Natural night ventilation as passive design strategy for a Net Zero Energy office building

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Abstract

The paper describes the case study of one of the new buildings placed in the new Technology Park in Bolzano (Italy). To achieve the targets of Net Zero Energy Building and total primary energy index lower than 60 kWh/m^{2}y, natural ventilation has been considered as a passive solution to reduce cooling needs and operation costs. As it depends on building envelope, indoor spaces layout and components sizing, natural ventilation has been taken into account since the early stage of design.

Thanks to an integrated design process, shared solution was found out that balances performances needs with constrains given by fire regulations, acoustic comfort and user's needs, and to satisfactorily maintain the architectural impact of the solution.

Outdoor environmental conditions have been analyzed and climate potentials for driving natural ventilation have been estimated. Considering building occupation, user comfort needs and climate, a night ventilation strategy has been chosen as the most suitable for the case.

A simplified airflow model was used to assess the design solutions, suggested inside the integrated design process, and to fix the minimum opening area that allows achieving the requested airflow rates. Then, a dynamic energy simulation model was run to assess the potential energy savings thanks to the night ventilation cooling and to estimate the cooling needs reduction.

Obtained results showed how natural ventilation can meaningful contribute to the cooling needs and overall primary energy consumption reduction, contributing to the fixed energy performance targets.

Introduction

The paper describes the case study of one of the new buildings placed in the new Technology Park in Bolzano (Italy). The project aims at regenerating an old industrial area, where three main existing blocks listed as industrial historical buildings will be renovated and other new buildings will be built. For the above mentioned building owner and design team have taken up the challenge to achieve the targets of Net Zero Energy Building and total primary energy index lower than 60 kWh/m^{2}y.

The building is architecturally conceived as a black monolithic block with a nearly-square plant. It has five floors and an underground floor. The main entrance is on the north side of the ground floor and on the south side there is the expo area. The upper floors will host offices, meetings rooms and service rooms, whereas in the underground floor there will be several conference rooms with direct external entrances. In the centre of the building and through the full height, a green patio is designed as a buffer zone to improve indoor comfort and daylighting.

The envelope is a metal-glass façade with a solar shading system in the south façade and a black surface with different series of horizontal windows in the other facades. The horizontal windows on north, east and west façade are positioned on the inner side of the external wall. In this way, the deep reveal due to the wall thickness and the low height of the windows work as a sun shading system and the glazed part of the façade will not be visible from the outside perspective.

Render of the building
CLEAA – Claudio Lucchin E Architetti Associati

The ambitious targets could be reached considering first of all the reduction of energy needs, in particular through passive solutions. The paper presents natural ventilation as a passive solution to reduce cooling needs and operation costs. Different natural ventilation strategies were analyzed:

