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Influence of Ambient Air Pollution on Natural Ventilation Potential in Europe

Evangelos Belias
Student Member ASHRAE

Dusan Licina
Associate Member ASHRAE

ABSTRACT

When designed and operated adequately, natural ventilation (NV) can improve the buildings' energy efficiency and indoor environmental quality. There is a plethora of factors that limit the effectiveness of NV, such as the climate, surrounding buildings, noise, and ambient air pollution, especially in urban environments. Nevertheless, the existing NV potential (NVP) calculation methods are complex and difficult to be used. This study proposes a new methodology for quantifying the NVP by considering the exterior climate and ambient air pollution. This methodology analyzes climatic and ambient air quality data to estimate the NVP of urban and suburban sites of 27 European cities. The results reveal that the level of urbanization and proximity to traffic significantly influence the applicability of NV. Taking ambient air pollution into account reduces the climatic NVP on average: 11% for suburban background sites, 28% for suburban traffic sites, 22% for urban background sites, and 50% for urban traffic sites. Building designers can use the proposed methodology in the building design phase in order to implement the NV without increasing occupants' exposure to outdoor air pollution. The results of the statistical analysis can be used by the public authorities and the decision-makers to better consider the limitations and opportunities of the NV use by the building stock.

INTRODUCTION

It is well established that when NV is adequately designed and operated, it is a technique that reduces energy use and, in parallel, improves the indoor environmental quality of buildings (Flourentzou et al., 2017; Psomas et al., 2017). Many factors influence the applicability of the NV in buildings, including the outdoor environment, building orientation and massing, openings, operation, and occupant behavior. Among them, the outdoor environment parameters should always be considered by designers as they are independent of the building's form and operation (Causone, 2016). These outdoor parameters include the climate and ambient air and noise pollution (Causone, 2016; Germano and Roulet, 2006; Ghiaus et al., 2006). The totality of these parameters defines the NVP of a site: the amount of time when NV is applicable. The NVP is usually measured in NV Hours (NVH): the hours over a typical year when the outdoor conditions permit the use of NV.

Several studies estimated the NVP by considering an area's climatic conditions (Causone, 2016; Pesic et al., 2018). Other developed methodologies can calculate the ventilative cooling potential of a building by taking into account the climate and the buildings' characteristics (Belleri et al., 2018). The limitation of these methods is that they do not consider the ambient air and noise pollution — parameters that are critical for the NV applicability (Germano and Roulet, 2006; Ghiaus et al., 2006). Other, more comprehensive studies included the ambient air pollution into the NVP calculation by considering some of the major ambient air pollutants ($PM_{2.5}$, PM_{10}, O_3) (Chen et al., 2019; Chen et al., 2020; Martins and Carrilho da Graça, 2017; Martins and Carrilho da Graça, 2018). Yet, in these studies, the ambient air pollution was considered as uniformly distributed across the cities, neglecting the influence of local sources like traffic. Until now, the impact of these

Evangelos Belias is a PhD candidate at the School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Switzerland. **Dusan Licina** is an Assistant Professor at the School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Switzerland.

local sources was only considered empirically and not quantitatively (Germano and Roulet, 2006; Ghiaus et al., 2006). Regarding noise, as hourly data are not available, only qualitative methods can be applied to estimate the NVP (Ghiaus et al., 2006).

The primary objective of this study is to develop a method that considers both climatic and air quality conditions comprehensively in order to calculate the NVP for the European context. By separating the air quality data into urban-suburban and traffic-background, this study aims to reveal the influence of urbanization and traffic on the NVP.

MATERIALS AND METHODS

The most comprehensive methodology for the climatic NVP is the one developed by (Causone, 2016), which considers the ambient air temperature (T) and humidity and, based on the ASHRAE adaptive thermal comfort model, sets the limits for the above parameters. If the ambient air T and humidity are between these limits, then the NV can be used without reducing the occupants' thermal comfort, neither drop/increase the indoor Relative Humidity (RH) levels beyond the set thresholds. Regarding ambient air pollution, the most comprehensive method for its consideration was developed by (Chen et al., 2019). This method uses the analogous procedure for the Typical Meteorological Years' (TMY) creation in order to select representative air quality data, which are used in the NVP calculation. The present study used the above methodologies as a baseline.

