Windows opening in naturally ventilated classrooms: management strategies to balance energy use and reduction of risk infection transmission

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Ensuring proper ventilation to reduce infection risks indoors has become increasingly important, especially during the COVID-19 pandemic. For naturally ventilated buildings, generic guidelines, such as "open windows as much as possible," pose challenges in effectively managing ventilation rates. This work addresses this complexity by focusing on classrooms at diverse educational stages to quantify the management of naturally ventilated spaces. The study presents a method to determine window opening time and frequency, considering window characteristics, indoor and outdoor conditions, and room occupancy. Results reveal that opening time correlates with room surface and occupancy but diminishes with larger window areas and favourable discharge coefficients based on window types. Additionally, in windless conditions, opening time decreases as the indoor-outdoor temperature difference increases.

This research emphasizes the urgent need for more efficient guidelines for naturally ventilated environments, ensuring healthy indoor conditions not only during the pandemic but also in the post-pandemic era. Implementing these findings will promote safer and healthier indoor spaces for educational settings and beyond.

Since people are spending an increasing amount of time indoors, Indoor Environmental Quality (IEQ) has become a very important issue to improve the health and well-being of occupants (Bluyssen, 2020). During the COVID-19 pandemic, the necessity to ensure healthy environments has become even more evident, since IEQ can have direct effects on occupants' safety (Awada et al., 2021) and environmental quality has a direct effect on infection control (Azuma et al., 2020).

The airborne transmission of COVID-19 has been widely recognised by researchers as one of the three modalities, together with large respiratory droplets (falling in a range of 1-2 m) and direct contact with contaminated surfaces (Morawska et al., 2020; Noorimotlagh et al., 2021). This evidence has been confirmed by several cases of COVID-19 spread due to environmental factors, such as the restaurant in Guangzhou, China (Lu et al., 2020) where the direction of the airflow from the air conditioners was consistent with the disease transmission. Li et al. (Li et al., 2020) also brought evidence that the aerosol transmission of COVID-19 was related to poor ventilation of buildings.

Further cases confirming this infection pathway are the call centre in Seoul, South Korea (Park et al., 2020), which showed that the exposure time is a determinant in increasing the risk, or the case of the choir in the Skagit Valley, USA (Hamner et al., 2020), which highlighted the influence of activity on COVID-19 spread. In particular, increasing the ventilation can reduce the infection risk indoors (Dai and Zhao, 2020; Lipinski et al., 2020; Morawska et al., 2020) and environmental parameters should be also used to prevent the pandemic (Yao et al., 2020). For this reason, several guidelines have been provided to manage buildings during this period. Generally, the indications for buildings provided by HVAC systems are much more detailed than the ones for naturally ventilated environments. In general, it was required to maintain ventilation systems as usual, keeping them on two hours before and after the room occupancy (ECDC, 2020). If possible, it was also required to avoid air recirculation and to increase the airflow in the space. Except for Norway, which suggests ACH=7l/s pers, for everyday environments (e.g. offices, schools, etc) the national and institutional guidelines do not provide an exact value of air changes required during the pandemic period, but they recommend at least maintaining usual the required airflow for a longer period.
For naturally ventilated buildings, the situation is even more complex as it is not possible to monitor directly the airflow passing through doors and windows. Indications are usually generic and specify that windows should be opened "regularly" and in some cases, they are in contrast with each other (e.g. Italy recommends keeping doors closed, while the Netherlands maintains windows and doors open). Moreover, guidelines provide approximate opening times such as 10 to 15 minutes once or more times per day, which is a very generic indication that does not take into account parameters such as the room characteristics or occupancy. Only Germany, Norway, and REHVA suggest the use of CO2 sensors as an indicator of potential SARS-CoV-2 presence, which has been demonstrated as a useful tool to assess infection probability (Peng and Jimenez, 2020; Fantozzi et al., 2022).
This paper, therefore, aims to evaluate window openings to ensure healthy conditions and reduce the risk of infection, taking school buildings as a reference.

	Kindergarten	Elementary school	Middle school	High school
Number of students	18 – 26	15 – 26	18 – 27	27 – 30
Area (gross) (m^2/class)	198 – 210	153 – 167	201.5 – 275.5	166 – 307
Area (gross) (m^2/student)	6.06 – 7.00	6.11 – 6.68	8.06 – 11.02	6.65 – 12.28
Area (net) (m^2/student)	1.8	1.8	1.8	1.96
Height (m)	3.0	3.0	3.0	3.0
Window area (m^2)	≥ 1/5 Area	≥ 1/5 Area	≥ 1/5 Area	≥ 1/5 Area
Air temperature (°C)	20 ± 2	20 ± 2	20 ± 2	20 ± 2
Relative humidity (%)	45 – 55	45 – 55	45 – 55	45 – 55

Tab. 1 - Classrooms' characteristics in Italy according to different educational stages (DM 18-12-1975, 1975).