- daytime ventilation
- night cooling
- ground cooling

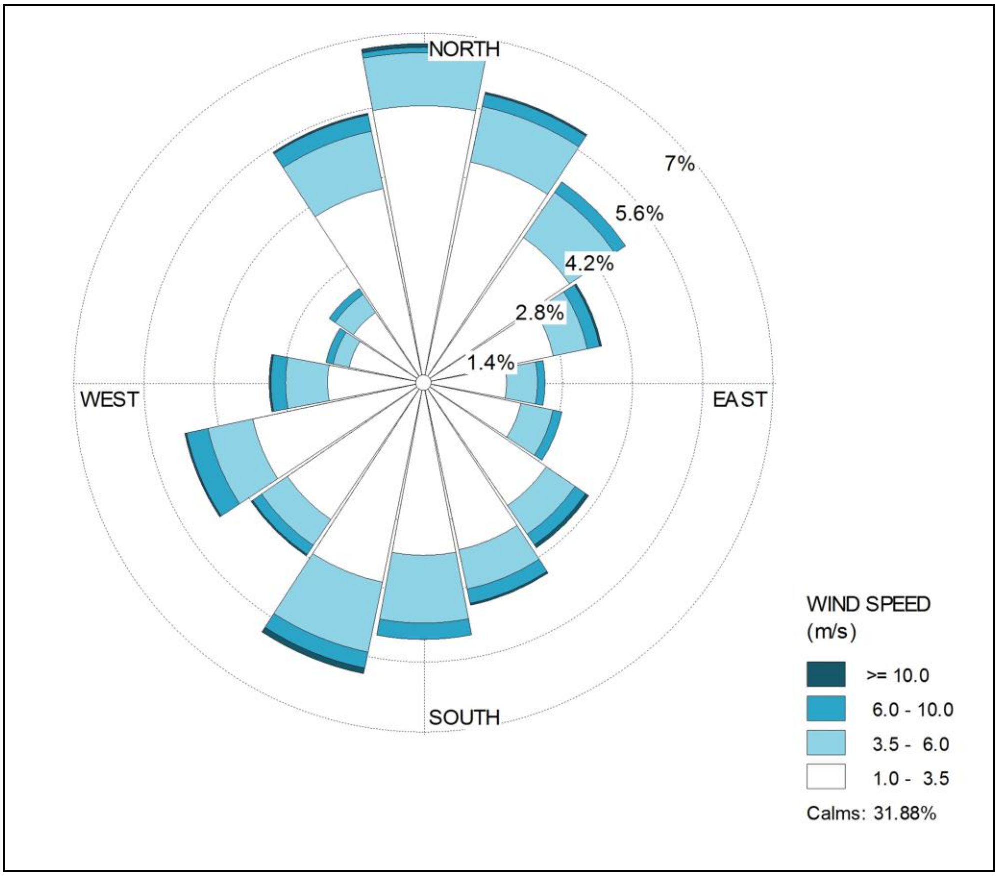
Windows cannot be opened during the occupancy period because of traffic noise or high air speed and therefore daytime ventilation is not feasible. Due to the high relative humidity rate during the summer in Bolzano, ground cooling could not be suggested because of possible air saturation problems caused by temperature decrease. Therefore, passive night cooling was proposed as the most reliable and easy solution to reduce HVAC working hours. The effectiveness of this solution increases if the following conditions are met:

- solar gains reduction through high thermal insulation and shading systems;
- internal loads reduction through low consumption appliances and lighting control;
- thermal capacity exploitation through exposed ceiling mass.

Climate potential analysis

As a starting point a climate analysis was carried out on the natural ventilation driving forces (hourly air-temperature and wind speed and direction) to verify the potential cooling need reduction of a night cooling strategy.

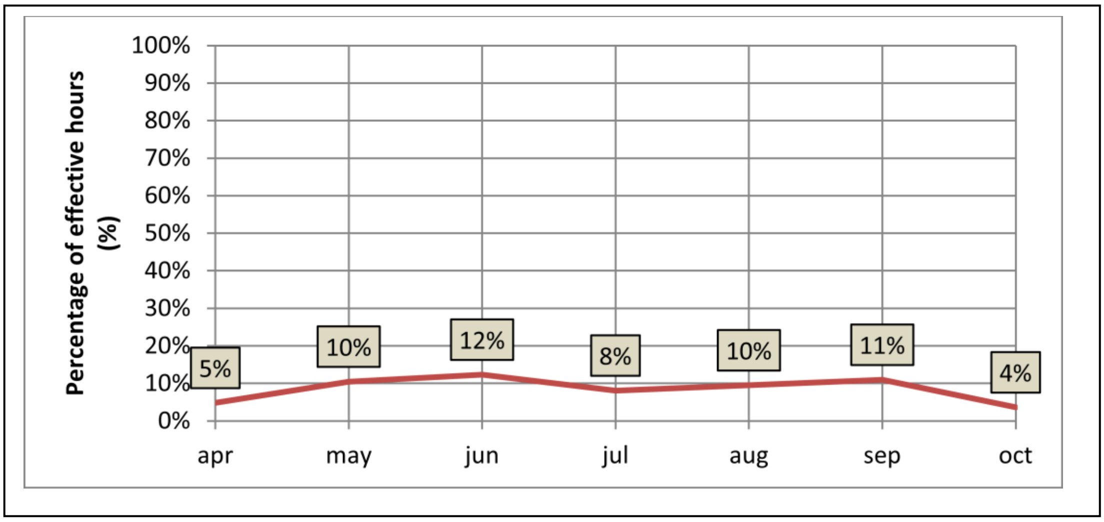
The wind rose shows that circa 30% of the night hours are calms and in the 80% of the night hours wind speed is under 3.5 m/s; wind-driven cross ventilation could not be always assured.



