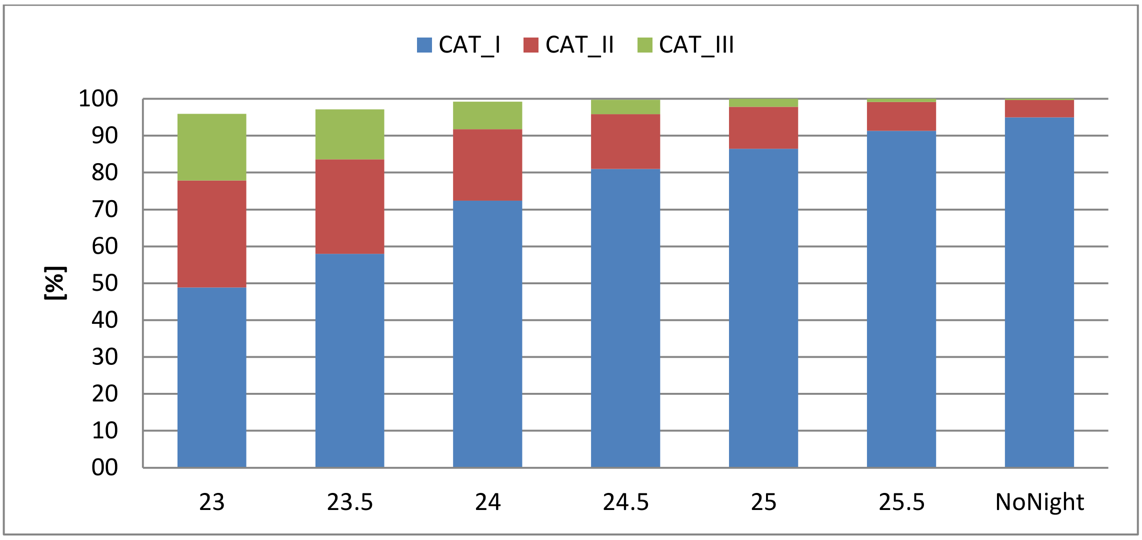
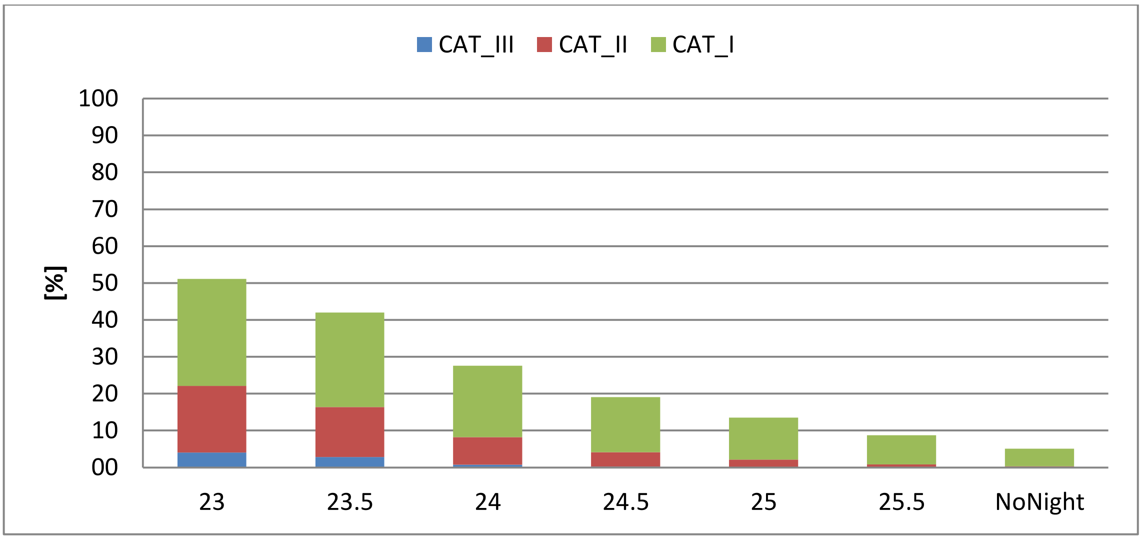


Figure 24 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested night thresholds.



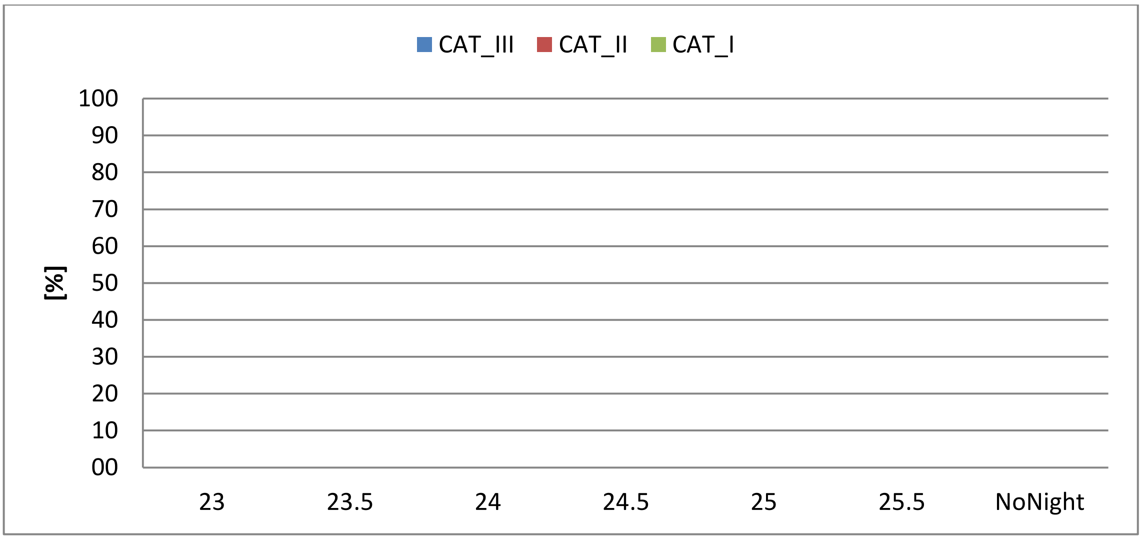


Figure 25 – Undercooling (top) and overheating (bottom) evaluated according to the EN15251 adaptive model for the tested night thresholds.

Before selecting a threshold, the energy consumption has to be evaluated. As mentioned before, there is no cooling system and thus the energy demand is for heating need only. The results are presented in Table 6 and Figure 26.

Night threshold [°C]	Energy consumption [kWh/m²]
23.0	54.7
23.5	7.3
24.0	4.7
24.5	4.6
25.0	4.6
25.5	4.6
NoNight	4.6

Table 6 – Energy consumption for the tested night thresholds.

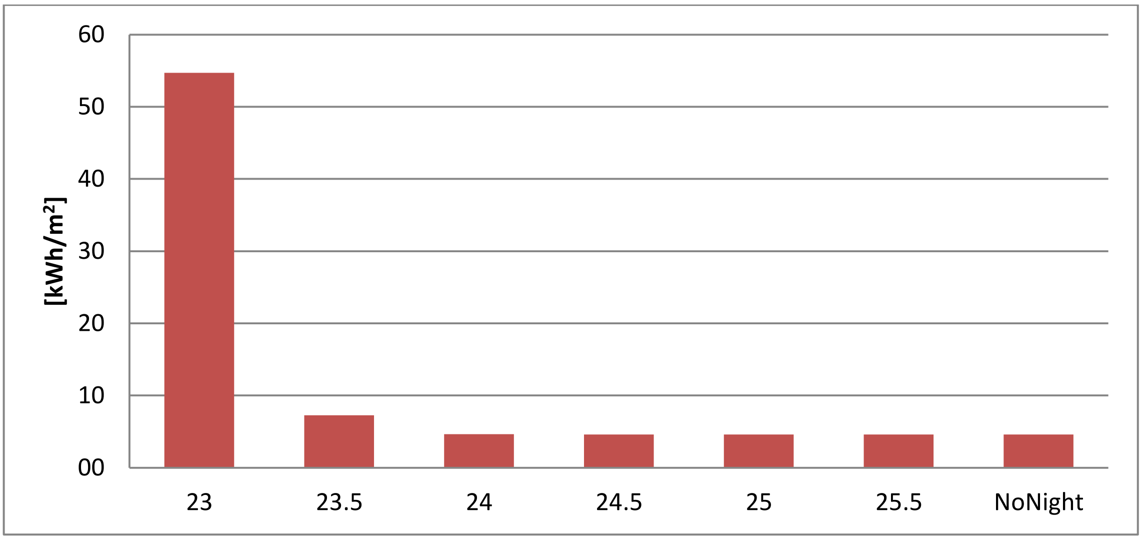


Figure 26 – Energy consumption for the tested night thresholds.

Both the table and the graph shows that a 23°C threshold is too low and in the transition seasons (spring and autumn) it leads to severe undercooling during night that has to be compensated for by the heating system, causing an enormous increase in the yearly energy consumption (when compared with the NoNight scenario the energy consumption is more than 10 time higher). Also the energy consumption of the 23.5°C scenario shows that an extra energy expense is required because of the too low threshold. All the other solutions, on the other hand, present the same energy consumptions. A straight comparison on a three days period (May 4th to May 6th) between the 23°C and the 24°C threshold solutions can prove what just stated. In Figure 27, Figure 28, Figure 29 such straight comparison is presented. It can be seen how the 23°C threshold scenario requires a very high energy consumption to compensate for the undercooling that occurs when the night cooling strategy is applied in a period during which the outdoor air temperature drops below 15°C, while the 24°C does not.

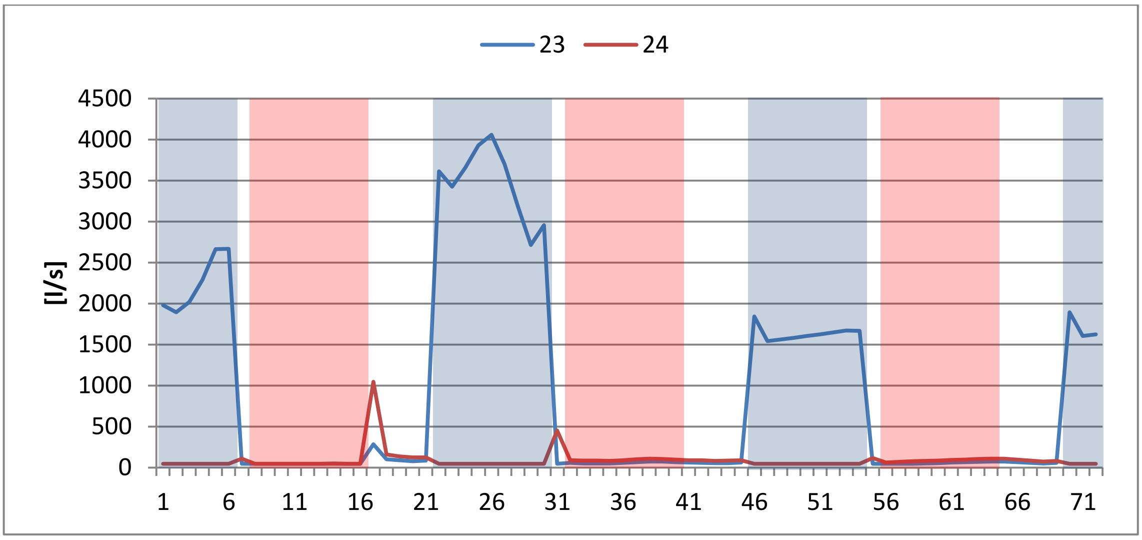


Figure 27 – Air flow rate.

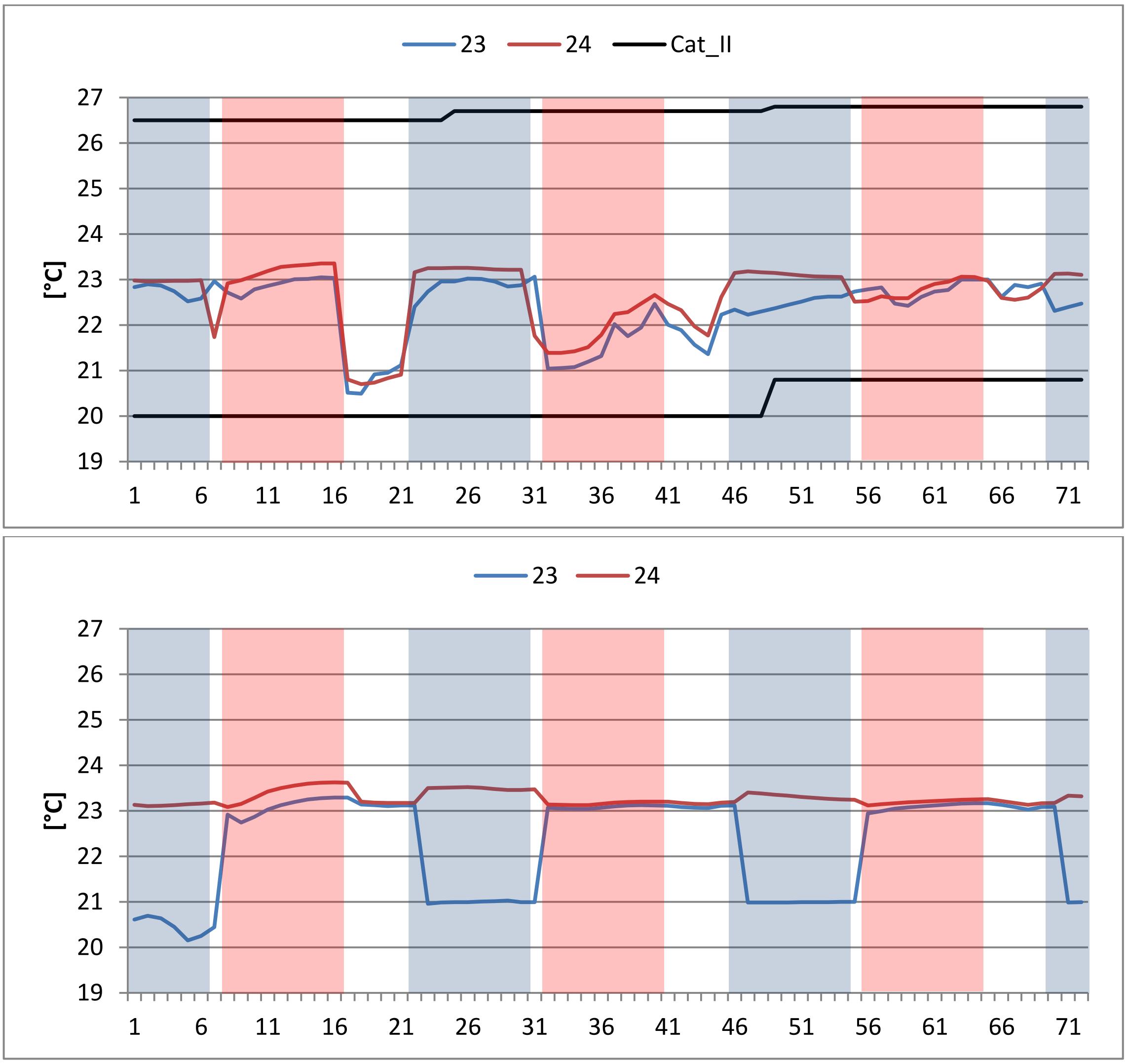


Figure 28 – Perceived operative temperature (top) and mean air temperature (bottom).

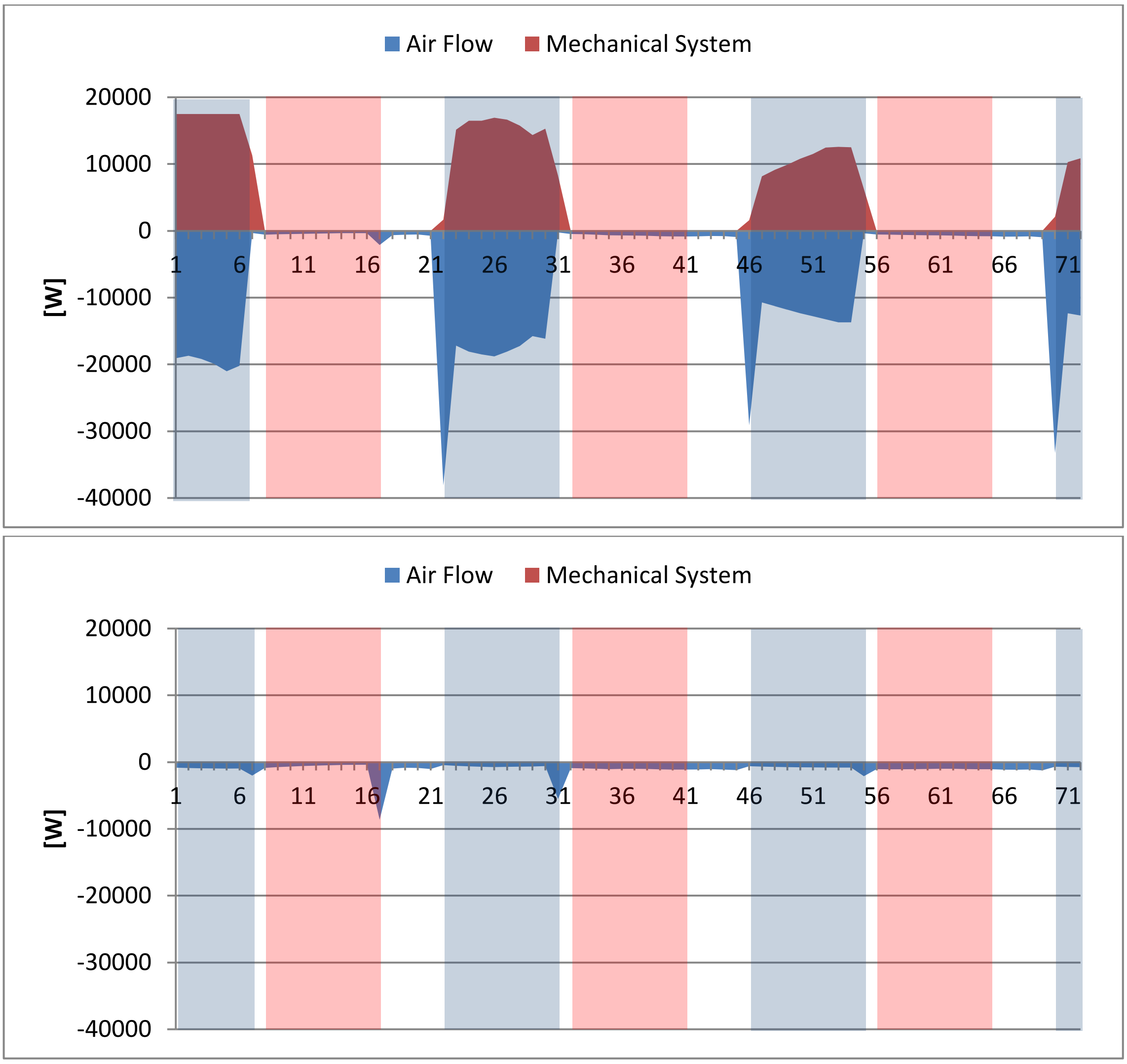


Figure 29 – Heat flux (23°C threshold at the top and 24°C threshold at the bottom).

Basing the decision on the observations about thermal comfort and energy consumption, a night ventilation threshold has to be chosen. Considering that the upper limits prescribed by the EN15251 for the three categories are quite high (according to some authors the fact whether such high temperatures can be considered comfortable or not is questionable [46]) and considering that the overheating prevention is a priority during the cooling season, a threshold of 24°C has been chosen for the night cooling strategy. The choice is corroborated by the fact that the 24°C threshold allows to fully take advantage of the night ventilation strategy without affecting the energy consumption. Furthermore if we evaluate the thermal comfort with the non-adaptive model prescribed by the standard EN15251 the 24°C is, among the best performing, the only one which does not cause an increase in the energy consumption for heating. If we consider that the adaptive model is based on the lower expectation of the occupants towards the indoor environment we can state that the comfort categories defined by the non-adaptive model are "more comfortable" than the comfort categories prescribed by the adaptive one. In addition the

PEP project [3] underlines how the comfort temperature should be lower when the occupants are asleep and, especially when they are trying to fall asleep, the categories limits should be lowered by 2°C. Then the 24°C threshold is probably the best compromise between thermal comfort and cooling potential.

Orientation

Chosen the night ventilation threshold, the building orientation has to be optimized with respect to wind direction and solar gain. Eight orientations have been tested, and this is consistent with the wind directions grouping made at the beginning of the project (the eight directions used are the same in both cases). As for the night ventilation threshold, also for the orientation the thermal comfort and the energy consumption have been calculated and compared. The building presents a wide glazed surface and, at the same time, a quite different distribution of such surface on the peripheral walls and roof slopes. When choosing the orientation, two should be the parameter taken into account. First is the capacity of the building to catch the wind in order to provide adequate ventilation and a sufficient indoor air velocity, second is the solar gain. The orientation of the building is identified with the direction that façade 3 (f3 in Figure 1) faces. In the following figures thermal comfort (Figure 30), energy consumption (Figure 31), solar gain (Figure 32) and average indoor air velocity (Figure 34) are presented.

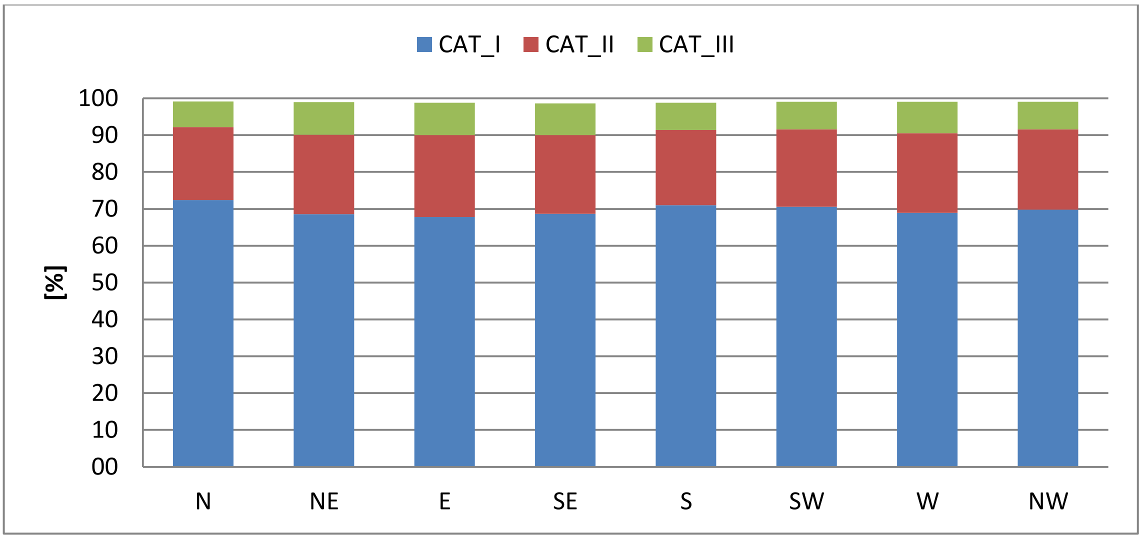


Figure 30 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested orientations.

If we refer to category I, the thermal comfort decreases moving from the orientation North (orientation that presents the highest thermal comfort) to the East, presents a minimum for East and then increases again up to the South orientation, moving from South to North-West there is another small decrease. Such variation, although present, is negligible when we referrer to category II (the difference between the maximum (N) and the minimum (E) number of hours in category II is equal to 2.3%, when we refer to category I such difference increases up to 6.4%).

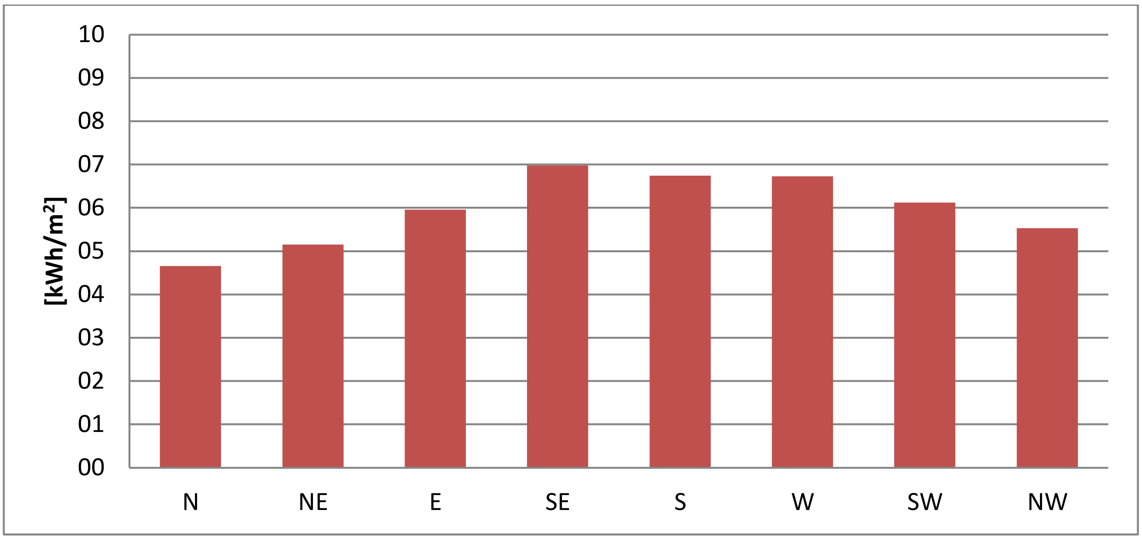


Figure 31 – Energy consumption for the tested orientations.

When the energy consumption is considered there is a remarkable difference between the various orientations. The specific consumption goes from a minimum of 4.7 kWh/m^2 for the North orientation to a maximum of 7.0 kWh/m^2 for the South-East orientation, with an increase in the heating demand equal to 33.3%. The reason for that is clear if we look at the solar radiation that enters the building through the windows (Figure 32). Since during the natural ventilation period a very efficient solar shading system is used when the indoor air temperature rises above 23°C and the solar gain is then very low, to explain the variation in the energy consumption we must refer to the yearly averaged solar gain. The yearly average solar gain presents a maximum of 362.1 W for the North orientation and a minimum of 311.7 W for the South-West orientation and in general it is lower for the orientations from South-East to South-West. In particular the graphs in Figure 33 shows that the heat delivered from solar radiation and heating system combined is the same, what changes is the percentage of heat provided during the heating season by the two mechanisms when the orientation is changed.

The explanation for the variation of energy consumption and solar radiation with the building orientation relies, as mentioned before, in the different distribution of the glazed surface on walls and roof slopes. Façade 1 (opposite to façade 3) has the largest glazed surface, then when the building is oriented to North the façade 1 faces South and exposes the glazed surface to the sun during the warmest hours of the day, maximizing the solar gain. When the building is oriented to South-West is the very opposite: the largest glazed surface faces the sun only in the early morning. To conclude: when the building is facing North, there is the largest glazed area towards South.

Because of the presence of the solar shading system the variation in the solar gain when the orientation is changed is limited to 3.5% during the natural ventilation period, while during the heating season is equal to 15.8%. It is then realistic to expect that the orientation with respect to the solar radiation will not strongly influence the thermal comfort in summer or, if a cooling system is present, the energy demand for cooling needs.

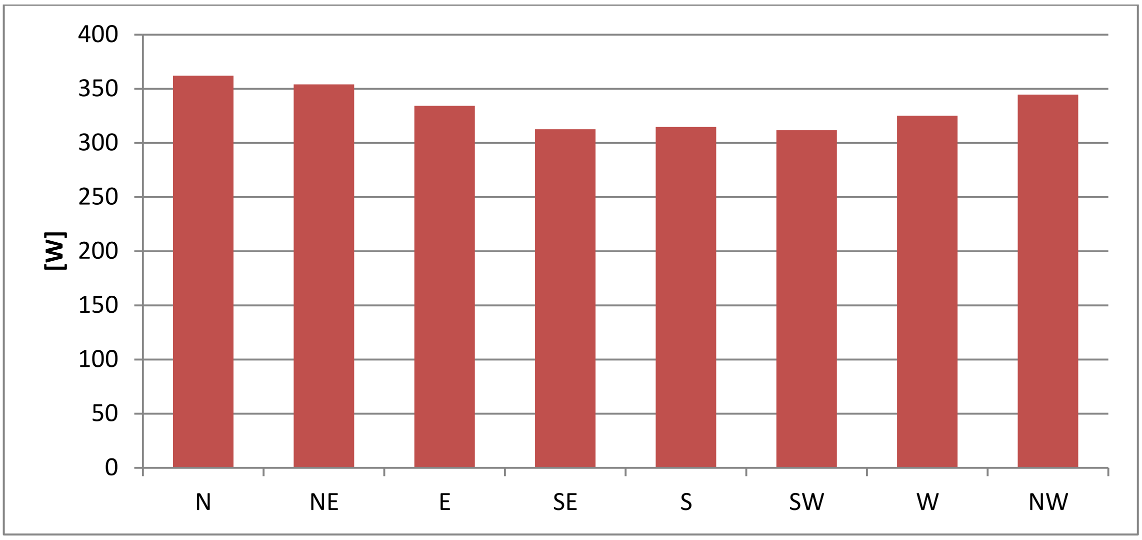


Figure 32 – Average solar gain for the tested orientations.

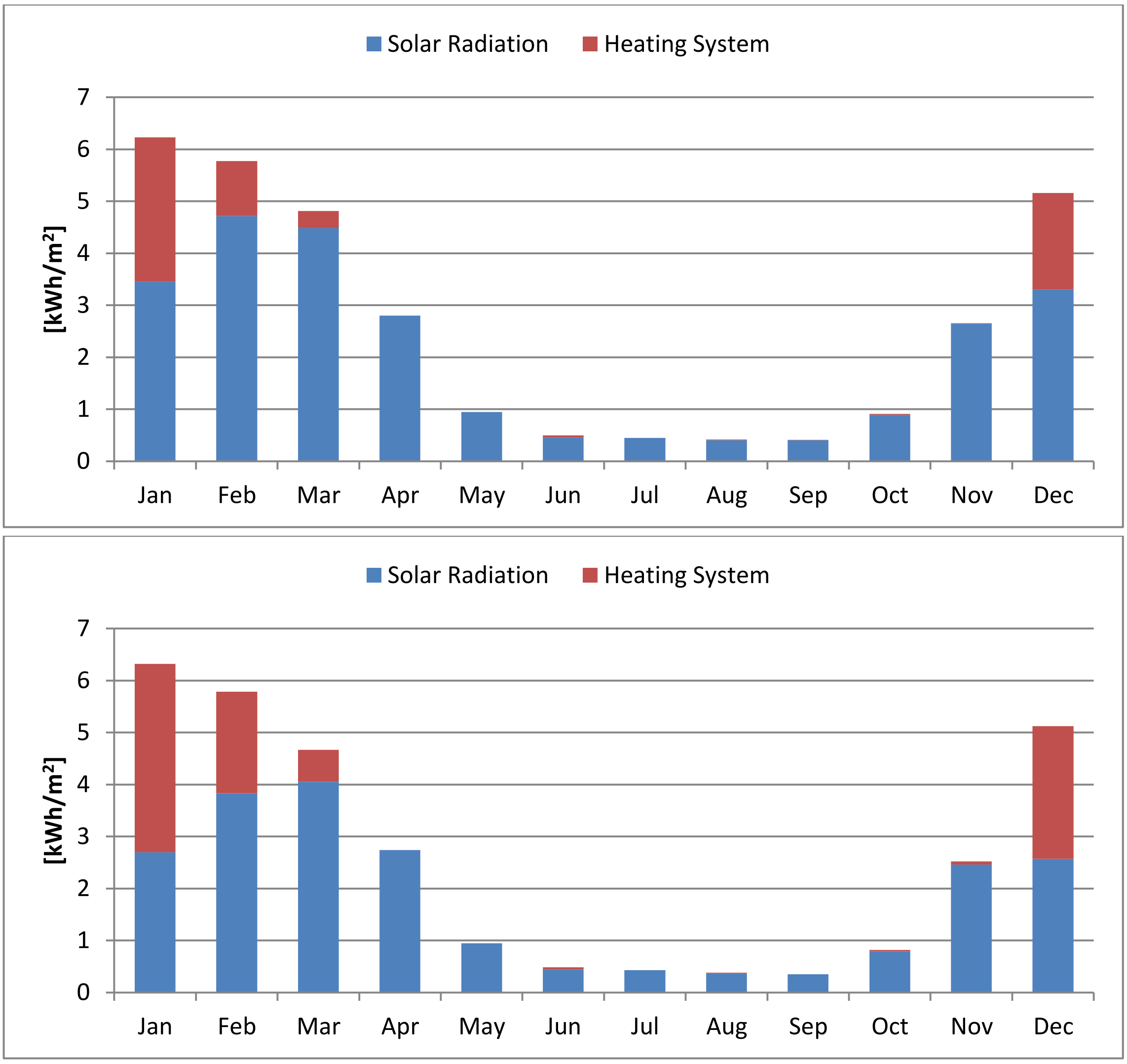


Figure 33 – Heat supplied by solar radiation and heating system for the orientations North (top) and South (bottom).

The last parameter is the average indoor air velocity. As widely discussed in the literature review an increased air velocity is capable to offset the increased temperatures that might occur in summer when the building is not equipped with a cooling system. Since testing the beneficial effect of increased air movement is one of the purposes of this project, to obtain a high indoor air velocity by means of natural ventilation is a priority. Figure 34 shows that the highest indoor air velocity (0.28 m/s) is reached when the façade 3 faces East and the building is capable to catch the prevailing wind blowing from West in a cross-ventilated configuration.
The orientation East, presenting the highest average indoor velocity, is then the most capable to offset the increased temperature during the cooling season. It is true that it presents also a quite high solar gain, but, as already explained, the solar gain is concentrated in the period between December and March. We then expect some potential benefits (both in the comfort and in the energy consumption) during the heating season, but no negative impact during the natural ventilation period.
Orientation East has then be selected.

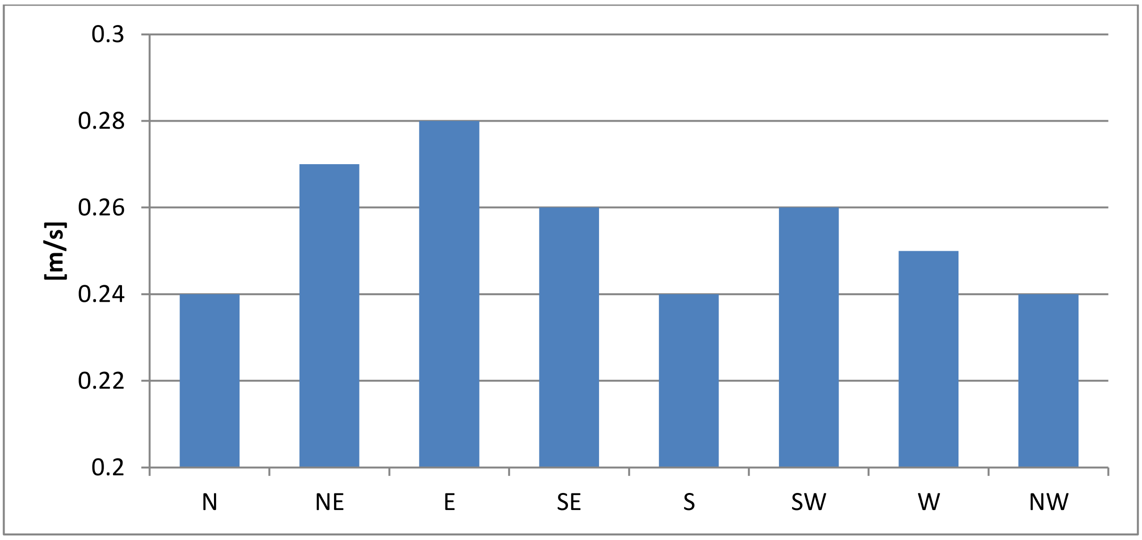


Figure 34 – Average indoor air velocity for the tested orientations.

Thermal mass

The last parameter to optimize is the building thermal mass. As extensively described in the literature review, an adequate thermal mass is essential for the night cooling to be effective, since the principle on which the cooling strategy is based is the storage of the heat in the building mass during the day, and its removal the following night. The sensitivity analysis showed that the influence of the thermal mass is not as relevant as expected. In particular the thermal comfort seems to be only slightly influenced by the increase in the building mass, as it can be seen in Figure 35. When category II is considered, the increase in the thermal comfort moving from a building structure with a 0.08 m concrete thickness (415 kg/m^2 of floor area) on the inside surface to a building structure with a 0.20 m concrete thickness (991 kg/m^2 of floor area) is slightly higher than 1.8%.

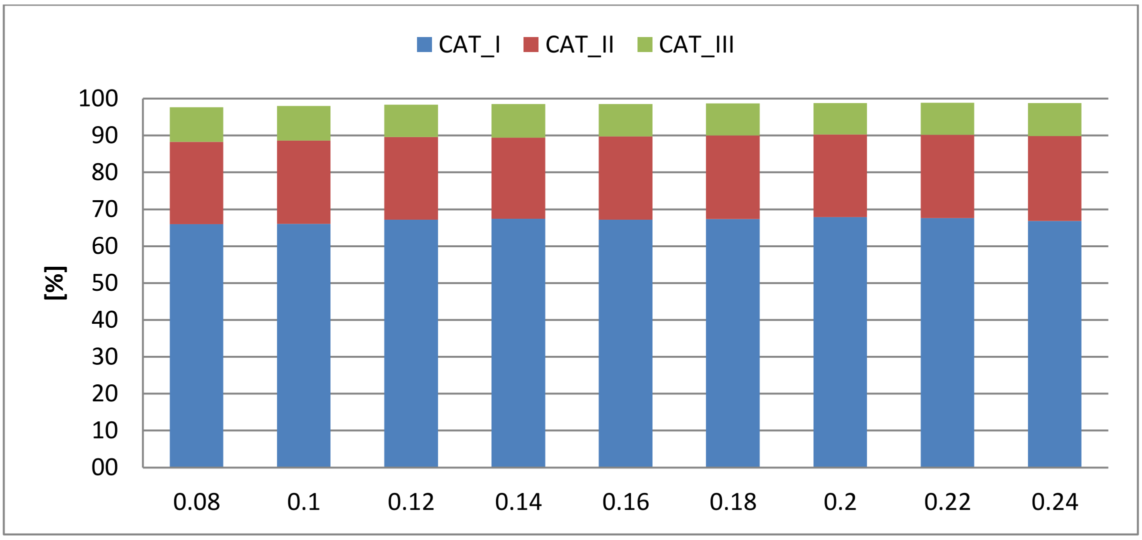


Figure 35 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested concrete layer thicknesses.

If the heat flux from the walls to the surrounding air is considered, the benefits of a heavy structure become more evident. The heat flux from the wall internal surface is quite higher when the concrete has a thickness of 0.20 m than in the situation when the concrete thickness is only 0.08 m and with a nighttime air flow rate of the same entity in the two situations, as shown in Figure 36 and Figure 37, where the heat flux and the air flow rate for the two mentioned thicknesses are compared on a three days period (August 21st to August 23rd). The graph in Figure 36 proves that increasing the thermal mass, the heat stored during daytime and then removed during nighttime is increased, thus flattening the operative temperature curve, preventing both undercooling during the coldest hours of the night and overheating during the warmest hours of the day. At the same time the graph in Figure 35 suggests that such flattening, although present, only marginally improves the thermal environment.

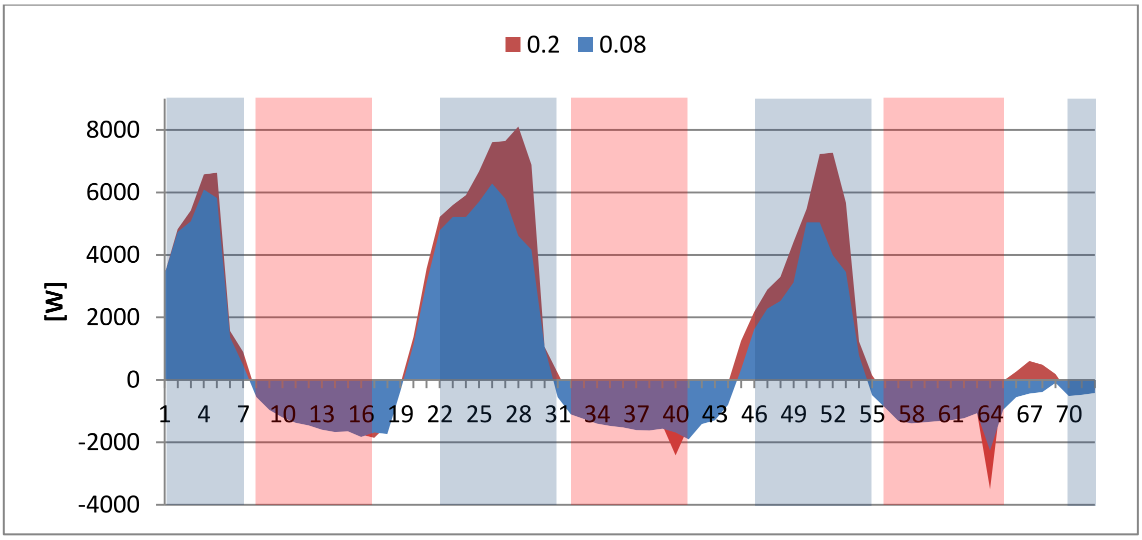


Figure 36 – Heat flux from the building mass.

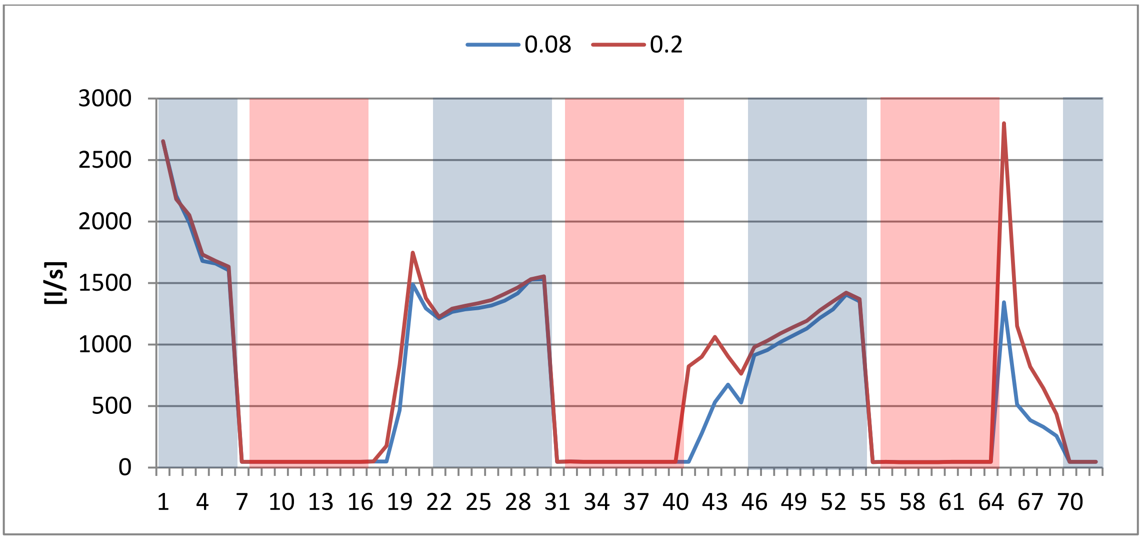


Figure 37 – Air flow rate.

Only moving the focus to the energy consumption the advantage of a heavier structure can be fully appreciated. The yearly energy consumption for the different thermal masses is shown in Figure 38. Moving from a 0.08 m thickness to a 0.20 m thickness the energy needed for heating decreases by 16.2% (from 6.3 kWh/m^2 to 5.3 kWh/m^2).

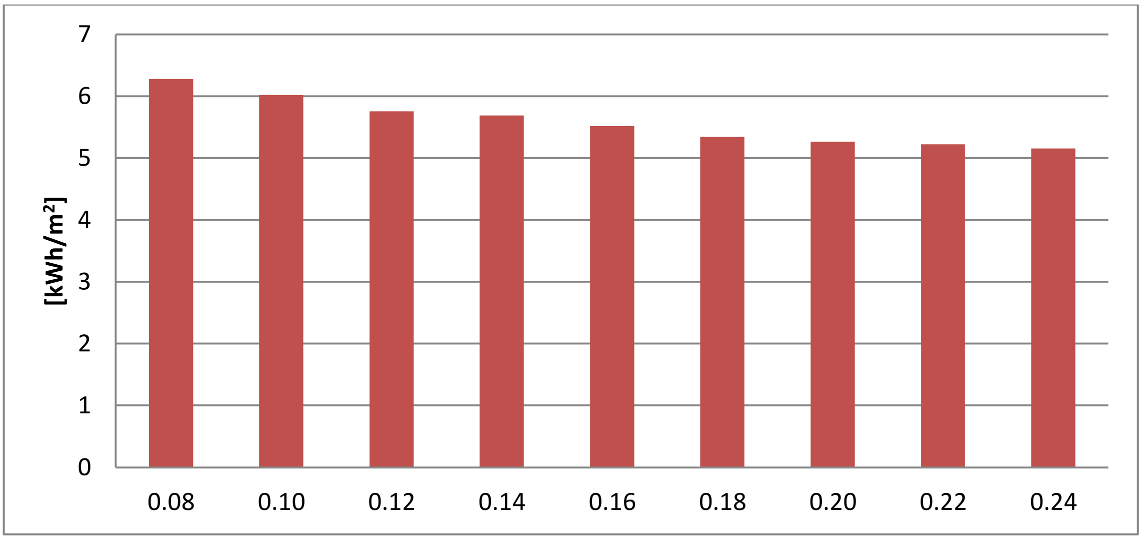


Figure 38 – Energy consumption for the tested concrete layer thicknesses.

There are two phenomena involved in this reduction of the energy consumption. The first, and more relevant one, is the fact that the wall with an increased concrete thickness is a better thermal sink during daytime, and then it is a better thermal source during nighttime. When the night cooling tents to excessively decrease the indoor air temperature, the higher amount of heat stored in the heavy structure is released, compensating such decrease, while in the light structure the heating system has to provide the heat necessary to avoid discomfort. This generally happens in the transition seasons, an example is shown in Figure 39 where a three days period (June 5th to June 7th) has been chosen as representative of the phenomenon.

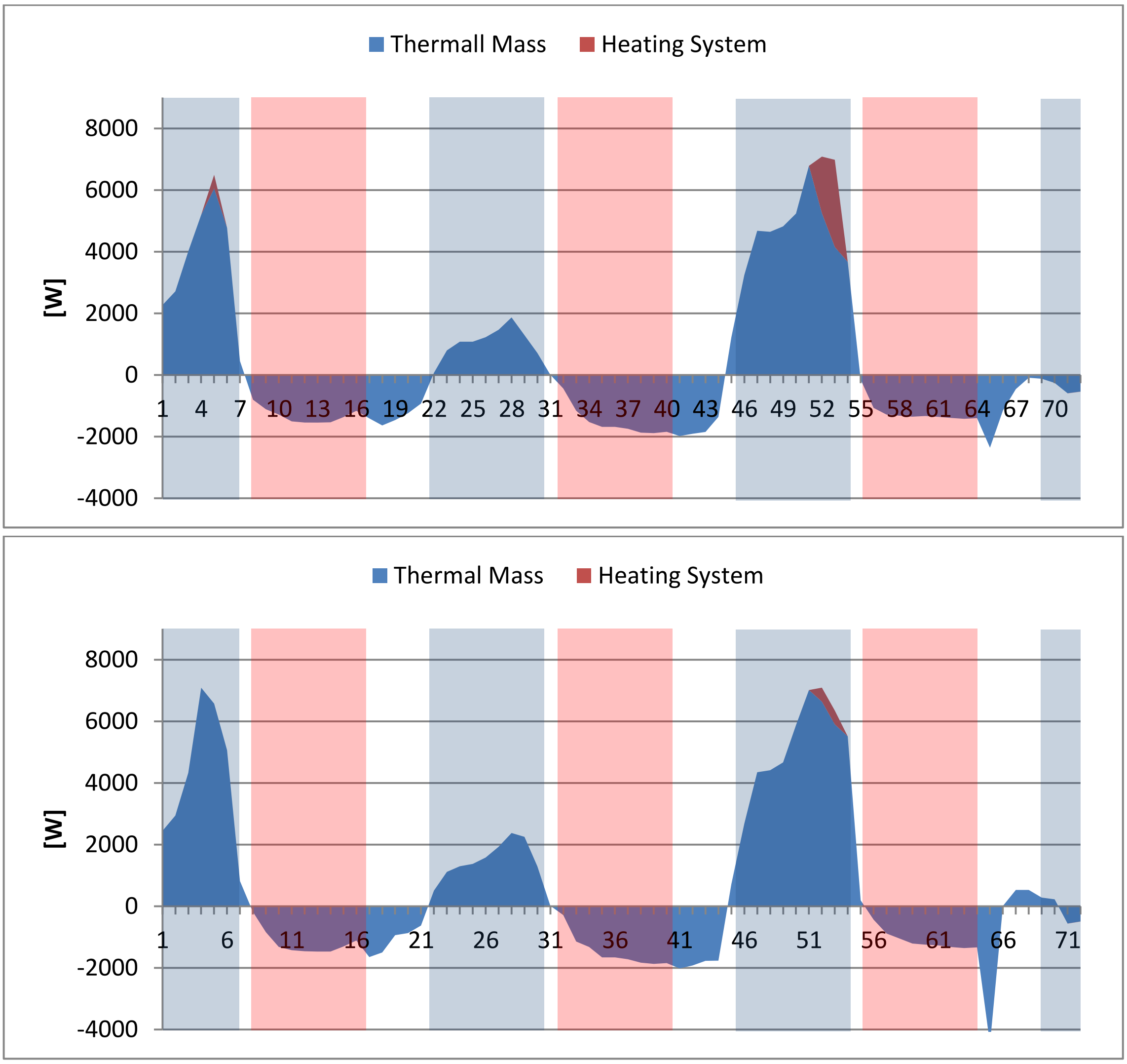


Figure 39 – Heat flux (0.08 m concrete layer thickness at the top and 0.20 m at the bottom).

The second phenomenon that influences the energy consumption is shown in Figure 40 for a three days period (September 25th to September 27th). The heavy structure acts like a thermal sink on a longer term, thus making a less intense use of night ventilation in the periods when the risk of night undercooling is very consistent. The use of night cooling at the end of September (when the outdoor temperature drops below 18°C during night) causes undercooling and the need for the heating system to reestablish the thermal comfort in the 0.08 m thickness scenario, while in the 0.20 m thickness one night cooling is not necessary since the 24°C threshold is not reached.

All this considered, it seems that increasing the concrete layer thickness up to 0.20 m gives some improvements in terms of energy consumption and, in minor amount, in terms of thermal comfort, and that a further increase brings no benefit, thus a concrete thickness of 0.20 m has been chosen as optimum value.

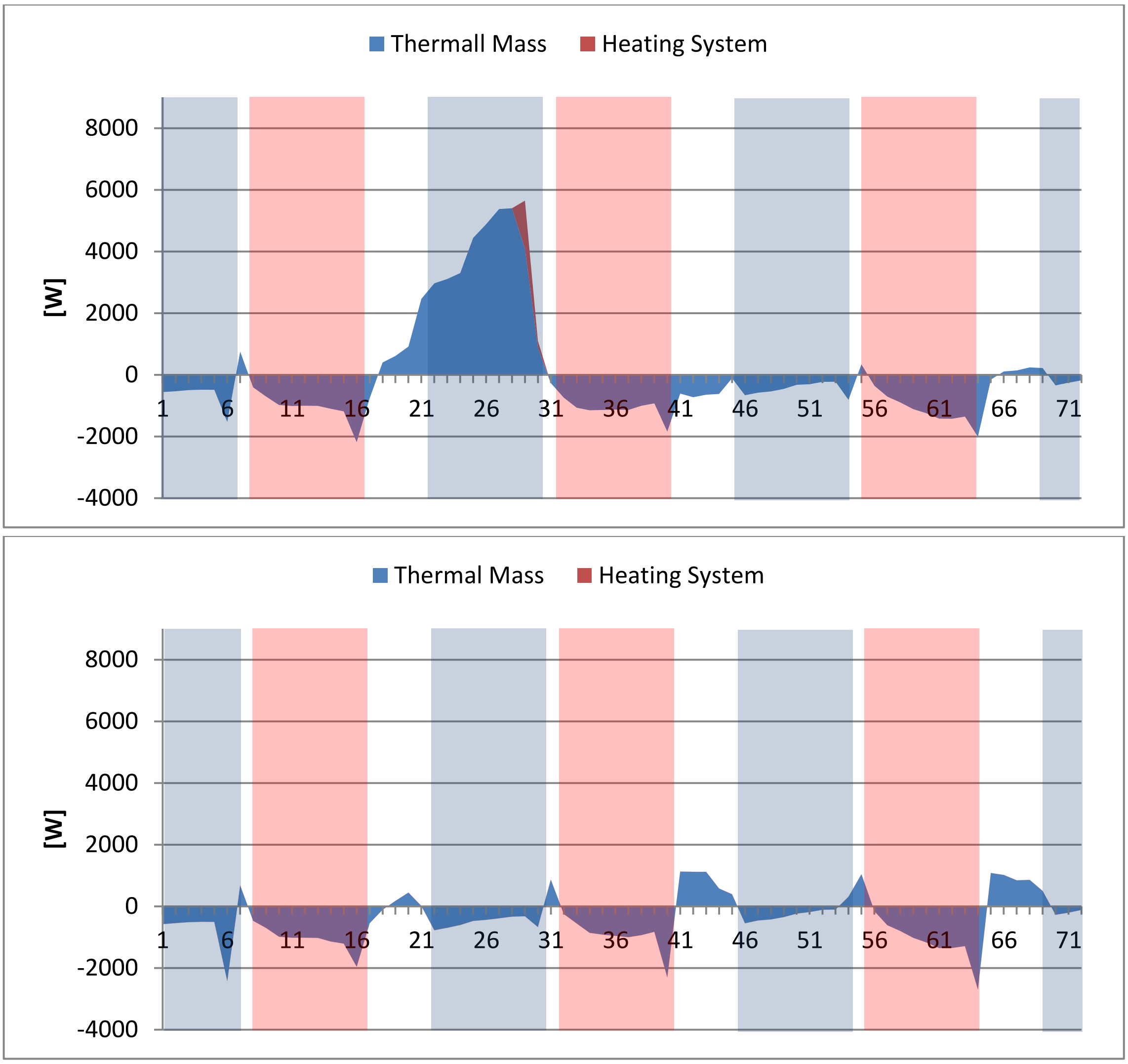


Figure 40 – Heat flux (0.08 m concrete layer thickness at the top and 0.20 m at the bottom).

5.2. Case studies

The same building has been equipped with ten different ventilation and cooling strategies, whose performance in terms of IAQ, energy consumption and thermal comfort will be compared in the following section. Here the ten scenarios' settings are briefly described.

- *N_02_H* allows an average indoor air velocity is 0.16 m/s.
- in *N_02_H_A* the P controller settings are: when the indoor air temperature is above 24°C the windows are fully opened, when the temperature is between 23°C and 24°C the window opening is modulated between fully opened (24°C) and fully closed (23°C), if the temperature drops below 23°C the windows are closed.

- *N_02_HC* switches from natural ventilation to mechanical cooling when the mean indoor air temperature rises above 24.6°C.
- *N_I_H* allows an average indoor air velocity: 0.28 m/s.
- *N_I_H_A* has the same proportional controller of the N_02_H_A case.
- *N_I_HC* has the same cooling set point of the N_I_HC case.
- *M_HC_NC_A* After some tests the best solution for the nighttime ventilation turned out to be: windows fully opened when the indoor air temperature is above 23.5°C, modulated for a temperature between 22.5°C and 23.5°C and closed when the temperatures drops below 22.5°C.

5.3. Indoor air quality

The CO_2 level has been chosen as indicator of the IAQ. The percentage of time in each one of the three categories prescribed by the standard EN15251 for the different configurations is presented in Figure 41 and Table 7 for the natural ventilation period only. It can be seen how the CO_2 level is very low in every scenario. In particular the naturally ventilated solutions which involve increased air velocities are the only one capable to generate a category I building.

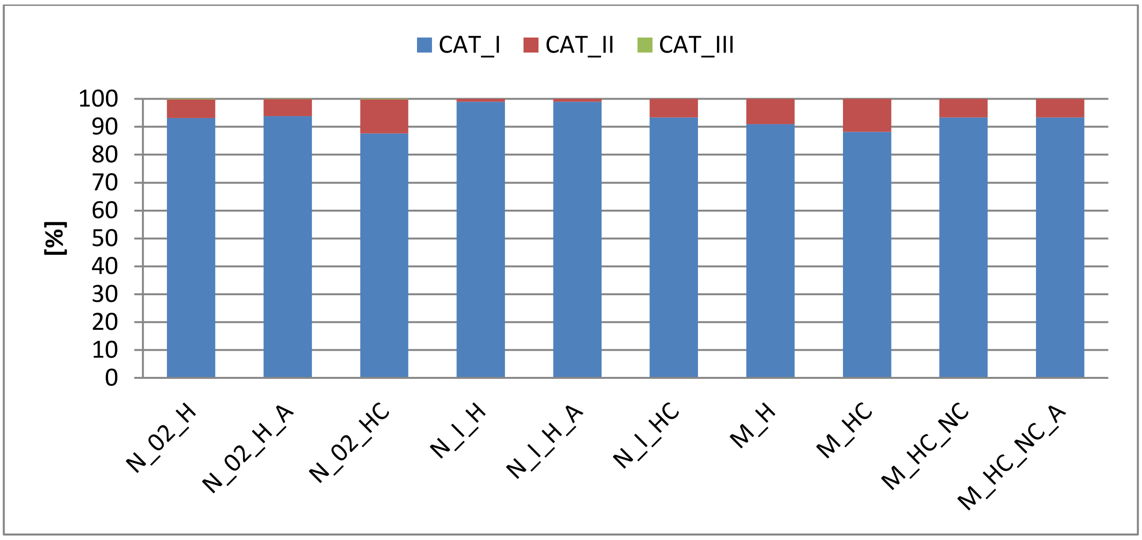


Figure 41 – IAQ evaluated according to the EN15251 for the ten scenarios.

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	93.2	99.8	100.0	+25.9
N_02_H_A	93.8	99.9	100.0	+26.3
N_02_HC	87.6	99.8	100.0	+5.0
N_I_H	99.0	100.0	100.0	+27.9
N_I_H_A	99.0	100.0	100.0	+28.0
N_I_HC	93.4	100.0	100.0	+5.9

M_H	90.9	100.0	100.0	+16.9
M_HC	88.2	100.0	100.0	-
M_HC_NC	93.4	100.0	100.0	+5.2
M_HC_NC_A	93.4	100.0	100.0	+5.3

Table 7 – IAQ evaluated according to the EN15251 for the ten scenarios.

At this point some considerations can be made. First of all when the N_02_H is compared with the N_02_H_A it can be seen that the CO_2 level is lower in the second one. This is because the reduced cooling effect of night ventilation requires a higher daytime comfort ventilation, thus creating a more even distribution of the air flow rate between day and night. What just stated can be appreciated in Figure 42 where the air flow rates for the two scenarios have been plotted for a three days period (June 25th to June 27th).

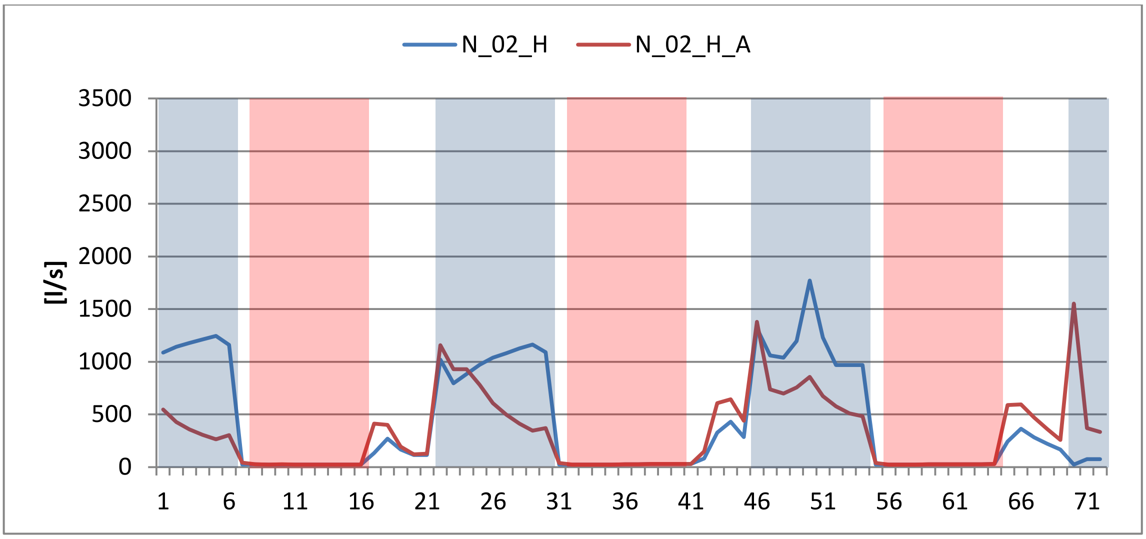


Figure 42 – Air flow rate.

This phenomenon is not present when the two correspondent scenarios with daytime increased velocities (N_I_H and N_I_H_A) are considered. A closer look reveals that the use of the automatic control does not change the amount of air that enters the building during daytime. There are two reasons for that and in Figure 43, where the air flow rates for the two mentioned scenarios are plotted for the same three days period, they can be appreciated. First the increased air velocities already limit the use of the night ventilation, being capable to prevent the temperature from excessively rising during the day. And indeed the night between June 26th and June27th the night ventilation is used in the non-increased air velocities scenario (Figure 42), but not in the increased one (Figure 43). Second, even if in some cases the use of night ventilation decreases the amount of air that enters the building during the following day, when increased air velocities are used the daytime air flow rate is more than enough to control the CO_2 level inside the dwelling (the daytime air flow rate is around 1500 l/s in the N_I_H scenario and below 500 l/s in the N_02_H one), then the further increase caused by the automatic controller is not relevant in terms of IAQ.

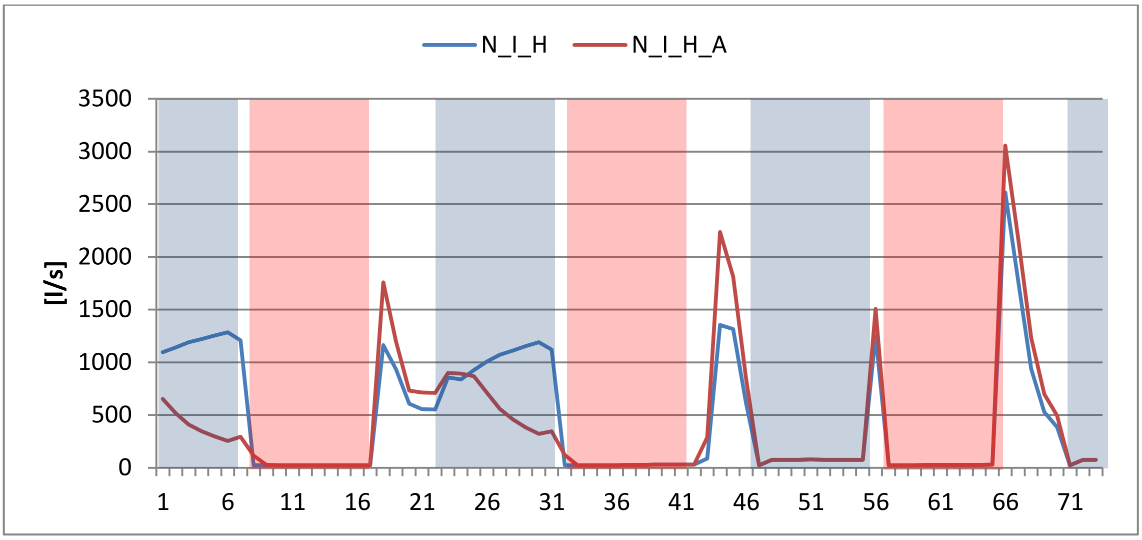


Figure 43 – Air flow rate.

A second phenomenon that looks interesting is the difference in the IAQ that exists between the mechanically ventilated and heated scenario (M_H) and the mechanically ventilated, heated and cooled one (M_HC). In those two situations the mechanical air flow rate is the very same, so the reason of this difference relies in the infiltrations. In the first case the indoor air temperature is quite higher than in the second one. Thus during night, when the outdoor temperature drops, the indoor – outdoor temperature difference is higher and, as consequence, the pressure difference is proportionally higher, resulting in an increased infiltration rate (Figure 44 reports as example the air flow rate for the same three days period).

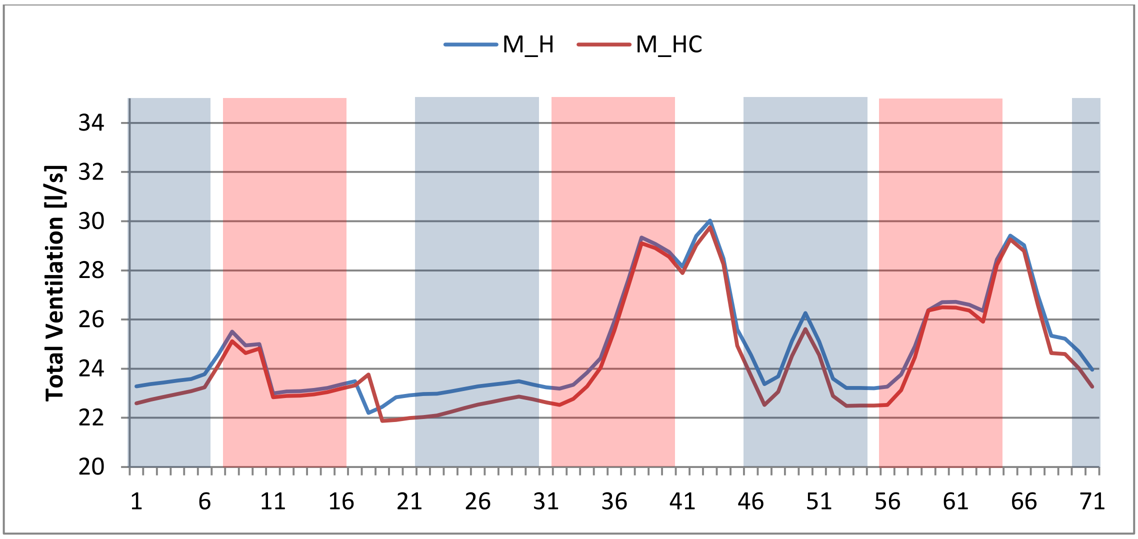


Figure 44 – infiltration rate.

5.4. Energy Consumption

In Table 8 and Figure 45 the energy consumption for the ten scenarios is shown. The scenarios that do not use mechanical cooling present remarkably lower energy consumption than the ones that use it, but also the hybrid solutions which combine mechanical cooling and passive strategy perform very well.

	Heating [kWh/m^2]	Cooling [kWh/m^2]	Mechanical Ventilation [kWh/m^2]	Total [kWh/m^2]	Variation [%] (reference case: M_HC)
N_02_H	18.7	0.0	0.6	19.3	-50.5
N_02_H_A	12.9	0.0	0.5	13.5	-65.4
N_02_HC	18.1	10.1	0.7	28.9	-25.9
N_I_H	13.1	0.0	0.6	13.8	-64.6
N_I_H_A	13.0	0.0	0.6	13.6	-65.1
N_I_HC	14.4	10.7	0.7	25.8	-33.8
M_H	12.9	0.0	0.9	13.8	-64.6
M_HC	12.9	25.1	0.9	39.0	-
M_HC_N	23.4	9.7	0.8	33.9	-13.1
M_HC_N_A	13.0	12.9	0.8	26.6	-31.8

Table 8 - Energy consumption for the ten scenarios.

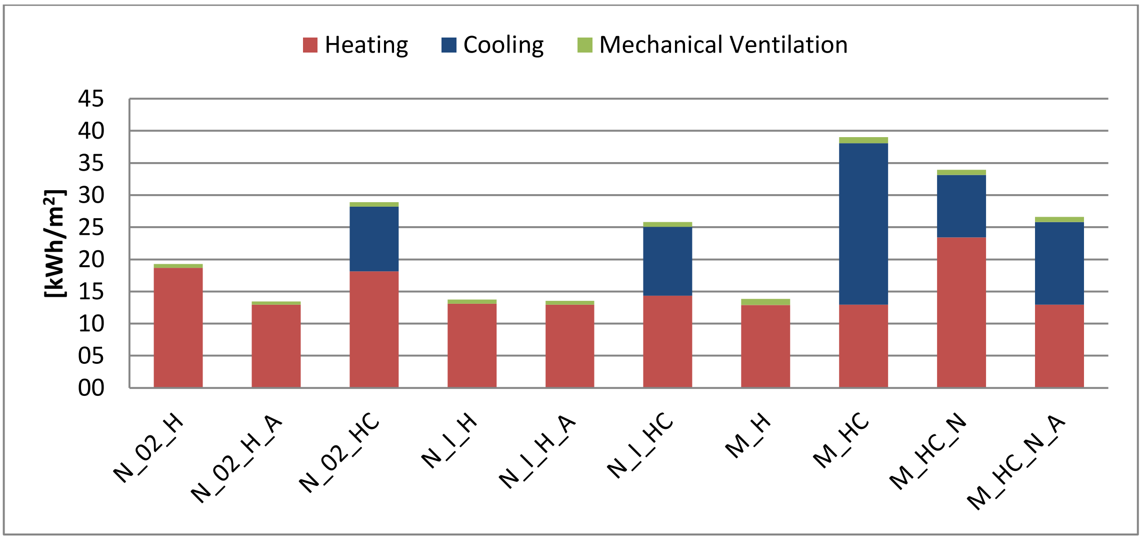


Figure 45 – Energy consumptions for the ten scenarios.

It is interesting to notice how the daytime increased velocity not only increases the thermal comfort providing ventilative cooling during the hottest days in summer, but also seems capable to reduce the energy demand for heating by 29.9%, when compared with the non-increased one. To see the reason of this difference in the energy consumption the N_02_H, the N_I_H and the M_H scenarios have been compared. Since an evaluation of the energy consumption that does not take into account the thermal comfort is not really significant, the perceived operative temperature will be shown along with the air flow rate and the heat fluxes.

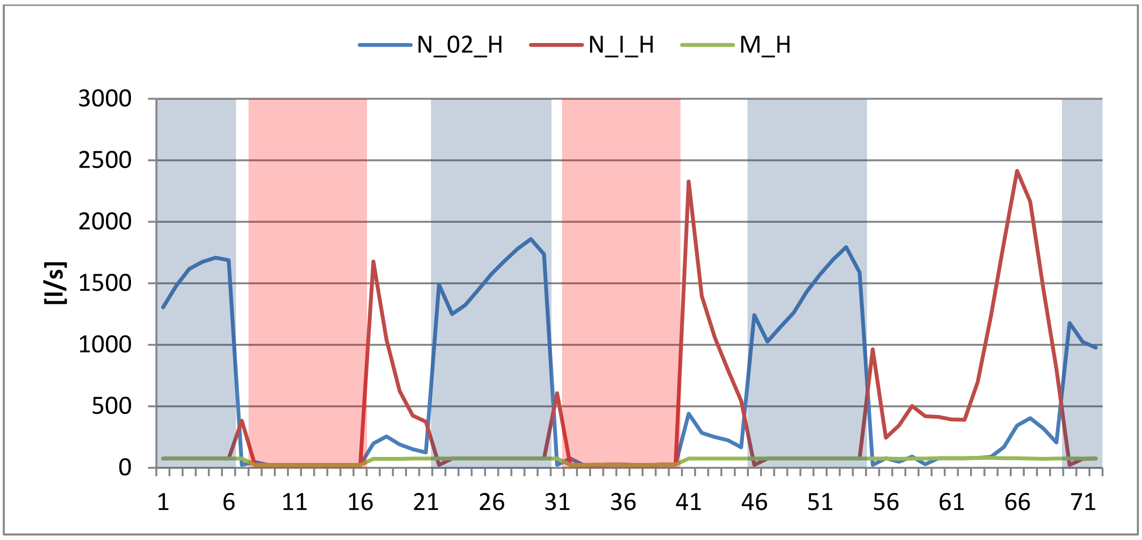


Figure 46 – Air flow rate.