Climatic and ambient air pollution data were collected from 27 European cities to calculate the European NVP. For climate consideration, the database of the International Weather for Energy Calculation (IWEC) was used to provide the TMY for all the investigated locations, as they contain the typical weather data for the long-term conditions. Concerning the ambient air pollution, the targeted pollutants in this study were $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, as they are the major pollutants used by the European Air Quality Index and the World Health Organization Air Quality Guidelines (EEA, 2017; WHO, 2006). In order to map the effect of urban environment and traffic, where available, the data were collected from four different types of localities in each city: Urban Traffic, Urban Background, Suburban Traffic, and Suburban Background. The air quality data were collected from the European Environment Agency's website (EEA, 2021) for a five-year time period between 2015 and 2019 in order to consider the representative long-term concentrations. Older than 2015 data were excluded as they cannot represent the present air pollution levels, given that the ambient air pollution trends change over the years (Chen et al., 2019). The 2020 data were also excluded as, due to COVID-19, they are not representative (Dutheil et al., 2020).

The NVP calculation was done in NVH, as it is the easiest quantitative method that permits direct comparisons. For this calculation, the ambient air T, RH, and air pollutant concentrations were evaluated in an hourly time step.

As the first step, the climatic NVP was calculated, which uses ambient air T and RH as parameters (Causone, 2016). The upper threshold, which defines if the outdoor air T was suitable for NV, was set based on the ASHRAE adaptive thermal comfort model (ASHRAE, 2020), while the lower T threshold was fixed at 10 ºC for simplicity, as suggested by (Causone, 2016). The indoor RH range was defined between 30% and 70%, as these levels assure acceptable indoor air quality and thermal comfort (ASHRAE, 2020). Thus, the limits for the outdoor air humidity ratio were set so that when the outdoor air enters the indoor space, the RH levels to be in between the defined thresholds.

In the second step, ambient air pollution was introduced in the NVP calculation in order to map its impact. To select the targeted air pollutants' hourly representative concentrations, the method utilized for the creation of TMY, which selects typical meteorological data, was applied. This process creates a standard year-long dataset with representative concentrations (Chen et al., 2019). These hourly concentrations were used in the NVP calculation.

Regarding ambient air pollution, according to the European standard (Directive 2008/50/EC), the thresholds were set at 25 $\mu g/m^3$ for $PM_{2.5}$, 40 $\mu g/m^3$ for PM_{10}, 120 $\mu g/m^3$ for O_3, 40 $\mu g/m^3$ for NO_2, and 125 $\mu g/m^3$ for SO_2. These thresholds can be considered as conservative, as they stand for the annual mean limits for $PM_{2.5}$, PM_{10}, and NO_2, the 8-hours mean limit for O_3, and the daily mean limit for SO_2. If at least one pollutant exceeded these limits, the outdoor air was considered inadequate for NV. If the outdoor air T, RH, and pollution concentrations were complying with the set conditions, then this hour was counted as NVH. We also calculated the ratio of the NVH to the total hours of a year (8760) to reveal the percentage of time when the NV can be applied at each location.

RESULTS

Across Europe, the climatic NVP was higher in the countries located in the Mediterranean climatic zones (Greece, Italy, Spain, Portugal). In these locations, the climatic NVP was higher than 50%. This potential was primarily reduced by the hot and humid weather during summers rather than the cold weather during the winters. Concerning the oceanic (France, UK, Ireland, Belgium, West Germany) and continental climates (North-East Germany, Serbia, Romania, Switzerland, Poland, Bulgaria, Austria, Norway, Sweden), the climatic NVP was around 40%. In the oceanic climates, the cold weather was the main factor limiting the NVP, while in the continental climates, the NVP is primarily limited by cold temperatures and dry air.

The introduction of ambient air pollution into the NVP calculation revealed that it is a critical factor that limits the NVP. The reduction in the NVP resulting from the ambient air pollution varied from ~0% to 94%, depending on the location of the site, the level of urbanization, and the proximity to traffic. Hence, neglecting outdoor air pollution data and their temporal variation could lead to misselection of building ventilation type and elevated indoor exposures.