Wind rose for Bolzano during the night hours (6pm – 8am) in the cooling period (15/04 - 14/10)
Lakes Environmental WRPLOT [1]

Therefore, stack driven cross ventilation was outlined as the most effective configuration. To estimate the number of effective hours the following activation conditions were assumed:

- From 6 pm to 8 am
- External temperature between 14°C and 26°C
- Dew point temperature lower than or equal to 17°C



Number of effective hours in the activation condition for passive night cooling during the cooling season
Weather data registered by the EURAC monitored weather station at Bolzano in 2010

It is a rough analysis to estimate the potential of passive night cooling and only few input data about the building are needed. "Climatic Cooling Potential", defined by Artmann N. [2] as a summation of products between building/external air temperature-difference and time interval, has been estimated as:

$$CCP = \frac{1}{N}\sum_{n=1}^{N}\sum_{h=h_s}^{h_f} m_{n,h}\left(T_{b,n,h} - T_{e,n,h}\right) \qquad \begin{cases} m = 1 & if\ 14°C \le T_e \le 26°C \\ m = 0 & other \end{cases}$$

where

T_b = building air temperature

T_e = external air temperature

N = number of nights

h = time of the day (h_i and h_f denote the initial and the final time of night-time ventilation)

The heat flux $\dot{q}$ which could be potentially rejected per CCP - Degree Hour can be calculated as:

$$\frac{\dot{q}}{CCP} = \frac{\rho c_p H\ ACH}{3600\ t_{occ}} \quad \left[\frac{W/m^2}{Kh}\right]$$

where

t_{occ} = time of building occupancy

H = floor height

Assuming airflow of 2 ACH to avoid too high air velocities, the heat that could be rejected is 12 W/m^2. Considering that the expected total internal heat gains[1] will be around 40 W/m^2, maximum 29% of the total internal heat gains could be potentially offset through a night cooling strategy.

This method allowed the building designer to quickly evaluate the potential effectiveness of night cooling strategies, given knowledge of the likely internal gains in the building and the estimation about the airflow rates. It has to be considered only as a preliminary analysis on the assumption that:

- thermal capacity of the building mass is sufficiently high and therefore does not limit the heat storage process;
- building temperature oscillates harmonically to simulate the dynamic effect of heat storage in the structure materials.

[1] The internal heat gains can be considered particularly low because of an effective shading system and energy efficient lighting system and electrical equipment.

Constraints analysis

As natural ventilation influences building envelope design, indoor spaces layout and components sizing, a shared natural ventilation solution from architectural and constructive point of view has been found out through the integrated design process. The agreed solution balances performance needs with constrains given by fire regulations, acoustic comfort and user's needs, and to keep acceptable the architectural impact of the solution.

To maintain the indoor spaces layout flexibility it was not possible to plan ventilation shaft or stack devices and to estimate accurately the pressure drops due to the internal walls and vent size.

Furthermore, the plan of natural ventilation has to strictly comply with fire regulations and plans. The building is divided into fire compartments enclosed with a fire resistive construction that have to be by definition air tight or closable. A natural ventilation configuration that involves more fire compartments should use components with high fire resistance ratings. Due to the high additional costs it was decided to study a natural ventilation configuration for every fire compartment.

Furthermore, acoustic problems due to air connections between offices and plans should not be neglected as the future users need privacy during the working hours.

Another constraint was about the architectural impact of the solutions. The monolithic block feature has to be maintained by reducing as much as possible the movable part in the façade, openable windows included.

Airflow models in the Integrated Design Process

As building design is characterized by even more detailed design level, airflow model with different detail level needs should be used to support the decision-making process.

