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Air change rates and infection risk in school environments: Monitoring naturally ventilated classrooms in a northern Italian urban context

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ABSTRACT

The importance of building ventilation in avoiding long-distance airborne transmission has been highlighted with the advent of the COVID-19 pandemics. Among others, school environments, in particular classrooms, present criticalities in the implementation of ventilation strategies and their impact on indoor air quality and risk of contagion. In this work, three naturally ventilated school buildings located in northern Italy have undergone monitoring at the end of the heating season. Environmental parameters, such as CO_2 concentration and indoor/outdoor air temperature, have been recorded together with the window opening configurations to develop a two-fold analysis: i) the estimation of real air change rates through the transient mass balance equation method, and ii) the individual infection risk via the Wells-Riley equation. A strong statistical correlation has been found between the air change rates and the windows opening configuration by means of a window-to-volume ratio between the total opening area and the volume of the classroom, which has been used to estimate the individual infection risk. Results show that the European Standard recommendation for air renewal could be achieved by a window opening area of at least 1.5 m^2, in the most prevailing Italian classrooms. Furthermore, scenarios in which the infector agent is a teacher show higher individual infection risk than those in which the infector is a student. In addition, the outcomes serve school staff as a reference to ensure adequate ventilation in classrooms and keep the risk of infection under control based on the number of the students and the volume of the classroom.

1. Introduction

School buildings, due to their high occupancy density, deserve special attention in terms of Indoor Environmental Quality (IEQ), and in particular in terms of Indoor Air Quality (IAQ), to ensure the well-being of students and teachers as well as good performance [1, 2]. Actually, several past studies have found a correlation between poor IAQ conditions in the classrooms and both a reduction in

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learning performance [2,3] and an increase in health problems such as headaches, respiratory symptoms, asthma, etc., [4–6].

Building ventilation is mandatory to ensure proper IAQ levels since the replacement of exhaust air with fresh outdoor air dilutes the concentration of air pollutants harmful to human health [7]. Among the indoor air pollutants, CO_2 is widely used to estimate the outdoor-indoor air exchanges in buildings, although it has some limitations [8]. In the past two decades, several studies monitoring CO_2 concentrations in school buildings in different countries have pointed out low ventilation rates [9].

In Europe, the lack of ventilation is a common issue in naturally ventilated schools which constitute 86% of the scholastic building stock, as reported by the SINPHONIE project [10]. Furthermore, according to the document entitled "*School Environment: policies and current status*" [11] issued by the World Health Organization (WHO), the ventilation problem in the educational environment is accentuated during the cold months due to the lack of heating systems in these buildings. In fact, thermal comfort was considered a priority over ensuring adequate IAQ by teaching staff and pupils during these periods [12].

On the other hand, the COVID-19 pandemic has relied on building ventilation as the main measure to reduce the spread of the virus in indoor environments since its role in controlling long-distance airborne transmission -which is the dominant route of transmission [13]-, has been widely acknowledged [14].

Based on this, the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) [15], in the absence of any ventilation standard related to the infection risk design criterion, has suggested referring to the European standards EN 16798–1:2019 [16], assuming the indoor environmental category II for low polluted building (7 l/s per person + 0.7 l/s per m^2) for the ventilation design of classrooms. Similarly, the WHO has recommended a minimum outdoor airflow value of 10 l/s per person (supplied through natural or mechanical ventilation) in the document "*Roadmap to improve and ensure good indoor ventilation in the context of COVID-19*" [17] for non-residential buildings.

In this context, several studies have analyzed the effects of the COVID-19 pandemic on the IEQ of naturally ventilated classrooms. Some of them, have evaluated the air changes per hour (ACH) of different natural ventilation strategies through tracer gas measurements, demonstrating that some window opening configurations are capable of both respecting the reference limits and drastically reducing the probability of airborne transmission [18–20]. However, the tracer gas method assesses the ACH during non-occupied periods setting fixed boundary conditions [21].

To date, there is still a lack of studies that address the impact of COVID-19 on ventilation conditions and its variations through time due to different window opening configurations and under variable occupancy periods. In this regard, the present research aims to address this breach of knowledge by presenting the assessment of the natural ventilation strategies implemented in real school classrooms of northern Italy during the winter of 2022, under COVID-19 measures. Besides, the correlation between the window opening configurations and the probability of infection is hereby presented as a novelty to the body of research. To do so, the ACH rates achieved by over-ventilating the classrooms are estimated through the Transient mass balance equation (TMBE) method which is suitable for assessing the ventilation performance variations in classrooms [21]. Then, an evaluation of the airborne infection risk was carried out to link the natural ventilation strategies with the relative probability of contagion. In addition, since studies on naturally ventilated schools under COVID-19 measures have shown internal temperatures below the thermal comfort (e.g., Refs. [22–24]), the thermal conditions that occurred during the investigation have also been checked.

The soundness of this work relies on the monitoring of environmental parameters of classrooms, representative of the most prevailing geometries within Italian school building stock, under over-ventilation strategies, during real occupancy and operation conditions.

The paper is structured as follows: Section 2 presents the materials and methods followed to carry out the monitoring in the three schools and the description of the models to assess ACH rates and infection risk from the onsite collected data; Section 3 reports the results and discussion of the outcomes and confronts them with other works in the field; and Section 4 provides for the conclusions of the work and gives an overview of further lines of research.

2. Materials and methods

This section reports the steps followed to assess the impact of natural ventilation strategies implemented in real school classrooms in northern Italy. The methodology is presented in the following four sections: (i) description of the case-study school buildings; (ii) analysis of the collected data through the monitoring; (iii) determination of the air changes rates; and (iv) assessment of the infection risk.

2.1. Case studies

Considering the limited number of acquired sensors and their availability in proximity of the end of the heating season, the measurement was designed to be carried out consecutively in three schools in the city of Milan, foreseeing a contemporaneous comparison between two classrooms in the same building. The case-study buildings belong to the municipality of Milan and are naturally ventilated, as almost all school buildings, excluding very few recent buildings, in Italy. Two primary schools (A and B) and a secondary school (C) participated in the study. The case studies are representative of the most common classroom pattern of the Italian school stock, i.e., the one referred to the 85% of the existing buildings, built based on the approach adopted after the World War II, having a height of around 3 m and a floor surface around 50 m^2, with a depth (walls perpendicular to the façade) between 6 and 7 m; the same range in depth is also common in the classrooms of the historical schools, in which, differently, the floor surface reveals a wider range, from 40 to 60 m^2, and the height usually reaches 4.5 m [25]. Two classrooms were monitored in each school, namely hereafter as A1C and A4B (for a first year and a fourth-year classrooms of School A); B4A and B5C (for a fourth year and a fifth-year classrooms of School B) and C3B and C3D (for two third-year classrooms of School C). Fig. 1 shows the location of the case studies in the city of Milan and Table 1 reports the main characteristics of the analyzed classrooms in each school.

2.2. Data collection and assumptions

The monitoring of the three schools was carried out for three different weeks at the end of the heating season between March and April 2022. Starting from school A, monitored from 12/03 to 18/03, school B and C were subsequently monitored from 19/03 to 25/03 and from 31/03 to 06/04 respectively. Teachers were asked to declare any operation of the windows and changes in the occupancy of the classroom throughout the duration of the daily lessons.

In each case, indoor air temperature, CO_2 concentration, and outdoor air temperature were recorded on a sub-hourly basis for one week (i.e., including the weekend). As assumed also by other studies [26,27], the variation of the outdoor CO_2 concentration was not measured, adopting a constant value of 400 ppm, which is also the value suggested by EN 16798-1 [16] in absence of measured data. It has to be noted that this is an approximation, because the external CO_2 concentrations actually change depending on the location and on the variation of the environmental conditions during the day [28,29]. Another approximated assumption, also adopted in other studies [30,31], can be referred to the local wind data, which were assumed as not relevant and aleatory for single side openings' spaces within the dense urban context of Milan. In fact, from all the available weather stations placed in the city, data on wind speed taken from the nearest weather stations to the surveyed schools, presented daily average values ranging between 1 m/s and 2.3 m/s during lesson hours [32]. As a matter of fact, and in line with other authors [27], since wind speed did not exceed 2 m/s over 79% of the whole measured time, wind speed and direction had a slight influence on the natural ventilation of the specific case studies.

A description of the tools employed to record the data is provided in the following sections.

2.2.1. Equipment to collect environmental parameters

The measuring instrumentation was provided by Capetti Elettronica s.r.l. [33], composed of wireless dataloggers for registering environmental parameters every 10-min and sending them to the control unit (base station) for storage and generation of the dataset. The sensors used non-dispersive infrared (NDIR) technology to measure CO_2 concentrations, and different transducers for recording air temperatures (NTC10KΩ for indoor air temperature, PT1000 for outdoor air temperature). A summary of the main characteristics of

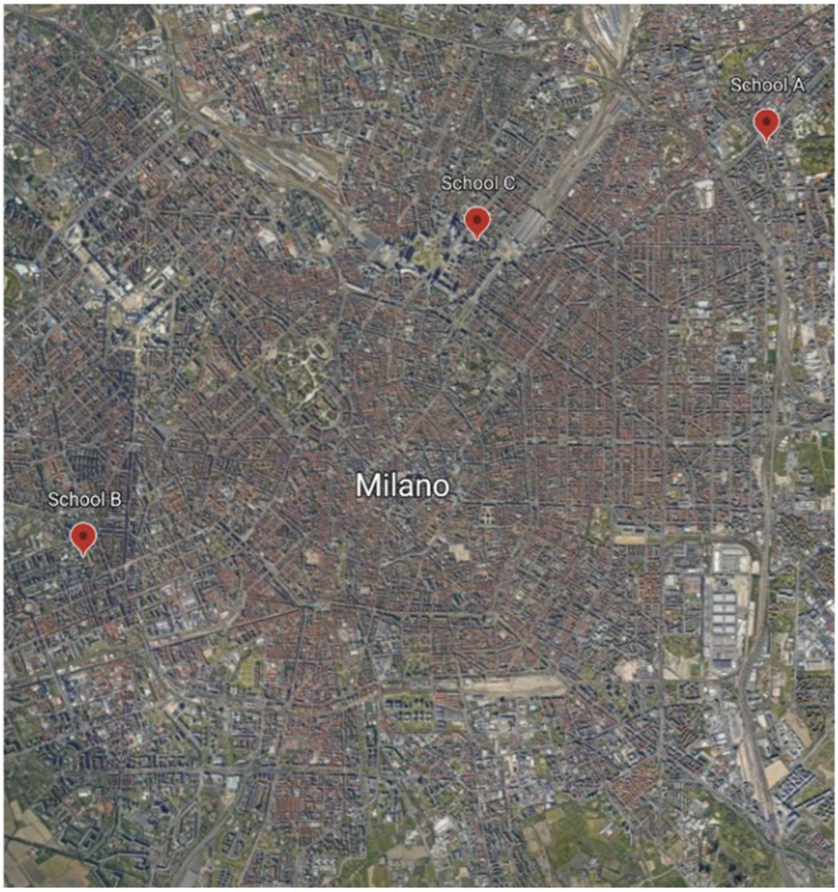

Fig. 1. Location of the case-study school buildings in the city of Milan.

Table 1
Description of the main characteristics of the analyzed classrooms.

Classroom	N° of students	Floor area [m^2]	Depth [m]	Height [m]	Volume [m^3]
A1C	20	49	7.0	2.9	142
A4B	23	52	7.0	2.9	151
B4A	24	50	6.2	3.0	150
B5C	24	48	6.2	3.0	144
C3B	20	49	6.0	3.2	157
C3D	22	49	6.0	3.2	157

the sensors used in the measurements is reported in Table 2.