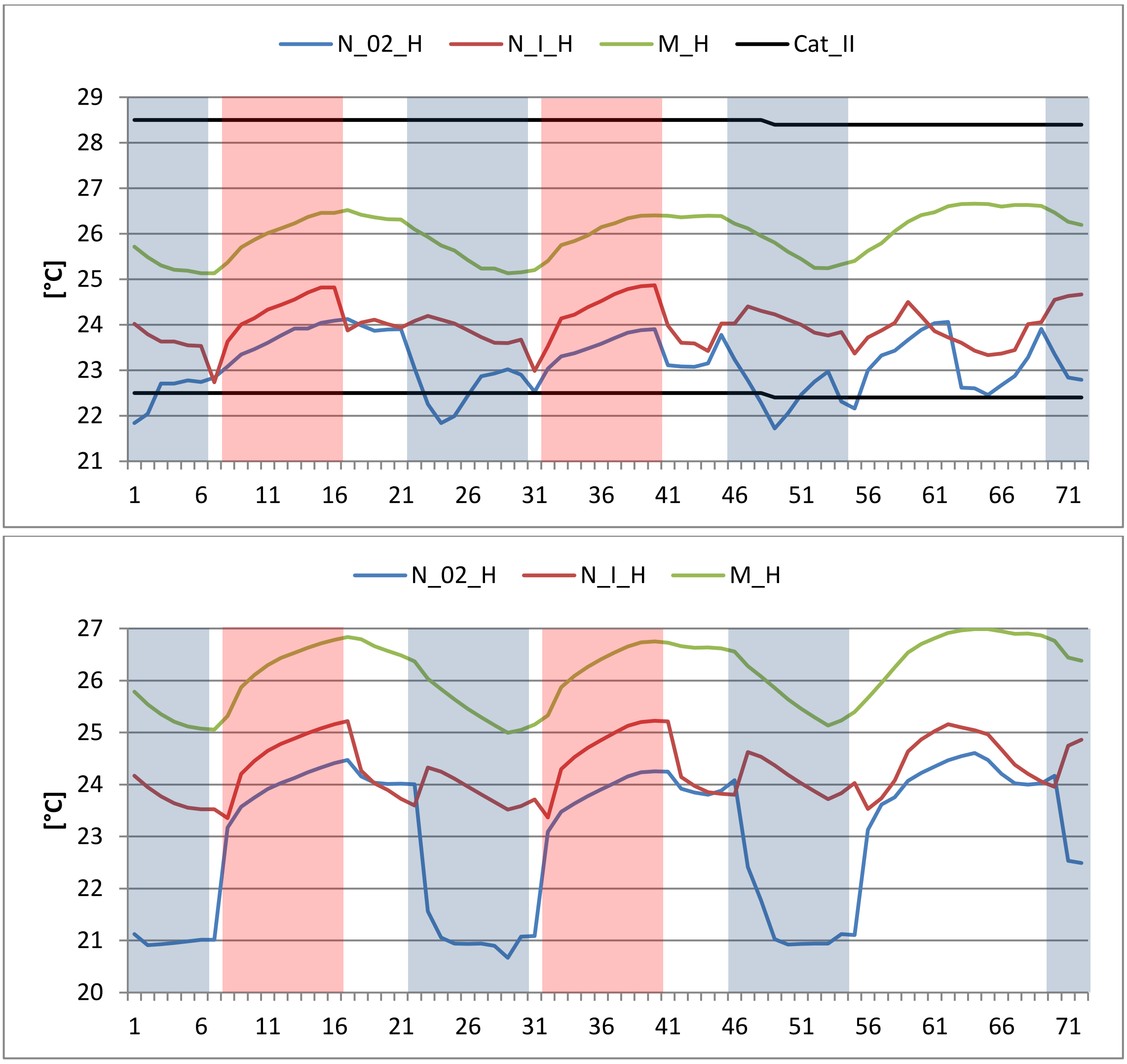


Figure 47 – Perceived operative temperature (top) and mean air temperature (bottom).

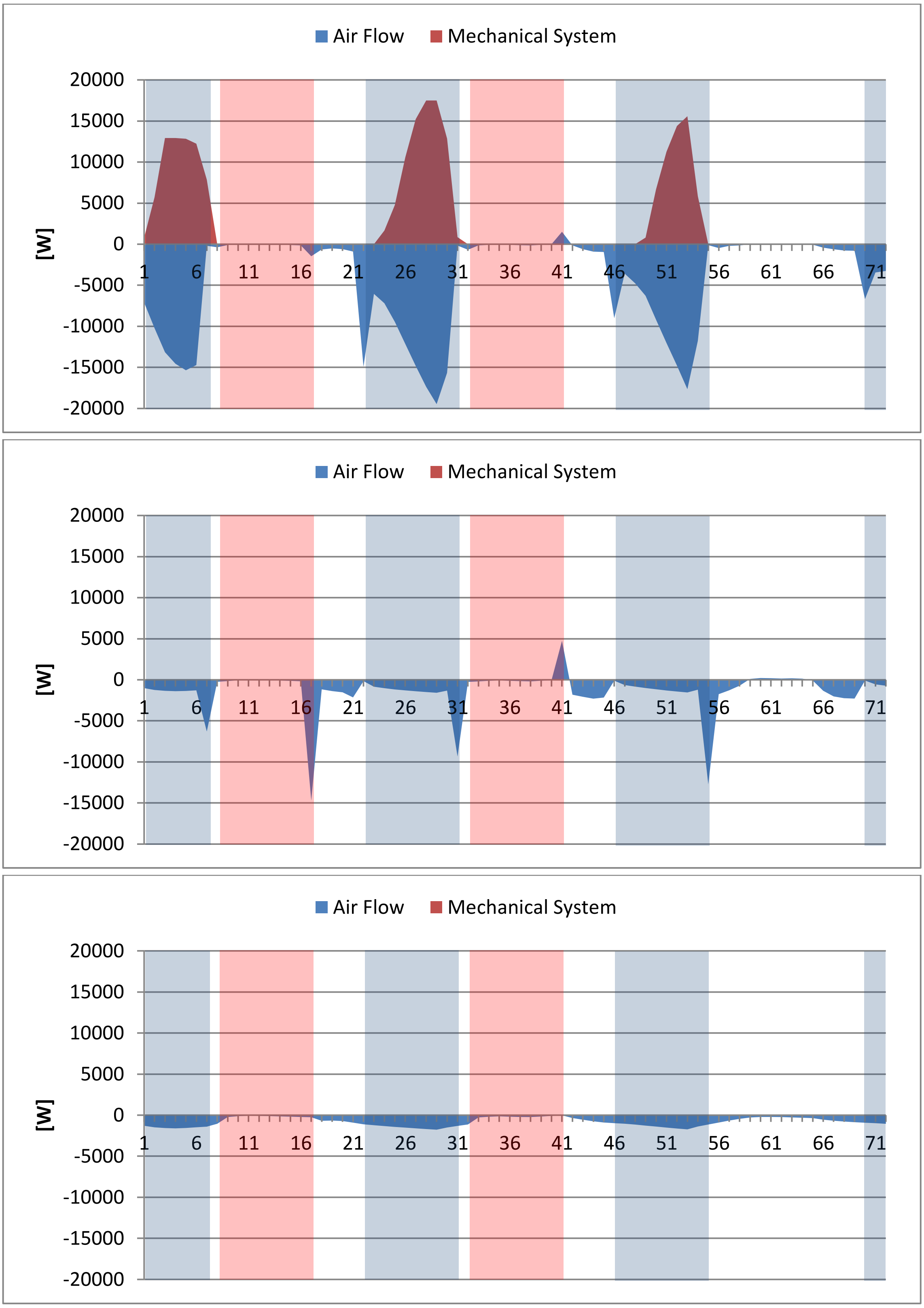


Figure 48 – Heat flux (N_02_H at the top, N_I_H in the middle and the M_H at the bottom).

A period of three days (May 31st to June 2nd) has been chosen to better explain the difference between the systems. In Figure 46 the total air flow rate (sum of mechanical, infiltration and natural), in Figure 47 the perceived operative temperature and the mean air temperature, and in Figure 48 the heat flux of air flow and heating system are shown for the three days period. During the transition seasons the increased velocities of the N_I_H scenario are capable to maintain the indoor temperature within an acceptable range, the night cooling strategy is not necessary and thus it is not applied. On the other hand the non-increased velocities of the N_02_H scenario cause the indoor air temperature to be above the 24°C threshold when the time comes to decide whether to open the windows or not for night ventilation (22:00) and then an intensive use of night ventilation is made. But the use of the night cooling strategy in a period of the year when the outdoor temperature drops below 15°C during nighttime, leads almost immediately to undercooling, that has to be compensated for by the heating system. Such undercooling is quite evident if we look at both the perceived operative temperature, that drops below the lower limit of the comfort range prescribed by the standard EN15251 for a category II building, and at the mean air temperature, that reaches the 21°C set point of the heating system very few hours after night ventilation is applied. In this period of the year the M_H scenario provides a perceived temperature within the category II building range, nonetheless such temperature is 2.0°C higher (on average) than the one granted by the N_I_H system (the first scenario has an average perceived temperature of 26°C, the second one of 24°C), the thermal environment can then be considered less comfortable.

In general the M_H scenario presents one of the lowest energy consumption, but it is not capable to ensure a comfortable thermal environment, as we will see further on, in the warmest period of the year. If we now look to a three days period in the middle of the summer (August 7th to August 9th) it is evident how natural ventilation provides an acceptable thermal environment, even with some undercooling during night, while the mechanical one leads to very high indoor temperatures. In particular the perceived temperature in the mechanically ventilated building is always above the category II upper limit during daytime. What just stated is shown in Figure 49 (total air flow rate), Figure 50 (perceived temperature and mean air temperature) and Figure 51 (heat fluxes).

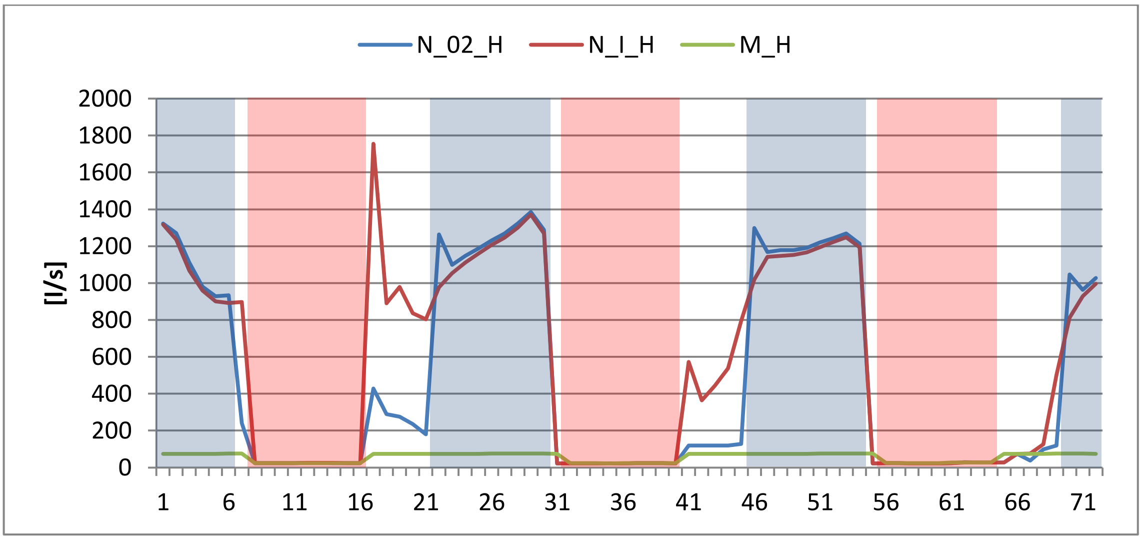


Figure 49 – Air flow rate.

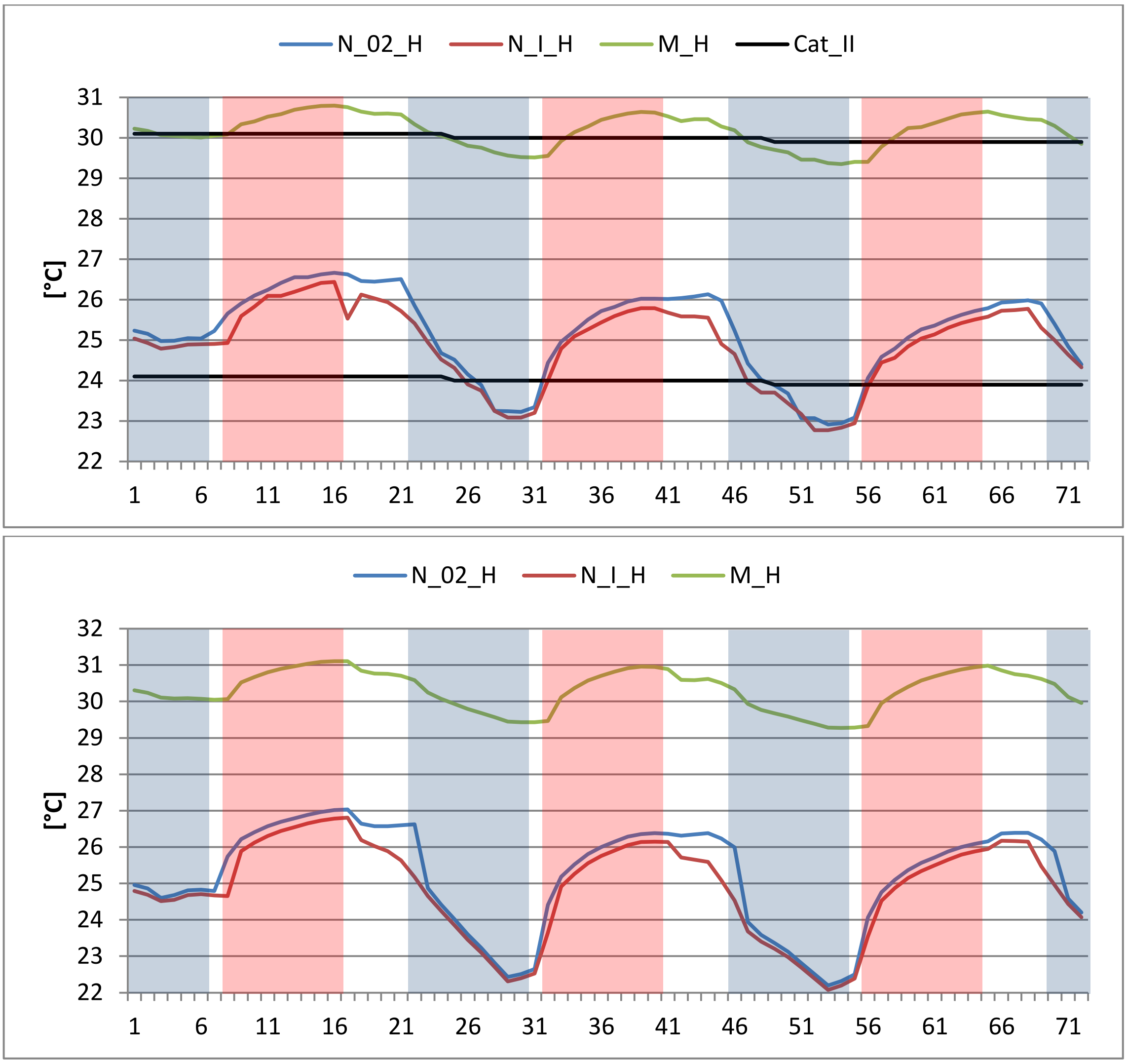
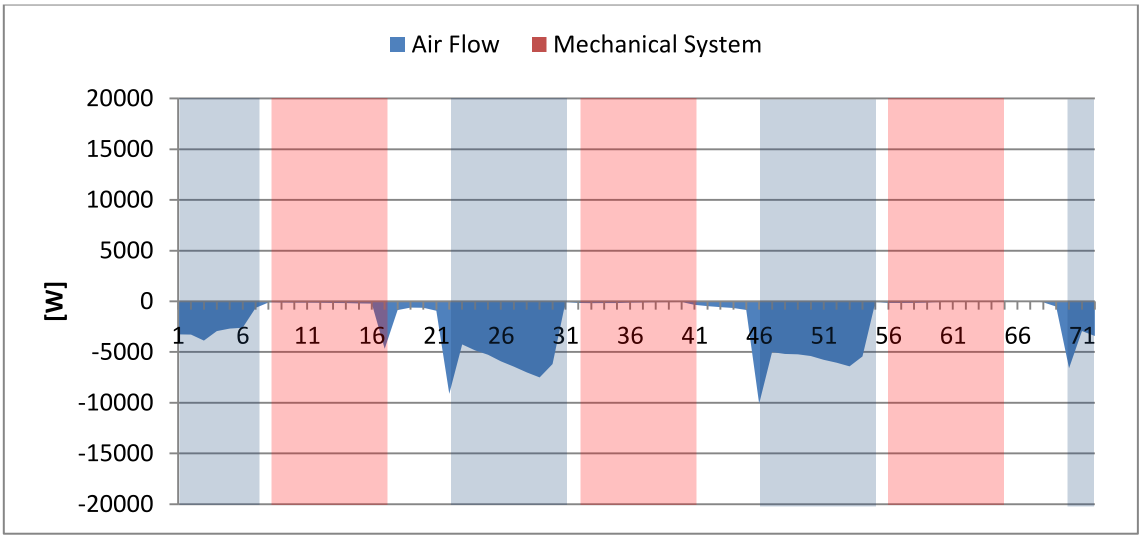
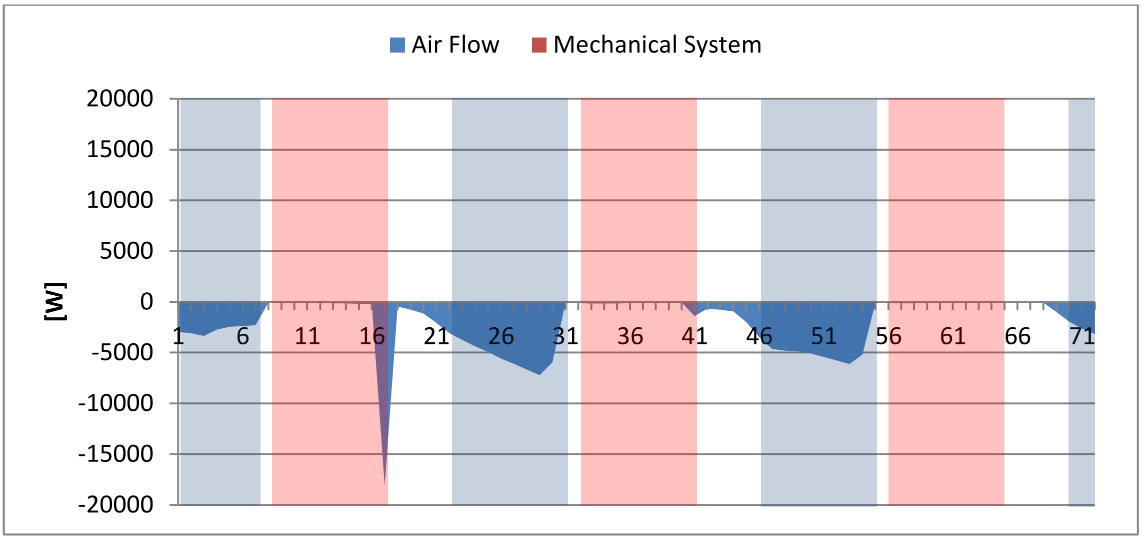


Figure 50 – Perceived operative temperature (top) and mean air temperature (bottom).





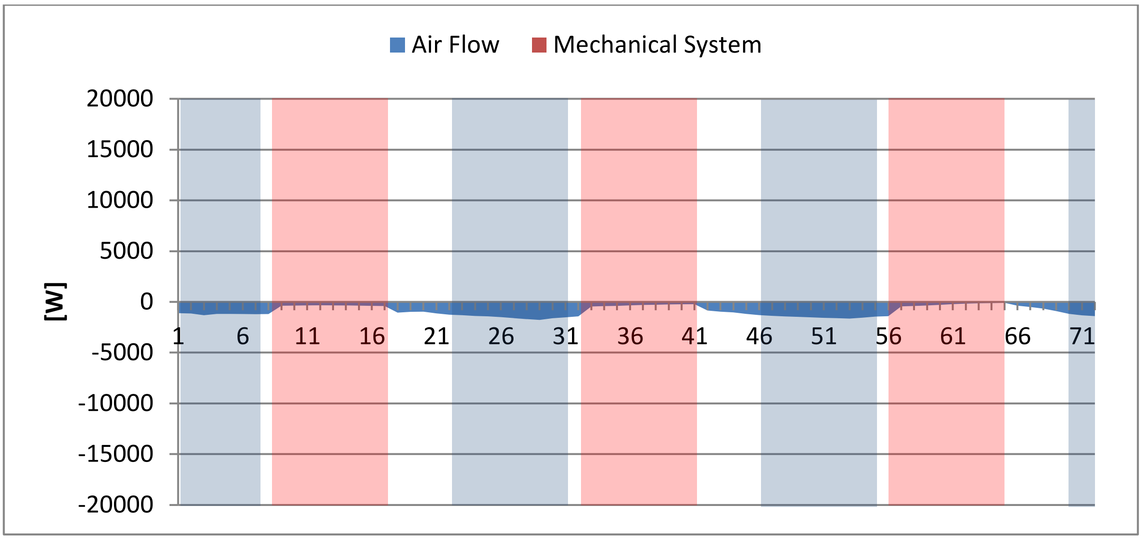


Figure 51 – Heat flux (N_02_H at the top, N_I_H in the middle and M_H at the bottom).

An effective strategy to reduce the undercooling that might occur during night is the use of an automatic control system that modulates the air that flows inside the building by adjusting the windows opening area. Such a system is the one implemented in the naturally ventilated scenarios called N_02_H_A and N_I_H_A and in the mechanically ventilated one M_HC_N_A.

When the scenario with natural ventilation and non-increased velocities is considered, the advantage that comes from the use of an automatic controller for night ventilation is significant both in terms of energy consumption and thermal comfort. As before, in the following figures the air flow rate (Figure 52), the perceived operative and mean air temperature (Figure 53) and the heat flux (Figure 54) are shown for the two solutions, with and without automatic control, for a three days period (May 31st to June 2nd).

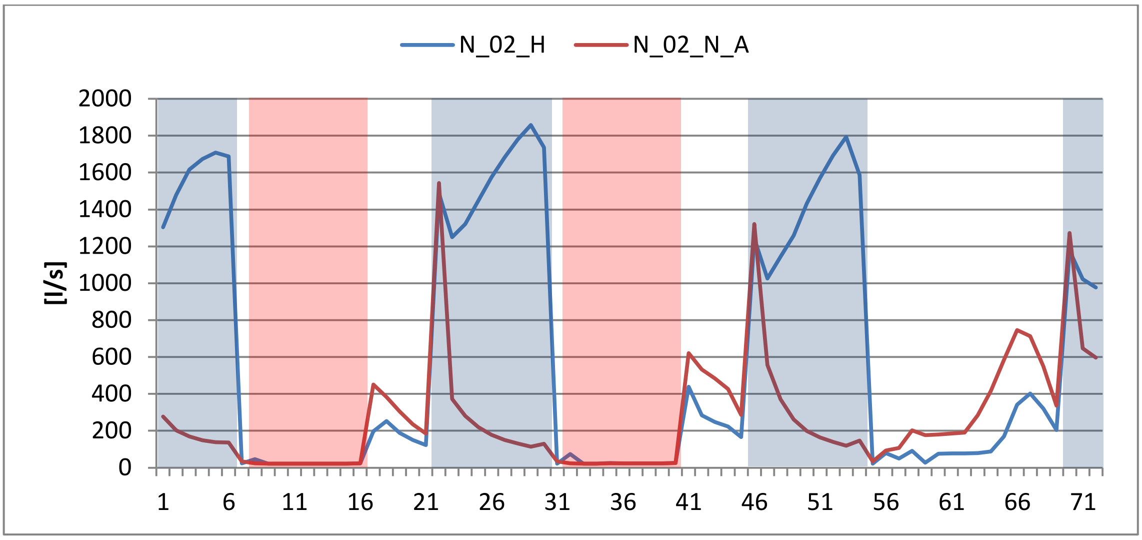


Figure 52 – Air flow rate (spring).

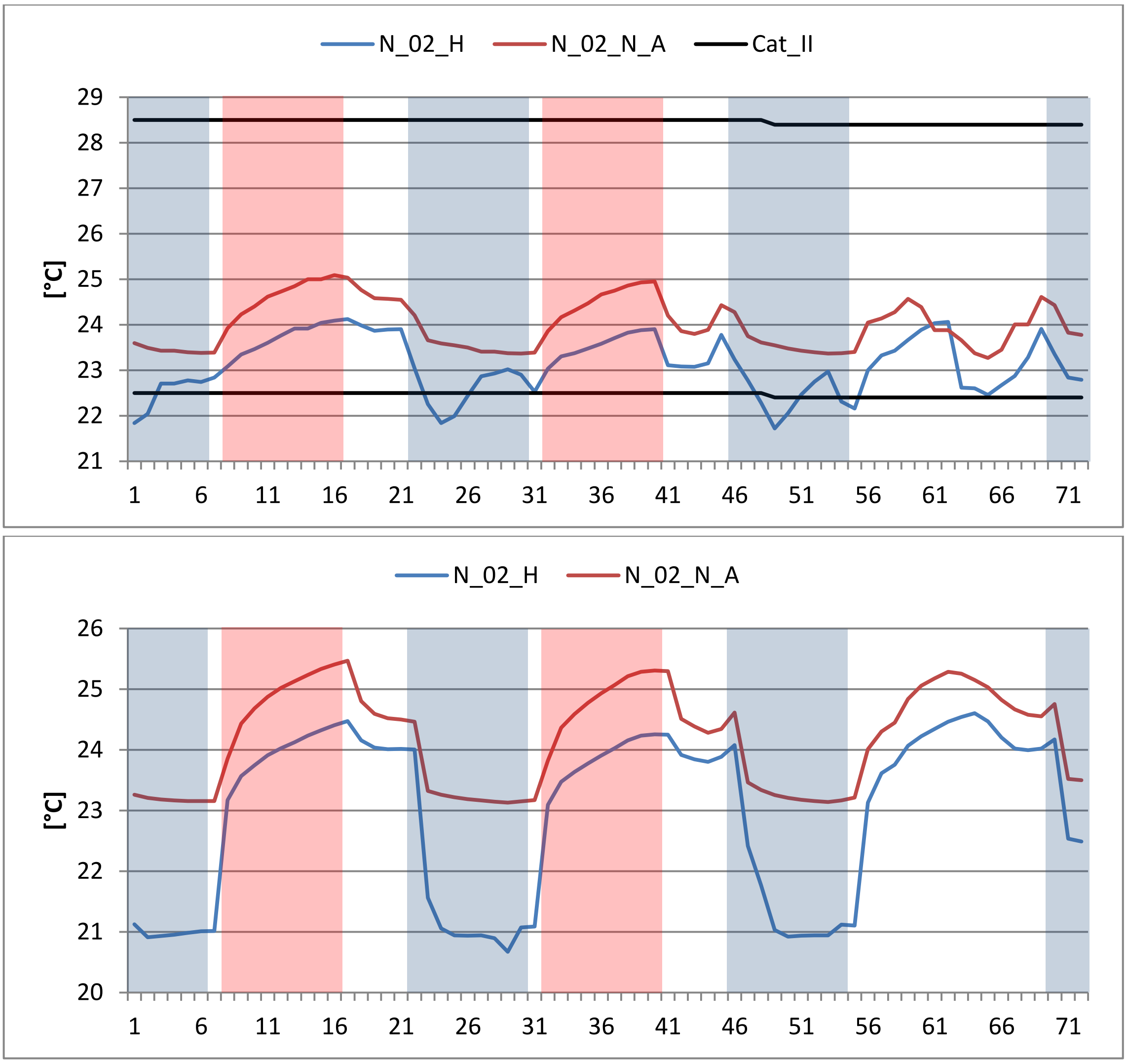


Figure 53 – Perceived operative temperature (top) and mean air temperature (bottom) (spring).

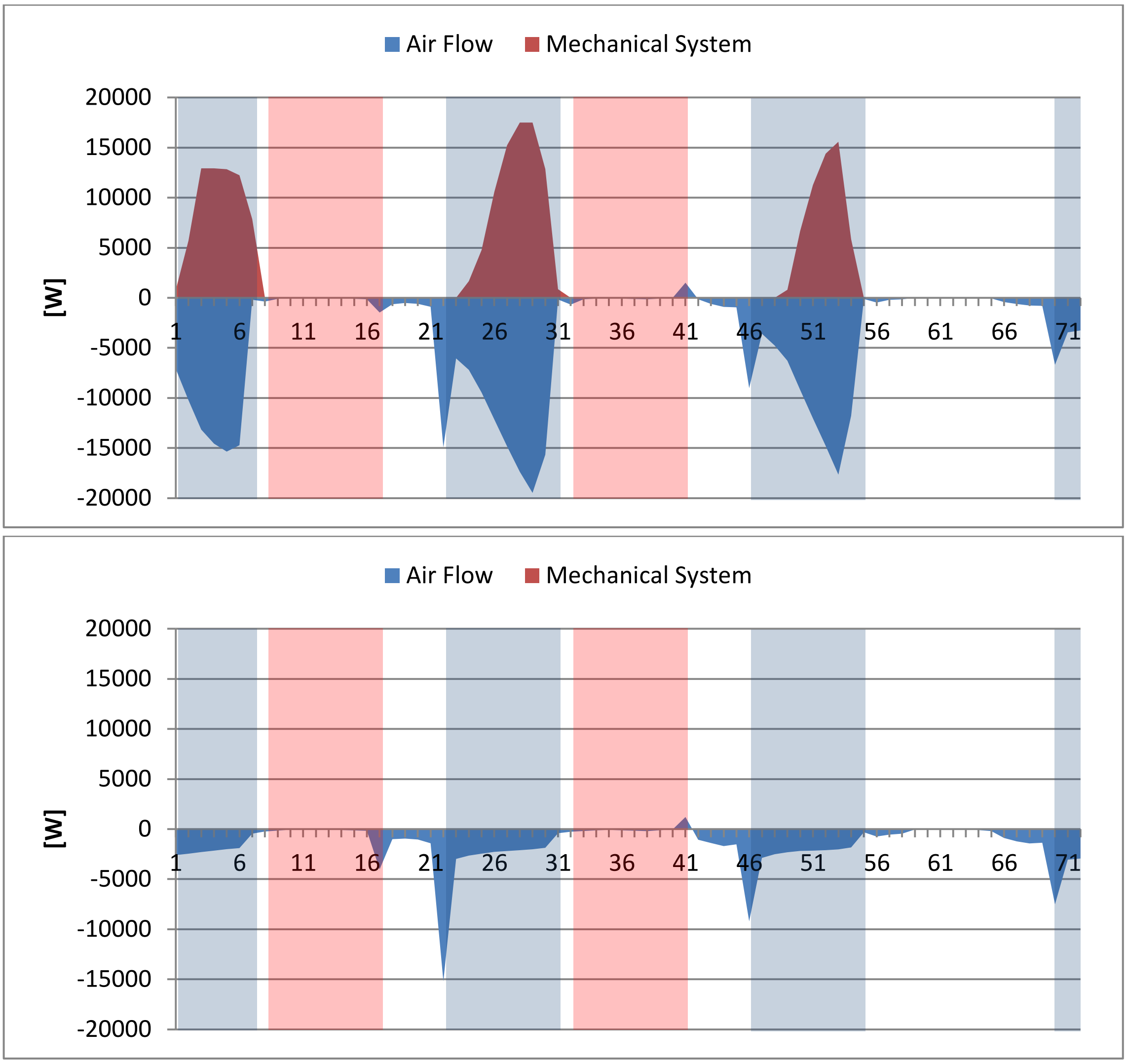


Figure 54 – Heat flux (N_02_H at the top and N_02_H_A at the bottom) (spring).

The figures above clarify how the use of an automatic control system reduces the undercooling that might occur during night in the transition seasons, increasing the thermal comfort (as we will see the percentage of time in category II increases by 9.1% introducing the automatic control) and lowering the energy consumption by 30%. As the increased air velocity, the use of an automatic controller increases the need for daytime comfort ventilation, thus creating a more even distribution of the air flow rate between day and night and, as consequence, a slightly higher IAQ. Also the use of the automatic controller does not compromise the efficiency of the ventilation strategy during summer, when the outdoor temperature is not low enough to cause undercooling and then the controller does not prevent the occupants from fully taking advantage of both night and day ventilation. In the figures below air flow rate (Figure 55), perceived operative and mean air temperature (Figure 56) and heat flux (Figure 57) are shown for the two solutions, with and without automatic control, on a three days period (August 18th to August 20th).

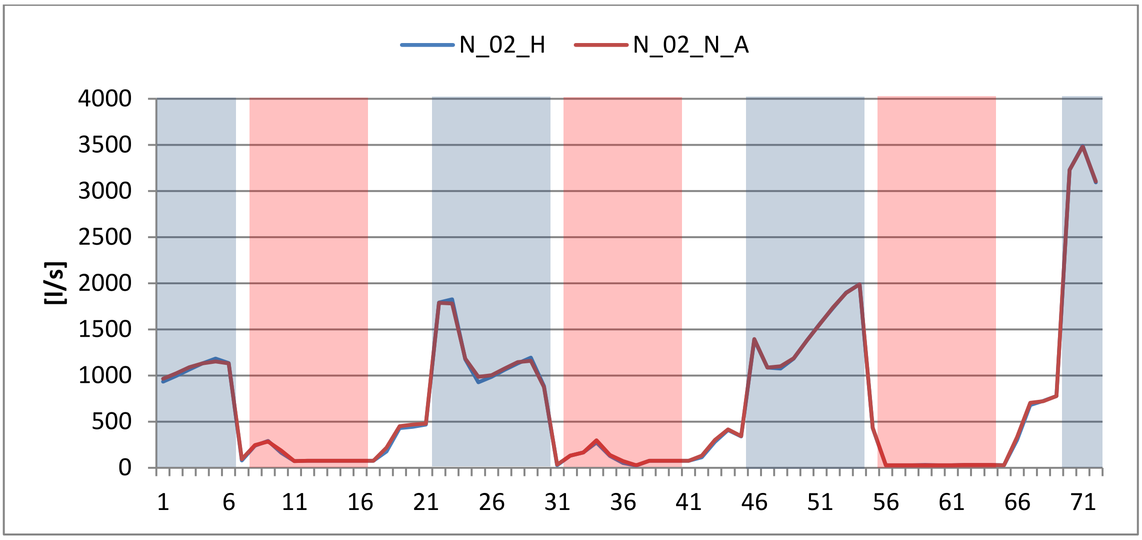


Figure 55 – Air flow rate (summer).

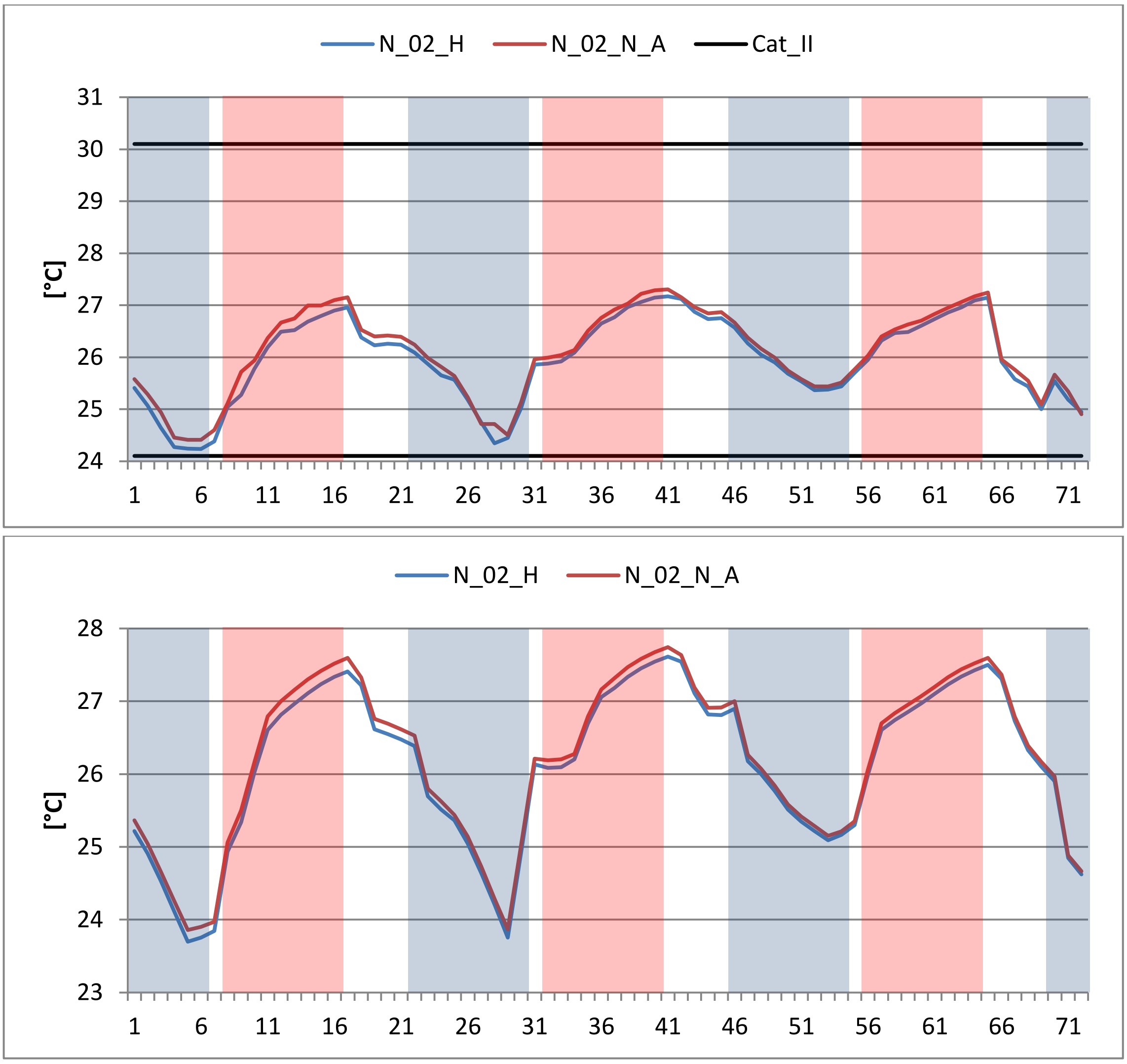


Figure 56 – Perceived operative temperature (top) and mean air temperature (bottom) (summer).

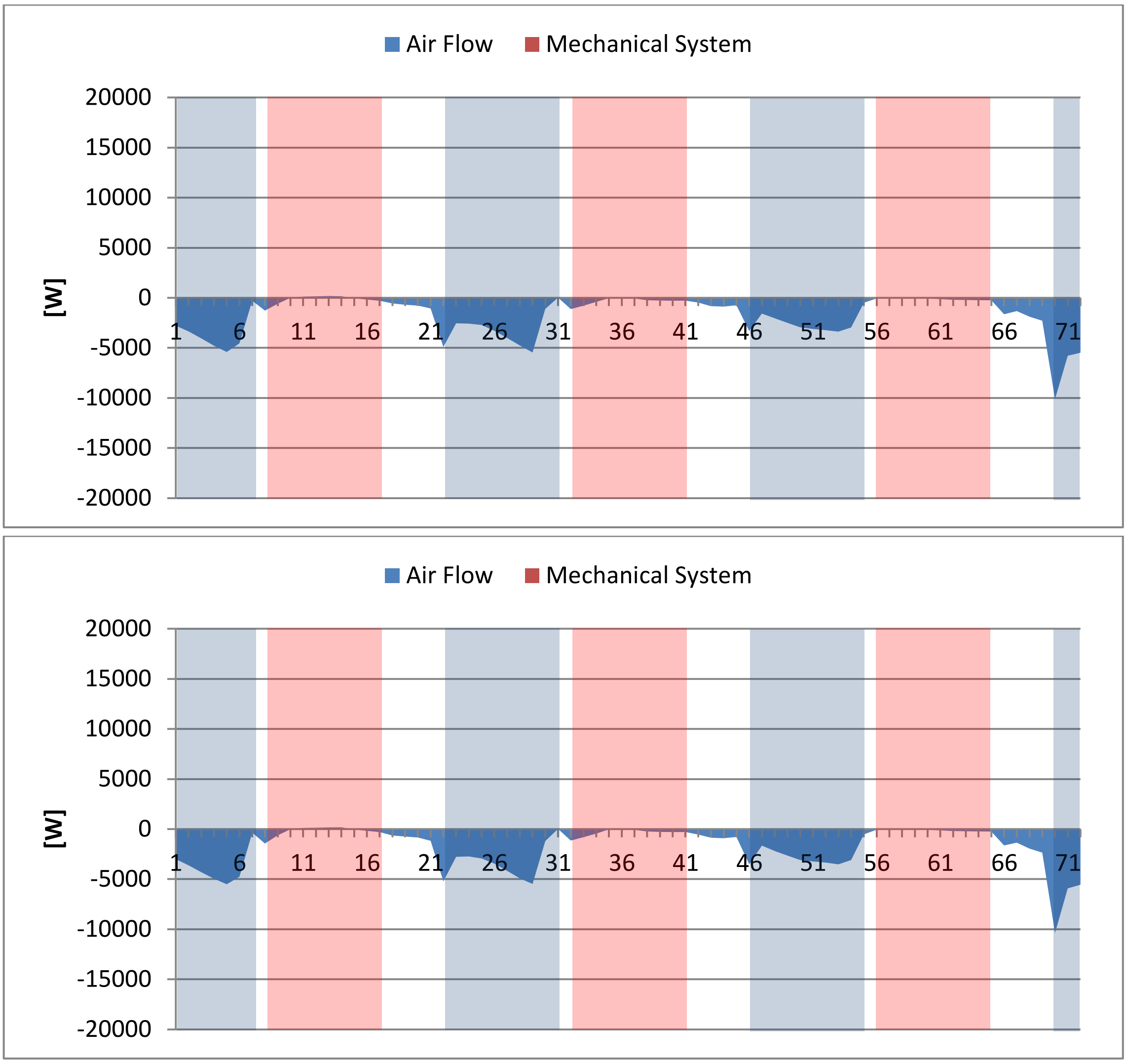


Figure 57 – Heat flux (N_02_H at the top and N_02_H_Aat the bottom) (summer).

The figures above show that during the hottest months the air flow rate, the indoor temperature and the heat flux are the same in the two scenarios.

When the automatic controller is introduced in an increased velocities scenario the improvements are not very consistent because, as mentioned before, the daytime air flow rate is already very high and capable to limit the use of night cooling to summer, when the automatic controller would not be used anyway. The following Figures (Figure 58, Figure 59 and Figure 60 for a three days period in spring (June 5th to June 7th) and Figure 61, Figure 62 and Figure 63 for a three days period in summer (August 18th to August 20th)) prove what just stated.

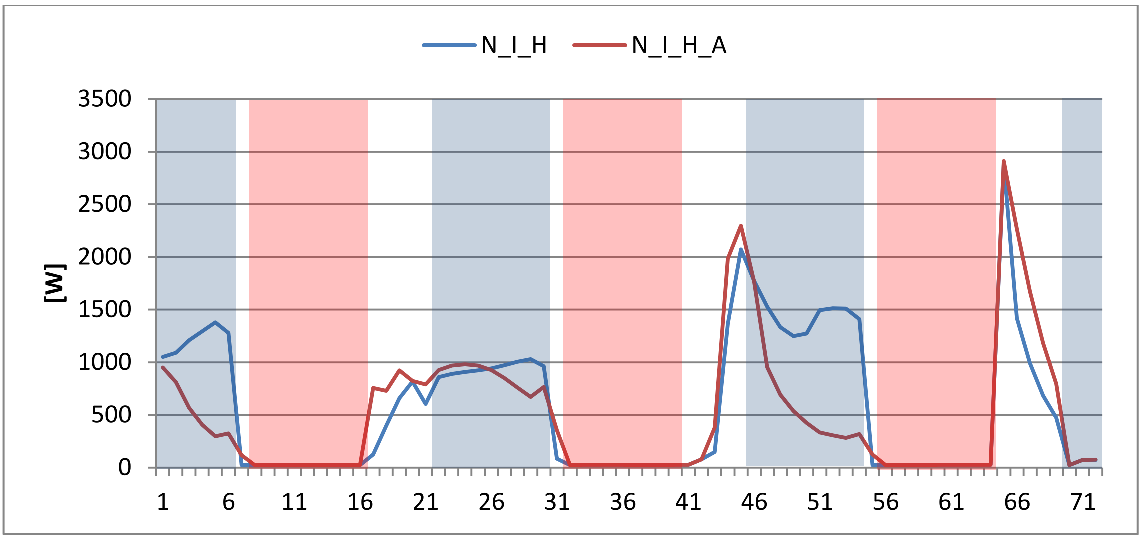


Figure 58 – Air flow rate (N_I_H and the N_I_H_A) (spring).

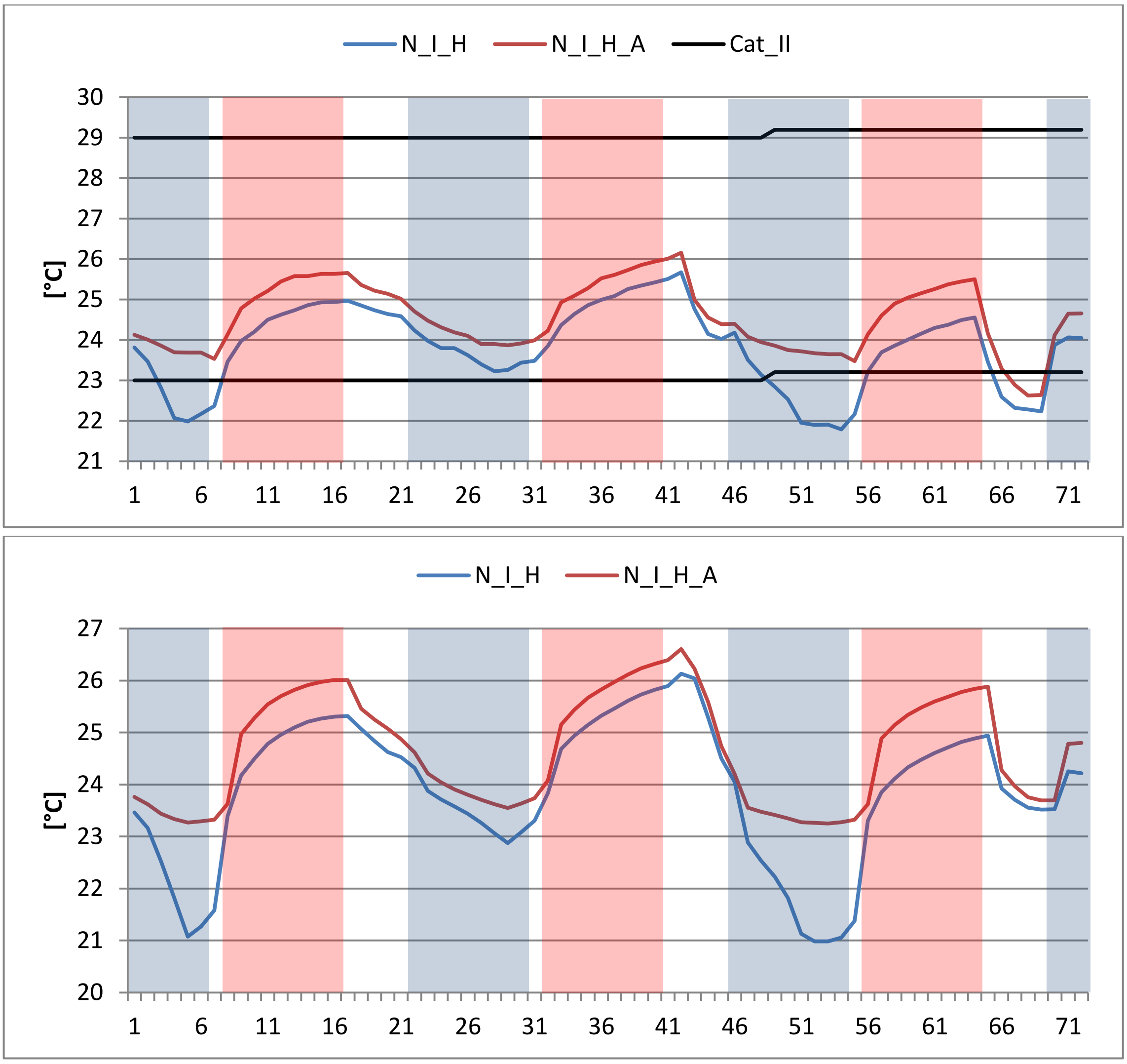


Figure 59 – Perceived operative temperature (top) and mean air temperature (bottom) (spring).

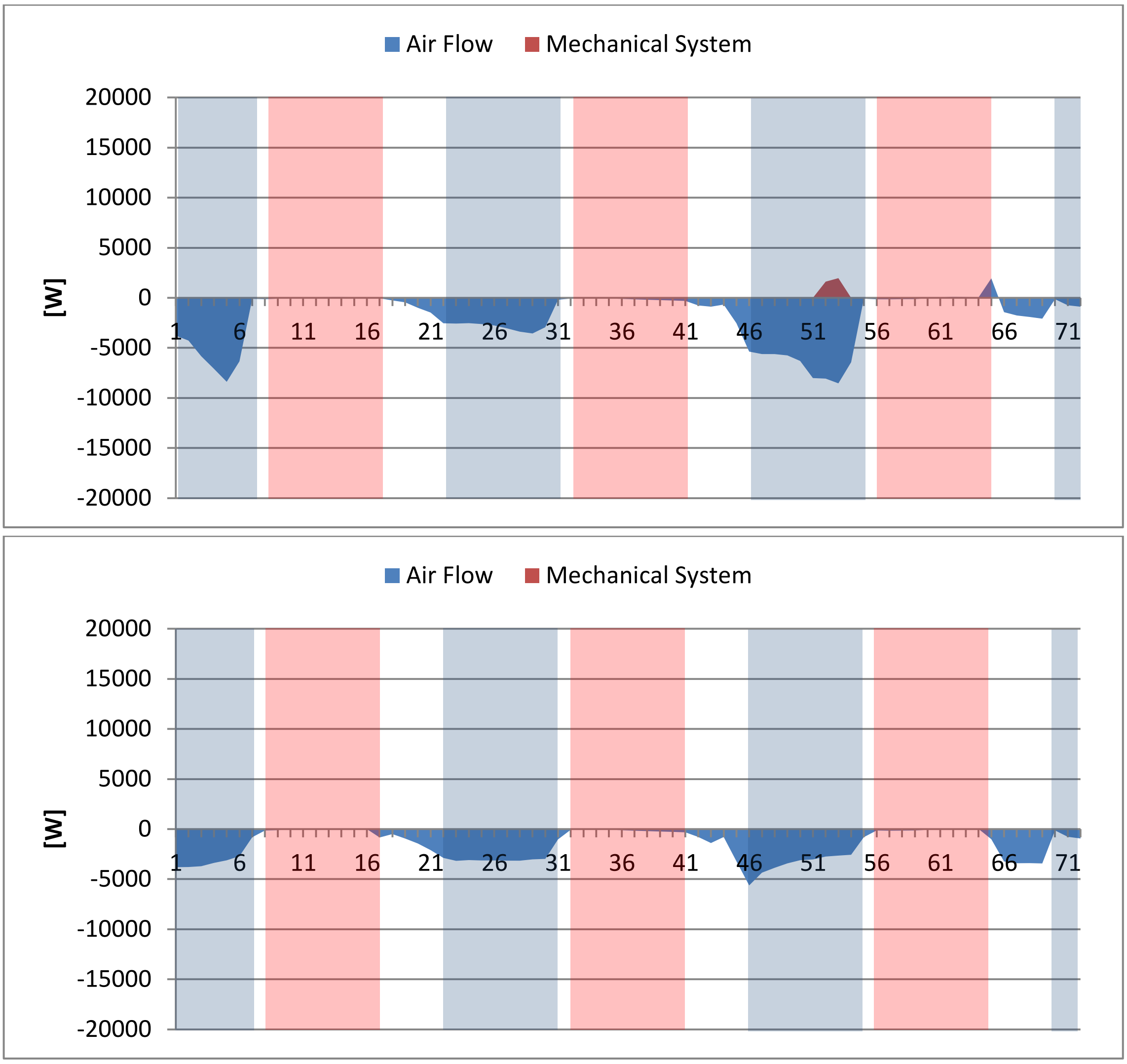


Figure 60 – Heat flux (N_I_H at the top and N_I_H_A at the bottom) (spring).

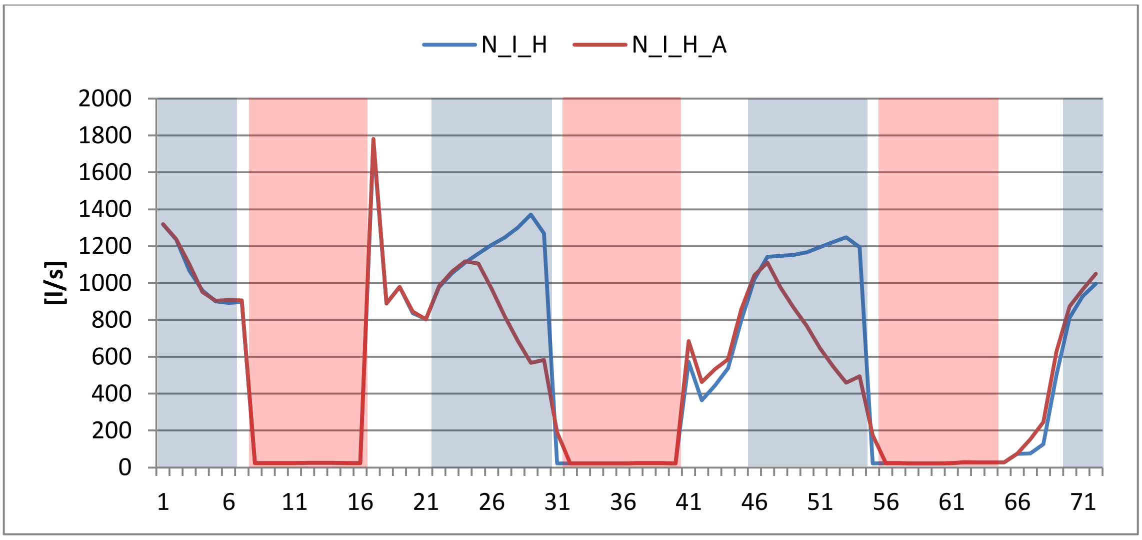


Figure 61 – Air flow rate (summer).

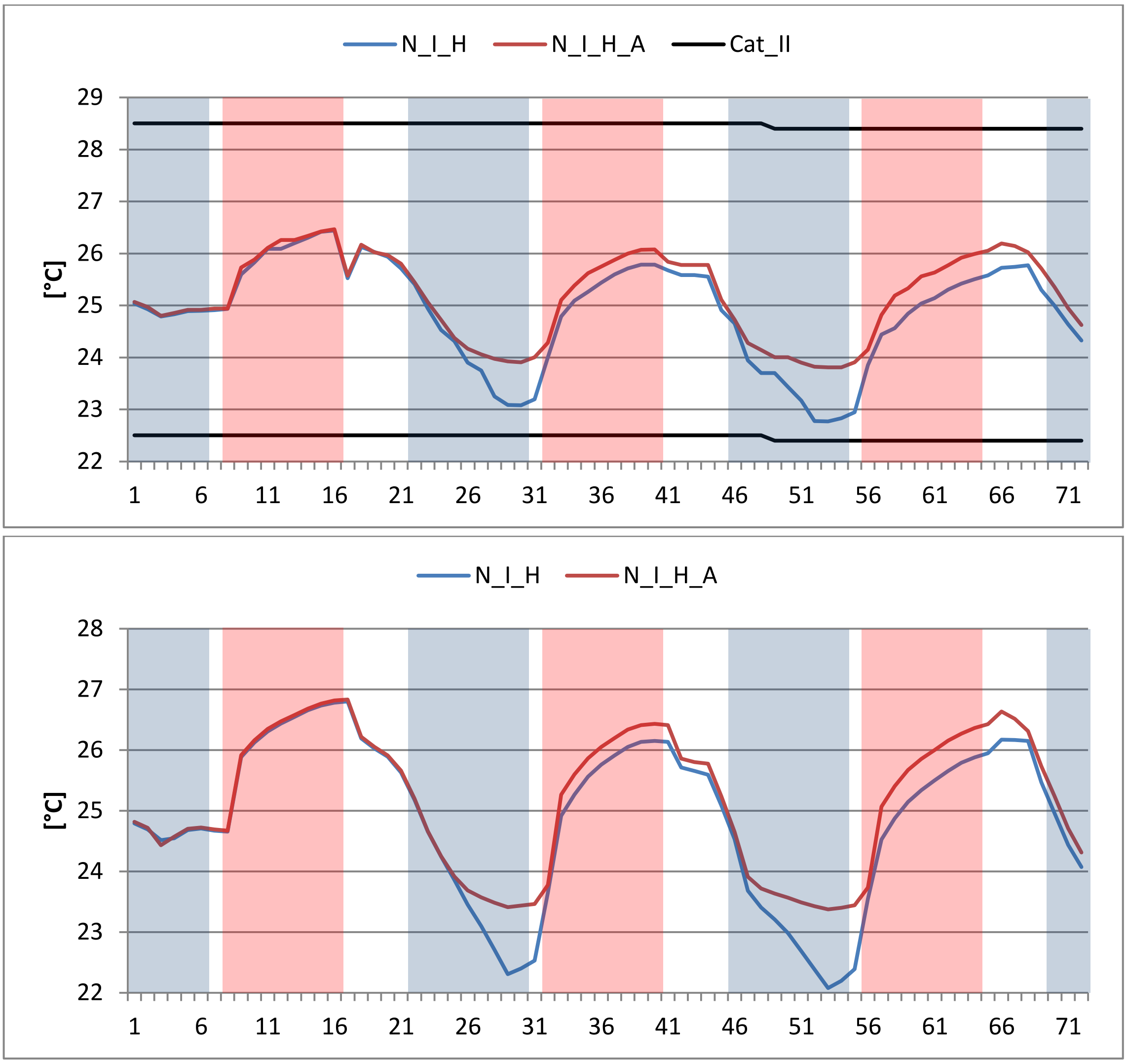
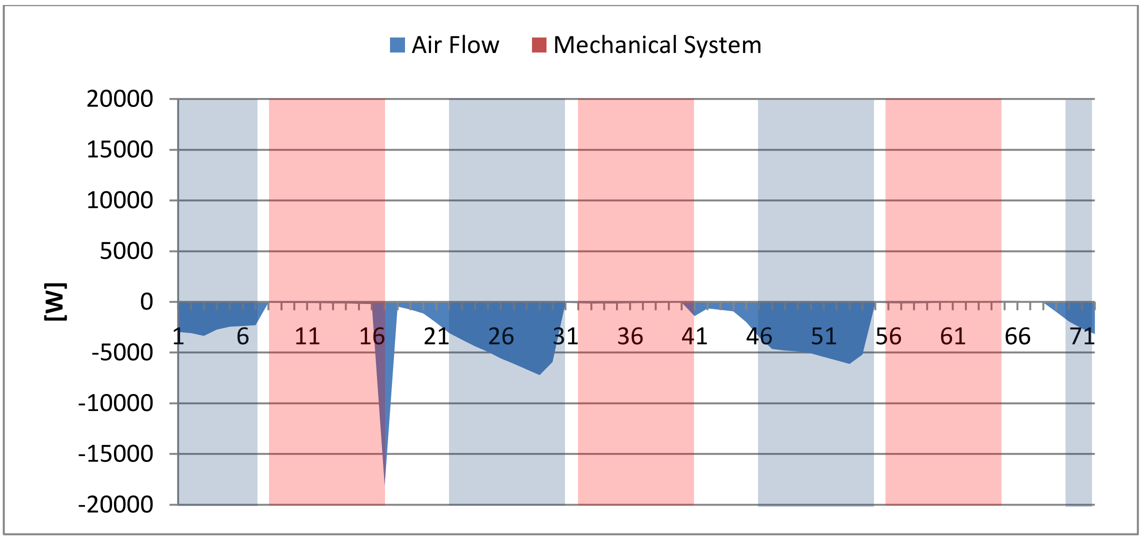


Figure 62 – Perceived operative temperature (top) and mean air temperature (bottom) (summer).



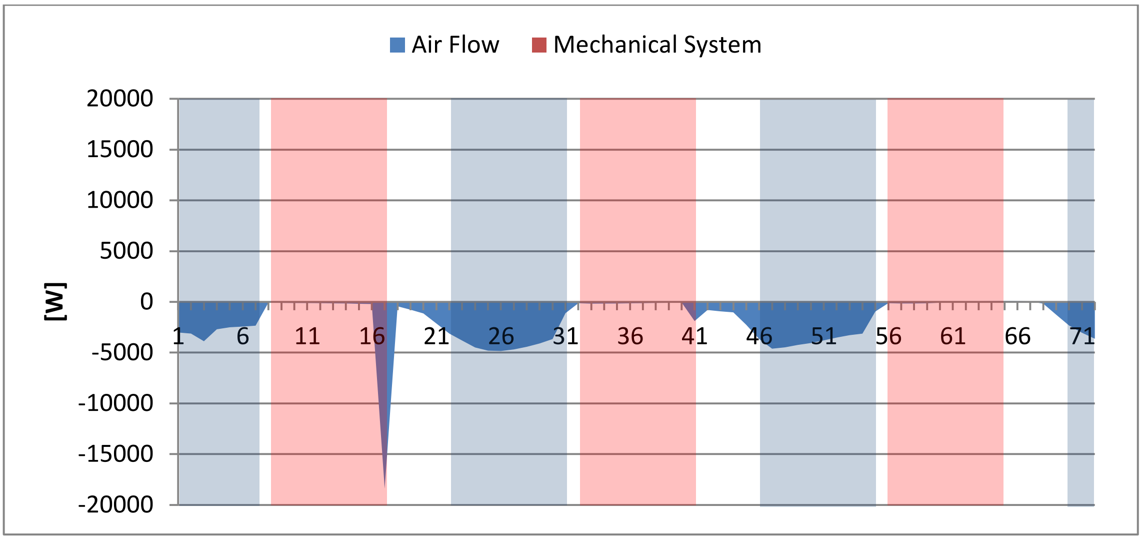


Figure 63 – Heat flux (N_I_H at the top and N_I_H_A at the bottom) (summer).

During the transition seasons the automatic controller prevents some undercooling (the percentage of time in the comfort category II is increased by 5% and the energy consumption is reduced by 0.7%). During summer there is no significant improvement.

We can then conclude that, while the use of an automatic control in the N_02_H scenario generates a ventilation and cooling strategy that is the best performing in terms of thermal comfort and energy consumption among the naturally ventilated solutions, the use of the same automatic controller in the N_I_H scenario does not modify the indoor environment in a relevant way. Thus the automatic control is desirable in the first case and not justified in the second one.

Five scenarios over ten use mechanical cooling. Those scenarios are: N_02_HC, N_I_HC, M_HC, M_HC_N and M_HC_N_A. In all five the cooling set point has been chosen equal to 24.6°C. The idea behind this choice is that an environment with such a tight control on the thermal comfort should be capable to ensure a category I building. If not, the extra energy expense is not justified since a natural ventilation strategy is already capable to grant a category II building, with, in addition, a much lower energy consumption. Indeed all the solutions with a mechanical cooling system produce a high quality environment. Basically the increase in the energy consumption corresponds to the amount of energy for cooling needs. What is interesting to investigate at this point is the effect that the night cooling, with and without automatic control, has on a fully mechanical system (mechanical ventilation, cooling and heating). In the following figures a comparison between the systems M_HC (mechanical ventilation, heating and cooling), M_HC_N (mechanical ventilation, heating and cooling with night ventilation) and M_HC_N_A (mechanical ventilation, heating and cooling with automatically controlled night ventilation) has been established on a three days period (June 22nd to June 24th).

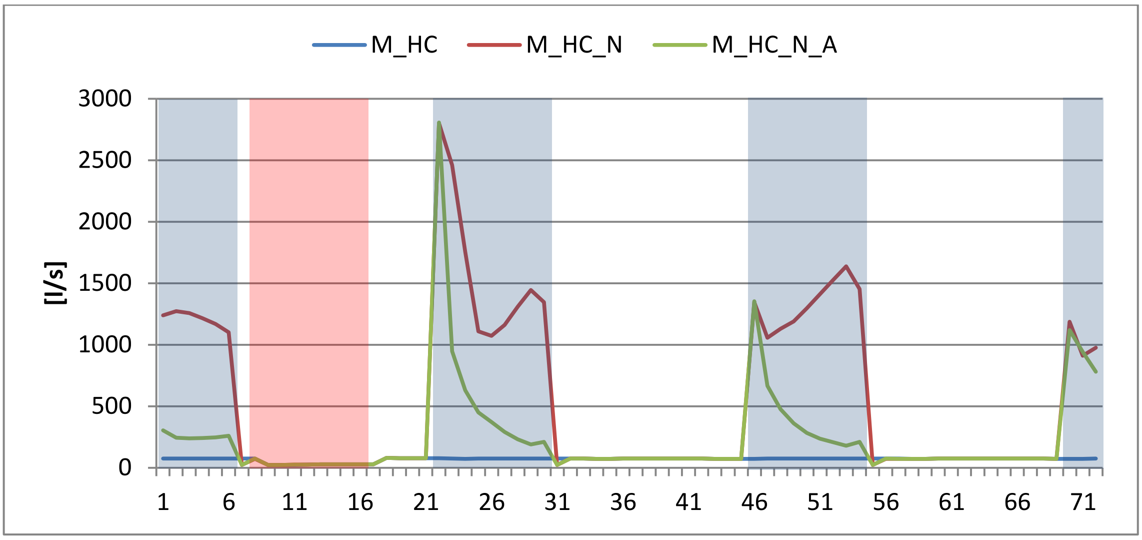


Figure 64 – Air flow rate (spring).

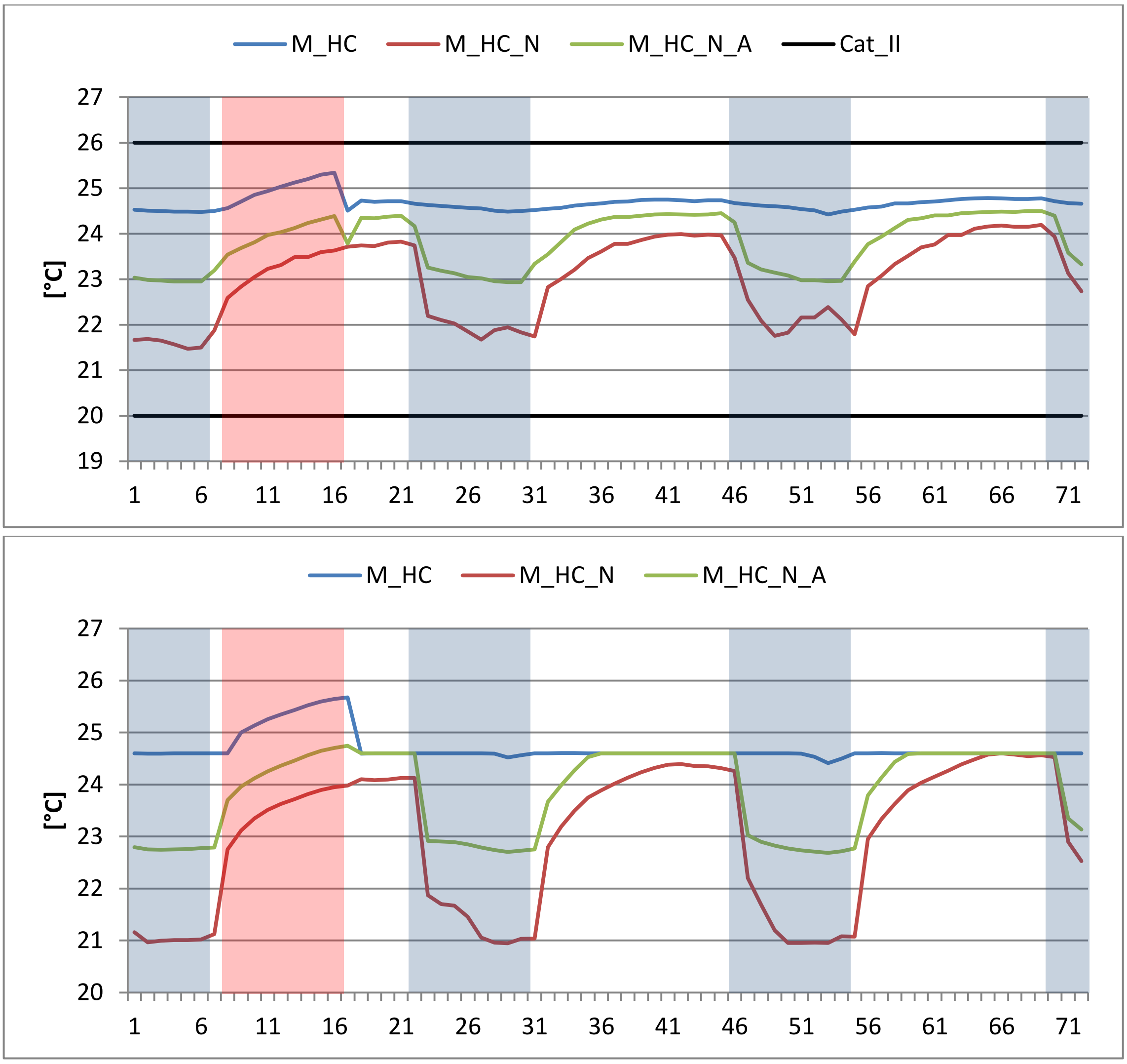


Figure 65 – Perceived operative temperature (top) and mean air temperature (bottom) (spring).