Available airflow models can be divided into three categories:

- Empirical models
- Network airflow models
- Computational Fluid Dynamics (CFD)

Empirical models are basically static correlations derived analytically or experimentally to predict ventilation airflow rates for simple opening configuration. They aim at sizing airflow, openings or air velocity. As they refer to a limited number of case studies, they are based on many assumptions. A review of the existing main empirical models can be found in [3] and [4].

Airflow network models have been developed to more quickly solve airflows throughout a building. They represent the building with one or more well-mixed zones, assumed to have a uniform temperature and a pressure varying hydrostatically, connected by one or more airflow paths. Each airflow path is mathematically described using the Bernoulli equation. A matrix of the equation is constructed and numerically solved. Convergence is reached when the sum of all mass flow rates through all components approaches zero within the tolerance band specified [3]. The most commonly models used are COMIS [5] and CONTAM [6].

These models can be coupled to dynamic simulation models to evaluate the whole building performance [4], taking into account the thermal mass effect as well. Different coupling approaches are possible [7]. Despite their simplicity, airflow network models have some important limitations:

- heavily dependency on coefficients like wind profile exponent, pressure coefficients and discharge coefficients;
- turbulent fluctuations of wind pressures are neglected [8];
- air speed in rooms cannot be calculated.

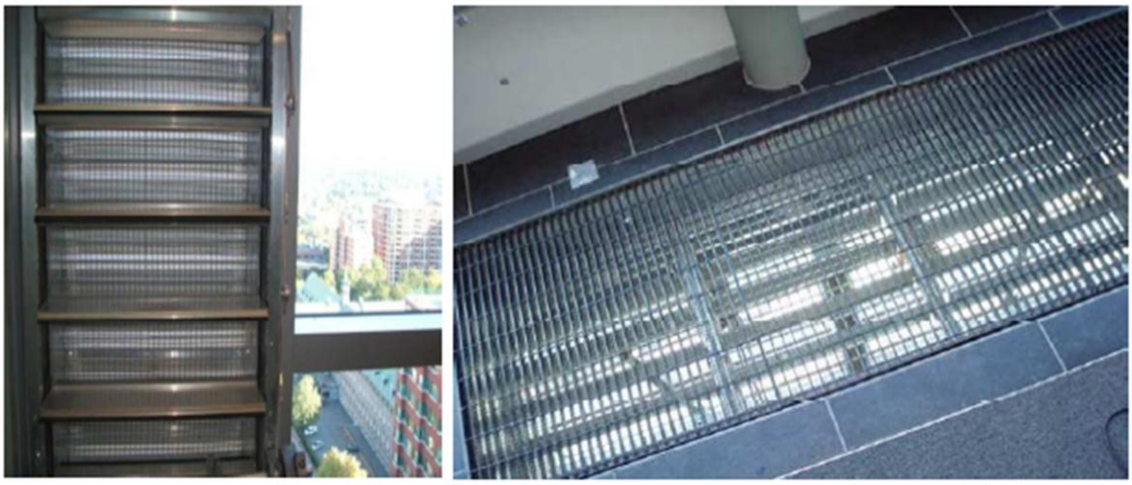
As stated by the experiences described in ASHRAE TRP-1456 [4], the network models are able to predict indoor temperatures within 30% error in general compared with measured data in laboratory experiments.

CFD aims at solving the Navier-Stokes equation in a fluid domain and can provide detail information about air velocity, temperature and pressure distribution at each point of the zone. Given the long calculation time and the high dependency on boundary condition, CFD simulations should be successfully applied only at an advanced design level to verify indoor comfort. Thermal domain and detailed airflow domain can also be coupled to achieve better results because the two can provide boundary conditions to each other [9].

Natural ventilation configuration

A stack driven cross ventilation was chosen as the most effective configuration that balances performances needs with constrains given by fire compartments, acoustic comfort and privacy needs in the offices during the working hours.

