IMPROVEMENT OF SUMMER COMFORT BY PASSIVE COOLING WITH INCREASED VENTILATION AND NIGHT COOLING

Tommaso Pellegrini*[1,3], Peter Foldbjerg[2], and Bjarne W. Olesen[3]

1 Department of Industrial Engineer, University of Padova,1 Venezia Street,35100 Padova, Italy
**Corresponding author: tommaso.pellegrini@gmail.com*

2 VELUX A/S, Daylight, Energy and Indoor Climate, 99 Ådalsvej Street, 2970 Hørsholm, Denmark

3 International Centre for Indoor Environment and Energy, Technical University of Denmark,b420 Nils Koppels Alle Street, 2800 Lyngby, Denmark

ABSTRACT

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). 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 overcooling and increasing the energy consumption. A moderate strategy performed well without overheating and overcooling in Rome, Berlin and Copenhagen. In general the 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.

KEYWORDS

Natural ventilation, ventilative cooling, night cooling, increased indoor air velocity, residential buildings.

INTRODUCTION

The 2007 report of the Intergovernmental Panel on Climate Change (IPCC) [1] stated that the warming of the climate global system is an ascertained problem. For this reason in 2008 the EU set the target of reducing by 20% the total energy consumption within 2020 [2]. According to the Promotion of the European Passive House (PEP) [3], buildings account for 40% of this total energy consumption, and through the application of the Passive House concept, a relevant reduction of the energy consumption, quantifiable in a CO_2 emission reduction between 50% and 65%, can be obtained. The aim is to lower the buildings' energy demand without affecting the thermal comfort or the IAQ. The comfort condition is function of different parameters and thermal comfort can be provided within a range of air temperatures. When the air temperature increases, the warm thermal sensation can be restored from warm to neutral by decreasing 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 *ventilative cooling*: thermal comfort is obtained by increasing the air velocity in the room through natural or mechanical ventilation.

The effectiveness of increased air velocity and night cooling in reducing the energy consumption has been proven by means of both field surveys and dynamic simulations. In particular E. Gratia et al. [5] showed it is possible to reduce the cooling needs by about 30% using the ventilative cooling strategy. S. Schiavon and A. K. Melikov [6] demonstrated that increased air velocities can improve the comfort and allows a cooling energy saving between 17% and 48% and a reduction of the maximum cooling power between 10% and 28%. Furthermore Yun et al. [7] stated that opening the windows at the ambient temperature higher than the indoor temperature does not help to cool down the office, but can still improve the thermal comfort providing direct cooling over the occupants.

According to many authors, night ventilation appears to be one of the most promising passive cooling techniques. The work of Böllinger and Roth [8] revealed that in Frankfurt a nighttime air flow rate of 3 ach can compensate for a specific load of about 35W/m^2, while for a 6 ach the compensated specific load rises up to 41W/m^2. Similarly Santamouris et al. [9] showed that night ventilation applied to residential buildings may decrease the cooling load up to 40 kWh/m^2. Santamouris [10] also found that, under free floating condition, the night ventilation decreases the next day peak indoor temperature up to 2.5°C and reduces the expected number of overheating hours between 64% and 84%. According to Shaviv et al. [11] depending on thermal mass, air flow rate and temperature swing, the night cooling can achieve a 3 – 6°C temperature reduction in the hot and humid climate of Israel.

The purpose of this project is to determine, by means of dynamic simulations with the EIC Visualizer software, under which climatic condition the passive cooling techniques are capable to reduce the energy need without compromising the occupants' thermal comfort and the IAQ, during summer. The tested scenarios include, beside a fully mechanical system regarded as a reference case, both natural and hybrid ventilation and cooling solutions.

THE METHODOLOGY

The building

A 1½-storey, single-family house with a 8x12 m footprint, corresponding to a 175 m^2 floor area, has been selected for the investigation (Figure 1). The dwelling has no internal partitions and has then been studied as a single-zone building. The building tightness allows an infiltration rate of 0.15 ach for an outdoor-indoor pressure difference of 50 Pa. The internal surface of roof, walls and floor is an exposed concrete layer whose thickness has been obtained by empirically optimizing the thermal mass.

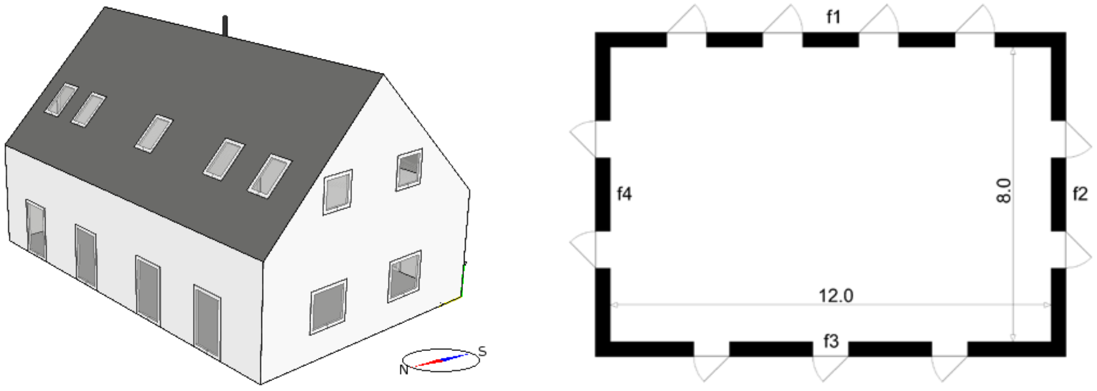

Figure 1. Visual representation (left) and footprint (right) of the building selected for the investigation.