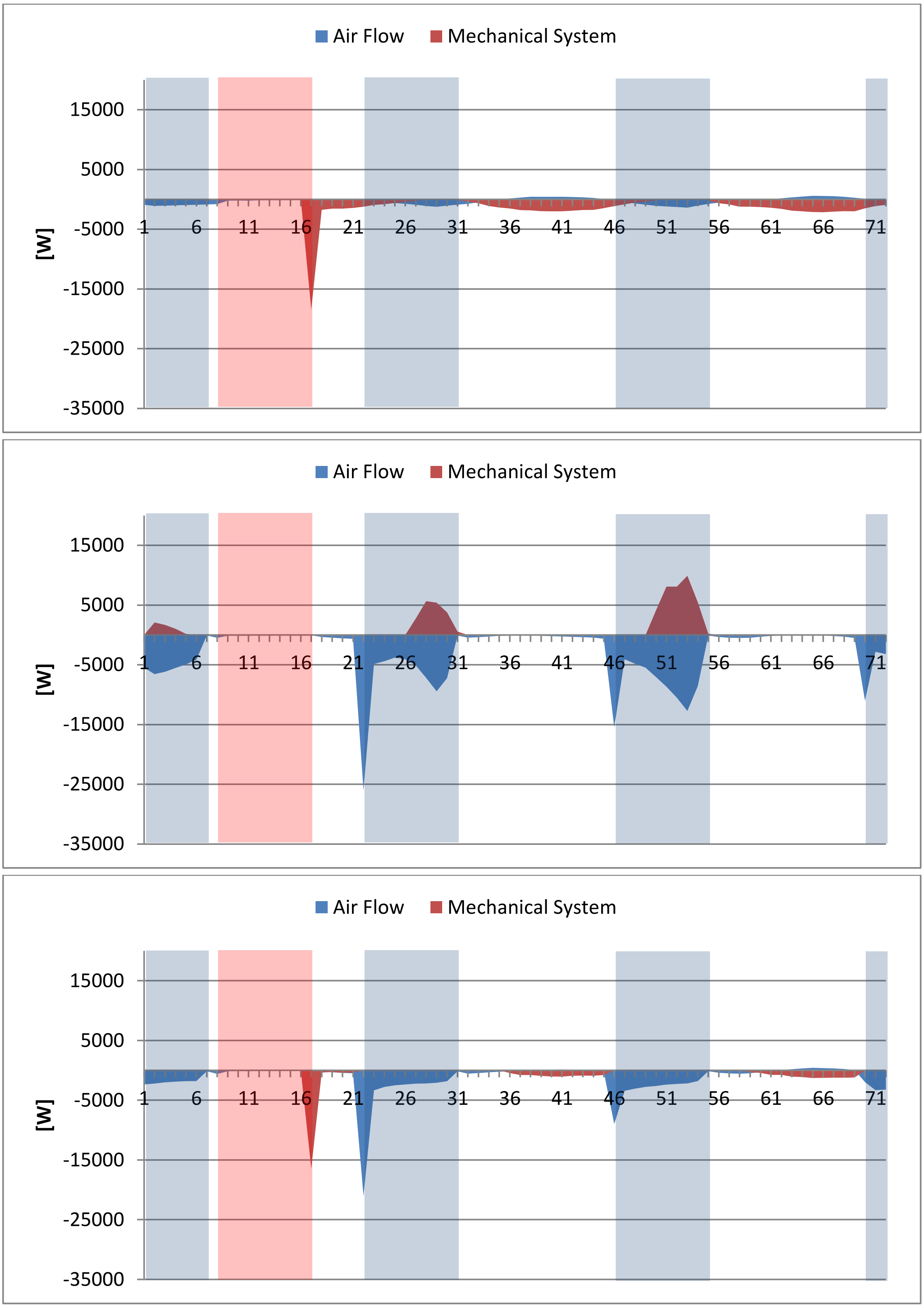


Figure 66 – Heat flux (M_HC at the top, M_HC_N in the middle and M_HC_N_A at the bottom) (spring).

In the fully mechanical system (M_HC) the thermal comfort is obtained by means of a very high energy consumption. Since such consumption is mainly (over 64%) for the cooling needs, it is reasonable to expect that the introduction of night ventilation will strongly reduce it. Indeed in the M_HC_N scenario the energy usage for cooling is decreased by over 61%, but at the same time the energy usage for heating is increased by more than 81%. This is because during the transition seasons the cooling system keeps the indoor air temperature around the 24.6°C set point. At 22:00 the night ventilation, which has a threshold of 24.0°C is activated, but there is not heat to remove from the building thermal mass, then a quite severe undercooling occurs during night and the heating system has to compensate for it. The implementation of night cooling has still a benefit from an energetic point of view: the total energy consumption is reduced by over 13%, but the temperature during night drops below 21°C and some discomfort might occur even if the category II lower limit is not reached. What allows to fully take advantage of the night ventilation potential without causing thermal discomfort is the automatically controlled system. In such configuration there is a decrease in the energy consumption for cooling equal to 48.6% with no effect on the energy consumption for heating. This results in a total decrease in the energy demand equal to 31.8%. When the comparison between the three system is made during a three days period in summer (August 29th to August 31st) it is possible to see how the benefits coming from the use of night ventilation, both in terms of thermal comfort and energy consumption, are very similar whether the automatic control is used or not. The just mentioned three days period is shown in the following figures.

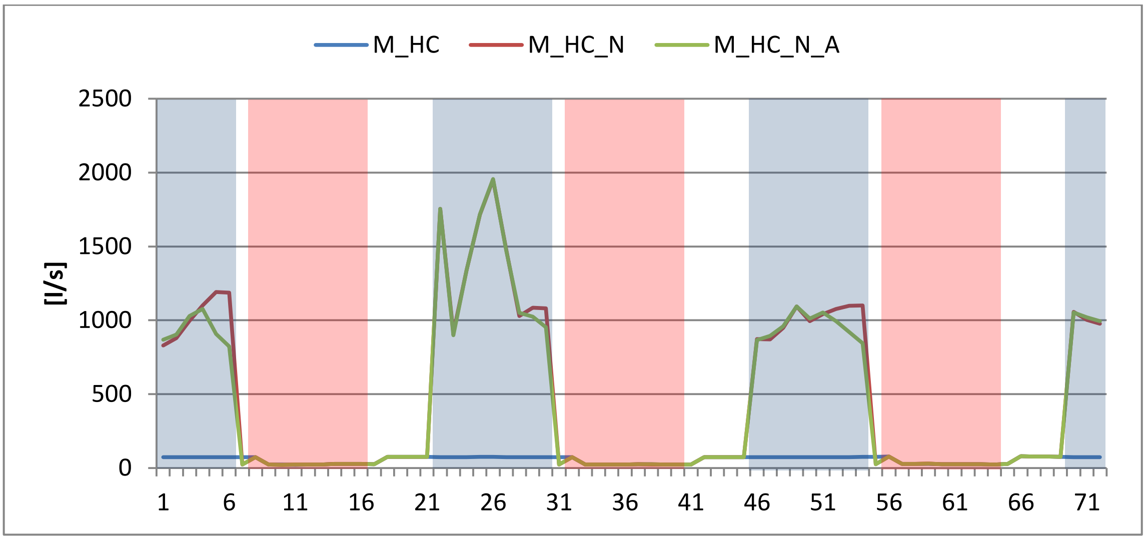


Figure 67 – Air flow rate (summer).

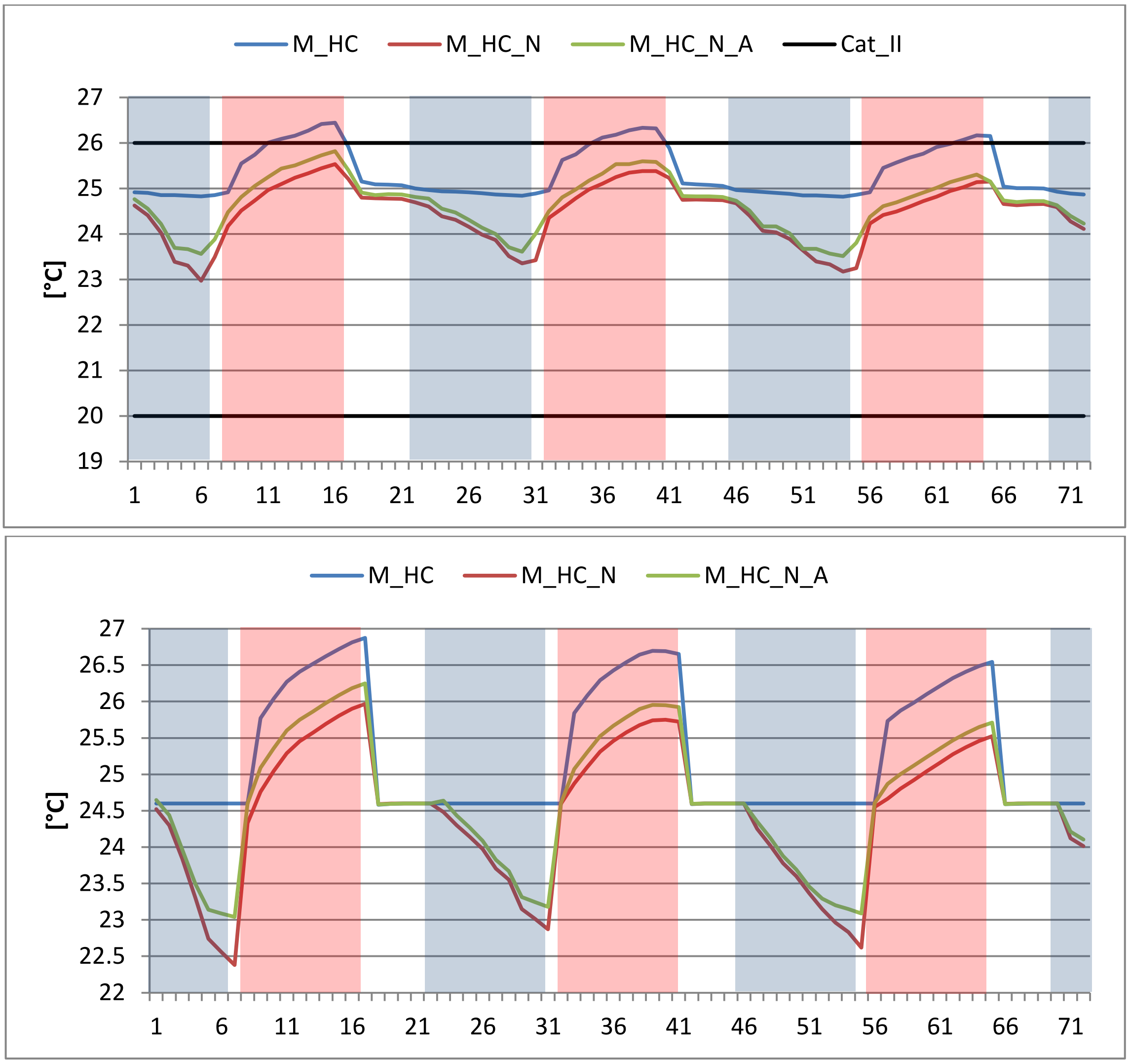
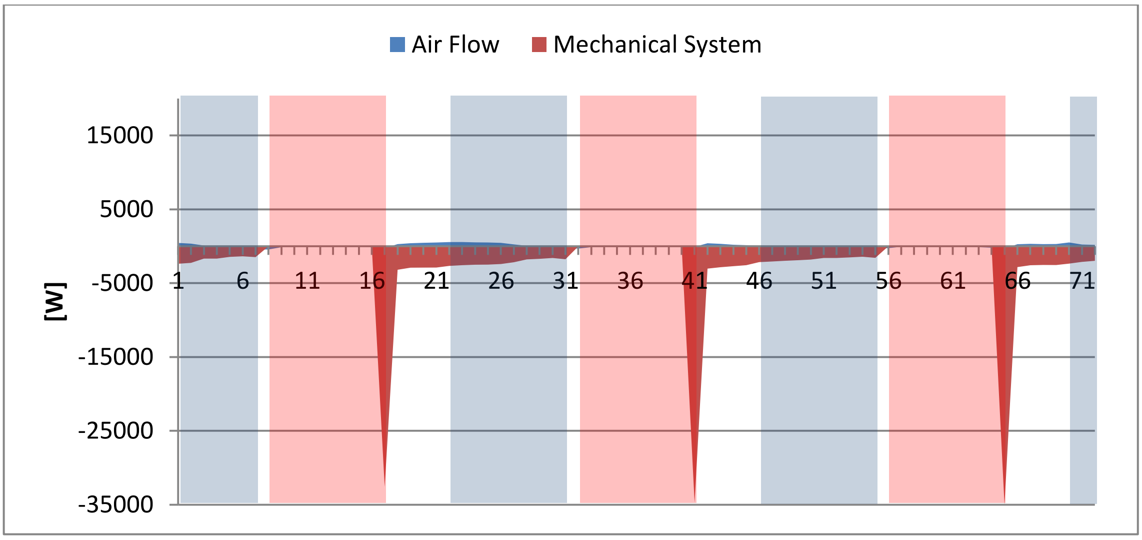


Figure 68 – Perceived operative temperature (top) and mean air temperature (bottom) (summer).



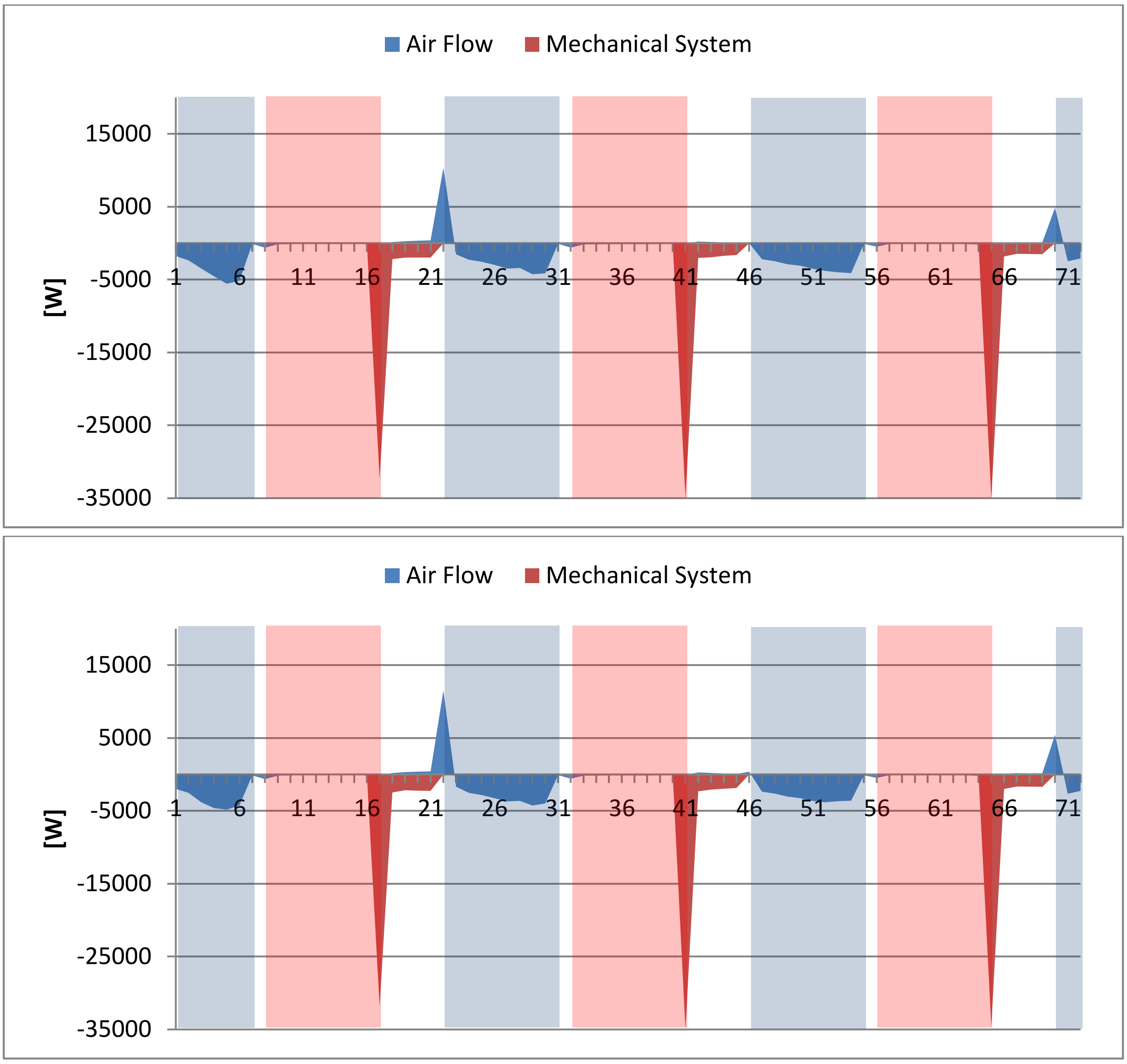


Figure 69 – Heat flux(M_HC at the top, M_HC_N in the middle and M_HC_N_A at the bottom) (summer).

It can be then recommendable not to use the night ventilation combined with a mechanical cooling system if an automatic controller is not installed to prevent undercooling during night in the transitional seasons.

5.5. Thermal Comfort

In Figure 70 and in Table 9 the percentage of time in each of the adaptive model comfort category, defined according to the EN15251, is shown for the scenarios not equipped with a mechanical cooling system.

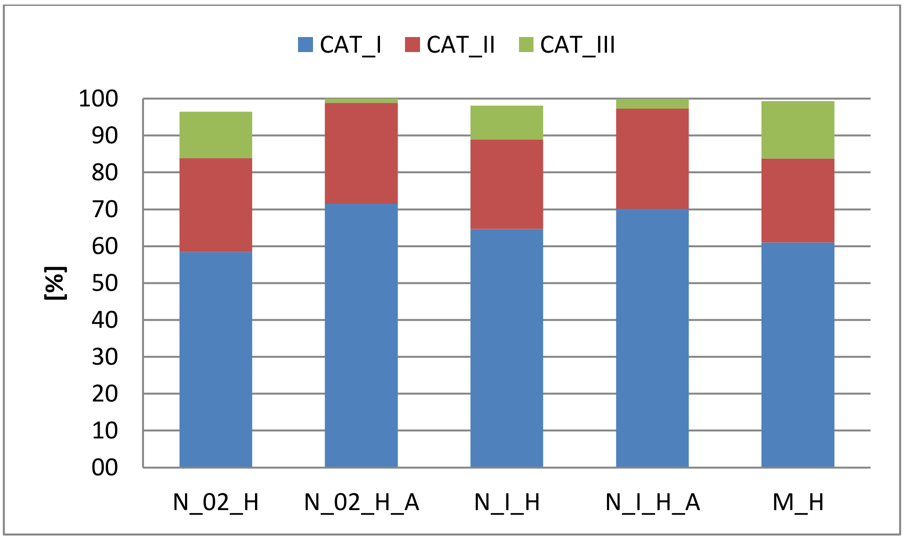


Figure 70 – Thermal comfort evaluated according to the EN15251 adaptive model for the five scenarios not equipped with a mechanical cooling system.

According to the model the only two category II buildings are the ones where the nighttime undercooling is prevented by means of an automatic control system, the N_02_H_A scenarios is in category II for 98.9% of the time and N_I_H_A for 97.3%. The other solutions, being outside category II for more than 5% of the total occupancy time (16.1% the N_02_H, 11.1% the N_I_H and 16.2% the M_H scenario) have to be considered category III buildings.

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	58.4	83.9	96.5	-15.3
N_02_H_A	71.5	98.9	100.0	-0.1
N_I_H	64.6	88.9	98.1	-10.2
N_I_H_A	70.1	97.3	99.9	-1.7
M_H	61.0	83.8	99.3	-15.4

Table 9 – Thermal comfort evaluated according to the EN15251 adaptive model for the five scenarios not equipped with a mechanical cooling system.

To better understand the percentages shown in Figure 70 it is important to distinguish between discomfort caused by undercooling and discomfort caused by overheating of the dwelling. In Figure 71 such distinction is shown.

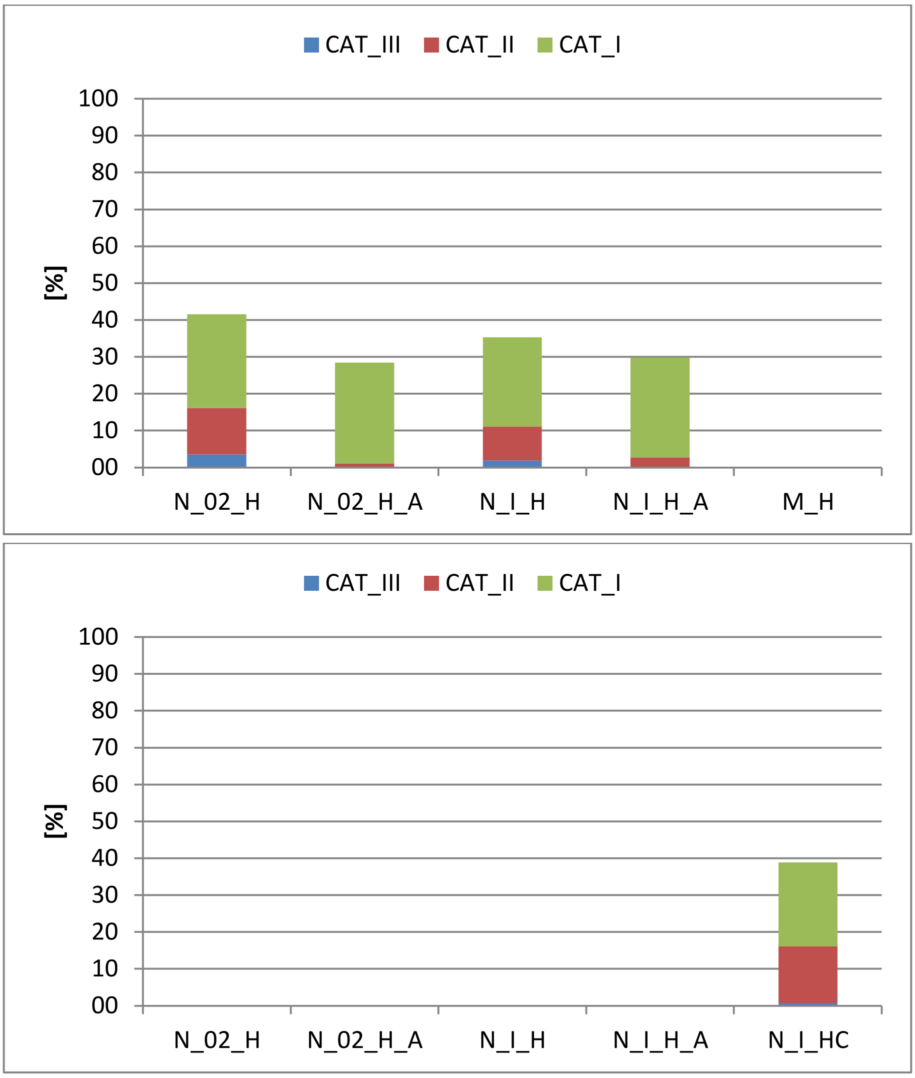


Figure 71 – Undercooling (top) and overheating (bottom) evaluated according to the EN15251 adaptive model for the five scenarios not equipped with a mechanical cooling system.

With the exception of the M_H scenario, the discomfort is caused only by the undercooling, that is mainly present during the transition seasons and it is caused by the use of night ventilation, as previously discussed. This is the reason why the introduction of an automatic controller for the night cooling strategy improves the thermal comfort. The only scenario where the overheating is the real cause of discomfort is the M_H. In this case the operative temperature rises up to 31.2°C and the absence of both a mechanical cooling system and a ventilative cooling strategy leaves the occupants without any mean to lower the temperature during the cooling season.
Figure 70 and Figure 71 give also confirmation of the more intense use of the night ventilation in the non-increase velocity scenario when compared with the increased one and shows how, as consequence, the automatic control is more effective in the N_02_H than in the N_I_H scenario (if we refer to category II the reduction in the discomfort caused by the undercooling is equal to 93.0% when the automatic control is introduced in the N_02_H scenario and to 75.6% when the automatic control is introduced in the N_I_H scenario).

The results are different if the perceived operative temperature is referred to the non-adaptive categories as it can be seen from Figure 72 and Table 10.

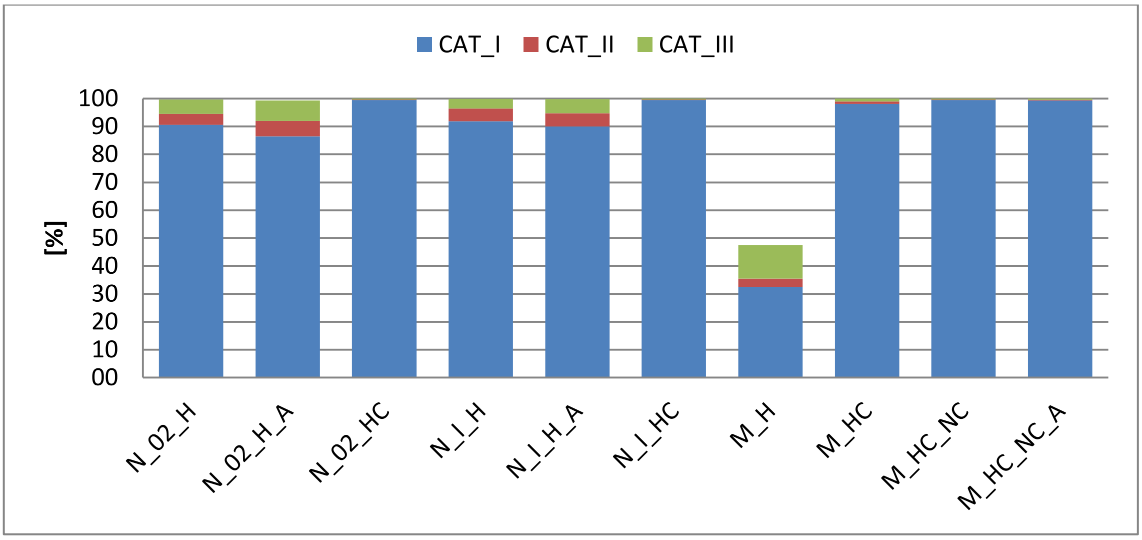


Figure 72 – Thermal comfort evaluated according to the EN15251 non-adaptive model for the ten scenarios.

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	90.6	94.6	99.7	-
N_02_H_A	86.4	92.0	99.3	-
N_02_HC	99.5	99.6	100.0	+0.6
N_I_H	91.8	96.4	99.9	-
N_I_H_A	90.1	94.8	99.8	-
N_I_HC	99.4	99.6	100.0	+0.6
M_H	32.5	35.5	47.4	-
M_HC	98.1	99.0	100.0	-
M_HC_NC	99.5	99.7	100.0	+0.7
M_HC_N_A	99.4	99.6	100.0	+0.6

Table 10 – Thermal comfort evaluated according to the EN15251 non-adaptive model for the ten scenarios.

According to the non-adaptive model the automatic control for night ventilation slightly decreases the thermal comfort inside the building. This is because in Rome, and as we will see even more in Athens, both the upper and lower limits of the comfort categories are considerably higher in the adaptive model than in the non-adaptive one, thus the automatic control causes an increase in the number of hours of overheating.

Referring to category II this increase is equal to 46.6% for the N_02_H scenario and to 46.5% for the N_I_H scenario. On the other hand no undercooling, or close to, is present even without the automatic control, thus its introduction brings no benefit at all. The graph in Figure 73 shows the distribution of undercooling and overheating: it is clear how the discomfort during the ventilation period is caused only by the overheating of the dwelling.

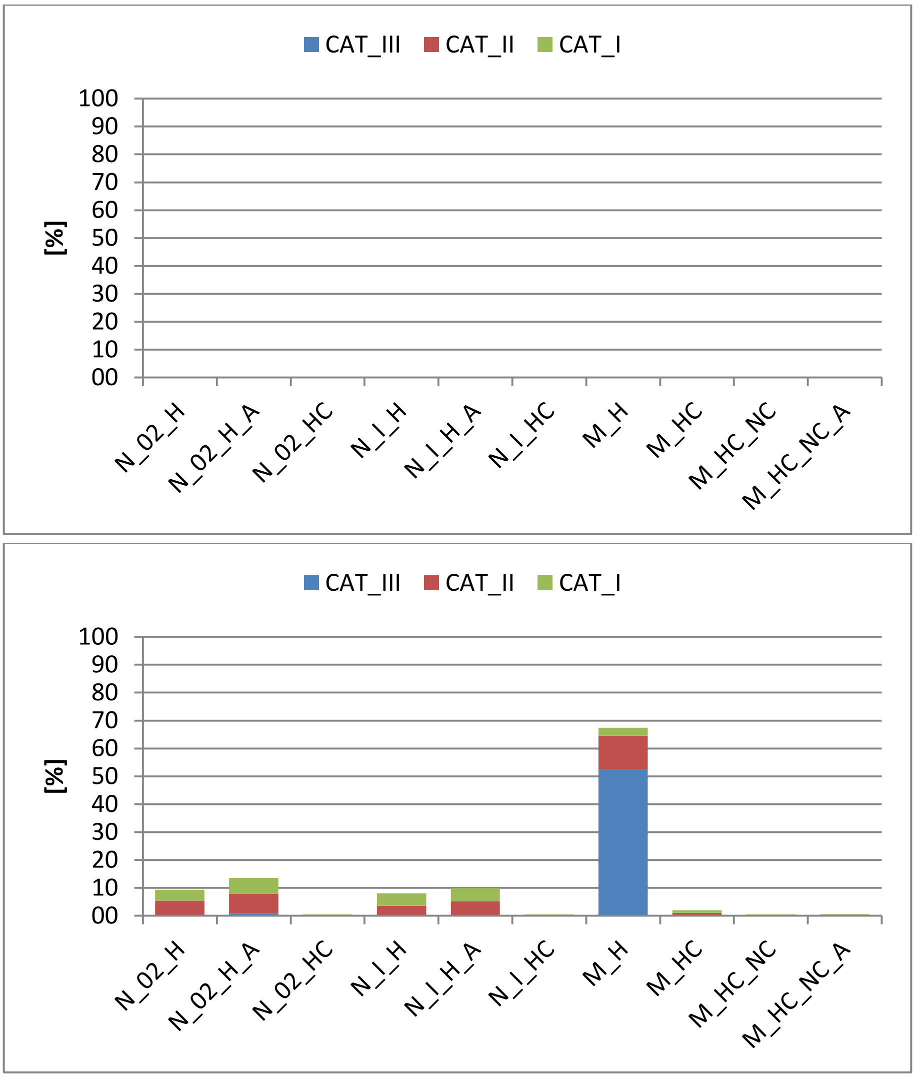


Figure 73 – Undercooling (top) and overheating (bottom) evaluated according to the EN15251 non-adaptive model for the ten scenarios.

The fact that some authors do not agree on the upper limits of the comfort categories of the adaptive model prescribed by the standard EN15251 has already been mentioned. This limits seem indeed to be very high (up to 29.1°C for category I, 30.1°C for category II and 31.1°C for category III) and whether such temperatures can be considered comfortable or not is disputable. For that reason a less relaxed adaptive model has been used to evaluate the thermal comfort. This model is the one adopted by the standard ASHRAE55. For a visual comparison between the EN15251 and the ASHRAE55 adaptive models see APPENDIX B.

In Figure 74 the evaluation of the thermal comfort according to the ASHRAE55 adaptive model is shown.

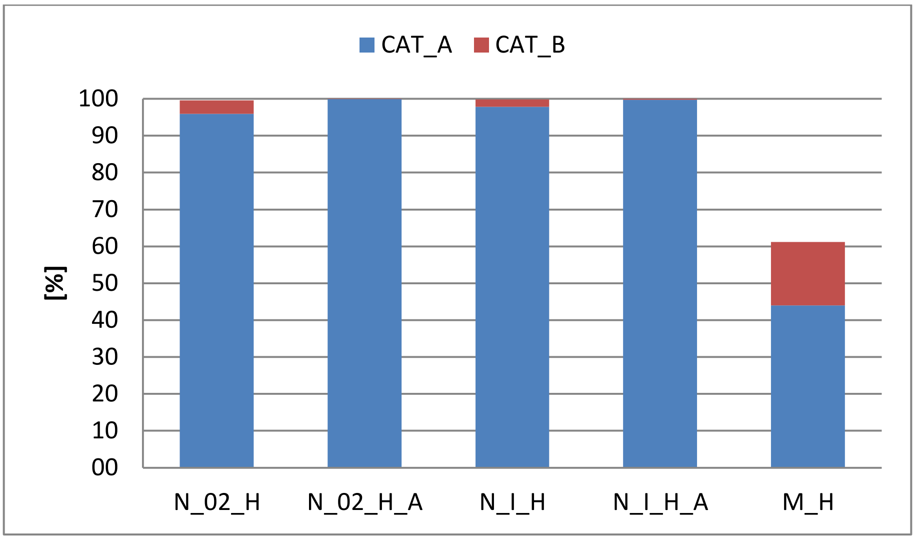


Figure 74 – Thermal comfort evaluated according to the ASHRAE55 adaptive model for the five scenarios not equipped with a mechanical cooling system.

When evaluating the thermal comfort with this new adaptive model the naturally ventilated scenarios seem to perform excellently, being capable to provide a category A building. In particular the solutions equipped with an automatic controller for the night ventilation generate an environment that is in category I for 100% of the time (or extremely close to it). On the other hand the M_H scenario presents a very uncomfortable thermal environment. In Table 11 are the percentages corresponding to Figure 74.

	CAT_A [%]	CAT_B [%]
N_02_H	95.9	99.5
N_02_H_A	100.0	100.0
N_I_H	97.8	99.8
N_I_H_A	99.8	100.0
M_H	44.0	61.2

Table 11 - Thermal comfort evaluated according to the ASHRAE55 adaptive model for the five scenarios not equipped with a mechanical cooling system.

The comparison of the results obtained with the two different adaptive models shows that the ASHRAE55 emphasizes the discomfort that can be originated by the summer overheating and thus prescribes more restrictive upper limits, while the EN15251 seems to rely more on the adaptation capacities of the occupants. This results clear if the discomfort caused by the undercooling is analyzed separately from the discomfort caused by the overheating (Figure 75). Undercooling is negligible in all the solution and is not present in the M_H scenario, where, on the other hand, the overheating is quite relevant, compromising thermal comfort for 39% of the occupancy time when we refer to category B and 56% of the occupancy time when we refer to category A.

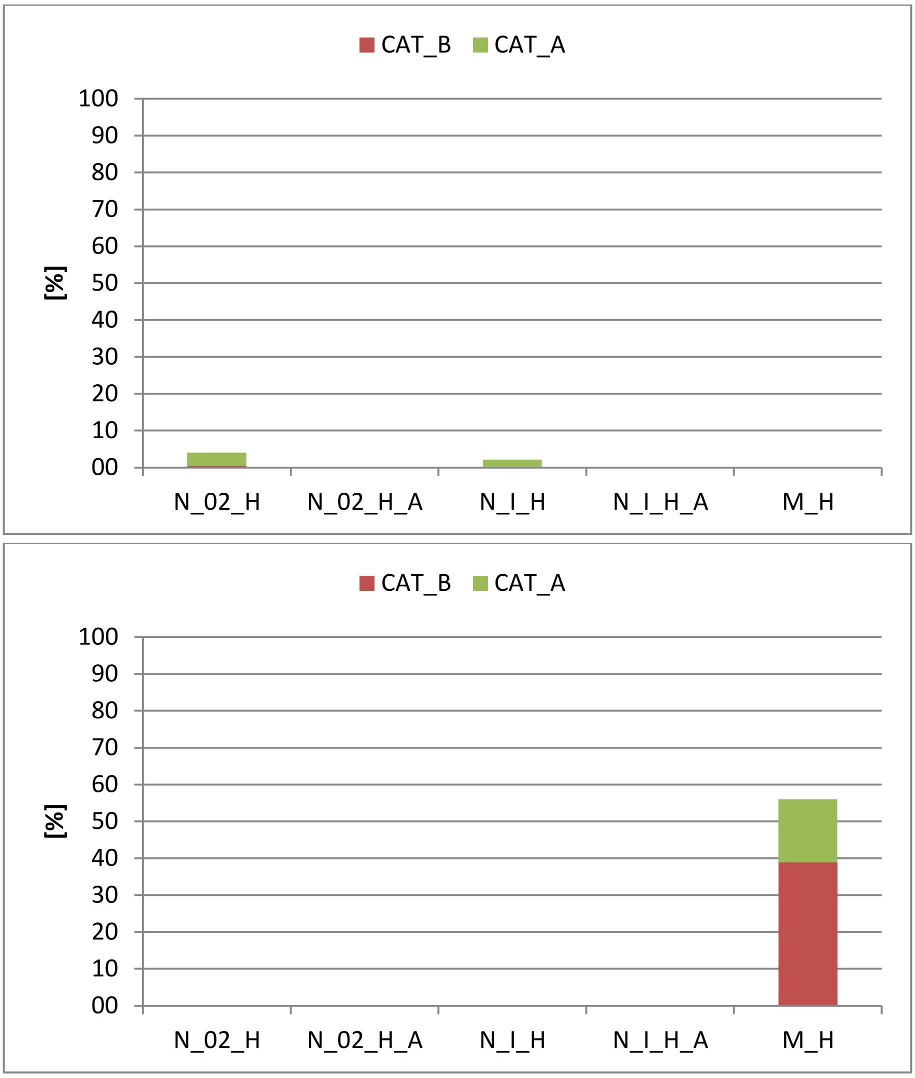


Figure 75 – Undercooling (top) and overheating (bottom) evaluated according to the ASHRAE55 adaptive model for the five scenarios not equipped with a mechanical cooling system.

Figure 76 illustrates the individual signature for the analyzed ventilation and cooling solutions. Although most of the buildings provide satisfying thermal comfort and a very good air quality, only two solutions achieve the trade-off between thermal comfort, IAQ and energy consumption. Those two solutions are the N_02_H_A and the N_I_H_A scenarios. Their performance in terms of thermal comfort is comparable to the ones of the fully mechanical scenario (the percentage of time in category II presents in both cases a slight decrease equal to 0.1% and to 1.7% for N_02_H_A and N_I_H_A respectively) and the IAQ is quite better (the number of hours in category I is increase by 6.3% for the N_02_H_A and by 12.2% with the other two). When their energy consumption is compared with the one of the fully mechanical system the reduction is equal to 65.4% and 65.1% respectively, proving that an intelligent implementation of natural ventilation strategies in a building designed to take proper advantage of such strategies allows an energy efficient solution for residential building, without any adverse effect, and even some improvement, on the indoor environmental quality even in a climatic zone like the Mediterranean

one, not particularly adapt to apply passive cooling by natural ventilation. What can be also deduced is the necessity to adequately constrain the night cooling potential if a good thermal environment has to be obtained.
Two of the non-mechanically cooled buildings have been excluded because of the poor thermal comfort that they can achieve. In particular the N_02_H leads to a significant undercooling during the transition seasons because of the intense use it makes of night ventilation, while the M_H is not effective in controlling the overheating during summer, as it can be seen in Figure 71.
On the other hand the mechanically cooled buildings are perfectly capable to provide both a good thermal comfort and a good air quality, but with a very high energy consumption.
The hybrid solutions have been proved to be capable to achieve a good indoor environment and to reduce the energy consumption for cooling need. Two were found to be particularly performing: N_I_HC and M_HC_N_A. When compared with the fully mechanical scenario they both provide a slight increase (1.4% referring to category II) in thermal comfort, an improvement in the IAQ (5.9% of extra hours in category I) and a consistent reduction in the energy consumption (33.8% for the N_I_HC and 31.8% for the M_HC_N_A). This proves that, even in thermostatically controlled buildings, the implementation of passive strategies (such as night cooling, ventilative cooling and solar shading in the first case, automatically controlled night cooling and solar shading in the second) can produce some benefits, not only from the energetic point of view, but also in terms of comfort.
To conclude: the solution which grants the best overall performance is the N_02_H_A. With its negligible decrease in the thermal comfort (-0.1%) and its remarkable improvement of IAQ (+26.3%) and reduction of energy consumption (-65.4%), it a desirable alternative to mechanical cooling.

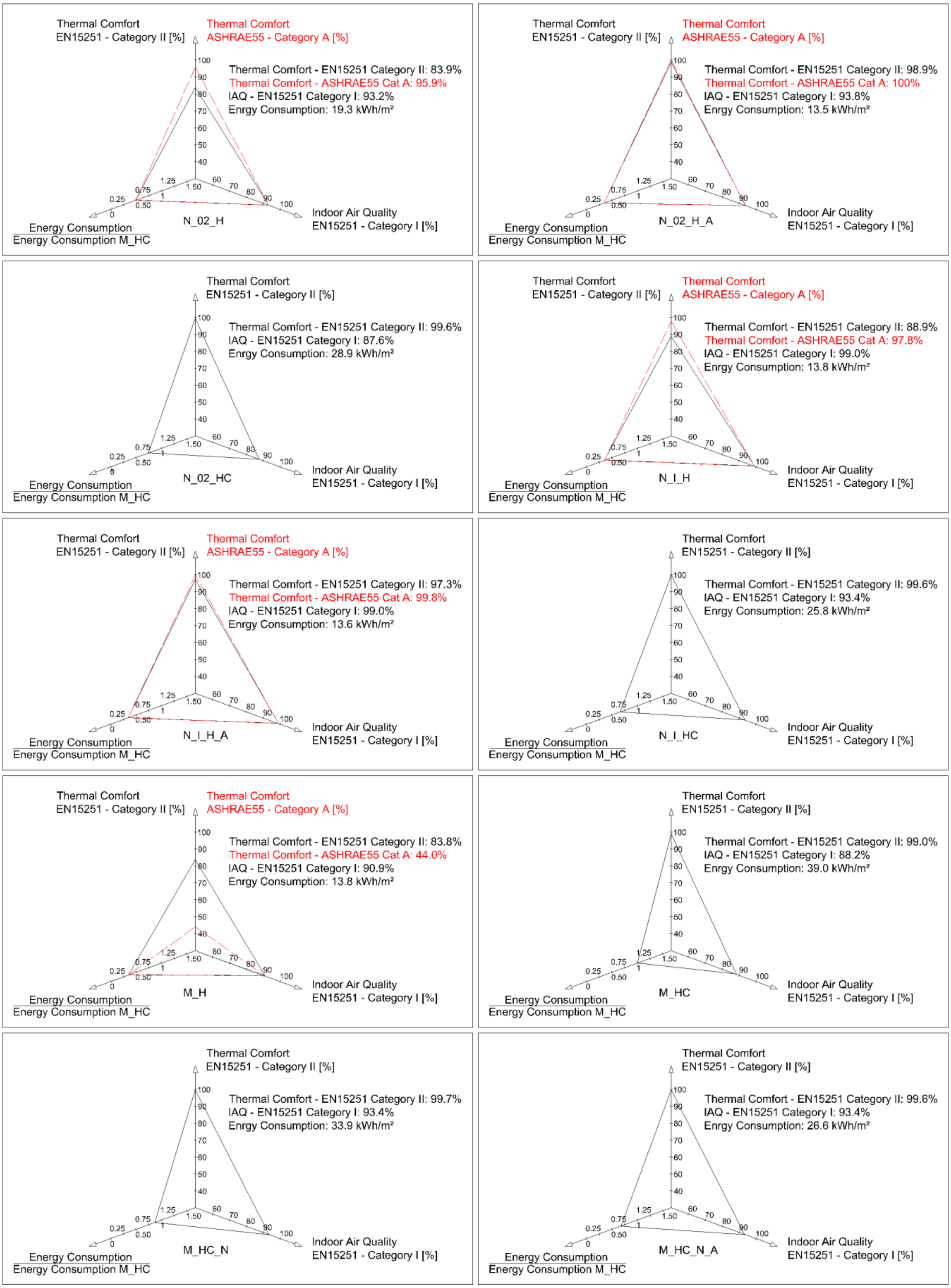


Figure 76 – Individual building signature for the ten scenarios.

6. BERLIN

Here the results from the ten configurations in a humid-continental climate such as the one of Berlin are discussed. For Berlin the natural ventilation period begin on May 7th and ends on October 5th. The passive cooling strategies are then applied for 152 days over 365 (42% of the year).

6.1. Preliminary Simulations

The same sets of preliminary simulations mentioned for Rome have been run also for Berlin. The optimization process of night ventilation threshold, orientation and thermal mass is hereby described.

Temperature threshold for night ventilation

For the climatic condition of Berlin the tested thresholds are 22.0°C, 22.5°C, 23.0°C, 23.5°C, 24.0°C, 24.5°C and the NoNight scenario as reference case. The daytime ventilation is here activated when the indoor air temperature gets close to the 23°C set point.

As before the parameters considered in the evaluation of the performances of the different solutions are thermal comfort and energy consumption. In Figure 77 a comparison between the comfort levels achieved by the tested night threshold has been established.

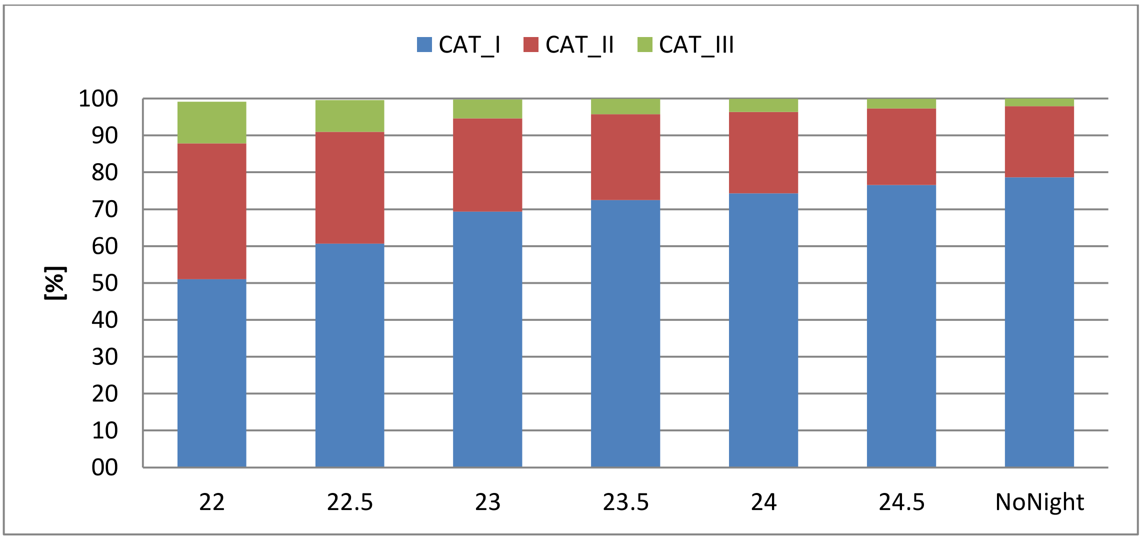


Figure 77 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested night cooling thresholds.

The best comfort (98% of time in category II) is achieved by the scenario without night cooling. As in Rome, decreasing the night threshold the comfort is reduced, because of the undercooling, up to a 12% (the 22.0°C threshold is in category II for 88% of the time). In Figure 78 undercooling and overheating are separately evaluated and it can be seen how, even when the night ventilation is not used, there is some undercooling in the building.

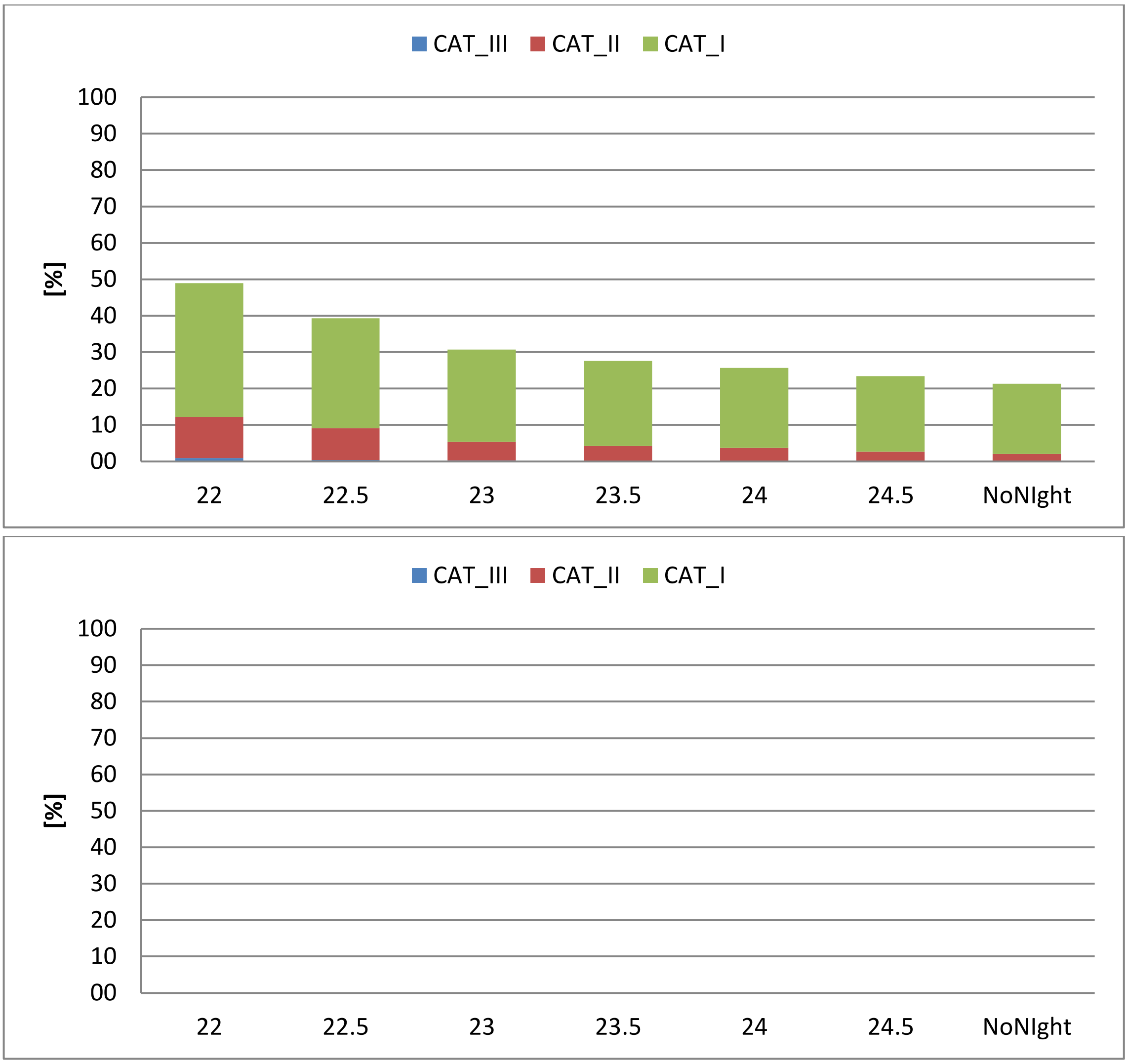


Figure 78 – Undercooling (top) and overheating (bottom) evaluated according to the EN15251 adaptive model for the tested night cooling thresholds

In Table 12 and Figure 79 the energy consumption for heating needs is reported.

Night threshold [°C]	Enrgy consumption [kWh/m^2]
22.0	123.5
22.5	54.9
23.0	45.1
23.5	44.0
24.0	43.7
24.5	43.5
NoNight	43.5

Table 12 – Energy consumption for the tested night cooling thresholds.

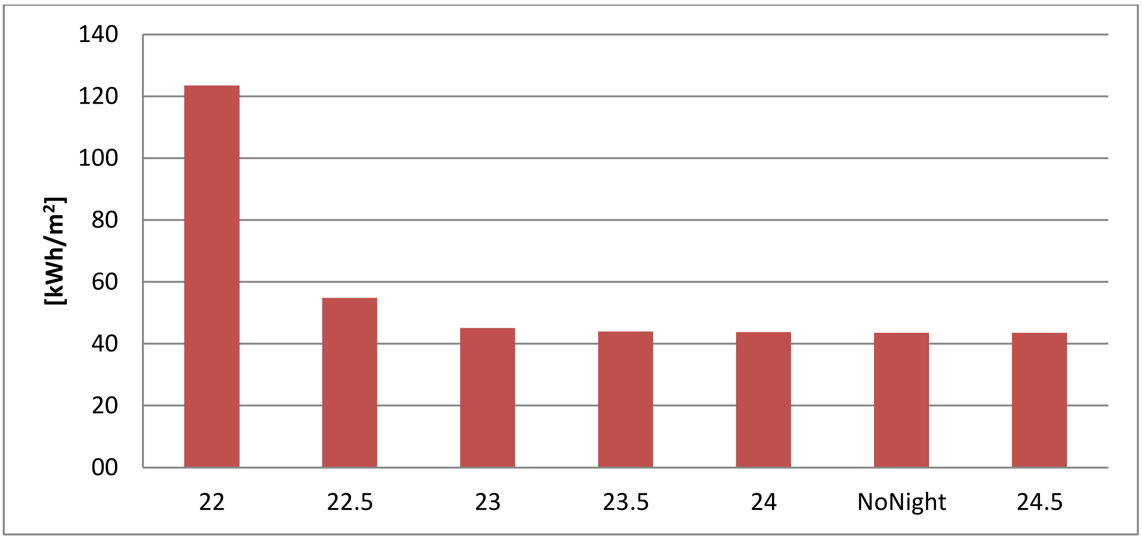


Figure 79 – Energy consumption for the tested night cooling thresholds.

Using the NoNight scenario as reference, the 22.0°C threshold leads to an energy consumption 2.8 times higher and the 22.5°C threshold cause a 26% increase. All the other solutions do not influence the heating requirement of the building.

Differently from Rome, the energy consumption for heating is very high (almost ten times higher), thus even a small percentage reduction can lead to some substantial primary energy saving. Considering that in the 23.5°C scenario there is only a slight decrease in the thermal comfort (2.2% less hours in category II) and a negligible increase in the energy consumption (1.1%), the 23.5°C value has been chosen as threshold for the night ventilation strategy in Berlin. Furthermore if we evaluate the thermal comfort with the non-adaptive model prescribed by the standard EN15251 the 23.5°C is one of the best performing (second only to the 23°C, which, on the other hand, causes quite an increase in the energy consumption). It can then be considered the best compromise between thermal comfort and cooling potential.

Orientation

The variation in thermal comfort and energy consumption as functions of the orientations is shown in Figure 80 and in Figure 81 respectively.

The percentage of time in category II presents no variation worthy to be mentioned.

The energy consumption presents a fluctuation: it has a minimum (44 kWh/m^2) when façade 3 is facing North and a maximum (46.5 kWh/m^2) when façade 3 is facing South. The reason is the very same already seen in Rome: façade 3 facing North means that façade 1, the one with the widest amount of glazed surface, is facing the sun during the warmest hours of the day, while façade 3 is facing South it is the other way around. But, differently from Rome, in Berlin the increase in the energy consumption moving from the North to the South orientation is limited to 5.7% (in Rome we observed a 33% increase from the North to the South-West orientation). This is quite obvious if we consider that, on one hand, the solar gain is lower in Berlin than in Rome and, on the other

hand, the energy consumption is higher, then the heat that the heating system does not have to deliver because supplied by the solar radiation is a much smaller percentage.
It is also possible to notice how the solar gain during the natural ventilation period is higher in Berlin, although the lower solar radiation. Indeed in Berlin the 23°C threshold is not reached so often and the solar shades are not activated as frequently as in Rome, especially during the transition season (just compare April, May and September in Figure 82 and in Figure 33 (bottom)).
Already in Rome it has been found that, because of the efficient external sunscreen, the solar gain did not deteriorate summer comfort and can potentially reduce the energy consumption during the heating season. In Berlin both the effects are, although present, much less relevant, then the solar gain in not regarded neither as a potential harm during summer, nor as a relevant benefit during winter.

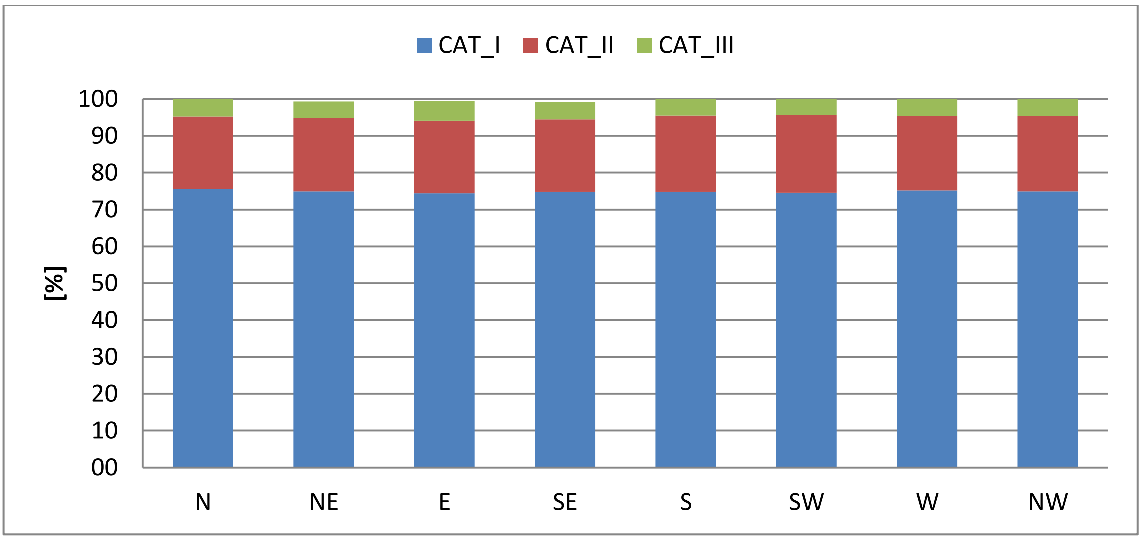


Figure 80 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested orientations.

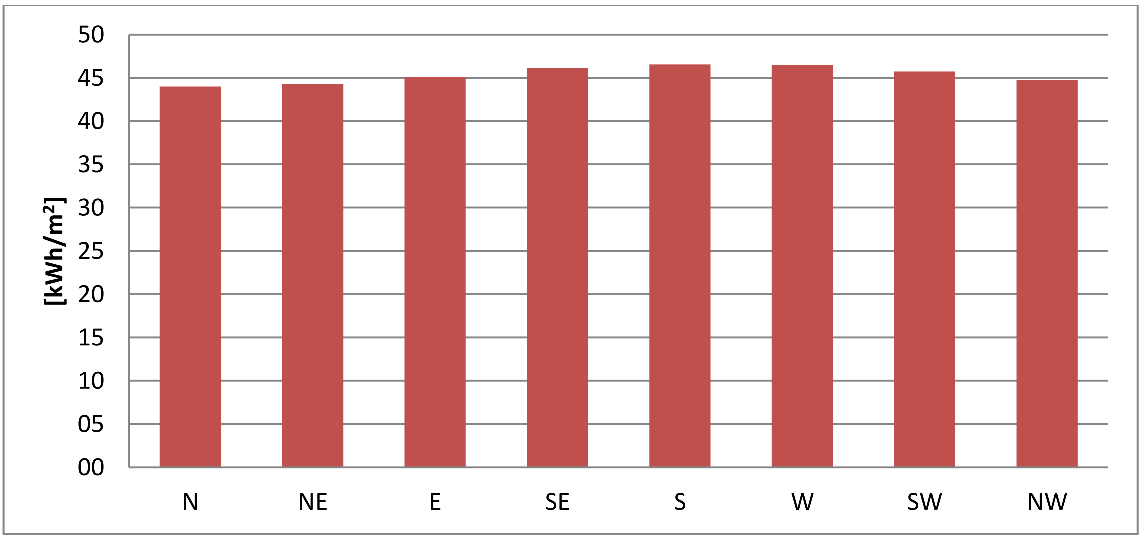


Figure 81 – Energy consumption for the tested orientations.

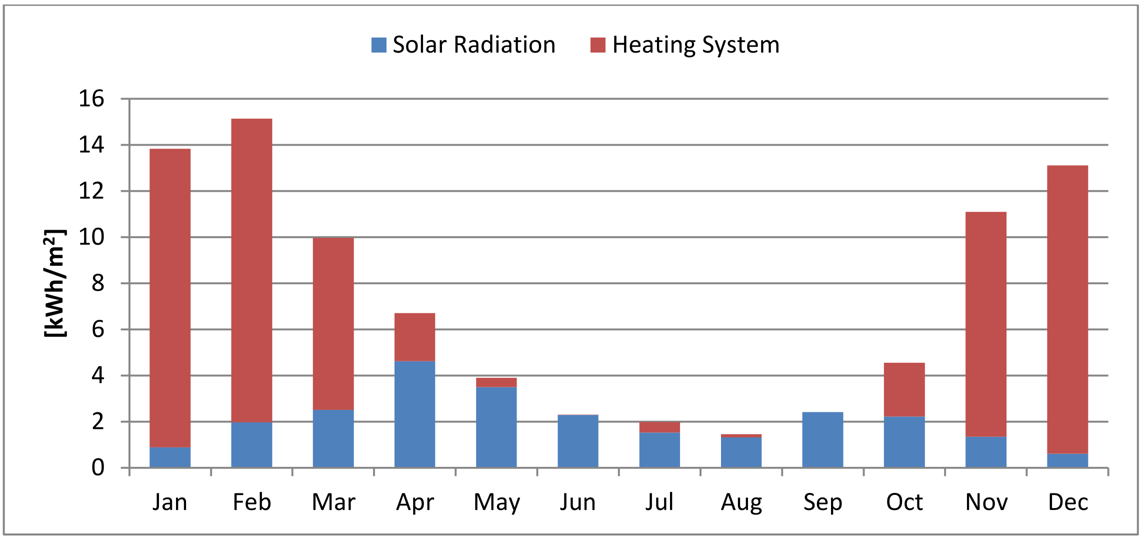


Figure 82 – Heat supplied by solar radiation and heating system for the South orientations.

Established that thermal comfort, solar gain and energy consumption give little indication on which orientation should be chosen, the decision depends on the indoor air velocity. Surprisingly also the indoor air velocity does not significantly change with the orientation, as shown in Figure 83.

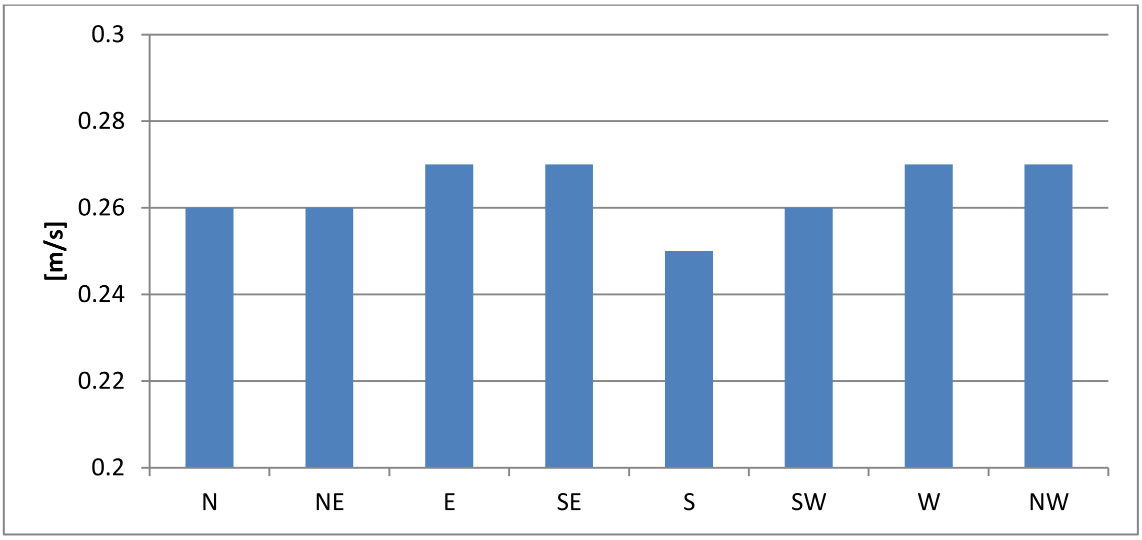


Figure 83 – Average indoor air velocity for the tested orientations.

If we consider that already in Rome a constraint to the daytime indoor air velocity was necessary to prevent discomfort, we can expect that in Berlin high indoor air velocities will be even less desirable. Then the North orientation has been selected among the tested ones.

Thermal mass

The thermal mass sensitivity analysis revealed that, as in Rome, there is a small improvement in the thermal comfort when the building mass in increased. Moving from a 0.08 m concrete layer thickness to a 0.20 m one the number of hours in category II increases by 2.3% only (Figure 84). The improvement is not impressive, but it is enough to pass from a category III building (the 0.08 m scenario is in category II for 93.4% of the times) to a category II one (the 0.20 m scenario is in category II for 95.6% of the time). When the energy consumption is considered, the reduction in the heating demand obtained by increasing the concrete layer thickness from 0.08 m to 0.20 m corresponds to 4.3% (from 44.2 kWh/m^2 for the 0.08 m to 42.3 kWh/m^2 for the 0.20 m thickness), as shown in Figure 85.

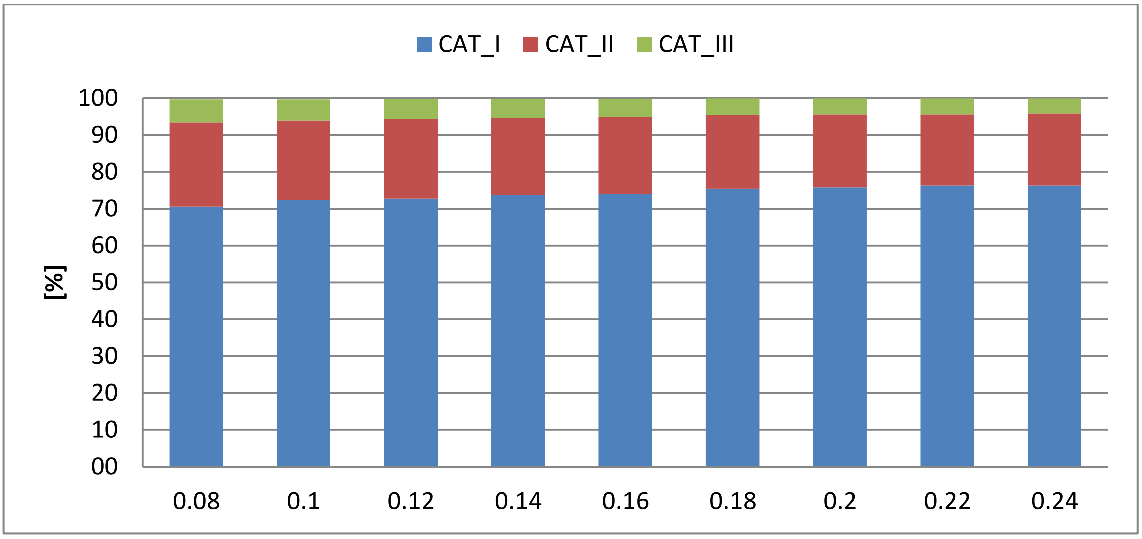


Figure 84 – Thermal comfort according to the EN15251 adaptive model for the tested concrete layer thicknesses.

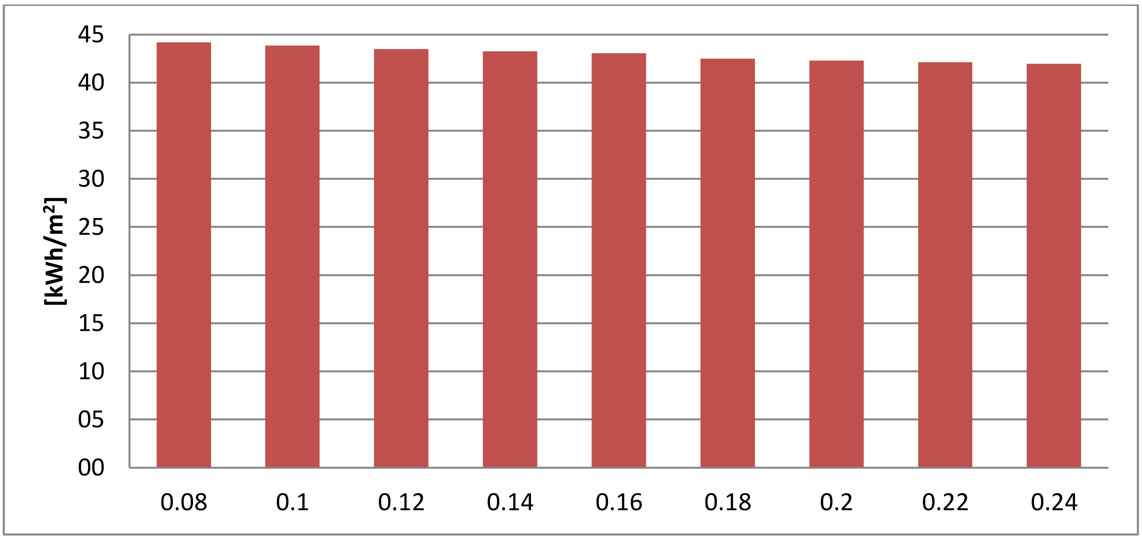


Figure 85 – Energy consumption for the tested concrete layer thicknesses.

From a closer look to the thermal comfort conditions it turns out that the discomfort is caused by undercooling (Figure 86): increasing the thermal mass the undercooling decreases. If we now establish a comparison between the 0.08 m and the 0.20 m scenario on a three days period (June 4th to June 6th) it turns out that the reason is the "long term" sink effect already observed in Rome. Increasing the efficiency of night cooling by increasing the thermal mass, the use of night ventilation is less frequent: the operative temperature peaks are leveled and the thermal comfort is easier to achieve. In Figure 88 the operative temperature is plotted for the two compared solutions on the three days period, along with the air flow rate in Figure 87 and the heat flux in Figure 89. The 0.08 m scenario presents a bigger fluctuation that means an operative temperature that gets closer to the upper limit of the comfort category II during day and closer to the lower limit of the comfort category II during night, even passing the limit on the third night.

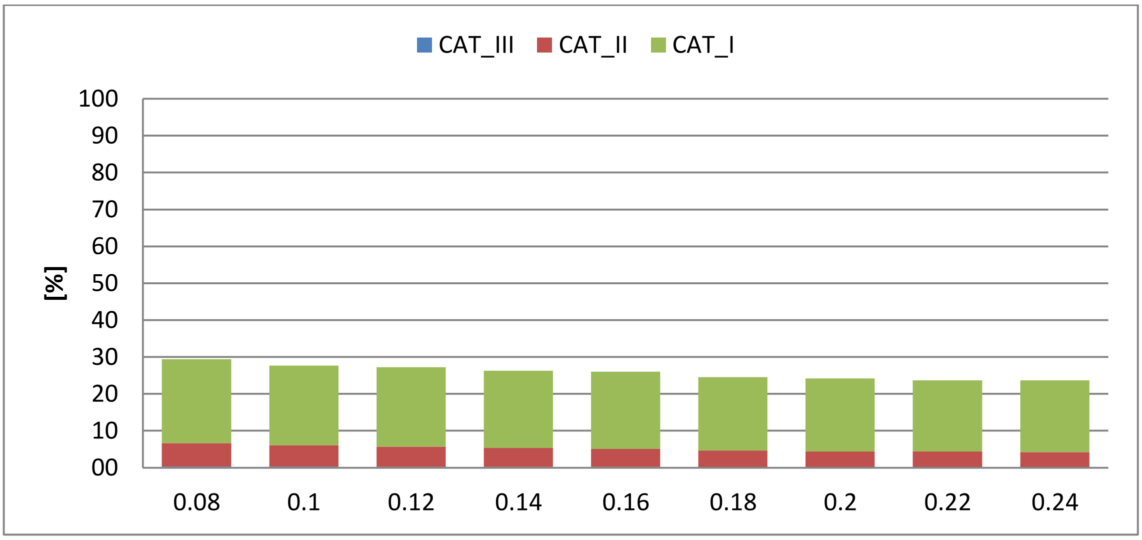


Figure 86 – Undercooling evaluated according to the EN15251 adaptive model for the tested concrete layer thicknesses.

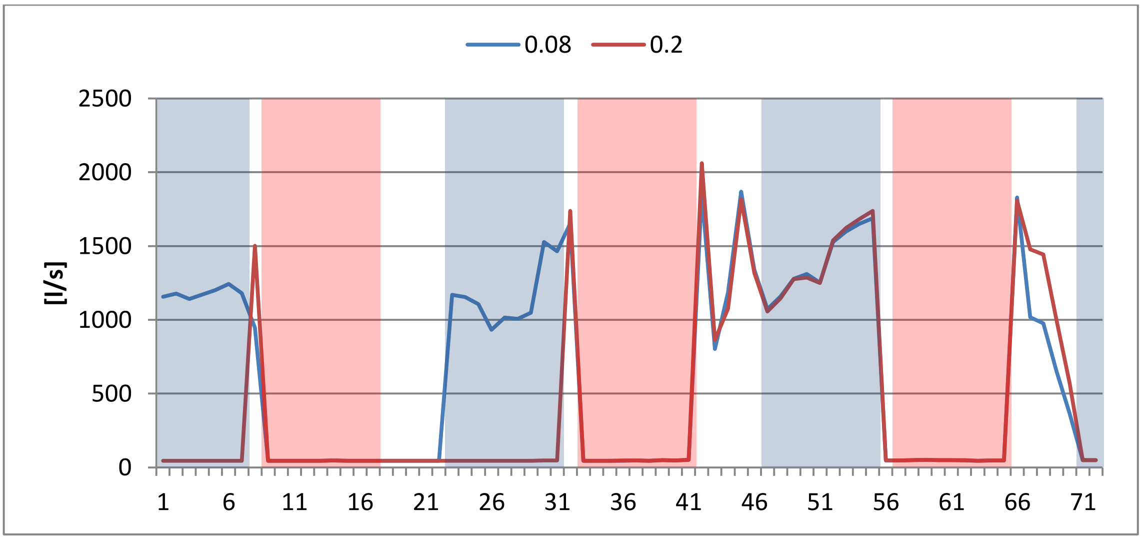


Figure 87 – Air flow rate.