The measurement devices were installed in the three schools during non-occupation periods, so as not to interfere with the course of the lessons. Since it was not possible to place dataloggers over the occupied area of the classrooms, and given the limited availability of equipment, each classroom was equipped with two devices installed on the walls at the height of 1.5 m from the ground and away from radiators and windows, as recommended by EN ISO 16000–26 [34]: one on the blackboard wall and the other one on the opposite wall (Figs. 2, 3). For the assessment, the average values of the 10-min recordings of the two opposed dataloggers in each classroom were used in this study. Regarding the outdoor measurements, each school was equipped with two outdoor dataloggers installed in available protected spaces. Again, the average of the values recorded every 10 min for each pair of devices in each school has been assumed.

2.2.2. Operation of windows

The monitoring took place during the period under the recommendations of the Italian Government to ventilate the classrooms as much as possible, without precise indications, to avoid the spread of SARS-CoV-2 [35]. For this reason, in addition to the collection of environmental data, teachers were asked to record the operation of windows and the occupancy of the classroom for all the duration of the lessons and to transcribe the information into a table. The operation of the windows distinguished between full and partial opening, was aimed at evaluating the useful opening area during the survey. It was intended as “full opening” when the windowpanes (either one or the two of them) were opened at their maximum, while “partial opening” indicated that only part of a windowpane remained open (i.e., in tilt mode for tilt-and-turn windows or partly opened in sliding ones). Table 3 shows detailed information on the types of windows found in the classrooms and their operation modes. Window typologies are named with a letter (A, B, C, D) based on their opening style. Besides, Figs. 4, 5, 6, 7 provide for a graphical description and a picture of the real windows.

To assess the impact of the window operation modes over the recorded indoor environmental parameters, an overall ratio referred to as window opening ratio Aw/Vc, between the total windows opening surface area Aw (m^2) and the volume of the classroom Vc (m^3) is calculated for each window opening configuration in the analyzed classrooms. Table 4 shows the resulting Aw/Vc ratios obtained, thanks to the information declared by the teachers during the whole measurement period.

2.3. Model for the estimation of air change rates

The Transient Mass Balance Equation (TMBE) is a method to estimate the air change rates of an indoor environment. To do so, it assumes the occupant-generated CO_2 as a tracer gas, and can be used for dynamic occupancy patterns and for different times of the day [21,36]. According to this, the present work uses this method to evaluate the air change rates in the classrooms, following the example of other works in the field [23,27,30,31].

Considering an occupied classroom, the air change rates are evaluated based on the concentration of the CO_2 entering the room, of the CO_2 leaving the room, and of the CO_2 generated by the people. Hence, the CO_2 mass balance equation can be written as Eq. (1):

$$V \bullet \frac{dC(t)}{dt} = G + Q \bullet C_{out} - Q \bullet C(t) \tag{1}$$

where $C(t)$ is the internal CO_2 concentration measured at time t (Kg m^{-3}); C_{out} is the external CO_2 concentration (Kg m^{-3}); G is the occupant generation of CO_2 (Kg s^{-1}); Q is the internal-external airflow rate (m^3 h^{-1}) and V is the volume of the classroom (m^3).

The mass balance equation of CO_2 is a differential equation that can be solved by integrating it over a time interval $\Delta t = t - t_0$ resulting in Eq. (2):

$$C(t) = C_{out} + \frac{G}{\lambda \bullet V} + \left(C_0 - C_{out} - \frac{G}{\lambda \bullet V}\right) \bullet e^{-\lambda \bullet \Delta t} \tag{2}$$

Table 2
Characteristics of the measurement equipment.

Sensor ID	Installation	Variables	Limit measurement range	Accuracy	Number
WSD00TH2CO	Indoor	CO_2 (PPM)	0 ÷ 5000 PPM	±50 PPM	4
		Temperature (°C)	−10 ÷ +60 °C	±0.2 °C	
WSD12-THEE	Outdoor	Temperature (°C)	−40 ÷ +80 °C	±0.1 °C	2

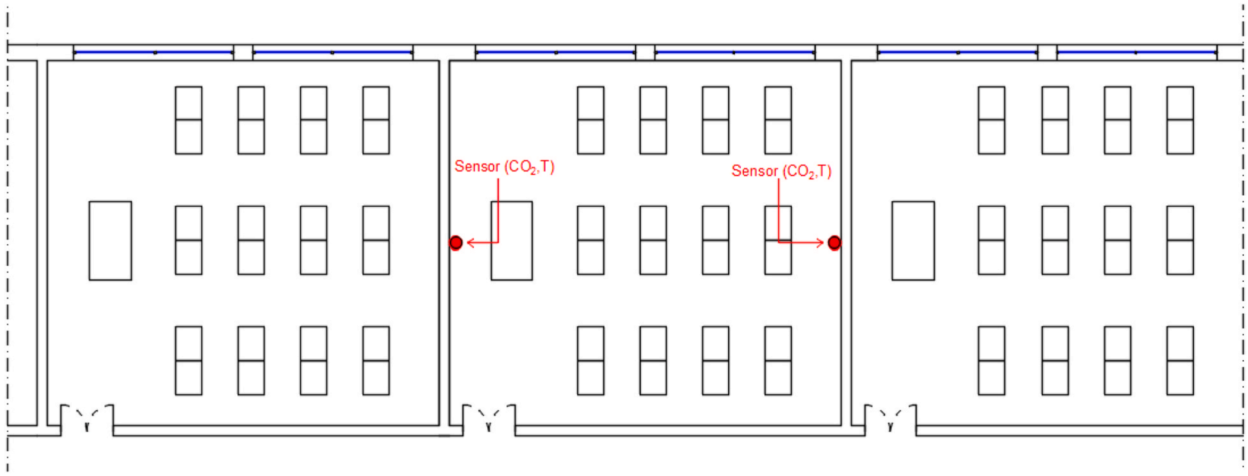

Fig. 2. Installation scheme of the indoor dataloggers.

Fig. 3. Indoor placement of the internal dataloggers: on the wall opposite the blackboard (a), on the blackboard wall (b) (pictures referred to classroom B4A).

Table 3
Detailed description of window operation modes and useful opening areas in the classrooms.

Classroom	Window typology	Number of windows	Window useful opening area [m^2]	Full opening [m^2]	Partial opening [m^2]
A1C	Type A	2	3.25	1.62	0.50
A4B	Type A	2	3.25	1.62	0.50
B4A	Type B	2	2.00	2.00	0.54
B5C	Type B	2	2.00	2.00	0.54
C3B	Type C	5	2.30	2.30	0.70
C3D	Type D	5	2.13	2.13	0.65

Fig. 4. Shape and typology of the windows found in classroom A1C. Type A: tilt-and-turn windows with two casements.

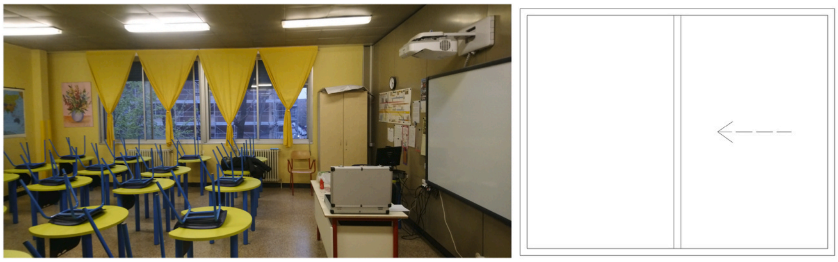

Fig. 5. Shape and typology of the windows found in classrooms B4A and B5C. Type B: Sliding windows.

Fig. 6. Shape and typology of the windows found in classroom C3D. Type C: Tilt-and-turn windows with one casement.

Fig. 7. Shape and typology of the windows found in classroom 3CB. Type D: Vertical pivot windows.

where λ is the air change rate (h^{-1}), given by the ratio between the internal-external airflow rate Q and the volume of the classroom V; C_0 is the internal CO_2 concentration measured at time t_0 (Kg m^{-3}); Δt is the time interval between the measure of $C(t)$ and C_0.

For the derivation of Eq. (2) G, Q, and C_{out} were considered constant during the time interval Δt.

To evaluate air change rates in the present study, Eq. (2) was solved iteratively with a numerical method written in Python [37], considering 10-min average values of the indoor CO_2 concentrations recorded onsite ($\Delta t = 10$ min) and calculating the generation rate G on the basis of the presences recorded.

For non-occupied periods $G = 0$, because there is no internal generation of CO_2, and therefore Eq. (2) can be rewritten as Eq. (3), directly giving the air change rates in the interval Δt:

$$\lambda = \frac{3600}{\Delta t} \bullet \ln\left(\frac{C(t) - C_{out}}{C_0 - C_{out}}\right) \tag{3}$$

2.3.1. Input parameters

$\boldsymbol{C(t)}$, $\boldsymbol{C_0}$, $\boldsymbol{C_{out}}$, and $\boldsymbol{G}$.

To estimate $\boldsymbol{C(t)}$, $\boldsymbol{C_0}$, and $\boldsymbol{C_{out}}$ parameters, the data on the CO_2 concentrations need to be expressed in Kg m^{-3}. Since the monitoring equipment recorded CO_2 concentrations in part per million (PPM), Eq. (4) has been used to convert the data into the proper measure [27,38]:

Table 4
Window opening ratio over the classroom volume (Aw/Vc) for each window opening configuration declared by the teachers.

Classroom	Window typology	Full opening windows	Partial opening windows	Aw/Vc [m^{-1}]
A1C	Type A	–	1	0.004
	Tilt-and-turn windows with two casements	1	1	0.015
A4B		–	2	0.007
		2	–	0.022
B4A	Type B	–	2	0.007
	Sliding windows	1	1	0.017
B5C		–	2	0.080
		1	1	0.018
C3B	Type C	–	1	0.004
	Tilt-and-turn windows with one casement	–	3	0.013
		–	4	0.018
		1	2	0.023
		2	2	0.038
		2	3	0.042
		4	1	0.062
C3D	Type D	–	1	0.004
	Vertical pivot windows	–	2	0.008
		–	3	0.012
		–	4	0.016
		1	3	0.025
		2	2	0.034
		3	1	0.043

$$\rho(CO_2) = \frac{10^{-6} \bullet (CO_2) \bullet 12.187 \bullet M_{CO_2}}{273.15 + T(CO_2)} \tag{4}$$

where $\rho(CO_2)$ is the density of the CO_2 level measured (Kg m^{-3}); CO_2 is the CO_2 concentration level (ppm); M_{CO_2} is the CO_2 molecular mass (Kg); and $T(CO_2)$ is the temperature of the CO_2 concentration (°C).

The calculation of the CO_2 generation rate G, was done based on the children's age, the body surface area, and the metabolic rate, using the formulas reported in the ASHRAE Handbook of Fundamentals [39], where the production of CO_2 is related to the volume of the consumed oxygen (O_2) as shown in Eq. (5):

$$V_{O_2} = \frac{0.00276 \bullet A_b \bullet M}{0.23 \bullet RQ + 0.77} \tag{5}$$

where V_{O_2} is the consumption rate of O_2 (l s^{-1}); A_b is the surface area of the human body (m^2); M is the metabolic rate (Met); RQ is the respiratory quotient, i.e., the ratio between the produced volume of CO_2 and the consumed volume of O_2, set as 0.83 [15]. Once V_{O_2} is calculated, the CO_2 generation rate G is evaluated with Eq. (6):

$$G = 1.98 \bullet RQ \bullet V_{O_2} \tag{6}$$

where 1.98 is the density of CO_2 (kg/m^3) at a temperature of 290 K.

The surface area of the human body, A_b, was evaluated with the formula proposed by DuBois [40] which relies upon the age of the subject as can be seen in Eq. (7):

$$A_b = 0.202 \bullet {W_b}^{0.425} \bullet {H_b}^{0.725} \tag{7}$$

where W_b is the body weight (Kgf), and H_b is the body height (m).