As it is demonstrated in Figure 1 (a), in Athens, the climate permits the utilization of NV 67% of the time. The ambient air pollution reduces this potential by ~19% in Suburban Background, ~32% in Urban Background, and ~78% in Urban Traffic sites. Generally, the results revealed that the specific location of a building within a city plays a significant role in its NVP. Relative to the base case scenario that neglects the influence of outdoor air pollution, as presented in Figure 1 (b), the reduction of NVP for all the investigated localities was on average ~11% for Suburban Background, ~28% for Suburban Traffic, ~22% for Urban Background, and ~50% for Urban Traffic sites. Thus, the designers should be aware of this influence already from the early design phase in order to plan the ventilation strategies accordingly.

All these results refer to the NVP of the site and are not linked with the buildings' characteristics. According to its operation and design, the maximum amount of time that a building can benefit from NV can differ significantly. For example, an office building can apply NV for cooling during the night, even though the ambient pollution levels are high, as there are no occupants during this time. In addition, the authors acknowledge that ambient air pollution is not only a problem for naturally ventilated buildings, but it also concerns the mechanically ventilated, when there is no adequate filtration.

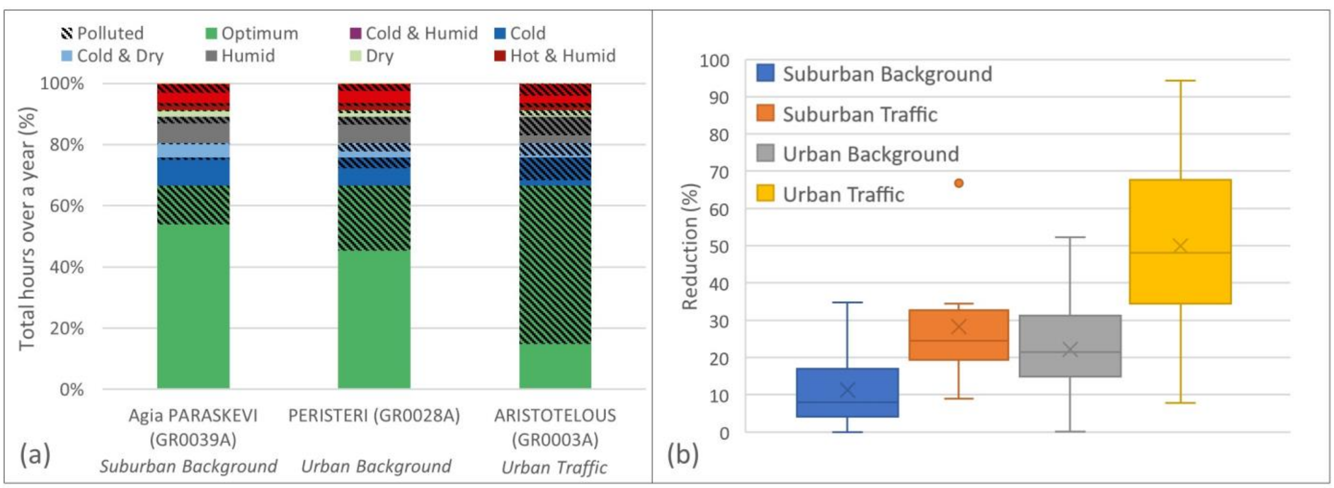

Figure 1 (a) Distribution of time according to weather conditions and ambient air pollution levels in three localities in Athens; (b) Reduction in NVP because of the ambient air pollution as a function of the level of urbanization and proximity to traffic for the totality of the investigated locations

CONCLUSION

This study presented a methodology that combines a detailed climatic and ambient air pollution evaluation, which can be used in the early design phase to calculate the NVP of a site. The knowledge of the NVP can aid designers in estimating the amount of time when a building can benefit from the NV without exposing the occupants to high levels of outdoor originating pollution and heat/cold stress. In addition, special attention should be given to the selection of the air quality measurement station, as the pollution levels vary significantly even in the same agglomeration. Finally, this study's results can be used by policymakers as it gives an overview of the impact of outdoor air pollution within European building stock.

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