Assessment of ventilation rates inside educational buildings in Southwestern Europe: Analysis of implemented strategic measures

Antonio J. Aguilar [a], María L. de la Hoz-Torres [a,*], Nélson Costa [b], Pedro Arezes [b], María D. Martínez-Aires [c], Diego P. Ruiz [a]

[a] *Department of Applied Physics, University of Granada, Av. Severo Ochoa s/n, 18071, Granada, Spain*
[b] *ALGORITMI Research Center, School of Engineering, University of Minho, Guimarães, 4800-058, Portugal*
[c] *Department of Building Construction, University of Granada, Av. Severo Ochoa s/n, 18071, Granada, Spain*

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ABSTRACT

The pandemic caused by COVID-19 has highlighted the need to ensure good indoor air quality. Public buildings (educational buildings in particular) have come under the spotlight because students, teachers and staff spend long periods of the day indoors. This study presents a measurement campaign for the assessment of ventilation rate (VR) and ventilation strategies in educational buildings in Southwestern Europe, Portugal and Spain. A representative sample of the teaching spaces of the Azurém Campus (Guimarães, Portugal) and the Fuentenueva Campus (Granada, Spain) have been analyzed. Natural ventilation is the predominant ventilation strategy in these spaces, being the most common strategy in educational buildings in Europe. VR was estimated under different configurations, using the CO_2 decay method. Subsequently, the CO_2 concentration was estimated according to occupancy and the probability of infection risk was calculated using the Wells-Riley equation. The obtained VR varied between 2.9 and 20.1 air change per hour (ACH) for natural cross ventilation, 2.0 to 5.1 ACH for single-sided ventilation and 1.8 to 3.5 for mechanically ventilated classrooms. Large differences in CO_2 concentrations were verified, depending on the analyzed ventilation strategy, ranging from 475 to 3903 ppm for the different scenarios. However, the probability of risk was less than 1% in almost all of the classrooms analyzed. The results obtained from the measurement campaign showed that the selection of an appropriate ventilation strategy can provide sufficient air renewal and maintain a low risk of infection. Ventilation strategies need to be reconsidered as a consequence of the health emergency arising from the COVID-19 pandemic.

Nomenclature

ACH	Air change per hour
ASHRAE	American Society of Heating, Ventilating, and Air-Conditioning Engineers
C_{MV}	Mechanical Ventilation
C_{AW+2D}	All windows +2 doors
C_{AW+1D}	All windows + Main door
C_{AW}	All windows

C_{EW+1D}	End windows + Main Door
IAQ	Indoor Air Quality
IEQ	Indoor Environmental quality
HVAC	Heating, Ventilation, and Air Condition
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
RITE	Regulation on Building Heating Installations
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus-2
SHASE	Society of Heating, Air-Conditioning, and Sanitary Engineers of Japan
VR	Ventilation rate
WHO	World Health Organization
MV	Mechanical ventilation
NDIR	Non-dispersive infrared
NV	Natural ventilation

1. Introduction

Indoor Environmental Quality (IEQ), and in particular the Indoor Air Quality (IAQ), is a crucial aspect to consider in the design of educational buildings. As these buildings are often designed for high occupancy density for long periods of the day, the quality of the indoor built environment is crucial to providing a healthy, safe and comfortable space [1]. In addition, exposure to indoor air pollutants might exacerbate diseases, such as asthma, or allergies [2] and can lead to a risk of short and long-term health problems, including various respiratory diseases [3,4], cardiovascular diseases [5], irritated nose and/or eyes, headaches, etc. [6]. Therefore, IAQ is an essential parameter for the well-being of students and teachers, as it can have a direct impact on concentration, productivity and academic achievement [7].

However, previous studies have shown that educational spaces in non-retrofitted buildings in Southern Europe do not have suitable conditions of comfort and IAQ [8]. Moreover, even in those educational buildings that have been retrofitted, the effect of the intervention showed some differences from what was expected at the design stage [8]. In fact, the effects of poor IAQ in these spaces have recently been put in the spotlight due to the global pandemic caused by COVID-19 since they are risk environments for the transmission of airborne viruses such as the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) [9]. This fact is a critical issue and has resulted in increased concern among building managers about IAQ. Measures to contain the transmission of SARS-CoV-2 constitute a major challenge inside enclosed environments such as classrooms. An asymptomatic, infected teacher or student could spread a virus-containing aerosol inside classrooms if the air is not adequately renewed. Factors that contribute to the increased transmission of SARS-CoV-2 include: high voice volume, intense physical activity, lack of well-fitting masks, large numbers of people in the same space, decreased interpersonal distance, increased exposure time and poor indoor Ventilation Rate (VR) [10].

On the basis of this evidence, governments took a wide range of measures in response to the COVID-19 outbreak, including the closure of educational buildings. As a result, millions of students were affected by it [11]. In the case of Spain and Portugal, a state of emergency was declared on March 15, 2020 and March 18, 2020, respectively. Teaching/learning activities took place off-campus in both countries from that date onwards, for the rest of the academic year. In order to mitigate the impact of this decision, infection risk control strategies were adopted and educational spaces were adapted over the next academic year (2020–2021). In this context, international organizations have published recommendations and guidelines to provide a basis for protecting public health from the adverse effects of air pollutants. The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and the American Society of Heating, Ventilating, and Air-Conditioning Engineers (ASHRAE) have published recommended ventilation control measures after recognizing the potential for indoor airborne hazards [12,13]. More specifically, the REHVA COVID19 Guidance document [13] states that, in rooms and classrooms where no national ventilation regulation exists, an Indoor Climate Category II (10–15 L/s per person outdoor airflow rates in offices and 8–10 L/s per person in meeting rooms and classrooms) is the typical sizing according to ISO 17772-1:2017 [14] and EN 16798-1:2019 [15]. In this regard, the World Health Organization (WHO) has also recommended measures, which include ensuring effective ventilation by frequently opening windows and doors [16].

In addition, CO_2 concentration was suggested as indicator of an effective ventilation. REHVA also recommends installing CO_2 sensors to warn against under-ventilation in indoor spaces such as classrooms and meeting rooms. Indeed, previous research studies have shown that CO_2 concentration is an indicator of ventilation efficiency [17]. REHVA also suggests using a traffic light indicator based on the level of concentration in the classroom: green light when the level is below 800 ppm (good ventilation), yellow/orange light when the concentration level varies between 800 and 1000 ppm (acceptable ventilation) and red light when the concentration level is above 1000 ppm (unacceptable ventilation). This system looks for providing information to the occupants in order to trigger prompt action to achieve sufficient air renovation.