Children's height and weight were derived from the anthropometric data about European population in a school age reported in Ref. [41] using average values. The metabolic rate depends on the physical activity carried out by the subject. For children carrying out classroom activity (e.g., sitting quietly, studying, taking notes, and writing) a value of 1.4 Met can be used [42], while for adults that

Table 5
CO_2 generation rates, G, calculated based on the age of the occupants and their metabolic rate.

Classroom	Age range	Metabolic rate [Met]	G per subject [cm^3 s^{-1}]
A1C	6–7	1.4	2.66
A4B	9–10	1.4	3.38
B4A	9–10	1.4	3.38
B5C	10–11	1.4	3.71
C3B	13–14	1.4	4.69
C3D	13–14	1.4	4.69
Teacher	/	1.7	7.82

develop a combination of sitting, standing, and walking activities, it is suggested to use a value of 1.7 Met [43].

The CO_2 generation rates G per subject, calculated with Eq. (6), range from 2.66 to 4.69 $cm^3\ s^{-1}$ for children and 7.82 $cm^3\ s^{-1}$ for the teacher (as reported in Table 5). These values are in line with those obtained in other similar studies: 3.34 to 5.89 $cm^3\ s^{-1}$ in Ref. [26]; 2.95 $cm^3\ s^{-1}$ (for children aged 6 to 7), 3.75 $cm^3\ s^{-1}$ (for children aged 9 to 10), 3.91 $cm^3\ s^{-1}$ (for children aged 10–11), 5.05 $cm^3\ s^{-1}$ (for children aged 13 to 14), and 7.85 $cm^3\ s^{-1}$ (for adults) [36]. Hence, the values reported in Table 5 were multiplied by the number of people registered in the different time intervals Δt and then inserted in Eq. (2) to solve the mass balance equation of CO_2.

In Italy, the first regulation on air quality in school buildings dates back to 1975 [44], reporting different ACHs depending on the order of the school. Alternatively, the recent European Standard EN 16798 [16] bases the required air renewal on the number of people per classroom surface area, while the WHO [17] relies on the number of people. Hence, to compare the air change rates obtained in the case studies with the ones stated by the three documents 2.3, a compilation of the calculated limit values in resulting ACH rates (h^{-1}) for each analyzed classroom is presented in Table 6.

2.4. Model for the estimation of the infection risk

The Wells-Riley equation [45] is a commonly used method to quickly assess the airborne infection risk in indoor environments assuming a steady-state and well-mixed airborne pathogen concentration [46]. This model is based on the concept of the "number of quanta", which is a hypothetical infectious dose that can infect susceptible people (as detailed in the next section 2.4.1). It considers that the infectious particles in the air follow the Poisson distribution, so the risk of infection P (probability of being infected) is given by Eq. (8):

$$P = \frac{C}{S} = 1 - e^{-\left(\frac{I \bullet q \bullet p \bullet t}{\lambda \bullet V}\right)} \tag{8}$$

where C is the number of cases that develop the infection; S is the number of susceptible people; I is the number of infectors; q is the quanta emission rate of one infector (quanta h^{-1}); p is the pulmonary ventilation rate ($m^3\ h^{-1}$); t is the time of exposure (h); λ is the air change rate (h^{-1}); and V is the room volume (m^3).

2.4.1. Quanta emission rate

The quanta emission rate of an infector is a critical parameter to evaluate in the Wells-Riley equation.

This study adopts the approach proposed by the authors of [47] which bases the estimation of the quanta emission rate on the viral load in the expiratory particles. The viral load model assumes that the droplets emitted by the infector have the same viral load in the sputum. Therefore, knowing the concentration of the virus in the sputum and the quantity of droplets emitted (which are different for each expiratory activity), the quantum emission rate q could be evaluated through a mass balance equation as shown in Eq. (9) [48]:

$$q_j = C_v \bullet C_i \bullet p \bullet \sum_{i=1}^{4} \left(N_{i,j} \bullet V_i\right) \tag{9}$$

where C_v is the viral load in the sputum (RNA copies mL^{-1}); C_i is the conversion factor defined as the ratio between one infectious quantum and the infectious dose expressed in viral RNA copies (quanta per RNA copies) (i.e., it represents the probability of a pathogen surviving inside the host to initiate the infection; thus $C_i = 1$ implicitly assumes that infection will occur for each pathogen received by the exposed people); N_i is the droplet concentration with the i-th droplet diameter (part. cm^{-3}); V_i is the volume of the i-th droplet diameter. Since different expiratory activities lead to different droplet size distributions, j indicates the expiratory activity carried out by the infected person.

The viral load in the sputum C_v for SARS-CoV-2 patients, was measured from past studies reporting values between 10^3-10^{11} RNA copies mL^{-1} for both symptomatic and asymptomatic people [49]. Furthermore, during the course of the disease this value changes in the same patient [50], and typically reaches values between 10^8 and 10^9 RNA copies mL^{-1} [51–53].

2.4.2. Simulated scenarios

The present study assesses the individual infection risk of susceptible subject exposed in classroom environments in the presence of an asymptomatic SARS-CoV-2 infected subject. To that aim, the probability of infection P was calculated through Eq. (8), considering the presence of one infector ($I = 1$). Two main scenarios were evaluated: i) scenario 1, with an infected student in a resting condition; and ii) scenario 2, with an infected teacher in a standing condition. In the first case, the considered exposure time t, entails the entire

Table 6
Minimum air change rates in resulting ACH rates (h^{-1}) set by the different regulative documents for the analyzed classrooms.

	Analyzed classrooms					
Regulation	A1C	A4B	B4A	B5C	C3B	C3D
DM 1975 [44]	2.5	2.5	2.5	2.5	3.5	3.5
EN 16798 [16]	4.2	4.7	4.8	5.0	4.0	4.2
WHO [17]	4.8	5.5	5.7	6.0	4.5	4.9

duration of the lessons (7 h for school A and B, since in both cases only 1 h was excluded due to the lunch time; and 5 h for school C), while in the second case, t was assumed as 2 h of lessons. In both cases, for the pulmonary ventilation rate p, values estimated in Ref. [54] were used.

In a further step, the quanta emission rate q was evaluated through Eq. (9), using an average value of the viral load in the sputum ($C_v = 1 \times 10^8$ RNA copies mL-1), and C_i equal to 0.02 quanta RNA copies^{-1} (corresponding to the average value of the infectious doses reported for SARS-CoV-2 in Ref. [55]).

Since different expiratory activities, i.e., oral breathing and speaking, lead to different droplet size distributions [48], to consider realistic scenarios an average value of q was considered taking into account both expiratory activities. Thus, in scenario 1, breathing activity was considered to last 80% of the time, with a remaining 20% for speaking activity, while, in scenario 2, both activities endured 50% of the time. Table 7 reports a detailed explanation of the considered scenarios.

To set a limit value for the probability of infection P, an acceptable individual infection risk was estimated. According to Ref. [56], to keep the infection under control, it is essential to set a limit value for the basic reproduction number R_0 which, in presence of only one infectious individual ($I = 1$), is defined as Eq. (10):

$$R_0 = P \bullet S \tag{10}$$

Since the same authors have set a limit value of $R_0 < 1$ for SARS-CoV-2, the acceptable individual infection risk could be estimated based on the maximum number of people expected in the classroom [57]. Thus, Eq. (11) has been used to set a limited probability of infection P_{limit} (hereafter referred to as individual infection risk) for each classroom, as reported in Table 8:

$$P_{limit} = \frac{1}{max.\ occupation\ in\ classroom} \tag{11}$$

3. Results and discussion

The results of this study are structured in the following three sections: Section 3.1 shows the results of the monitored parameters crossed with the occupation of the classrooms and the operation of the windows; Section 3.2 presents a statistical comparison between the air change rates obtained by the proposed model and the windows opening configurations; and Section 3.3 displays the infection risk evaluation in the analyzed classrooms based on the air change rates obtained through the different windows opening configurations.

3.1. Effect of windows operation on the indoor parameters of the analyzed classrooms

Fig. 8 reports a typical week of measurement in one of the monitored classrooms, as an example, where the indoor parameters recorded by dataloggers 1 and 2 are plotted. It can be observed that values have followed very similar trends. In particular, the CO_2 concentration during the unoccupied period of the weekend reveals almost the same value. Since this period is not affected by indoor CO_2 generation, the recorded values, slightly higher than 400 PPM, support the outdoor standard value assumption as a first approximation for this study.

More in detail, Fig. 9 (A, B) reports the absolute differences between the data recorded by the two data sensors in each classroom. The average CO_2 concentration differences set at 36 PPM, 69 PPM, 68 PPM, 148 PPM, 32 PPM, and 54 PPM for classrooms A1C, A4B, B4A, B5C, C3B, and C3D, respectively. For what concerns the indoor air temperature, the average differences stay in 0.34 °C, 1.93 °C, 0.86 °C, 0.20 °C, 0.41 °C, and 0.91 °C by the same order for each of the analyzed classrooms.

Considering that the accuracy of the sensors stays between ±50 PPM and ±0.2 °C, no significant spatial variations of the parameters were detected. Hence, within the limits of having only two detection points, it is assumed that the condition of well-mixed air stated by the Wells-Riley equation is fulfilled.

3.1.1. CO_2 concentration and indoor air temperature

Figs. 10, 11, and 12 plot together the sub-hourly variation of CO_2 concentrations and indoor air temperature for the different window opening ratios Aw/Vc obtained in each classroom during the occupied periods (i.e., from 8:30 a.m. to 16:30 p.m. in schools A and B, and from 8:10 a.m. to 13:10 p.m. in school C). The periods where the classrooms were empty (e.g., due to moving the children to the dining hall, the garden, or the gym) have been marked in the charts as "no occupation". The standard regulation for IAQ [16] states that for cases in which no data on outdoor CO_2 concentrations is available, the quality of indoor air can be considered acceptable whenever indoor CO_2 concentrations set under a difference of 800 PPM with respect to an assumed outdoor value of 400 PPM.

Table 7
Detailed description of the simulated scenarios.

	Scenario 1 (Infected student)	Scenario 2 (Infected teacher)
Activity	Resting (20% speaking, 80% breathing)	Standing (50% speaking, 50% breathing)
Pulmonary ventilation rate	0.41 [m^3/h]	0.60 [m^3/h]
Exposure time	5-7 [h^{-1}]	2 [h^{-1}]
Quanta emission rate	8.12 [quanta h^{-1}]	25.40 [quanta h^{-1}]

Table 8
Individual infection risk limit P_{limit} obtained in each analyzed classroom.

Classroom	Maximum occupation	P_{limit} [%]
A1C	21	4.7
A4B	23	4.3
B4A	24	4.2
B5C	24	4.2
C3B	20	5.0
C3D	22	4.5

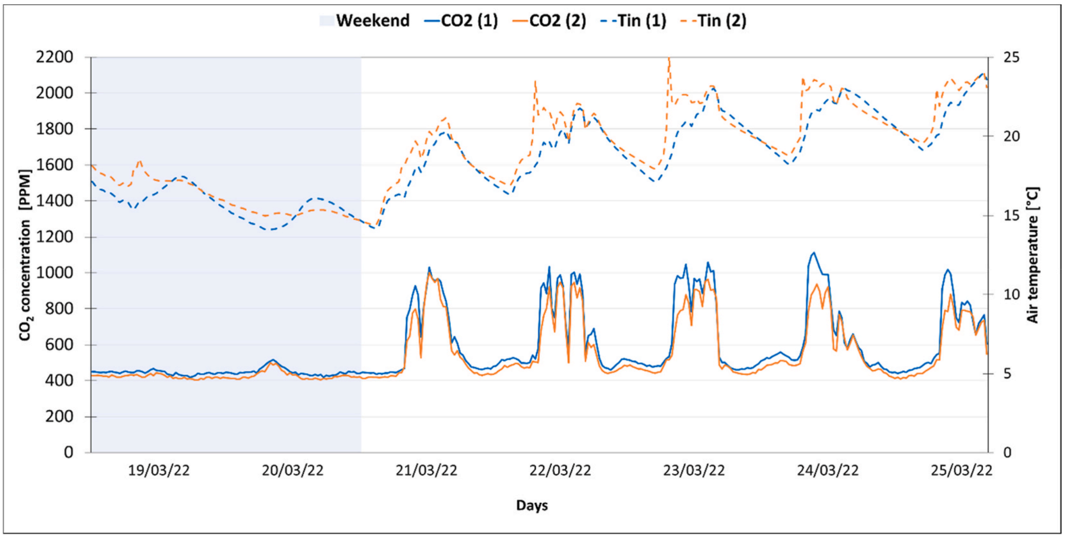

Fig. 8. Example of CO_2 concentration and indoor air temperature measurements in two points of a classroom (B4A).