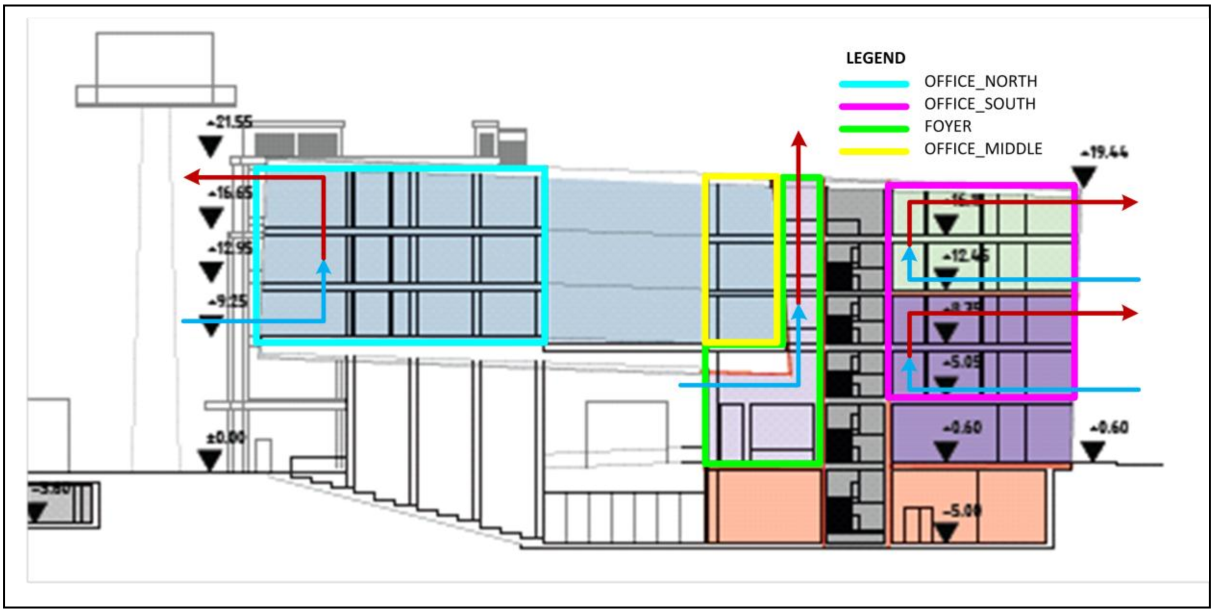
To increase the height difference between inlet and outlet openings, connecting floor vents will be applied. This solution keeps acceptable the architectural impact by reducing the movable part in the façade and by keeping free the internal layout of the spaces. The floor vents can be closed during the working hours to avoid acoustic discomfort and maintain privacy between offices.



An example of corridor inlet vents (left) and atria connecting floor vents (right), installed for natural ventilation of the Concordia University building in Montreal (Canada)
Source: Mouriki E. [10]

The foyer is directly connected to a lightwell and to the hall of every floor and is ventilated through a stack driven cross ventilation that allows avoiding overheating.

Due to safety reasons underground floor and expo areas are mechanically ventilated. A small office area in the center part of the building is single-sided ventilated and connected with the green patio.



Cross section of the building from fire regulation plan with fire compartments, model zones and a scheme of the selected stack-driven cross ventilation configurations for the considered zones

Fire compartments are filled with different colors whereas the selected zones for natural ventilation configurations are outlined with the colors indicated in the legend. Airflow paths are designed as well.

Once opening position was roughly configured, minimum openings area was sized through the ASHRAE equation for flow caused by thermal forces only [11], as follows.

$$Q = c_d A \sqrt{2g\Delta H_{NPL}\frac{T_i - T_o}{T_i}\frac{3600}{V}} = Z\sqrt{\frac{T_i - T_o}{T_i}}$$

Q = airflow rate [vol/h]

c_d = discharge coefficient

ΔH_{NPL} = height from midpoint of lower opening to Neutral Pressure Level [m]

A = cross sectional area of inlet and outlet opening [m²]

V = zone volume [m^3]

The equation terms dependent on building geometry and opening position were assumed equal to a constant Z. The constant Z was estimated by fixing a maximum airflow rate of 2 ACH and assessing the dynamic terms of the equation through a simulation in Trnsys [12].