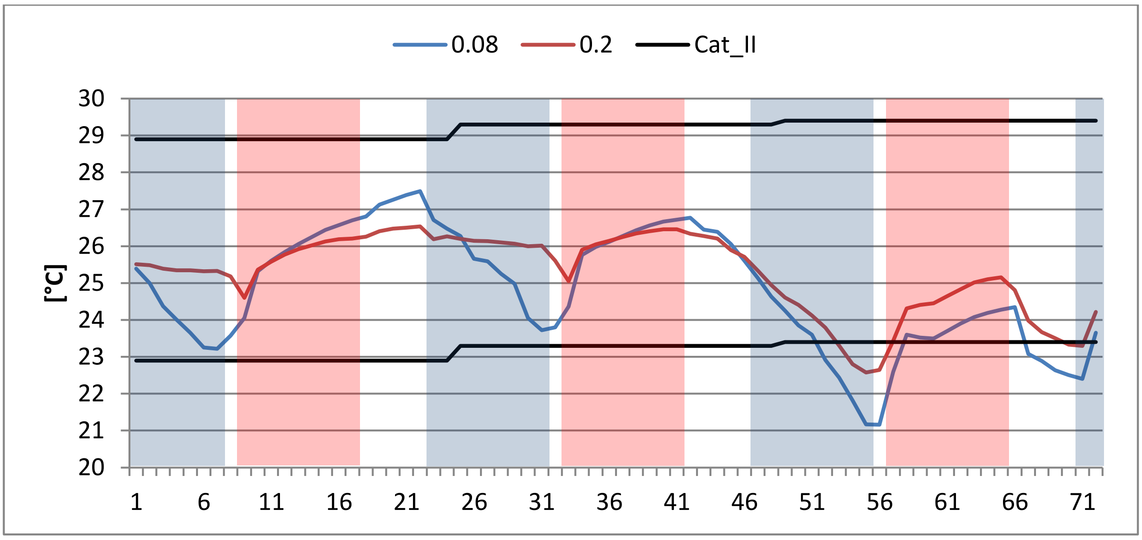


Figure 88 – Operative temperature.

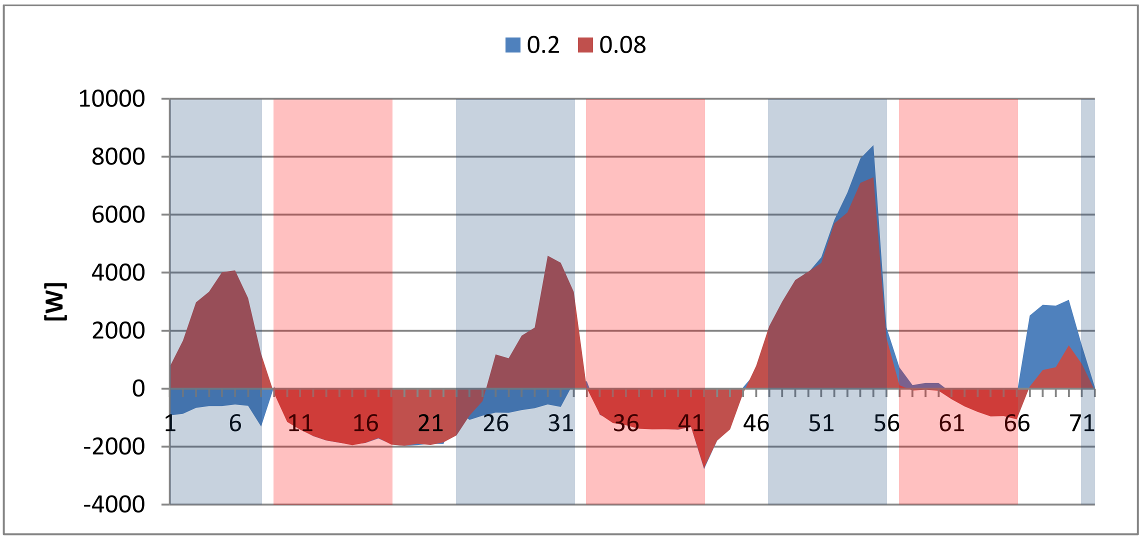


Figure 89 – Heat flux from the building thermal mass.

The heat flux from the thermal mass shows how the night ventilation, when applied, is more efficient with a thicker concrete layer and how, as consequence, the heavier structure is capable to store more heat during day, preventing the temperature from rising.

The benefits of an increased thermal mass are quite interesting up to a 0.20 m concrete layer thickness, a heavier structure gives no further improvement. Then a 0.20 m thick concrete layer has been considered adequate for the night ventilation to be efficient.

6.2. Case studies

For Berlin the ten configurations have the following settings.

- N_02_H presents an average indoor air velocity of 0.10 m/s.
- N_02_H_A uses a proportional controller set between 23.5°C (lower limit for the fully opened windows) and 22.5°C (upper limit for the fully closed windows). Between these two values the windows opening area is modulated.
- N_02_HC switches from natural ventilation to mechanical cooling when the indoor air temperature rises above 24.5°C.
- N_I_H grants an average indoor air velocity of 0.26 m/s.
- N_I_H_A is equipped with the same proportional controller installed in the N_02_H_A scenario.
- N_I_HC switches from natural ventilation to mechanical cooling when the indoor air temperature rises above 24.5°C.
- M_HC_N is mechanically ventilated and night cooled
- M_HC_N_A combines mechanical ventilation with modulated night cooling. During night when the indoor air temperature is above 23.0°C the windows are fully opened, between 22.0°C and 23.0°C are modulated and below 22.0°C are fully closed. The set point and the modulating range derive from an optimization process.

6.3. Indoor air quality

All the solutions grant a very high IAQ, as it can be seen from Figure 90 and Table 13.

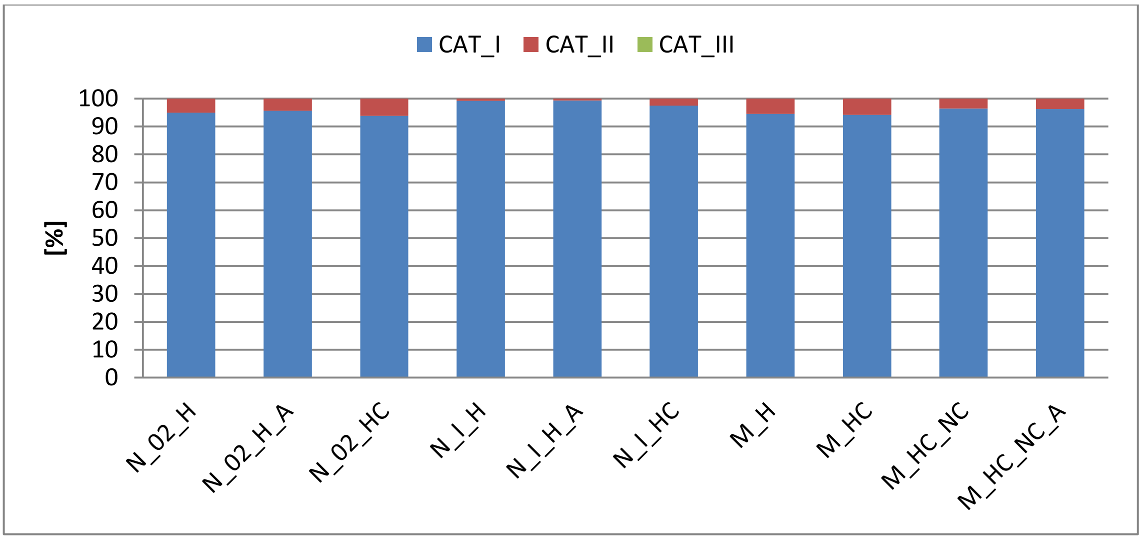


Figure 90 – IAQ evaluated according to the EN15251 for the ten scenarios

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	95.0	100.0	100.0	+1.0
N_02_H_A	95.7	100.0	100.0	+1.7
N_02_HC	93.8	100.0	100.0	-0.3
N_I_H	99.2	100.0	100.0	+5.4
N_I_H_A	99.3	100.0	100.0	+5.5
N_I_HC	97.5	100.0	100.0	+3.6
M_H	94.6	100.0	100.0	+0.5
M_HC	94.1	100.0	100.0	-
M_HC_N	96.4	100.0	100.0	+2.4
M_HC_N_A	96.2	100.0	100.0	+2.2

Table 13 – IAQ evaluated according to the EN15251 for the ten scenarios

Only three cases are in category II: the two fully mechanically ventilated (M_H and M_HC) and the N_02_HC. This proves that, being all the others buildings in category I, with the chosen mechanical air flow rates, the natural ventilation performs better in terms of air quality level. In particular the N_I_H and the N_I_H_A solutions, thanks to the higher amount of fresh air that enters the building (during daytime they allow 2.4 ach and 2.5 ach respectively, during nighttime the air changes per hour are 1.3 and 1.0, against the constant 0.5 ach of mechanical ventilation), generate a building in category I for almost 100% of the time. The comparison between the N_02_H, the N_I_H and the M_H scenarios (the ones that can be regarded as basic strategies since they involve neither mechanical cooling nor automated controls) shows how the natural ventilation adjusted only to achieve the thermal comfort can lead to air flow rates below the minimum requirement for a good IAQ. In Figure 91 the total (including infiltrations) flow rate is compared for the three scenarios on a three days period (September 13th to September 25th).

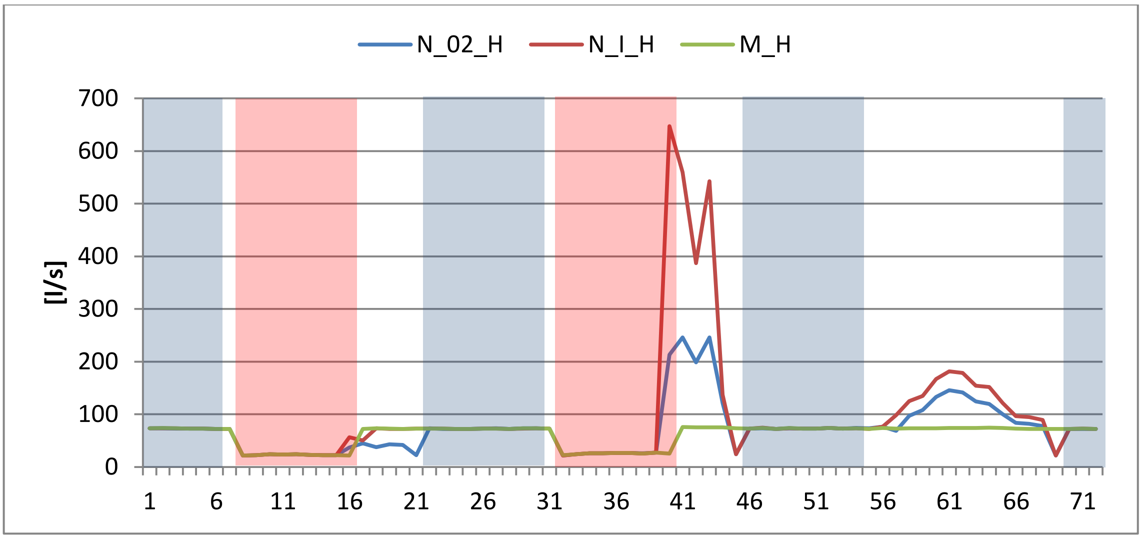


Figure 91 – Air flow rate.

The first day when the occupants enter in the building at 17:00 in the evening, the conditions for the natural ventilation to be applied are satisfied, but the indoor air temperature is very close to the threshold, then the opening area is very narrow and the air flow rate for the N_02_H scenario is lower than the mechanical one. This does not happen in the N_I_H scenario because all windows are operated and, even if partially open, they allows a bigger air flow rate, also the temperature drops faster below the switching set point between the natural and the mechanical system and the windows are closed after very short time.
Other phenomena take place but have already been discussed. Among these the slight increase in the IAQ when the night ventilation is modulated and the increased infiltration rate during nighttime when no cooling system is used in the mechanically ventilated scenario.

6.4. Energy consumption

The second parameter is the energy consumption (Figure 92 and Table 14). When compared with Rome the very low energy demand for cooling need (5.1% of the total demand) stands out.

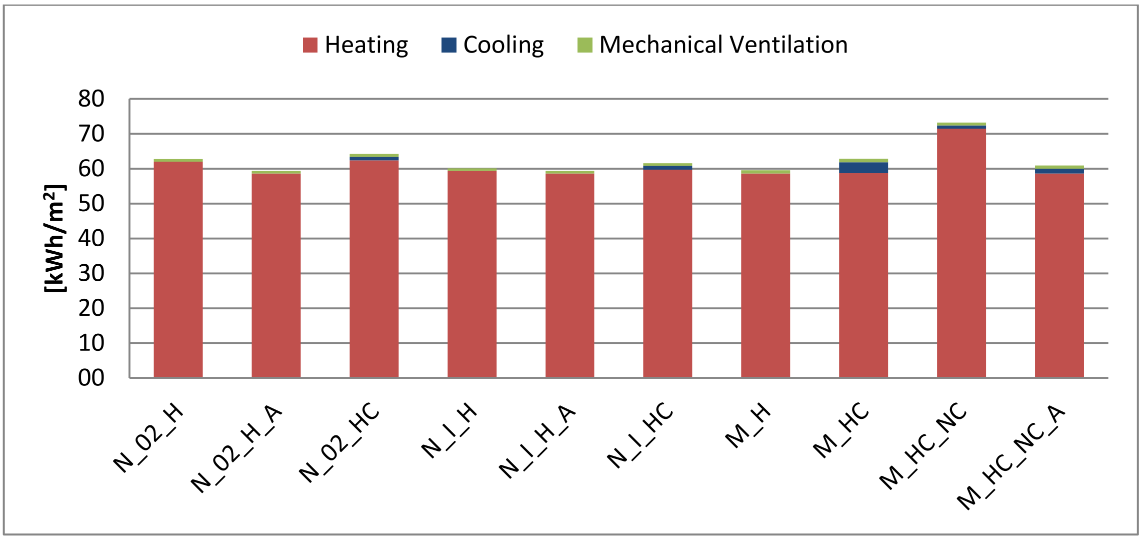


Figure 92 – Energy consumption for the ten scenarios.

	Heating [kWh/m^2]	Coolig [kWh/m^2]	Mechanical Ventilation [kWh/m^2]	Total [kWh/m^2]	Variation [%] (reference case: M_HC)
N_02_H	62.0	0.0	0.7	62.7	-0.2
N_02_H_A	58.6	0.0	0.7	59.3	-5.6
N_02_HC	62.4	1.1	0.7	64.2	+2.2
N_I_H	59.4	0.0	0.8	60.1	-4.3
N_I_H_A	58.6	0.0	0.7	59.4	-5.4
N_I_HC	59.7	1.1	0.8	61.6	-1.9
M_H	58.6	0.0	0.9	59.6	-5.1
M_HC	58.7	3.2	0.9	62.8	-
M_HC_N	71.5	0.9	0.9	73.3	+16.7

M_HC_N_A	58.7	1.4	0.9	60.9	-3.0

Table 14 – Energy consumption for the ten scenarios.

In Berlin as in Rome the building benefits from the introduction of an automatic controller. The energy consumption for heating is reduced by 5.5% when it is used in the N_02_H scenario, by 1.3% when it is introduced in the N_I_H scenario and by 17.9% when it is introduced in the M_HC_N scenario. The increased air velocity, limiting the use of night ventilation, also reduces the energy consumption for heating by 4.2%.
A consideration on the combination of mechanical cooling and night ventilation can be made, so let us compare the M_HC, the M_HC_N and the M_HC_N_A solutions on a three days period (July 27th to July 29th). From Figure 93 (air flow rate), Figure 94 (perceived operative temperature and mean air temperature) and Figure 95 (heat flux from air flow and heating/cooling system) we can see how, even in the middle of the summer, night cooling combined with mechanical cooling causes a strong decrease in the temperature during night (there is no heat to remove from the building mass): all three nights the 21°C set point of the heating system is reached very few hours after 22:00, and heat has to be supplied by the mechanical system to prevent thermal discomfort.

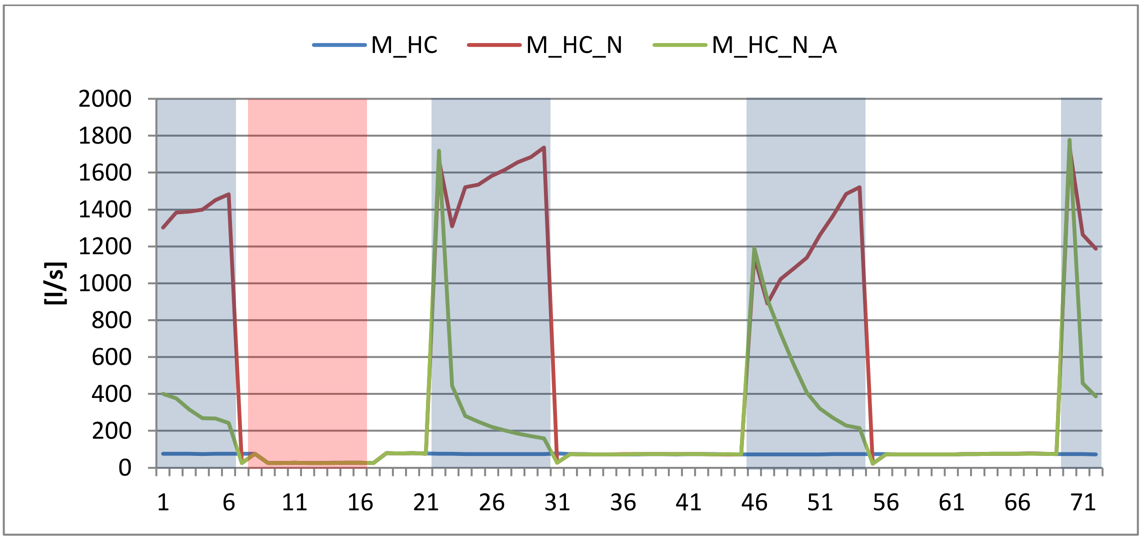


Figure 93 – Air flow rate.

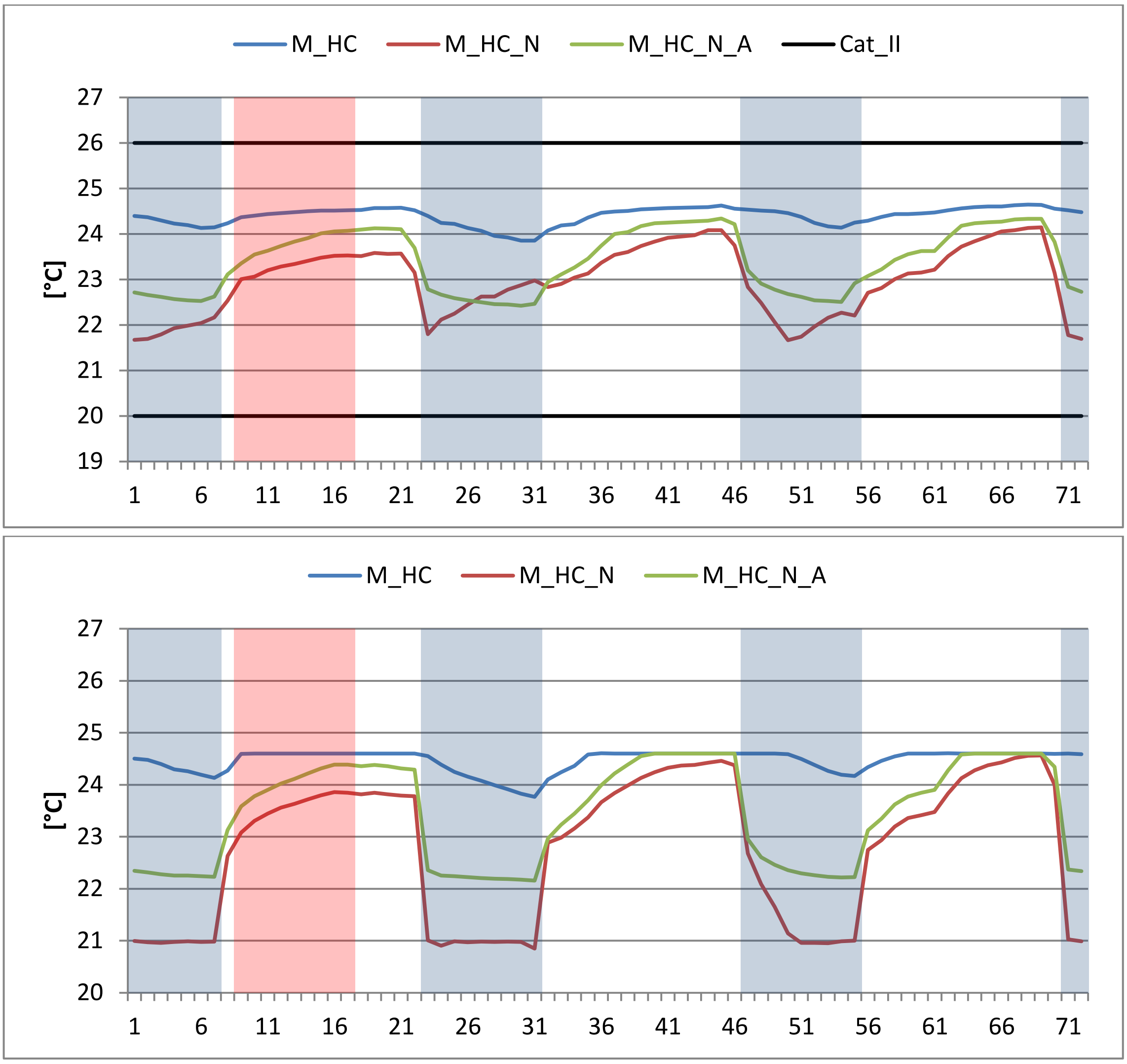
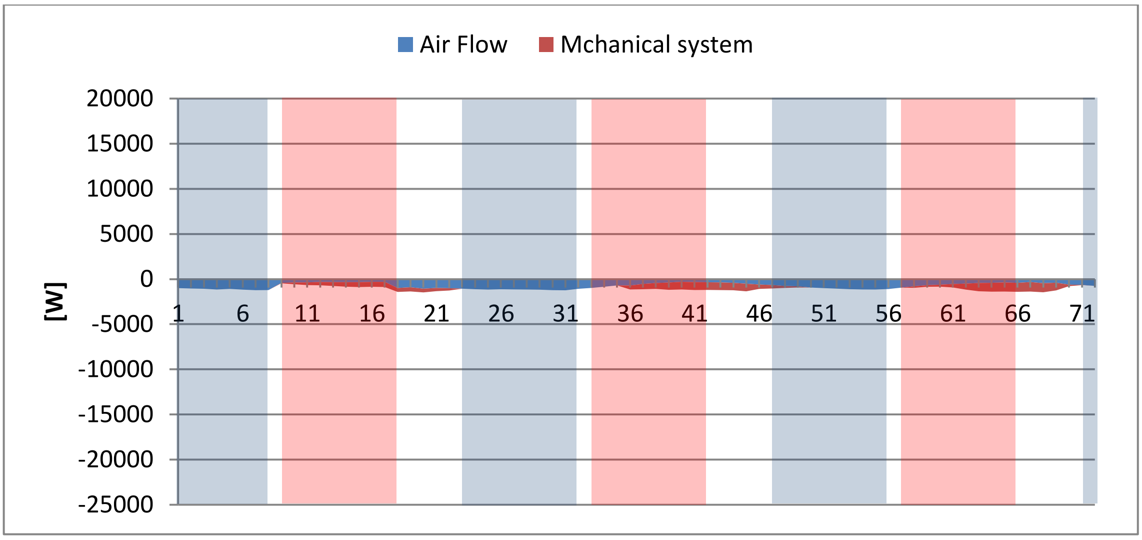


Figure 94 – Perceived operative temperature (top) and mean air temperature (bottom).



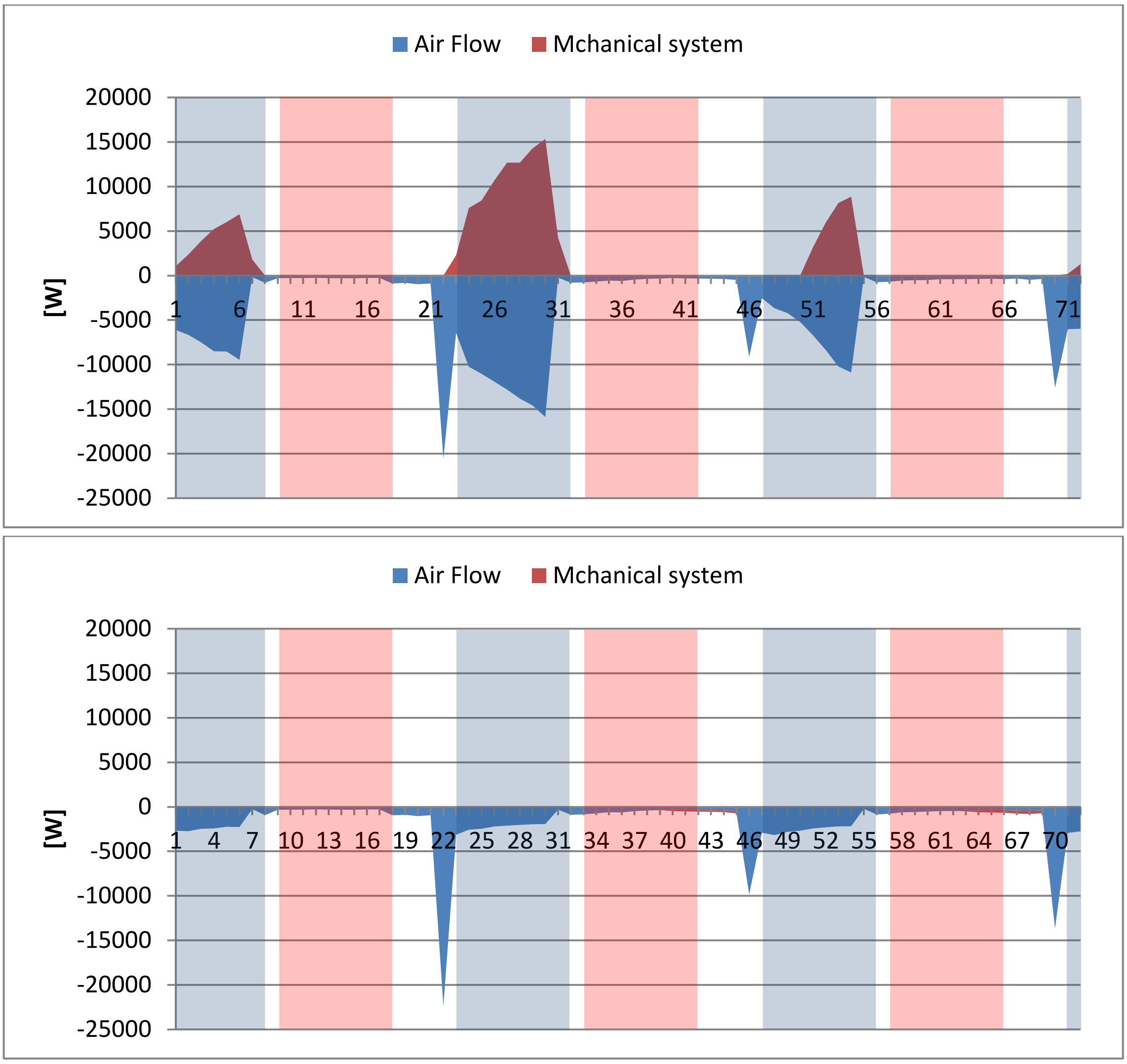


Figure 95 – Heat flux (M_HC at the top, M_HC_N in the middle and M_HC_N_A at the bottom).

When the M_HC_N_A is compared with the M_HC there is some energy saving: in the M_HC scenario the energy consumption for cooling on the three days period is equal to 22.8 kWh, while in the M_HC_N_A it is 3.0 kWh, with a reduction in the cooling demand equal to 87% (on the three days). It also true that such saving is just slightly higher than 3% when the entire natural ventilation period is considered, since only in the warmest period of the year there is need for cooling, while during the transition seasons night ventilation is applied seldom and for very short time (just a couple of hours after 22:00, then windows are closed to prevent undercooling) thus the cooling energy saved is rather low.

Differently from Rome, where the combination of night ventilation and mechanical cooling allows a remarkable energy saving, in Berlin it is advisable to avoid the use of night ventilation when the building is mechanically cooled because if the night ventilation strategy is manually controlled, it will certainly lead to both thermal discomfort and increased energy consumption for heating. If the windows are operated by an automatic controller the energy saving is negligible and there is no improvement in the thermal comfort (no improvement is possible).

6.5. *Thermal Comfort*

First the strategies which do not involve mechanical cooling are evaluated according to the adaptive model. The performance comparison is shown in Figure 96 and Table 15.
The thermal comfort improvement obtained when the proportional controller is introduced, and mostly the classification of the M_H scenario as a category I building, suggest that the climatic conditions of Berlin combined with an excessively efficient passive cooling strategy will lead to the undercooling of the building. The conclusion is supported by the graphs in Figure 97 where the undercooling and overheating are separately considered. No overheating is ever present and in the N_I_H scenarios the undercooling is so severe that the dwelling is the only one that does not even reach the status of category II building. The increased air velocity causes, every other condition left unchanged, a reduction in the thermal comfort: comparing the N_02_H scenario with the N_I_H the decrease amounts to 2.8% while the comparison between the N_02_H_A scenario and the N_I_H_A shows a decrease equal to 4.5% (the percentages are referred to category II).

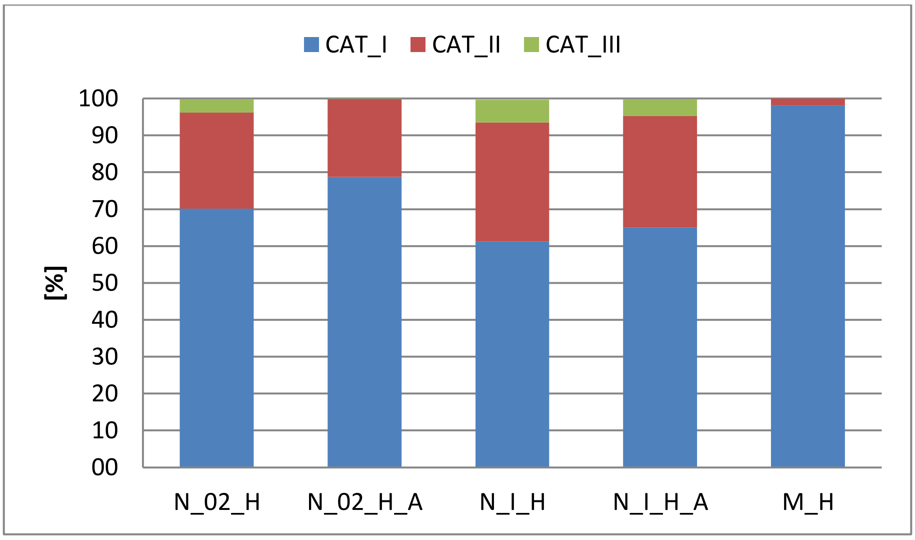


Figure 96 – Thermal comfort evaluated according the EN15251 adaptive model for the five scenarios not equipped with a mechanical cooling system.

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	70.1	96.2	99.8	-3.8
N_02_H_A	78.7	99.8	100.0	-0.2
N_I_H	61.3	93.5	99.7	-6.5
N_I_H_A	65.0	95.3	99.8	-4.7
M_H	98.1	100.0	100.0	0.0

Table 15 – Thermal comfort evaluated according the EN15251 adaptive model for the five scenarios not equipped with a mechanical cooling system.

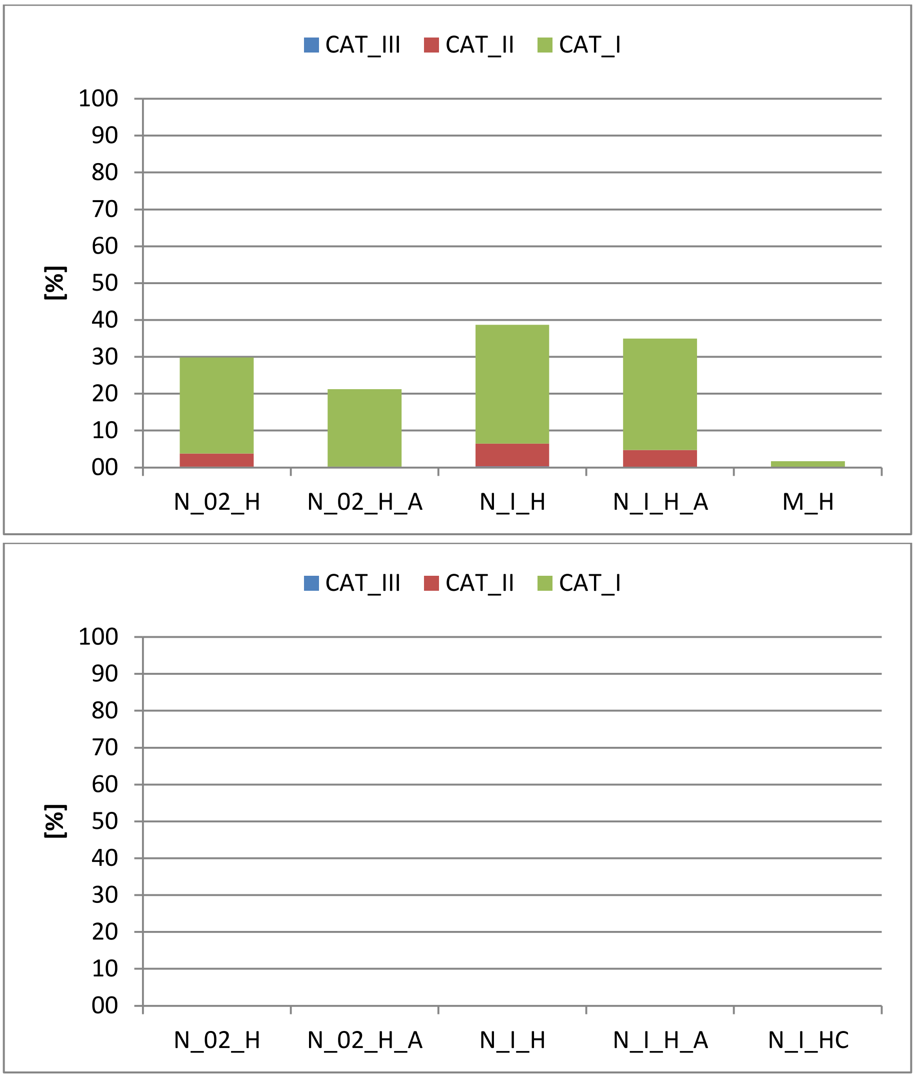


Figure 97 – Undercooling (top) and overheating (bottom) evaluated according the EN15251 adaptive model for the five scenarios not equipped with a mechanical cooling system.

Thermal performances change if evaluated with the non-adaptive model (Figure 98 and Table 16).

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	98.2	99.3	100.0	-
N_02_H_A	97.2	98.4	100.0	-
N_02_HC	99.8	100.0	100.0	0.0
N_I_H	96.7	99.0	100.0	-
N_I_H_A	96.6	98.7	100.0	-
N_I_HC	98.8	100.0	100.0	0.0
M_H	81.0	88.4	97.5	-
M_HC	100.0	100.0	100.0	-
M_HC_N	99.9	100.0	100.0	0.0
M_HC_N_A	99.9	99.9	100.0	-0.1

Table 16 – Thermal comfort evaluated according the EN15251 non-adaptive model for the ten scenarios.

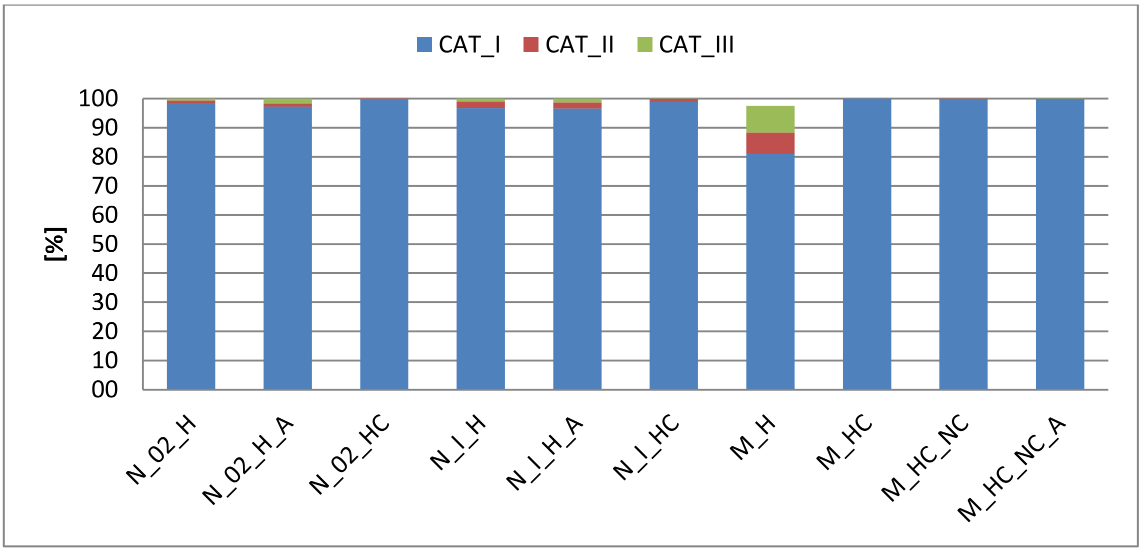
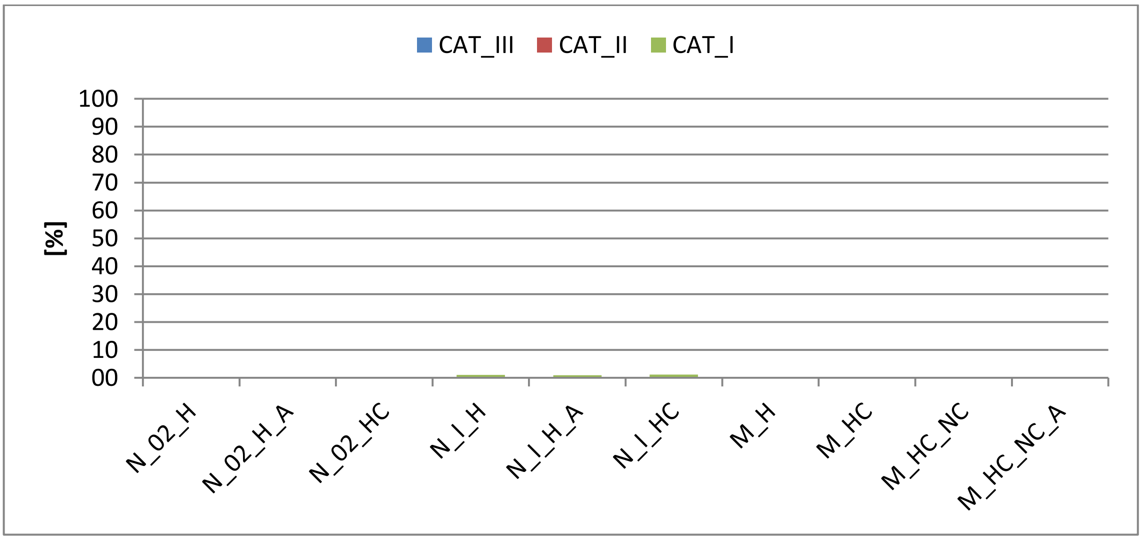


Figure 98 – Thermal comfort evaluated according the EN15251non-adaptive model for the ten scenarios.

The mechanically cooled buildings are the ones which perform better in term of thermal comfort, but also the naturally ventilated ones are category I buildings. The only exception is the M_H which is in category III. To understand the cause we need to look at the discomfort originated by undercooling and overheating separately. From Figure 99 it results clear that is the overheating to cause a decrease of the thermal comfort in the scenarios which do not rely on a mechanical cooling system.



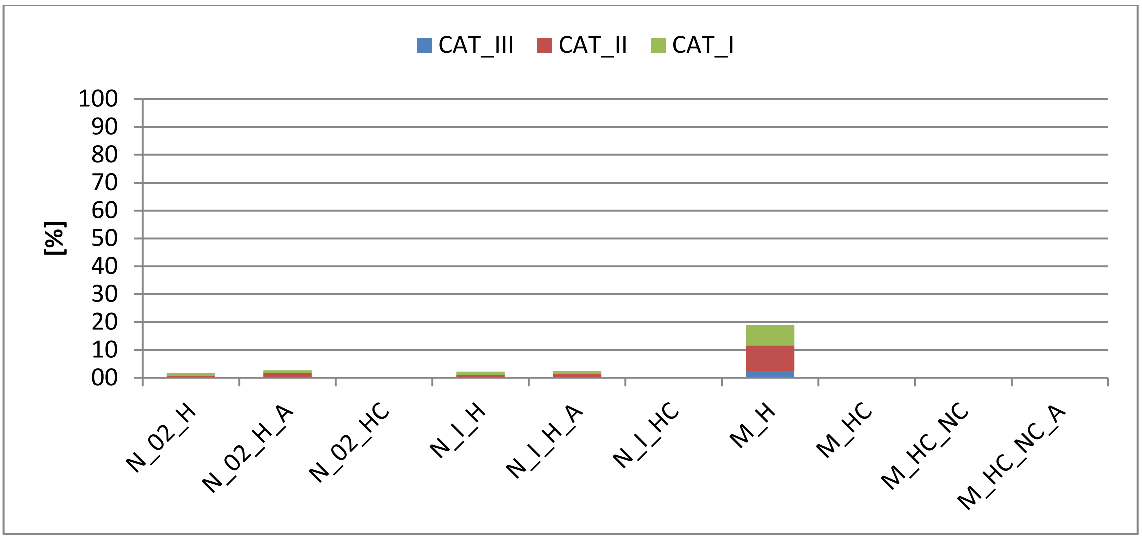


Figure 99 – Undercooling (top) and overheating (bottom) evaluated according the EN15251non-adaptive model for the ten scenarios.

It is worth to have a closer look at the increased velocity scenarios since they show an unwanted effect on the thermal comfort: they are indeed the only ones which present undercooling and in particular the N_I_H, when compared with the non-increased solution (N_02_H), is also less efficient in counteracting the overheating. Consider the N_02_H and N_I_H: a comparison between the air flows (Figure 100) and the temperatures (Figure 101) have been established on a three days period (October 3rd to October 5th). The increased air flow rate of the N_I_H scenario during the transition seasons cause both a decrease in the indoor air temperature and an increase in the temperature offset, the combination of the two effects results in the undercooling of the dwelling, as it can be seen in Figure 101 (top) where the perceived temperature for the increased velocity solution reaches the lower limit of the category II in the last day of the sorted out period, while in the non-increased one the perceived operative temperature fluctuates around 21°C.

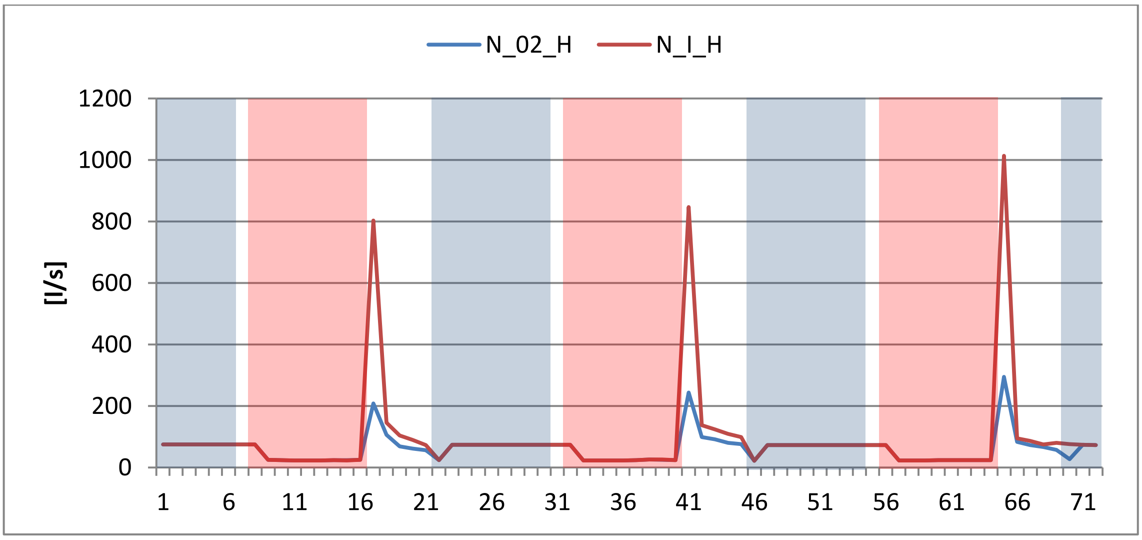


Figure 100 – Air flow rate.

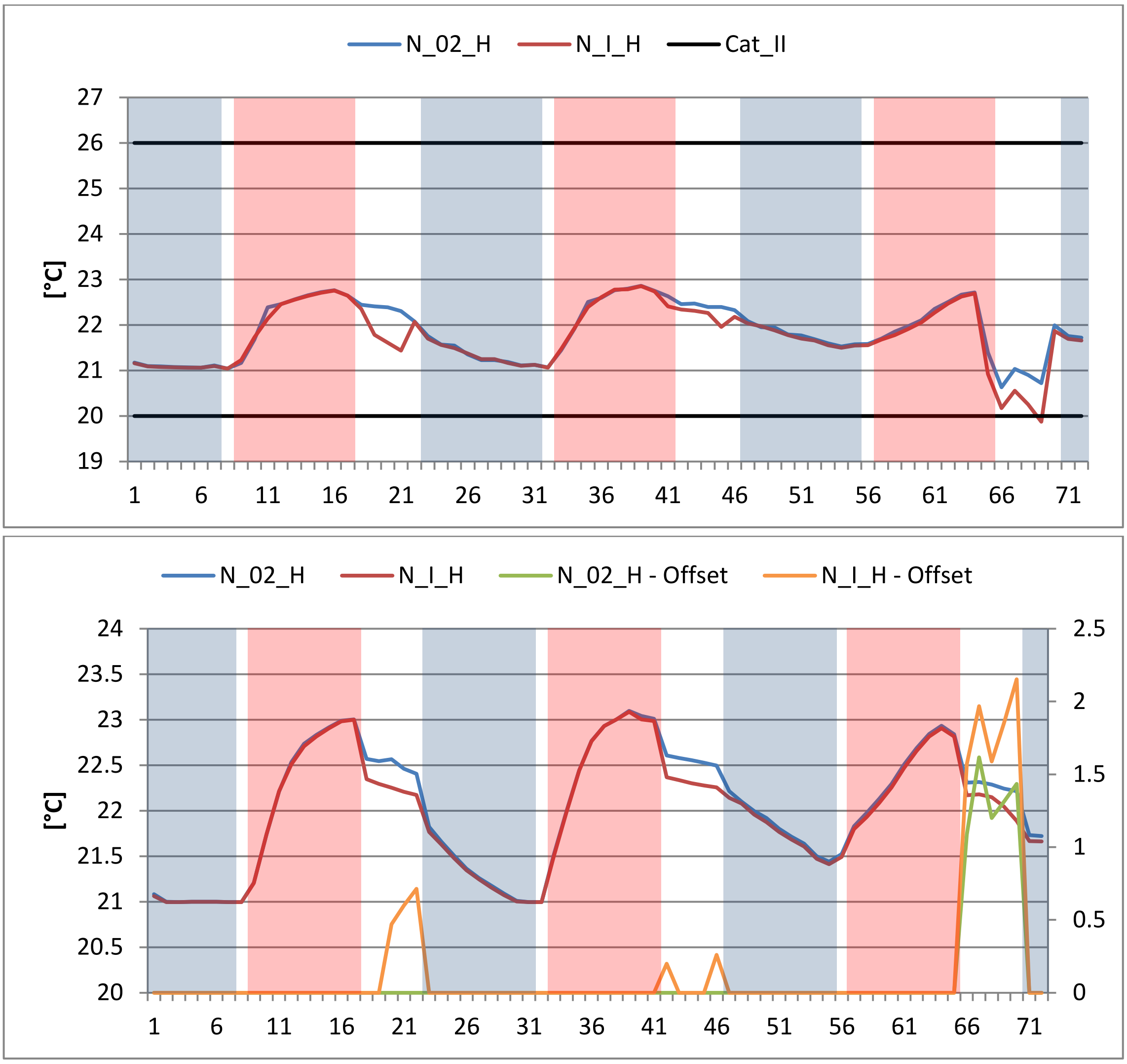


Figure 101 – Perceived operative temperature (top) and mean air temperature (bottom).

To explain the overheating a three days period (June 1st to June 3rd) under warmer weather conditions has been chosen (Figure 102 and Figure 103). On June 1st at around 19:00 the system switches from mechanical to natural ventilation since both the condition are satisfied: the indoor air temperature is above 23°C and the difference between the outdoor and the indoor temperature is below 2°C (the outdoor air temperature will drop below the indoor air temperature at around 21:00). But in this period of the year, and in particular at this time of the day, the wind speed is quite low (1.5 m/s) then natural ventilation relies on the buoyancy force. The N_02_H windows configuration is not capable to properly ventilate the building only by stack effect since all the operable windows are at the same level (ground floor) and the opening area is limited. Then the air flow rate that enters the building is very low (lower than the mechanical one), the cooling effect is negligible and the indoor air temperature remains high. On the other hand the N_I_H windows configuration grants efficient ventilation, whether the air is forced to enter the building by the wind or by the stack effect. The windows are in fact located on two levels (ground floor and roof) and all windows are operable, then, between 19:00 and 22:00, the air flow rate

cools down the building. But this is not enough. There is a second contribution coming from the building mass, whose temperature, in both cases, is lower than the air one. This second contribution in the N_02_H case is not capable, alone, to decrease the indoor air temperature below the outdoor one, but in the N_I_H case, since it is obtained with the contribution of the outdoor air entering the building, it is. Then in the first case scenario the windows are kept open during night and in the second one they are not. The heat removed during this extra ventilation night decreases the thermal mass temperature allowing the prevention of an operative temperature increase on a long term (several days). For this reason in the days that follow the indoor air temperature does not rise above the upper limit of the category II in the N_02H scenario, while in the N_I_H one there are some hours of overheating between 17:00 and 21:00 in the evening of the third day, as it can be seen in Figure 103 (top). The phenomenon is constrained to a short period of the year and this is why the increase in the overheating is negligible. On the other hand the increased air velocity allows a reduction in the energy consumption that justifies the use of an enhanced natural ventilation strategy during daytime.
A consideration has at this point to be made. The software uses a given threshold of 23.5°C, in the N_02_H scenario the temperature is some fraction of degree above the threshold, while in the N_I_H it is some fraction of degree below. We then think that such a small temperature difference would not be perceived by the human body, then it is not expected to lead to different behaviors from a real subject (in other words we think that the occupants would either open or close the windows in both situations).

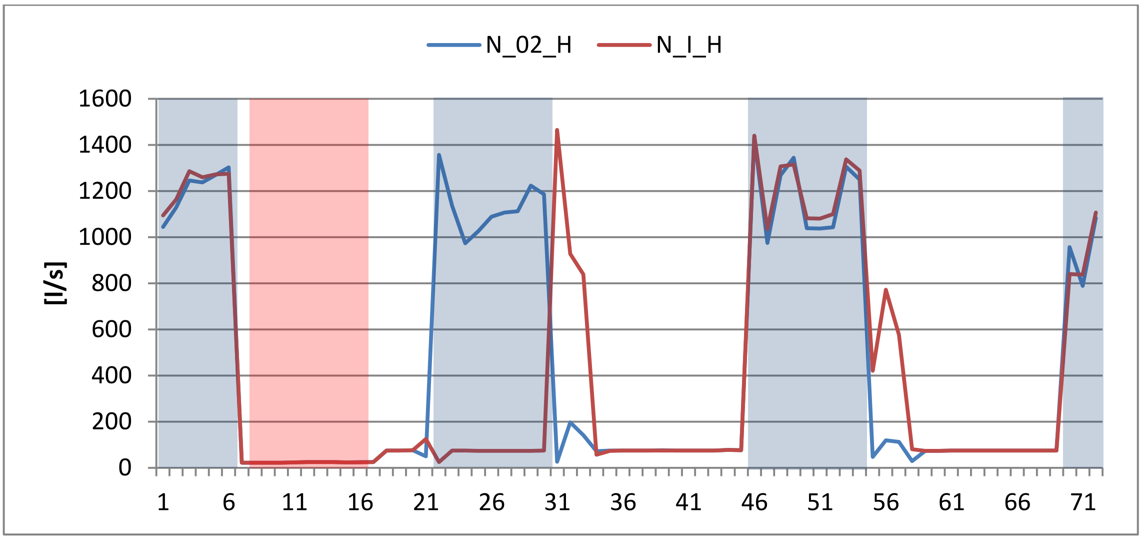


Figure 102 – Air flow rate.

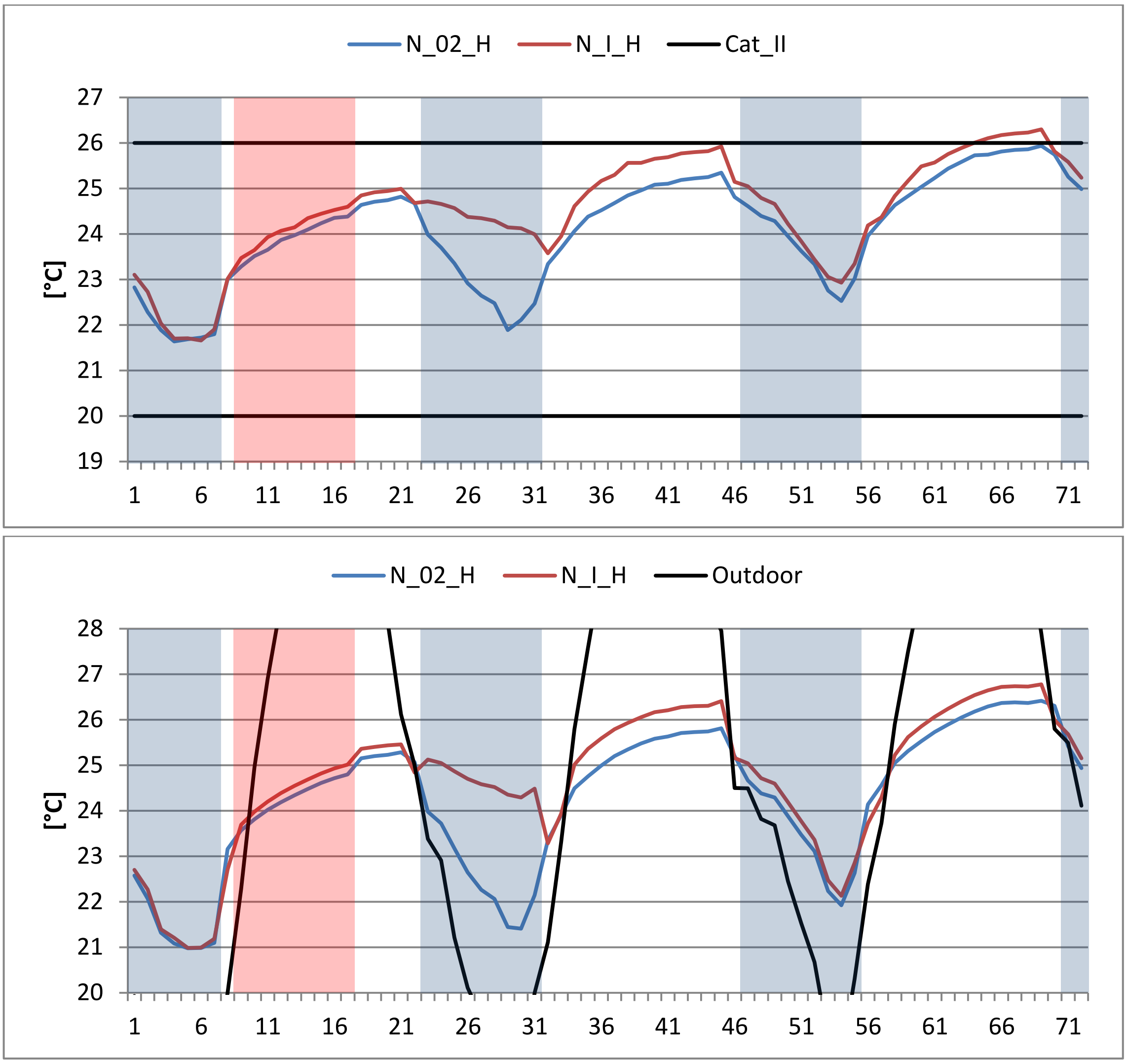


Figure 103 – Perceived operative temperature (top) and mean air temperature (bottom).

The second adaptive model, the one from ASHRAE55, changes a little the terms of the comparison, as it can be seen from Figure 104 (thermal comfort) and Figure 105 (undercooling and overheating). As in Rome, the only cases where the undercooling is present are the increased velocities ones, this proves the initial intuition on the unnecessity of enhanced cooling strategies to be correct. Also the window automation with the chosen set points seems to increase the overheating of the dwelling, but, even if the percentage increase is relevant (92.9% from N_02_H to N_02_H_A and 15.6% from N_I_H to N_I_H_A in category A), the difference in the comfort is not that important since all the solutions are in category A, with the only exception of the M_H one.

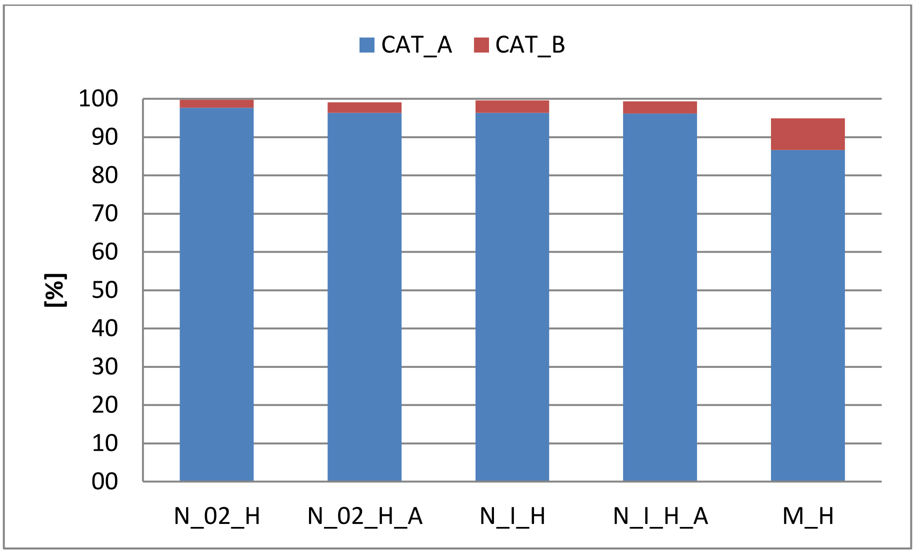


Figure 104 – Thermal comfort according to the ASHRAE55 adaptive model for the scenarios not equipped with a MCS.

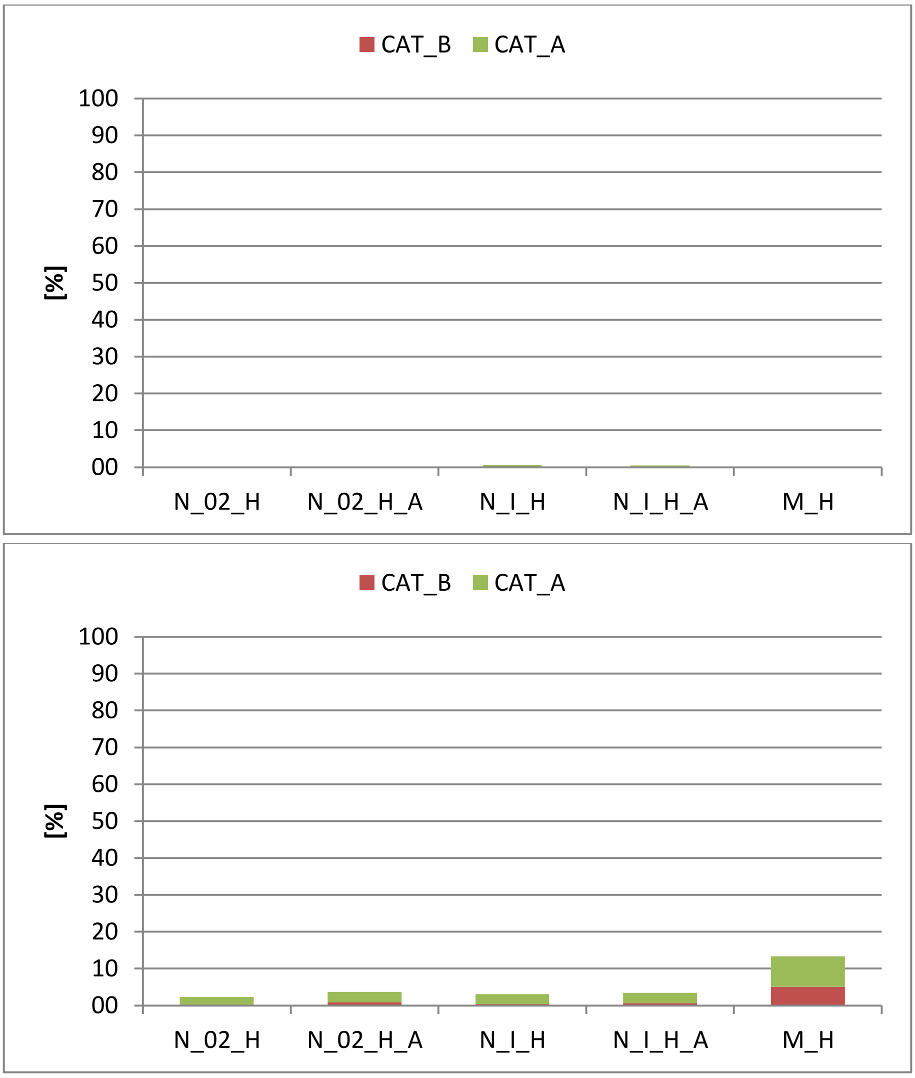


Figure 105 – Undercooling (top) and overheating (bottom) according to the ASHRAE55 adaptive model for five scenarios not equipped with a MCS.

Figure 106 illustrates the individual signature for the analyzed ventilation and cooling solutions. All the scenarios perform very well from both a thermal comfort and an IAQ point of view.
Among the naturally ventilated scenarios the one that performs best is the N_02_H_A, which proves that in the humid-continental climate there is no need for enhanced passive cooling strategy since the cooling load is quite low. It is true that the N_I_HC achieve better thermal comfort and IAQ than the N_02_H_A, but the improvement is so limited (0.2% the thermal comfort and 1.9% the IAQ, moreover with respect to category I), that the installation of a mechanical cooling system coupled with a change of strategy is not justified.
The best performing among the solutions that do not use mechanical cooling is the M_H that generate a 100% category II building with one of the lowest energy consumption. However we are not suggesting that the M_H should be the preferable solution as it has been evaluated according to the adaptive model (no cooling system is used) but using the mechanical ventilation instead of the natural one deprive the occupants from probably the best adaptation chance: the possibility to manually operate the windows according to the ventilation and thermal needs. Furthermore a domestic building completely lacking of operable windows is not realistic.
Comparing the performances of the M_H and the M_HC evaluated with two different comfort models (adaptive and non-adaptive respectively) might then be a misjudgment. If the comparison is made using the non-adaptive model for both the cases the M_H turns out to be absolutely inadequate. Another solution capable to ensure an excellent indoor environment with a reduced energy consumption is the M_HC_N_A, but again we believe that a 0.2% improvement in the thermal comfort and a 0.5% increase in the air quality do not justify the installation cost of a mechanical cooling system.
All this considered we are convinced that the N_02_H_A system is the best one because it combines the high quality environment of the mechanically cooled systems with the low energy consumption of the passively cooled ones.

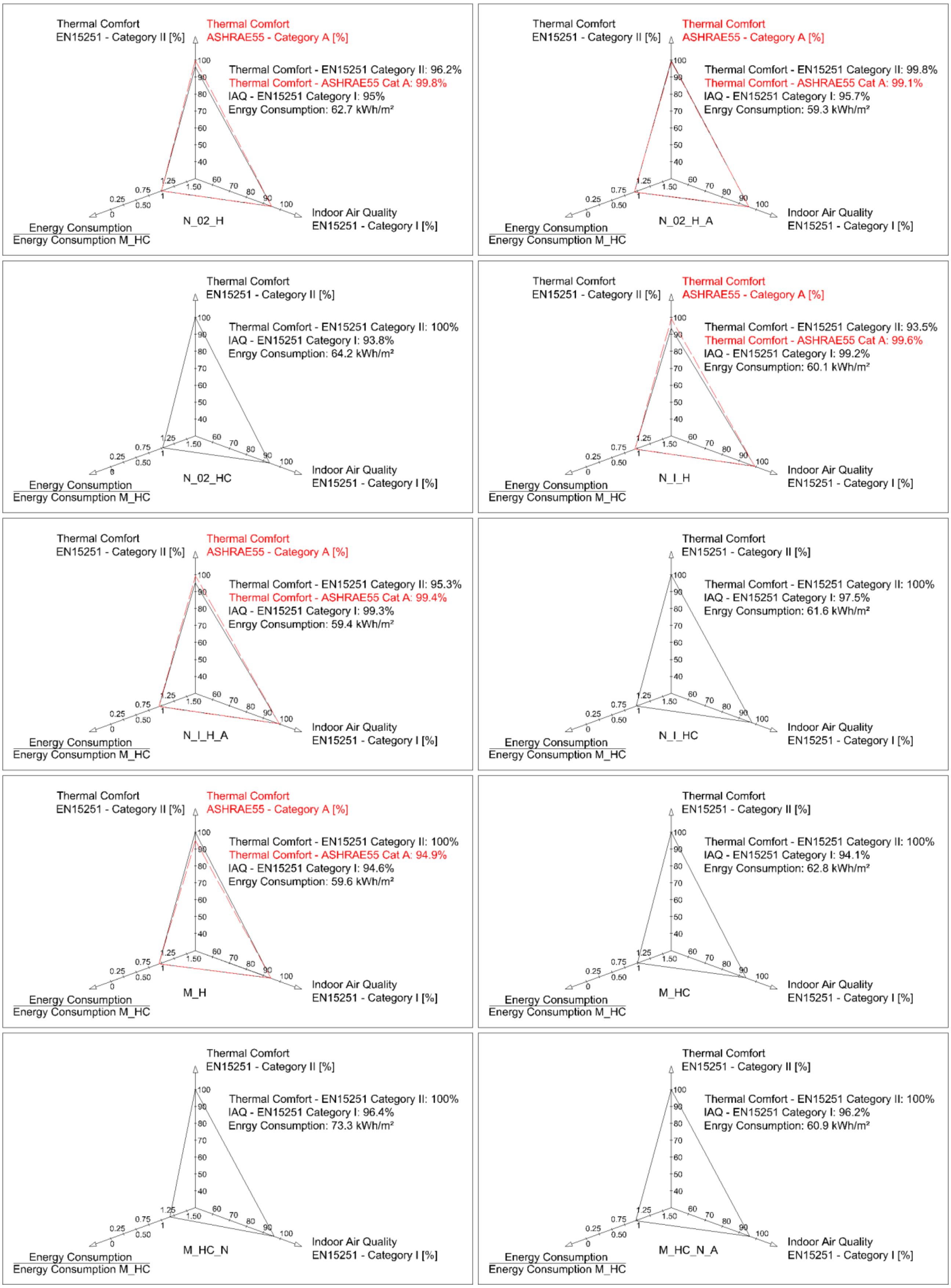


Figure 106 – Individual building signature for the ten scenarios.

7. ATHENS

This chapter is dedicated to the discussion of the results obtained for the city of Athens. Because of the climate conditions of the zone where the city is located, in particular the very high air temperatures reached in summer, the passive cooling strategies allows a consistent reduction in the energy consumption along with good performances in terms of both air quality and thermal comfort.

In Athens, with the selected thresholds (24°C for the daytime comfort ventilation and 25°C for the night cooling, as results of the thermal comfort and energy consumption optimization) the ventilation period goes from April 20th to October 30th, which means 194 days of natural ventilation over 365 (53% of the year).

7.1. Preliminary simulations

Temperature threshold for night ventilation

Night ventilation thresholds from 23.0°C to 25.5°C with a 0.5°C increase step have been tested, along with the reference case (NoNight). The results obtained are compared in Figure 107.

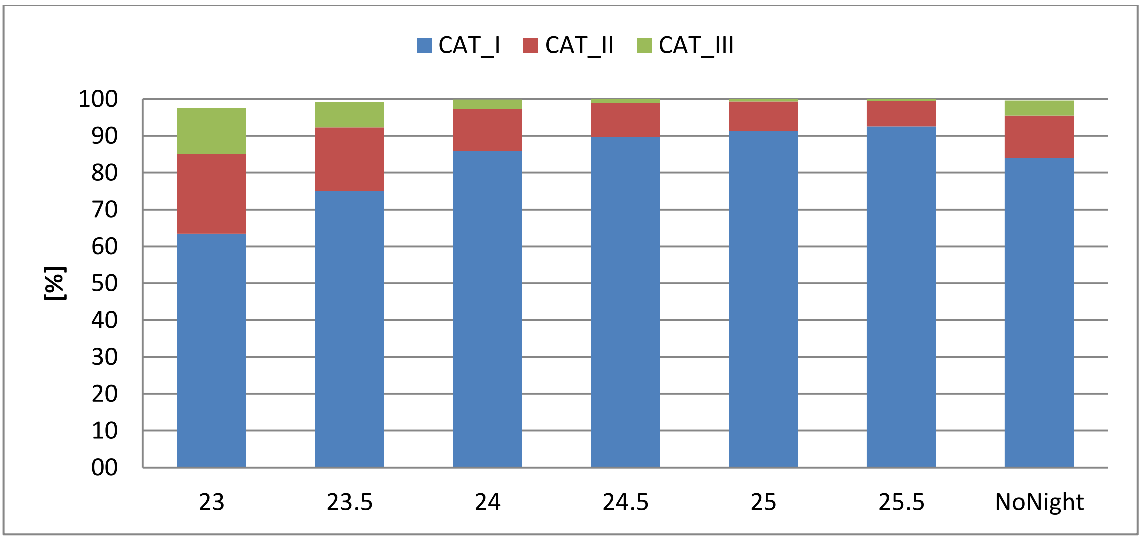


Figure 107 – Comparison of the thermal comfort, evaluated according to the adaptive model prescribed by the standard EN15251, for the tested night thresholds.

With respect to category II, the thermal comfort goes from a minimum of 85.1% for the 23.0°C solution to a maximum of 99.5% for the 25.5°C solution. The main cause of discomfort is the excessive cooling due to night ventilation. Looking at the separated undercooling and overheating (Figure 108) it is possible to see that in every scenario the temperature rises above the comfort level for a small percentage of hours during the ventilation period, but only in the scenario where the night ventilation strategy is not applied the temperature exceed the category II upper limit. The temperature is indeed too high to be considered comfortable for 4.5 % of the occupancy time.

Figure 108 – Undercooling (top) and overheating (bottom) of the dwelling according to the adaptive model prescribed by the standard EN15251.

Table 17 and Figure 109 prove that the 23.0°C and the 23.5°C thresholds not only cause discomfort, but also an increase in the energy consumption (a remarkable one for the 23.0°C threshold). For all the other solutions the energy demand for heating is equal to 1.2 kWh/m^2.

Night threshold [°C]	Enrgy consumption [kWh/m^2]
23.0	43.7
23.5	2.9
24.0	1.2
24.5	1.2

25.0	1.2
25.5	1.2
NoNight	1.2

Table 17 – Energy consumption for the tested night cooling thresholds.