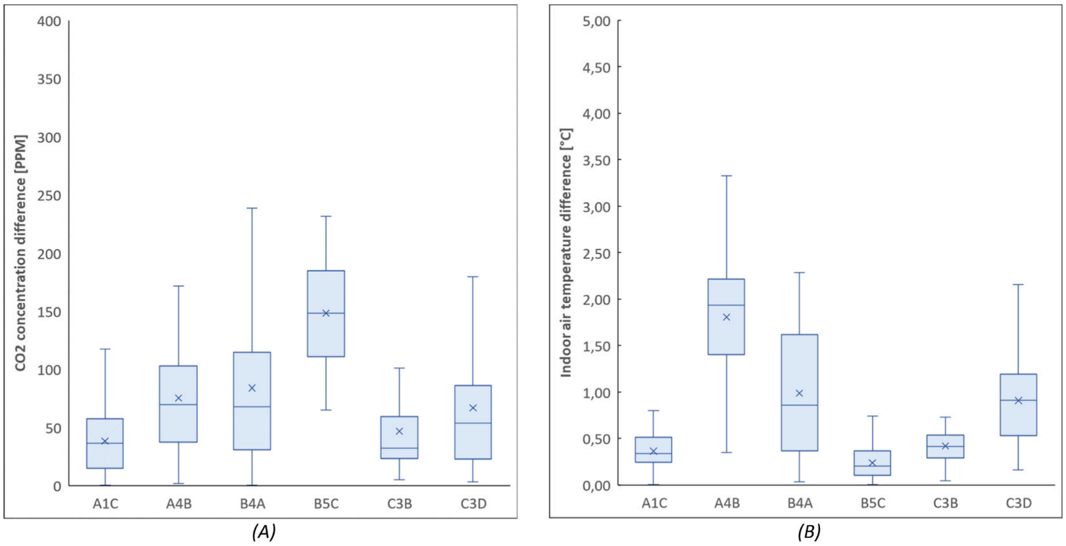

Fig. 9. Absolute differences on CO_2 concentration (A) and indoor air temperature (B) between the dataloggers in each classroom.

Accordingly, a CO_2 concentration limit of 1200 PPM was set in the charts as a reference for IAQ assessment. It must be noted that the small CO_2 oscillations reported in the charts are likely due to short openings of the windows or temporary leaving of the classroom by some pupils that were omitted by the teachers in the compilation of the declaration tables.

For what regards the observations on indoor air temperatures, the static range between 20 and 24 °C reported in the EN 16798–1:2019 for category II [16] has been assumed as a reference for thermal comfort.

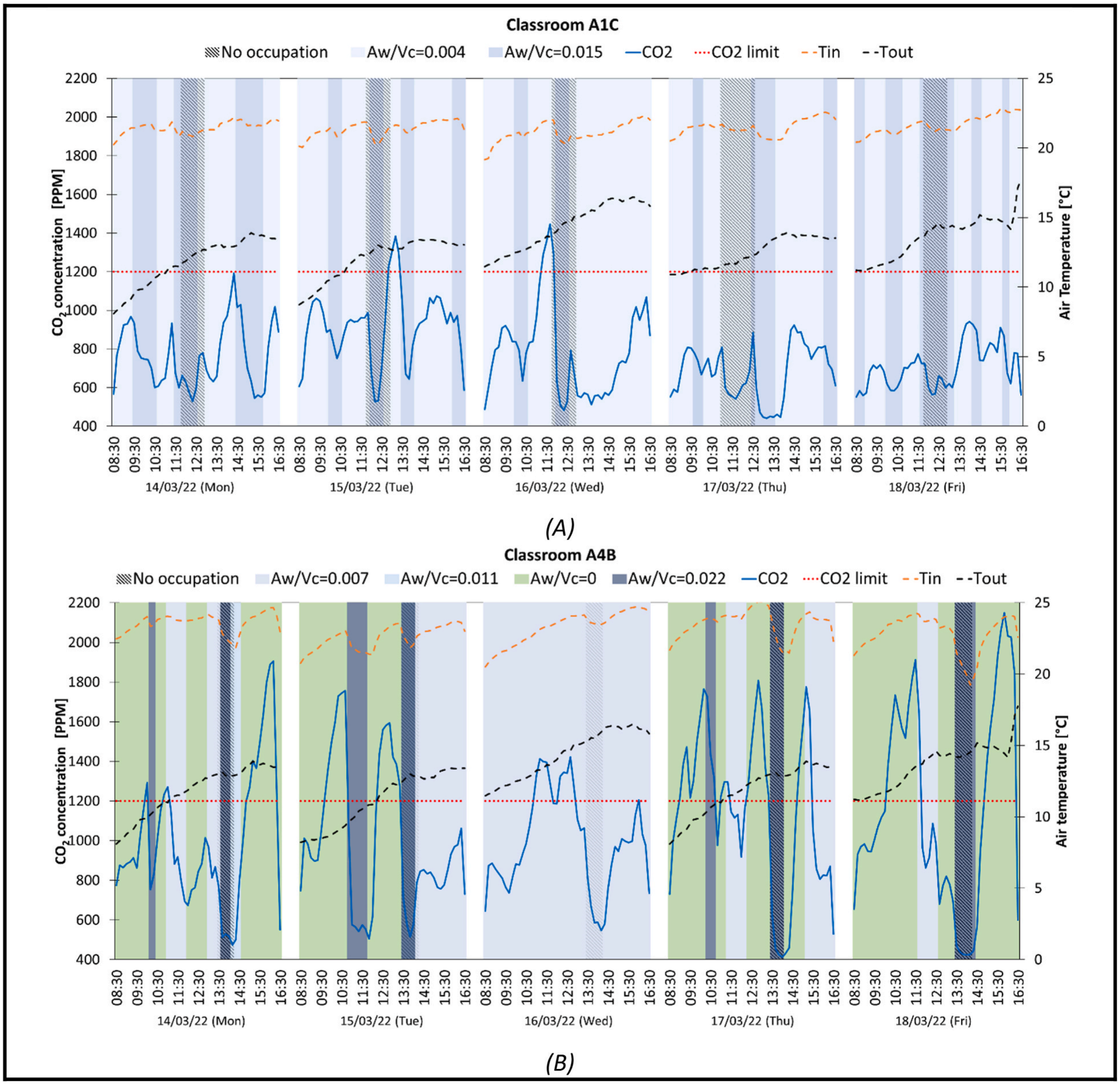

Fig. 10. Trend of indoor CO_2 concentration (CO2), indoor air temperature (Tin), outdoor air temperature (Tout), and window opening ratios (Aw/Vc) during the occupied period in School A classrooms A1C (A) and A4B (B).

3.1.1.1. School A. From Fig. 10 it can be observed that, during the monitored period to which School A was submitted, outdoor air temperatures ranged between 8 °C and 17 °C throughout the occupied period of the building. In this school, students left the classrooms to go to the dining hall during the lunch break, hence classroom A1C was empty from 11:30 p.m. to 12:30 p.m. and classroom A4B from 13:30 p.m. to 14:30 PM.

In classroom A1C, one of the windows was left partially open (top-hung inward opening) during the lessons, while the other window was intermittently fully opened (side-hung inward opening) reaching seldom window opening ratios of 0.004 m^{-1} and 0.015 m^{-1}, respectively. The classroom door was declared to be opened most the time. Indoor CO_2 concentrations exceeded the limit set by the standard [16] only on two days of the week for a total of 3.43% of the lesson hours. The recorded internal air temperature remained around 21 °C, setting within the established thermal comfort range [16]. On the other hand, in classroom A4B, the window operation did not follow a continuous and homogeneous pattern, remaining completely closed 48% of the time. In addition, the door was declared as kept closed most of the time. CO_2 concentrations set over 1200 PPM around 33% of the time, with a maximum peak of 2150 PPM. The indoor air temperature was always within the range of thermal comfort, with an average value of 23 °C.

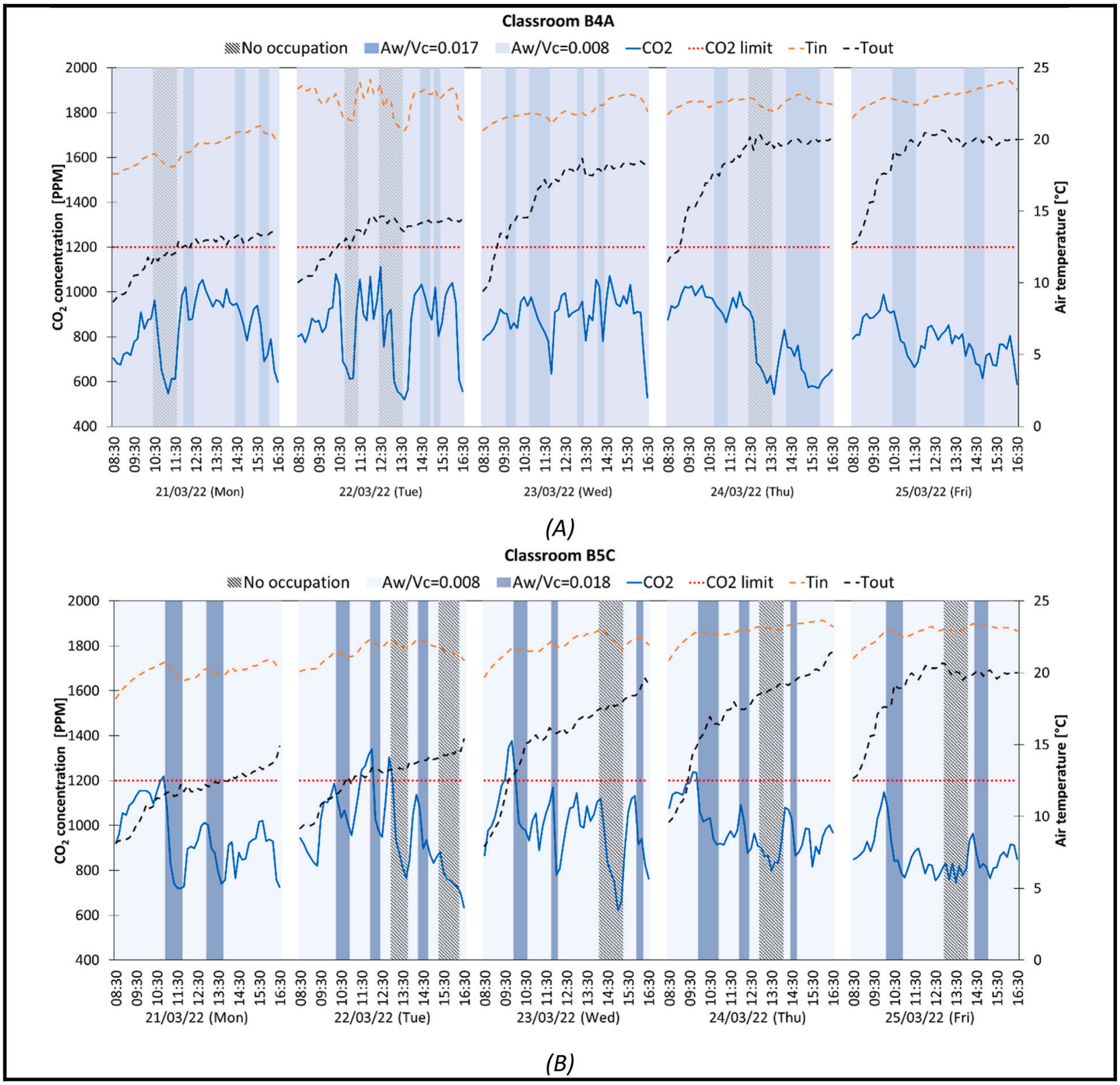

Fig. 11. Trend of indoor CO_2 concentration (CO2), indoor air temperature (Tin), outdoor air temperature (Tout), and window opening ratios (Aw/Vc) during the occupied period in School B classrooms B4A (A) and B5C (B).