Minimum opening area estimated for every building zone

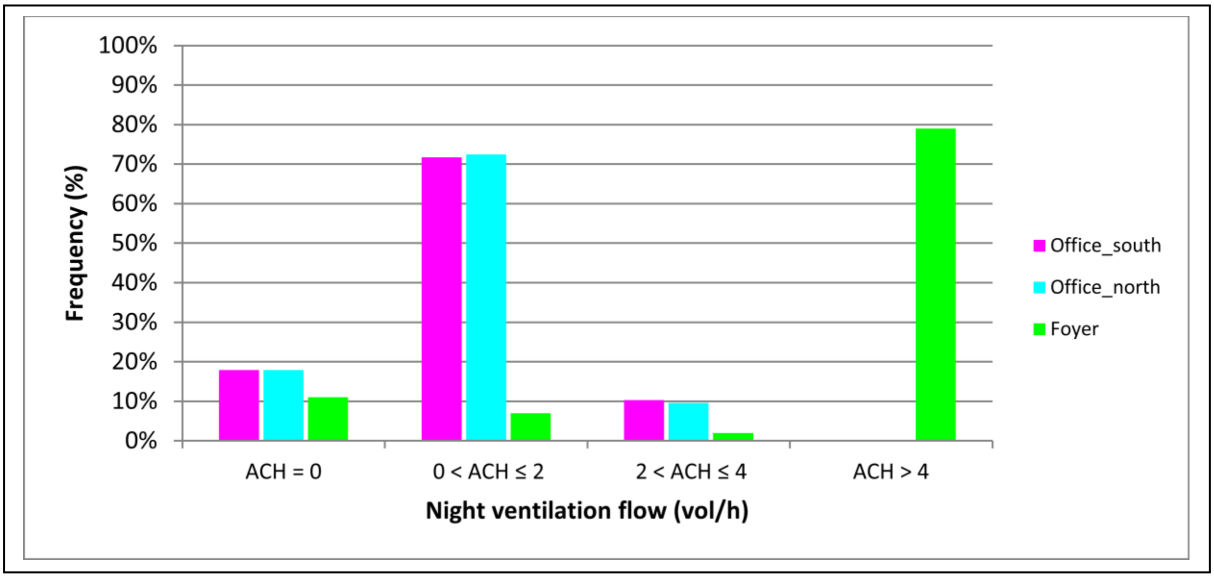
Zone	Inlet area [m^2]	Outlet area [m^2]	Floor vents area [m^2]
Office_south	3.2	3.2	6.4
Office_north	10.5	10.5	21
Foyer	10	10	-

To assess the airflow paths a transient analysis was performed by the CONTAM airflow model. As the model does not handle with heat transfer phenomena, a model was performed separately for every zone.

The models were simplified by neglecting wind effects and air leakages. Internal building layout was not considered, as it was not yet defined. For façade openings airflow is represented in CONTAM by an equivalent flow through a flat plate orifice through the Powerlaw Model. Floor vents are modelled through the Stairwell version of the Powerlaw Model [6].

Building temperature is scheduled daily and assumed to oscillate harmonically to simulate the dynamic effect of heat storage in the structure materials. Occupancy is set from 8 am to 6 pm during working days only. Windows opening is activated only when external temperature is between 14°C and 26°C during the night. As control signal will take precedence over the schedule, results data was elaborated to cut the day hours.

CONTAM is an advantageous tool for natural ventilation design to assess bulk airflow rate and verify the configuration suitability. Positive flow direction was set in the wanted flow way, so that negative airflow indicates an unwanted flow direction. Pressure difference and flow direction was plotted for every airflow path to check the flow direction and verify the configuration concept. Flow direction resulted negative in less than 1% of the night hours.