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): 23.1 m^2 are façade windows and 7.3 m^2 are roof windows. All windows are operable and equipped with an external sunscreen.
The thermal properties of opaque and glazed surfaces are summarized in Table 1.

	U-value [W/(m^2K)]	**Solar heat gain coefficient (g)**	**Solar transmittance (T)**	**Solar transmittance for the visible spectrum (T_{vis})**	**Internal/external emissivity**
Roof	0.23	-	-	-	-
Wall	0.34	-	-	-	-
Floor	0.32	-	-	-	-
Glass	1.47 (0.90)	0.6 (0.1)	0.54 (0.05)	0.77	0.84

Table 1. Thermal properties of opaque and glazed furface (in brackests the multiplier due to the sunscreen).

In the AHU a supply fan introduce fresh air from outside the building through a grid at the ground level and an extraction fan extracts the exhausted air through a grid located 2.5 m from the ground. Both the supply and the extraction fans give a pressure rise of 200 Pa with a 0.8 electricity-to-air efficiency and a 0.25 kW/(m^3/s) specific power. A 5 Pa pressure loss has been assumed for the grid. No heat recovery has been used: the air is then supplied at the outdoor thermodynamic condition.
The heating system is an ideal heater with a 17500 W maximum power and a 0.9 generation efficiency, the cooling system is an ideal cooler with a 35000 W maximum power and a COP of 2.4. The distribution losses have been assumed to be equal to 1% of the heat delivered by the plant for the heating system and to 0.10 W /m^2 of the internal floor area for the cooling system.

Standard EN15251

Thermal comfort, IAQ and energy consumption are the three parameters used to quantify the performance of the tested ventilation and cooling strategies. The thermal comfort and the IAQ (the CO_2 level has been chosen as indicator of the IAQ) have been evaluated according to the standard EN15251 [12]. For the thermal comfort the standard prescribes two models. In buildings equipped with a mechanical cooling system the comfort categories are defined according to the non-adaptive model of the ISO7730. In naturally ventilated buildings the standard prescribes an adaptive model comparable to the one developed by de Dear and Brager [13]. In addition the EN15251 adopts the temperature offset that can be obtained by means of increased air velocities under summer comfort condition proposed in the ISO7730. Since only a graphical representation of the temperature offset is reported in the standard, an approximation had to be made. Four easy-to-identify points ((0.2;0), (0.3;1), (0.9;2.75) and (1.2;3.3)) have been isolated and interpolated with a logarithmic trend line. The equation of the trend line (1) has then been used to calculate the temperature offset.

$$\Delta T = 1.777 \cdot \ln(v) + 2.9782 \qquad (1)$$

Where ΔT is the temperature offset and v is the indoor air velocity.
Thermal comfort and IAQ have been evaluated only during 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).

Assumptions and system setup

The simulations have been run with the software Energy and Indoor Climate Visualizer (EIC Visualizer), which is based on the commercial software IDA Indoor Climate and Energy 4 (IDA ICE).

The dwelling is occupied by four people who leave the house at 8:00 in the morning and return at 17:00 in the afternoon every weekday. During the weekend they spent 24 h/day inside the building. 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 respectively. Other contributions to the internal load are the constant 4 W/m^2 due to the equipment and the load from electrical lighting with an installed capacity of 4 W/m^2. The lights are switched on only when the average daylight level is below 50 lux and with a percentage of lighting on simultaneously equal to 75% (2.4 W/m^2). The sunscreens used to reduce the solar gain are operated by a PI controller and are automatically activated when the indoor air temperature rises above 23°C.

The windows controller is intended to simulate human behaviour [14]. During daytime (from 7:00 to 22:00) the window opening is modulated to maintain an air temperature set point by cooling when the outdoor temperature is lower than the indoor by 2°C. During night the windows are opened between 22:00 and 7:00, if at 22:00 the indoor air temperature is higher than the outdoor and it is above the given threshold.

When window opening is not required with regards to thermal comfort, the mechanical system supplies a constant air flow rate of 0.29 l/s/m^2 calculated, according to EN15251, as sum of the amount of fresh air needed to compensate for the pollution from the occupants (4 l/s/person for category III) and the amount of fresh air necessary to remove the building emission of pollutants (0.2 l/s/m^2 for a very low polluting building).

The set points for the heating and for the cooling systems are 21.0°C and 24.6°C respectively.

An approximated method has then been used to calculate the mean indoor air velocity. The air flow rate through the windows has 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.