3.1.1.2. School B. The monitoring of School B took place under outdoor air temperature oscillations between 8 °C and 21 °C. The window opening configurations foresaw a constant partial opening of the two windows, alternating with the full opening of one of the windows, reaching Aw/Vc values of 0.007 m^{-1} and 0.017 m^{-1} in classroom B4A and values of 0.008 m^{-1} and 0.018 m^{-1} in classroom B5C. The doors were declared as open most of the time. Furthermore, the classrooms were already equipped with CO_2 sensors that warned the necessity of air exchange via a red light whenever the internal CO_2 concentration settled between 800 and 1000 PPM. In this case, the lunch break, lasting from 12:30 p.m. to 14:30 p.m., was made in the classroom because no dinning hall was present in the building. The classrooms remained empty for the hours in which students had music and gymnastics lessons, or due to breaks in which they went out to the school garden.

CO_2 concentrations in classroom B4A never reached the stated limit of 1200 PPM. Actually, the peaks of CO_2 concentrations only reach values slightly above 1000 PPM, as can be seen from Fig. 11. This is thanks to the correct use of the CO_2 sensors that were already available in the classrooms, where upon reports of excessive CO_2 concentrations, the teachers operated additional windows for a few minutes to induce air renovation. During the reported days, average daily indoor air temperatures fell within 21–23 °C. In classroom B5C, an average CO_2 concentration of 954 PPM was observed, punctually exceeding the limit in three days for only 5.31% of the lesson

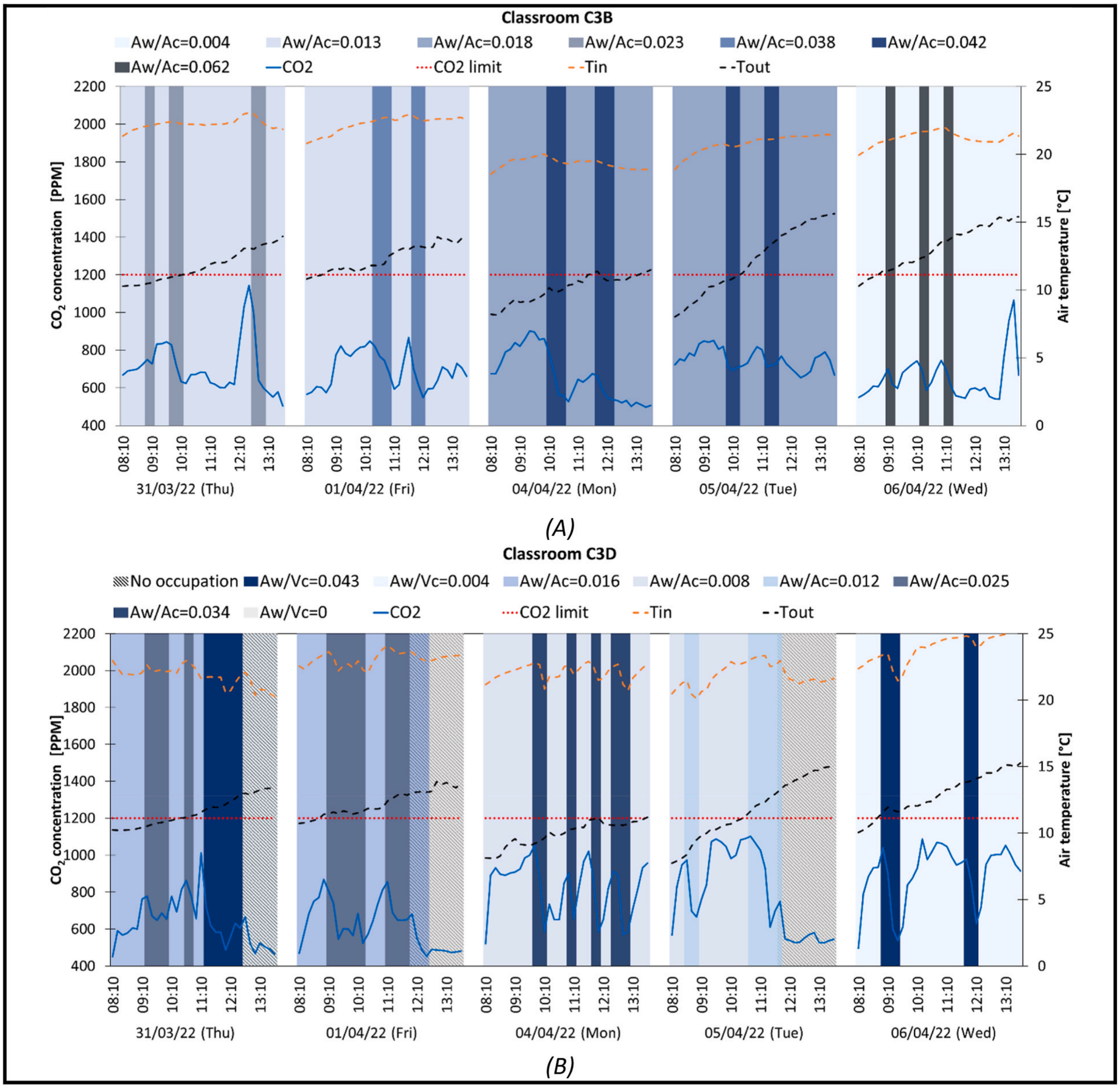

Fig. 12. Trend of indoor CO_2 concentration (CO2), indoor air temperature (Tin), outdoor air temperature (Tout), and window opening ratios (Aw/Vc) during the occupied period in School C classrooms C3B (A) and C3D (B).

hours. The presence of the CO_2 sensor alerting of excessive levels of CO_2 can be observed too, resulting in a timely opening of the windows. Daily average values of indoor air temperature stayed between 20 and 23 °C. Fig. 11 shows the recorded data related to school B.

3.1.1.3. School C. School C was monitored under outdoor air temperature variations from 8 °C to 15 °C. As in the other two schools, some windows remained partially open during the lessons while others were intermittently fully opened. Students had two breaks of 10 min after the second and the fourth hour that was spent in the classroom to avoid crowding the corridors.

Both classrooms C3B and C3D present similar indoor conditions as shown in Fig. 12. The CO_2 concentration limit was never reached, with average CO_2 concentrations of 694 PPM and 753 PPM recorded in classroom C3B and C3D, respectively. For what concerns the indoor air temperature, thermal comfort was ensured most of the time with average values between 21 and 22 °C.

In general, it can be observed that all the strategies have guaranteed CO_2 concentration below the limit established in the Standard, with infrequent peaks slightly higher than 1200 PPM, in the three case studies. The worst situation was found in classroom A4B, where several peaks of CO_2 concentration up to 2150 PPM were spotted. Indeed, that classroom reported the lowest weekly average window opening ratio, with several hours in which windows remained closed and with the door closed most of the time. Notwithstanding this, the weekly average CO_2 concentration in this classroom (1062 PPM) stayed under the limit, and only 30% of the lesson hours were characterized by values beyond the limit. Table 9. Week specific values for each classroom. Table 9 shows a summary of the measurements.

Similar results were obtained in Refs. [20,22–24,58], where monitoring was carried out in schools during the context of COVID-19 pandemics. As in this study, the consequence of having adopted international guidelines to over-ventilate school buildings has led to record indoor CO_2 concentrations well below the limit established by the Standard, with daily average values ranging between 600 and 1100 PPM.

From the charts in Figs. 10, 11, and 12 it can be said that the effect of the COVID-19 pandemics, which brought about greater awareness in indoor air quality, had a positive effect in terms of indoor CO_2 concentrations (that were found to be lower than expected) due to the increase of the windows opening during the end of the heating period in Milan, without affecting the average indoor thermal comfort, excluding the possible local discomfort of the pupils placed near the windows. Despite the recording of weekly average values of CO_2 concentrations ranging between 694 and 1062 PPM, indoor air temperatures stayed within 21–23 °C while average outdoor temperatures fluctuated from 12 °C to 15 °C. Differently, in Refs. [22,24], up to 80% of the lesson hours were found to be in thermal discomfort, with average indoor air temperature values of 18 °C due to low outdoor air temperatures (weekly average values between 5 and 7 °C). Likewise, in Ref. [58], though at a lower extent, 18-11% of lesson hours were found to be in thermal discomfort, with weekly outdoor air temperatures in the range of 9–12 °C.

Certainly, the thermal and energy aspects of naturally ventilated heated schools remain to be properly investigated. For instance, a study carried out in 9 schools in Pamplona (Spain) during January 2021 found a 31% of increase in heating energy consumption compared to the same month before the outbreak of the pandemics. This was due to an increase in the use of heating to obtain adequate indoor temperatures beside the natural over-ventilation of the classrooms [24].

3.2. Air change rates

Air change rates are assessed through Eq. (2) for occupied periods and Eq. (3) for non-occupied periods during the lesson hours. In the following, daily values of ventilation rates are evaluated. Table 10 reports a comparison between the daily air change rates obtained in the classrooms and the corresponding air change rates prescribed in the technical regulations (see Section 2.3.2, Table 6).

As can be seen from Table 10, the air change rates set in the Italian regulation [44] are always satisfied, with values up to three times higher than those required. On the contrary, the values prescribed by the Standard EN 16798-1 [16] and by the WHO [17] in case of pandemics, are not always fulfilled.

Classroom A4B, with daily average window opening ratio between 0.004 and 0.008 m^{-1}, results in daily air change rates under 4 ACH, staying below the values recommended by the Standard [16]. In fact, since the windows remained closed during part of the lessons together with having the door closed most of the time, cross-ventilation was not allowed. However, in classrooms where doors have been left open most of the time, and with slightly higher window opening ratios (between 0.007 and 0.010 m^{-1}), air change rates ranged between 4 and 6 ACH. Despite this, the observed window opening ratios are not always sufficient to guarantee the air change rates of the Standards. Actually, in classrooms B4A and B5C that count with 24 students, the Standard values are not respected for most of the week, while classroom A1C with 19 students almost always fulfills the Standard [16]. With even higher window opening ratios (from 0.016 m^{-1} to 0.026 m^{-1}), air change rates up to 12 h^{-1} are reached, also achieving 10 l/s pp recommended by the WHO in case of pandemic [17].

It has to be noted that the obtained ACH rates are conservative, compared to typical winter conditions, because they are derived from a survey carried out at the end of the heating season, where an average indoor-outdoor temperature difference of about 9 °C was found. In fact, with the same opening ratio, an increase in temperature difference leads to an increase in the incoming air flow rate. On the other hand, larger temperature differences negatively affect indoor thermal comfort leading to an overuse of the heating system.

More in general, it should be mentioned that neither the uncertainty about the level of accuracy of the information provided by the teachers nor the possible effect of the air entering from interzones, i.e., at the corridors conditions, are accounted for by the obtained results as these two aspects cannot be detailed through the assumed model (TMBE).