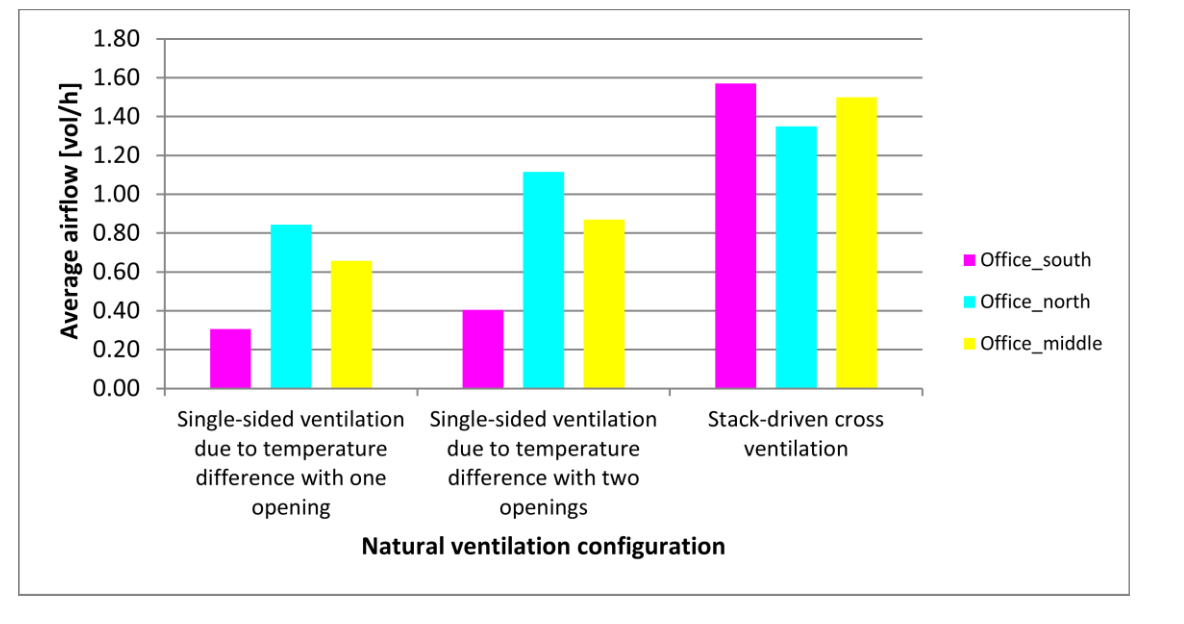


ACH frequency in the building zones during night (from June to September) thanks to the natural ventilation
CONTAM simulation results elaboration

As the graph shows in north and south office zone, the airflow rate is between 0 and 2 ACH for the 70% of the night hours, whereas the airflow rate in the foyer zone are higher because of the openings elevation difference that enhances the stack effect.

A comparison was performed between the chosen solution and other allowable solutions, like single-sided ventilation due to temperature difference with one opening or with two openings at different elevation. The configurations were compared for a floor type and for the same opening area and a fixed opening height of 50 cm, to prove the architect that the solution proposed has better performance than other solutions with the same architectural impact.

The central office area cannot be connected with the lightwell because of the fire regulation plan. Single-sided ventilation will be here configured.



Comparison between the allowable natural ventilation configuration solutions for the same opening area in a floor type

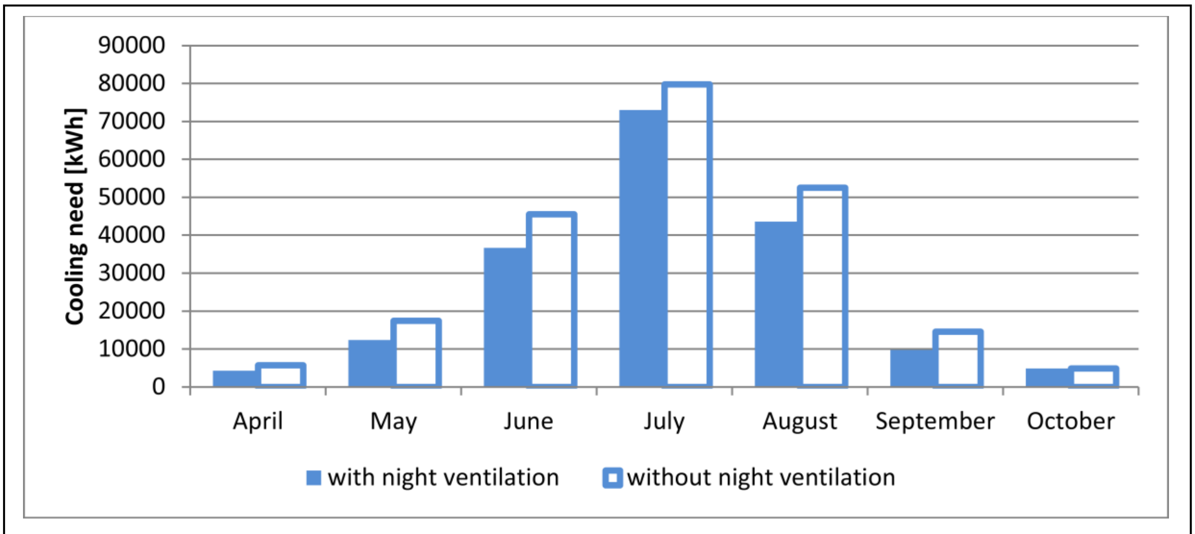
Airflow due to single-sided ventilation with one and two openings has been estimated through the BS 5925:1991 [13] formulas. Stack-driven cross ventilation effect has been estimated with CONTAM airflow model [6].