This monitoring system is especially relevant in spaces with natural or hybrid ventilation systems, where ventilation control requires for action from building occupants (i.e. opening doors and windows). The CO_2 concentration data obtained from monitoring provides key information to both manage building facilities and identify poorly ventilated spaces where the risk of indoor-cross contamination via aerosol is very high [13]. In the case of spaces mechanically ventilated, reducing air recirculation and increasing the VR are suggested by the REHVA Guidance [13]. However, most educational buildings in Europe do not have mechanical ventilation systems [18]. Therefore, since the ventilation system determines the strategies that can be implemented to control or increase

the air renewal rate, increasing VR in these spaces can only be achieved through natural ventilation.

As can be seen, the analysis and management of ventilation strategies is crucial to ensuring that spaces are healthy and safe. Air flow measurements [19], CO_2 generated by building occupants [20], injection of a tracer gas [21] and comparison of outdoor indoor gas concentrations [22] are methods used to determine ventilation metrics (i.e. ACH (h^{-1}), VR per person (dm^3/s per occupant) and VR ($m^{-3}h^{-1}$)) [23].

Previous studies have used these methods to assess the probability of the airborne spread of SARS-CoV-2 (COVID-19 virus) [24,25]. Berry et al. [26] reviewed methods to reduce the probability of the airborne spread of COVID-19 virus in ventilation systems and enclosed spaces. They highlighted that ventilating an enclosed space is an effective way to reduce the concentration of airborne particles carrying COVID-19. Li et al. [27] concluded that there is evidence of an association between the transmission and spread of infectious diseases (i.e. measles, Tuberculosis (TB), chickenpox, anthrax, influenza, smallpox, and SARS) and the ventilation and the control of airflow direction in buildings. In addition, Guo et al. [28] analyzed the operation guidelines from different countries (including ASHRAE, REVHA, SHASE, the Architectural Society of China, and the Chinese Institute of Refrigeration). This review concluded that all guidelines emphasize the importance of ventilation (both natural and mechanical), which can effectively decrease the concentration of virus-containing droplets. However, it is still unclear as to the specific ventilation rate that can eliminate the risk of transmission of airborne particulate matter. Pan et al. [29] concluded that Heating, Ventilation, and Air Conditioning (HVAC) system design should be adaptive, in anticipation of the needs of emerging situations, such as the pandemic. The supply of fresh air, in higher volumes, should be considered in the design. Li and Tang [30] evaluated the VR in spaces of an outpatient building in Shenzhen. The average VR in the 20 waiting rooms was 77.6 m3/h (2 times of the Chinese standard). The study concluded that the design of semiclosed hospital street reduces the infection risk of COVID-19 since it improves the natural ventilation. Park et al. [24] conducted field measurements to analyze natural ventilation strategies by opening windows in a school building in Korea to address the COVID-19 situation. The authors recommended cross-ventilation to minimize the possibility of infection in high-density public buildings compared to unilateral ventilation. Kurnitski et al. [31] proposed a new design method to calculate outdoor air ventilation rates to control respiratory infection risk in indoor spaces. This model was evaluated using different case studies (offices, classrooms, meeting areas and cafeteria). The Category I ventilation rate prescribed in the EN 16798-1 standard satisfied many, but not all, types of spaces examined.

Nevertheless, despite the impact of the compulsory preventing ventilation measures on indoor air quality and occupant health, very little related research has been conducted in Southwestern Europe due to the time that has elapsed since the outbreak of the COVID-19 pandemic. In this context, the aim of this study is to analyze the ventilation strategies in teaching spaces in university buildings located in Portugal and Spain. For this purpose, a representative sample of teaching spaces located in the Azurém Campus (Guimarães, Portugal) and the Fuentenueva Campus (Granada, Spain) were selected for the analysis. The field measurements and subsequently data post-processing followed the following phases: 1) study of the characteristics of the indoor spaces at the Azurem Campus and Fuentenueva Campus; 2) definition and selection of different ventilation strategies in each teaching space; 3) assessment of the VR using the decay method; 4) estimation of the CO_2 concentrations and identification of the probability of airborne virus infection risk as a function of the VR obtained in the field measurements.

2. Materials and methods

In order to characterize the ventilation strategies implemented in educational buildings in Portugal and Spain, field measurements

Fig. 1. Locations of Fuentenueva campus (Granada, Spain) and Azurém campus (Guimarães, Portugal).
a) Azurém Campus
b) Fuentenueva Campus

were carried out with the aim of analyzing their impact on the IAQ and the safety of the built environment. With this objective in mind, two university campuses (Azurém Campus of the University of Minho and Fuentenueva Campus of the University of Granada) were selected for the study. The experimental campaign was carried out from March to July 2021.

2.1. Area description and climatic conditions

The educational buildings are located at the Fuentenueva Campus of the University of Granada (Granada, Spain) and the Azurém Campus of the University of Minho (Guimarães, Portugal). Fig. 1 shows the location of the two campuses. The climate in Granada is classified as Csa, according to the Köppen-Geiger climate classification. It is characterized by short, very hot and mostly clear summers and long, cold and partly cloudy winters. During the course of the year, the temperature generally varies from 0 °C to 34 °C and rarely drops below −4 °C or rises above 38 °C. The climate in Guimarães is classified as Csb, according to the Köppen-Geiger climate classification. It is characterized by short, warm, dry, and mostly clear summers and cold, wet, and partly cloudy winters. During the course of the year, the temperature typically varies from 5 °C to 28 °C and rarely drops below 0 °C or rises above 33 °C.

The classrooms were selected in order to provide a representative sample of typical classrooms on both campuses. Fourteen classrooms were selected between the two sites, eight of them at Azurém and six at Fuentenueva. The classrooms are located in 4 buildings on the Azurém Campus (A1: School of Engineering, A2: School of Architecture, A3: School of Science and A4: Pedagogical Complex) and in 2 buildings on the Fuentenueva Campus (F1: Advanced Technical School for Building Engineering and F2: Advanced Technical School for Civil Engineering). Table 1 shows the characteristics of the classrooms. Appendix A shows the layouts of the classrooms tested in this study (see Figures in Appendix A).

2.2. Description of the tests

In order to quantify the VR, different configuration scenarios were defined and evaluated during the tests. In the case of mechanically ventilated classrooms, standard operation was evaluated. For the other classrooms, different window and door opening configurations were established. Table 2 shows a summary of the different configurations tested.

The method used in the experimental test was the decay method. This method consists of increasing a tracer gas concentration by using a generator source in the unoccupied indoor space until a homogeneous and well-mixed mixture is reached [23,32,33]. Subsequently, without the gas source, the rate of decreased concentration of the tracer gas is determined under a ventilation rate strategy. In this study, carbon dioxide (CO_2) was used in the tests.

The decay method uses CO_2 as a tracer gas, and it is based in Equation (1). From this equation, the CO_2 concentration C(t) in an effective mixed zone at time t is given by:

$$\ln[C(t) - C_{out}] = \ln[C(t_1) - C_{out}] - ACH(t - t_1) \tag{1}$$

where C_{out} is the outdoor CO_2 concentration, $C(t_1)$ is the CO_2 concentration at initial time and ACH is the air change per hour. This equation assumes that the concentration distribution in an effective mixed zone is maintained uniform and the ventilation rate does not fluctuate over time [34].