The temperature offset has then been subtracted from the operative temperature to calculate the *perceived operative temperature* (2), a parameter whose purpose is to express the temperature actually experienced by the body.

$$T_{op,\ perceived} = T_{op} - \Delta T \qquad (2)$$

THE CLIMATIC ZONES

The analyses have been performed by testing the ventilation and cooling strategies in four different climatic conditions. The selected cities are Athens, Rome, Berlin and Copenhagen. According to the Köppen-Geiger climate classification system [15], both Athens and Rome have a Mediterranean climate, Berlin has a humid-continental climate and Copenhagen is in the oceanic climatic zone.

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[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.

In Athens the climate is hot and dry, with a maximum monthly average high temperature of 33.1°C in July. Rome is hot and humid; the highest monthly average high temperature (30.6°C) is reached in August. Berlin has a temperate climate; the monthly average high temperature rises up to 24°C in July. Lastly Copenhagen has a cold climate and the monthly average high temperature presents a maximum of 20.4°C in July.

Rome presents very good night cooling potentials because of a 12°C day-to-night temperature swing. Also in Athens the night cooling is expected to perform well. Berlin and especially Copenhagen present a lower day-to-night temperature difference. All the locations are windy enough to provide an adequate air flow rate. In particular Athens and Copenhagen preset a prevailing wind blowing from North and from West respectively.

The climatic data used in the simulations are obtained from the ASHRAE's International Weather for Energy Calculations (IWEC) database.

CASE STUDIES

The analysis can be divided in two steps. First a set of preliminary simulation has been run to empirically optimize the thermal threshold for the night ventilation, the orientation, defined referring to façade 3 (f3 in Figure 1) and the building thermal mass, with respect to the climatic condition of each location. After, ten different ventilation strategies have been tested. The examined cases are described inTable 2.

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 2 – Case studies

RESULTS

For every location the performances of the analized cases are graphically represented by mean of the *individual signature*. In a 3D graph the thermal comfort, the IAQ and the energy consumption have been correlated. The data used to plot the individual signatures and to compare the performances of the different strategies are: for the thermal comfort the percentage of hours in category II (the static or adaptive model has been used depending on whether the mechanical cooling system had been used or not), for the IAQ the percentage of hours in category I and for the energy consumption the energy used on a year long period expressed as a percentage of the energy consumption of the M_HC scenario.

Athens

The tested night thresholds for Athens range from 23.0°C to 25.5°C with a 0.5°C incrase step. The sesnitivity analysis proved the 25.0°C threshold to be the best performing: when compared with the 23.0°C one, the number of hours of comfort increases by 16.7% and the energy consumption is reduced from 43.7 kWh/m^2 to 1.2 kWh/m^2 because of the overcooling prevention. Also it shows a 4.0% increase in the thermal comfort and the same energy consumption if compared with a scenario where the night ventilation is not used (the overheating is avoided). For the strategies which combine mechanical cooling and night ventilation the threshold has been lowered to 24.5°C.

Eight orientatios have been tested (N, NE, E, SE, S, SW, W, NW). The SW orientation, exposing to NE the façade with the largest glazed surface, allows to achieve a very good thermal comfort (for 98.5% of the time the building is in category II) by reducing the solar gain. The price to pay is that, with its 2.2 kWh/m^2, the SW presents one of the highest energy consumption among the tested orientations (the solar gain is reduced during winter as well, the heating system must then supply more heat to the dwelling). Also, with a 0.25 m/s average indoor air velocity, the SW orientation has the largest potential for ventilative cooling.

The thermal mass optimization evaluated the bulding performances for concrete layer thicknesses ranging from 0.08 m (415 kg/m^2 of floor area) to 0.24 m (1183 kg/m^2) with a 0.02 m increase step. Comparing the 0.24 m with the 0.08 m thickness, the thermal comfort increases by 1.5% (both overheating and overcooling are reduced) and the energy demand is decreased by 37%. Increasing the building mass is beneficial up to a 0.20 m concrete layer thickness (991 kg/m^2), a further increases gives only a negligible performance improvement.

For the daytime ventilation a 24°C threshold has been chosen.

With the selected parameters the mean air velocity for the non-increased air velocity cases is 0.12 m/s, while for the increased air velocity ones is 0.25 m/s. The natural ventilation period goes from April 20th to October 30th, that is 194 days of natural ventilation (53% of the year).

The individual signatures (Figure 2) show that the N_02_H_A scenario is the best performing. When compared with the fully mechanical system N_02_H_A grants only a slight improvement in the thermal comfort (1.2%), but an 83% decrease of the energy consumption. The IAQ is much higher as well: the mechanical system supplies 0.5 ach only, while the natural ventilation strategy provides 4.8 ach during nightime and 1.7 ach during daytime, which results in a 26% increase of time in category I. It is also true that the N_02_H_A requires an automatic controller for the windows opening and such systems are not very common in domestic buildings. If we limit the choice to the manually operated systems the best performing is the N_I_H. Infact during the transition seasons the increased velocities of the N_I_H scenario are capable to maintain the indoor temperature within an acceptable range, thus limiting the use of night ventilation and, with it, the overcooling (task that in the non-increased air velocities scenario required the installation of the automatic controller). The N_I_H, when compared with the M_HC case, presents a slight decrease in the thermal comfort (0.6%), an improvement in the IAQ (28%) thanks to the increased air flow rates (4.1 ach during night and 5.6 ach during day), and a reduction in the energy consumption (83%).