3.2.1. Air change rates with different window opening ratios

Comparing the frequency distribution of the air change rates obtained for each window opening configuration in the classrooms, a statistical correlation with the window opening ratio (Aw/Vc) was found. The linear regression was defined with the average air change rates obtained by the window opening ratio registered in the classrooms (Fig. 13). In addition, the values within the 2nd and the 3rd quartile of the respective frequency distribution were also plotted. The results confirm that the more the increase in window opening ratio, the more the air change rates increase, as also found in Ref. [27]. The observed regression presents a strong statistical correlation, accounting the previously mentioned uncertainties of the study, between the air change rates and the window opening ratio, with an R^2 of 0.88. Looking at Fig. 13, a typical classroom with a 50 m^2 surface, a 150 m^3 volume and an occupation of 25 individuals, would need an average window opening ratio of almost 0.01 m^{-1} (corresponding to 1.5 m^2 of window opening area), to respect a ventilation rate of 5 ACH required for this case in the standard EN 16798 [16].

It has to be noted that the variations of ACH rates around the average value of each window opening ratio can refer to the variation of outdoor conditions [59], in this case limited to average outside temperatures between 11 °C and 15 °C. Also, the wind speed and direction variation, despite less relevant for single-sided ventilated spaces placed in the dense urban context of Milan, can have some impact.

Table 9
Week specific values for each classroom.

	Unit	A1C	A4B	B4A	B5C	C3B	C3D
Maximum occupation	[pp]	19	23	24	24	20	22
Volume	[m^3]	142.10	150.22	150.90	142.80	159.09	160.00
CO_2 concentration (CO2)							
Maximum	[PPM]	1446.55	2149.00	1111.30	1375.70	1145.00	1101.00
Average	[PPM]	769.47	1062.07	835.21	953.70	694.00	753.00
Minimum	[PPM]	441.55	412.25	519.05	621.45	498.00	450.00
Standard deviation	[PPM]	191.50	392.08	137.74	145.30	116.11	193.16
Window opening ratio (Aw/Vc)							
Maximum	[m^{-1}]	0.015	0.022	0.010	0.010	0.062	0.043
Average	[m^{-1}]	0.009	0.006	0.010	0.010	0.017	0.017
Minimum	[m^{-1}]	0.004	0.000	0.009	0.009	0.004	0.010
Standard deviation	[m^{-1}]	0.010	0.007	0.000	0.000	0.004	0.007
Average indoor air temperature (Tin)	[°C]	21.42	23.16	21.52	21.82	21.16	22.55
Average outdoor air temperature (Tout)	[°C]	12.85	12.55	15.74	15.21	11.93	11.70
Average ΔT (Tin-Tout)	[°C]	8.39	10.43	6.31	6.24	9.42	11.36
CO2 > 1200 PPM	[%]	3.27	33.06	0.00	5.31	0.00	0.00

Table 10
Daily window opening ratios (Aw/Vc) obtained in the classrooms and related air change rates. Comparison with Standards and recommendations.

Classroom	Occupation	Volume	Day	Aw/Vc	ACH	Comparison with Standards and recommendations		
						DM 1975 [44]	EN 16798 [16]	WHO [17]
A1C	19	142.1	Monday	0.009	5.0	✓	✓	✓
			Tuesday	0.007	3.2	✓	×	×
			Wednesday	0.007	5.1	✓	✓	✓
			Thursday	0.009	5.2	✓	✓	✓
			Friday	0.010	5.4	✓	✓	✓
A4B	23	150.2	Monday	0.005	3.3	✓	×	×
			Tuesday	0.008	3.4	✓	×	×
			Wednesday	0.007	3.7	✓	×	×
			Thursday	0.006	2.8	✓	×	×
			Friday	0.004	3.1	✓	×	×
B4A	24	150.9	Monday	0.009	4.6	✓	×	×
			Tuesday	0.009	4.4	✓	×	×
			Wednesday	0.010	4.3	✓	×	×
			Thursday	0.010	5.0	✓	✓	×
			Friday	0.010	6.7	✓	✓	✓
B5C	24	142.8	Monday	0.010	4.9	✓	×	×
			Tuesday	0.010	4.4	✓	×	×
			Wednesday	0.009	4.0	✓	×	×
			Thursday	0.010	4.2	✓	×	×
			Friday	0.010	5.1	✓	✓	×
C3B	20	159.9	Thursday	0.016	9.7	✓	✓	✓
			Friday	0.019	9.5	✓	✓	✓
			Monday	0.023	12.9	✓	✓	✓
			Tuesday	0.023	7.6	✓	✓	✓
			Wednesday	0.018	12.9	✓	✓	✓
C3D	22	160.0	Thursday	0.026	10	✓	✓	✓
			Friday	0.021	10.1	✓	✓	✓
			Monday	0.019	7.2	✓	✓	✓
			Tuesday	0.010	5.4	✓	✓	✓
			Wednesday	0.011	4.3	✓	✓	×

✓ limit respected; × limit not respected.

3.3. *Individual infection risk*

This section presents the evaluation of the individual infection probability obtained in the analyzed classrooms and the impact of the different window opening configurations over the potential infection of susceptible people present in the same space.

3.3.1. *Weekly individual infection risk*

The individual infection probability was evaluated through Eq. (8), using the average weekly air change rates and the volume of each classroom. Fig. 14 presents the results of the individual infection probability *P* for each classroom in the simulated scenarios. As can be seen from the chart, Scenario 2 (i.e., with an infected teacher) provides a slightly higher risk of infection than Scenario 1 (i.e., with an infected student), even if the exposure time is smaller in the first case. This result was expected since the quanta emission rate

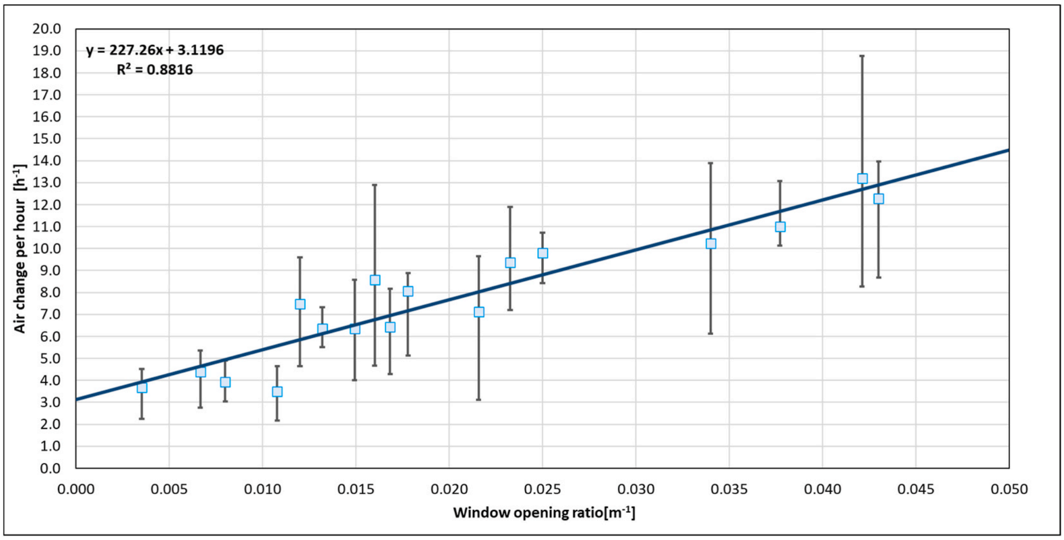

Fig. 13. Impact of window opening ratio (Aw/Vc) on air change per hour.

expired from a speaking adult subject for 50% of the time is much higher than a breathing pupil subject for 80% of the time, and it is in line with the results of other authors [60]. The risk of infection decreases progressively as the air change rates increase, passing from a value of 5.98% with 3.27 ACH to a value of 1.79% with 10.50 ACH.

Table 11 reports a comparison of the obtained individual infection probability in the classrooms with the recommended limit P_{limit}. It can be observed that obtained the weekly air change rates are not always enough to set the contagion under control. A value of 3.27 ACH is not sufficient in any of the two scenarios considered, while a value of 4.52 ACH is enough in Scenario 1. From this analysis it can be concluded that at least 5 ACH should be guaranteed in the classroom to keep the risk of contagion under control.

3.3.2. Infection risk related to the window opening ratio

The equation of linear regression that relates the air change rates and the window opening ratio reported in Fig. 15 is used to define a correlation between them and the individual infection probability P. To that aim, the following system of equations shown in Eq. (12) was used, and the results can be observed in Fig. 15.

$$\begin{cases} \lambda = 227.26\dfrac{A_w}{V_c} + 3.11 \\ P = 1 - e^{-\left(\frac{I \bullet q \bullet p \bullet t}{\lambda \bullet V}\right)} \end{cases} \tag{12}$$

Since the individual infection risk also depends on the volume of the room (V), a range of classroom volumes were considered starting from a minimum of 120 m^3 (considering a small class of 40 m^2 and a height of 3 m) up to a maximum of 270 m^3 (considering a large class of 60 m^2 and a height of 4.5 m). Again, the two scenarios previously considered are hereafter assessed too, with a single difference in Scenario 1 (i.e., with an infected student), where 5 h of consecutive exposure were considered, assuming a continuous

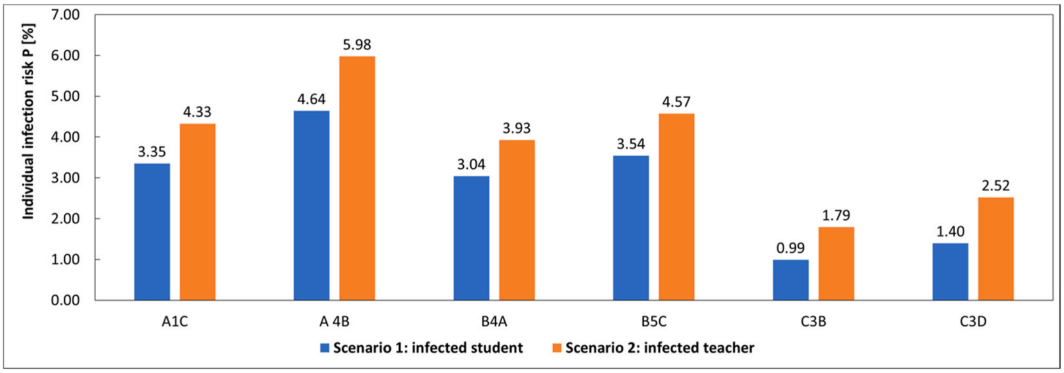

Fig. 14. Comparison of individual infection probability (%) of Sars-CoV-2 for Scenario 1 (i.e., with an infected student) and Scenario 2 (i.e., with an infected teacher).

Table 11
Comparison between the individual infection risk (%) and the recommended individual infection risk limit (%).