When the measured data are obtained from the sampling in multiple times during the decay process, the multipoint decay method is used. The least square method is applied to calculate the air change per hour (ACH) [35] to those data measured in field measurements. Equation (2) shows the expression used to calculate it.

$$ACH_C = \frac{\left(\sum_{j=1}^{n} t_j\right) \cdot ln\left[C(t_j) - C_{out}\right] - n \cdot \sum_{j=1}^{n} t_j \cdot ln\left[C(t_j) - C_{out}\right]}{n \cdot \sum_{j=1}^{n} t_j^2 - \left(\sum_{j=1}^{n} t_j\right)^2} \tag{2}$$

Table 1
Buildings and selected classrooms.

Campus	Building	Class	Ventilation System	Windowsm Orientation	Area (m²)	Volume (m³)	Normal occupation (seats)	COVID occupation (seats)
Azurém	A1	A1-1	NV	SE	76	218	48	24
		A1-2	M	SW	85	287	80	40
	A2	A2-1	NV	NW	68	196	53	27
		A2-2	M	NW	127	341	122	60
	A3	A3-1	NV	NE	68	185	41	23
		A3-2	M	SW	50	148	60	30
	A4	A4-1	NV	SE	48	151	30	19
		A4-2	M	SE	132	470	130	65
Fuentenueva	F1	F1-1	NV	N	172	518	156	78
		F1-2	NV	S	174	522	156	78
		F1-3	NV	W	265	796	91	45
	F2	F2-1	NV	S	106	410	76	38
		F2-2	NV	W	164	542	62	32
		F2-3	NV	SW-NE	175	500	61	35

[a]M – Mechanical ventilation; NV – Natural Ventilation. SE – Southeast; SW – Southwest; NE – Northeast; NW – Northwest; W – West; S – South; N – North.

Table 2

Description of the different configurations evaluated during the tests.

Ventilation configurations	
C_{MV}	Mechanical Ventilation
C_{AW+2D}	All windows +2 doors
C_{AW+1D}	All windows + Main door
C_{AW}	All windows
C_{EW+1D}	End windows + Main Door

where C denotes the ventilation configuration under study, ACH_C is the air change per hour with the ventilation strategy selected, j is the counter of data samples, n is the number of data samples, t_j is the j-th time value, and $C(t_j)$ is the CO_2 concentration at t_j.

Since the multi-point decay method was applied, the UNE-EN ISO 12569:2017 standard [34] establishes the following procedure to calculate the level of confidence for the estimated airflow rate ($\overline{ACH}$). The confidence intervals denoted as F_{ACH} for the estimated ACH can be calculated for a level of confidence of $100(1 - \alpha)$ as:

$$F_{ACH} = \overline{ACH} \pm E_{ACH} \cdot t(k-2,\ 1-\alpha) = \overline{ACH} \pm e \tag{3}$$

where $t(k-2,1-\alpha)$ is the value calculated from the Student's t-distribution table; k being the number of samples, $1-\alpha$ is the confidence level of ACH (set up as $\alpha = 0.05$ and the results are analyzed at a confidence interval of 95%) and E_{ACH} being the predicted standard error for the specific airflow rate ACH (the regression coefficient) which is the standard deviation of the sample mean or the mean variance.

Taking into account the previous equations (1) and (2), the experimental setup to analyze the decay process of the gas concentration was divided into two phases, on the basis of the continuous monitoring carried out by CO_2 sensors. During the first phase, five sensors were evenly distributed throughout the classroom (Annex A shows the location of the sensors in each classroom). The outdoor CO_2 concentration was then measured before the start of the test. Next, windows and doors were closed, and in those cases where the classroom has mechanical ventilation systems installed, the system was switched off. With this setup, the CO_2 concentration inside the classroom was increased using a source of this tracer gas, in this case dry ice [25]. In order to achieve a homogeneous concentration, two fans were used to mix the generated CO_2 into the air in the room. Once the required CO_2 concentration level was reached (around 2000 ppm), the CO_2 source was removed and the fans were turned off, thus ending the first phase. In the second phase, the ventilation strategy under study was set up (i.e. windows and doors are opened according to Table 2). Once the CO_2 level decayed 37% of its peak concentration above the background, the test ended [32,33]. This process was repeated to analyze all the ventilation strategies identified for each classroom are analyzed. It should be remarked that the room must be unoccupied during the experimental test.

HOBO® MX1102 sensors were used to measure CO_2 concentration at know times during the experimental tests. The sensing method of this instrument is based on non-dispersive infrared (NDIR) absorption and a measurement range from 0 to 5000 ppm (accuracy ± 50 ppm ±5% of readings at 25 °C, less than 90% RH non-condensing and 1.013 mbar).

The ACH is a parameter that is regulated in the national ventilation regulations of many countries. Regarding Spanish regulations, the Real Decreto 1027/2007 [36] states that, depending on the use of the building, a minimum indoor air quality (IDA) is established. This parameter is equivalent to the categories defined in the EN 16798-3 standard [37] about ventilation for non-residential buildings (the categories are shown in Table 3). In the case of spaces dedicated to teaching and learning uses, a minimum Category 2 is required by the Regulation on Building Heating Installations (RITE) [38]. In the case of Portugal's national regulations, Decree-Law n.° 118/2013 [39] establishes a minimum outdoor air flow rate value of 24 m³/(h· occupant) for teaching/learning spaces. This required value is between Category 3 and Category 4 of the EN 16798-3 standard.

2.3. Evaluation of the CO_2 concentrations and airborne virus infection risk

Since the health and safety of indoor spaces can be compromised when rooms are not well ventilated, as the risk of cross-contamination through aerosols is very high, CO_2 concentration is a parameter that can be used to warn against lack of ventilation. In fact, during the COVID-19 pandemic, monitoring of CO_2 concentration levels has been highlighted as an indicator of indoor air quality and ventilation effectiveness. In this study, based on the data obtained from the field measurements, the indoor CO_2 concentration trend is estimated for different occupancy scenarios (100% and COVID protocol). For this purpose, a mass balance equation of the tracer gas (i.e. CO_2) concentration was used. This expression can be expressed as Equation (4):

$$V \frac{dC_t}{dt} = Q(C_{OUT} - C(t)) + E(t) \tag{4}$$

Table 3

IDA categories. (Fuente: RITE).

Category	Outdoor air flow rates [dm³/s per occupant]
1 (optimum air quality)	20.0
2 (good quality air)	12.5
3 (medium air quality)	8.0
4 (low quality air)	5.0

Table 4
ACH (h^{-1}) results through different ventilation configurations at Azurém Campus.