It is clear at this point how in Athens night cooling is essential to achieve a thermal comfort level that a strategy based only on increased air velocities is not capable to obtain, but also that a misjudgment can cause an impressive percentage increase in the energy consumption. Based on those observations a 25.0°C threshold has been chosen for the night cooling with the intent to limit the overheating without causing the temperature to drop as well. For the strategies which combine mechanical cooling and night ventilation the threshold has been lowered to 24.5°C.

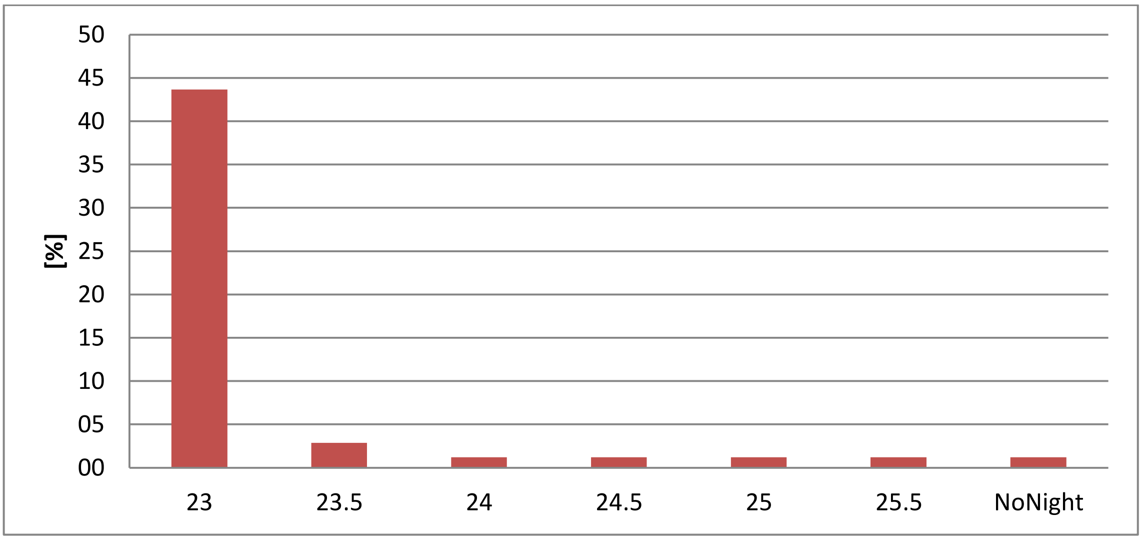


Figure 109 – Energy consumption for the tested night thresholds.

Orientation

Thermal comfort (Figure 110) and energy consumption (Figure 111) show the same trend: the North orientation, exposing to South the façade with the largest glazed surface, maximizes the solar gain. The heat delivered by the solar radiation reduces the energy that the heating system has to supply to the building and the undercooling during the transition season, phenomena already observed. On the other hand the summer overheating is slightly increased, which is new (in Rome and Berlin there was no overheating due to solar gain). For the South-West orientation it is true the opposite: the solar gain is minimized, the energy consumption and the undercooling increases and the overheating presents a minimum.

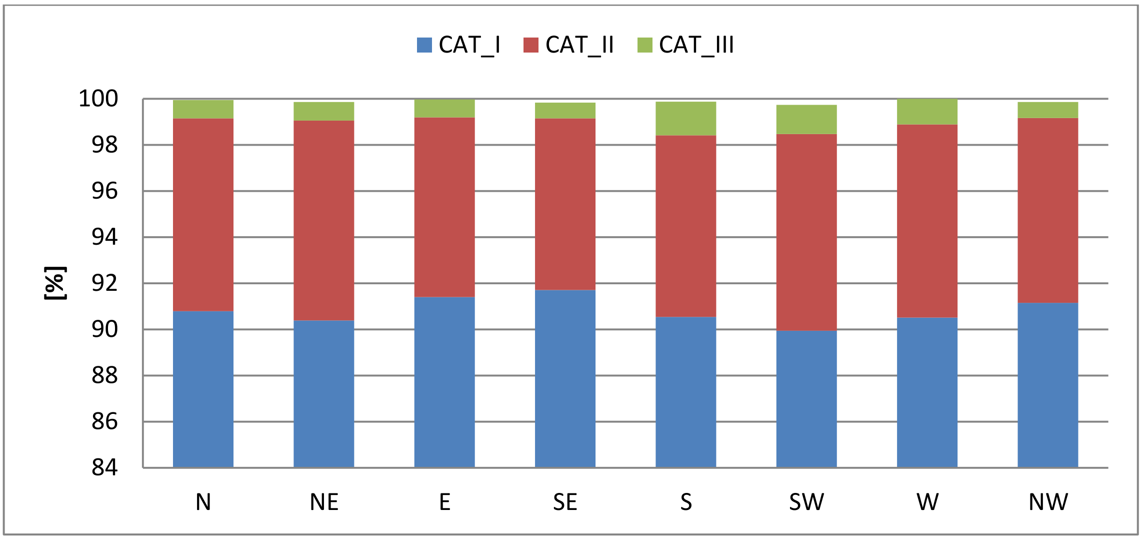


Figure 110 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested orientations.

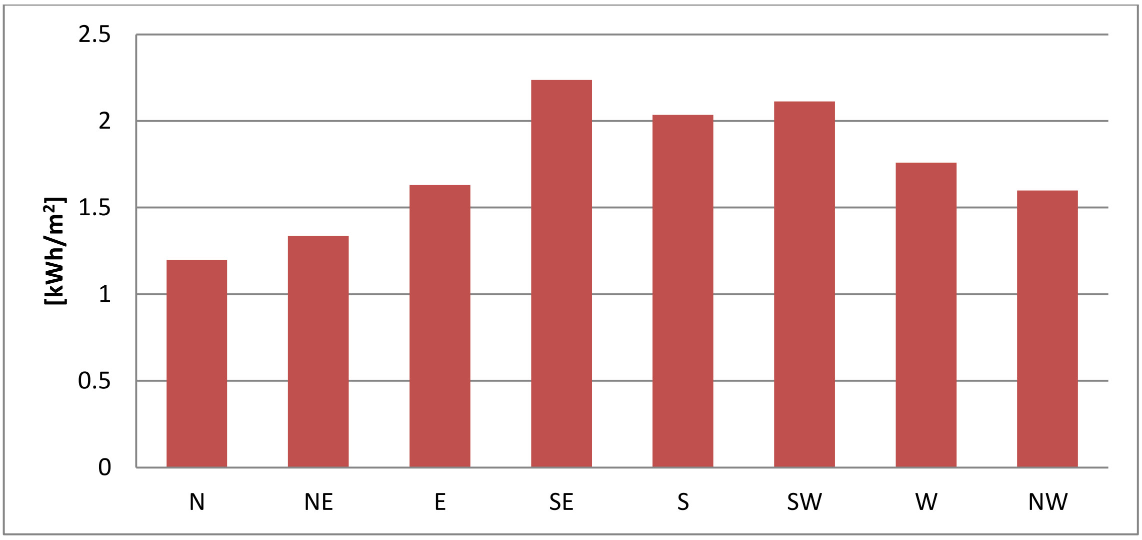


Figure 111 – Energy consumption for the tested orientations.

For the mean indoor air velocity (Figure 112), we can say that there is no a significant variation. Considered the climate conditions of Athens, the overheating prevention should be the main concern. The South-West orientation, minimizing the solar gain and showing one of the highest mean indoor air velocities (0.25 m/s), can be considered the best option, even if it presents some extra undercooling when compared with the other possible orientation.

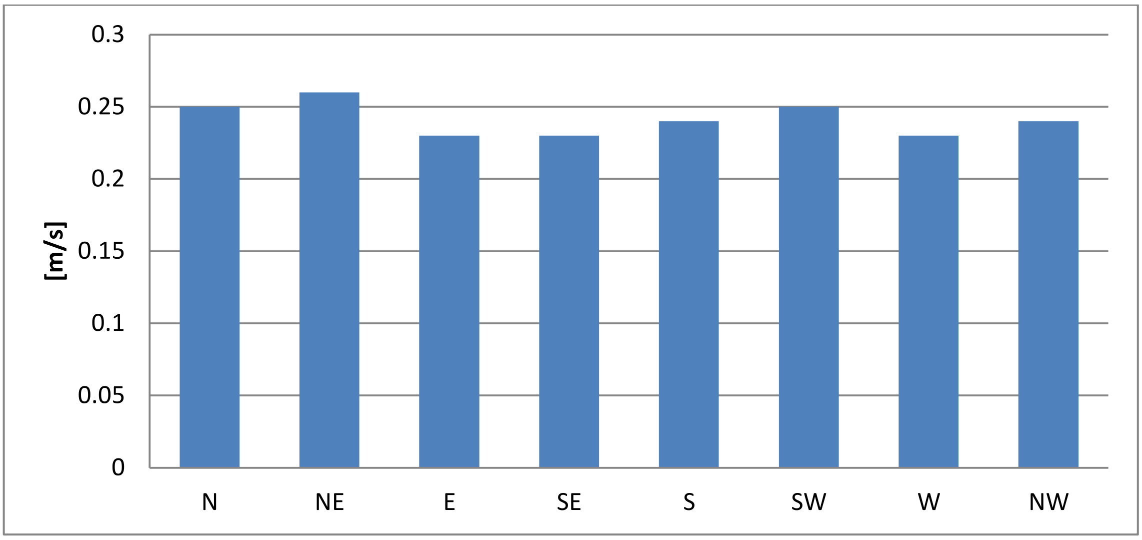


Figure 112 – Average indoor air velocity for the tested orientation.

Thermal mass

The sensitivity analysis showed a much larger influence of the building mass on the thermal comfort than Rome and Berlin (Figure 113). The reason is the larger amount of heat stored in the building structure during day. In Athens the air temperature is higher than in the other two locations and remains higher until late in the day (21:00), as it can be seen from Figure 115. Thus the building structure accumulates a larger amount of heat, which is released during night.

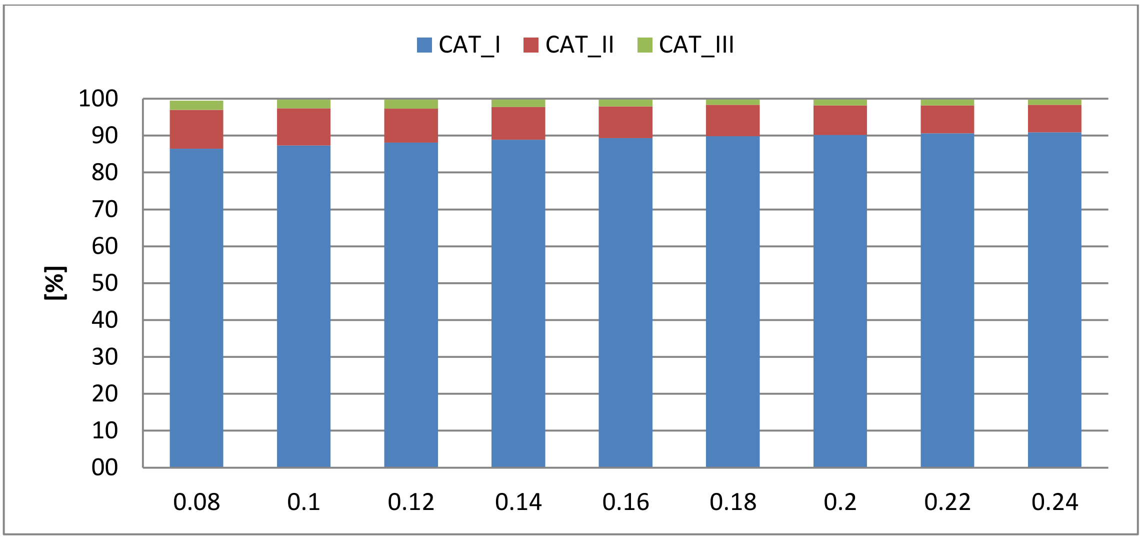


Figure 113 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested concrete layer thicknesses.

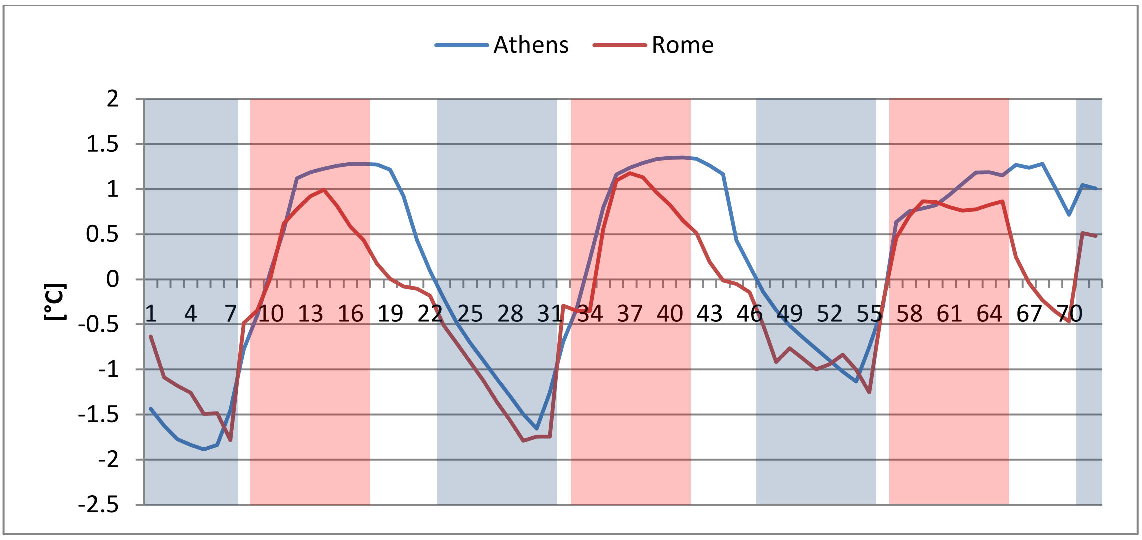


Figure 114 – Wall-to-air temperature difference.

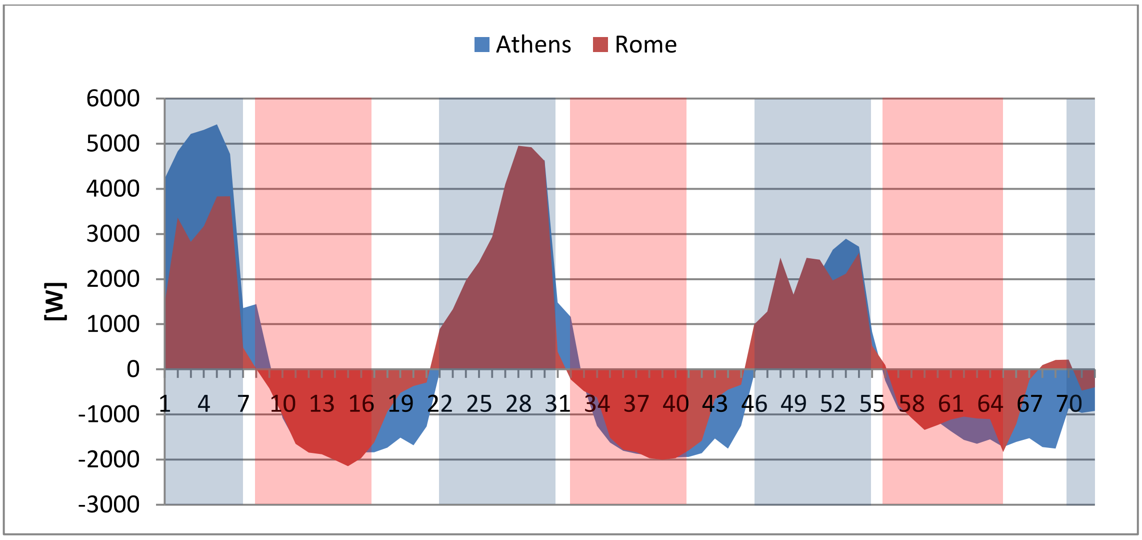


Figure 115 – Wall-to-air heat flux for.

The heat exchange rate is more efficient in Athens because the wall-to-air temperature difference is larger, even if the day-to-night temperature swing is higher in Rome. In Figure 114 and Figure 115 the phenomenon is shown on a three days period (September 8th to September 10th). From Figure 114 the larger temperature difference between wall and air results evident, especially during daytime (when the heat is stored in the mass). From Figure 115 the heat flux proves the higher efficiency of night ventilation in Athens: a larger amount of heat is stored in the building mass during day and is removed during night and early morning.

This is why increasing the concrete layer thickness from 0.08 m to 0.20 m the thermal comfort increases by 1.3% (in Rome we observed a 1.8% increase, this is because in Athens we have a much more adverse climatic condition, it is then harder to obtain a thermal comfort improvement. The 1.3% increase of Athens has then to be regarded as a better goal than the 1.8% of Rome) and the operative temperature in the warmest period of the year is considerably lower. Figure 116 shows a comparison between the operative temperatures for the two thicknesses on a three days period (August 2nd to August 4th). When the thermal mass is increased the operative temperature is decreased by 1°C on average, with a maximum difference between the two configurations of 1.7°C on August 3rd at 19:00, when the operative temperature is 32.3°C and 30.6°C for the 0.08 m thickness and the 0.20 m thickness respectively.

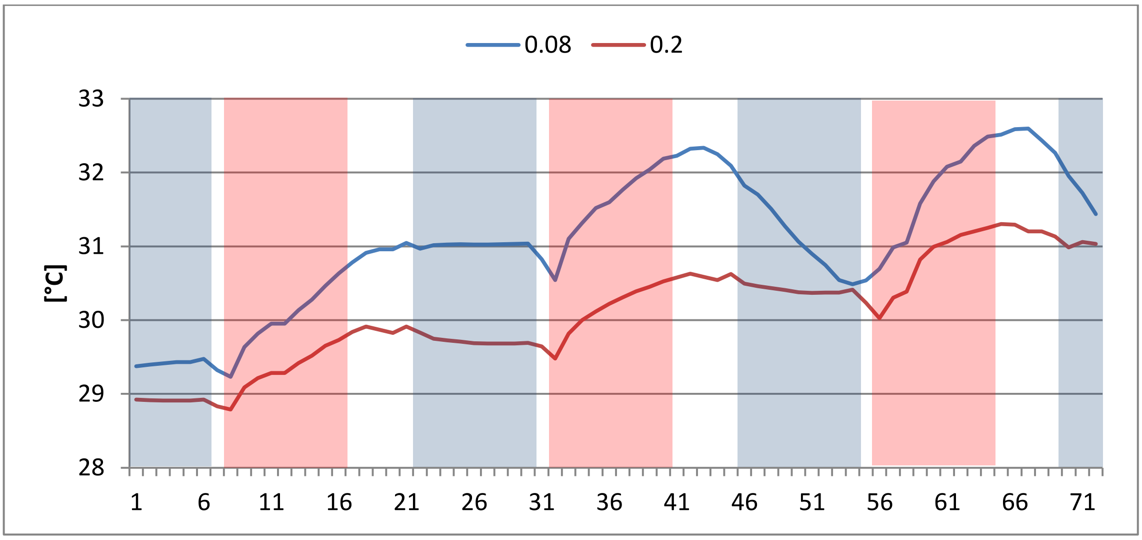


Figure 116 – Operative temperature.

The augmented thermal mass is beneficial also from an energetic point of view: the heating demand decreases by 31.7% moving from the 0.08 m to the 0.20 m thickness (Figure 117). For the same thickness increase the decrease was equal to 16.2% and 4.3% in Rome and Berlin respectively. From both Figure 113 and Figure 117 it is evident that increasing the concrete layer thickness above 0.20 m gives only a negligible improvement to the thermal comfort and a marginal reduction in the energy consumption, then 0.20 m have been chosen.

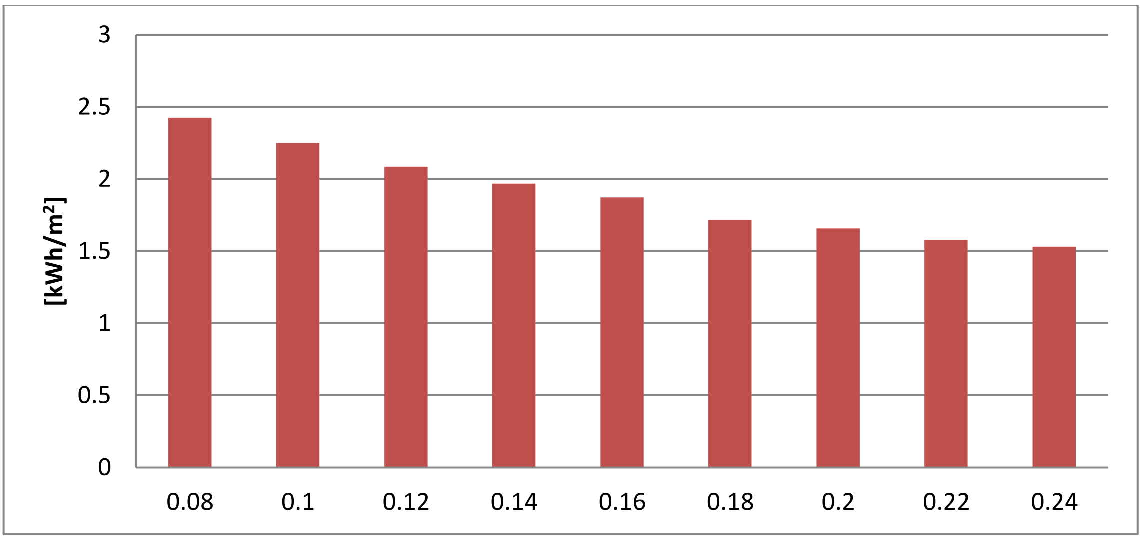


Figure 117 – Energy consumption for the tested concrete layer thicknesses.

An interesting phenomenon has been observed in Athens during the hottest period: if the building has a lot of internal mass the increase in the air temperature is slow. In Figure 118 the operative temperature for the 0.08 m and for the 0.24 m thicknesses is shown for a three days period (August 10th to August 12th). A squared marker identifies the temperature peak: the first day the increased thermal mass postpone the peak by 2 hours, the second and the third day there is a 1 hour shifting.

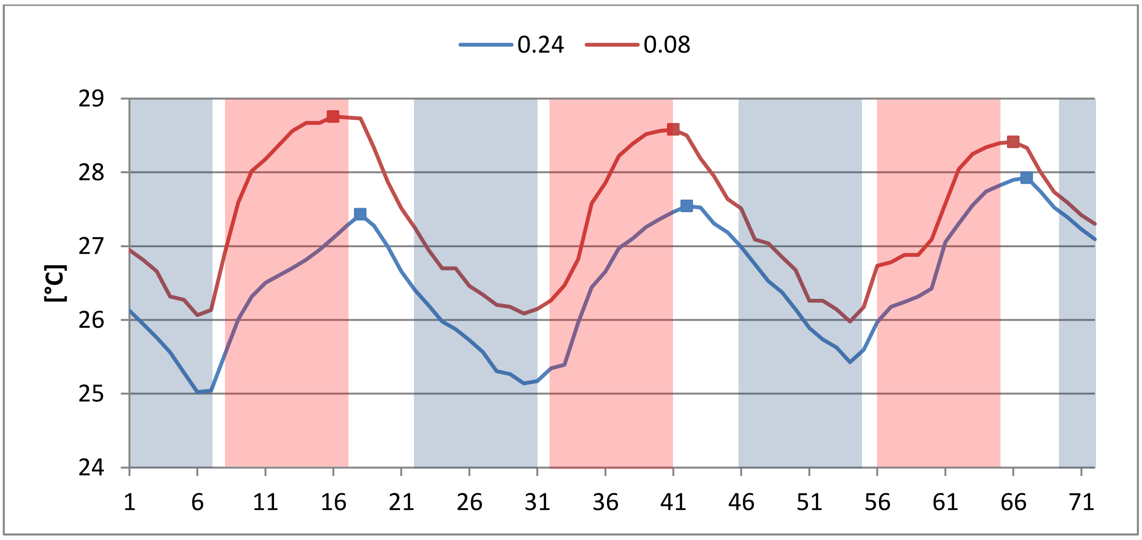


Figure 118 – Operative temperature.

7.2. Case studies

For Athens the ten configurations have the following settings.

- N_02_H presents an average indoor air velocity of 0.12 m/s.
- N_02_H_A uses a proportional controller set between 24.5°C (lower limit for the fully opened windows) and 23.5°C (upper limit for the fully closed windows). Between these two values the windows opening area is modulated.
- N_02_HC switches from natural ventilation to mechanical cooling when the indoor air temperature rises above 24.6°C.
- N_I_H grants an average indoor air velocity of 0.25 m/s.
- N_I_H_A is equipped with the same proportional controller installed in the N_02_H_A scenario.
- N_I_HC switches from natural ventilation to mechanical cooling when the indoor air temperature rises above 24.6°C.
- M_H is the reference case.
- M_HC is the fully mechanical system
- M_HC_N is mechanically ventilated and night cooled
- M_HC_N_A combines mechanical ventilation with modulated night cooling. During night, when the indoor air temperature is above 24.5°C, the windows are fully opened, between

23.5°C and 24.5°C are modulated and below 23.5°C are fully closed. The set point and the modulating range derive from an optimization process.

7.3. Indoor air quality

All the ventilation and cooling systems assure a fully category II building, but in particular the four naturally ventilated cases grant a category I one (Figure 119 and Table 18).

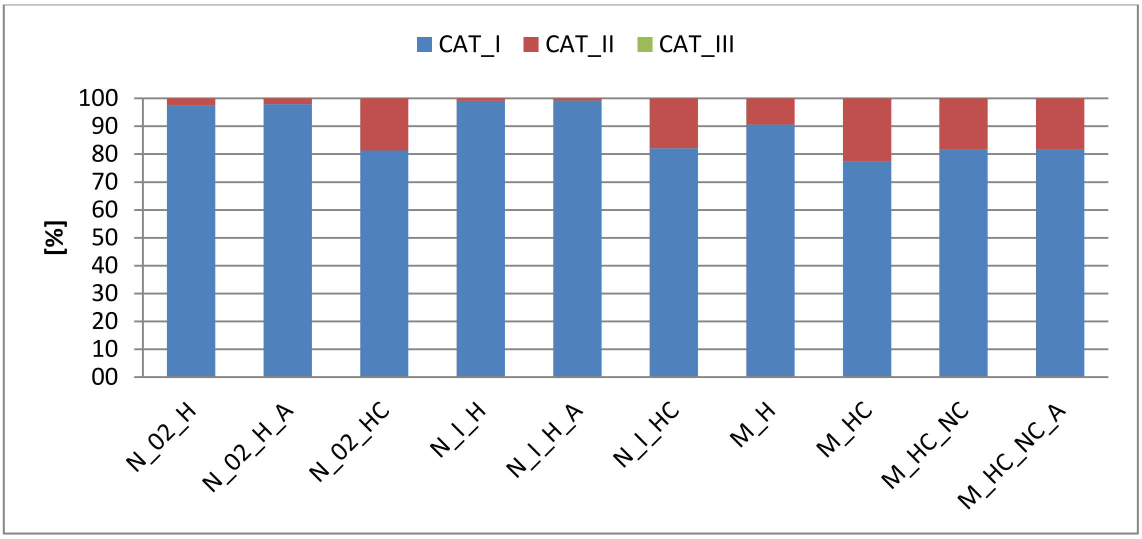


Figure 119 – IAQ evaluated according to the EN15251 for the ten scenarios.

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	97.6	100	100	+25.9
N_02_H_A	97.9	100	100	+26.3
N_02_HC	81.4	100	100	+5.0
N_I_H	99.1	100	100	+27.9
N_I_H_A	99.2	100	100	+28.0
N_I_HC	82.1	100	100	+5.9
M_H	90.6	100	100	+16.9
M_HC	77.5	100	100	-
M_HC_NC	81.5	100	100	+5.2
M_HC_NC_A	81.6	100	100	+5.3

Table 18 – IAQ evaluated according to the EN15251 for the ten scenarios.

What it is interesting is the lower IAQ of the mechanically ventilated cases when compared with the correspondent ones in Rome and especially in Berlin. The mechanical air flow rate is the very same, the explanation must then be found in the infiltration rate. Indeed the average infiltration rate is higher (e.g.) in Berlin than in Athens because of the higher temperature difference between inside and outside, that means because of the larger pressure difference (Figure 120 and Figure

121 shows the difference in the infiltration rate and in the pressure gap respectively on a four days period from June 1st to June 4th for the M_H case). Thus in Athens the IAQ improvement that can be achieved by mean of natural ventilation, when compared with the mechanical one, is higher (between 26% and 28%, while in Berlin it ranged from 1% to 5.5%).

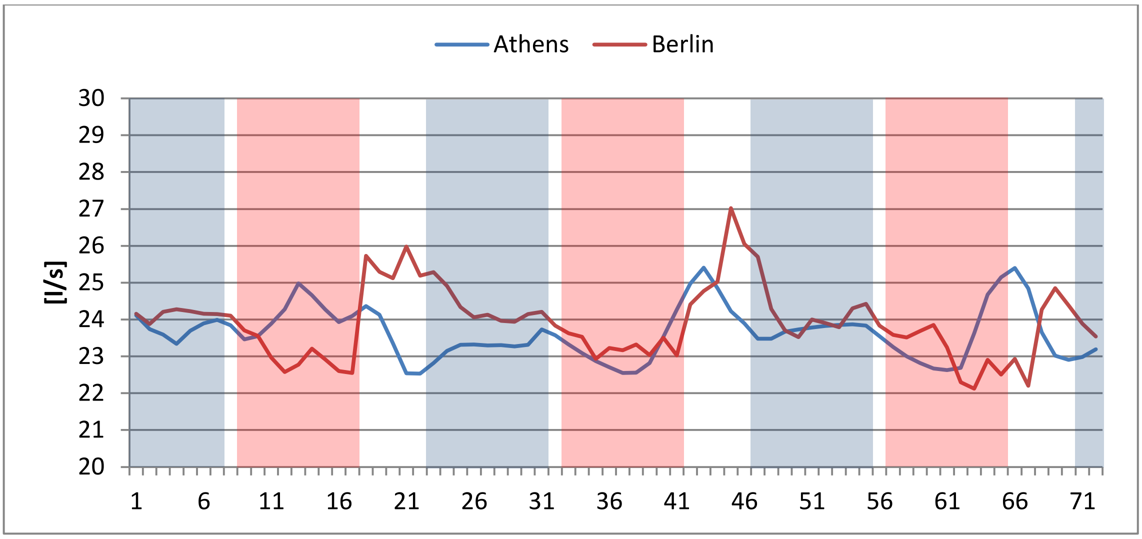


Figure 120 – Infiltration rate.

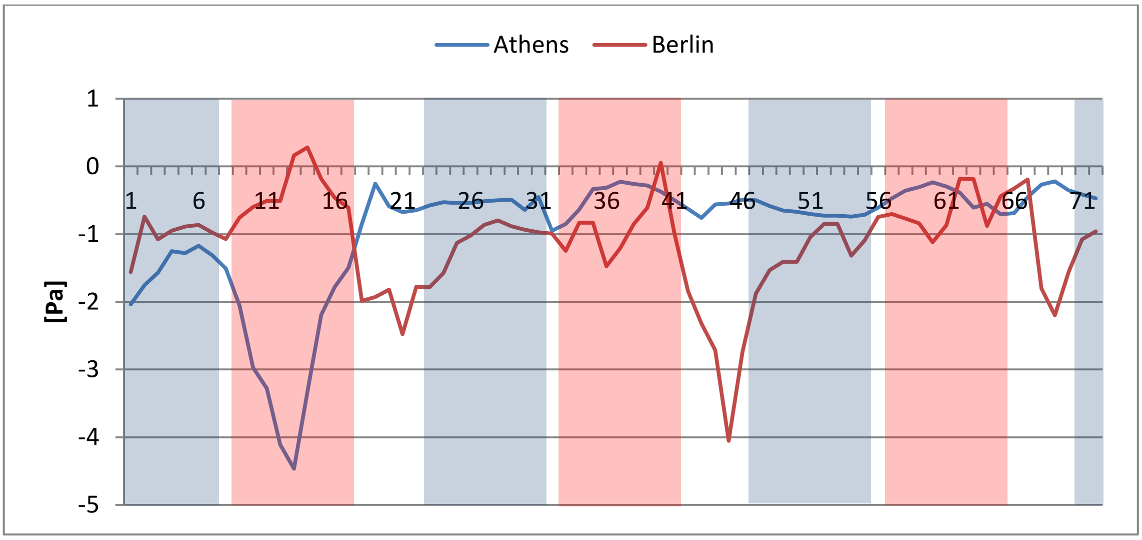


Figure 121 – Outdoor-indoor pressure diference.

7.4. Energy consumption

In the warm and dry climate of Athens most of the energy consumption is for cooling need (82%), then the cases which rely on natural ventilation are capable to achieve a very high reduction in the energy demand. Indeed from Figure 122 and Table 19 it is possible to notice how all solutions, natural and hybrid, present a decreased total energy consumption when compared with the reference case (M_HC). In particular the N_02_H and the N_02_H_A, thanks to the intense use of the night cooling strategy, present a reduction of 83% (that is higher than the energy saved for cooling need only because also the fans present a lower consumption). Differently from Rome and Berlin, the implementation of an automatic window controller in the naturally ventilated scenarios do not reduce the energy consumption (but, as we will see, slightly improves the thermal comfort), thus showing that in Athens the night undercooling risk is not a big issue.

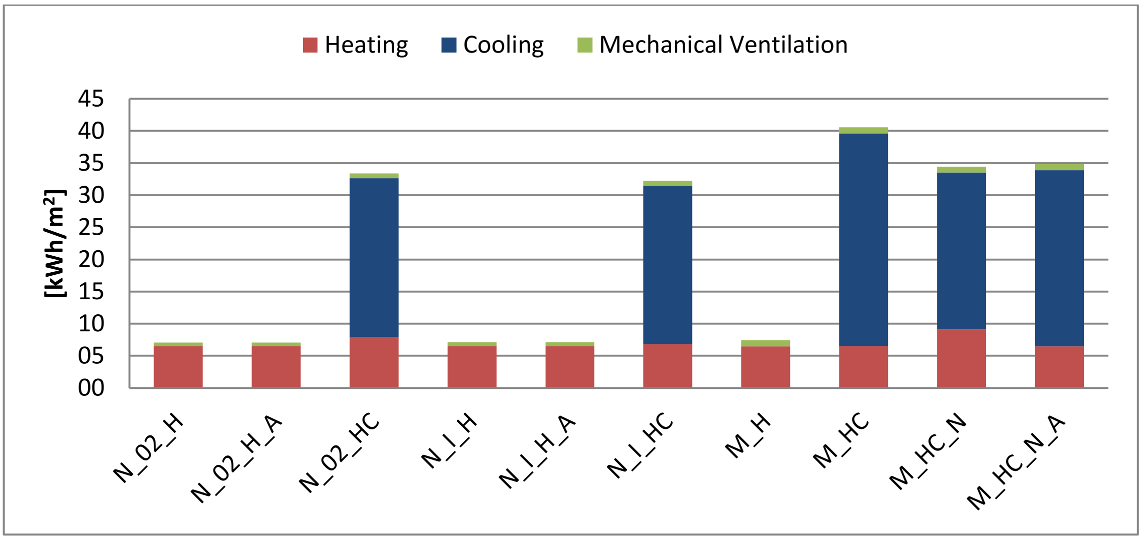


Figure 122 – Energy consumption for the ten scenarios.

Case studies	Heating [kWh/m^2]	Coolig [kWh/m^2]	Mechanical Ventilation [kWh/m^2]	Total [kWh/m^2]	Variation [%] (reference case: M_HC)
N_02_H	6.5	0.0	0.6	7.1	-82.5
N_02_H_A	6.5	0.0	0.6	7.1	-82.5
N_02_HC	7.9	24.7	0.8	33.4	-17.7
N_I_H	6.5	0.0	0.6	7.1	**-82.5**
N_I_H_A	6.5	0.0	0.6	7.1	-82.5
N_I_HC	6.8	24.7	0.8	32.3	-20.4
M_H	6.5	0.0	0.9	7.4	-81.8
M_HC	6.5	33.1	0.9	40.6	-
M_HC_N	9.1	24.4	0.9	34.4	-15.3
M_HC_N_A	6.5	27.4	0.9	34.8	-14.3

Table 19 – Energy consumption for the ten scenarios.

In general the combination of passive and active cooling strategies allows a reduction of the total energy consumption, but, with the exception of the M_HC_N_A, also produces a slight increase in the heating demand. This occurs because in the transition seasons during daytime the temperature rises above the 24.6°C cooling set point and the mechanical cooling system is switched on, the following night the windows are left open and the temperature drops below the 21.0°C heating set point (there is no heat to remove from the building mass) then the heating system is operated. An example is given in Figure 123 for the M_HC_N on a three days period (May 11th to May 13th).

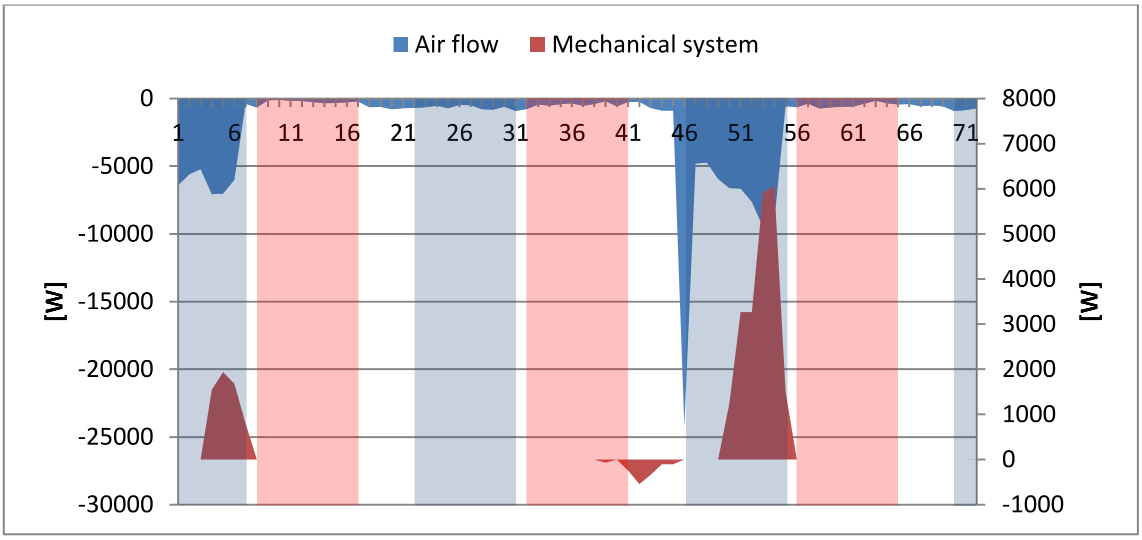


Figure 123 – Heat flux.

Nevertheless if we look at the overall energetic performance, when a hybrid system is used in Athens, a limitation to the night cooling potential, imposed by mean of an automatic controller, increases the energetic consumption (while in Rome and Berlin it required a constraint to the nighttime air flow rate). In Figure 124 (air flow rate), Figure 125 (perceived operative and mean air temperature) and Figure 126 (heat flux) a comparison between the M_HC, the M_HC_N and the M_HC_N_A cases is established on a three days period (May 21st to May 23rd).

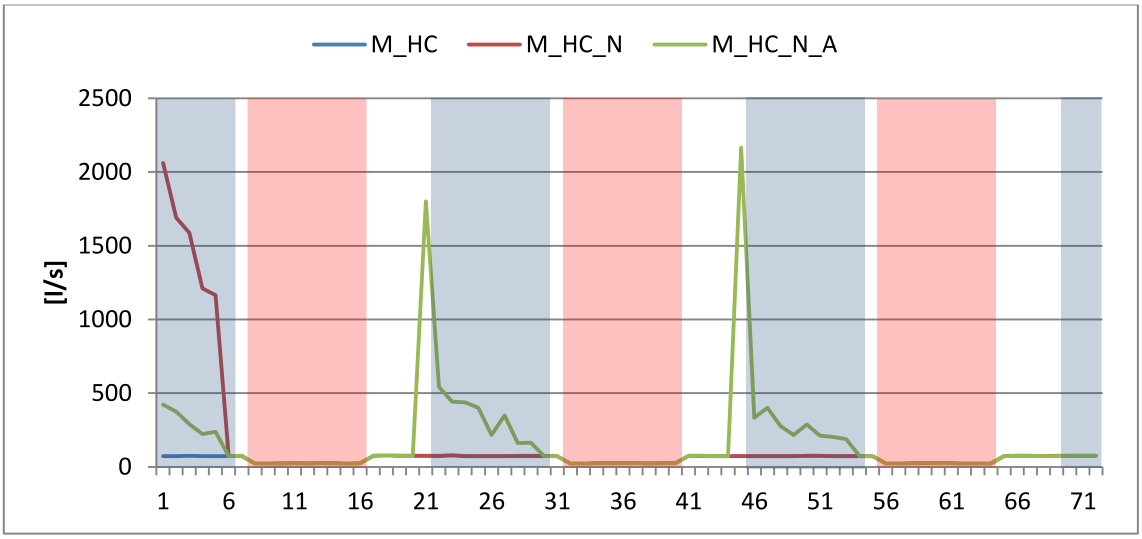


Figure 124 – Total air flow rate.

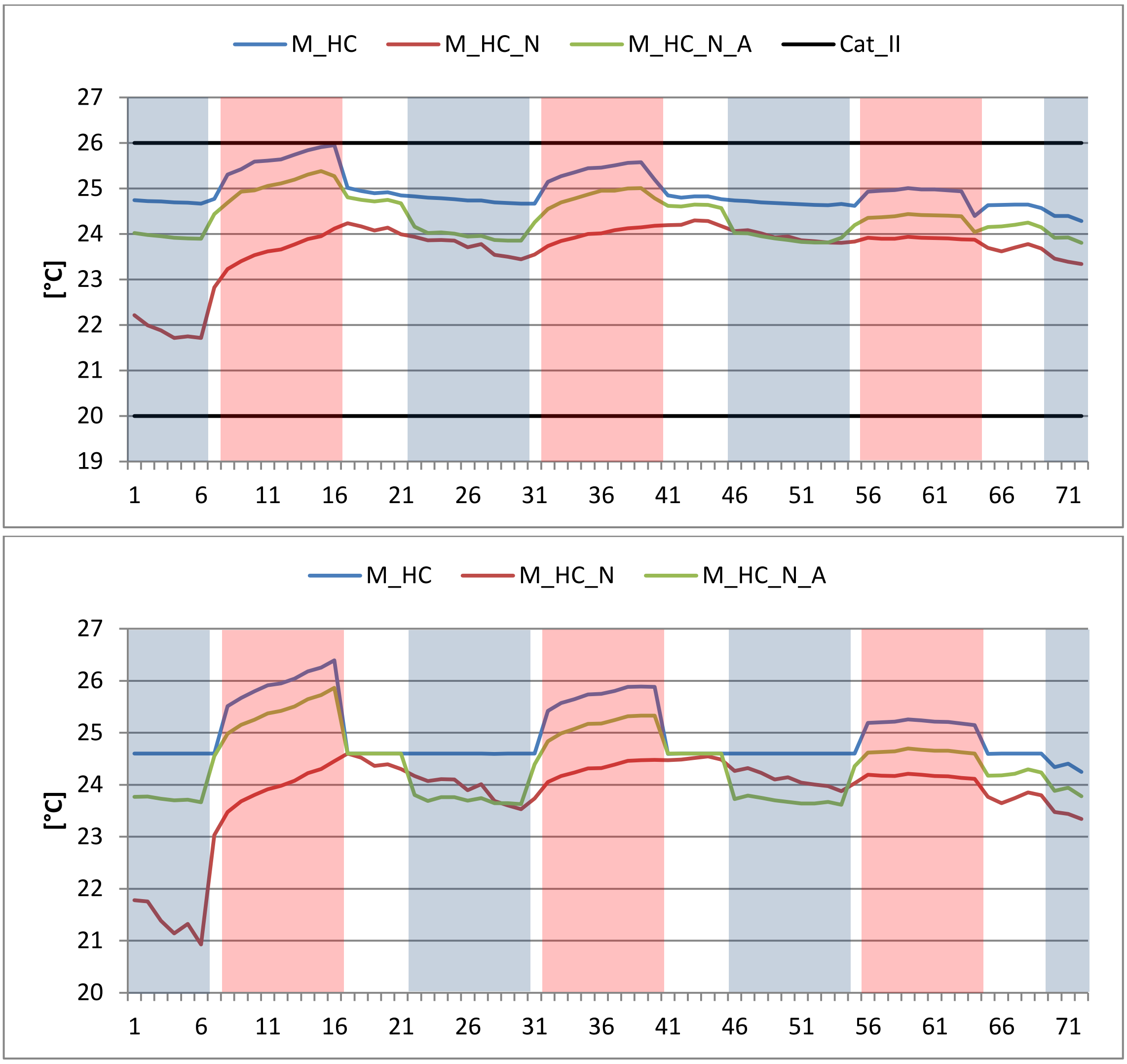
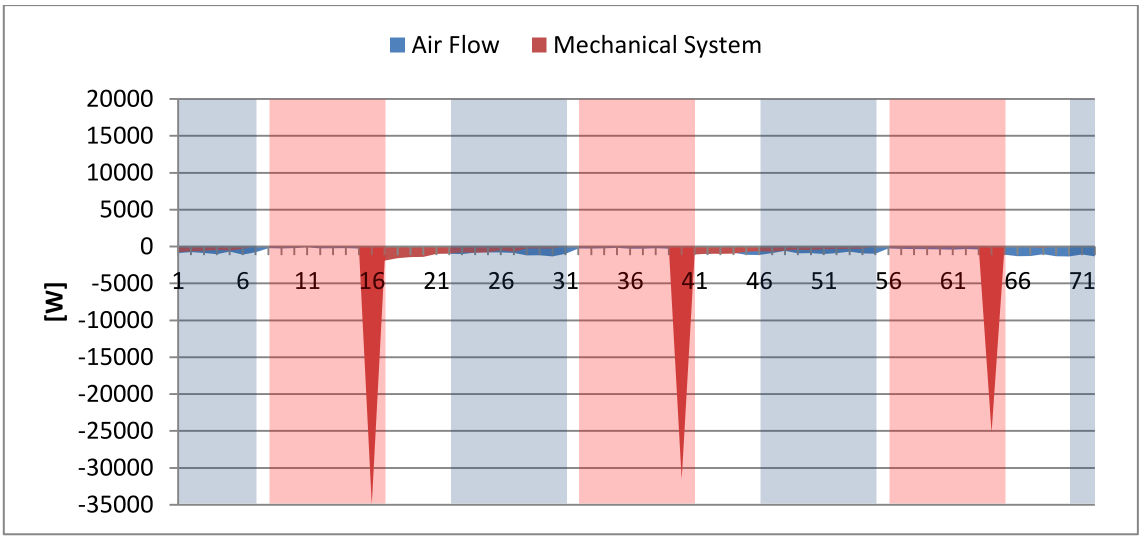
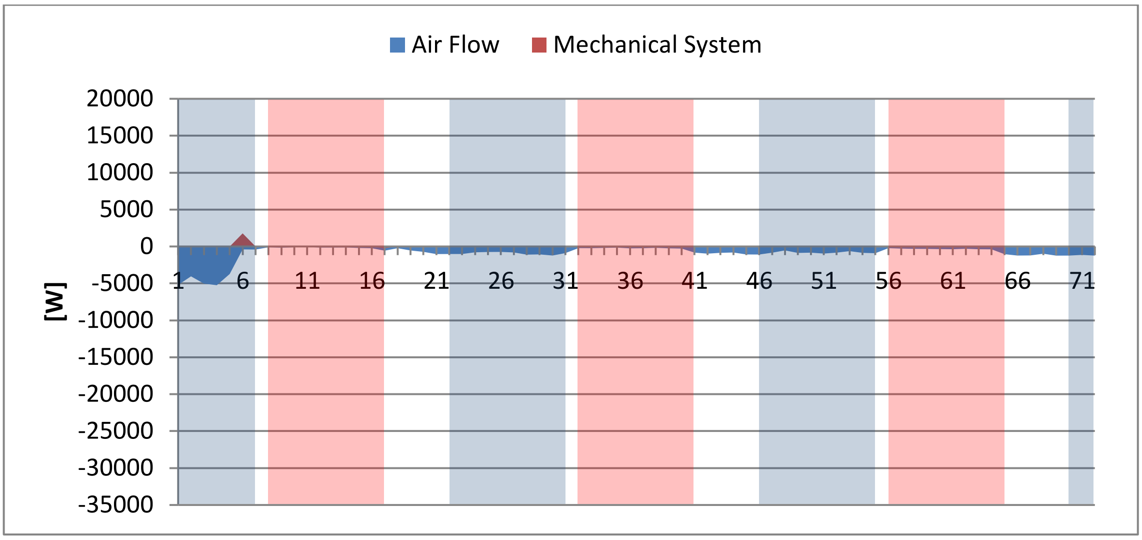


Figure 125 – Perceived operative temperature (top) and mean air temperature (bottom).





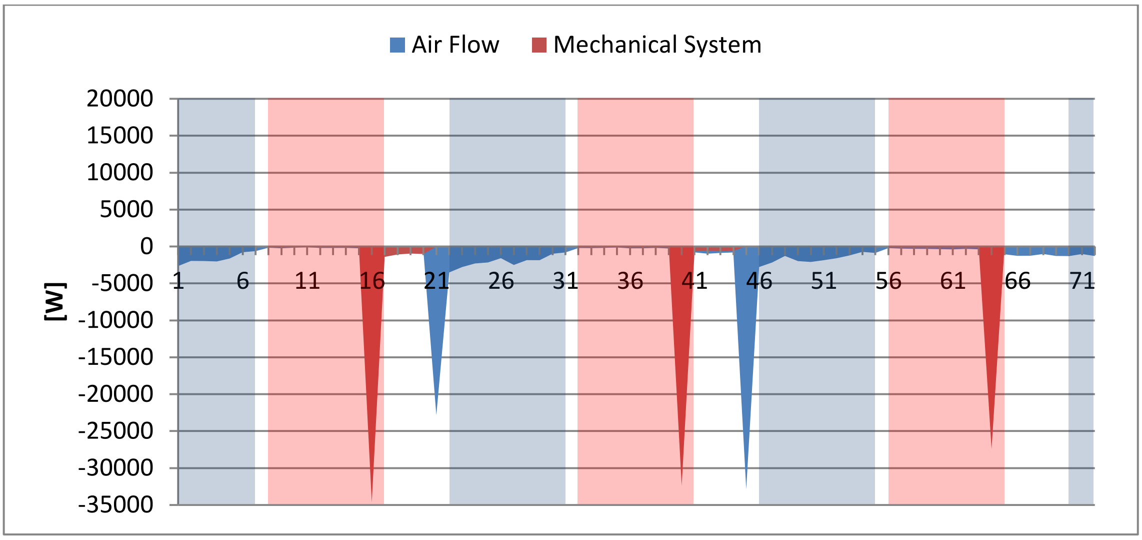


Figure 126 – Heat flux (M_HC at the top, M_HC_NC in the middle and M_HC_NC_A at the bottom).

During the transition seasons the mechanical cooling system is on for most of the occupancy time, even during night, and the energy consumption for cooling is elevate (117.8 kWh in the three days). The M_HC_N_A solution reduces the number of hours during which the cooling system has to operate and, with it, the energy consumption (101.2 kWh in the three days). But it is with the M_HC_N strategy that the best performances are obtained: the strategy reduces to 0.2 kWh the cooling load in the three days period, with a slight increase in the heating demand (1.8 kWh). With the exception of the first night, when the temperature drops causing some discomfort and the extra heating demand, the M_HC_N present an operative temperature close to 24°C and a very flatten curve: the peaks are leveled and the temperature is more homogeneous.

7.5. Thermal comfort

The adaptive model has been used to evaluate the thermal comfort in the scenarios without mechanical cooling (Table 20 and Figure 127).

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	86.2	96.9	100.0	-0.9
N_02_H_A	90.7	99.0	100.0	+1.2
N_I_H	85.4	97.2	99.6	-0.6
N_I_H_A	86.6	97.5	99.6	-0.3
M_H	37.0	48.4	62.1	-50.5

Table 20 – Thermal comfort according to the EN15251 adaptive model for the scenarios not equipped with a MCS.

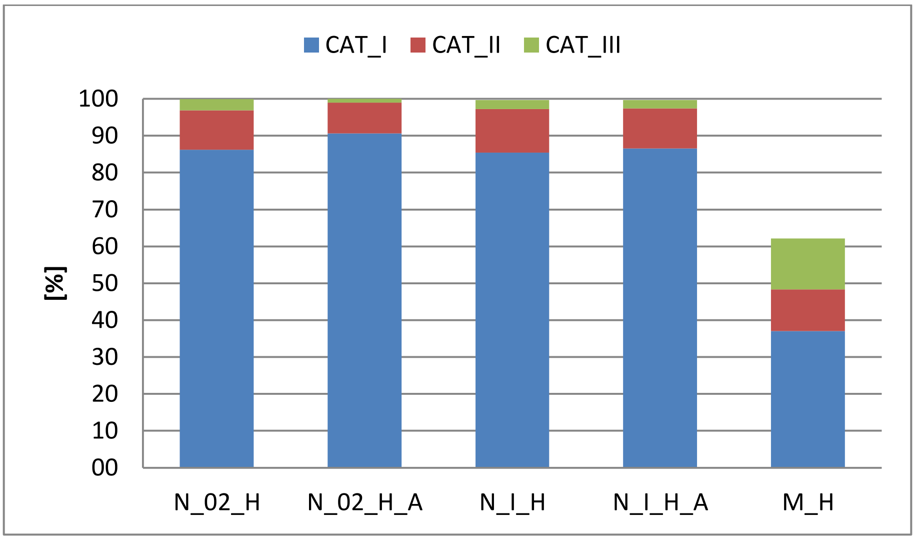


Figure 127 – Thermal comfort according to the EN15251 adaptive model for the scenarios not equipped with a MCS.

When the dwelling is naturally ventilated it obtains the status of category II building. Again increasing the daytime air velocity the comfort is improved. In Rome and Berlin we saw that the increased air velocity reduces the application of the night ventilation and improves the comfort by preventing the undercooling generated by the nighttime temperature dropping. In Athens it is quite the opposite: the increased air velocities reduce the overheating by providing ventilative cooling in addition to the night cooling. Indeed the undercooling with and without increased air velocities is the very same (2.3%) but the overall thermal performance is slightly improved when the daytime air velocity is increased (Figure 128).

As expected the M_H case is absolutely not comfortable, being unable to achieve a category II indoor environment for even half of the occupancy time.

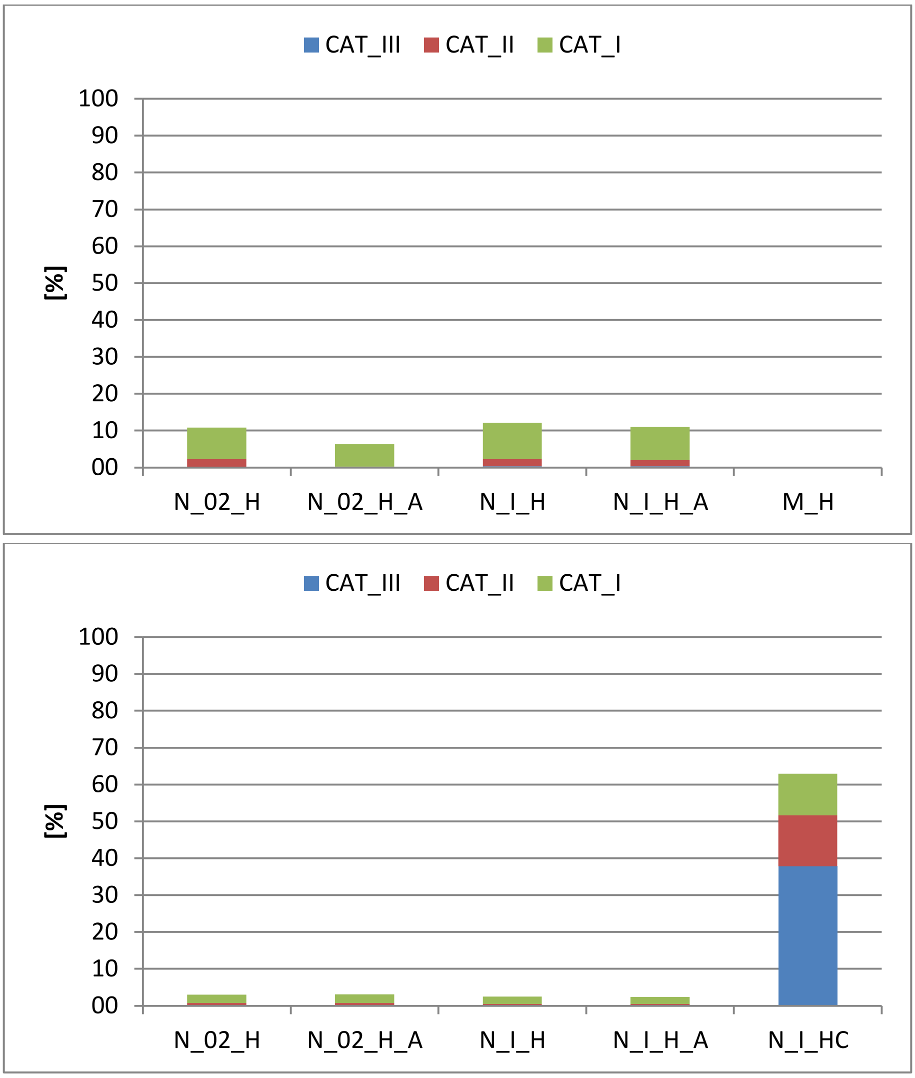


Figure 128 – Undercooling (top) and overheating (bottom) according to the EN15251 adaptive model for the scenarios not equipped with a MCS.

In general the passive cooling strategies do not achieve the same comfort of the reference case (M_HC), with the exception of the N_02_H_A one, which is capable to improve the thermal comfort by 1.2%. According to the adaptive model the best performing solution is then the N_02_H_A one, which, in addition, presents the lowest energy consumption. But the N_I_H solution achieves a very good thermal comfort, combined with a drastically decreased energy consumption and an improved IAQ, without requiring an automatic controller. Then it is our opinion that the N_I_H strategy should be preferred to the N_02_H_A one.

The evaluation made with the non-adaptive model is shown in Figure 129 and Table 21 and Figure 130, where the inadequacy of the passively cooled scenarios seems evident: apparently natural ventilation is not capable to grant a perceived operative temperature below the 26°C category II threshold for c.a. 40% of the occupancy time.

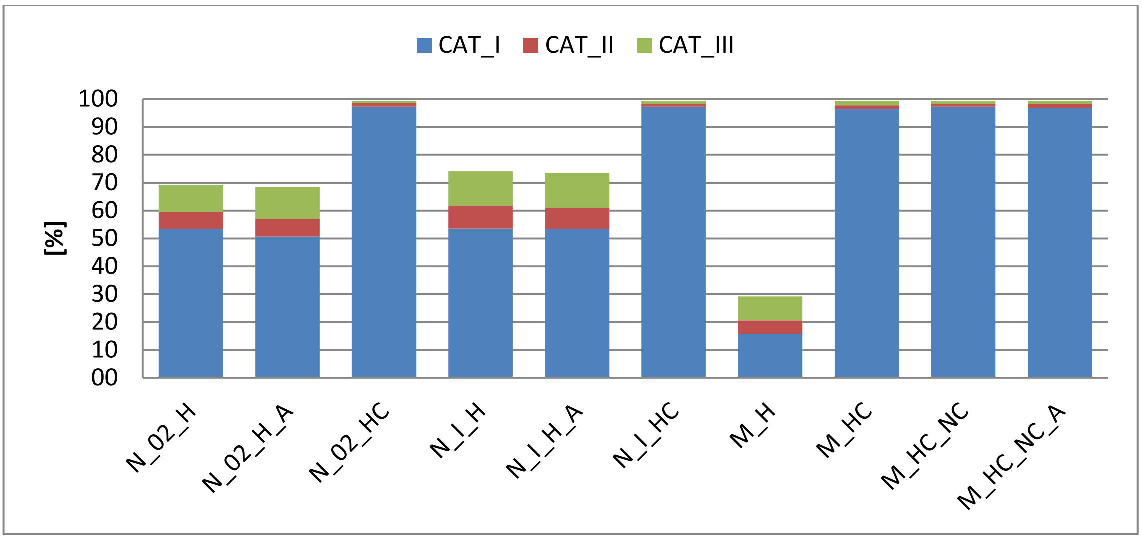
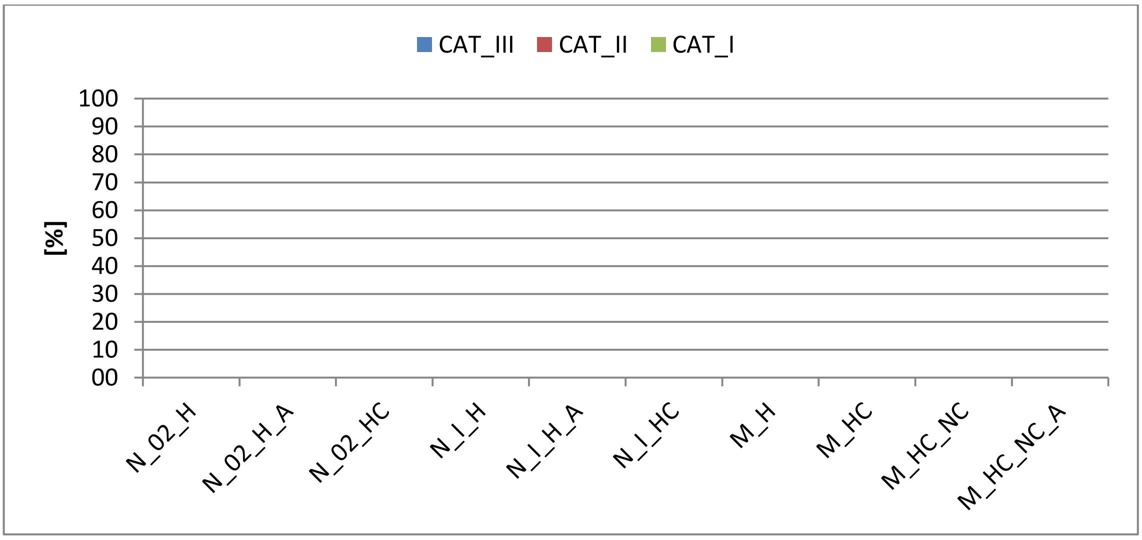


Figure 129 – Thermal comfort according to the EN15251 non-adaptive model for the ten scenarios.

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	53.3	59.5	69.2	-
N_02_H_A	50.7	57.0	68.4	-
N_02_HC	97.2	98.5	99.4	-2.0
N_I_H	53.6	61.7	74.1	-
N_I_H_A	53.3	60.9	73.5	-
N_I_HC	97.3	98.4	99.3	+0.6
M_H	15.8	20.6	29.2	-
M_HC	96.5	97.8	99.4	-
M_HC_NC	97.3	98.4	99.4	+0.6
M_HC_NC_A	96.7	98.2	99.3	+0.4

Table 21 – Thermal comfort according to the EN15251 non-adaptive model for the ten scenarios.



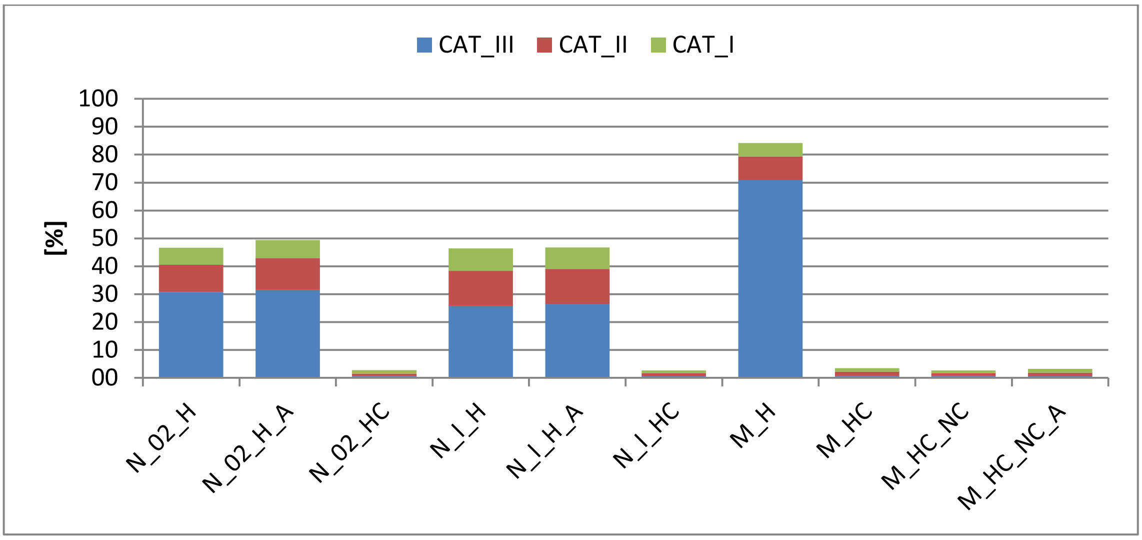
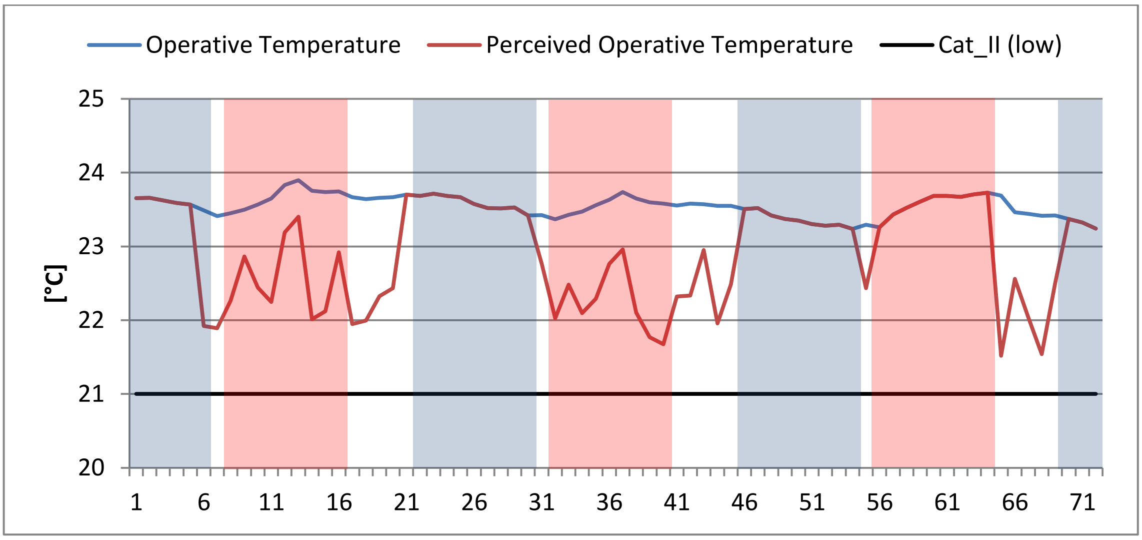


Figure 130 – Undercooling (top) and overheating (bottom) according to the EN15251 non-adaptive model for the ten scenarios.

Form Figure 131 (comparison on a three days period between October 27th and October 29th) it possible to see that the operative temperature in the N_I_H scenario is, except for the first day, very close to the operative temperature and in the N_02_H one, and that what causes the perceived operative temperature to drop below the category I lower threshold is the ventilative cooling that leads to a decrease in the temperature experienced by the body equal to 2.6°C and 2.0°C for the N_I_H and for the N_02_H case respectively. It is true, on the other hand, that the lower limit for category II defined according to the adaptive model rises above 25°C (APPENDIX B) and that, when evaluated with the non-adaptive model or the ASHRAE55 adaptive model (Figure 132), N_I_H performs even better than N_02_H_A.



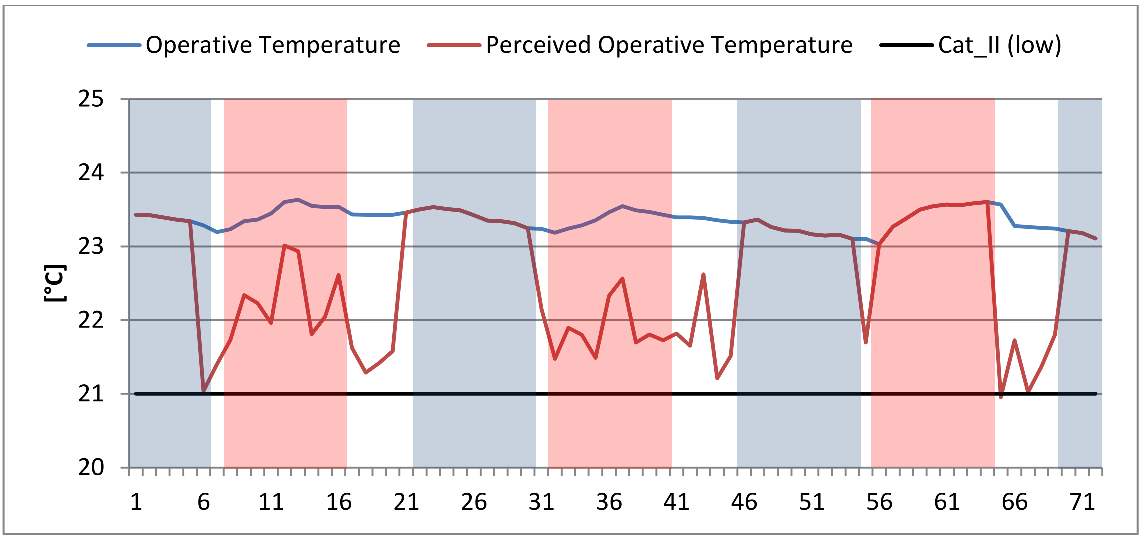


Figure 131 – Operative and perceived operative temperature (N_02_H at the top and N_I_H at the bottom).

When the building is thermostatically controlled, the thermal comfort is very high (all five scenarios are in category I), but, how we could see, the energy consumption is very high as well.
Among the solutions which combine active and passive cooling the N_I_HC is the one which is capable to obtain the largest improvements with a 0.6% increase in thermal comfort, a 5.9% increase in the IAQ and a 20.5% reduction in energy consumption. Also the night cooling alone achieves a general improvement of the indoor environment (+0.6% the thermal comfort, + 5.2% the IAQ and -15.3% the energy consumption) when applied in a building thermostatically controlled.
In Athens more than in any other location, when the mechanical system is assisted by natural means to control the overheating, especially night cooling, the indoor environment is beneficially affected and the energy consumption is lowered.
And always in Athens more than in other location, the comfort categories prescribed by the EN15251 adaptive model present very high upper limits (30.7°C for category I, 31.7°C for category II and 32.7°C for category III), and it is hard to believe that a temperature close to 32°C (category II) can be considered comfortable. The purpose of the project is not to criticize the standard, but it is very interesting at this point to evaluate the results with the less relaxed comfort categories prescribed by the standard ASHRAE55. According to the American standard all naturally ventilated cases are affected by overheating. In three scenarios there is some undercooling when we refer to category A: N_02_H because of the abuse of night ventilation, N_I_H and N_I_H_A because of the draft sensation. Figure 134 shows the night undercooling that occurs in the N_02_H and not in the N_I_H case, while Figure 135 shows the draft sensation that affects the N_I_H and not the N_02_H case, proving what just stated.