Among the mechanically cooled building the N_I_HC ensures the best comfort conditions: the thermal comfort is increased by 0.6%, the IAQ by 5.9% (the hybrid ventilation system supplies 2.6 ach during night and 1.5 ach during day) and the energy demand is reduced by 20% (the consumption is lowered by 8.3 kWh/m^2, of which 8.0 kWh/m^2 for cooling needs). This proves that if the mechanical system is assisted by passive ventilation and cooling strategies, even based on a very simple logic, the result is a relevant reduction in the energy consuption and a potential increase in the quality of the indoor environment.

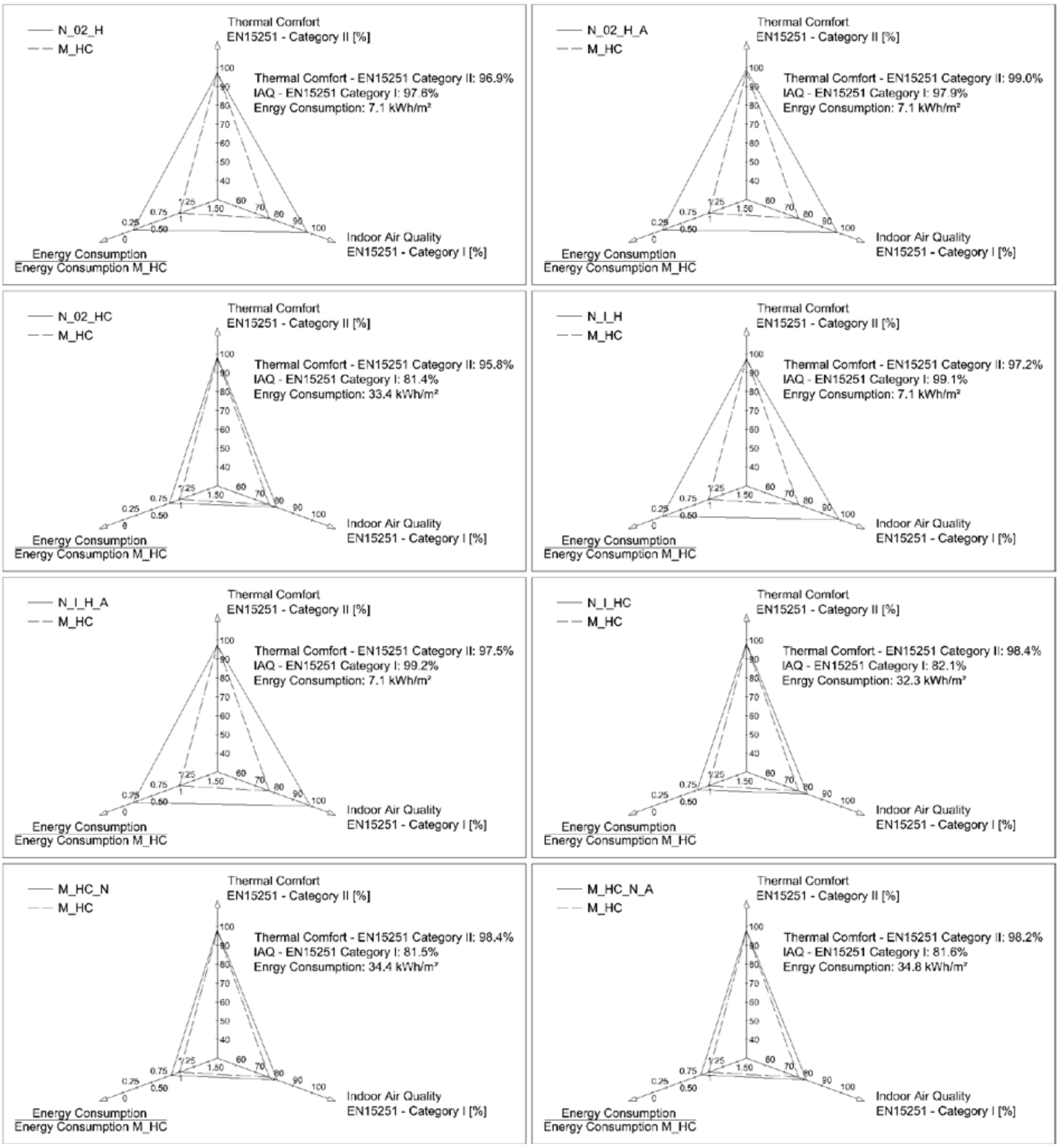

Figure 2. Individual signatures for the case studies in Athens, reference case: M_HC (Thermal Comfort – EN15251 Category II: 97.8%, IAQ – EN15251 Category I: 77.5%, Energy consumption: 40.6 kWh/m2).

Rome

The same night cooling thresholds used in Athens have been tested in Rome (i.e. 23.0°C to 25.5°C with a 0.5°C increase step), where the best thermal comfort has been obtained when the nigth cooling strategy is not applied. In all cases the discomfort is caused by the overcooling of the building, due to the large day-to-night temperature swing mentioned before. Nonetheless a 24.0°C night ventilation threshold has been chosen since the prevention of the summer overcooling is a priority.