Building	Room	Ventilation configuration	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	$\overline{ACH}$	National Limit ACH[a]		REVHA recommended ACH	
									Normal occup.	COVID occup.	Normal occup.	COVID occup.
A1	A1-1	C_{AW-MD}	**15.76±1.61**	**10.51±0.42**	**7.95±0.35**	**9.56±0.23**	**8.27±0.18**	**10.41±0.77**	5.3	2.6	7.9	4.0
		C_{EW-MD}	**6.64±0.49**	**5.60±0.48**	**6.63±0.26**	**6.45±0.26**	**6.17±0.23**	**6.30±0.36**				
		C_{AW}	3.85±0.09	3.32±0.05	3.08±0.03	2.81±0.08	2.86±0.05	3.18±0.06				
	A1-2	C_{MV}	3.7±0.04	3.54±0.07	3.33±0.09	3.32±0.06	3.45±0.04	3.47±0.06	6.7	3.3	10.0	5.0
A2	A2-1	C_{AW-MD}	**9.62±0.55**	**8.13±0.24**	**7.74±0.41**	**9.03±0.51**	**7.29±0.28**	**8.36±0.42**	6.5	3.3	9.7	5.0
		C_{EW-MD}	**7.18±0.55**	**8.28±0.22**	**8.01±0.38**	**7.08±0.41**	**6.42±0.25**	**7.39±0.38**				
		C_{AW}	3.55±0.11	1.37±0.04	1.64±0.02	1.79±0.06	1.76±0.05	2.02±0.06				
	A2-2	C_{MV}	2.23±0.04	2.41±0.02	2.68±0.04	2.28±0.03	3.26±0.04	2.57±0.03	8.6	4.2	12.9	6.3
A3	A3-1	C_{AW-MD}	4.00±0.19	**5.79±0.27**	**5.96±0.27**	**11.51±0.31**	**6.94±0.27**	**6.84±0.26**	5.3	3.0	8.0	4.5
		C_{EW-MD}	2.42±0.04	2.89±0.05	3.13±0.05	2.92±0.16	3.32±0.10	2.94±0.09				
		C_{AW}	1.65±0.03	1.75±0.03	2.00±0.04	2.79±0.09	2.51±0.07	2.14±0.06				
	A3-2	C_{MV}	1.61±0.03	1.52±0.02	1.80±0.01	1.97±0.02	1.89±0.02	1.76±0.02	9.7	4.9	14.6	7.3
A4	A4-1	C_{AW-MD}	4.89±0.14	**8.53±0.40**	5.04±0.14	5.80±0.14	5.51±0.34	**5.95±0.26**	4.8	3.0	7.2	4.5
		C_{EW-MD}	3.45±0.07	**4.68±0.27**	3.35±0.08	4.42±0.06	**4.86±0.25**	4.15±0.17				
	A4-2	C_{MV}	1.75±0.02	1.82±0.03	1.69±0.02	1.92±0.02	2.04±0.01	1.84±0.02	6.6	3.3	10.0	5.0

[b]Bold numbers indicate that the value is higher than the REHVA recommended ACH value assuming the COVID-19 rule-based occupation.

[a] These values have been calculated based on the Portuguese national regulations.

where V is the volume of the indoor space; C_{OUT} is the outdoor CO_2 concentration level; $C(t)$ is the CO_2 concentration in the room at time t; $E(t)$ is the CO_2 emission rate of indoor sources at time t and Q is the volumetric airflow rate of outdoor or replacement air. If Q. C_{OUT} and E are assumed constant. The previous equation can be solved as follows:

$$C_t = C_{out} + \frac{E}{Q} + \left(C_0 - C_{out} - \frac{G}{Q} \right) \cdot e^{-\frac{Q}{V} \cdot t} \tag{5}$$

where C_0 is the CO_2 concentration at t=0. In addition. if the outdoor C_{OUT} is assume equal to the initial CO_2 concentration (C_0) and ACH is expressed as ACH = G/V. Equation (5) can be expressed as follow:

$$C_t = C_{out} + \frac{E}{Q} \left(1 - e^{-\frac{Q}{V} \cdot t} \right) \tag{6}$$

$$C_{in}(t) = C_{out} + \frac{E}{V \cdot ACH} \left(1 - e^{-ACH \cdot t} \right) \; [ppm] \tag{7}$$

where $C_{in}(t)$ is the CO_2 concentration at any time point (t), C_{out} is the outdoor CO_2 concentration, E is the overall exhaled CO_2 emission rate in the indoor environment under study (this value depends on the activity level, age and gender), V is the volume of the indoor space and ACH is the air change per hour. Therefore, the indoor CO_2 concentration (for known and steady state outdoor CO_2 concentration and emission rate) depends on the volume and ACH of the indoor space. In this study, since occupants are seated during lectures, the assumed E value was 0.0042 L/s ·occupant [40].

If the classroom ventilation requires action by the occupants (i.e. natural ventilation or hybrid systems), REHVA recommends the use of the CO_2 concentration level as a ventilation indicator during pandemic situations. Specifically, the REHVA guidelines recommend setting a warning signal when 800 ppm is exceeded and an alarm to trigger rapid action to achieve sufficient ventilation when 1000 ppm is exceeded, even in situations where occupancy has been reduced [13]. In addition, with regard to national regulations, the maximum CO_2 concentration limit is 1250 ppm and 900 ppm in the Portuguese and Spanish regulations, respectively (assuming an outdoor CO_2 concentration of 400 ppm in the case of the Spanish regulations).

As can be seen, since the control of virus-containing aerosol concentrations depends on ventilation solutions when the social distance is greater than 1.5 m, the CO_2 concentration can be used to assess the effectiveness of ventilation and, thus, the likelihood of infection. The risk of infection can be calculated for different activities and rooms using a standard Wells-Riley airborne disease transmission model, which can be calibrated for viruses such as SARS-Cov-2 by adjusting the correct source intensity, i.e. quanta emission rates. Equation (8) shows the Wells-Riley equation model [41].

$$P = \frac{C_i}{C_S} = 1 - e^{-I \, q \, p \, t \, / \, ACH} \tag{8}$$

where P is the probability of infection risk, C_i is the number of cases that develop infection, C_S is the number of susceptible people, I is the number of infectors (I =1 has been assumed in this study), q is the quantum generation rate by an infected person (h^{-1}), t is the exposure time (h), ACH is the air change per hour in the room (m^3/h) and p is the pulmonary ventilation rate of susceptible people. In this study, a quanta emission rate equal to 5.0 *quanta/h* has been assumed and, since students are sitting, *p* has been assumed to be $p =$
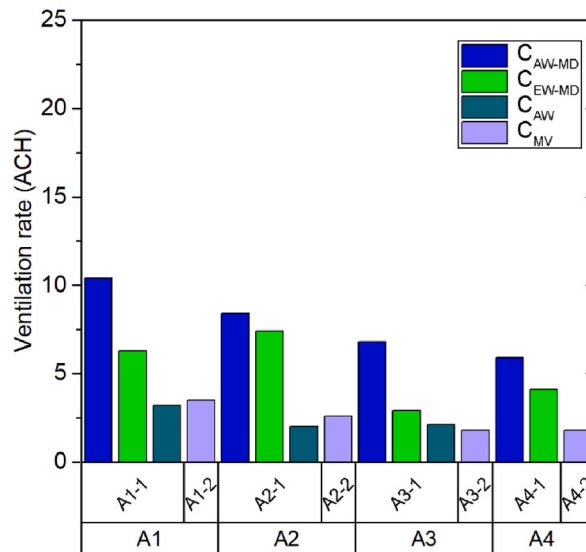

Fig. 2. VR results obtained from the measurement campaign carried out at Azurém Campus.