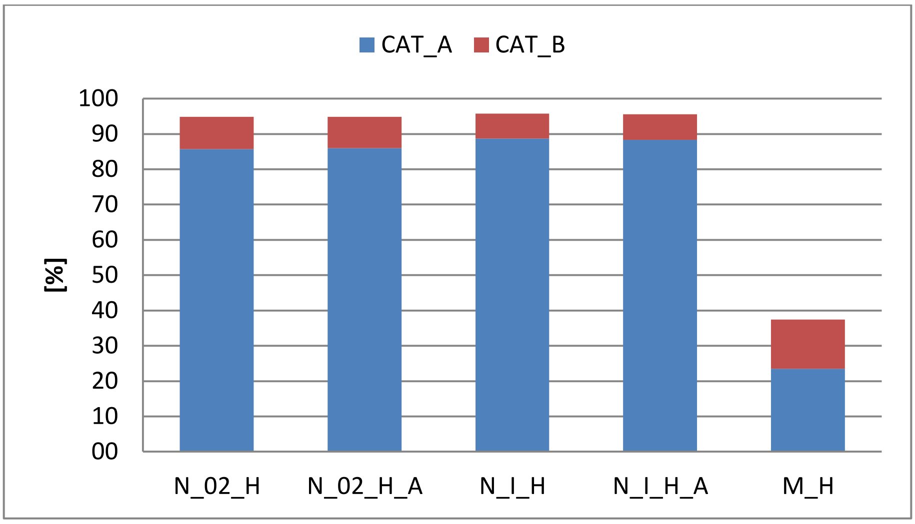


Figure 132 – Thermal comfort according to the ASHRAE55 adaptive model for the scenarios not equipped with a MCS.

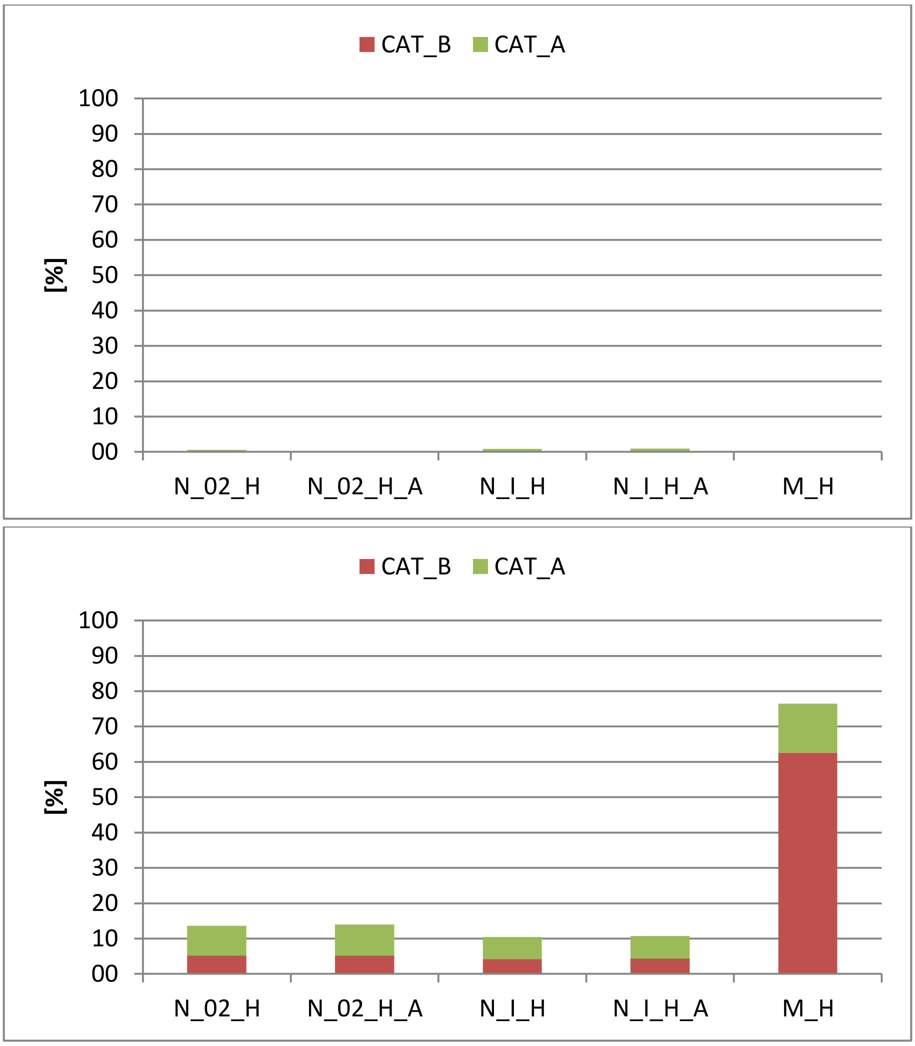


Figure 133 – Undercooling (top) and overheating (bottom) according to the ASHRAE55 adaptive model for the scenarios not equipped with a MCS.

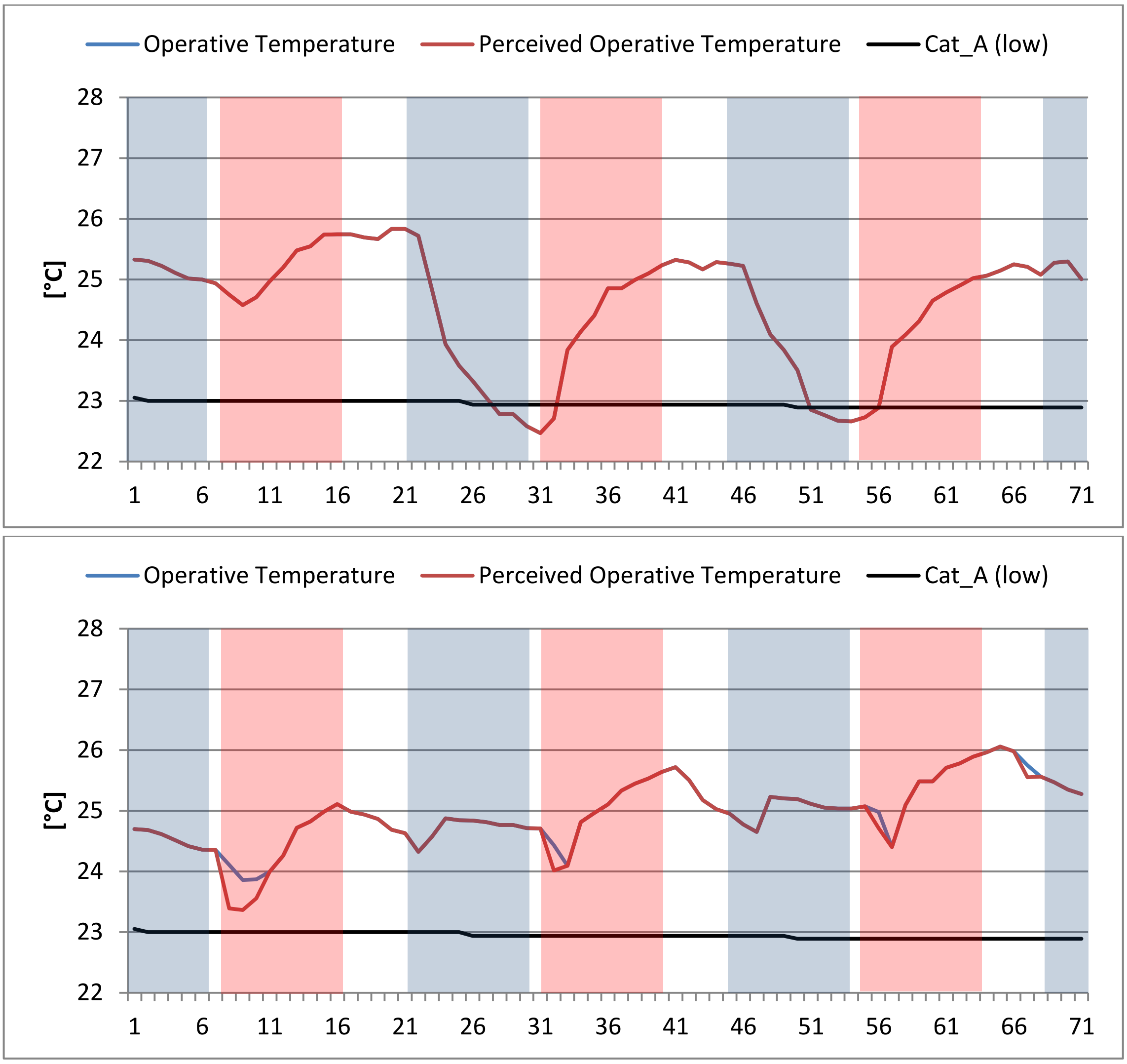
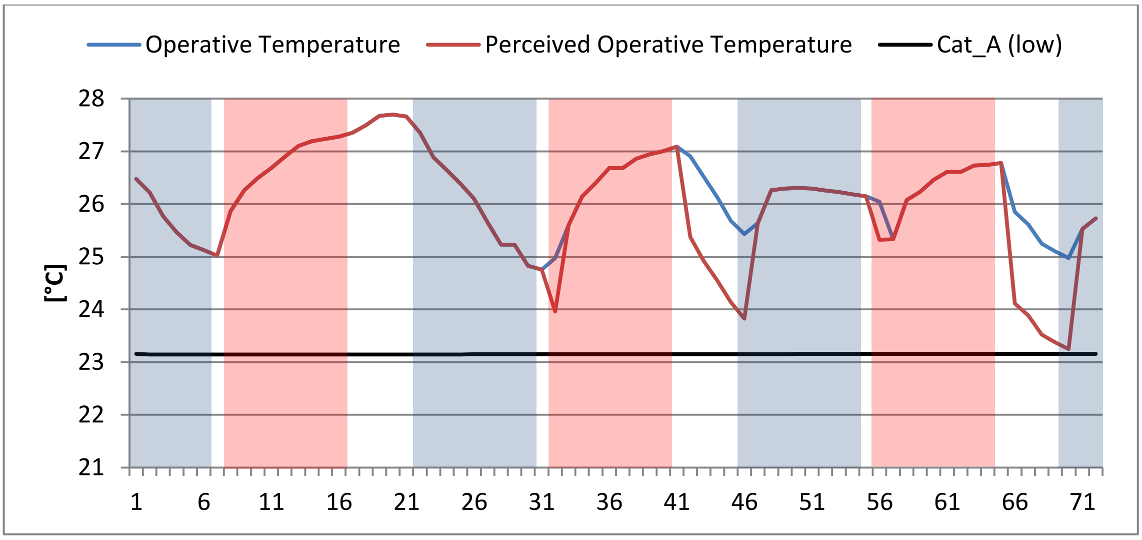


Figure 134 – Night undercooling affecting the N_02_H scenario (top), but not the N_I_H one (bottom).



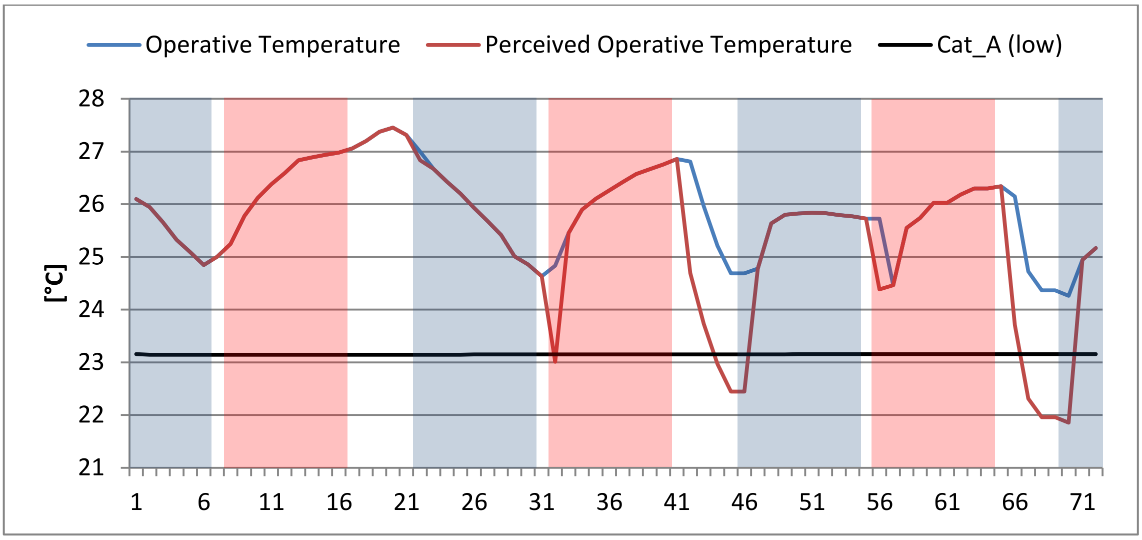


Figure 135 – Draft sensation affecting the N_I_H case (bottom), but not the N_02_H one (top).

Figure 136 shows the individual building signatures for Athens.
In Athens the passive cooling strategies have been proven to be very efficient in providing a good indoor environment and a remarkable reduction in the energy consumption for cooling need (from 82.4% for the N_I_H to the 82.6% of the N_02_H and of the N_02_H_A cases).
In particular from Figure 136 it seems clear that the N_02_H_A and the N_I_H performs excellently, but while the first one requires an automatic controller to prevent the night cooling strategy form causing undercooling, in the second one it is the ventilation strategy itself that allows to obtain a better comfort condition, improving, in addition, the IAQ. Then in our opinion the N_I_H, being a more reasonable solution for a domestic building, should be preferred to the N_02_H_A. Furthermore the comfort of the N_I_H is higher according to both the EN15251 non-adaptive and the ASHRAE55 adaptive models.
As for the hybrid systems, very good results are obtained when the night ventilation potential is not constrained by an automatic controller, in particular the implementation of both ventilative and night cooling grants the highest energy saving (-20.4%) and the best indoor environment (+0.6% the thermal comfort and +5.9% the IAQ).
We can then conclude that, differently from Rome and Berlin, the increased air velocities represent a very reliable and energy saving technique to increase the comfort inside the building, but they need to be combined with night cooling to generate a passive cooling strategy capable to achieve good thermal environment.

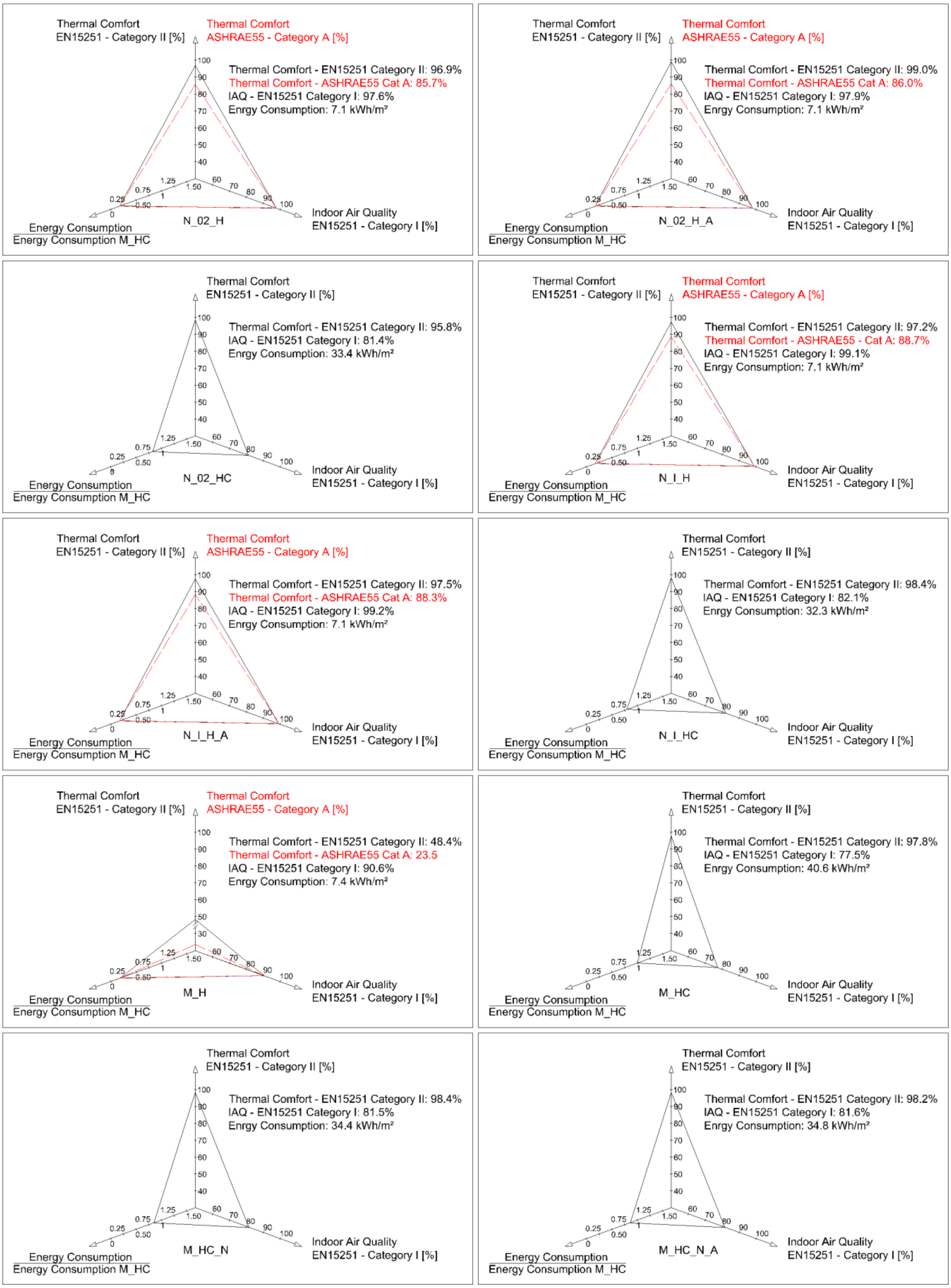


Figure 136 – Individual building signature for the ten scenarios.

8. COPENHAGEN

Among the chosen locations, Copenhagen is the one that presents the coldest climatic condition. As we will see in this chapter the passive cooling strategies that performed well in the other cities result excessively aggressive and cause undercooling in the dwelling. In particular the draft sensation is responsible for the discomfort during the natural ventilation period. As in Berlin, night cooling is the best strategy to reduce the cooling load, but differently from Berlin, night ventilation is here capable to meet the cooling load during the entire natural ventilation period, providing very good thermal comfort.

The natural ventilation period starts on April 30th and ends on September 17st, passive cooling strategies are then applied for 141 days over 365 (39% of the year).

8.1. Preliminary simulations

Temperature threshold for night ventilation

The evaluation of the influence of the night cooling threshold on thermal comfort and energy consumption took into account temperature levels between 22.0°C and 24.5°C with a 0.5°C increase step (Figure 137 and Figure 139). The analysis revealed that for thresholds higher than 23.5°C (included) the night cooling strategy is never applied during the year, while for thresholds lower than 22.5°C (included) the use of night ventilation increases the discomfort, causing undercooling (Figure 138), and the energy consumption for heating need (Figure 139 and Table 22).

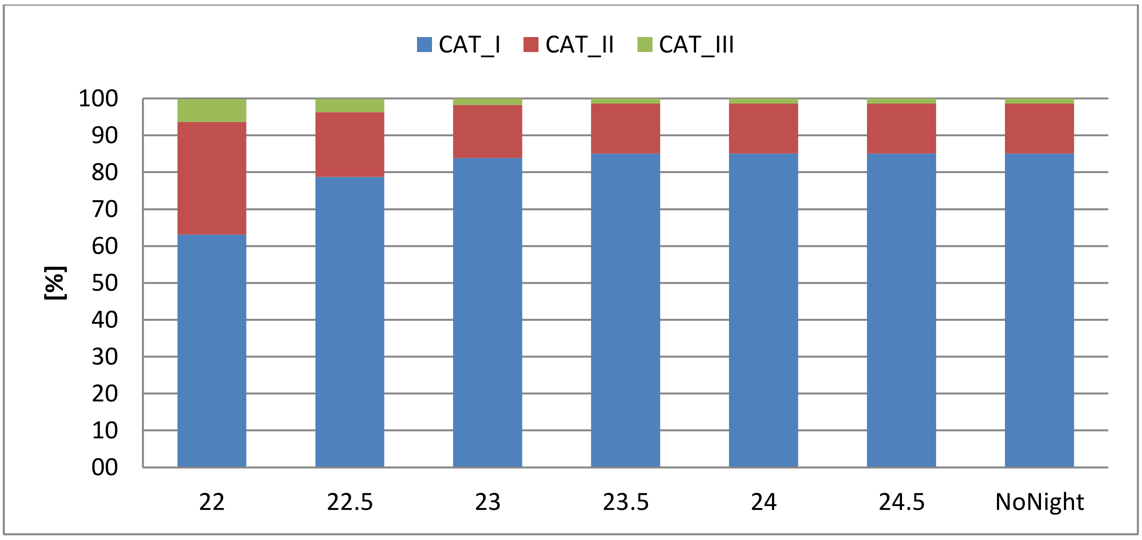
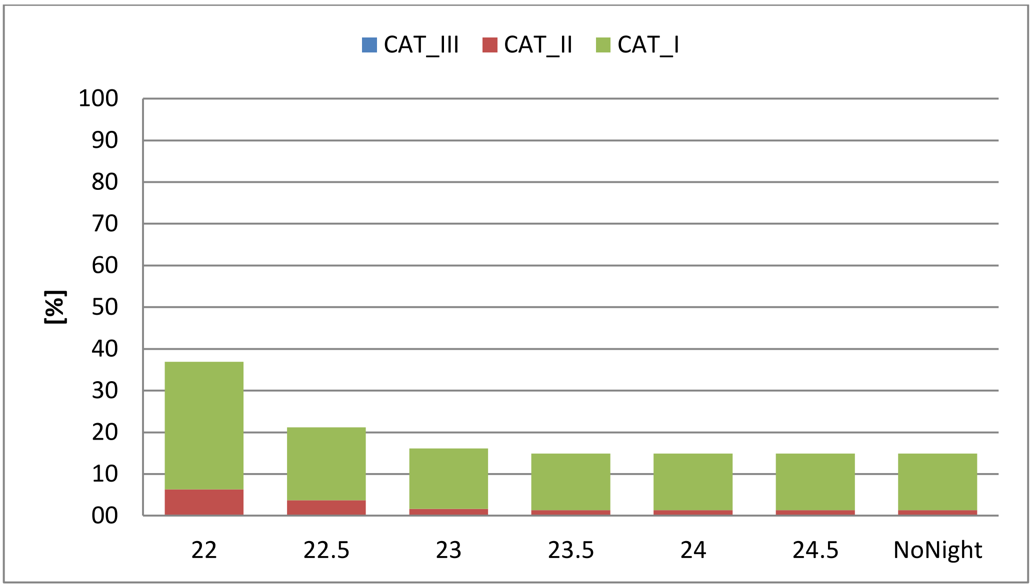


Figure 137 – Thermal comfort according to the EN15251 adaptive model for the tested night cooling thresholds.



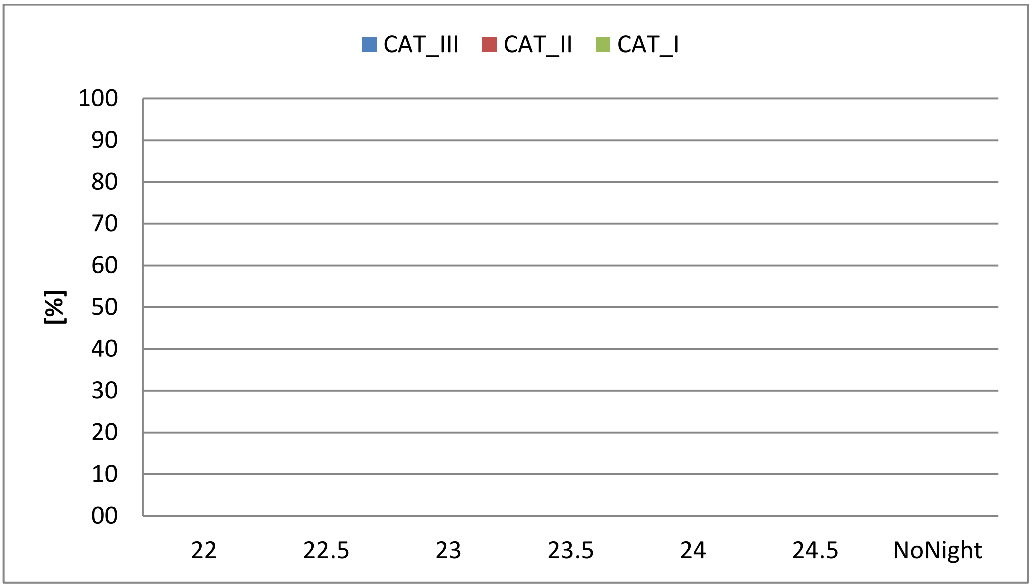


Figure 138 – Undercooling (top) and overheating (bottom) according to the EN15251 adaptive model for the tested night cooling thresholds.

The 23.0°C threshold can be then considered the best option, allowing the application of night ventilation only when strictly necessary: thermal comfort is not compromised and there is no extra energy consumption to offset nighttime undercooling.

This is the very first proof that in a cold climatic zone such as the one of Copenhagen, being the cooling load is very low, an enhancement of the ventilation will lead to a certain amount of hours of discomfort.

Case studies	Energy consumption [kWh/m^2]
22.0	142.3
22.5	52.6
23.0	48.8

23.5	48.4
25.0	48.4
24.5	48.4
NoNight	48.4

Table 22 – Energy consumption for the tested night cooling thresholds.

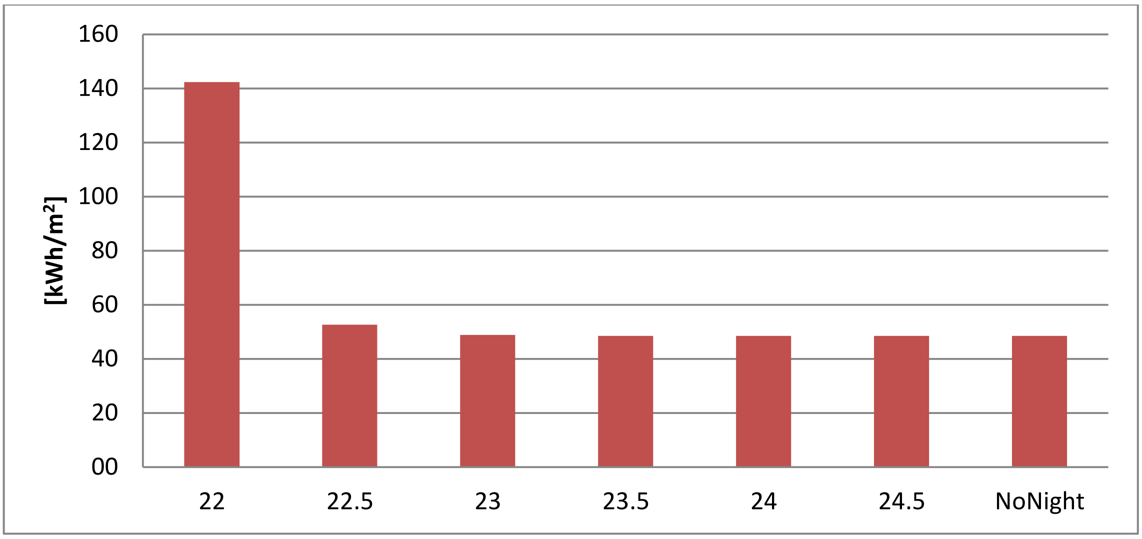


Figure 139 – Energy consumption for the tested night cooling thresholds.

Orientation

The risk of overheating is limited to very few days in summer, during most of the year the discomfort is caused by undercooling. When optimizing the orientation the aim should then be to maximize the solar gain, the potential discomfort during summer will be prevented by activating the solar shadings.

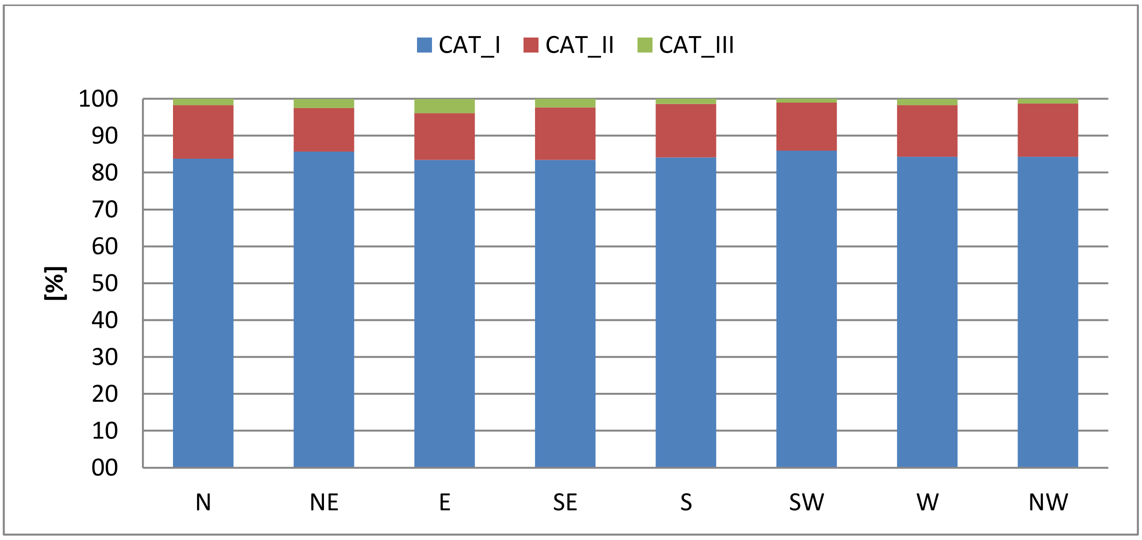


Figure 140 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested orientations.

From Figure 141 it is clear that the solar radiation entering the building through the windows is maximum when the façade 3 is facing NE (this is consistent with the consideration on the glazed surface distribution and exposition made for the other locations): the energy consumption reaches indeed its minimum value (48.7 kWh/m^2). On the other hand the building is not well performing in terms of comfort (Figure 140): with 97.5% of time in category II it is actually the second worst performing.

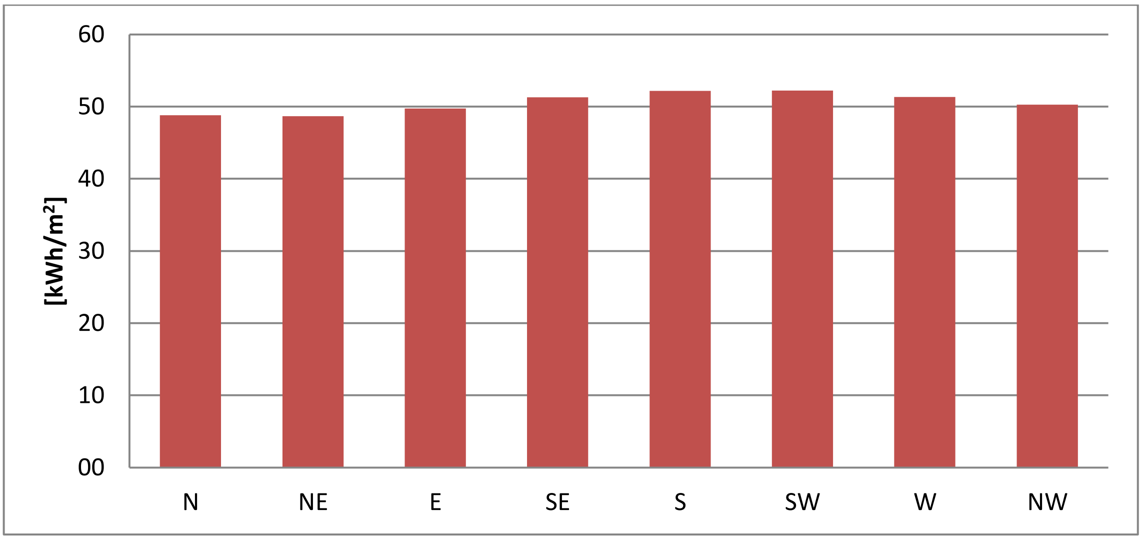
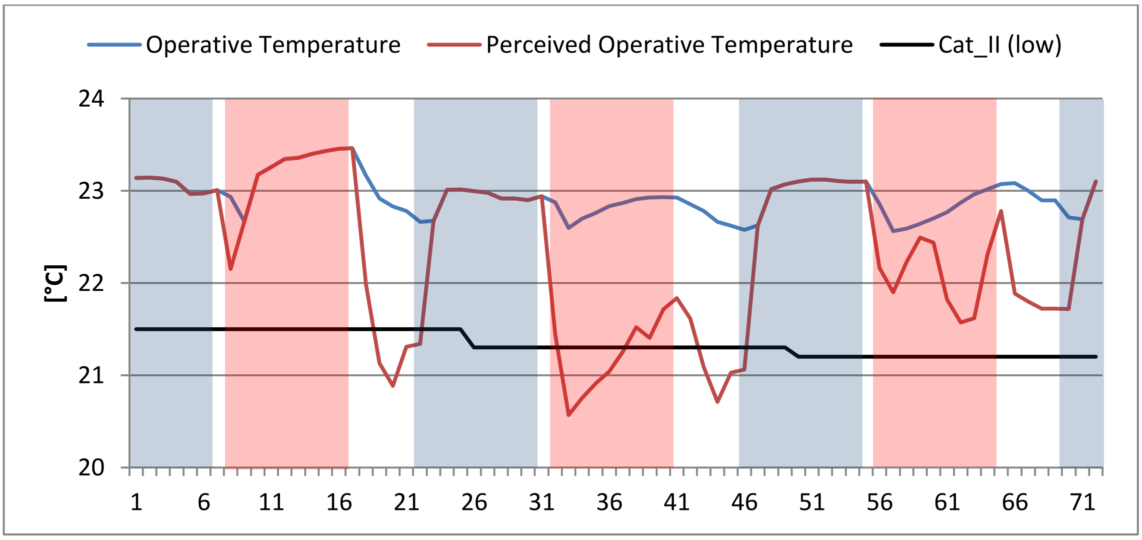


Figure 141 – Energy consumption for the tested orientations.

The cause is the draft sensation originated by very high average indoor air velocity (0.30 m/s) as it can be seen from Figure 142, where the comparison between the operative temperature and the perceived operative temperature shows, with regards to the lower limit of the category II, that is the ventilative cooling the primary cause of discomfort.



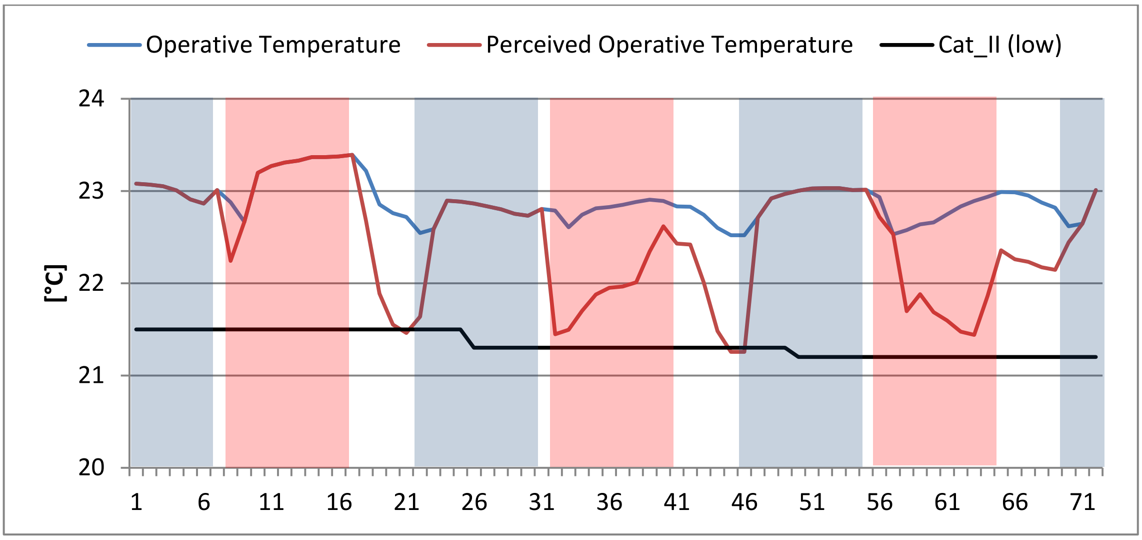


Figure 142 – Operative temperature and perceived operative temperature (NE orientation at the top and SW orientation at the bottom).

Furthermore the comparison with the thermal response of the SW orientation reveals that, when façade 3 is facing NE, the operative temperature is higher (0.1°C on average) both during day and during night because of the higher heat delivered by the solar radiation and stored in the building thermal mass.
The mean indoor air velocity is shown in Figure 143. When compared with the other locations, the mean indoor air velocity is very high, due to the high wind speed (see Appendix A), ranging from 0.28 m/s (SW) to 0.31 m/s (E). The North-East orientation presents one of the highest values, and can potentially lead to an increase in the discomfort, but, as we will see in the following, if the ventilative cooling is adequately constrained, natural ventilation is capable to achieve a very good thermal comfort.
The NE orientation has then been chosen.

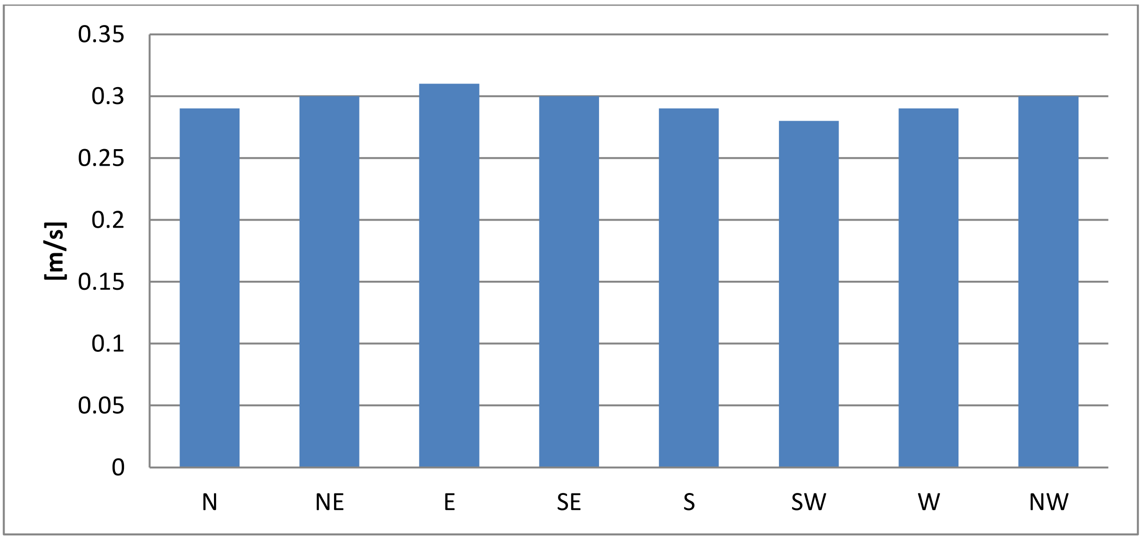


Figure 143 – Average indoor air velocity for the tested orientations.

Thermal mass

With the 23.5°C night cooling threshold, during the entire natural ventilation period the night cooling strategy is applied for just 13% of the night. Then the thermal mass has no influence on the thermal comfort.

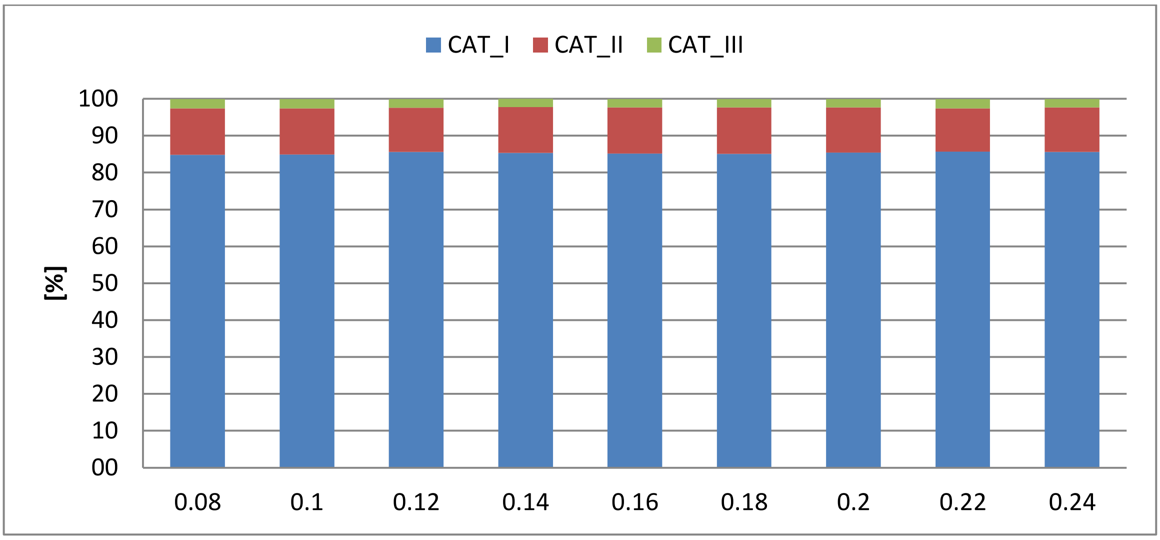


Figure 144 – Thermal comfort evaluated according to the EN15251 adaptive model for the tested concrete layer thicknesses.

Differently from the other scenarios the percentage of time in category II does not increase with the concrete layer thickness, but remains constant (97.5%). The energy consumption slightly decreases (Figure 145), not because of the better coupling between thermal mass and night air flow rate, but because the higher amount of heat delivered by the solar radiation and stored in the building structure reduces the heat that the boiler has to provide during the cold season.

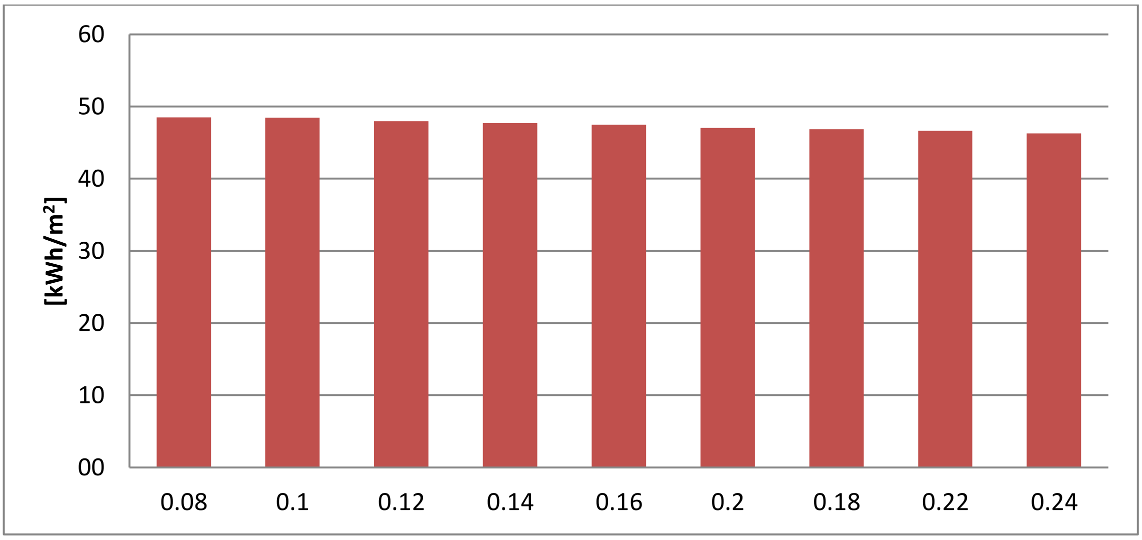


Figure 145 – Energy consumption for the tested concrete layer thicknesses.

A 0.20 m concrete layer thickness has been chosen not because of the better performance it offers, but for similarity with the other locations.

8.2. Case studies

The natural ventilation strategies that presented good results in the other three locations, in a colder climate such as the one of Copenhagen turned out to be too aggressive. In particular the daytime increased velocity was found responsible for the too low temperature experienced by the occupants. For this reason an eleventh natural ventilation strategy, namely N_CV_H_A, has been tested. The strategy is based on daytime mechanical ventilation and automatically controlled night cooling, but the windows can be opened, according to the occupants comfort, for a short period of time (15 min.) in the early morning (8:00 a.m.) and when the occupants go back home (17:00 in the afternoon) for airing the dwelling. The daytime natural ventilation achieved in this way does not provide ventilative cooling, but allows the occupants to better control the indoor environment. In the results comparison the N_CV_H_A has been substituted to the M_H.
For Copenhagen the ten configurations have the following settings:

- N_02_H presents an average indoor air velocity of 0.17 m/s.6
- N_02_H_A uses a proportional controller set between 23°C (lower limit for the fully opened windows) and 22°C (upper limit for the fully closed windows). Between these two values the windows opening area is modulated.
- N_02_HC switches from natural ventilation to mechanical cooling when the indoor air temperature rises above 24.6°C.
- N_I_H grants an average indoor air velocity of 0.30 m/s.
- N_I_H_A is equipped with the same proportional controller installed in the N_02_H_A scenario.
- N_I_HC switches from natural ventilation to mechanical cooling when the indoor air temperature rises above 24.6°C.
- N_CV_H_A is based on mechanical ventilation and automatically controlled night cooling, but allows the occupants, in accordance to their comfort, to open the windows for 15 minutes in the early morning (8:00) and in the afternoon (17:00) for airing the dwelling.
- M_HC is the fully mechanical system
- M_HC_N is mechanically ventilated and night cooled
- M_HC_N_A combines mechanical ventilation with modulated night cooling. During night, when the indoor air temperature is above 22.5°C, the windows are fully opened, between 22.5°C and 21.5°C are modulated and below 21.5°C are fully closed. The set point and the modulating range derive from an optimization process.

8.3. *Indoor air quality*

The IAQ is extremely high: all the solutions are capable to achieve a 100% category I building, or very close to, as it can be seen from Figure 146 and Table 23. The increased outdoor-indoor pressure that already led to a higher infiltration rate, and thus a higher IAQ, in Berlin than in Athens it is here further enhanced. Even the M_HC system is capable to grant an indoor CO_2 level within 350 ppm above the outdoor one, for almost all the occupancy time. Natural ventilation gives then no improvement in terms of IAQ, because no improvement is possible, and the potential advantages that remain are in terms of thermal comfort and energy consumption. In particular the solutions without increased air velocities actually present a decrease in the IAQ. This is because of the combination of two factors: first the operable window area is smaller, second during the transition seasons, even if the conditions for the window opening are satisfied, the windows are very close to the closing point. The result is an air flow rate lower that the one granted by a mechanical ventilation system (Figure 147).

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	99.4	100.0	100.0	-0.3
N_02_H_A	99.6	100.0	100.0	-0.1
N_02_HC	99.4	100.0	100.0	-0.3
N_I_H	100.0	100.0	100.0	+0.3
N_I_H_A	100.0	100.0	100.0	+0.3
N_I_HC	100.0	100.0	100.0	+0.3
N_CV_H_A	99.8	100.0	100.0	+0.1
M_HC	99.7	100.0	100.0	-
M_HC_NC	100.0	100.0	100.0	+0.3
M_HC_NC_A	100.0	100.0	100.0	+0.3

Table 23 – IAQ according to the EN15251 for the ten scenarios.

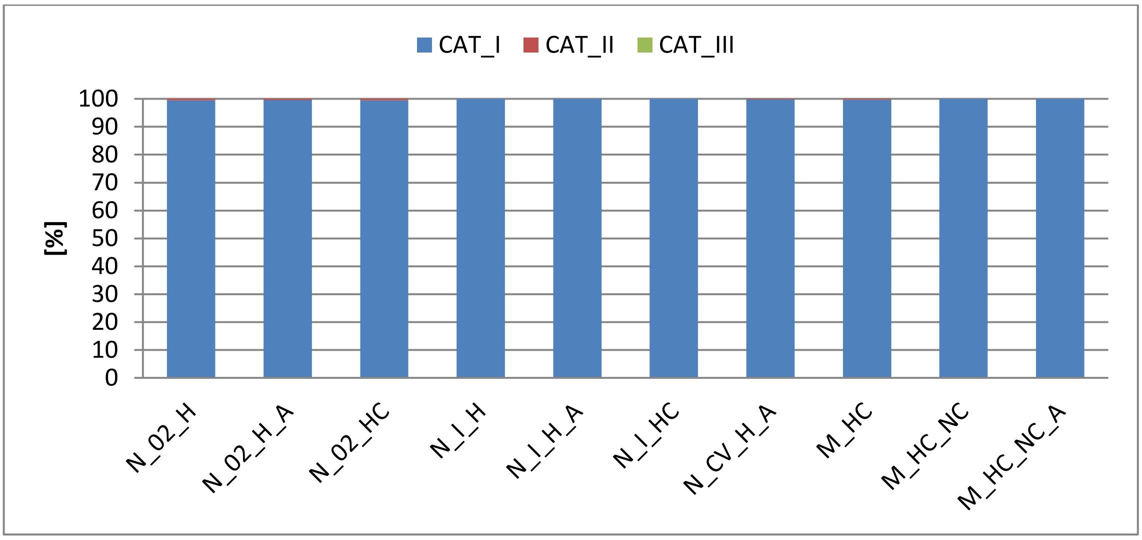


Figure 146 – IAQ according to theEN15251 for the ten scenarios

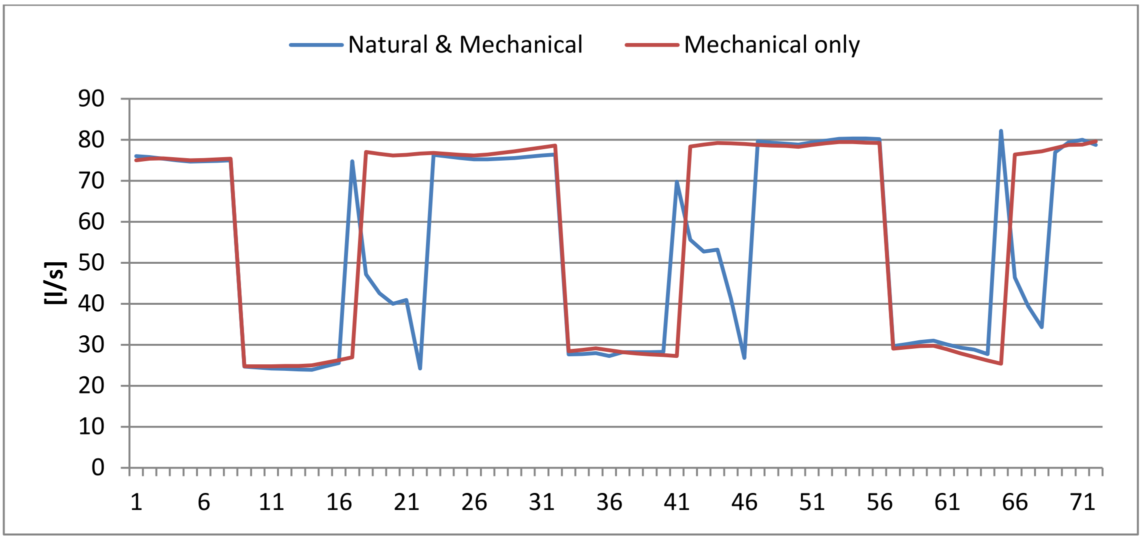


Figure 147 – Air flow rate.

8.4. Energy consumption

In Copenhagen the energy consumption for cooling is a negligible percentage of the heating need (0.6%). Because of that, the passive cooling strategies, even if they do not require any energy for cooling, either cause an increase of the energy consumption (because of the increased heating need) or a negligible decrease of it. In general, the solutions that tend to abuse night cooling present a consistent increase in the heating need. In particular when night cooling is not modulated and it is applied in a building thermostatically controlled during daytime, the increase is relevant (9.8% for the N_02_HC and 37.8% for the M_HC_N scenario). If, on the other hand, the night cooling is constrained either by means of increased ventilative cooling or with an automatic controller, some energy saving is achieved.

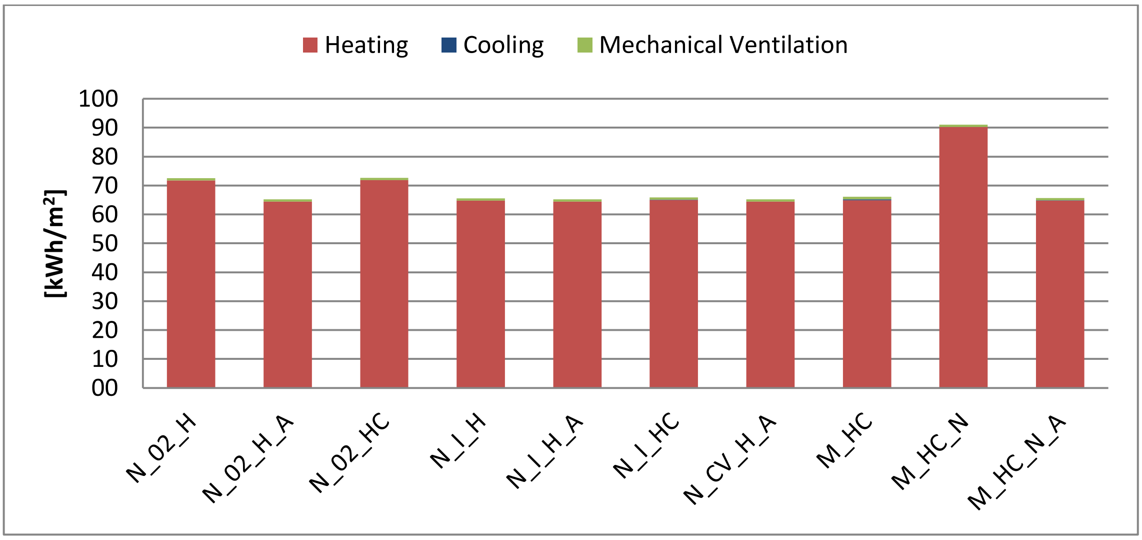


Figure 148 – Energy consumption for the ten scenarios.

Case studies	Heating [kWh/m^2]	Coolig [kWh/m^2]	Mechanical Ventilation [kWh/m^2]	Total [kWh/m^2]	Variation [%] (reference case: M_HC)
N_02_H	71.8	0.0	0.8	72.5	9.7
N_02_H_A	64.4	0.0	0.7	65.2	-1.4
N_02_HC	71.9	0.0	0.8	72.6	9.8
N_I_H	64.8	0.0	0.8	65.6	-0.8
N_I_H_A	64.5	0.0	0.8	65.3	-1.3
N_I_HC	65.0	0.0	0.8	65.9	-0.4
N_CV_H_A	64.4	0.0	0.8	65.3	-1.3
M_HC	64.9	0.4	0.9	66.1	-
M_HC_N	90.2	0.0	0.9	91.1	37.7
M_HC_N_A	64.8	0.0	0.9	65.7	-0.6

Table 24 – Energy consumption for the ten scenarios.

If a closer look is taken at the M_HC_N_A it is possible to notice that, although designed as a thermostatically controlled solution, there is no energy consumption for cooling. Night ventilation is capable alone to reduce the cooling load to zero: indeed the reduction in the energy consumption corresponds entirely to the cooling need and the automatic window closing protects the building from undercooling (there is no increase in the energy demand for heating).

Considering that the manually controlled night cooling tends to cause an increase in the energy consumption and, as we will see, the ventilative cooling decreases the thermal comfort, the idea for an eleventh scenario, namely N_CV_H_A, that relies on automatically controlled night ventilation to meet the cooling need, and daytime ventilation only for airing, seemed reasonable and promising. Indeed the scenario turned out to perform very well from an energetic point of view, allowing a 1.3% reduction in the energy consumption, as well as from a comfort perspective.

We can then conclude that the night ventilation can be used to prevent the temperature from increasing during the warmest days of the year, but the window opening should be properly modulated in order to prevent the increase in the heating demand, even during summer. Ventilative cooling should be avoided and the daytime window opening should aim to improve the IAQ without affecting the thermal sensation.

8.5. *Thermal comfort*

The comfort evaluation made according to the standard adaptive model is shown in Figure 149 and Table 25. As for the other locations, undercooling and overheating are separately presented in Figure 150.

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	79.9	97.1	99.9	-2.9
N_02_H_A	83.0	99.2	100.0	-0.8

N_I_H	74.7	96.0	99.8	-4.0
N_I_H_A	75.0	96.3	99.8	-3.7
N_CV_H_A	84.4	100.0	100.0	0.0

Table 25 – Thermal comfort according to the EN15251 adaptive model for the scenarios not equipped with a MCS.

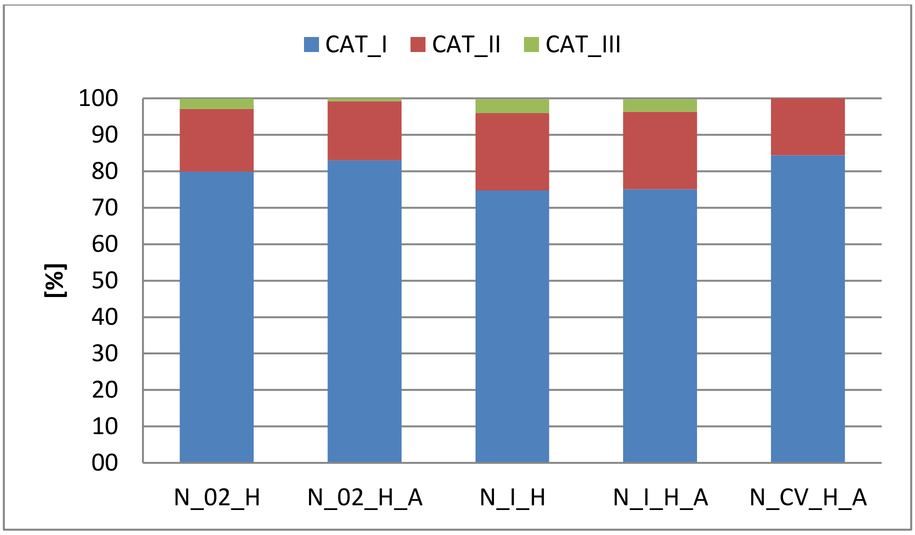
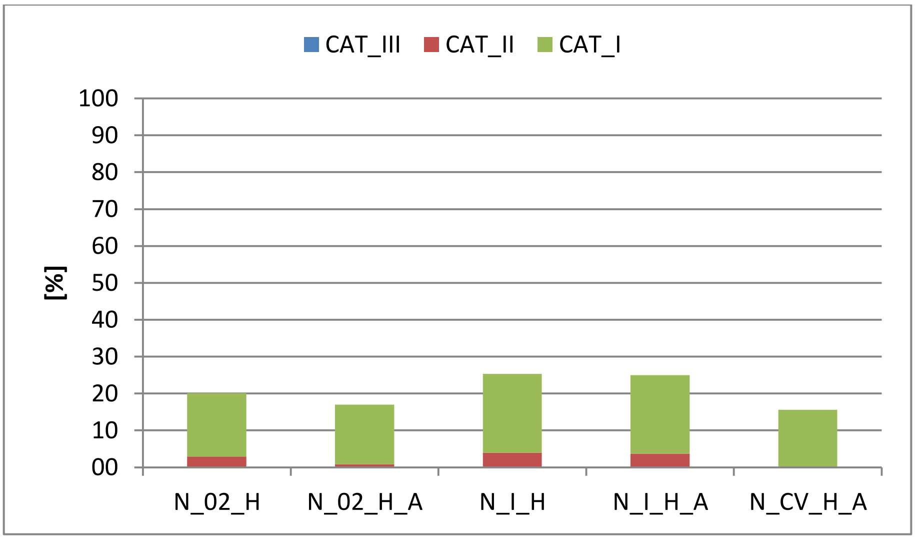


Figure 149 – Thermal comfort according to the EN15251 adaptive model for the scenarios not equipped with a MCS.

The N_CV_H_A turned out to be the only one capable to generate an environment in category II for 100% of the time, i.e. the only one which does not deteriorate thermal comfort with regards to the reference case.



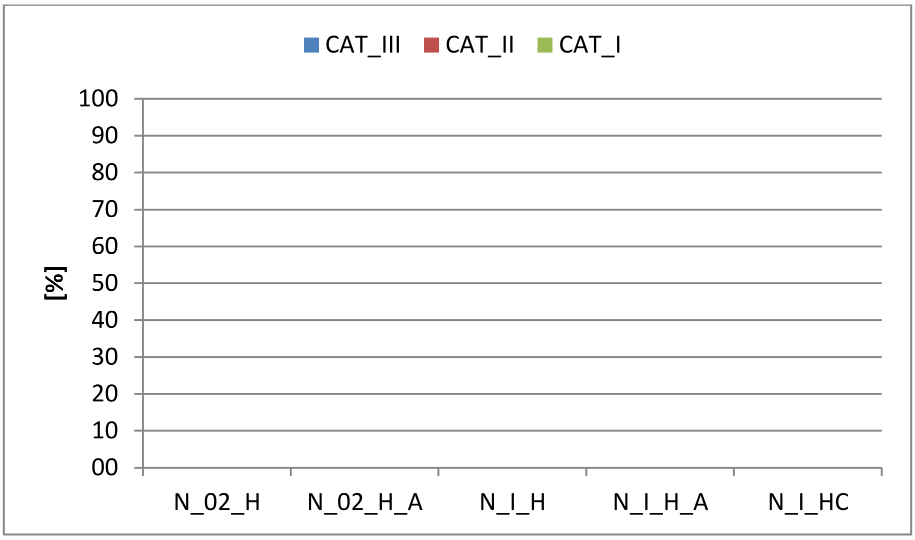


Figure 150 – Undercooling (top) and overheating (bottom) according to the EN15251 adaptive model for the scenarios not equipped with a MCS.

The use of an automatic controller prevents night undercooling (in Figure 151 N_02_H and N_CV_H_A are compared on a three days period between August 5th and August 7th), while the use of daytime ventilation for airing need only prevents the discomfort caused by the draft sensation that affects the increased air velocity scenarios (Figure 152 compares N_I_H and N_CV_H_A on a three days period from July 20th to July 22nd).

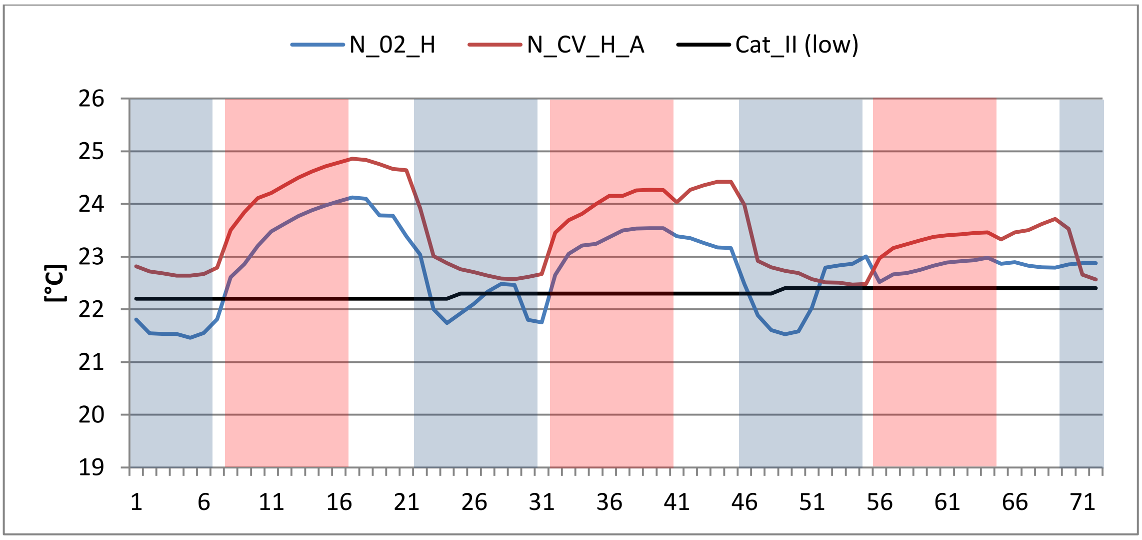
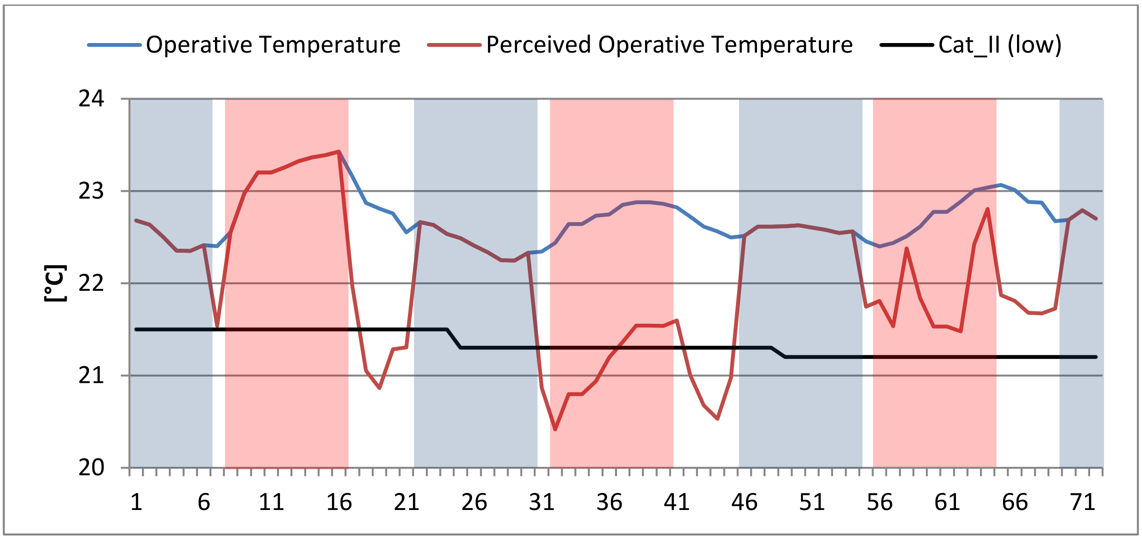


Figure 151 – Operative temperature.



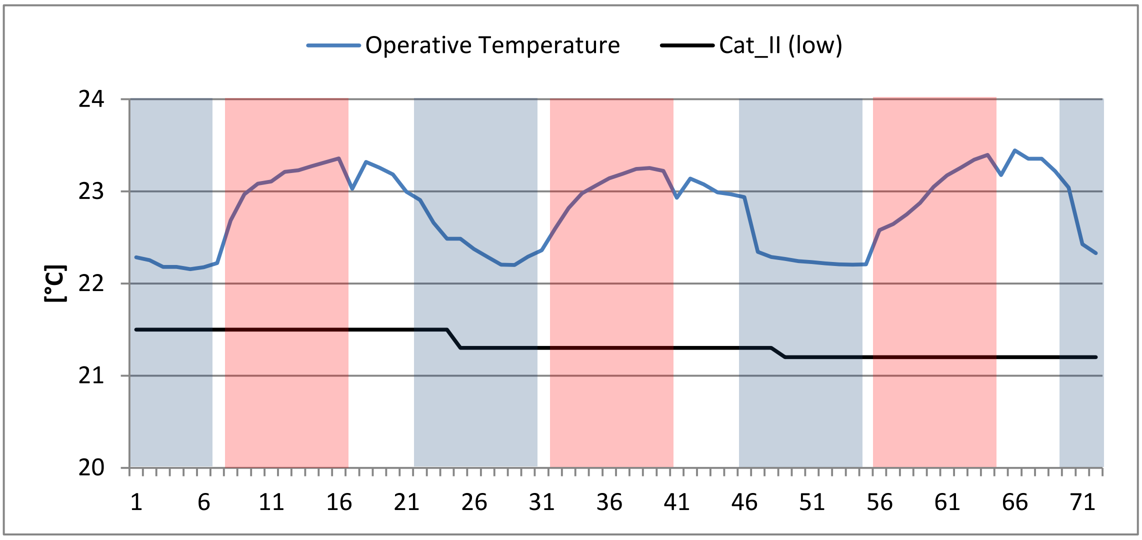


Figure 152 – Operative and perceived operative temperature (N_I_H at the top and N_CV_H_A at the bottom).

The performances according to the non-adaptive model are shown in Table 26 and Figure 153.

	CAT_I [%]	CAT_II [%]	CAT_III [%]	Variation [%] (reference case: M_HC)
N_02_H	99.7	100.0	100.0	0.0
N_02_H_A	99.7	100.0	100.0	0.0
N_02_HC	99.7	100.0	100.0	0.0
N_I_H	97.2	99.8	100.0	-0.2
N_I_H_A	97.3	99.8	100.0	-0.2
N_I_HC	97.4	99.9	100.0	-0.1
N_CV_H_A	99.8	100.0	100.0	0.0
M_HC	99.8	100.0	100.0	-
M_HC_NC	99.8	100.0	100.0	0.0
M_HC_NC_A	99.8	100.0	100.0	0.0

Table 26 – Thermal comfort according to the EN15251 non-adaptive model for the ten scenarios.

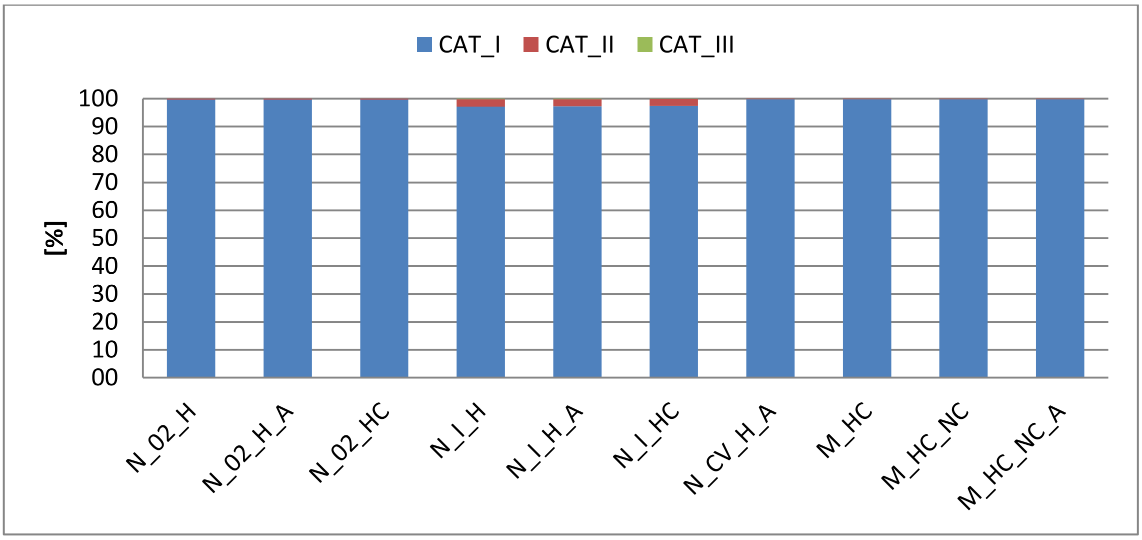
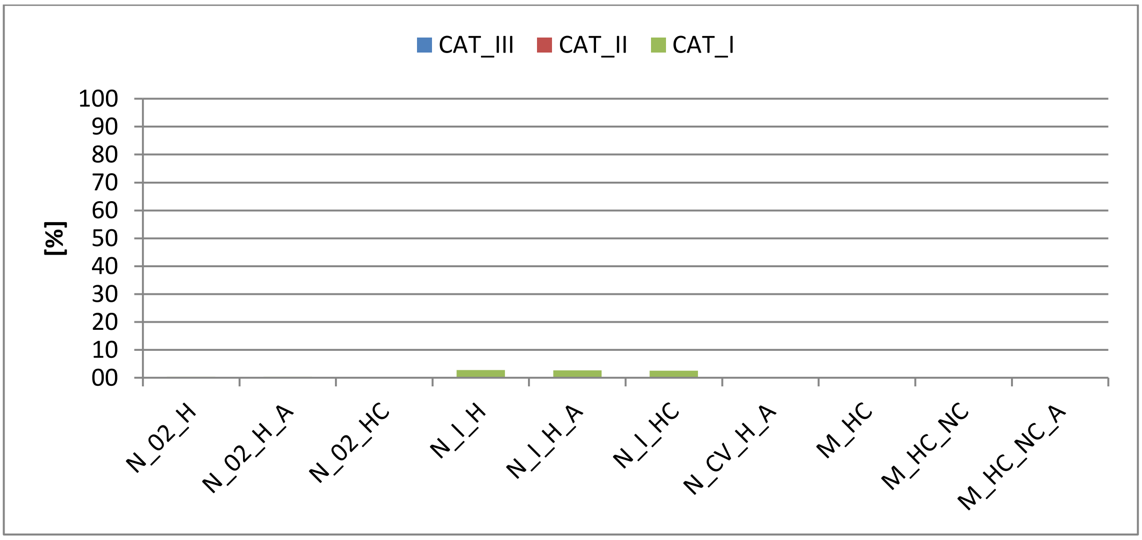


Figure 153 – Thermal comfort according to the EN15251 non-adaptive model for the ten scenarios.