The E orientation has been considered the best performing.

For the thermal mass analysis the considerations made for Athens are valids for Rome as well, i.e. increasing the thermal mass is beneficial up to a 0.20 m concrete layer thickness.

For the daytime ventilation a 24°C threshold has been chosen.

With the selected parameters the mean air velocity for the non-increased air velocities cases is 0.16 m/s while the mean air velocity for the increased air velocities ones is 0.28 m/s. The natural ventilation period starts on April 7th and ends on October 25th, the natural ventilation strategies are then applied for 202 days over 365 (55% of the year).

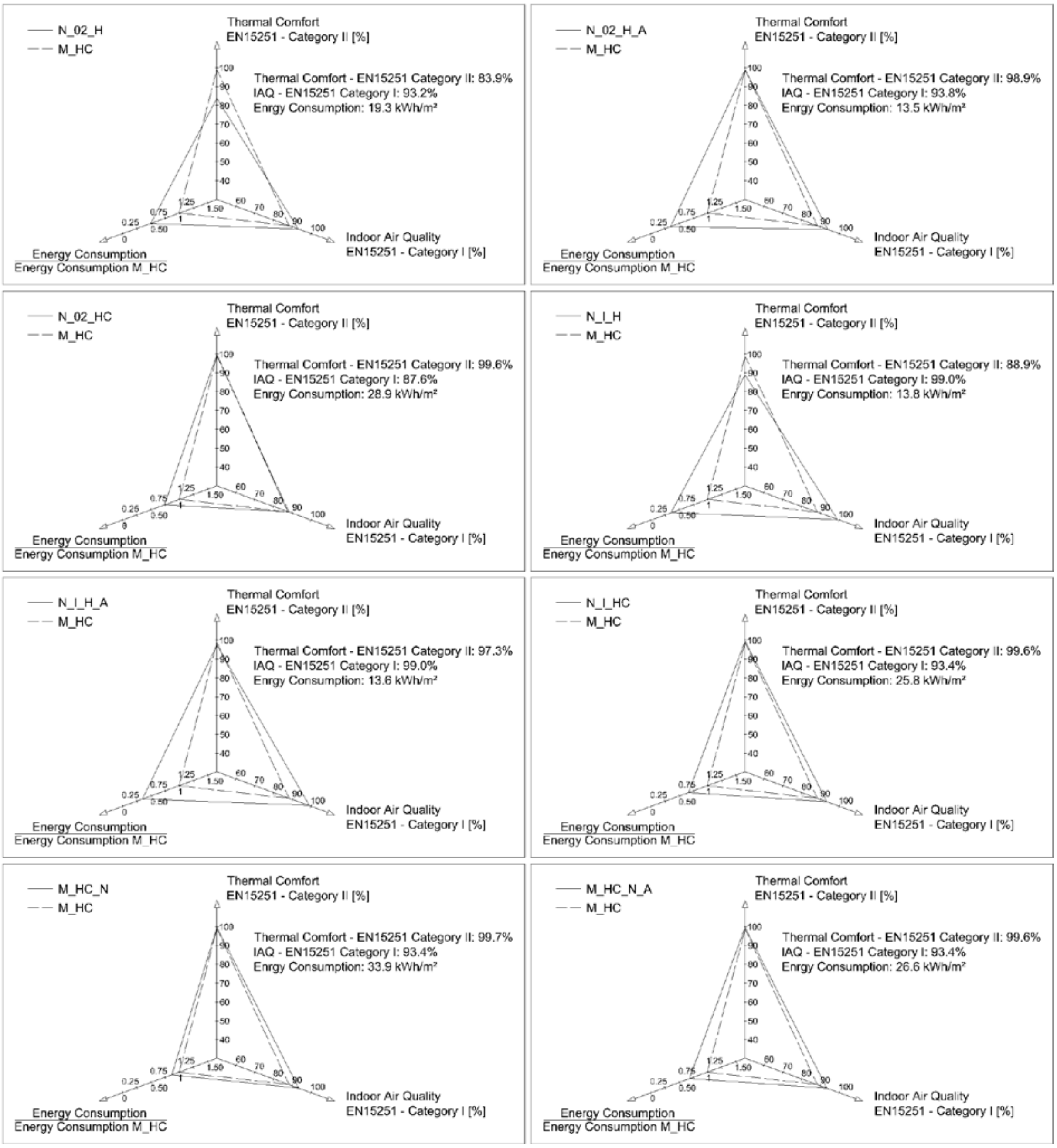

Figure 3. Individual signatures for the case studies in Rome, reference case: M_HC (Thermal Comfort – EN15251 Category II: 99.0%, IAQ – EN15251 Category I: 88.2%, Energy consumption: 39.0 kWh/m2).