Classroom	Number of susceptible individuals	Aw/Vc [m^{-1}]	ACH [h^{-1}]	*P* Scenario 1 [%]	*P* Scenario 2 [%]	P_{limit} [%]
A1C	20	0.008	4.8	3.35	4.33	5.00
A4B	22	0.006	3.3	4.64	5.98	4.55
B4A	23	0.010	5.2	3.04	3.93	4.35
B5C	23	0.010	4.5	3.54	4.57	4.35
C3B	19	0.020	10.5	0.99	1.79	5.26
C3D	21	0.017	7.4	1.40	2.52	4.76

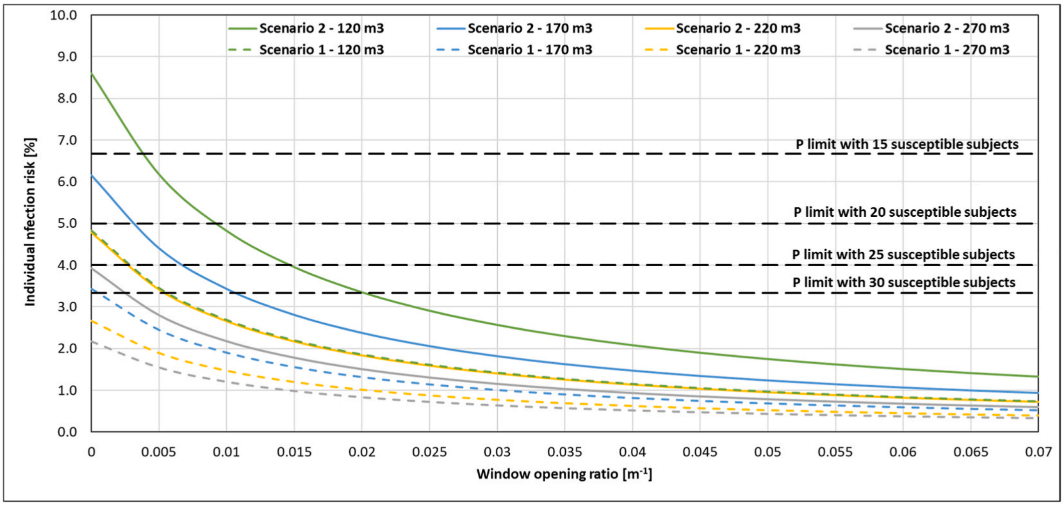

Fig. 15. Individual infection probability (%) as a function of the window opening ratio (Aw/Vc) and different classroom dimensions. Dashed lines represent Scenario 1 (i.e., with an infected student), while continuous lines represent Scenario 2 (i.e., with an infected teacher).

school day. In addition, different limit values for individual infection risk have been marked in the chart, based on regular numbers of people that may be present in a classroom, to wit 30, 25, 20, and 15 individuals.

As expected, the higher the window opening ratios, the higher the air change rates, and the lower the individual infection probability. Furthermore, in accordance with the Wells-Riley equation, the higher the volume of the classroom, the lower the concentration of the virus, resulting in a lower individual infection probability. In fact, after a certain amount of supplied fresh air, it is possible to achieve a small reduction in the individual infection risk, which is in line to what reported in a recent study [54]. This can be seen in Fig. 15, where after a certain value, the individual infection risk series becomes a horizontal asymptote as the window opening ratio increases. The recommended individual infection risk limits (marked with black dashed lines) confirm that the greater the number of susceptible people, the greater the window opening ratio should be to guarantee a risk infection under the recommended limit.

In line with the results obtained in Section 3.3.1, Scenario 2 (i.e., with an infected teacher) brings to higher individual infection probability than Scenario 1 (i.e., with an infected student) where, for classrooms bigger than 170 m^3, the recommended individual infection risk limits are not overcome. In fact, Scenario 2 always surpasses the recommended individual infection risk limits. For instance, considering a classroom with 25 individuals, window opening ratios of 0.015 m^{-1}, 0.007 m^{-1}, 0.003 m^{-1}, are required for a volume of 120 m^3, 170 m^3, and 220 m^3, respectively (these window opening ratios correspond to 1.8 m^2, 1.2 $m^{2,}$ and 0.6 m^2 of window opened area, respectively). If the number of individuals is reduced, these values decrease as well. In line with the results of previous sections, the airborne transmission probability of an infected student is lesser than that of an infected teacher, even if the time of exposure is more than two times higher. Thus, the chart in Fig. 15 could serve school staff to know when and how much they need to open the windows based on the classroom volume and the number of students present to avoid the risk of contagion.

4. Conclusions

The paper presents a protocol for evaluating the impact of natural ventilation strategies in school environments over the IAQ of the classrooms and the risk of contagion among the teacher and the pupils. It presents the analysis of results obtained from a short-term monitoring carried out at the end of the heating season in three naturally ventilated school buildings in a northern Italian urban context, under the measures of over-ventilation of indoor spaces due to the COVID-19 pandemic. CO_2 concentrations, besides indoor and outdoor air temperatures, were recorded and used to estimate real air change rates in the analyzed classrooms, correlated to different window operation strategies declared by the occupants. The study delves on the impact of these ventilation rates on the IAQ and reports an innovative method to assess infection risk based on the window opening ratio.

Accepting the assumptions and uncertainties detailed in the description of the study, and being aware that only 6 case studies have been assessed, the following outcomes can be highlighted:

- Despite the limitations of the Wells-Riley equation, which rely on the well-mixed hypothesis for the spread of the virus, the very similar trends of the recorded data from two opposite walls of the considered spaces guarantee the use of the model as a useful tool to quickly assess infection risk scenarios in classrooms.
- The collected data on indoor parameters suggest that CO_2 concentrations remained below the levels suggested by the European standard, with weakly average values between 694 and 1062 PPM.
- The recommended daily air change rates by the Italian regulation were always satisfied, whereas the values reported in the EN 16798-1 standard (about 5 ACH for a standard classroom with a 50 m^2 surface, a 150 m^3 volume and an occupation of 25 individuals) were not achieved unless the window opening ratio of the classroom reached 0.010 m^{-1}.
- As observed, to maintain the individual risk of infection under the recommended limits, an air change rate of 5 ACH is needed for the worst scenario where the infector agent is the teacher.
- A strong statistical correlation ($R^2 = 0.88$) was found between the window opening ratio and the air change rates.

Moreover, the generated graph representing the defined correlation between the individual infection probability and the window opening ratio could serve a school staff of similar contexts (in terms of climate, classrooms pattern, and dense urban site with negligible presence of wind) to define, in first analysis, a natural ventilation strategy that both provides adequate ventilation and controls airborne transmission based on the classroom volume and the number of individuals.Finally, for what regards the thermal conditions, as the monitoring was carried out at the end of the winter season, the indoor temperatures recorded during lesson hours were found to be acceptable, settled within the range of 21–23 °C, with outdoor temperatures within 12–15 °C, while having the heating system activated and opened windows. However, external temperatures typical of the winter season of the considered climatic context would have negatively influenced thermal comfort leading to an overuse of the heating system. As far as the results obtained are concerned, with the same opening of windows, the lowering of the external temperatures would have led to an increase in the air flow. Having therefore verified the ventilation conditions at the end of the winter season, this study provides conservative ACHs and windows opening values to guarantee standard levels of IAQ in classroom.

Anyway, in the current context towards greater energy efficiency of buildings, considering the implementation of mechanical ventilation systems with heat recovery remains a key option to properly control both IAQ and thermal comfort in indoor school spaces.

The findings reported in this study should be considered in the light of some limitations. Since the empirical results obtained are based on a few classrooms, with similar layout and floor area, the extension of the outcomes in other classroom configurations should be applied with caution. Besides, as it is well known in the scientific literature, the opening type, size, and position of windows, as does the room layout, affect the amount of incoming fresh air. Analyzing the collected data on an average basis, only based on the window opening ratio of the selected case studies, the influence of these parameters does not emerge in the results.

Another limitation is not having measured wind speed and direction in the close vicinity of the windows of the studied classrooms. Indeed, the wind data taken from close weather stations are valid within a nearby area. These parameters could vary due to obstacles and the morphology of surrounding constructions, especially in urban contexts. However, while recording local values entails a more detailed analysis when calculating ventilation rates, it also restricts the validity of the results to the individual case study, limiting a wider replication. Indeed, this paper was aimed at providing results that could be assumed as a first reference by school staff, without having to worry about opening the windows according to their typology and the specific outdoor wind conditions at each time step.

Future research could adopt the proposed method increasing the number of case-study classrooms (other layout, floor area, opening type, and size and position of windows) and extending the period of measurement to rigid winter conditions. For more detailed evaluations, the real time external CO_2 concentrations should be recorded together with an increase of the number of indoor measurement points. The method could also be implemented by considering detailed wind data recorded in the close vicinity of the windows of the case studies, and extending the assessment to other urban contexts where wind effect may be significant, also by accounting the possible interzones transport of air and CO_2 to explore its contribution.