Once opening area was sized, building energy simulations, with and without natural ventilation, were run to estimate the night cooling effect on the whole building performance. Dynamic simulations were performed by Trnsys 17 [12] with the following openings activation thresholds:

- from 6 pm to 8 am
- 14°C $< T_{out} < T_{in}$
- $T_{in} > 24$°C
- $T_{out\text{-}dp} \leq 17$°C

The air humidity control was introduced to avoid an air absolute humidity higher than the comfort one (air temperature of 26°C with relative humidity of 60%).

Due to night cooling the cooling need reduction was estimated around 15%.



Dynamic simulation results comparison between monthly cooling need with and without night ventilation.

Dynamic simulations performed in Trnsys show a total cooling need reduction of about 15%.

Discussion and outlook

The assumptions made for the assessment of the natural ventilation strategy allowed performing a simplified analysis on night cooling strategies. The comparison confirms that the solution proposed gives better performances than single-sided ventilation, considering the constraints given. The rough cooling need reduction estimation has to be proven with more detailed simulation and further more by (foreseen) monitoring.

As the design becomes more and more detailed, more detailed simulations have to be performed with less assumption on input data. Pressures lost along the airflow path have to be assessed. Airflow and thermal model will be coupled to consider the thermal mass effect and the real internal temperature fluctuation.

In the early stage climate evaluation wind was not taken into account, because the available wind directions, velocities and frequency did not allow designing a wind-driven natural ventilation configuration. However, wind can affect negatively or positively the found results. An urban CFD study should be performed to understand the possible wind impact on air velocities and pressure around the building. More accurate climate data are needed, as Bolzano is placed where two valleys meet and prevailing wind direction can vary significantly from one part of the city to another.

The more accurate wind analysis aims at evaluating the dependency of the control strategy on wind direction and velocity. The control strategy will allow through a windows automation system a programmed opening/closing of windows group controlled by indoor temperature, outdoor temperature and humidity, as in dynamic simulations settings.

Conclusion

The paper highlights the fundamental importance of an integrated design process to conceive a natural ventilation strategy that can meaningful contribute to the cooling needs and the overall primary energy consumption reduction towards a Net Zero Energy building.

Main design professionals (owner, designer, consultants) worked together to find out a shared solution that balances performances needs with constrains given by fire regulations, acoustic comfort and user's needs, and to keep acceptable the architectural impact of the solution. Qualitative and quantitative analysis were performed to support the decision process in the early stage of the design.

First, the potential effectiveness of night cooling strategies was analyzed. Taking into account the constraints given, allowable natural ventilation configurations were suggested and compared. Minimum opening area needed to obtain the desired airflow was sized. Trnsys was used to perform a comparison between the baseline model and the natural ventilation model. Obtained results showed how the potential cooling need reduction of the night cooling strategy suggested is around 15%.

It is recognised that natural ventilation design could give an important contribution to achieve the Net Zero Energy target, without increasing significantly operation and construction costs.

Acknowledgments

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