For Rome in the mechanically cooled building the thermal comfort is generally higher than in the naturally ventilated and cooled ones. The cause is the overcooling of the building during nightime and indeed the introduction of the automatic controller, creating a constrain on the night air flow rate, improves the thermal comfort in both the N_02_H (17.9%) and the N_I_H (9.4%) solutions. Among the passive cooling systems the one that give the best results is the N_02_H_A. From a comfort point of view the solution performs as good as the M_HC system (there is a negligible 0.1% decrease), the IAQ is increased by 6.0% because, again, the natural ventilation provide much higher air flow rates (4.2 ach during night and 1.5 ach during day), and the energy consumption is reduced by 65%. In Rome when the mechanical cooling system is assisted by an automatically controlled night ventilation strategy, the improvements are relevant: the consumption is reduced by 31.8% and the indoor environment is more comfortable (+0.6% thethermal comfort and +5.9% the IAQ). The energy demand can be further decreased if the mechanical system is assisted by ventilative and night cooling (-33.8%), in which case the automatic control becomes unnecessary.

Berlin

In Berlin the upper limits for the comfort categories defined according to the adaptive model are quite lower than in Athens and Rome, then the tested night ventilation thresholds have been proportionally decreased. For the sensitivity analysis the potential thresholds go from 22.0°C to 24.5°C with a 0.5°C increase step. As in Rome, the solution that generates the best thermal comfort is the one without night cooling and, as in Rome, the overcooling prevention has been considered a priority. Then a 23.5°C threshold has been adopted.

In Berlin the influence of the orientation on the building performance is negligible, then the N orienation, being capable to provide a 0.26 m/s average indoor air velocity, has been chosen. A 0.20 m concrete layer has been considered sufficient (2.3% increase in the thermal comfort and 4.3% reduction of the energy consumption when compared with the 0.08 m thickness). For the daytime ventilation a 23°C threshold has been chosen.

With the selected parameters the mean air velocity for the non-increased air velocitites cases is 0.12 m/s while the mean air velocity for the increased air velocities ones is 0.26 m/s. The natural ventilation period starts on May 7th and ends on October 5th, the natural ventilation strategies are then applied for 152 days over 365 (42% of the year).

In Berlin the energy demand for cooling accounts for only 5.4% of the total consumption, then the passive cooling strategies are not paricularly beneficial from an energetic point of view: the highest reduction in the energy consumption is indeed equal to 5.6% (N_02_H_A). If we limit the choice to the solutions without mechanical coolig, N_02_H_A is the scenario with the highest performances: the 0.2% reduction in the thermal comfort is compensated by the improved IAQ (1.7%) and by the decreased energy consumption. Among the mechanically cooled buildings the optimum is reached by the N_I_HC system, which increases the IAQ by 3.6% and reduces the consumption by 2.6%, mantaining the building in category II for 100% of the occupancy time.