With the exception of the increased air velocity cases, which present a slight decrease in the thermal comfort, the passive cooling strategies perform as good as the active ones.

Given the low cooling load and the capability of the passive cooling techniques to achieve a very good indoor environment in terms of both thermal comfort and IAQ, we can conclude that in a cold climate, such as the one of Copenhagen, the installation of a mechanical cooling system is not justified. Night ventilation presents already a cooling potential more than sufficient to avoid an excessive temperature increase even in the warmest days of summer.

Undercooling and overheating are shown in Figure 154, as expected the discomfort is present because of the temperature drop below the category lower limit.



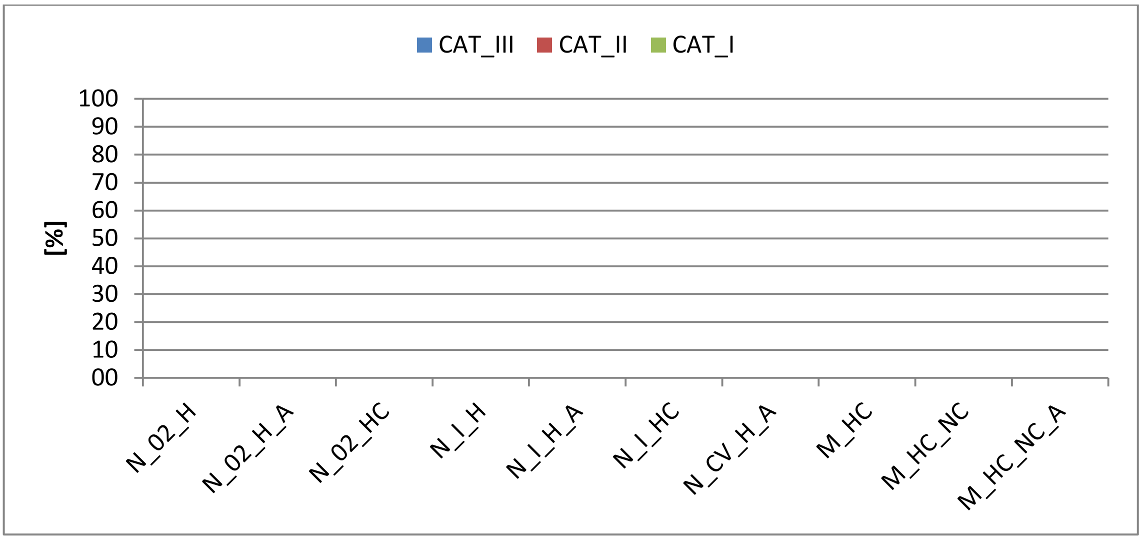


Figure 154 – Undercooling (top) and overheating (bottom) according to the EN15251 non-adaptive model for the ten scenarios.

According to the ASHRAE55 comfort limits, the naturally ventilated scenarios perform excellently (Figure 155): all solutions provide a category A building. Again, some draft sensation decreases the thermal comfort in the increased velocity scenarios by a negligible 0.3%.

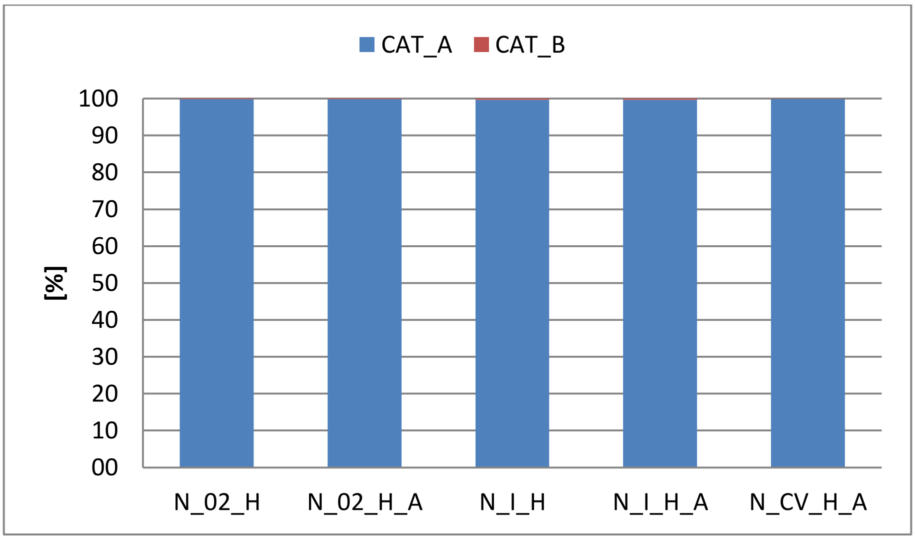


Figure 155 – Thermal comfort evaluated according to the ASHRAE55 adaptive model for the five scenarios not equipped with a mechanical cooling system.

In Figure 156 the individual signatures for the tested scenario are shown.

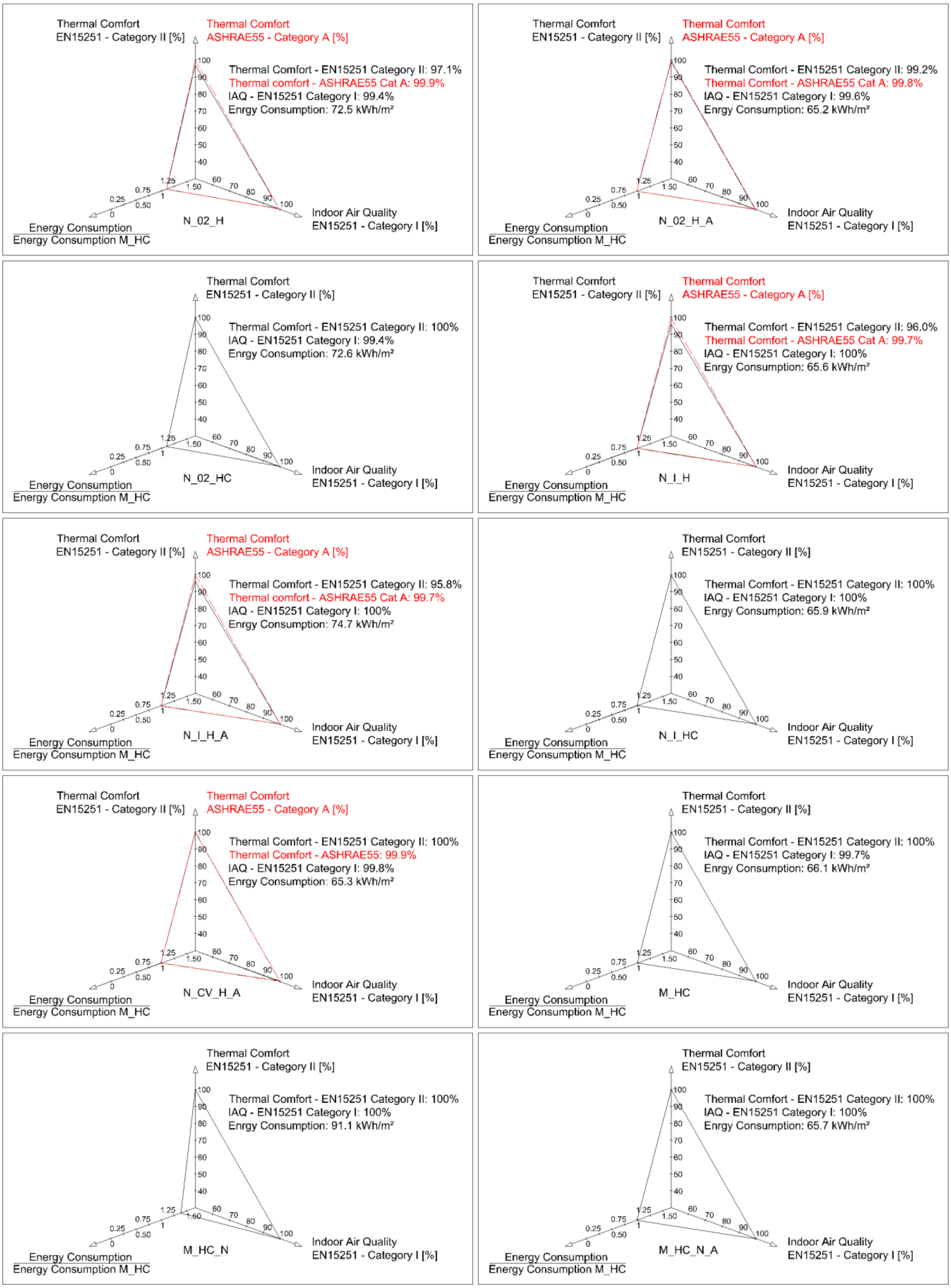


Figure 156 – Individual building signature for the ten scenarios.

The data here presented suggests that in Copenhagen the passive strategies are in general over performing. Whether because of the temperature offset during daytime or because of the temperature drop during nighttime, if not properly constrained in their cooling potential, they cause discomfort. Although, if intelligently implemented, natural ventilation is more than capable to meet the cooling load during the entire natural ventilation period, to provide very good IAQ and to reduce the energy consumption.
An observation: the moderate scenario (N_CV_H_A) suggests that night cooling alone can achieve an excellent indoor environment, but the ventilative cooling alone could be capable to obtain similar results, without the necessity to install an automatic controller on the windows. To take into account the temperature offset granted by the air velocity, it would have been necessary to base the decisions (e.g. whether to open or not the windows) on the perceived operative temperature instead that on the mean indoor air temperature. Unfortunately the average indoor air velocity, and thus the temperature offset, is calculated only on a second moment, which makes it impossible to test the theory.

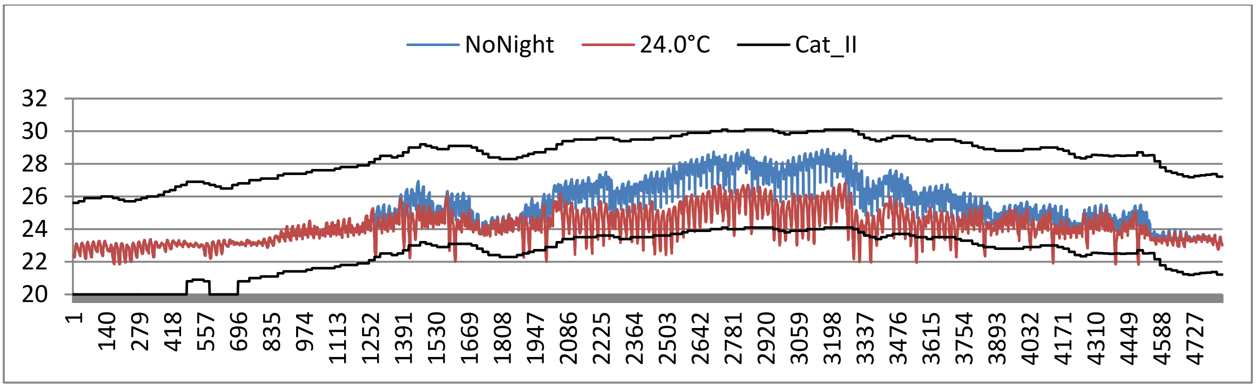
9. DISCUSSION AND CONCLUSIONS

The project evaluates the possibility to improve summer comfort and reduce the energy consumption by means of passive cooling techniques, such as daytime comfort ventilation with increased air velocity and night cooling. Four locations (Athens, Rome, Berlin and Copenhagen) have been chosen to determine the applicability and the performances of the passive strategies in different climatic zones. The investigation revealed that natural ventilation techniques perform very well in terms of both thermal comfort and IAQ, allowing a reduction in the energy demand when compared with mechanical ventilation and cooling. It was also found that, depending on the local weather condition, the efficiency of the ventilation strategy has to be properly constrained or enhanced in order to achieve thermal comfort.

In this section the main results presented in the previous chapters are summarized and discussed.

9.1. Preliminary simulations

The sensitivity analysis of the **night cooling threshold** showed that the nighttime ventilation is capable to reduce the temperature peak in the following day up to 4.7°C in Rome, 3.6°C in Berlin, 4.2°C in Athens and 2.3°C in Copenhagen. It also revealed that, with the exception of Athens, the night ventilation initial configuration originates discomfort, causing more undercooling than the overheating that is capable to prevent (Figure 157). This is why in Rome, Berlin and Copenhagen the best comfort performance was offered by the NoNight scenario.



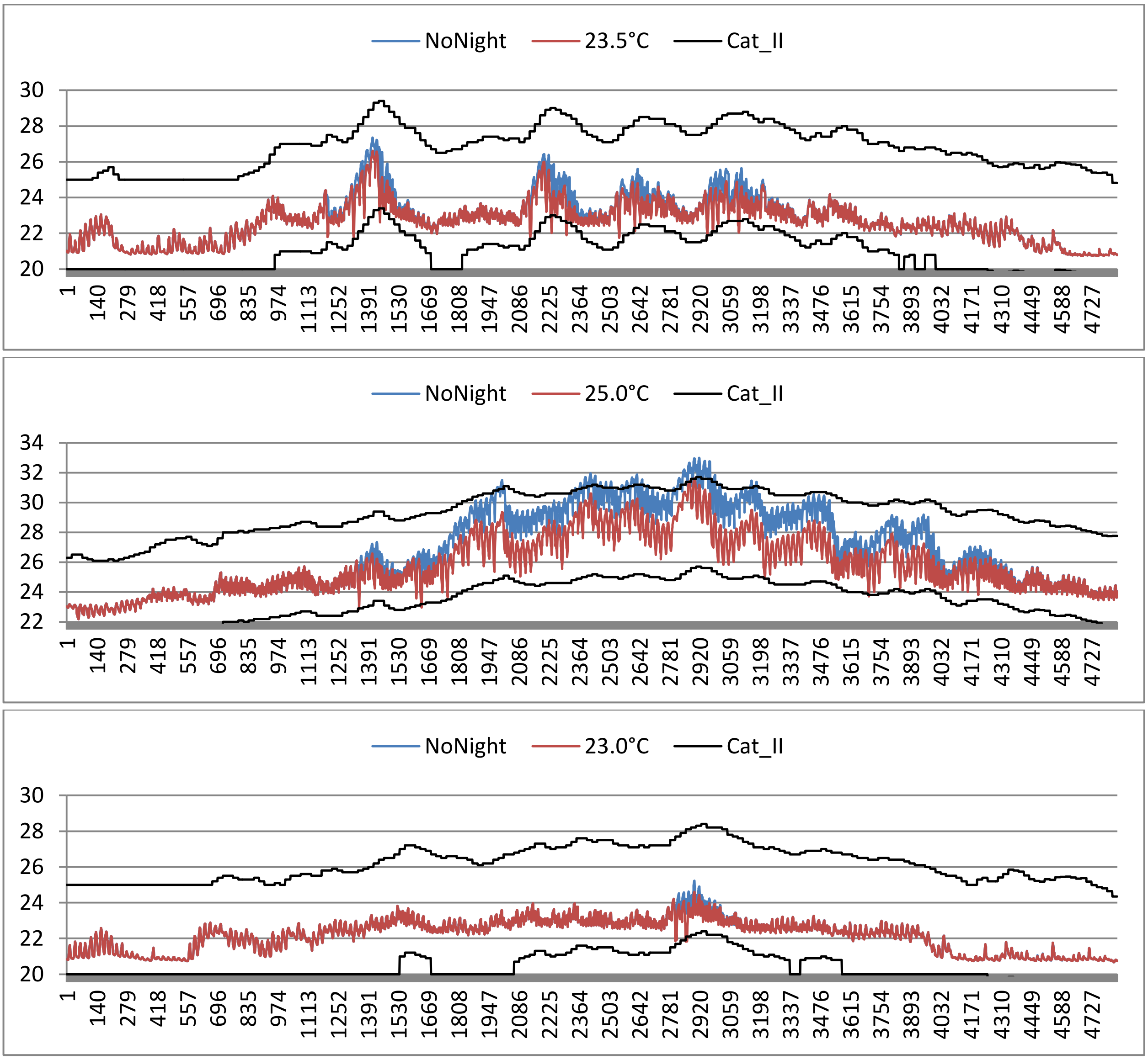


Figure 157 – Comparison between the operative temperatures with and without night cooling in Rome (top), Berlin (middle top), Athens (middle bottom) and Copenhagen (bottom) between April 7th and October 25th.

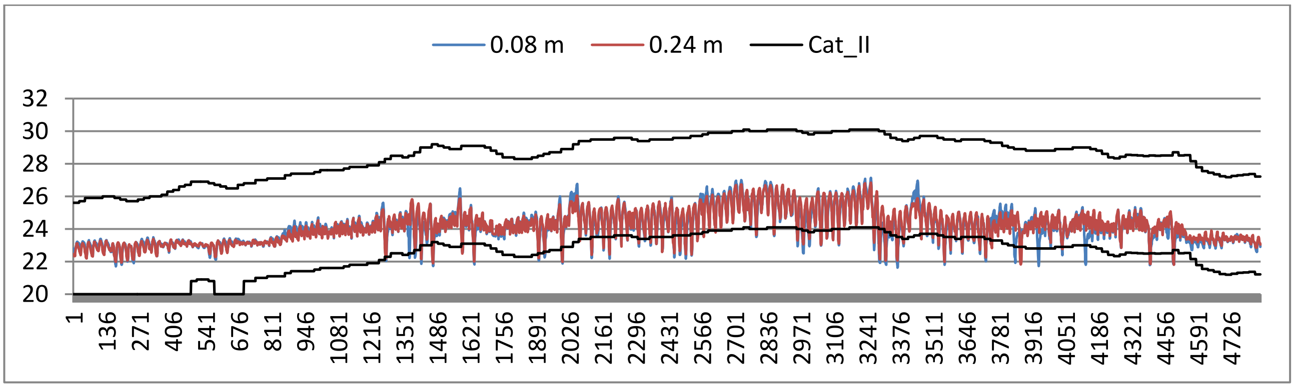
The reduction in the following day temperature peak is more than double in Rome than in Copenhagen, this can be easily explained if we look at the temperature swing between day and night in the four locations (Figure 13): the higher is the day-to-night temperature difference, the higher is the efficiency of night ventilation. This confirms what has been reported by Givoni [29], i.e. that the main aspects that influence the night ventilation are the diurnal temperature range and the building thermal mass.

The second parameter that strongly influences the night ventilation is indeed the thermal mass. To determine the minimum required thickness of exposed concrete layer is important for the night cooling to efficiently lower the operative temperature the following day. The optimization process investigated exposed concrete layer thicknesses ranging from 0.08 m (415 kg/m^2 of floor area) to 0.24 m (1183 kg/m^2 of floor area). By increasing the concrete layer thickness from 0.08 m to 0.24

m, a decrease in the following day operative temperature up to 2°C in Rome, Berlin and Athens and 1°C in Copenhagen is achieved (Figure 158). The results are similar to the ones obtained by Geros et al. [43], who found a decrease in the next day peak indoor temperature up to 2.5°C for a heavy building in the Mediterranean climatic zone. In Athens, because of the high cooling load, the sink effect is fully taken advantage of the thermal mass is actually capable to prevent some overheating during summer, granting an improvement in the thermal comfort. In Rome and Berlin the increase in the thermal comfort comes from the *long term sink effect*: being the cooling load lower than in Athens, the thermal mass acts like a sink for more than just the following day, avoiding an abuse of night cooling that would lead to more nights of ventilation and then a larger undercooling. In other words in a light building (0.08 m) the cooling effect of night ventilation is mainly due to the reduction of the air temperature, which does not last until the following night, while in a heavy one (0.24 m) night ventilation lowers the temperature of the thermal mass, thus lowering the mean radiant temperature, for more than a one day long period. In Copenhagen the thermal comfort is not affected by the night ventilation because the strategy is applied for just 13% of the nights during the natural ventilation period.

Beside the different thermal response in the four locations, an increase in the concrete layer thickness up to 0.20 m (991 kg/m^2) was proven to increase the efficiency of the night cooling strategy. When the thermal mass is further increased the night cooling performance improvement becomes less and less significant. The result is similar to the one obtained by Böllinger, who stated that the building should have a mass of at least 800 kg/m^2 [33], and Shaviv [30]. Also the larger energy contribution of night ventilation observed in Athens agrees with the results obtained by Santamouris et al., according to whom the utilisability of the energy offered by night ventilation techniques increases as a function of the initial cooling load of the building [34].

Furthermore a heavy structure has been proven to be capable to retain the heat delivered by the solar radiation that enters the building through the glazed surface, lowering the energy consumption for heating during winter.



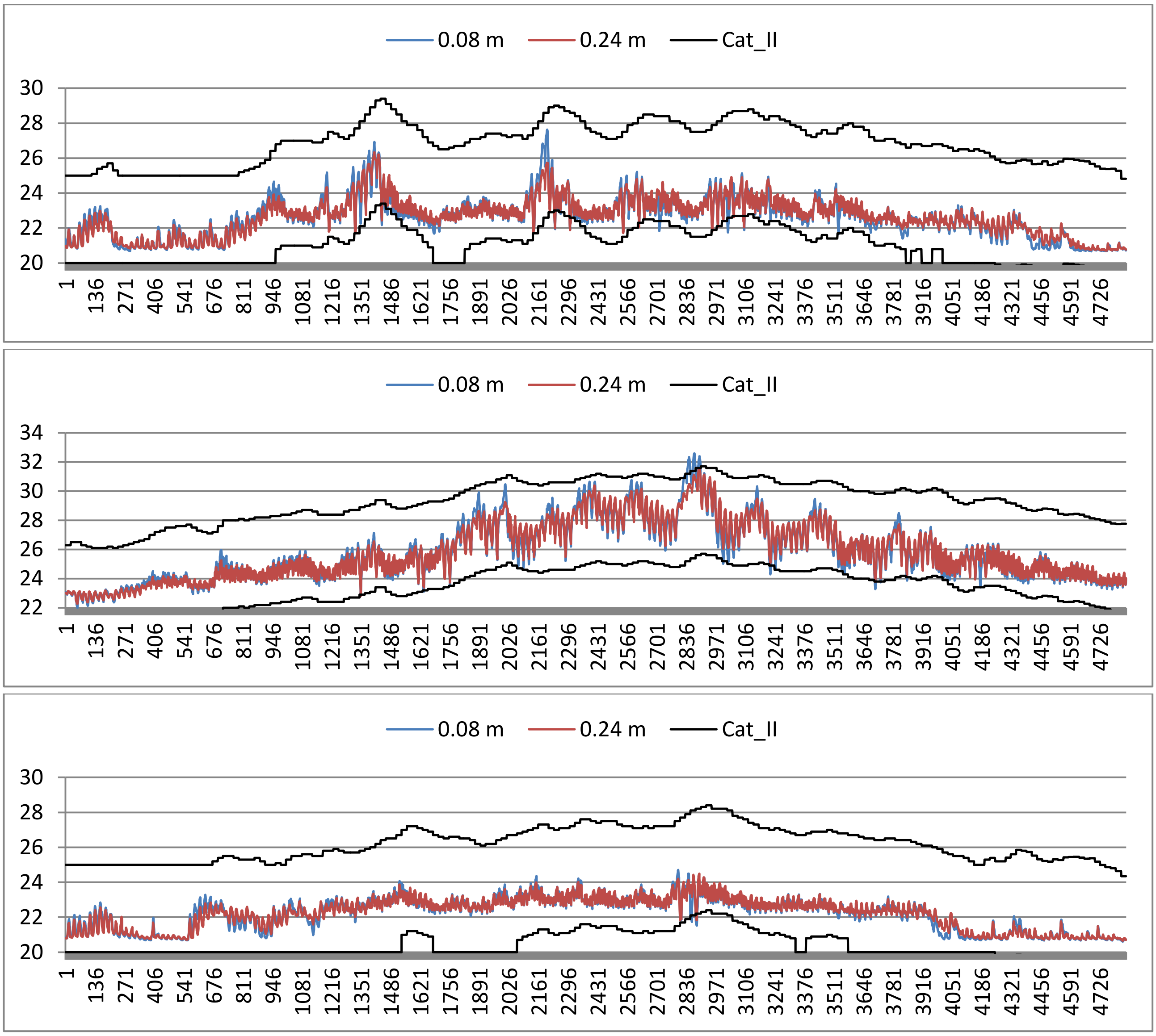


Figure 158 – Comparison between the operative temperatures for a 0.08 m and a 0.24 m concrete layer thickness in Rome (top), Berlin (middle top), Athens (middle bottom) and Copenhagen (bottom) between April 7th and October 25th.

Differently from what is reported by Shaviv [30], the results showed that the increased thermal mass do not provide the slower heating of the building that should postpone the daytime temperature peak to the late hours of the day, when the outdoor air temperature is already low. The only exception is Athens, where the *shifted temperature peak phenomenon* has been observed in the warmest days of summer. The reason is probably once again the increased utilisability of the energy offered by night ventilation due to the higher cooling load. The similarity of Athens and the deviation presented by the other locations is consistent with the results of Shaviv, who observed the phenomenon in the hot climate of Israel.

9.2. Case studies

Table 27 summarizes the results obtained from the investigated ventilation and cooling strategies in the four locations: along with the percentage of time in category II for the thermal comfort, in category I for the IAQ and the energy consumption, the percentage variation with respect to M_HC is shown.

For every location the line reporting to the characteristics of the scenario selected as the best performing is bold.

		Thermal Comfort		IAQ		Energy Consumption	
		Category II [%]	Variation [%]	Category I [%]	Variation [%]	Consumption [kWh/m^2]	Variation [%]
Rome	N_02_H	83.9	-15.3	93.2	+5.7	19.3	-50.5
	N_02_H_A	**98.9**	**-0.1**	**93.8**	**+6.3**	**13.5**	**-65.4**
	N_02_HC	99.6	+0.6	87.6	-0.7	28.9	-25.9
	N_I_H	88.9	-10.2	99	+12.2	13.8	-64.6
	N_I_H_A	97.3	-1.7	99	+12.2	13.6	-65.1
	N_I_HC	99.6	+0.6	93.4	+5.9	25.8	-33.8
	M_H	83.8	-15.4	90.9	+3.1	13.8	-64.6
	M_HC	99.0	-	88.2	-	39.0	-
	M_HC_N	99.7	+0.7	93.4	+5.9	33.9	-13.1
	M_HC_N_A	99.6	+0.6	93.4	+5.9	26.6	-31.8
Berlin	N_02_H	96.2	-3.8	95	+1.0	62.7	-0.2
	N_02_H_A	**99.8**	**-0.2**	**95.7**	**+1.7**	**59.3**	**-5.6**
	N_02_HC	100	0.0	93.8	-0.3	64.2	+2.2
	N_I_H	93.5	-6.5	99.2	+5.4	60.1	-4.3
	N_I_H_A	95.3	-4.7	99.3	+5.5	59.4	-5.4
	N_I_HC	100	0.0	97.5	+3.6	61.6	-1.9
	M_H	100	0.0	94.6	+0.5	59.6	-5.1
	M_HC	100	-	94.1	-	62.8	-
	M_HC_N	100	0.0	96.4	+2.4	73.3	+16.7
	M_HC_N_A	100	0.0	96.2	+2.2	60.9	-3.0
Athens	N_02_H	96.9	-0.9	97.6	+25.9	7.1	-82.5
	N_02_H_A	99.0	+1.2	97.9	+26.3	7.1	-82.5
	N_02_HC	95.8	-2.0	81.4	+5.0	33.4	-17.7
	N_I_H	**97.2**	**-0.6**	**99.1**	**+27.9**	**7.1**	**-82.5**
	N_I_H_A	97.5	-0.3	99.2	+28.0	7.1	-82.5
	N_I_HC	98.4	+0.6	82.1	+5.9	32.3	-20.4
	M_H	48.4	-50.5	90.6	+16.9	7.4	-81.8
	M_HC	97.8	-	77.5	-	40.6	-
	M_HC_N	98.4	+0.6	81.5	+5.2	34.4	-15.3
	M_HC_N_A	98.2	+0.4	81.6	+5.3	34.8	-14.3

Copenhagen	N_02_H	97.1	-2.9	99.4	-0.3	72.5	+9.7
	N_02_H_A	99.2	-0.8	99.6	-0.1	65.2	-1.4
	N_02_HC	100	0.0	99.4	-0.3	72.6	+9.8
	N_I_H	96.0	-4.0	100	+0.3	65.6	-0.8
	N_I_H_A	96.3	-3.7	100	+0.3	65.3	-1.3
	N_I_HC	99.9	-0.1	100	+0.3	65.9	-0.4
	N_CV_H_A	**100**	**0.0**	**99.8**	**+0.1**	**65.3**	**-1.3**
	M_HC	100	-	99.7	-	66.1	-
	M_HC_N	100	0.0	100	+0.3	91.1	+37.7
	M_HC_N_A	100	0.0	100	+0.3	65.7	-0.6

Table 27 – performances of the different ventilation and cooling strategies in terms on thermal comfort, IAQ and energy consumption in the four locations.

In general a mechanically ventilated, heated and cooled building in the Mediterranean climatic zone presents very high energy consumption for cooling need (82% for Athens and 65% for Rome), on the other hand, it grants a quite good summer comfort and high IAQ, but there is still room for improvement. The implementation of passive cooling strategies shows then a great potential for reducing the energy demand and turned out, at the same time, to be capable to improve the thermal comfort as well as the IAQ.

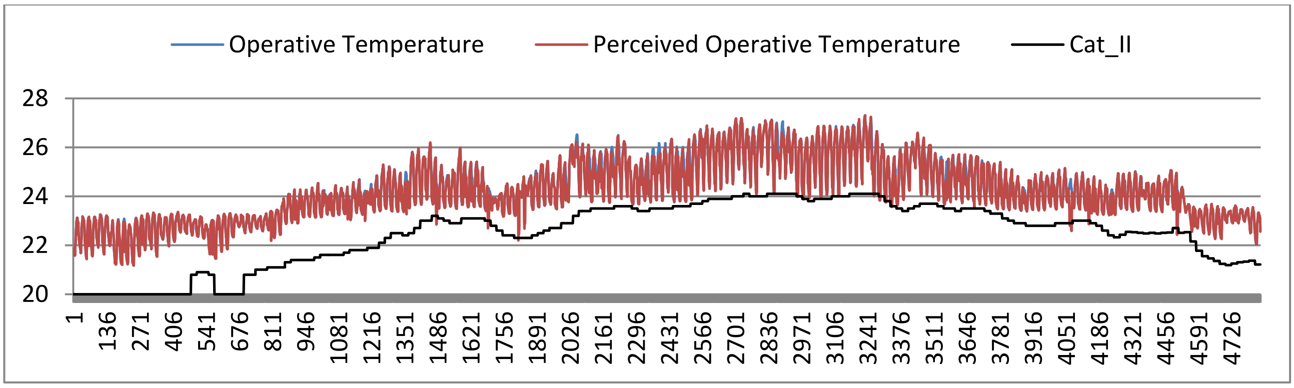
In Berlin and in Copenhagen the energy for cooling is a negligible percentage of the total consumption (5.1% for Berlin and 0.6% for Copenhagen). Summer comfort and IAQ are in general higher than in warmer climates. Then the passive strategies not only do not grants an improvement in thermal conditions and IAQ (because no improvement is possible), but if not adequately constrained lead to undercooling and increased energy consumption for heating need. On the other hand, when intelligently applied, passive techniques have been proved to be capable to increase the thermal comfort and reduce, as far as a reduction is possible, the energy consumption.

In **Athens** passive techniques are generally incapable to achieve the same summer comfort of a mechanical cooling system: the reduction in terms of thermal comfort is however negligible, ranging from 0.3% (N_I_H_A) to 0.9% (N_02_H), the only exception is the N_02_H_A, which actually improves the comfort by 1.2% by preventing both daytime overheating and nighttime undercooling.

The IAQ, on the other hand, is far improved by natural ventilation. In particular, if an equilibrium between ventilative and night cooling is obtained by means of an automatic controller or thanks to the “self-regulating” phenomenon observed when increased daytime air velocities are used, the CO_2 level is lowered during the entire occupancy time. The energy consumption, as already said, is remarkably reduced.

Even if the best performing solution is the one that relies on a constriction of both daytime and nighttime air flow rate (N_02_H_A), we believe that the scenario with increased daytime air velocities and manually controlled night cooling (N_I_H) should be preferred since the

performance are very similar and it does not requires to automate the windows (a control system seldom applied in domestic buildings).
Also the integration of both passive and active cooling systems, mainly mechanical cooling and night ventilation, was proved to increase the performance (in terms of thermal comfort, IAQ and energy consumption), showing that, even if the adaptation chances are not taken advantage of, a mechanical system assisted by natural ventilation provide a better indoor environment than the mechanical system alone.
In general the natural ventilation strategies are the ones which perform best, achieving a comfort improvement and a reduction in the energy consumption.
In **Rome** the night cooling threshold has been chosen not according to the performance optimization, but moving from the consideration that avoiding the summer undercooling was a priority. The decision turned out to be not completely right: the 24°C threshold is indeed capable to prevent overheating, but, according to the EN15251 adaptive model, it causes some undercooling during night, even in summer. Such undercooling leads to a decrease in the thermal comfort that ranges from 0.1% (N_02_H_A) to 15.3% (N_02_H). Because of the selected night threshold and because of the large day-to-night temperature difference, night cooling turned out to be too aggressive. Nonetheless the natural ventilation strategies were found to perform well: they improve the IAQ between 5.7% (N_02_H) and 12.2% (N_I_H and N_I_H_A) and, as in Athens, reduce the energy consumption quite a lot (between 51% for N_02_H and 65% for N_02_H_A). In Rome it is then necessary to constrain both the daytime air flow rate to avoid the draft sensation caused by the increased air velocities (Figure 159) and the night cooling potential, by limiting the nighttime air flow rate with the use of an automatic controller (Figure 160).
Then the best performing solution is the N_02_H_A, which presents a negligible decrease in the thermal comfort (0.1%), more than compensated by the increase in the IAQ (6.3%) and by the reduced energy consumption (65%).



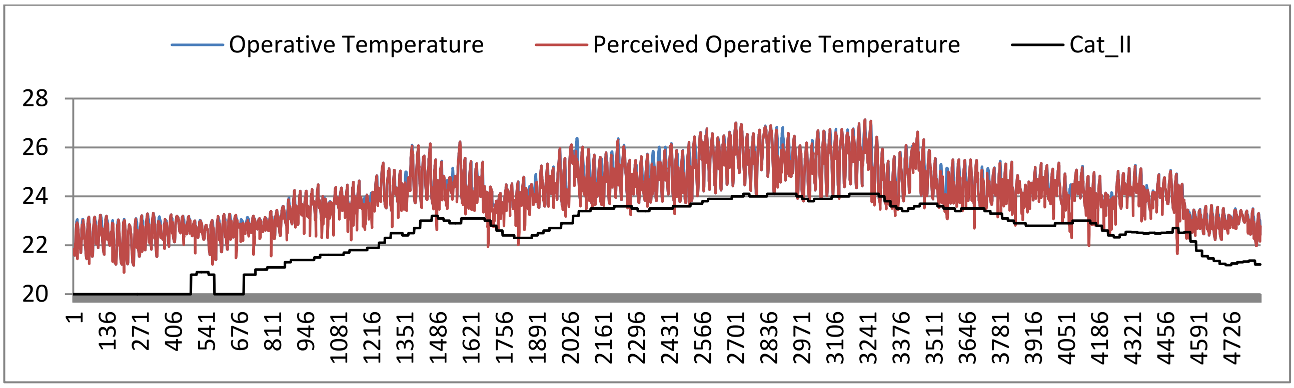


Figure 159 – Draft sensation: comparison between the operative temperature and the perceived operative temperature for the N_02_H_A scenario (top) and the N_I_H_A scenario (bottom) between April 7th and October 25th (Rome).

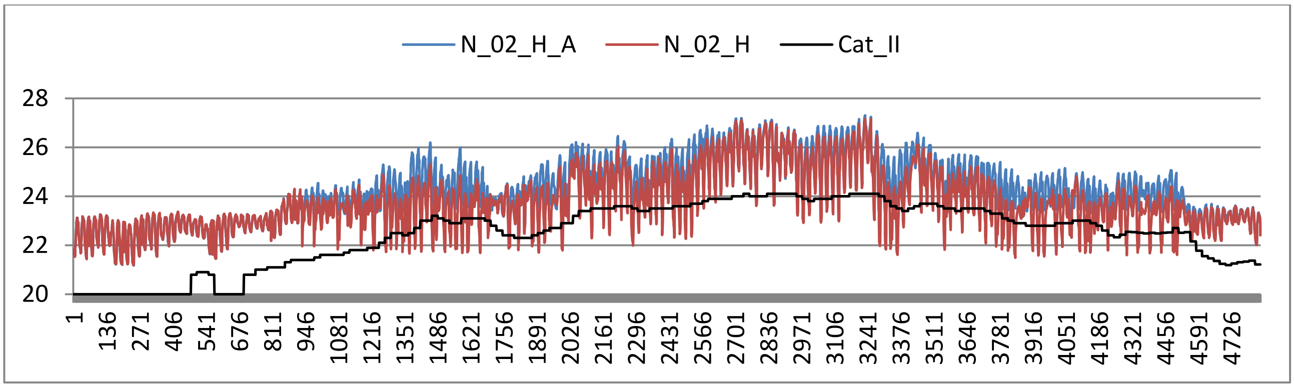


Figure 160 –Night undercooling: comparison between the perceived operative temperatures of the N_02_H and the N_02_H_A scenarios between April 7th and October 25th (Rome).

It is our opinion that an increase by 0.5°C in the night cooling threshold would provide an improvement in the performances, especially in the thermal comfort, since it would prevent the temperature from dropping during night in all the manually ventilated scenarios.

As in Athens, a hybrid system that combines passive and active cooling strategies allows to improve the indoor environment and to lower the energy consumption when compared to an entirely mechanical system.

In **Berlin** climatic conditions, the mechanical cooling system is capable to achieve a category I thermal environment for 100% of the occupancy time, with very low energy consumption for cooling: passive strategies can hardly perform better from a comfort point of view and also there is little room for reduction in the energy consumption. As expected, the cooling potential has to be constrained in order to prevent thermal discomfort, which, as in Rome, is due to both the draft sensation during daytime and the mean air temperature dropping during nighttime. The solution found to perform best is the M_H, thus proving that there is almost no need for either active or passive cooling. As already stated, it is questionable though whether or not the adaptive model can be used to evaluate the scenario performances. Among the naturally ventilated cases the

N_02_H_A is capable to achieve a very good indoor environment (the best in terms of thermal comfort) and the largest saving in the energy demand.
A hybrid solution might improve the environment quality, but it is a risky choice since the combination of mechanical and night cooling can lead to a 17% increase in the energy consumption if the windows are manually operated during night. Then we do not suggest the use of a hybrid solution, also because we do not believe that the installation of a mechanical cooling system is justified in Berlin.
Copenhagen presents the coldest climate among the selected ones. By using a mechanical cooling system the thermal comfort is excellent (the building is in category I for 100% of the occupancy time) with an energy consumption that is basically only for heating needs. The tested natural ventilation strategies turned out to be extremely aggressive: the combination of ventilative and night cooling caused a decrease in the thermal comfort that ranges from 0.8% (N_02_H_A) to 4.0% (N_I_H), because of both draft sensation (ventilative cooling) and mean air temperature dropping (night cooling). A new scenario, which relies on daytime ventilation only for airing the building, and on automatically controlled night cooling (N_CV_H_A) has then been built and has been found to perform excellently. In particular it turned out that the night cooling alone is perfectly capable to meet the cooling need during the entire ventilation period. We believe that the installation of a mechanical cooling system in a dwelling sited in Copenhagen is not justified at all. Similarly there is no need for hybrid systems: natural ventilation represents the best option.
In Figure 161 the individual building signature for each of the selected strategy is shown, along with the signature of the M_HC system, for the four locations. The figure shows what has just been discussed, i.e.:

- In a warm climate (Athens) the combination of ventilative cooling with increased air velocity and night cooling is necessary to achieve a good indoor environment. The passive cooling techniques allow a very high energy saving.
- In a moderate climate (Rome and Berlin) daytime air velocity and nighttime air flow rate have to be constrained to prevent the cold sensation due to both undercooling and draft. The energy saving is consistent for Rome, less relevant for Berlin.
- In a cold climate (Copenhagen) there is almost no need for cooling. Night cooling alone was found to be capable to meet the cooling load during the entire natural ventilation period. The ventilative cooling should be avoided: during daytime the windows should be opened only for airing the dwelling.

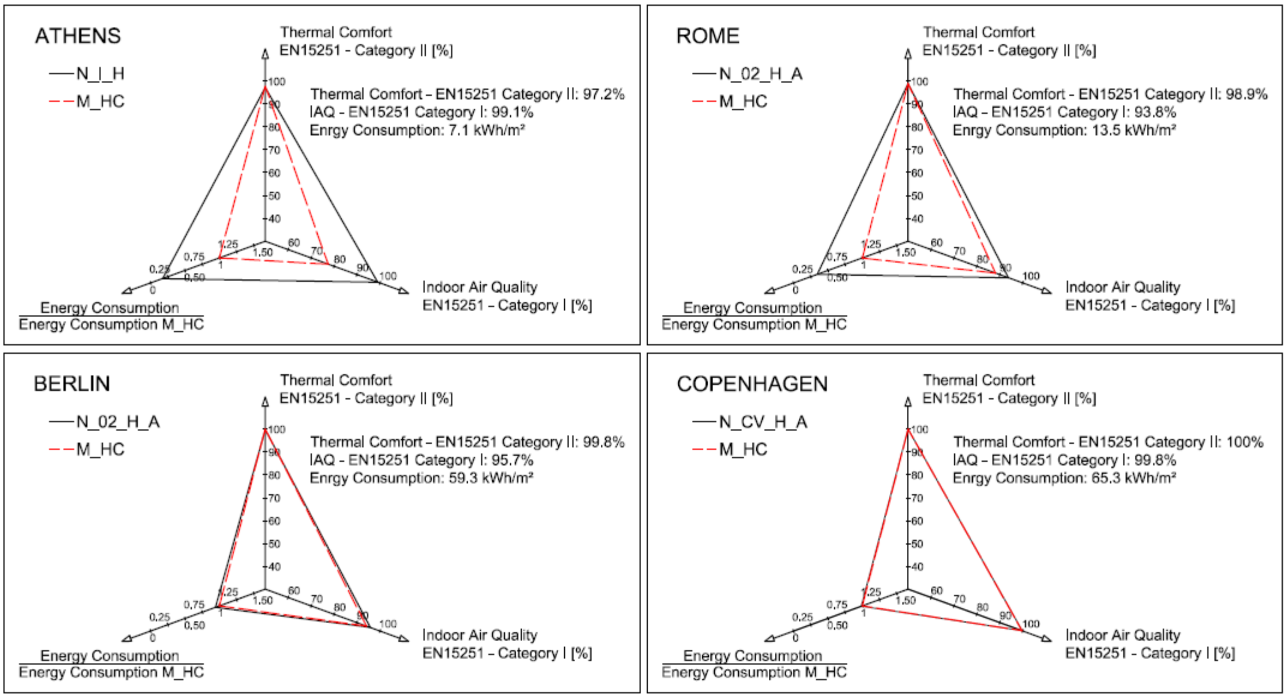


Figure 161 – Individual building signature: performance comparison between the selected strategy and the fully mechanical system for Athens (top left), Rome (top right), Berlin (bottom left) and Copenhagen (bottom right).

In all locations the passive cooling strategies have been proven efficient in achieving a good thermal comfort, in particular in Copenhagen night cooling alone is capable to meet the cooling load during the entire natural ventilation period.

We can conclude that in general passive cooling strategies showed very good performances and turned out to be the only solutions capable to achieve the tradeoff between good indoor environment (in terms of both thermal comfort and IAQ) and low energy consumption, especially in the warm Mediterranean climate, where summer comfort is conventionally obtained by mechanically cooling the building.

The study showed in its first part that the parameters which define the ventilation strategy, i.e. the night cooling threshold, the daytime air velocity and the nighttime air flow rate, have to be carefully chosen in order to obtain thermal comfort. A misjudgment can indeed cause either undercooling or overheating, compromising the thermal comfort and, in some cases, increasing the energy consumption.

We can make one last observation on the EN15251 standard. In all locations, and especially in Rome, when the thermal comfort is evaluated according to the EN15251 adaptive model, the discomfort is due to the undercooling that occurs during night. Referring to category II, during summer the lower limit rises up to 24°C in Rome and above 25°C in Athens, in Berlin and Copenhagen the limit is lower (close to 23°C in both locations), but still very high. If we now consider that, according to the Active House specifications [49], when people are sleeping, or trying to fall asleep, they are more sensitive to high temperatures and the comfort temperature has then to be lower, the noticed undercooling should not be regarded as a cause of serious discomfort.

10. REFERENCES

[1] IPCC (2007). Climate Change 2007: The physical science basis. Working Group I of the IPCC.

[2] European Commission (2008). 20 20 by 2020: Europe's climate change opportunity. Commission of the European Communities.

[3] L. Joosten, I. Strom, C. Boonstra (2006). Energy saving potential. Promotion of European Passive houses (PEP).

[4] AIVC (1996). The role of natural ventilation in cooling non-domestic buildings. Technical note AIVC 48.

[5] E. Gratia, I. Bruyère, A. De Herde (2004). How to use natural ventilation to cool narrow office buildings. Elsevier, Building and Environment 39.

[6] J. T. Lin, Y. K. Chuah (2010). A study on the potential of natural ventilation and cooling for large spaces in subtropical climatic regions. Elsevier, Building and Environment 46.

[7] L. de Santoli, M. Mariotti (2009). Assessment of the indoor condition of a naturally ventilated nursery school in Rome. 30th AIVC Conference: Trends in High Performance Buildings and the role of Ventilation.

[8] C. Qin, L. Zhao (2012). The energy saving effect of the natural ventilation for residential building in Guanzhou. Building Environment and Energy Laboratory, South China University of Technology.

[9] S. Schiavon, A. K. Melikov (2008). Energy saving and improved comfort by increased air movement. Elsevier, Energy and Buildings 40.

[10] M. Santamouris (1998). Natural ventilation in buildings: A design handbook. Francis Allard Editor.

[11] D. R. Ernest (1991) Predicting wind-induced air motion, occupant comfort and cooling loads in naturally ventilated buildings. PhD thesis, University of California (Berkeley).

[12] B. J. Vickery, C. Karakatsanis. External wind pressure distributions and induced internal ventilation flow in low-rise industrial and domestic structures. ASHRAE Transaction.

[13] D. R. Ernest, F. S. Bauman, E. A. Arens (1992). The effect of external wind pressure distribution on wind-induced air motion inside buildings. Elsevier, Journal of Wind Engineering and Industrial Aerodynamics.

[14] E. Descalaki, M. Santamouris, A. Argiriou, C. Helmis, D. N. Asimakopoulos, K. Pappadopoulos, A. Soilemes (1996). On the combination of air velocity and flow measurements in single sided natural ventilation configurations. Elsevier, Energy and Buildings 24.

[15] P. Karava, T. Stathopoulos, A. K. Athienitis (2011). Airflow assessment in cross-ventilated buildings with operable façade elements. Elsevier, Building and Environment 46.

[16] H. B. Awbi (1996). Air movement in naturally-ventilated buildings. WREC.

[17] M. Z. I. Bangalee, S. Y. Lin, J. J. Miau (2012). Wind driven natural ventilation trhough multiple windows of a building: A computational approach. Elsevier, Energy and Buildings 45.

[18] M. A. Humphreys, J. F. Nicol. Understanding the adaptive approach to thermal comfort.

[19] S. Borgeson, G. Brager (2008). Occupant control of windows: accounting for human behavior in building simulation. Center for the built environment, University of California, Berkeley.

[20] CEN (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings: addressing indoor air quality, thermal environment, lighting and acoustic. EN15251.

[21] W.F. de Gids (2010). Hybrid ventilation. AIVC Ventilation Information Paper n° 32.

[22] P. Foldbjerg, T. F. Asmussen, K. Duer (2011). Hybrid ventilation as a cost-effective ventilation solution for low energy residential buildings. VELUX A/S. Proceedings of Indoor Air conference, Austin, Texas.

[23] A. Martin (1995). Automatic control of natural ventilation and passive cooling. 16th AIVC Conference: Implementing the results of ventilation research.

[24] M. P. Deuble, R. J. De Dear (2012). Mixed-mode buildings: A double standard in occupants' comfort expectations. Elsevier, Building and Environment 54.

[25] K. H. Lee, R. K. Strand (2009). Enhancement of natural ventilation in buildings using a thermal chimney. Elsevier, Energy and Buildings 41.

[26] X. Q. Zhai, Z. P. Song, R. Z. Wang (2011). A review for the applications of solar chimneys in buildings. Elsevier, Renewable and Sustainable Energy Reviews 15.

[27] R. Khanal, C. Lei (2011). Solar chimney – A passive strategy for natural ventilation. Elsevier, Energy and Buildings 43.

[28] O. Saadatian, L. C. Haw, K. Sopian, M. Y. Sulaiman (2012). Review of windcatcher technologies. Elsevier, Renewable and Sustainable Energy Reviews 16.

[29] B. Givoni (1990). Performance and applicability of passive and low-energy cooling system. Elsevier, Energy and Building 17.

[30] E. Shaviv, A. Yezioro, I. G. Capeluto (2001). Thermal mass and night ventilation as passive cooling design strategy. Pergamon, Renewable Energy 24.

[31] M. Santamouris (2004). Night ventilation strategies. AIVC Ventilation Information Paper n°4.

[32] M. Santamouris, D. Asimakopoulos (2001). Passive cooling of buildings. James and James (Science Publisher) Ltd.

[33] A. Böllinger, H. W. Roth (1993). Benefits and limits of free cooling in non-residential buildings. 14th AIVC Conference: Energy Impact of Ventilation and Air Infiltration.

[34] M. Santamouris, A. Sfakianaki, K. Pavlou (2010). On the efficiency of night ventilation techniques applied to residential buildings. Elsevier, Energy and Buildings 42.

[35] D. Rennie, F. Parand (1998). Environmental design guide for naturally ventilated and daylit offices. Building Research Establishment Ltd.

[36] J. M. Salmerón Lissen, F. J. Sánchez de la Flor, S. Álvarez Domínguez, A. Ruiz Pardo. Flow patterns effects on night cooling ventilation.

[37] http://www.epa.gov/

[38] M. W. Liddament (1999). A review of ventilation and the quality of ventilation air. 20th AIVC Conference: Ventilation and indoor air quality in buildings.

[39] N. H. Wong, B. Huang (2004). Comparative study of the indoor air quality of naturally ventilated and

air-conditioned bedrooms of residential buildings in Singapore. Elsevier, Building and Environment 39.

[40] Y. Takemasa, A. Moser (1999). Comparison of mechanical and natural ventilation using long-term evaluation model for indoor air quality, thermal environment and energy consumption. 20th AIVC Conference: Ventilation and indoor air quality in buildings.

[41] M. C. Peel, B. L. Finlayson, T. A. McMahon (2007). Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences.

[42] V. Geros, M. Santamouris, A. Tsangrassaoulis, G. Guarraccino (1999). Experimental evaluation of night ventilation phenomena. Elsevier, Energy and Buildings 29.

[43] V. Geros, M. Santamouris, G. Guarraccino (1997). Applying night ventilation techniques in office buildings. 18th AIVC Conference.

[44] G. C. de Graça, Q. Chen, L.R. Glicksman, L.K. Norford (2002). Simulation of wind driven ventilative cooling systems for an apartment building in Beijing and Shanghai. Department of Architecture, Massachusetts Institute of Technology.

[45] I. Pollet, P. Renson (2007). Nightcooling: practical experiences in offices and the need for standard implementation into energy performance legislations. 28th AIVC Conference: Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century.

[46] M. Sourborn, L. Helsen (2011). Evaluation of adaptive thermal comfort models in moderate climates and their impact on energy use in office building. Elsevier, Energy and Building 43.

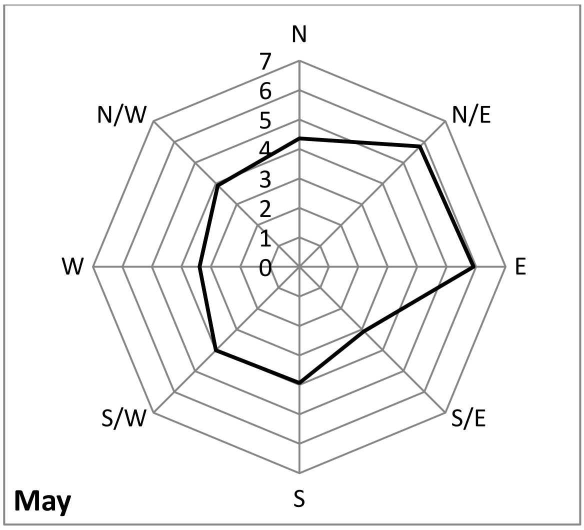
[47] J. Kragh, J. B. Laustsen, S. Svendsen (2008). Proposal for Energy Rating System of windows in EU. DTU Civil Engineering-Report R-201.

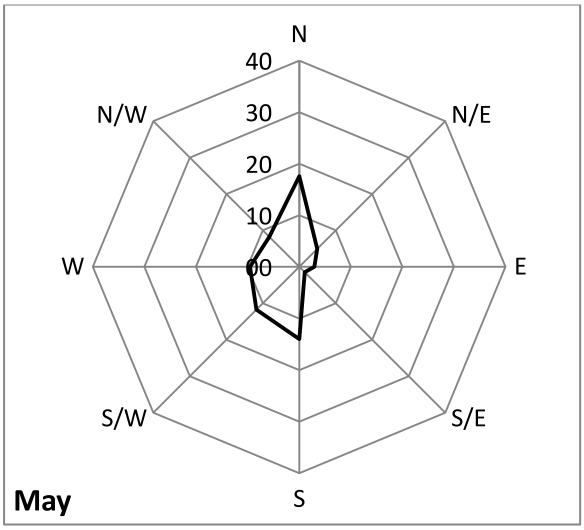
[48] P. A. Andersen et al. (2012). Daylight, Energy and Indoor Climate Basic Book. Editorial team: Daylight Energy and Indoor Climate (DEIC), VELUX A/S.

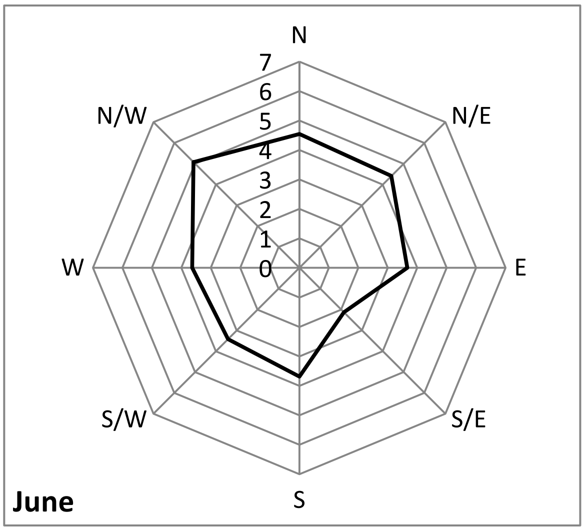
[49] ACTIVE HOUSE Alliance (2011). ACTIVE HOUSE – Specifications. Buildings that give more that they take. 1st edition.

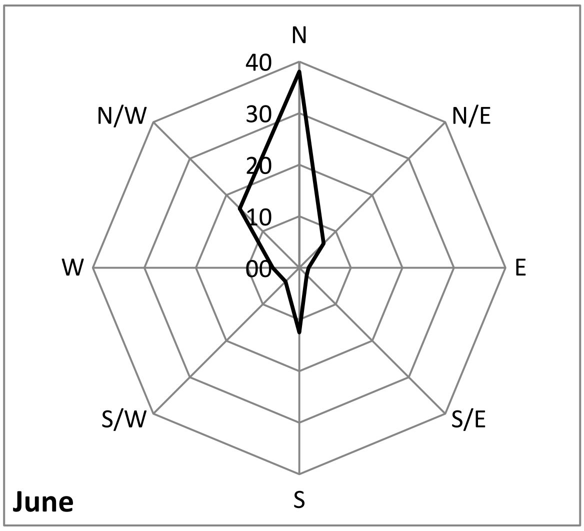
APPENDIX A

In the Figures Figure A1 - Figure A4 (above) the wind velocity (on the left) and the wind frequency (on the right) are shown for the four locations. For every main direction a mean value of the velocity and the frequency, calculated as direction-averaged, is presented on a monthly base. The higher is the value on the axis, the greater is the wind velocity, or frequency, of the wind blowing *from* that direction.









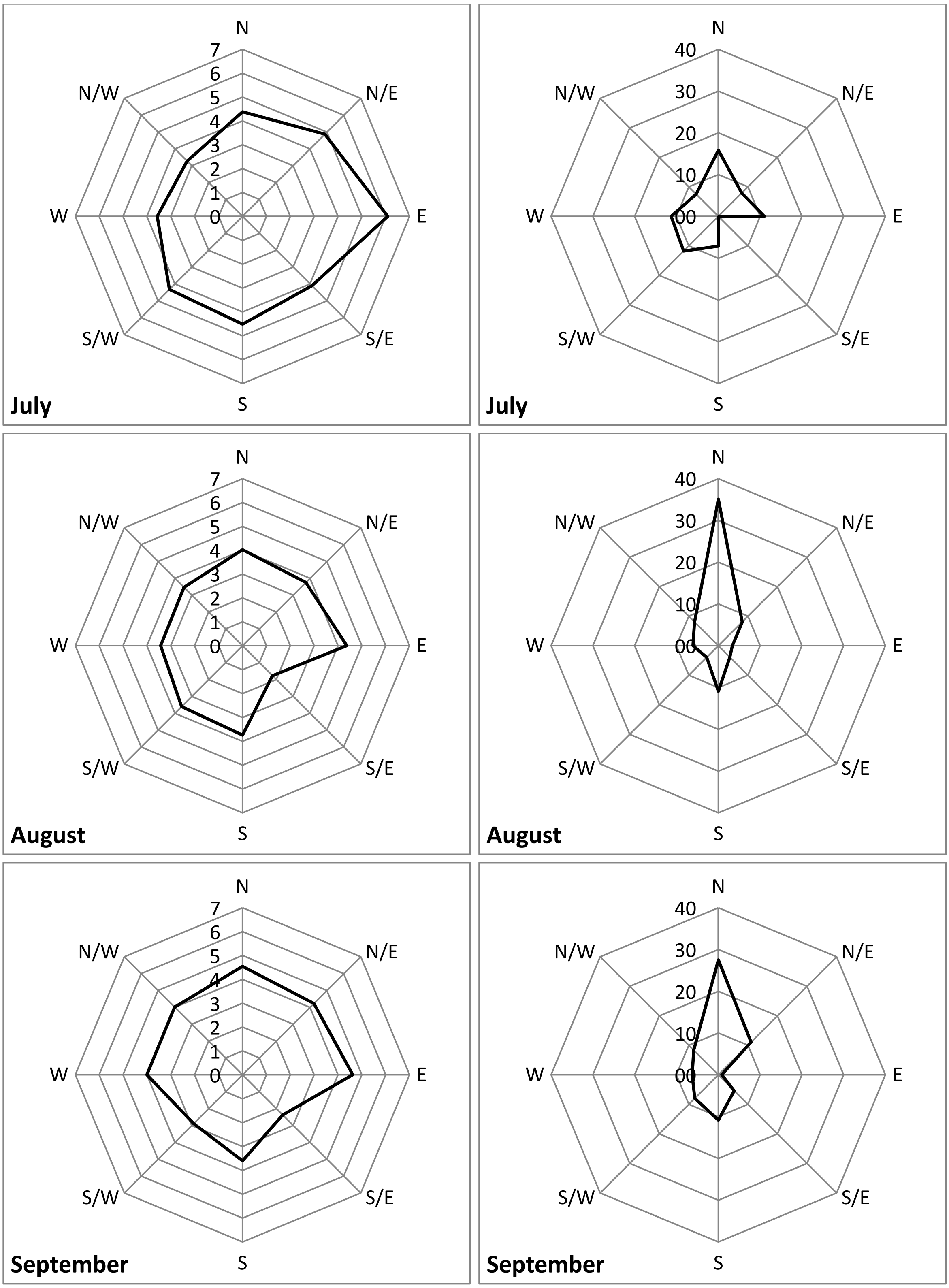
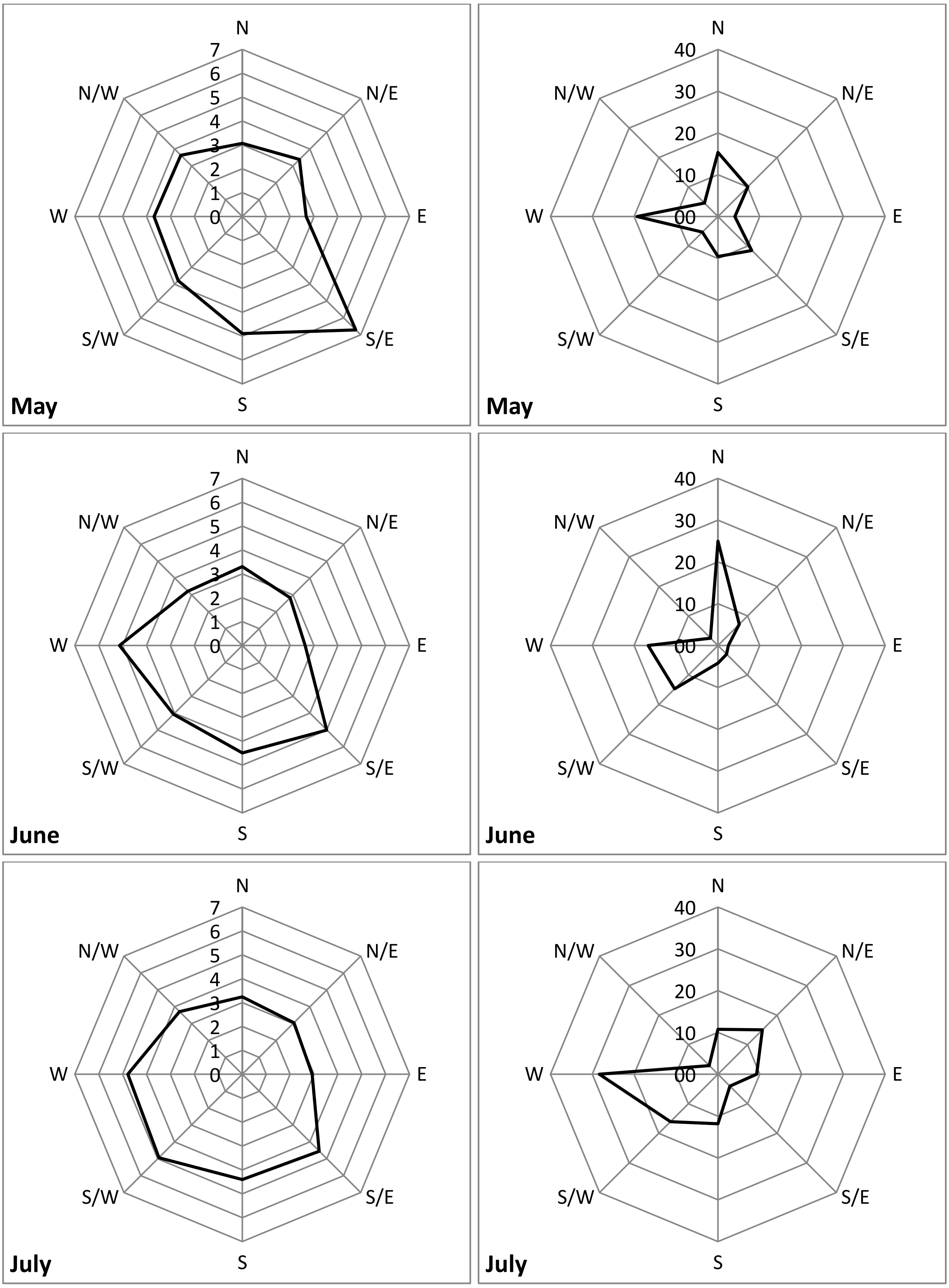


Figure A1 – Wind velocity (left) and frequency (right) for the city of Athens during the cooling season.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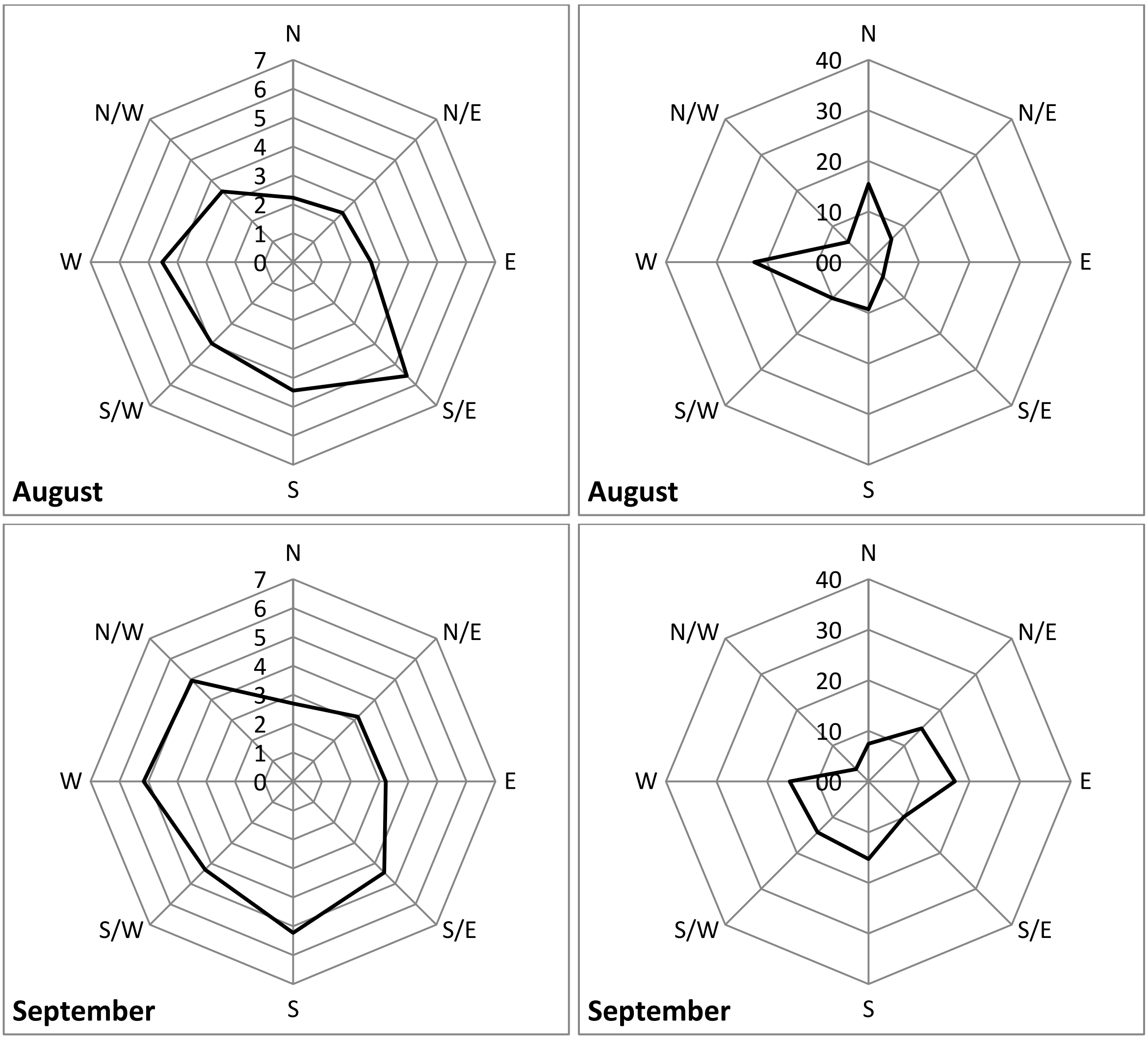
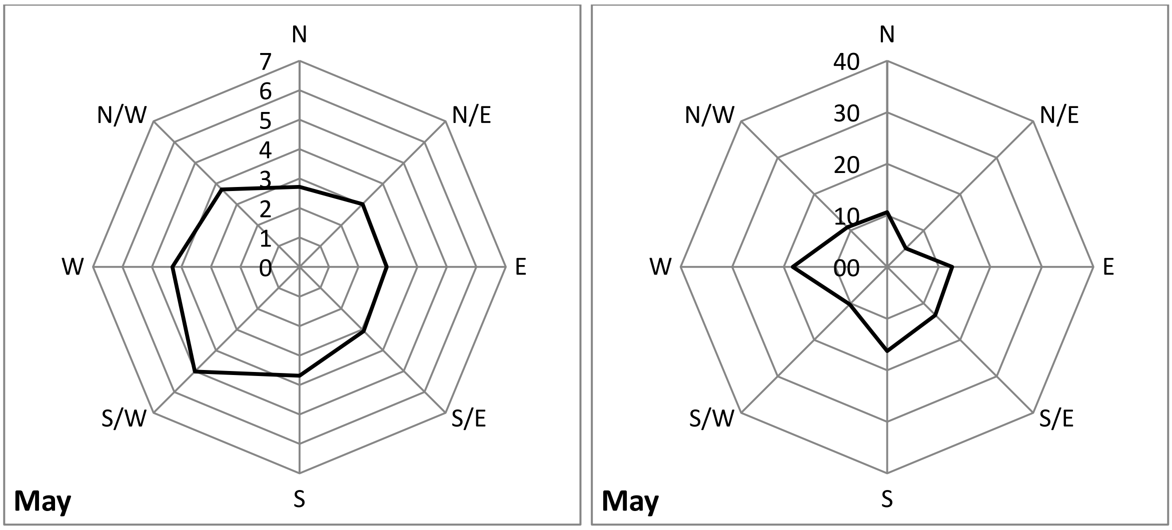
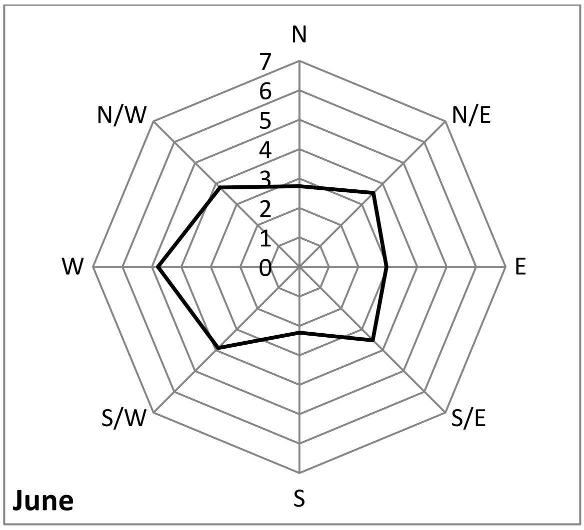


Figure A2– Wind velocity (left) and frequency (right) for the city of Rome during the cooling season.