Table 5
ACH (h^{-1}) results through different ventilation configurations at Fuentenueva Campus.

Building	Room	Ventilation configuration	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	$\overline{ACH}$	National Limit ACH[a]		REVHA recommended ACH	
									Normal occup.	Covid occup.	Normal occup.	Covid occup.
F1	F1-1	C_{AW-2D}	**27.09±1.13**	**28.17±0.97**	**15.12±0.62**	**12.61±0.48**	**17.44±0.53**	**20.09±0.79**	13.6	6.8	10.8	5.4
		C_{AW-MD}	**10.09±0.43**	**11.69±0.52**	**11.29±0.42**	**11.00±0.45**	**11.48±0.37**	**11.11±0.44**				
		C_{EW-MD}	**7.45±0.15**	**9.60±0.19**	**9.33±0.09**	**8.08±0.14**	**8.14±0.20**	**8.52±0.16**				
	F1-2	C_{AW-2D}	**20.17±0.57**	**19.05±0.47**	**19.84±0.4**	**17.85±0.77**	**12.55±0.48**	**17.89±0.55**	13.4	6.7	10.8	5.4
		C_{AW-MD}	**9.44±0.24**	**10.97±0.49**	**9.17±0.18**	**9.83±0.36**	**8.31±0.22**	**9.54±0.32**				
		C_{EW-MD}	**6.07±0.12**	**7.12±0.09**	**6.83±0.14**	**5.72±0.10**	**6.53±0.18**	**6.45±0.13**				
	F1-3	C_{AW-MD}	**16.03±1.66**	**14.45±0.68**	**16.54±0.78**	**16.96±2.59**	**10.21±0.46**	**14.84±1.47**	5.1	2.5	4.1	2.0
		C_{EW-MD}	**6.66±0.39**	**11.40±0.41**	**7.85±0.56**	**9.09±0.83**	**7.97±0.22**	**8.59±0.52**				
F2	F2-1	C_{AW-MD}	**11.81±0.55**	**10.17±0.37**	**13.03±0.93**	**18.13±1.10**	**11.63±0.71**	**12.95±0.78**	8.3	4.2	4.2	6.7
		C_{EW-MD}	7.52±0.63	12.89±0.67	6.49±0.36	7.82±0.17	13.32±1.09	9.61±0.66				
		C_{AW}	5.94±0.26	5.15±0.11	5.19±0.10	4.36±0.14	4.67±0.07	5.06±0.15				
	F2-2	C_{AW-MD}	**6.70±0.35**	**6.76±0.18**	**6.81±0.48**	**8.82±0.45**	**7.60±0.32**	**7.34±0.37**	5.1	2.7	4.1	2.1
		C_{EW-MD}	5.03±0.15	5.00±0.17	5.05±0.12	3.81±0.11	4.56±0.22	4.69±0.16				
		C_{AW}	4.17±0.16	4.18±0.14	3.51±0.16	3.32±0.11	2.95±0.11	3.63±0.14				
	F2-3	C_{AW-MD}	**8.41±0.19**	**7.99±0.21**	**8.34±0.21**	**7.78±0.17**	**7.28±0.12**	**7.96±0.18**	5.5	3.2	4.4	2.5
		C_{EW-MD}	**6.78±0.28**	**6.06±0.47**	**6.60±0.45**	**6.33±0.08**	**6.53±0.14**	**6.46±0.32**				
		C_{AW}	5.70±0.22	5.52±0.14	5.36±0.14	5.00±0.10	5.20±0.08	5.36±0.14				

[a]These values have been calculated based on the Spanish national regulations.
[b]Bold numbers indicate that the value is higher than the REHVA recommended ACH value assuming the COVID-19 rule-based occupation.

$0.54 \, m^3/h$ [42,43].

The Wells-Riley method assumes a steady-state infectious particle concentration that varies with the VR and well-mixed room air. In consequence, it supposes a limitation in large rooms where the virus concentration is not necessarily well-mixed in the air. Moreover, the quanta emission rates are currently being researched, are not definitive and the uncertainty of these values is high [13, 44,45].

3. Results and discussion

3.1. Ventilation rate assessment

This section shows the results from the field measurement campaign carried out in the selected classrooms at both locations. In this study, occupancy has been considered at a normal scenario (100% occupancy) and COVID protocol scenario (reduced occupancy as a measure taken during the reopening of the centers to minimize the transmission of SARS-CoV-2 in educational centers in 2021). Table 4 and Fig. 2 show the results obtained from the tests performed in the Azurém Campus.

In addition, Table 5 and Fig. 3 show the results obtained from the tests performed at Fuentenueva Campus.

It should be noted that those classrooms with mechanical ventilation systems (C_{MV}) either do not have windows, or they are not operable, so these spaces cannot be naturally ventilated. Such classrooms were only found in the Azurém Campus. All the classrooms in the Fuentenueva Campus had no mechanical ventilation system, so they could only be ventilated naturally through doors and windows.

In this sense, the mechanically ventilated spaces of the Azurém Campus were among the lowest ACH values (ranging from 1.8 to 3.5 h^{-1}). Since it is not possible to establish another ventilation strategy for this type of classroom, the only possible action to increase the VR is to modify the mechanical ventilation system. If these results are compared with the ventilation requirements of the Portuguese regulations, none of the mechanically ventilated classrooms meet the minimum ventilation requirement, assuming 100% occupancy. Moreover, if it is taken into account that the REHVA recommendation to prevent the transmission of airborne disease is more restrictive, the REVHA recommended ACH value is not reached in any of the cases.

Regarding the naturally ventilated classrooms, the ventilation strategies have been defined based on the characteristics of the classrooms. In the Azurém Campus, the configuration that provides the highest ACH value is C_{AW-MD}, whereas the one that provides the lowest is C_{AW}. From the results obtained it can be concluded that, assuming 100% occupancy for each of the classrooms, it is possible to implement at least one window and door opening configuration that provides the VR required by the Portuguese ventilation regulations. Nevertheless, in the case of the mechanically ventilated classrooms, in the 100% occupancy scenario none of the ventilation configurations provides a VR that reaches the REHVA recommended value (except for the A1-1 C_{AW-MD} configuration). However, if the COVID occupancy scenario is considered, the C_{AW-MD} cross-ventilation configuration provides a VR that reaches the REHVA's recommended ACH.