Methodology

Characteristics of the classrooms

Classrooms' characteristics may vary according to the school stage considered. Standards report the typical features that classrooms at various school stages present, as reported in Table 1.
For calculation purposes, the dimensions of the classrooms were assumed equal to 45 m^2 for kindergartens, primary and middle schools, and 60 m2 for high schools.
Required ventilation rate for reducing the infection risk
Since in the guidelines, the required ventilation rates were very variable between countries, room management generally

Ref	Educational stage	Age	Assumed N° students per class	$\dot{Q}_{req,p}$ (m^3/s·person)	$\dot{Q}_{req}$ (m^3/s)
1	Kindergarten	3 – 6	22	$4 \cdot 10^{-3}$	0.088
2	Elementary school	6 – 11	21	$5 \cdot 10^{-3}$	0.105
3	Middle school	11 – 14	23	$6 \cdot 10^{-3}$	0.138
4	High school	14 – 19	29	$7 \cdot 10^{-3}$	0.203

Tab. 2 - Characteristics and ventilation rates for different educational stages according to the Italian standard (UNI 10339, 1995).

referred to existing standards. As this paper considers Italian classrooms, the required ventilation rates (Ǭreq, m³/s) provided by UNI 10339 (UNI 10339, 1995) were assumed as reference values. Values reported for different types of classrooms are reported in Table 2.

Determination of the natural ventilation rate

Natural ventilation is a function of different factors, such as the position and flow characteristics of the opening, the surface mean pressure coefficient distribution for the wind direction considered, and the internal and external air temperature (BS 5925, 1991). In the case of educational buildings, which are in most cases naturally ventilated, classrooms present openings on one side only. Since the aim of this work is to provide a simplified methodology that can be used by buildings managers to reduce the infection probability in classrooms, the effect of air infiltration and wind were neglected as a precaution. The first is because the air infiltration is a function of the buildings' characteristics and cannot be generalized to every educational building, while the second is because the wind is variable and depends on the localization of the building and on weather conditions, which cannot be controlled in advance.

Moreover, for precautionary reasons, the aim is to evaluate the most critical conditions that are represented by the absence of wind. The natural ventilation rate from window (ǬW, m3/s) was calculated for spaces with one opening on one wall only and due to temperature difference (BS 5925, 1991):

$$\bar{Q}_W = C_d \frac{A}{3}\sqrt{\frac{\Delta T\, g\, H}{T_M}} \qquad (1)$$

where:

C_d is the discharge coefficient for the opening (n.d.),

A is the equivalent area of the opening (m^2),

ΔT is the indoor-outdoor temperature difference (K),

g is the gravity acceleration (m/s^2),

H is the vertical difference between the top and bottom edges of a rectangular opening (H),

TM is the average of inside and outside temperatures (K).

The discharge coefficient Cd depends on the pressure drop encountered by the air flow as it crosses the opening and it can quantify, other parameters being equal, the airflow efficiency of an opening. Table 3 shows some typical discharge coefficients for windows under buoyancy-driven ventilation, which were obtained from a single width-to-height opening ratio (Brandan and Espinosa, 2018).

Calculation of the minimum time of window opening

Knowing the Ǭreq value for ensuring adequate ventilation (from Table 2), and the ǬW value (from Equation 1, which requires knowledge of the environmental conditions, and the geometrical characteristics of the windows), it is possible to calculate the ratio

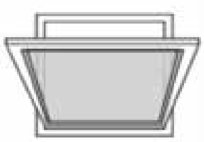
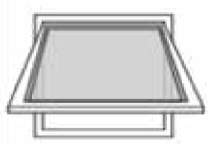
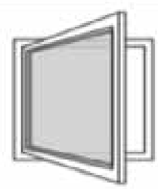
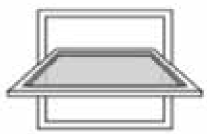
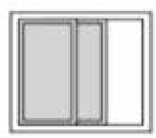
$$R = \bar{Q}_{req} / \bar{Q}_W \qquad (2)$$

If R >1, the ventilation flow rate Q is not sufficient to guarantee the required conditions and more in-depth analyses should be conducted (e.g. evaluation of the contribution of the wind action). If R ≤1, fixing a reference time interval Δτ (s), R can be used to suggest the minimum duration of the windows opening (τmin), according to the following equation

$$\tau_{min} = R \cdot \Delta\tau \qquad (3)$$

In particular, Δτ=3600 s (one hour) can be usually assumed as a reference time interval for educational buildings, as it is the minimum duration of a single lecture.