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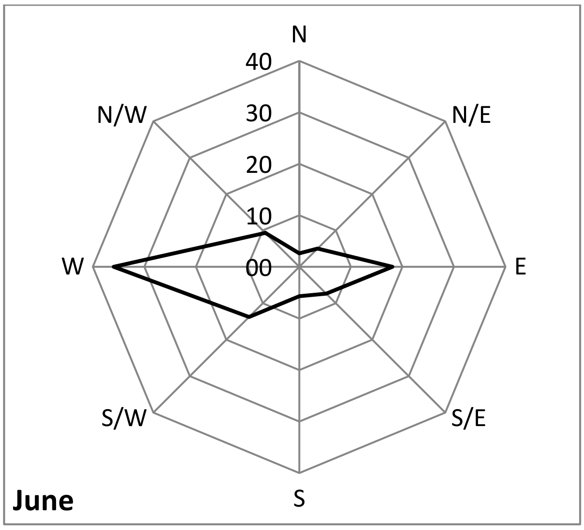
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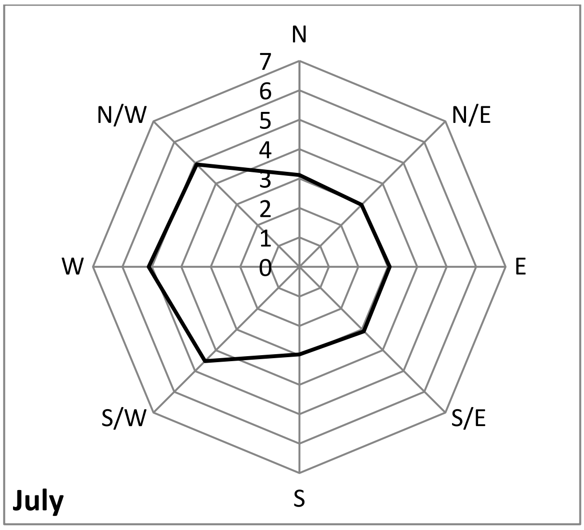
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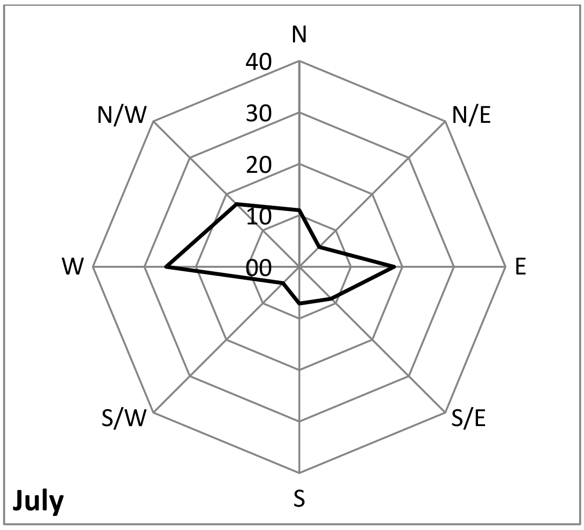
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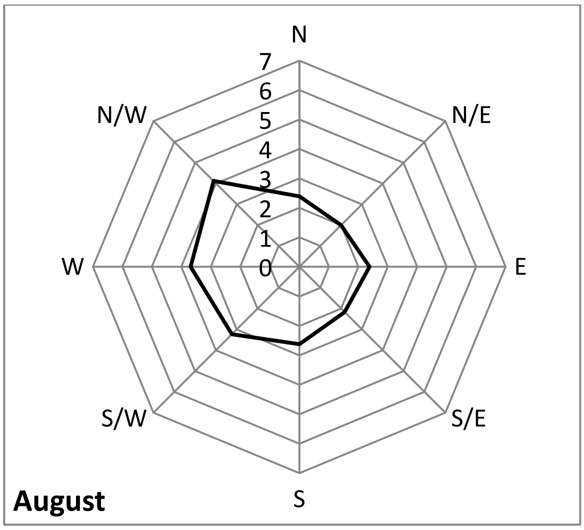
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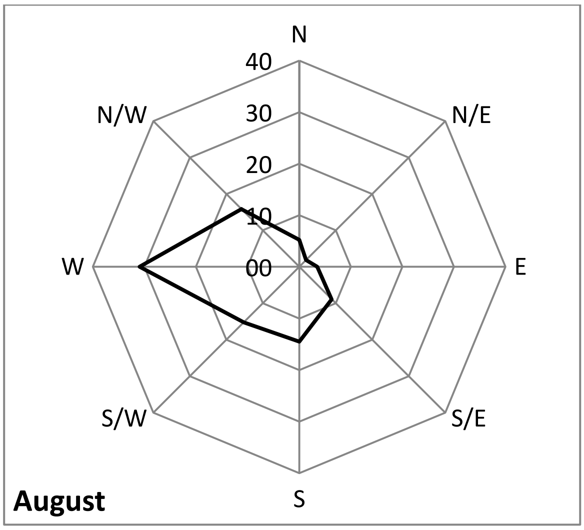
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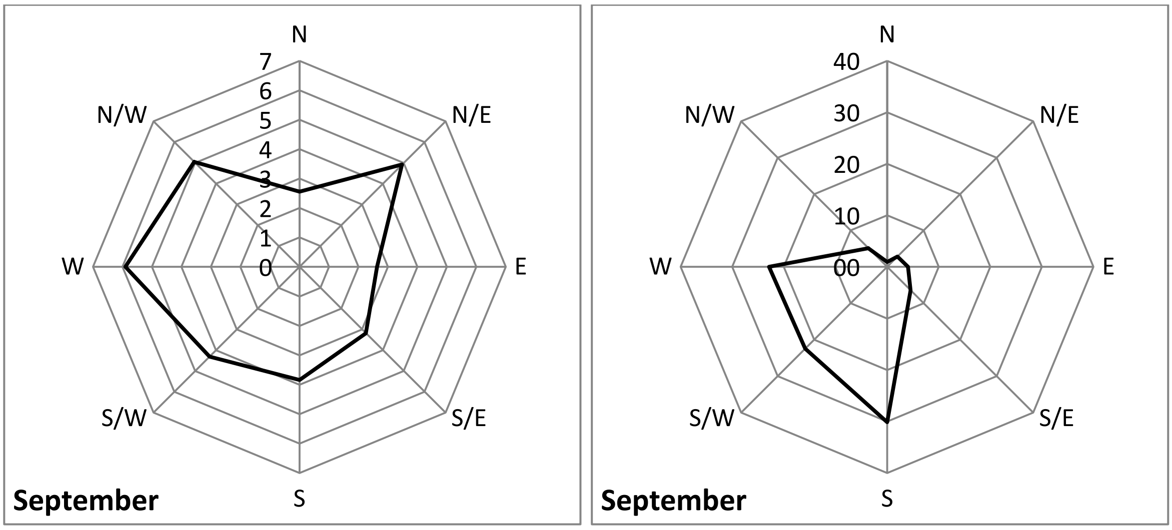
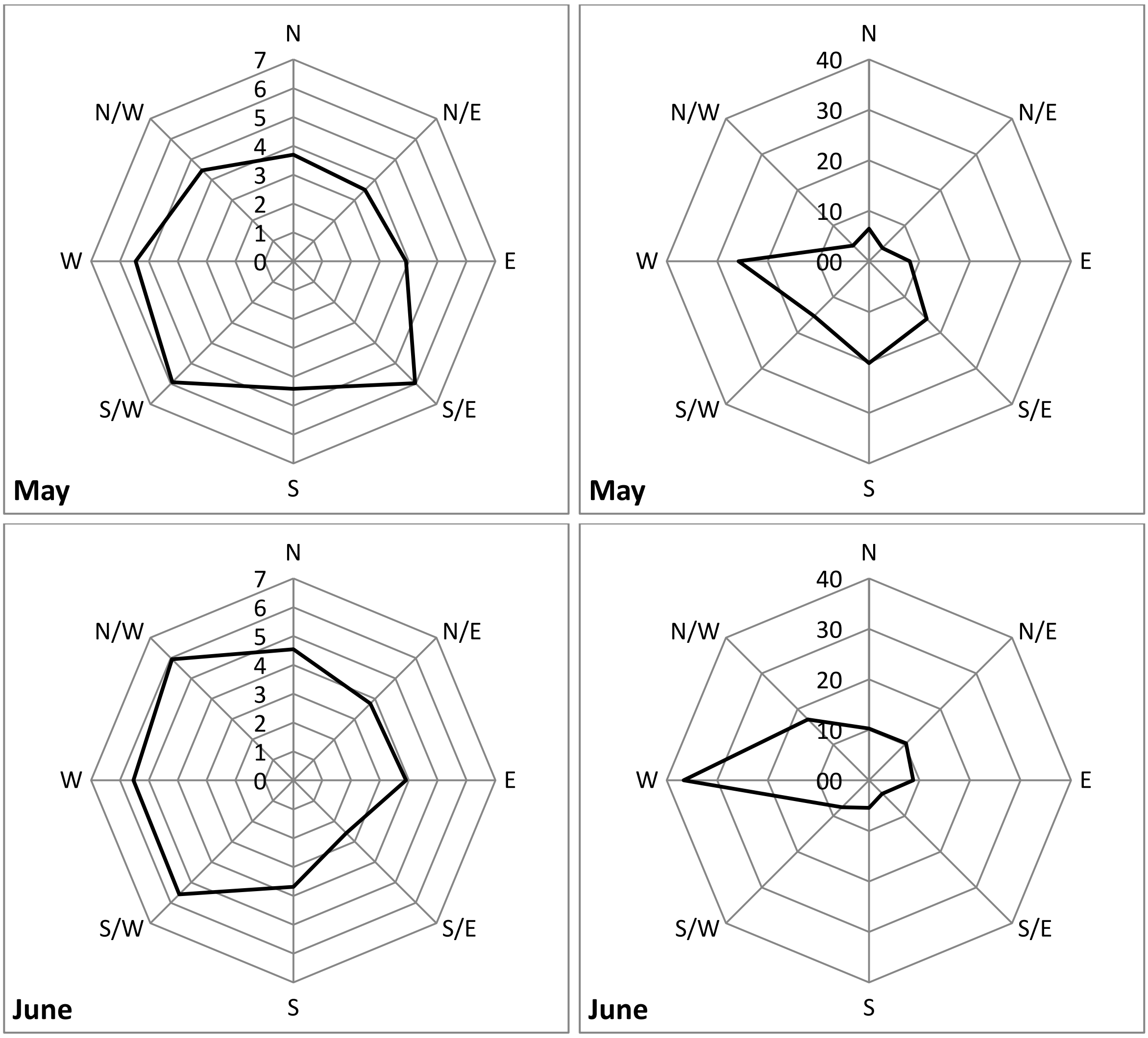


Figure A3 – Wind velocity (left) and frequency (right) for the city of Berlin during the cooling season.



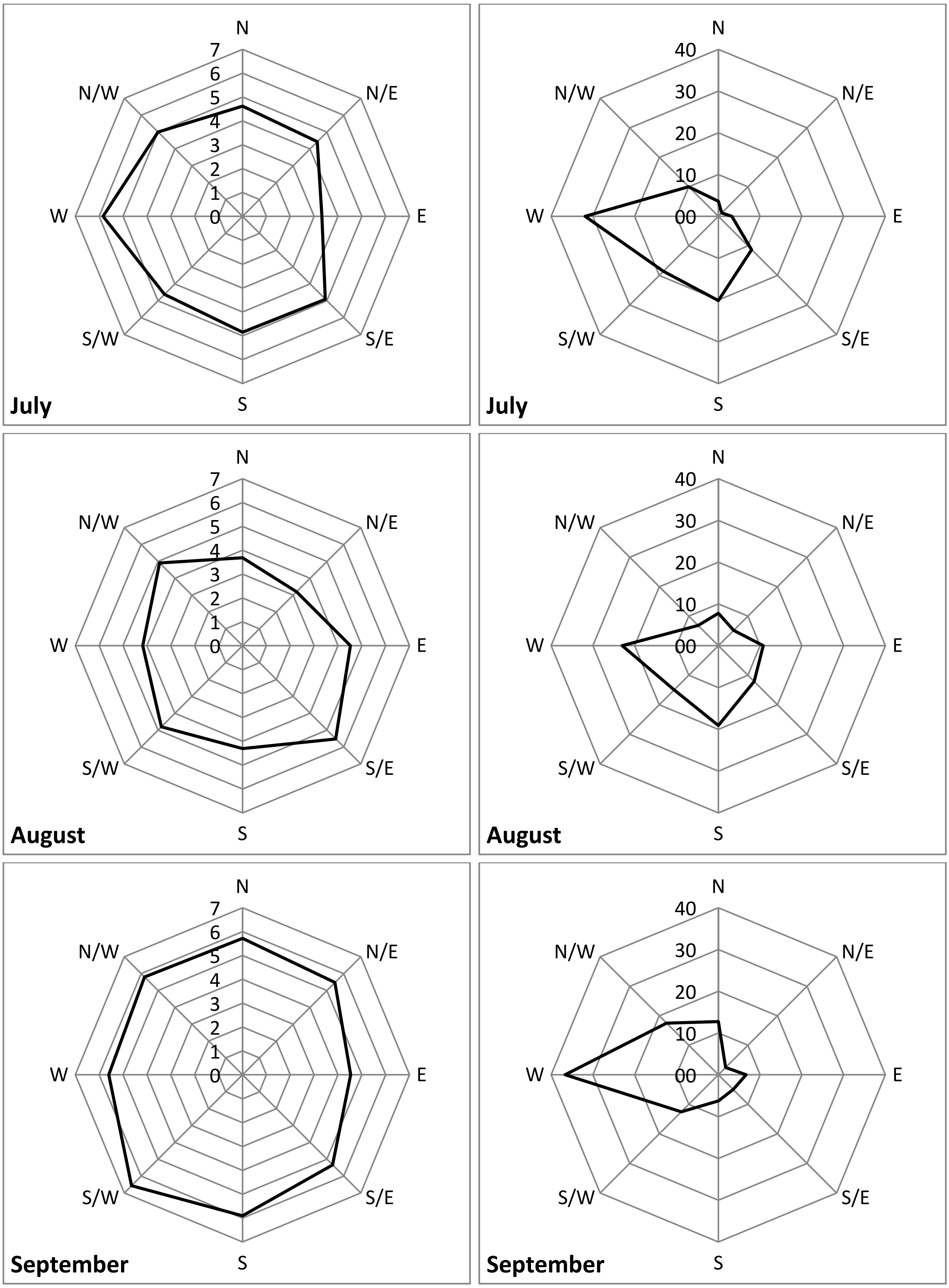


Figure A4 – Wind velocity (left) and frequency (right) for the city of Copenhagen during the cooling season.

APPENDIX B

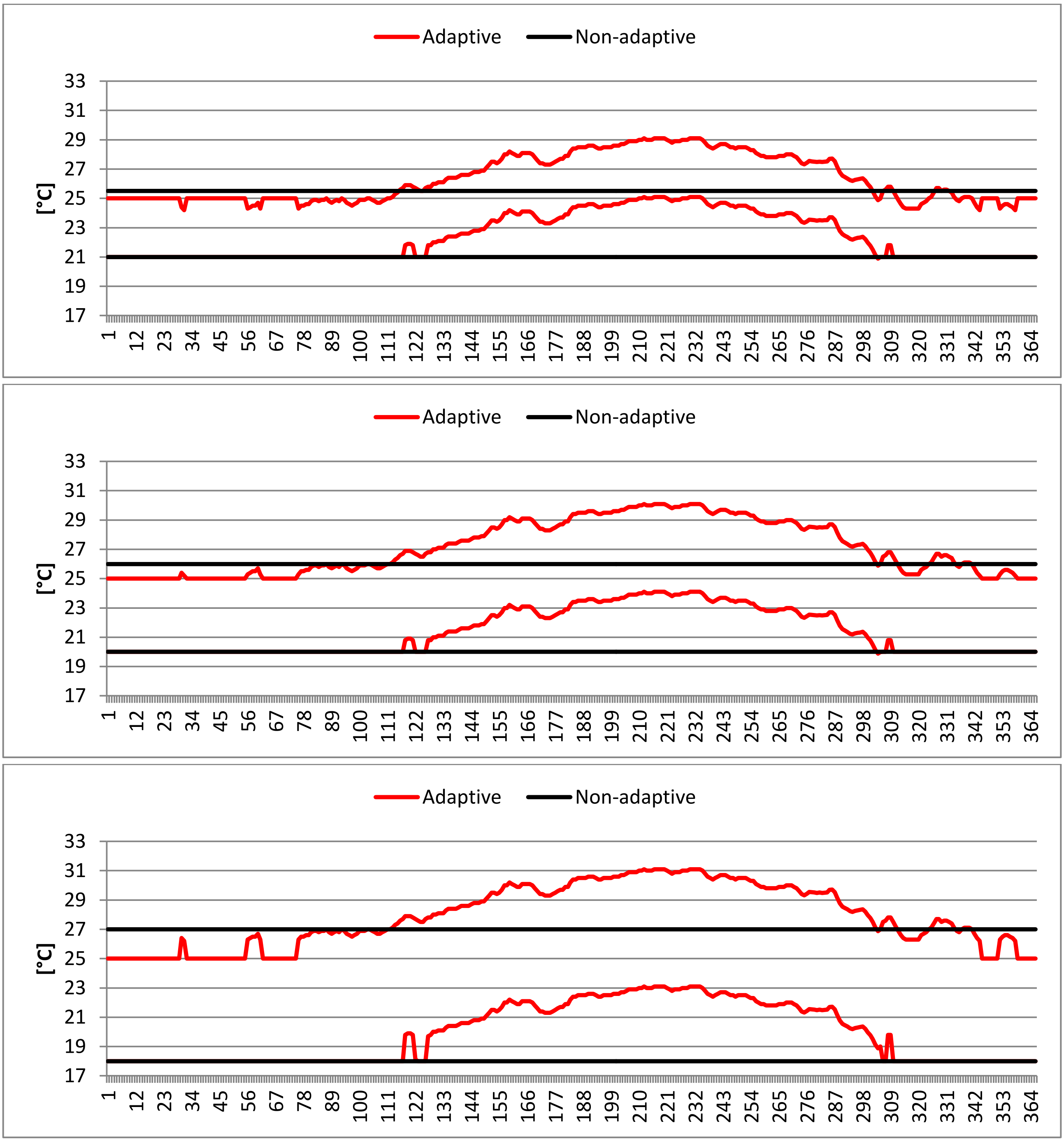


Figure B1 – Upper and lower comfort limits for the category I (top), category II (middle) and category III (bottom) according to both the adaptive and non-adaptive model prescribed in the standard EN15251 for the city of Rome.

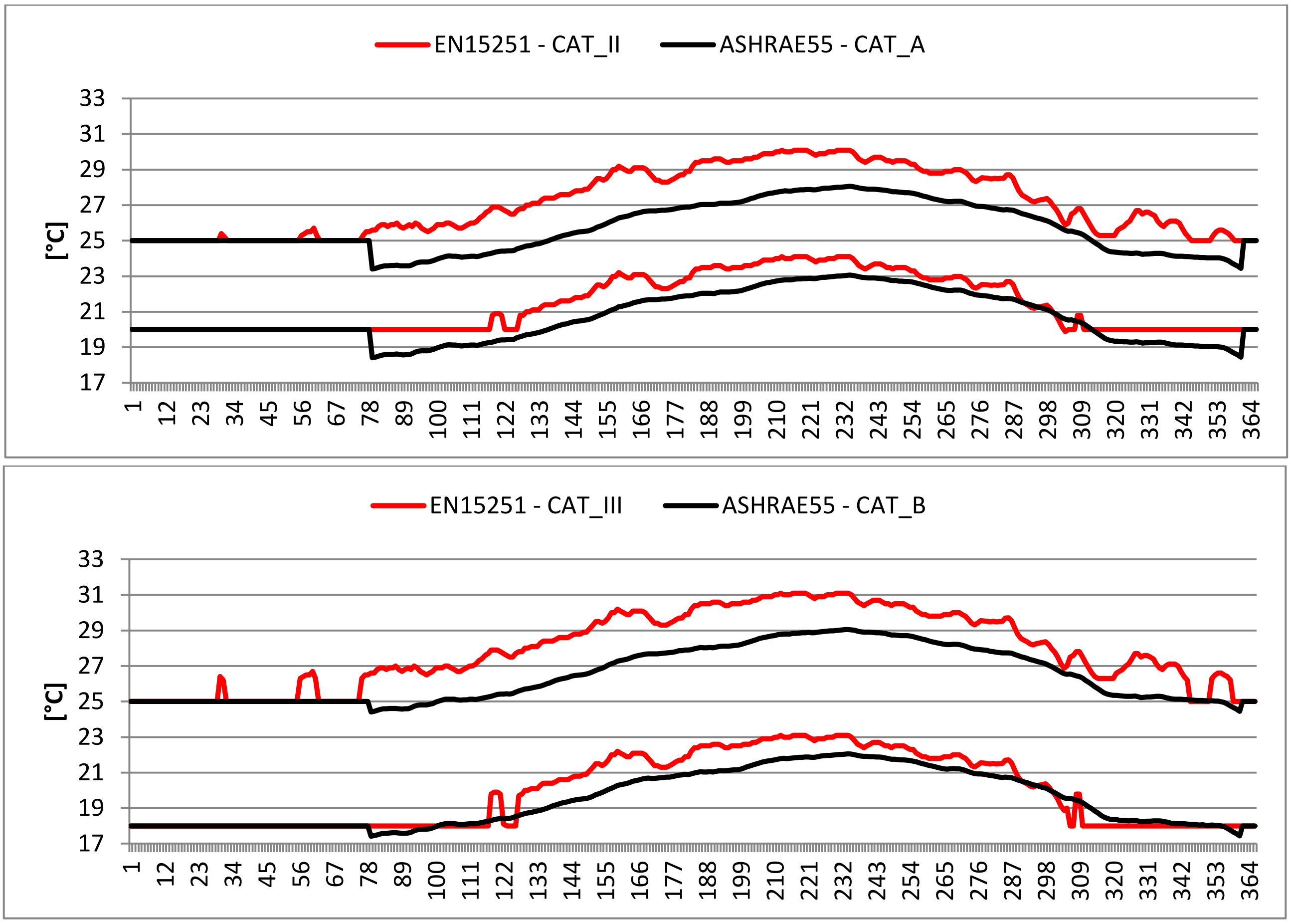
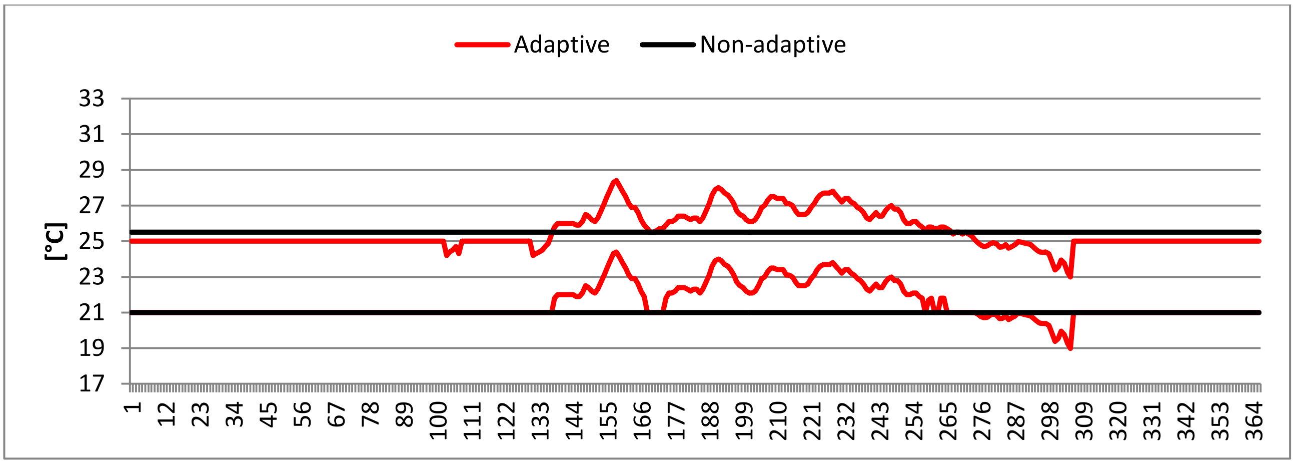


Figure B2 – comparison between the ASHRAE55 and the EN15251 adaptive models for the city of Rome.



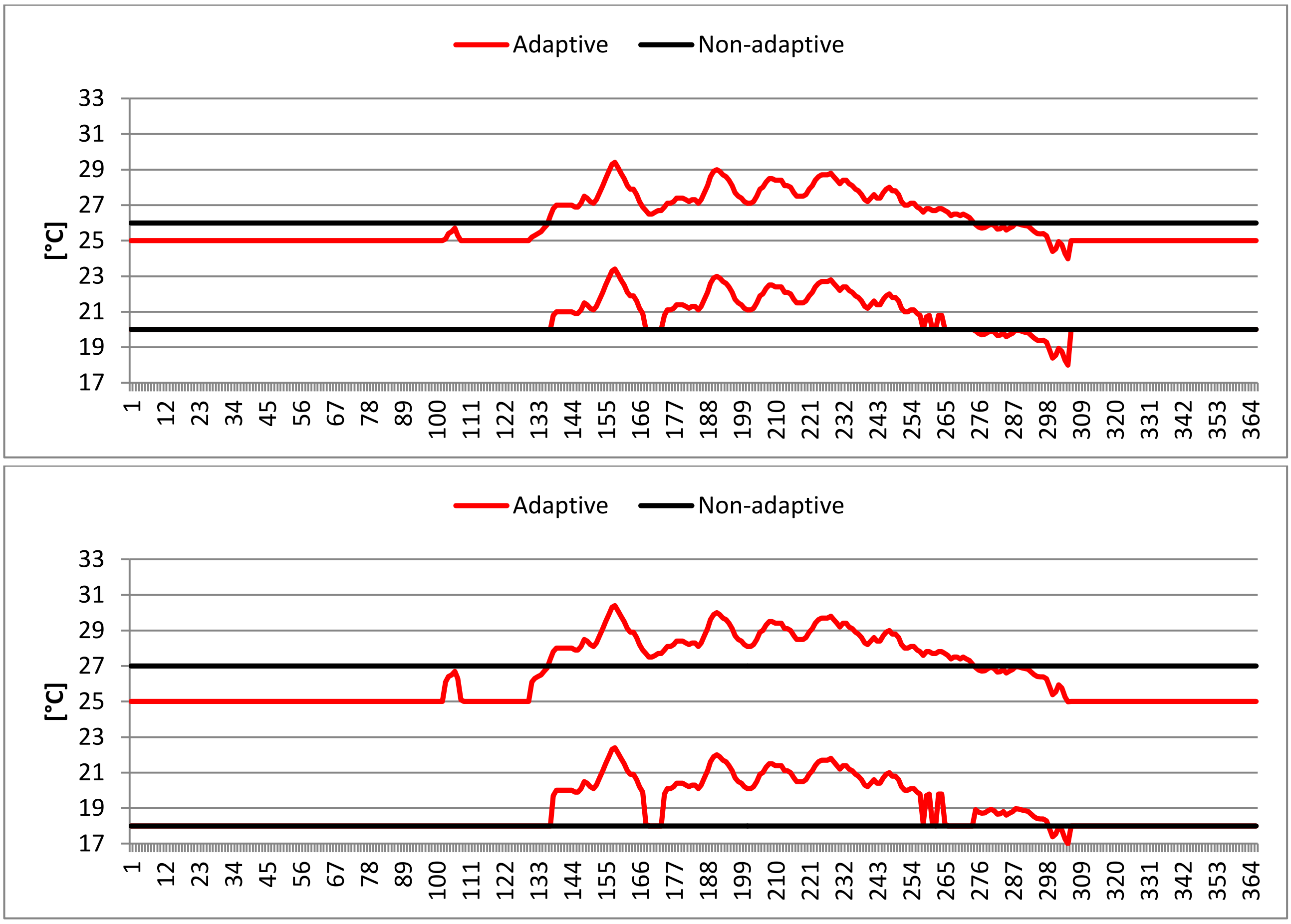
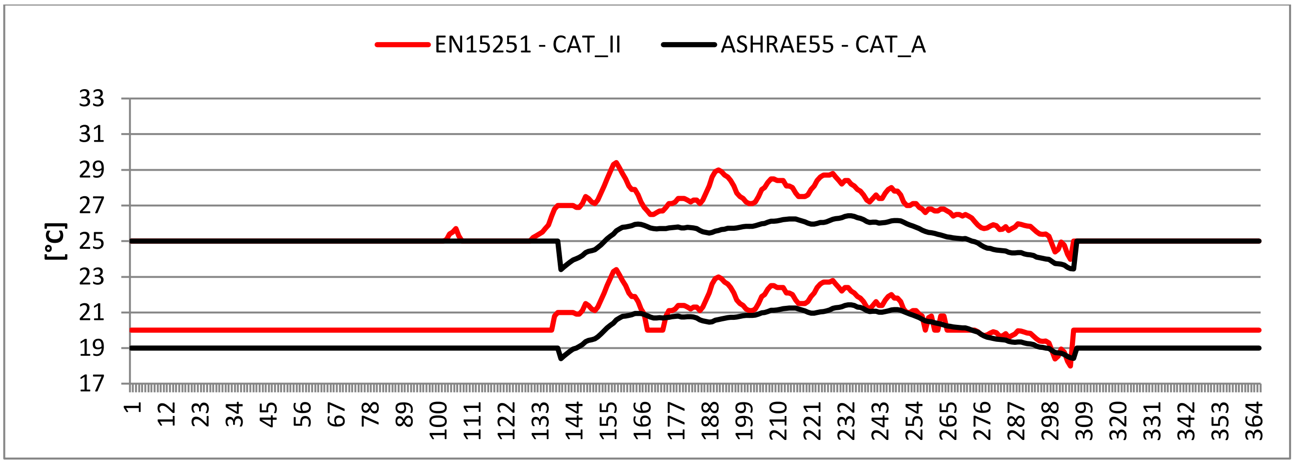


Figure B3 – Upper and lower comfort limits for the category I (top), category II (middle) and category III (bottom) according to both the adaptive and non-adaptive model prescribed in the standard EN15251 for the city of Berlin.



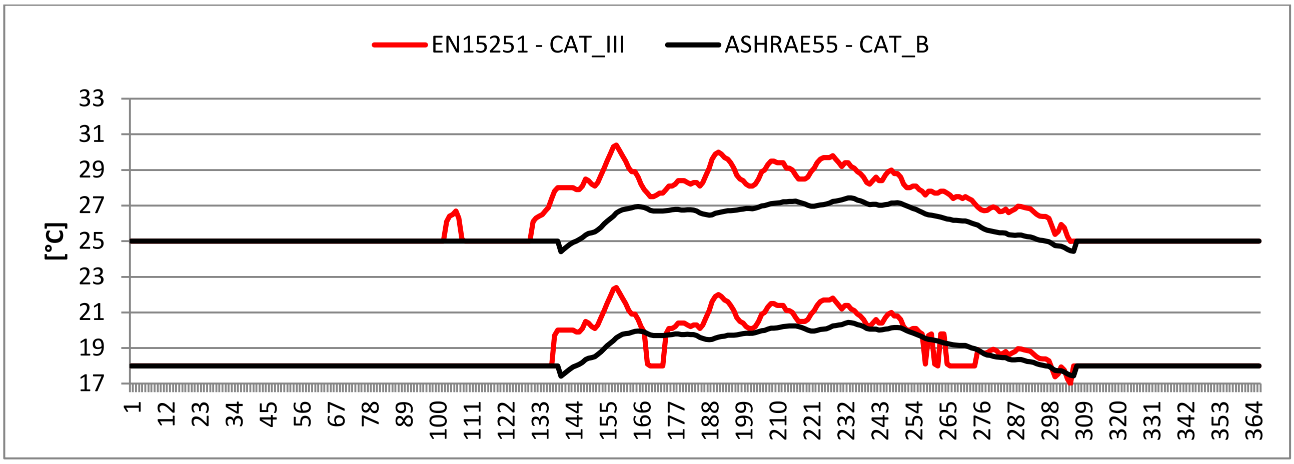
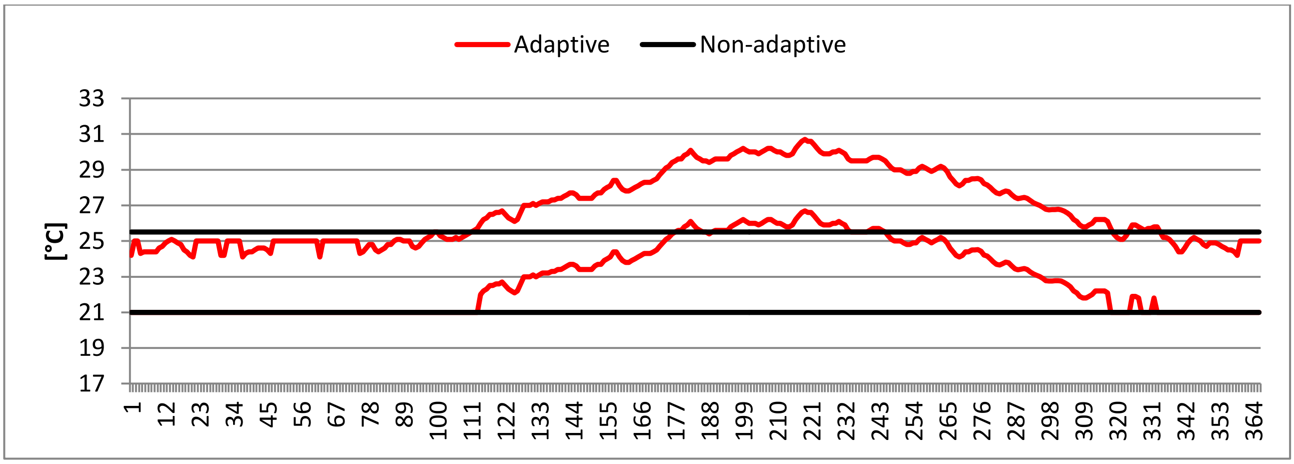
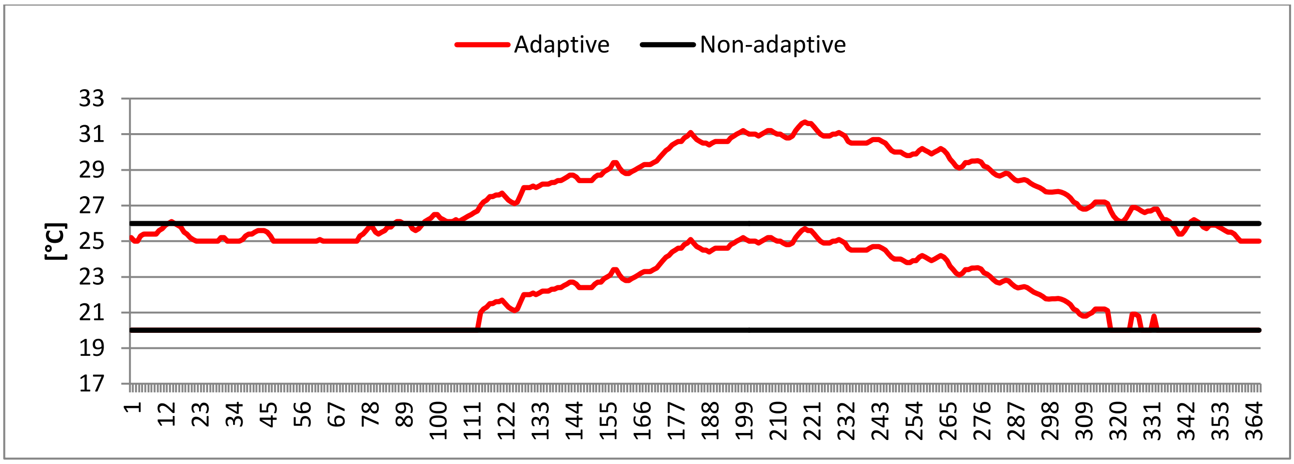


Figure B4 – comparison between the ASHRAE55 and the EN15251 adaptive models for the city of Berlin.





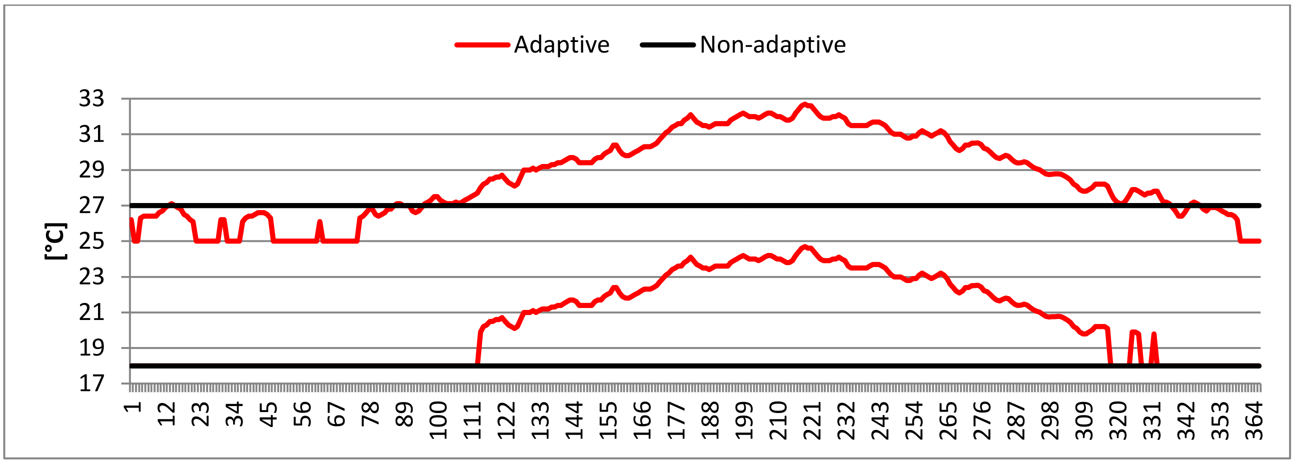


Figure B5 – Upper and lower comfort limits for the category I (top), category II (middle) and category III (bottom) according to both the adaptive and non-adaptive model prescribed in the standard EN15251 for the city of Athens.

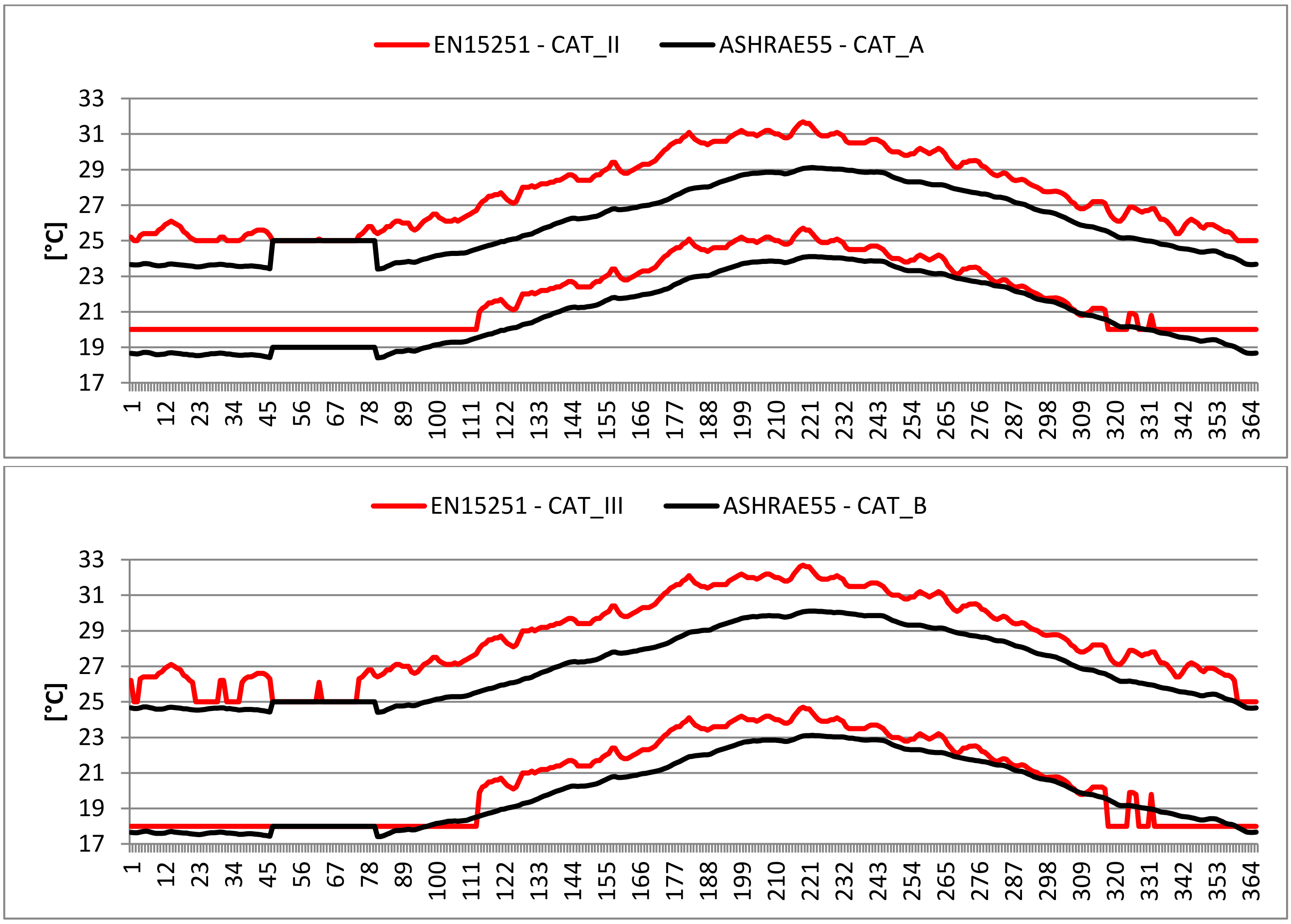


Figure B6 – comparison between the ASHRAE55 and the EN15251 adaptive models for the city of Athens.

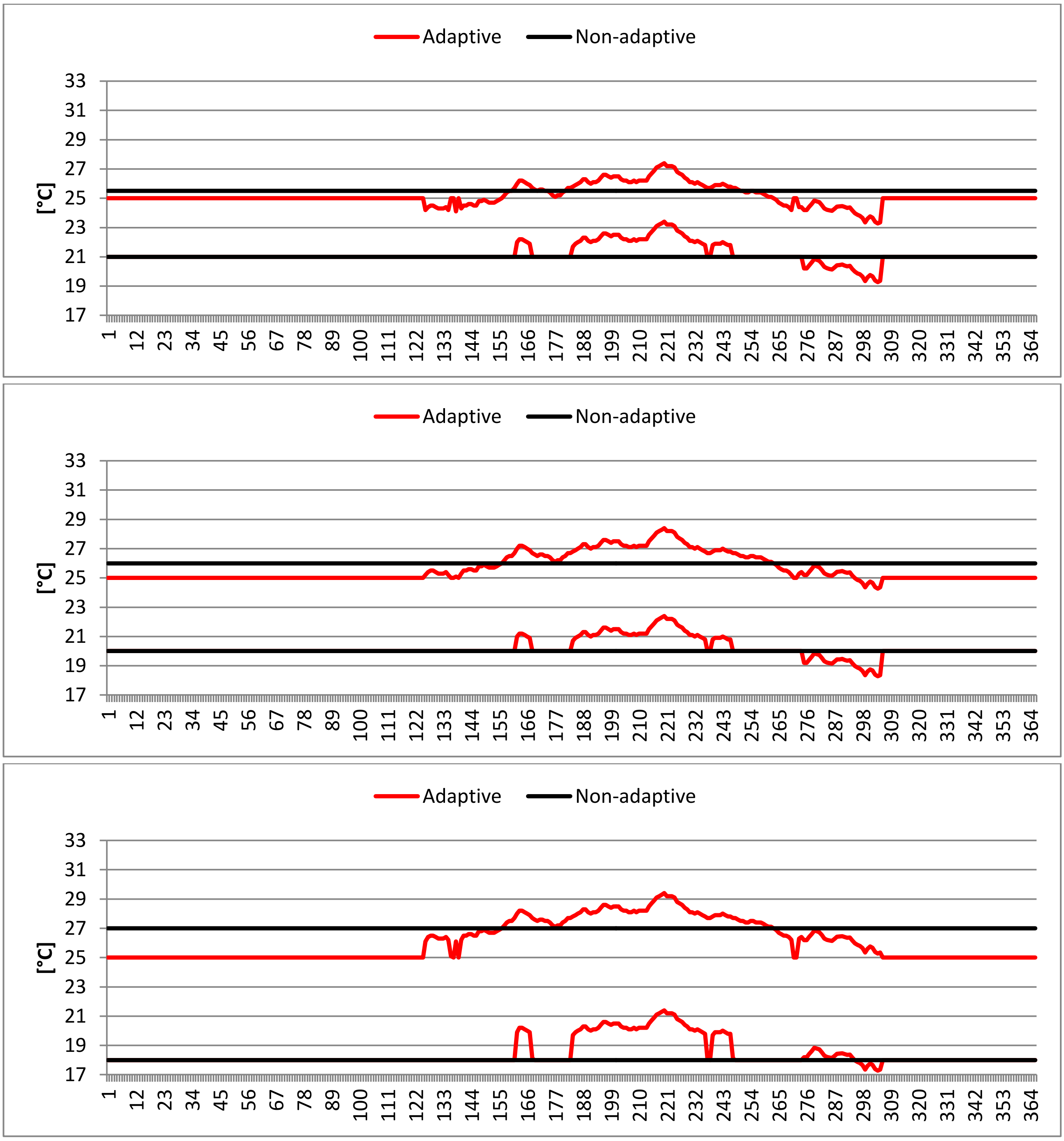


Figure B7 – Upper and lower comfort limits for the category I (top), category II (middle) and category III (bottom) according to both the adaptive and non-adaptive model prescribed in the standard EN15251 for the city of Copenhagen.

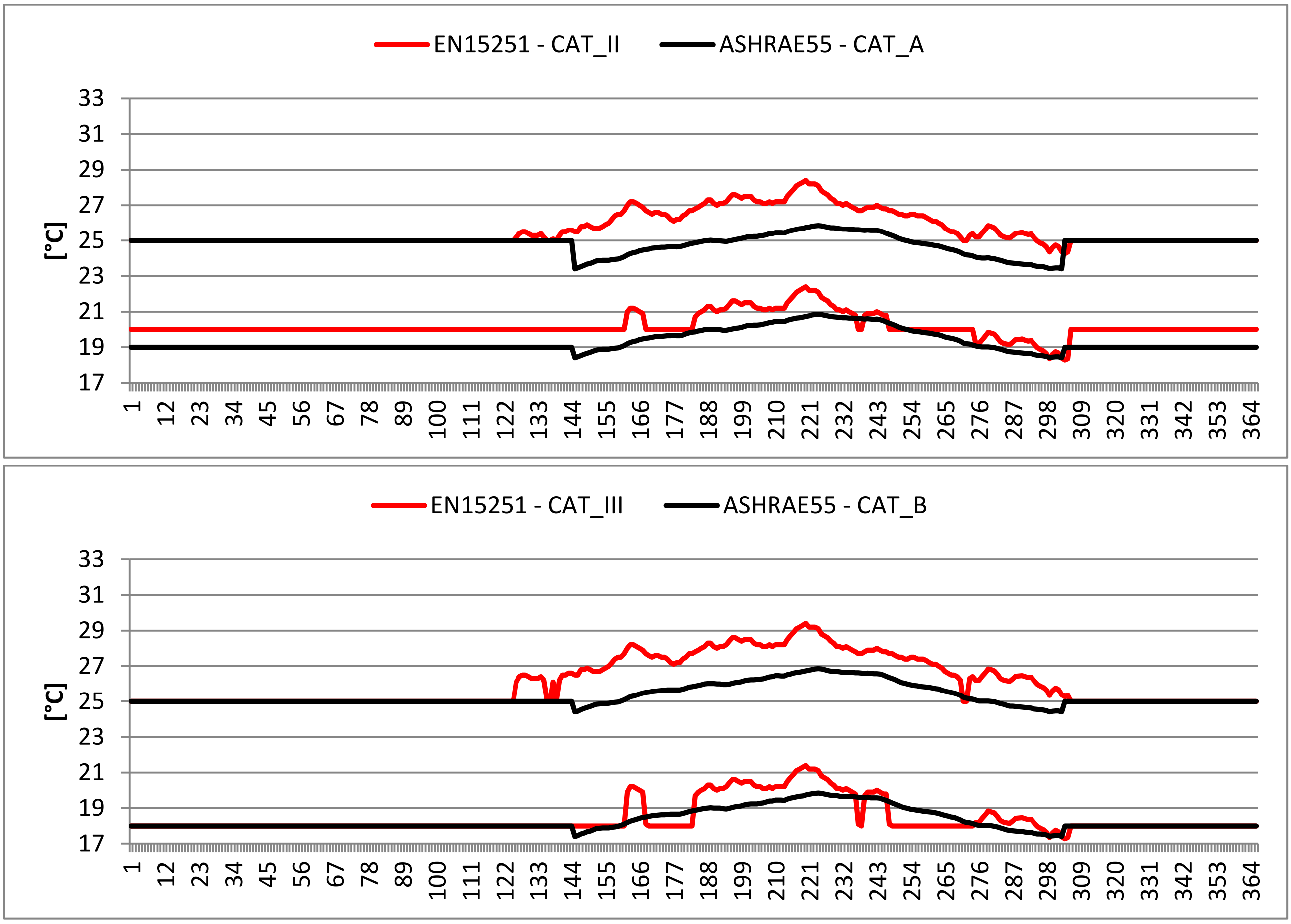


Figure B8 – comparison between the ASHRAE55 and the EN15251 adaptive models for the city of Copenhagen.

APPENDIX C

In this appendix the hourly mean indoor air velocity is shown for both the increased and the non-increased air velocity cases. The velocities shown in the following figures are the ones calculated according to the approximated procedure described in chapter 4. (Model and Methodology), paragraph 4.5. (Methodology). Along with the air velocities, the temperature offset, calculated according to the EN15251, is shown.

As reference cases the N_02_H and the N_I_H has been chosen of the non-increased and increased air velocities scenarios respectively.

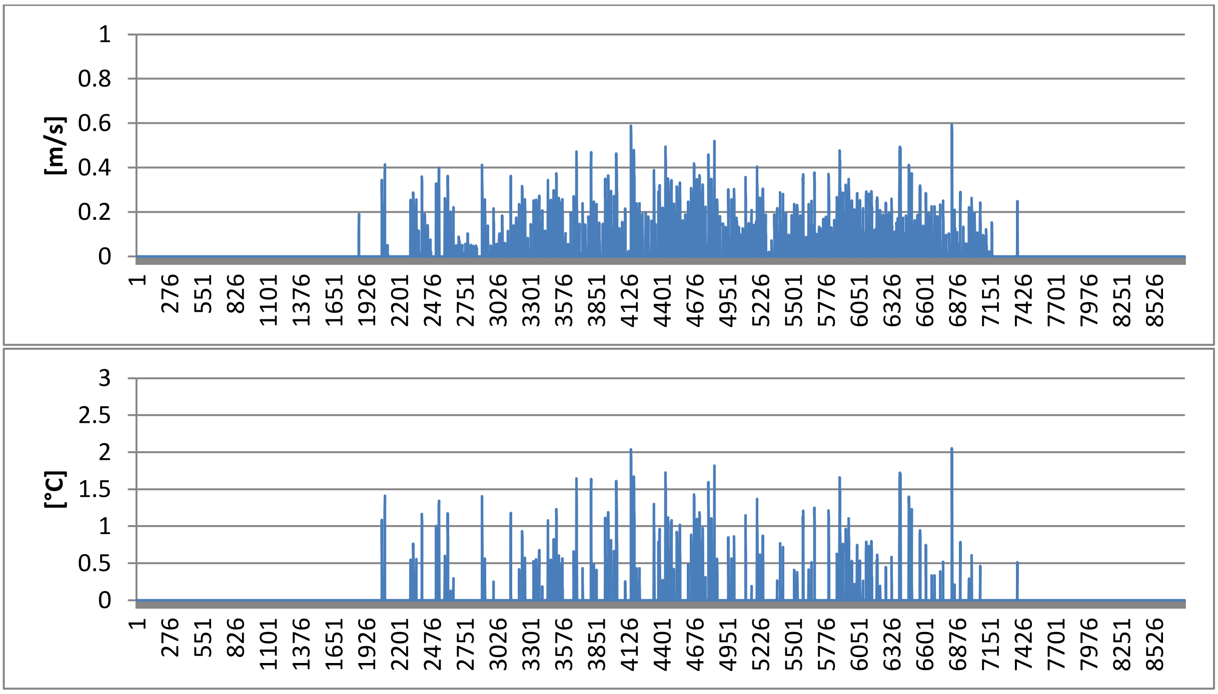


Figure C1 – Hourly mean indoor air velocity (top) and temperature offset (bottom) for the non-increased air velocity cases in Rome (mean indoor air velocity: 0.16 m/s).

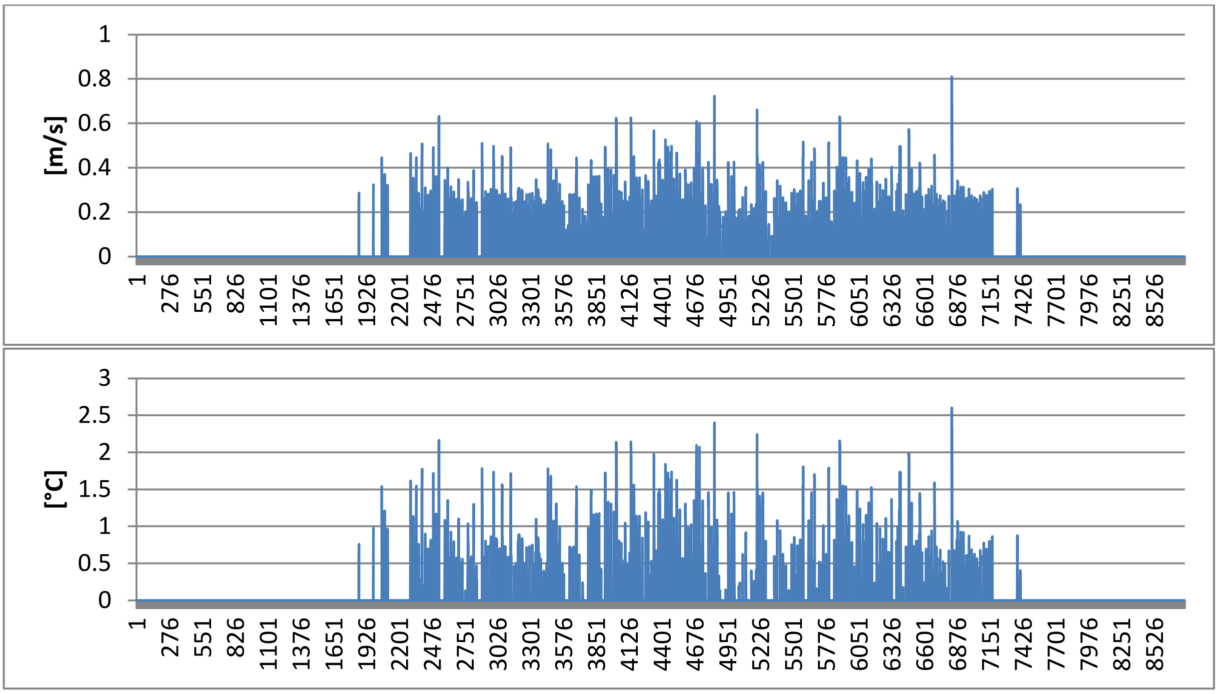


Figure C2 – Hourly mean indoor air velocity (top) and temperature offset (bottom) for the increased air velocity cases in Rome (mean indoor air velocity: 0.28 m/s).

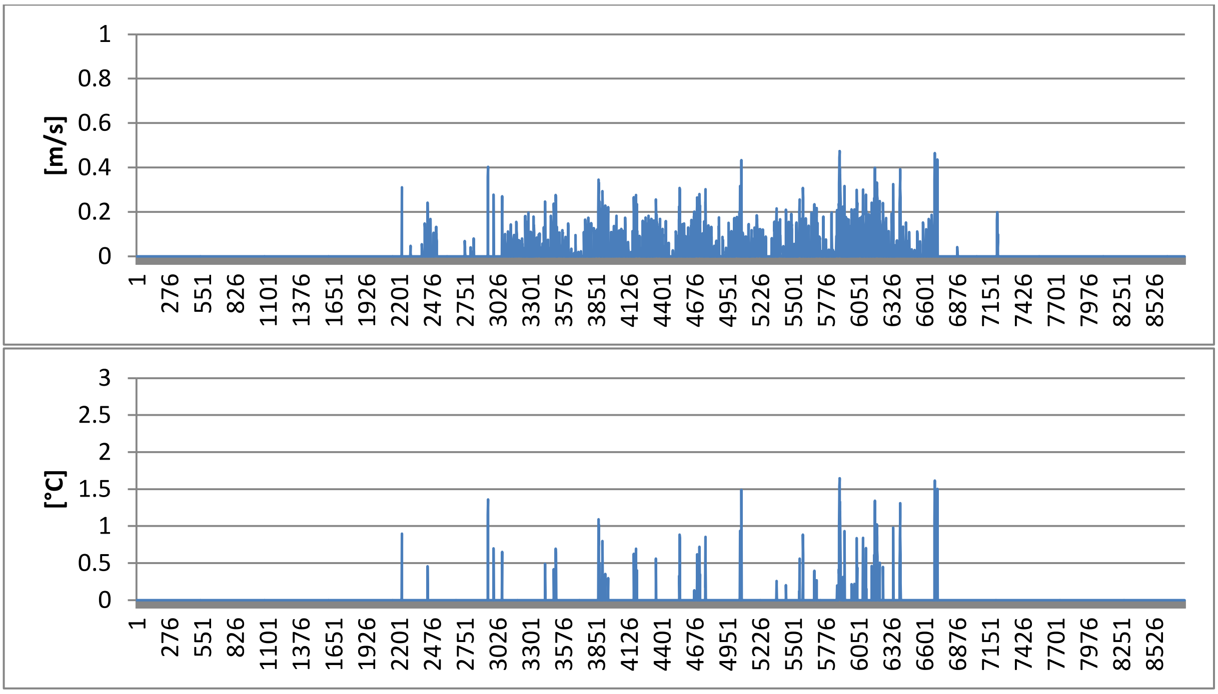


Figure C3 – Hourly mean indoor air velocity (top) and temperature offset (bottom) for the non-increased air velocity cases in Berlin (mean indoor air velocity: 0.12 m/s).

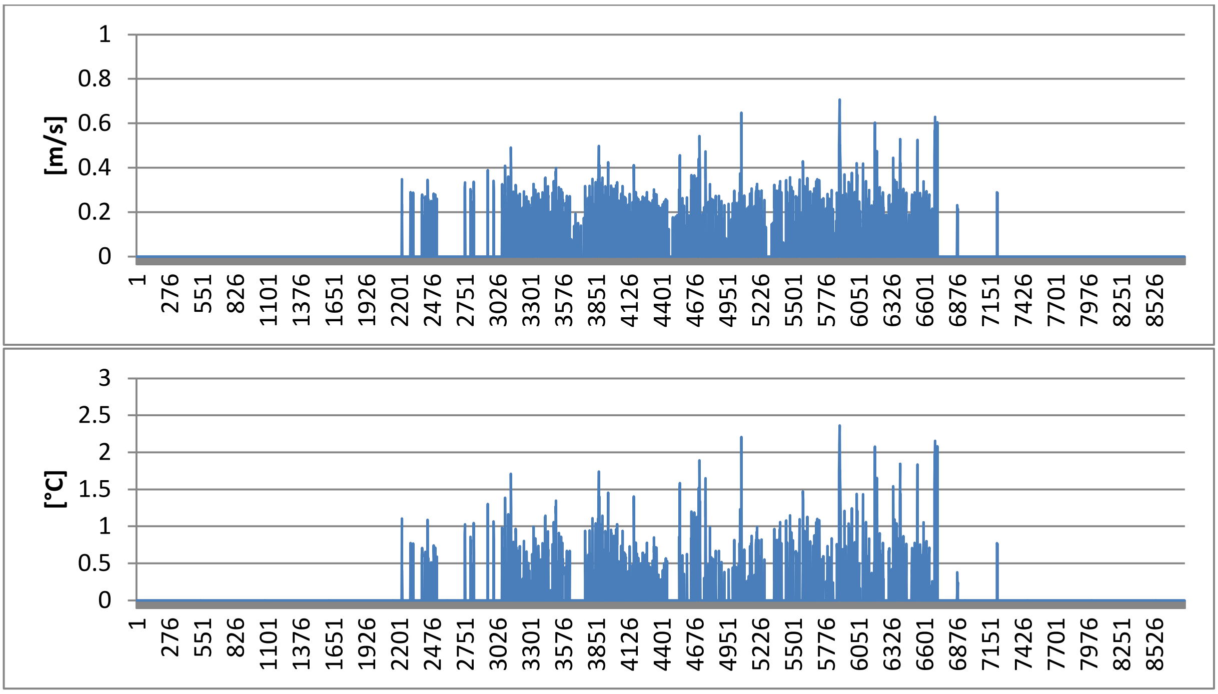


Figure C4 – Hourly mean indoor air velocity (top) and temperature offset (bottom) for the increased air velocity cases in Berlin (mean indoor air velocity: 0.26 m/s).

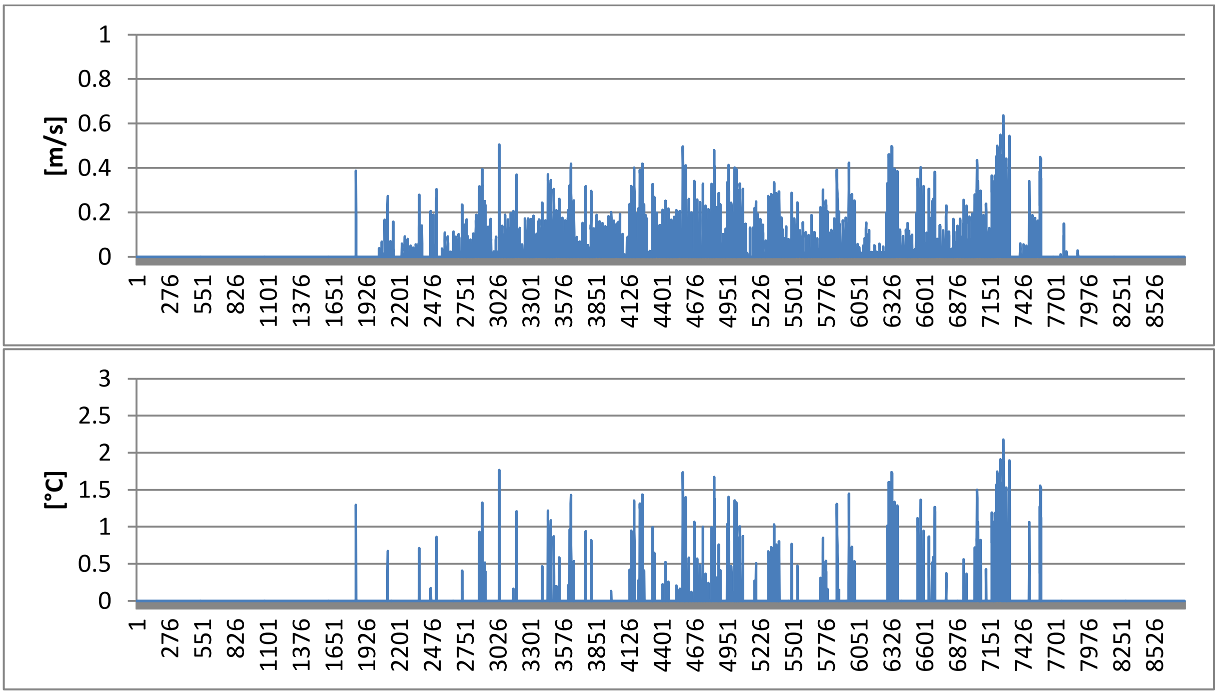


Figure C5 – Hourly mean indoor air velocity (top) and temperature offset (bottom) for the non-increased air velocity cases in Athens (mean indoor air velocity: 0.12 m/s).

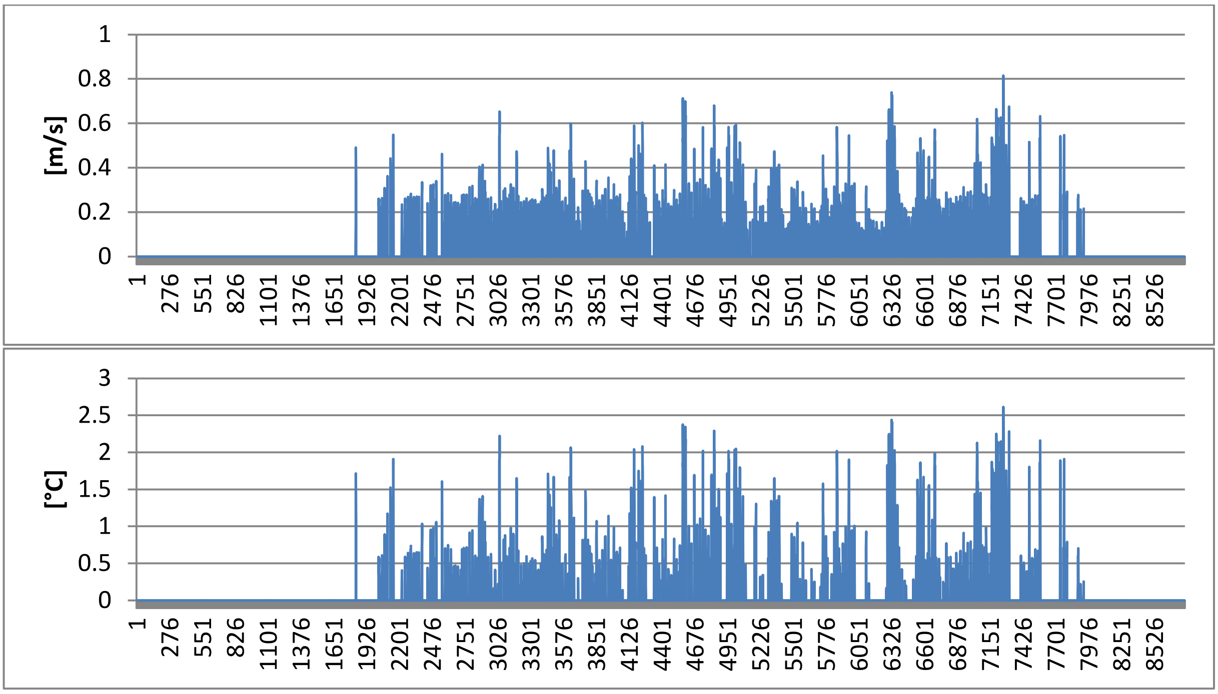


Figure C6 – Hourly mean indoor air velocity (top) and temperature offset (bottom) for the increased air velocity cases in Athens (mean indoor air velocity: 0.25 m/s).

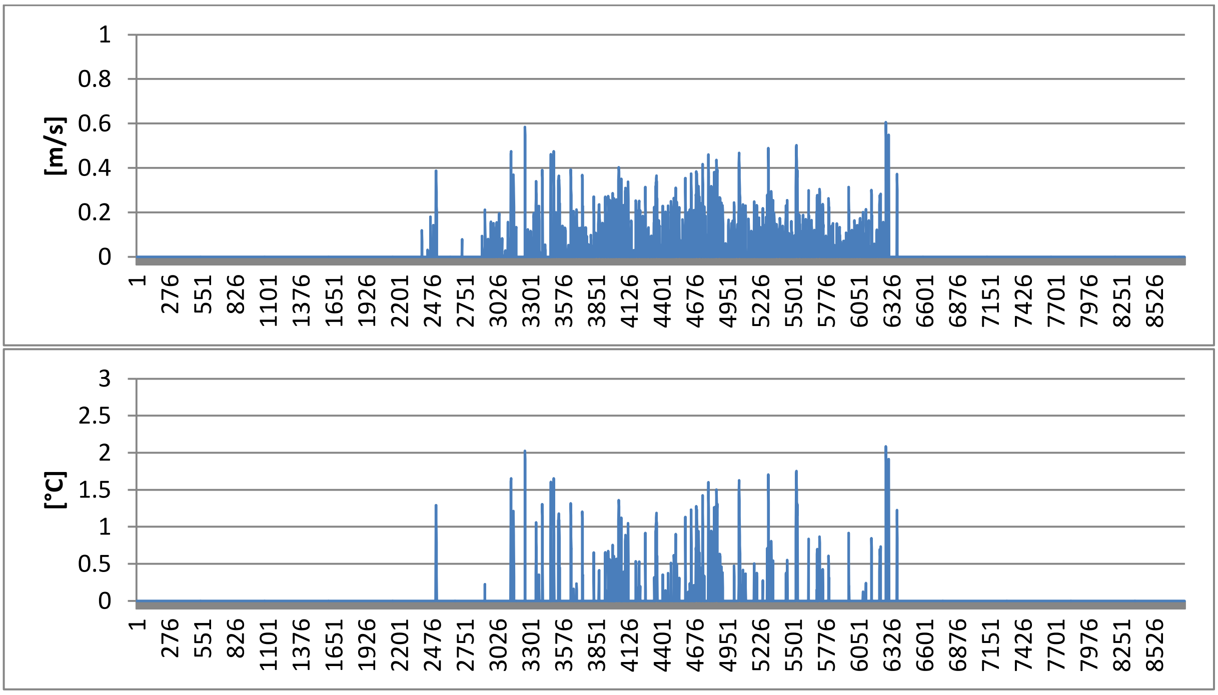


Figure C7 – Hourly mean indoor air velocity (top) and temperature offset (bottom) for the non-increased air velocity cases in Copenhagen (mean indoor air velocity: 0.16 m/s).

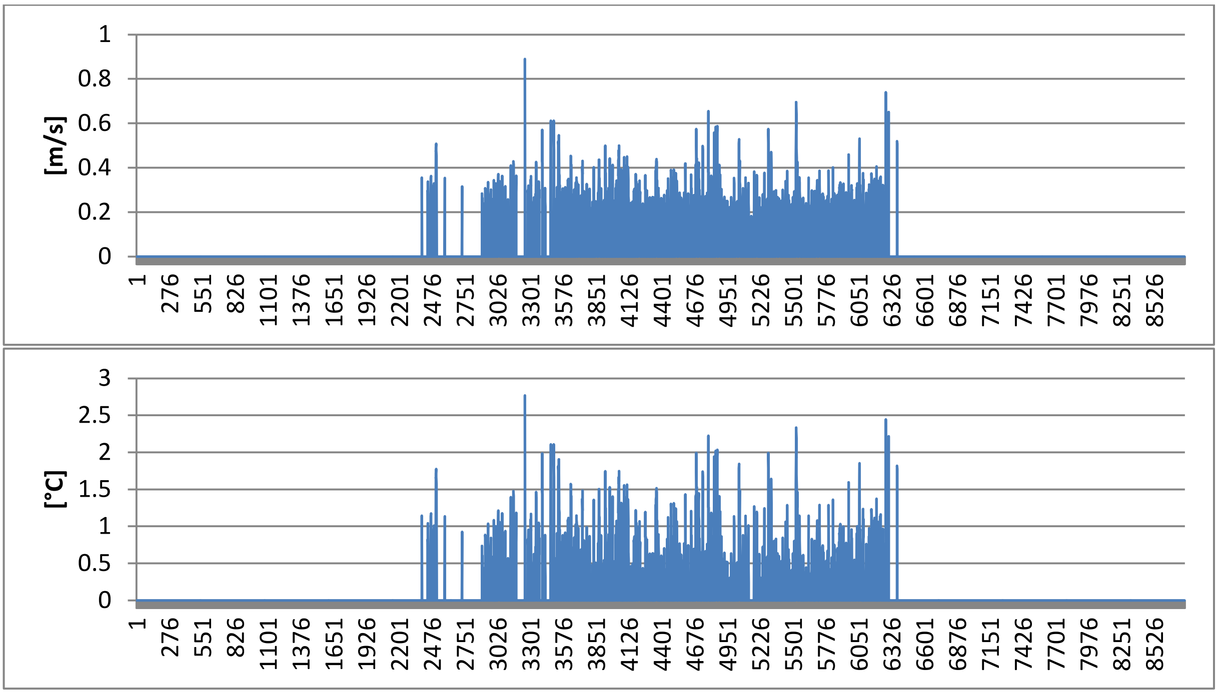


Figure C8 – Hourly mean indoor air velocity (top) and temperature offset (bottom) for the increased air velocity cases in Copenhagen (mean indoor air velocity: 0.30 m/s).