In the case of the Fuentenueva Campus, only two of the classrooms evaluated have two access doors (F1-1 and F1-2), see Fig. A9 and A10 in Annex A. In this case, the opening of both doors and all windows (C_{AW-2D}) is the ventilation configuration that provides the highest ACH (17.9–20.1 h^{-1}). In contrast, the configuration that provides the lowest ACH is the C_{AW}. As in the results obtained in the tests performed at the Azurém Campus, and assuming the 100% occupancy scenario, there is at least one natural ventilation strategy for each classroom that provides the VR required by the Spanish ventilation regulations. As this VR requirement is more restrictive than the REHVA recommendations, all of the natural ventilation configurations that reach the minimum required by the Spanish
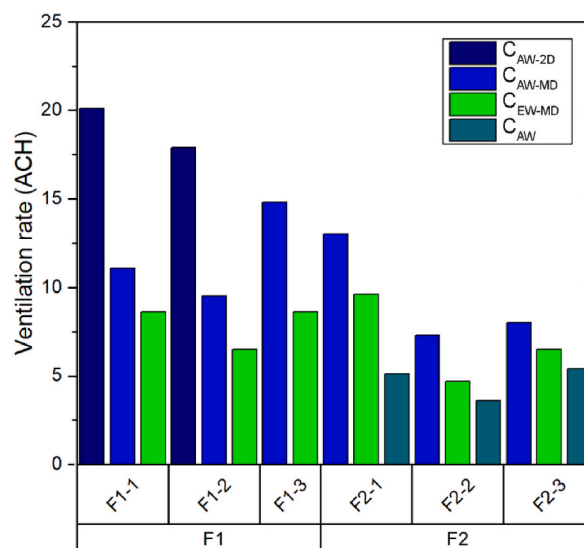

Fig. 3. VR results obtained from the measurement campaign carried out at Fuentenueva Campus.

regulations, provide a higher VR value than the REHVA recommendations.

In summary, in both locations, the cross-natural ventilation configuration (i.e. C_{AW-MD} and C_{AW-2D}) provided more effective air renovation than the single-side ventilation configuration (i.e. C_{AW}). Moreover, it should be pointed out that the possible configurations that can be implemented in each classroom depend on its characteristics and, hence, the VR that is possible to achieve with these strategies is conditioned by the classroom design.

3.2. CO_2 concentration and infection rates estimation

The CO_2 concentration inside the classrooms was estimated based on the results obtained in the field measurements and the occupancy. Additionally, the probability of COVID infection risk has also been estimated. A 2 h duration was assumed to calculate the probability, due to the fact that it is the average lecture time in both universities. The results obtained are shown in Table 6.

The CO_2 concentration results, assuming normal occupancy (100%), show that the values obtained in more than 50% of the scenarios in Azurém Campus are above 1000 ppm, where the C_{AW-MD} configuration is the one with the lowest concentrations. In the COVID occupancy scenario, most of the classrooms have CO_2 concentration levels below 1000 ppm, except for classrooms with mechanical ventilation systems and the single-side natural ventilation configuration C_{AW}.

Regarding the results obtained for the Fuentenueva Campus, the estimated levels of CO_2 concentration in the classrooms assuming normal occupancy (100%), show that most of the classrooms exceed the limit of good ventilation recommended by REHVA, with the C_{AW-MD} and C_{AW-2D} configurations (configurations with all possible windows and doors open) providing the best results. These results are similar to those obtained at the Azurém campus. In the case of the COVID occupancy scenario, all ventilation configurations show CO_2 concentrations below 800 ppm.

As can be seen, the CO_2 concentration in indoor spaces is related to different factors such as the volume of the space, the VR and the number of CO_2 generation sources (i.e. occupants). Fig. 4 shows the estimated CO_2 concentrations based on these factors. Given that CO_2 concentration is a parameter that has been recommended for the assessment of the effectiveness of indoor ventilation, this color map can be used to quickly identify how to adapt these factors in order to ensure that the CO_2 concentration limits are not exceeded. From this figure and to accomplish the required limits, the following measures could be adopted: (1) limitation of space occupancy, (2) increase of VR or (3) mixture of both options.

The first option requires limiting the number of occupants in the room to ensure that the CO_2 concentration remains below the limit. This measure has to be implemented in those spaces where the maximum achievable VR is limited (e.g. classrooms with mechanical ventilation systems sized below the required or recommended ACH value, ventilation limitations arising from design

Table 6

CO_2 concentration results according to the expected classroom occupancy (normal occupancy and COVID protocol occupancy).

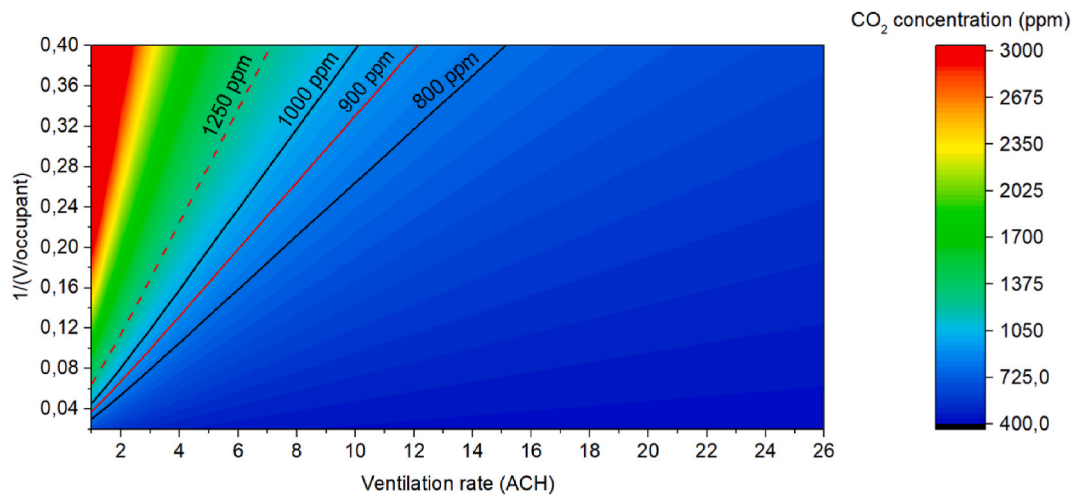| Building	Room	Normal Occup.	COVID Occup.	Ventilation configuration	ACH	CO_2 Steady-State Normal occup.	Covid occup.	Probability of infection
A1	A1-1	48	24	C_{AW-MD}	10.4	745	585	0.36%
				C_{EW-MD}	6.3	960	695	0.56%
				C_{AW}	3.2	1487	967	0.94%
	A1-2	80	40	C_{MV}	3.5	1641	1039	0.67%
A2	A2-1	53	27	C_{AW-MD}	8.4	915	676	0.48%
				C_{EW-MD}	7.4	983	712	0.54%
				C_{AW}	2.0	2516	1513	1.40%
	A2-2	122	60	C_{MV}	2.6	2520	1463	0.69%
A3	A3-1	41	23	C_{AW-MD}	6.8	925	709	0.61%
				C_{EW-MD}	2.9	1612	1104	1.19%
				C_{AW}	2.1	2068	1367	1.45%
	A3-2	60	30	C_{MV}	1.8	3903	2201	1.96%
A4	A4-1	30	19	C_{AW-MD}	5.9	949	762	0.85%
				C_{EW-MD}	4.1	1183	915	1.14%
	A4-2	130	65	C_{MV}	1.8	2765	1577	0.62%
F1	F1-1	156	78	C_{AW-2D}	20.1	644	530	0.08%
				C_{AW-MD}	11.1	829	624	0.14%
				C_{EW-MD}	8.6	949	685	0.18%
	F1-2	156	78	C_{AW-2D}	17.9	670	544	0.09%
				C_{AW-MD}	9.5	895	657	0.16%
				C_{EW-MD}	6.5	1117	769	0.23%
	F1-3	91	45	C_{AW-MD}	14.8	534	475	0.07%
				C_{EW-MD}	8.6	619	518	0.12%
F2	F2-1	76	38	C_{AW-MD}	13	770	559	0.20%
				C_{EW-MD}	9.6	896	610	0.26%
				C_{AW}	5.1	1321	782	0.45%
	F2-2	62	32	C_{AW-MD}	7.3	825	556	0.22%
				C_{EW-MD}	4.7	1052	634	0.31%
				C_{AW}	3.6	1247	701	0.39%
	F2-3	61	35	C_{AW-MD}	8.0	651	553	0.20%
				C_{EW-MD}	6.5	706	585	0.24%
				C_{AW}	5.4	765	619	0.28%