Equation 3 gives the minimum window opening duration but

	Bottom hung window	Top hung window	Side hung window	Horizontal pivot window	Sliding non-pivoting window
Window type					
C_d	0.09	0.11	0.13	0.16	0.21

Tab. 3 - Typical discharge coefficients for windows under buoyancy-driven ventilation (Brandan and Espinosa, 2018).

not its frequency. The windows opening could be continuous, for a time τmin, or it could be repeated (series of openings and subsequent closures, so that the sum of the times in which the windows are open is equal to τmin).
A useful criterion for deciding the frequency of windows openings is to create cycles of opening and subsequent closing based on the complete exchange of the air volume. That is, the windows are opened and, once the volume of air in the classroom has been completely replaced, they are closed. It is then possible to calculate the number of times (n) that the window should be kept open in the reference time interval, and the duration of each single opening (τop), according to the following equations:

$$\tau op = V/\bar{Q}W \quad ; \quad n = \tau min/\tau op \qquad (4)$$

where V is the room volume (m3). Obviously, the strategy described by equations 4 can be applied only if n>1.

Results and discussion

Effect of occupancy
The number of people in a room affects the infection probability (Fantozzi et al., 2022). To study its impact on window opening time, typical characteristics of naturally ventilated classrooms were considered. Four windows, each 2.0 m x 2.2 m, with a total area of 10.6 m2 and a discharge coefficient of 0.13 were assumed, to meet hygienic standards. The indoor temperature was set at 20°C for comfort, while the outdoor temperature was 10°C for comparison.
Figure 1 shows the increase in window opening time based on the number of people and the educational stage. Ventilation rates, determined by standards (UNI 10339, 1995), vary for different stages. Kindergarten requires 11-18 minutes of opening per hour, elementary school 14-21 minutes, middle school 16-27 minutes, and high school 19-32 minutes.
The opening time significantly rises with the number of occupants, and for high schools, it can reach half of the class hour. This increase has implications for energy consumption and thermal discomfort, particularly for students close to windows experiencing cold air currents.
Effect of window area and type
Figure 2 demonstrates how window area and type directly influence the natural ventilation rate ($\bar{Q}$W) and subsequently the required opening time.
To evaluate this effect across different educational stages, 25 students in a room with an indoor temperature of 20°C and an outdoor temperature of 10°C were considered. Standard windows, 1.2 m in length and 2.2 m in height were used.
For the window area (Figure 2, left), having only one window is insufficient to meet ventilation requirements, resulting in opening times exceeding 60 minutes. Increasing the window area reduces the required opening time, reaching a minimum of 6 minutes for kindergartens. However, very large window areas are impractical for classrooms.
For different window types

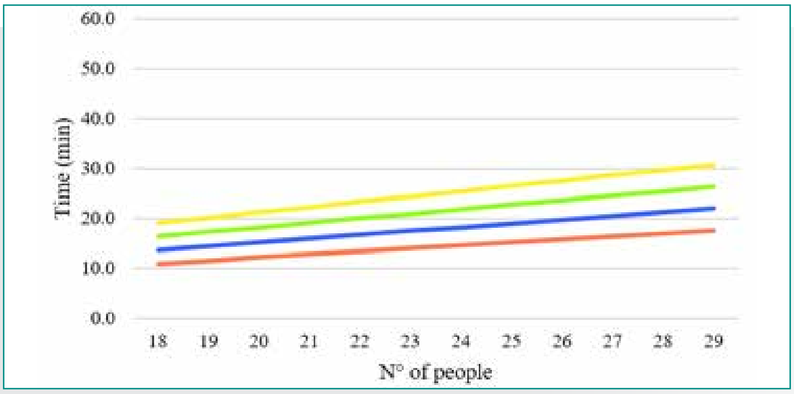


Fig. 1 - Windows' opening time to ensure the required ventilation rate as a function of the number of people. Legend: opening time for kindergartens (red line), elementary schools (blue line), middle schools (green line), and high schools (yellow line).