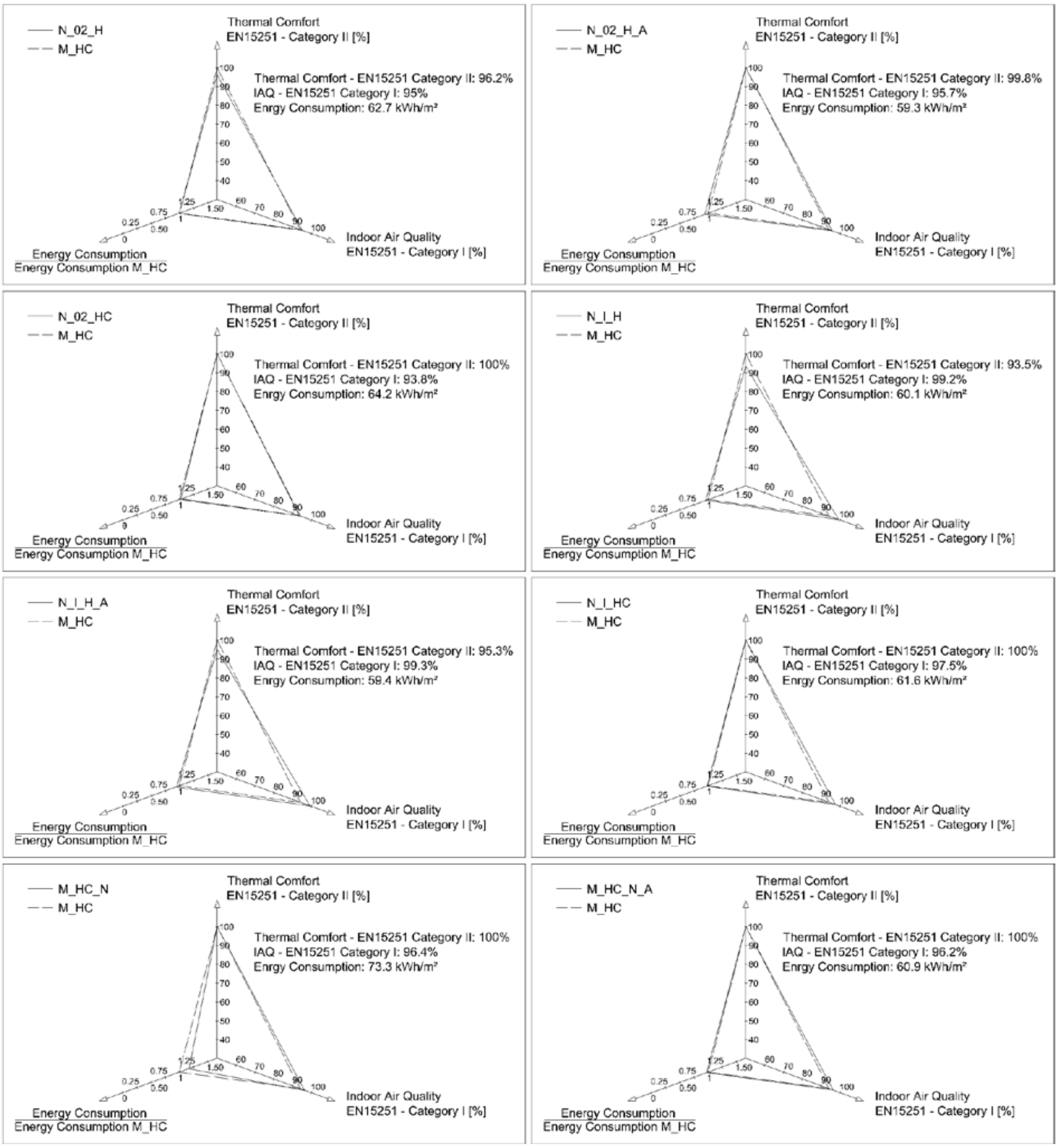

Figure 4. Individual signatures for the case studies in Berlin, reference case: M_HC (Thermal Comfort – EN15251 Category II: 100%, IAQ – EN15251 Category I: 94.1%, Energy consumption: 62.8 kWh/m^2).

Copenhagen

For the night thresholds optimization the temperatures taken into account range from 22.0°C to 24.5°C with a 0.5°C increase step. 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 on night ventilation increases the discomfort, causing the overcooling of the dwelling, and the energy consumption for heating. The 23.0°C threshold can be then considered the best option, allowing the application of the night ventilation only when strictly necessary.

In Copenhagen the risk of overheating during summer is limited to very few days, during most of the year the discomfort is caused by the overcooling of the building. Thus the NE orientation has been selected since it maximize the solar gain, improving the thermal comfort and reducing the energy consumption. During summer, when needed, the solar gain can be decreased by activating the solar shading.

As the windows are almost always closed during night, no improvement at all in the thermal comfort have been obtained by increasing the thermal mass, then, in accordance with the other locations, a 0.20 m concrete layer thickness has been chosen.

For the daytime ventilation a 23°C threshold has been chosen.