Fig. 4. CO_2 concentration (color map) as a function of the VR and the ratio of occupant and volume in indoor spaces. Portuguese limit CO_2 concentration (dashed red line); Spanish limit CO_2 concentration (solid red line) and REHVA recommended CO_2 concentration (both solid black line, 800 and 1000 ppm). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

characteristics, etc.) For example, as can be seen in Fig. 4, if the objective is to maintain the CO_2 concentration at a level of 1.000 ppm in a classroom whose volume and ACH is 300 m^3 and 4 h^{-1} respectively, the maximum occupant/volume ratio in that scenario is 0.10 occupants•m^{-3}. i.e., 30 occupants. However, many teaching spaces are designed for high volume occupancy with a low VR, so severely limiting the number of occupants can lead to under-utilization.

Regarding the second option, the VR can be increased in those spaces where the CO_2 concentration limit is exceeded while maintaining a 100% occupancy. This measure is easily implemented in mechanically ventilated spaces where the size of the ventilation system can be increased. However, ACH values above 10 are hardly achievable through natural ventilation, which is the system mostly used in the analyzed classrooms. This is similar in other European countries, where most schools (86%) use natural ventilation; 7% of schools use assisted ventilation and 7% of schools use mechanical ventilation [18]. For example, classroom A2-2, (whose volume and occupancy is 341 m^3 and 120 seats, respectively) requires 15 h^{-1} to maintain the CO_2 concentration at a level around 1000 ppm (as shown in Fig. 4). Moreover, in continuously naturally ventilated classrooms with high ACH values, IEQ variables (such as temperature or pollutants) are closely related to the outdoor environment. Therefore, keeping the indoor temperature in a comfortable range will require higher energy consumption in the heating and cooling systems of educational buildings. Consequently, in many cases, adapting spaces to limit the level of CO_2 concentration may require a combination of the aforementioned measures, i.e., both increasing the ventilation strategy to achieve a minimum ACH value while limiting the number of occupants.

With respect to the analysis of the values obtained for the probability of infection using the Wells-Riley equation (Equation [8]) (Table 6), it is possible to conclude that all classrooms have a probability of infection of less than 1%, exception the scenarios of
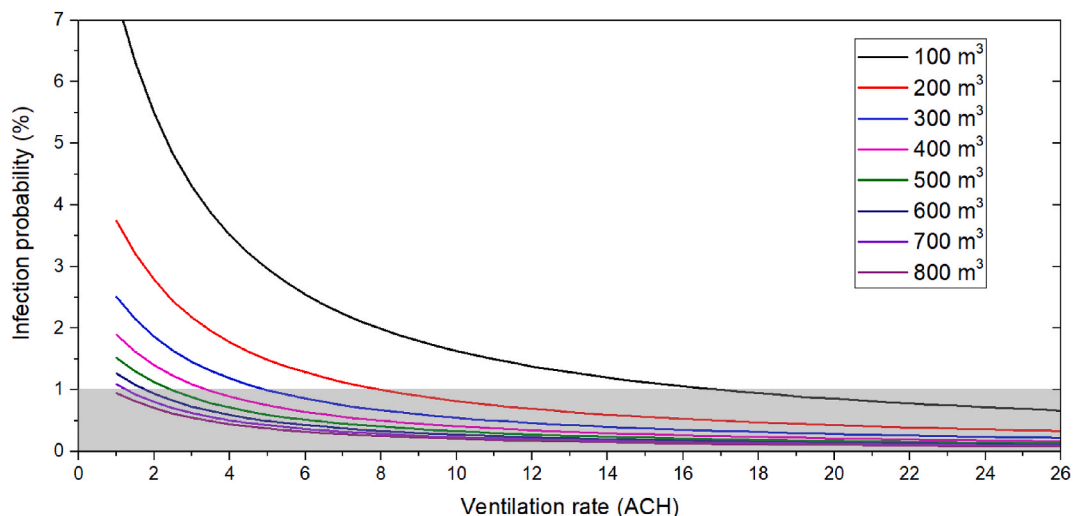

Fig. 5. Infection probability as a function of ventilation rate and different dimension of classroom, estimated using the Wells-Riley equation.

Azurém Campus for classrooms A2-2 (C_{AW}), A3-1 (C_{EW-MD} and C_{AW}), A3-2 (C_{MV}) and A4-1 (C_{EW-MD}). Therefore, it can be seen that, although in the estimation of CO_2 concentration we obtain values above 1000 ppm, it does not necessarily imply a high probability of infection risk. Therefore, although a high level of CO_2 concentration indicates poor ventilation, it does not establish a high risk of airborne transmission in the case of COVID-19. In this regard, the duration of the class, the occupancy and the dimensions of the room should be taken into account when assessing the COVID-19 airborne transmission risk.