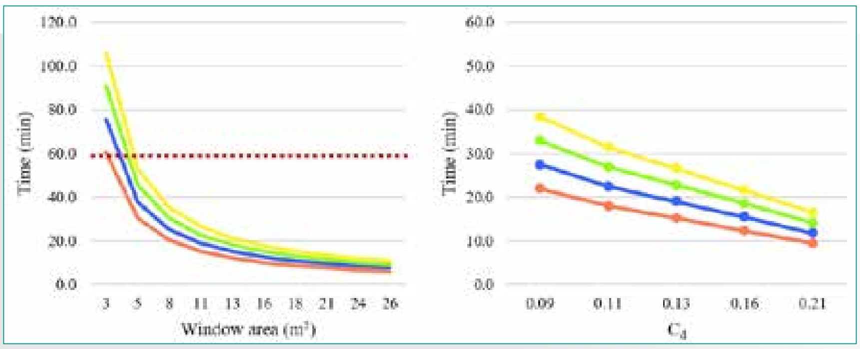


Fig. 2 - Windows' opening time to ensure the required ventilation rate as a function of the window area (left) and discharge coefficient (right). Legend: opening time for kindergartens (red line), elementary schools (blue line), middle schools (green line), and high schools (yellow line)

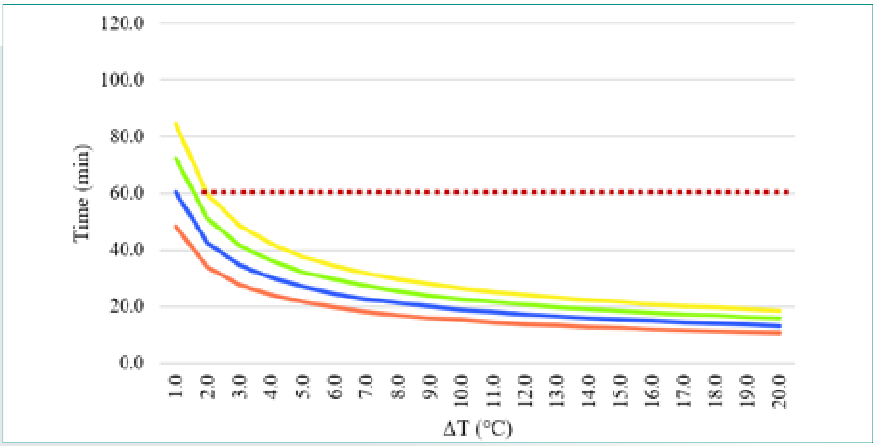


Fig. 3 - Windows' opening time to ensure the required ventilation rate as a function of ΔT. Legend: opening time for kindergartens (red line), elementary schools (blue line), middle schools (green line), and high schools (yellow line).

(Figure 2, right), increasing the discharge coefficient (Cd) significantly reduces the opening time, highlighting its importance on the ventilation rate. Although precise values of Cd can be obtained for specific cases, using recommended values in this study provides valuable information for building practitioners.

Effect of temperature difference
Figure 3 illustrates the investigation of temperature difference's impact on opening time. The ventilation rate was calculated for spaces with one opening on one wall, and the temperature difference plays a crucial role, especially in the absence of wind. The study assumed 25 people in the room, the same window characteristics as in the previous case (four windows 1.2 x 2.2 m, Cd=0.13), and varied the outdoor temperature from 0°C to 19°C.
The relationship between window opening time and temperature difference (ΔT) is shown as a curve in Figure 3: as ΔT increases, the opening time decreases. However, for low ΔT, the opening time exceeds one hour for middle and high schools, indicating that even keeping windows open throughout the lecture won't meet the required ventilation rate.
The difference between indoor and outdoor temperatures is influenced by the climate zone, season, and indoor comfort requirements. Setting outdoor temperatures is not possible, and indoor conditions must remain within an acceptable range for comfort. Studies on adapting to the thermal environment during the pandemic period are needed to understand occupants' needs. Higher ΔT reduces opening time but may lead to discomfort and increased energy consumption, especially with high indoor-outdoor temperature differences.

Conclusions

During the COVID-19 pandemic, the need to maintain indoor health was crucial. However, guidelines for naturally ventilated buildings lack precision in controlling ventilation rates. This study offers a method to determine window opening time and frequency based on window characteristics, indoor and outdoor conditions, and room occupancy. Different ventilation rates, aligned with national and international standards for building types or educational stages, were considered to reduce infection probability. The results show that opening time increases with room surface and occupancy, while it decreases with larger window areas and favourable discharge coefficients based on window types. In the absence of wind, opening time decreases as the indoor-outdoor temperature difference increases.
Balancing increased ventilation rates with energy consumption control and ensuring comfort remains a crucial area for further investigation. Nonetheless, this study provides a useful tool to enhance indoor environmental quality, promoting healthier buildings not only during but also post-pandemic periods, guiding building practitioners towards improved awareness of indoor health.

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ABSTRACT

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