Author contribution statement

S. Ferrari: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

T. Blázquez; R. Escandón: Analyzed and interpreted the data; Wrote the paper.

Riccardo Cardelli: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

E. De Angelis: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

G. Puglisi; R. Suárez: Conceived and designed the experiments.

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Data availability statement

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] T. Salthammer, et al., Children's well-being at schools: impact of climatic conditions and air pollution, Sep, Environ. Int. 94 (2016) 196–210, https://doi.org/10.1016/j.envint.2016.05.009.
[2] M.J. Mendell, G.A. Heath, Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature, Indoor Air 15 (1) (Jan. 2005) 27–52, https://doi.org/10.1111/j.1600-0668.2004.00320.x.
[3] P. Wargocki, J.A. Porras-Salazar, S. Contreras-Espinoza, W. Bahnfleth, The relationships between classroom air quality and children's performance in school, Build. Environ. 173 (Apr. 2020), 106749, https://doi.org/10.1016/j.buildenv.2020.106749.
[4] V.S. Chithra, S.M. Shiva Nagendra, A review of scientific evidence on indoor air of school building: pollutants, sources, health effects and management, Asian J. Atmospher. Environ. 12 (2) (Jun. 2018) 87–108, https://doi.org/10.5572/ajae.2018.12.2.87.
[5] B. Esty, W. Phipatanakul, School exposure and asthma, Ann. Allergy Asthma Immunol. 120 (5) (May 2018) 482–487, https://doi.org/10.1016/j.anai.2018.01.028.
[6] H.-Y. Liu, D. Dunea, S. Iordache, A. Pohoata, A review of airborne particulate matter effects on young children's respiratory symptoms and diseases, Apr, Atmosphere 9 (4) (2018) 150, https://doi.org/10.3390/atmos9040150.
[7] J. Sundell, et al., Ventilation rates and health: multidisciplinary review of the scientific literature: ventilation rates and health, Indoor Air 21 (3) (Jun. 2011) 191–204, https://doi.org/10.1111/j.1600-0668.2010.00703.x.
[8] Feb. 02, ASHRAE Position Document on Indoor Carbon Dioxide, 2022, p. 6 [Online]. Available: https://www.ashrae.org/file%20library/about/position%20documents/pd_indoorcarbondioxide_2022.pdf.
[9] W.J. Fisk, The ventilation problem in schools: literature review, Nov, Indoor Air 27 (6) (2017) 1039–1051, https://doi.org/10.1111/ina.12403.
[10] European Commission, Joint Research Centre, Institute For Health And Consumer Protection, European Commission. Directorate General For Health And Consumers, Regional Environmental Centre For Central And Eastern Europe. SINPHONIE: Schools Indoor Pollution & Health Observatory Network In Europe : Final Report, LU: Publications Office, 2014, p. 37. Accessed: Nov. 29, 2022. [Online]. Available: https://data.europa.eu/doi/10.2788/99220.
[11] 'World Health Organization, School Environment: Policies and Current Status, WHO Regional Office for Europe, Denmark: Copenhagen, 2015.
[12] M. Griffiths, M. Eftekhari, Control of CO2 in a naturally ventilated classroom, Energy Build. 40 (4) (Jan. 2008) 556–560, https://doi.org/10.1016/j.enbuild.2007.04.013.
[13] R. Zhang, Y. Li, A.L. Zhang, Y. Wang, M.J. Molina, Identifying airborne transmission as the dominant route for the spread of COVID-19, Proc. Natl. Acad. Sci. USA 117 (26) (Jun. 2020) 14857–14863, https://doi.org/10.1073/pnas.2009637117.
[14] R.K. Bhagat, M.S. Davies Wykes, S.B. Dalziel, P.F. Linden, Effects of ventilation on the indoor spread of COVID-19, Nov, J. Fluid Mech. 903 (2020) F1, https://doi.org/10.1017/jfm.2020.720.
[15] J. Kurnitski, A. Boerstra, F. Franchimon, REHVA COVID19 Guidance [Online]. Available:, 2021 https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4.1_15042021.pdf.
[16] 'EN, EN 16798-1: 2019 Energy Performance of Buildings - Ventilation for Buildings - Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics - Module M1-6, Brussels', Belgium, 2019.
[17] World Health Organization, Regional Office for the Western Pacific, 'Repurposing Facilities for Quarantine or Isolation and Management of Mild COVID-19 Cases', Jun, WHO Regional Office for the Western Pacific, Manila, 2020. Accessed: Aug. 25, 2022. [Online]. Available: http://iris.wpro.who.int/handle/10665.1/14528.
[18] A.J. Aguilar, M.L. de la Hoz-Torres, N. Costa, P. Arezes, M.D. Martínez-Aires, D.P. Ruiz, Assessment of ventilation rates inside educational buildings in Southwestern Europe: analysis of implemented strategic measures, J. Build. Eng. 51 (Jul. 2022), 104204, https://doi.org/10.1016/j.jobe.2022.104204.
[19] A. Vignolo, A.P. Gómez, M. Draper, M. Mendina, Quantitative assessment of natural ventilation in an elementary school classroom in the context of COVID-19 and its impact in airborne transmission, Appl. Sci. 12 (18) (Sep. 2022) 9261, https://doi.org/10.3390/app12189261.
[20] A.J. Aguilar, M.L. de la Hoz-Torres, M.D. Martínez-Aires, D.P. Ruiz, Monitoring and assessment of indoor environmental conditions after the implementation of COVID-19-based ventilation strategies in an educational building in southern Spain, Sensors 21 (21) (Oct. 2021) 7223, https://doi.org/10.3390/s21217223.
[21] G. Remion, Review of tracer gas-based methods for the characterization of natural ventilation performance_ Comparative analysis of their accuracy, Build. Environ. 12 (2019).
[22] A. Alonso, J. Llanos, R. Escandón, J.J. Sendra, Effects of the COVID-19 pandemic on indoor air quality and thermal comfort of primary schools in winter in a mediterranean climate, Mar, Sustainability 13 (5) (2021) 2699, https://doi.org/10.3390/su13052699.
[23] M. Gil-Baez, J. Lizana, J.A. Becerra Villanueva, M. Molina-Huelva, A. Serrano-Jimenez, R. Chacartegui, Natural ventilation in classrooms for healthy schools in the COVID era in Mediterranean climate, Build. Environ. 206 (Dec. 2021), 108345, https://doi.org/10.1016/j.buildenv.2021.108345.
[24] A. Monge-Barrio, et al., Encouraging natural ventilation to improve indoor environmental conditions at schools. Case studies in the north of Spain before and during COVID, Energy Build. 254 (Jan. 2022), 111567, https://doi.org/10.1016/j.enbuild.2021.111567.
[25] Fondazione Giovanni Agnelli, Rapporto Sull'edilizia Scolastica, Laterza, Rome, 2020.
[26] S.S. Korsavi, A. Montazami, D. Mumovic, Indoor air quality (IAQ) in naturally-ventilated primary schools in the UK: occupant-related factors, Build. Environ. 180 (Aug. 2020), 106992, https://doi.org/10.1016/j.buildenv.2020.106992.
[27] S.S. Korsavi, A. Montazami, D. Mumovic, Ventilation rates in naturally ventilated primary schools in the UK; Contextual, Occupant and Building-related (COB) factors, Build. Environ. 181 (Aug. 2020), 107061, https://doi.org/10.1016/j.buildenv.2020.107061.
[28] H. Takahashi, M.P. Bivolarova, A. Keli, J. Nickel, A.K. Melikov, Non-uniformity in outdoor CO $_2$ concentration in city of Copenhagen, in: E3S Web Conf., 111, 2019, 02007, https://doi.org/10.1051/e3sconf/201911102007.
[29] K. George, L.H. Ziska, J.A. Bunce, B. Quebedeaux, Elevated atmospheric CO2 concentration and temperature across an urban–rural transect, Atmos. Environ. 41 (35) (Nov. 2007) 7654–7665, https://doi.org/10.1016/j.atmosenv.2007.08.018.
[30] D.L. Johnson, R.A. Lynch, E.L. Floyd, J. Wang, J.N. Bartels, Indoor air quality in classrooms: environmental measures and effective ventilation rate modeling in urban elementary schools, Build. Environ. 136 (May 2018) 185–197, https://doi.org/10.1016/j.buildenv.2018.03.040.
[31] L. Schibuola, M. Scarpa, C. Tambani, Natural ventilation level assessment in a school building by CO2 concentration measures, Energy Proc. 101 (Nov. 2016) 257–264, https://doi.org/10.1016/j.egypro.2016.11.033.
[32] Agenzia regionale per la Protezione dell'Ambiente (ARPA), Accessed: May 11, 2023. [Online]. Available: https://www.arpalombardia.it/Pages/ARPA_Home_Page.aspx.
[33] Capetti elettronica s.r.l.'[Online]. Available: http://www.capetti.it/.
[34] I.S.O. 'EN, EN ISO 16000-26:2012, Indoor Air - Part 26: Sampling Strategy for Carbon Dioxide (CO2), Brussels', Belgium, 2012.

[35] Ministero dell'Istruzione. PROTOCOLLO D'INTESA PER GARANTIRE L'AVVIO DELL'ANNO SCOLASTICO NEL RISPETTO DELLE REGOLE DI SICUREZZA PER IL CONTENIMENTO DELLA DIFFUSIONE DI COVID 19". Aug. 08, 2020. Italy: Rome..
[36] S. Batterman, Review and extension of CO2-based methods to determine ventilation rates with application to school classrooms, Feb, Int. J. Environ. Res. Publ. Health 14 (2) (2017) 145, https://doi.org/10.3390/ijerph14020145.
[37] G. van Rossum, Python, 11/22. [Online]. Available: https://www.python.org/.
[38] F. Liu, C. Fiencke, J. Guo, R. Rieth, R. Dong, E.-M. Pfeiffer, Performance evaluation and optimization of field-scale bioscrubbers for intensive pig house exhaust air treatment in northern Germany, Sci. Total Environ. 579 (Feb. 2017) 694–701, https://doi.org/10.1016/j.scitotenv.2016.11.039.
[39] American Society of Heating Refrigerating and Air-Conditioning Engineers Inc. (ASHRAE), *2021 ASHRAE Handbook - Fundamentals*, 2021. Accessed: Aug. 13, 2022. [Online]. Available:.
[40] B. Shuter, A. Aslani, Body surface area: Du Bois and Du Bois revisited, Eur. J. Appl. Physiol. 82 (3) (Jun. 2000) 250–254, https://doi.org/10.1007/s004210050679.
[41] A.F.R. d'Ambrosio, REHVA Guidebook No. 13 - Indoor Environment and Energy Efficiency in Schools - Part 1 Principles, Place of publication not identified: REHVA, 2010. Accessed: Aug. 13, 2022. [Online]. Available: https://app.knovel.com/web/toc.v/cid:kpREHVAGA2/viewerType:toc/root_slug:rehva-guidebook-no-13?kpromoter=federation.
[42] K. Ridley, B.E. Ainsworth, T.S. Olds, Development of a compendium of energy expenditures for youth, Int. J. Behav. Nutr. Phys. Activ. 5 (1) (2008) 45, https://doi.org/10.1186/1479-5868-5-45.
[43] R.J. Shephard, '2011 compendium of physical activities: a second update of codes and MET values, Jan. 2012, Yearb. Sports Med. (2012) 126–127, https://doi.org/10.1016/j.yspm.2011.08.057.
[44] Decreto Ministeriale 18 dicembre 1975, 'Norme tecniche aggiornate relative alla edilizia scolastica, ivi compresi gli indici minimi di funzionalità didattica, edilizia ed urbanistica, da osservarsi nella di opere di edilizia scolastica, Dec. 18, p. 30, 1975. [Online]. Available: https://www.minori.gov.it/sites/default/files/dm_18_dicembre_1975.pdf.
[45] E. Riley, G. Murphy, R. Riley, Airborne spread of measles in a suburban elementary school, Airborne Spread Measles Suburb. Elem. Sch. 107 (1978) 421–432.
[46] G.N. Sze To, C.Y.H. Chao, Review and comparison between the Wells–Riley and dose-response approaches to risk assessment of infectious respiratory diseases, Feb, Indoor Air 20 (1) (2010) 2–16, https://doi.org/10.1111/j.1600-0668.2009.00621.x.
[47] G. Buonanno, L. Stabile, L. Morawska, Estimation of airborne viral emission: quanta emission rate of SARS-CoV-2 for infection risk assessment, Aug, Environ. Int. 141 (2020), 105794, https://doi.org/10.1016/j.envint.2020.105794.
[48] L. Morawska, et al., Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities, J. Aerosol Sci. 40 (3) (Mar. 2009) 256–269, https://doi.org/10.1016/j.jaerosci.2008.11.002.
[49] S. Mattar, et al., Epidemiological and viral features of a cohort of SARS-CoV-2 symptomatic and asymptomatic individuals in an area of the Colombian Caribbean, Dec, Ann. Clin. Microbiol. Antimicrob. 19 (1) (2020) 58, https://doi.org/10.1186/s12941-020-00397-5.
[50] Y. Pan, D. Zhang, P. Yang, L.L.M. Poon, Q. Wang, Viral load of SARS-CoV-2 in clinical samples, Lancet Infect. Dis. 20 (4) (Apr. 2020) 411–412, https://doi.org/10.1016/S1473-3099(20)30113-4.
[51] M. Möckel, et al., SARS-CoV-2 antigen rapid immunoassay for diagnosis of COVID-19 in the emergency department, Biomarkers 26 (3) (Apr. 2021) 213–220, https://doi.org/10.1080/1354750X.2021.1876769.
[52] T.C. Jones, et al., Estimating infectiousness throughout SARS-CoV-2 infection course, Jul, Science 373 (6551) (2021) eabi5273, https://doi.org/10.1126/science.abi5273.
[53] R. Wölfel, et al., Virological assessment of hospitalized cases of coronavirus disease 2019, preprint, Mar, Inf. Dis. (except HIV/AIDS) (2020), https://doi.org/10.1101/2020.03.05.20030502.
[54] Y. Xu, J. Cai, S. Li, Q. He, S. Zhu, Airborne infection risks of SARS-CoV-2 in U.S. schools and impacts of different intervention strategies, Sustain. Cities Soc. 74 (Nov. 2021), 103188, https://doi.org/10.1016/j.scs.2021.103188.
[55] T. Watanabe, T.A. Bartrand, M.H. Weir, T. Omura, C.N. Haas, Development of a dose-response model for SARS coronavirus: dose-response model for SARS-CoV, Risk Anal. 30 (7) (Apr. 2010) 1129–1138, https://doi.org/10.1111/j.1539-6924.2010.01427.x.
[56] G. Buonanno, L. Morawska, L. Stabile, Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications, Environ. Int. 145 (Dec. 2020), 106112, https://doi.org/10.1016/j.envint.2020.106112.
[57] L. Stabile, A. Pacitto, A. Mikszewski, L. Morawska, G. Buonanno, Ventilation procedures to minimize the airborne transmission of viruses in classrooms, Build. Environ. 202 (Sep. 2021), 108042, https://doi.org/10.1016/j.buildenv.2021.108042.
[58] A. Meiss, H. Jimeno-Merino, I. Poza-Casado, A. Llorente-Álvarez, M.Á. Padilla-Marcos, Indoor air quality in naturally ventilated classrooms. Lessons learned from a case study in a COVID-19 scenario, Sustainability 13 (15) (Jul. 2021) 8446, https://doi.org/10.3390/su13158446.
[59] E. Dascalaki, M. Santamouris, D. N. Asimakopoulos, K. Papadopoulos, and A. Soilemes, "PREDICTING SINGLE SIDED NATURAL VENTILATION RATES IN BUILDINGS".
[60] J. Shen, M. Kong, B. Dong, M.J. Birnkrant, J. Zhang, A Systematic Approach to Estimating the Effectiveness of Multi-Scale IAQ Strategies for Reducing the Risk of Airborne Infection of SARS-CoV-2, Aug vol. 200, Building and Environment, 2021, 107926, https://doi.org/10.1016/j.buildenv.2021.107926.