The individual infection risk calculated for different classrooms as a function of VR and volume, assuming a class duration of 2 h, is shown in Fig. 5. As expected, higher VR ratios provide probabilities of infection of less than 1%. Furthermore, according to the Wells-Riley equation, the higher the volume of the room, the lower the concentration of the virus, resulting in lower individual infection risk. As can be seen in Fig. 5, ACH of $17\,h^{-1}$ is required in a typical $100\,m^3$ classroom, compared to $8\,h^{-1}$ in a 200 m3 classroom. As shown in Tables 4 and 5, the most common natural ventilation ACH values are between 2 and $9\,h^{-1}$, for the tested classrooms. To achieve higher values of VR, the required ventilation strategies are configuration solutions of the type C_{AW-MD} and C_{AW-2D} (i.e. ventilation strategies with all possible windows and doors open). These types of natural ventilation strategies also present problems due to their impact on the recommended IEQ factors, especially those related to thermal and acoustic comfort [46–48].

In the case of mechanically-ventilated classrooms, achieving such high levels of VR results in an increase in energy costs, with the possible consequence of non-compliance with energy saving regulations. Consequently, the selection of teaching/learning spaces and ventilation strategies is a crucial process in the management and adaptation of university spaces to such pandemic events.

In summary, while the results of this study show that it is important to analyze and select an appropriate ventilation strategy and configuration inside classrooms, the characteristics of some of these spaces (number of windows, configuration of the mechanical ventilation system, etc.) limits achieving a suitable VR. This fact is decisive in ensuring that the use of educational spaces is safe and healthy in the face of such an alarming situation as the COVID global pandemic.

The retrofitting of public spaces to make them more sustainable through the adoption of strategies, measures and constructive solutions has been a concern at European level, with a particular focus on educational buildings. Directive 2010/31/EU sets targets for reducing energy consumption with the aim of "*promoting the improvement of the energy performance of buildings*". Specifically, the directive states that all new buildings should be Nearly Zero Energy Buildings by 2020 and public buildings by 2018.

In this context, the retrofitting and renovation process of existing educational buildings offers an exceptional opportunity to not only take into account improvements in the energy performance of buildings but also, to ensure retrofitting measures that will guarantee an adequate IAQ after the renovation, at the design phase of the building. However, given that retrofitting interventions require a high level of time and money for the design and execution of works, building managers may be limited in adapting buildings. In these cases, where the required IAQ standards are not achieved, organizational measures and ventilation strategies must be implemented to minimize the IAQ impact on occupants' health, despite the possible under-utilization of spaces.

Finally, if these conclusions are going to be extrapolated to other situations or contexts, it should be taken care of some characteristics of the methodology or the experimental setup presented in this study that may condition further results, coming from the influence of the effect of indoor and outdoor environmental conditions. In fact, the local and particular conditions of each indoor space, as well as the wind speed and outdoor temperatures are critical variables and the validity of the results are conditioned on compliance with the values used in the experimental tests used in this research. Since this study assesses continuous natural ventilation strategies, the indoor environmental condition is highly affected by the outdoor conditions, and in our research, the indoor air temperature was close to the outdoor air temperature, so when there is a significant thermal gradient, the results obtained should be revised.

In addition, risk control of infection through natural ventilation has some constraints as it was stated in Ref. [49]. The natural airflow rate is generated by two driving forces (wind and temperature difference), and they may change quickly. For example, the normal operation of natural ventilation systems may be affected by unfavorable weather conditions or windows or doors not opened [49–51], possibly changing the direction or velocity of room outdoor winds. For these cases and since the probability of infection risk increases if ACH decreases (Wells-Riley equation model (8)), the influence of these parameters is relevant, and, for example, in lower wind condition, ACH will decrease and the risk of infection may increase [49]. Consequently, the effects of these factors should be analyzed and considered if different climatic circumstances apply for each experimental situation.

4. Conclusion

In this study, field measurements were carried out in order to analyze ventilation strategies in educational buildings located in Southern Europe. Two university campuses (the Azurém Campus in Portugal and Fuentenueva Campus in Spain) were selected and ventilation tests were conducted in representative classrooms at both locations. Based on the analysis and discussion of the obtained results, the following conclusions can be drawn:

- Ventilation strategies have to be reconsidered as a consequence the COVID-19 pandemic emergency. The results obtained from measurements of natural ventilation strategies show that the selection of the appropriate combination of door and window openings can provide sufficient air renewal. The VR value obtained ranged from 2.0 to $20.1\,h^{-1}$, indicating that the selection of the correct combination is not trivial but requires consideration by building managers. In addition, cross-ventilation strategies provide much more effective air renewal (i.e. C_{AW-MD}) than single-sided opening strategies (C_{AW}).
- Regarding mechanical ventilation systems, given that the spaces do not have accessible windows to provide additional natural ventilation, it is not possible to implement hybrid ventilation strategies. The VR value obtained in the mechanically ventilated classrooms ranged from 1.8 to 3.5 h^{-1}. Therefore, retrofitting interventions should consider increasing the VR of mechanical ventilation systems to make the buildings more resilient to future pandemics.

- Indoor CO_2 concentration shows a wide dispersion with the different ventilation configurations, ranging from 534 to 3903 ppm, considering the sizing and occupancy of the original room design. In some cases, these obtained values are higher than those recommended by the WHO for indoor educational spaces. However, with the protocol for the reduction of room occupancy due to COVID-19 during the academic year 2020/2021, the CO_2 concentration is significantly reduced, ranging from 475 to 2201 ppm (a reduction between 11 and 44%).
- Regarding the infection risk, it is only higher than 1% in four of the scenarios studied (A2-2, A3-1, A3-2 and A4-1). The analysis of the results has shown that, although the estimated CO_2 level is above the REHVA recommended level for good ventilation, it does not necessarily imply that the risk of infection is higher.
- The characteristics and equipment in classrooms influence the possible ventilation strategies that can be implemented. For this reason, and given the limitation to achieve adequate indoor air quality, retrofitting interventions in teaching spaces should not only prioritize energy efficiency, but should also ensure the IAQ is safe for the occupants. In the case of buildings where retrofitting is not possible in the short term, ventilation strategies should be analyzed and protocols (e.g. occupancy limitation, ventilation strategies, etc.) should be established to ensure that they are safe for use.

Finally, in light of the consequences of the recent COVID-19 pandemic, the ventilation rate of buildings must be improved, either through adaptations of spaces or the adoption of protocols, to ensure that they are safe for occupants to use. Additionally, it is recommended that an action plan be developed that establishes protocols that not only meet national indoor air quality standards, but also activate previously established protocols, in the event of a new outbreak of an airborne virus. This rapid response will enable the continued safe use of spaces without disrupting the learning of millions of students around the world. Future research should address the development of monitoring devices (e.g. IEQ sensors) where, apart from CO_2 concentration, the assessment of infection risks and indoor ventilation needs to be evaluated.

Author statement

Antonio J. Aguilar and María L. de la Hoz-Torres: conceptualization, performed the experiments, formal analysis, carried out the post-processing and supervised the manuscript; **Nélson Costa and Pedro Arezes**: conceptualization, resources and supervised the manuscript; **Mᵃ Dolores Martínez-Aires and Diego P. Ruiz**: conceptualization, resources, project administration, funding acquisition and supervised the manuscript.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2022.104204.

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