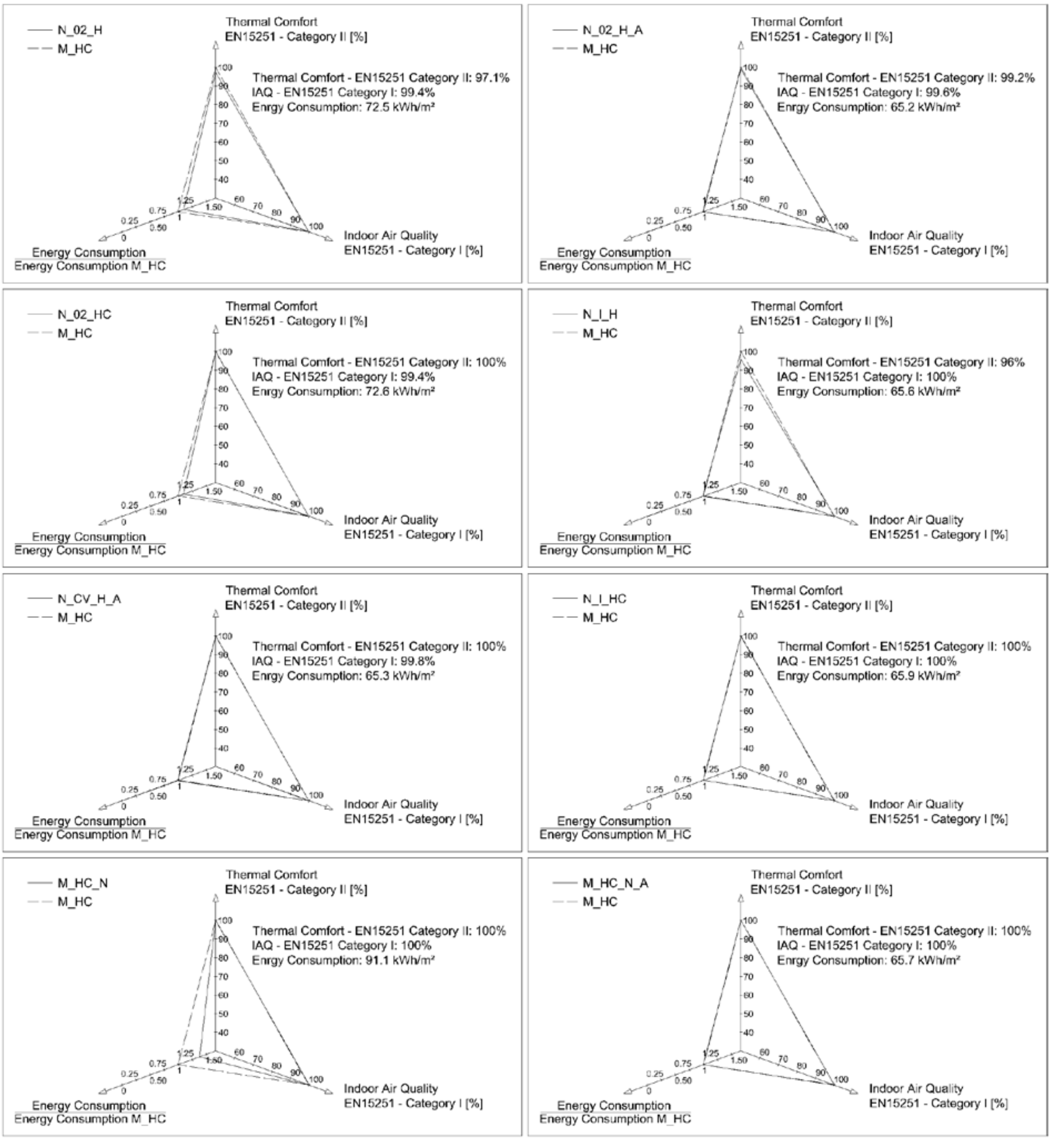

Figure 5. Individual signatures for the case studies in Copenhagen, reference case: M_HC (Thermal Comfort – EN15251 Category II: 100%, IAQ – EN15251 Category I: 99.7%, Energy consumption: 66.1 kWh/m2).

With the selected parameters the mean air velocity for the non-increased air velocitites cases is 0.16 m/s while the mean air velocity for the increased air velocities ones is 0.30 m/s. The natural ventilation period starts on April 30th and ends on September 17st, the natural ventilation strategies are then applied for 141 days over 365 (39% of the year).

As a matter of fact the night ventilation is almost never used: over the entire natural ventilation period the windows are opened for 13% of the nights in the N_02_H scenario and for 1.5% of the nights in the N_I_H one. Indeed in Copenhagen only 0.6% of the energy consumption is for cooling, it means that the cooling load is almost zero. This is the reason why all the passive cooling strategies, beeing too efficient for the local climate conditions, reduces the thermal comfort (from a minimum of 0.8% for N_02_H_A, to a maximum of 4.0% for N_I_H), sometimes increasing the thermal comfort (e.g. by 9.7% for N_02_H).
The M_HC_N_A solution has been designed as a thermostatically controlled one, but the energy consumption reveals that the mechanical cooling system is never turned on and there is no extra heating demand: the night cooling seems then capable alone to reduce the cooling load to zero without causing overcooling. The observation suggested us to test one more ventilation strategy in Copenhagen, namely N_CV_H_A. The strategy is based on daytime mechanical ventilation and automatically controlled nigth 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. The solution performs excellently: the building is for 100% of time in category II (thermal comfort), for 99.8% of time in category I (IAQ) and requires 1.3% less energy than the thermostatically controlled one. Beig capable to prevent both the nighttime overcooling that affects the non-increased air velocities scenarios, and the draft sensation that affects the increased air velocities ones, it is the only passive cooling solution which does not decrease the thermal comfort.

DISCUSSION AND CONCLUSIONS

The project here reported investigated the potential energy saving and summer comfort improvement that can be achieved by mean of passive cooling strategies such as solar shading, ventilative cooling and night cooling. In general the passive approach seems capable to ensure a good indoor environment in terms of high IAQ and prevention of both overheating and overcooling, as well as a reduction in the energy consumption.
In Athens the increased air velocities, being capable to maintain the mean air temperature within an acceptable range, are efficient in limiting the use of night cooling without the need of an automatic controller. The combination of the two strategies seems then capable to achieve a very good thermal comfort.
For Rome, Berlin and Copenhagen the same combination of daytime increased air velocities and night cooling turned out to be too aggressive, causing some overcooling and an increase in the energy consumption for heating that ranged from the 1.6% of Rome to the 9.7% of Copenhagen. A moderate approach showed good results.
In Rome and Berlin a constraint to both the daytime air velocity and the nighttime air flow rate was capable to provide a very good indoor environment, even more comfortable than the one obtained by mechanically cooling the building. For colder climates, such as the one of Copenhagen, the best performance on thermal comfort (100% of the time in category II) was obtained with the use of the night cooling strategy only.
The hot Mediterranean climate of Athens and Rome presents a very high cooling load, thus the adoption of the passive technique leads to a consistent reduction in the energy consumption (83% for Athens and 65% for Rome). In Berlin and Copenhagen the reduction in the energy demand (5.6% and 1.3% respectively) corresponds entirely to the energy used by the chiller, showing that the strategy is capable to lower the cooling load, in particular in Copenhagen the selected strategy is capable to reduce the cooling load to zero.

When the IAQ is looked at, the natural ventilation performs much better than the mechanical one in all cases. The air flow rate ranges from 1.1 ach (Copenhagen) to 4.8 ach (Athens) during nighttime and from 0.7 ach (Copenhagen) to 1.7 ach (Athens) during daytime.
In general, the scenarios that performed best on all three parameters (thermal comfort, IAQ and energy), were the ones based on natural ventilation.

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