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IMPROVING INDOOR AIR QUALITY OF NATURALLY VENTILATED CLASSROOMS IN THE NORTHEAST OF PORTUGAL

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Abstract

This article addresses CO_2 dynamics in school classrooms and analyses the improvement of ventilation and indoor air quality resulting from the simple window-opening ventilation strategies. CO_2, temperature and relative humidity were measured in four different naturally ventilated classrooms of a Northeastern Portuguese education institution for a wide range of environmental conditions. Indoor CO_2 levels were also simulated with a numerical model to help manage the indoor air quality of these spaces through scenario analysis. The results stressed that the occupants were potentially exposed to uncomfortable and unhealthy indoor air quality conditions, since ventilation occurs primarily through infiltration. Under low ventilation conditions, CO_2 concentrations easily exceeded the standard of 1250 ppm, even for occupation rates lower than 50%. To provide healthy indoor air to the occupants, acceptable and affordable ventilation rates can be assured by opening at least a small window for a few minutes over the typical 60 minute class period or during class breaks. For occupation rates close to the nominal capacity of classrooms, longer periods and larger opening areas are required to reduce the discomfort and health risks from potential exposure to indoor air pollutants.

Key words: air exchange rate, carbon dioxide, measurement, modelling, school

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1. Introduction

Indoor air quality (IAQ) in schools has received particular attention in recent years (Salthammer et al. 2016) with many researches carried out worldwide (e.g. Bakó-Biró et al., 2012 (United Kingdom); Daisey et al., 2003 (USA); Madureira et al., 2016 (Portugal); Fuoco et al., 2015 (Italy); Godwin and Batterman, 2017 (USA); Hou et al., 2015 (China); Jovanović et al., 2014 (Serbia); Jurado et al., 2014 (Brasil); Rosbach et al., 2013 (Netherlands); Synnefa et al., 2003(Greece)), as many of these built structures are poorly ventilated and have occupancy rates generally higher than other categories of buildings. Most school buildings were built a few years or even decades ago when indoor air quality was not a major concern and, therefore, they tended to be more air tight. Many of the existent school buildings have been refurbished with HVAC systems, but to reduce energy costs they are rarely used. Under conditions of insufficient ventilation, a classroom even with an occupancy rate not too high can quickly be loaded with carbon dioxide and other indoor contaminants such as formaldehyde, total volatile organic compounds (TVOC) and aerosols (Chatzidiakou et al., 2012; De Giuli et al. 2012; Mentese et al., 2018; Salthammer et al. 2016; Viana et al., 2013).

In the last decade many studies have investigated levels of specific pollutants in school environments, but the majority of them have been focused on CO_2 levels and ventilation rates (Bakó-Biró et al., 2012; Griffiths and Eftekhari, 2008; Santamouris et al., 2008; Turanjanin et al., 2014). In fact, carbon dioxide has been commonly measured as a screening procedure to evaluate ventilation and indoor air quality. Although it has been widely

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recognized that complaints related to IAQ in schools are not directly related to CO_2 itself, its indoor concentrations correlate well with the insufficient supply of fresh air and the increase of various contaminants inside the building (Daisey et al., 2003; Jones and Kirby, 2012; Latif et al., 2018; Mudarri, 1997), particularly with the indoor bioeffluents (e.g. body odors) (ASHRAE, 2013; Godish, 1989). More recently CO_2 measurements gain even more relevance because CO_2 itself has been also associated with adverse effects, especially of cognitive nature with negative consequences in learning performance for the typical concentrations found in classrooms (Kajtar and Herczeg, 2012; Satish et al., 2012).

The common CO_2 limit established in many countries ranges between 1000 and 1500 ppm usually over a day (8-hour average), with a 5000 ppm exposure being the maximum tolerable concentration for health safety (ASHRAE, 2013; Griffiths and Eftekhari, 2008; Roulet, 2008). Portuguese standards, updated in late 2013, established the CO_2 limit in 1250 ppm with a tolerance margin of 30% for existing buildings and new ones without HVAC systems (MESPEHSESS, 2013), following the ASHRAE Standard 62.1 (ASHRAE, 2013) that recommends an indoor-outdoor differential concentration not exceeding 700 ppm. In practice, these CO_2 levels are associated to a minimum ventilation rate around 7 liters per second and per person for sedentary activities, in accordance with the ASHRAE recommendation rate to dilute offensive pollutants (Dougan and Damiano, 2004).

As reported by Salthammer et al. (2016), observed CO_2 concentrations in classrooms feature a broad regional variability ranging on average from outdoor typical levels (about 400 ppm) to maximum values higher than 5000 ppm, well above the aforementioned standards. Schools should therefore adopt measures to prevent and control indoor air quality problems such as providing sufficient outdoor air to dilute indoor contaminants to levels that are not harmful to human health and do not have a negative impact on occupant perceptions of the indoor environment (ASHRAE, 2013; De Giuli et al. 2012; Jones and Kirby, 2012). Although ventilation can be efficiently done by means of mechanical ventilation systems, in existing buildings with these systems either not installed or out of operation, the manual or automatic opening of windows and/or doors can be the most useful solution to ventilate classrooms, especially in mild climate regions (Griffiths and Eftekhari, 2008; Salthhammer et al., 2016; Wang et al., 2014). Stazi et al. (2017) developed and tested an automatic window-operating system driven by an adaptive control algorithm that, combining both temperature and CO_2 concentration inputs. In situations where no automatic control system for windows opening and closing exist, simple questions such as “how many windows should be open in a given space under certain conditions?” or “how long does a window or several windows need to be opened to properly ventilate a room under certain outdoor conditions?” need to be answered to help school staff define a plan able to assure safe and comfortable indoor environments to occupants of these spaces.

Although there are many experimental and modeled studies addressing indoor air quality in naturally ventilated buildings (Mishra and Ramgopal, 2015; Stabile et al., 2017), information is limited and not always clear regarding the simple window-opening ventilation strategies, which are fundamental to improve ventilation in air tight buildings where control measures only comprise single, voluntary and not systematic actions, usually triggered upon the occurrence of discomfort conditions or critical situations. In this context, Silva et al. (2017) applied a numerical computational fluid dynamic (CFD) model to quantitatively assess the impact of several proposed improvement measures, based on window/door opening strategies. Over the last years, CFD has been largely adopted as an efficient tool to simulate the indoor air flow and indoor air quality of several typologies of buildings and spaces, including its application to school buildings (Li, 2012; Gilania et al., 2016; Guo et al., 2015). One of its main advantages over other tools is its ability to simulate a wide range of configurations. However, CFD models are time-consuming, often difficult to set up, and their application requires much specialized knowledge (Li et al., 2014). Furthermore, they continue to present problems of reliability and for practical situations simpler models may be more useful.

This study analyses CO_2 levels and the overall ventilation rates of four naturally ventilated classrooms, with the objective of supporting indoor air quality management strategies based on window opening and closing practices. Additionally, a simple well-mixed zonal model was used for evaluating the data reliability, to better understand the experimental results and to demonstrate its usefulness to quantitatively assess the impact of improvement measures, through scenario analysis.

This study also provides a significant structured set of indoor air quality data and a comprehensive and detailed analyses for a region where there is still an important gap concerning IAQ meeting the European recommendations regarding the need for measuring IAQ in Schools (SCHER, 2007).

In the next sections, besides to the methodological and model description, temporal profiles of measured and modeled CO_2 concentrations, air renewal rates and scenario analysis are described and discussed.

2. Materials and method

This section addresses the main physical characteristics of the classrooms, the experimental setup and a brief description of the model used to predict the indoor CO_2 levels.

2.1. Location and characteristics of the classrooms

This study was carried out in classrooms of a higher education institution located in the northeastern region of Portugal. The region has a very distinct seasonality with low temperatures in winter, sometimes below 0 ºC, and high temperatures during summer, reaching on average values above 35 ºC. The prevailing winds are from the west and northwest, with annual average speeds between 2 and 3.4 m s^{-1}. According to the latest version of the Köppen Climate Classification (AEMET/IM, 2011), this region is classified as a temperate region with dry and mild summers.

Experiments were conducted in four distinct classrooms, hereafter identified by the letters A through D. These classrooms are part of two different buildings: classrooms A and B are in building 1, and C and D are in building 2 (Fig. 1).

These two buildings are very close to each other, but they have different layouts, designs and constructive characteristics. Both building envelops have globally good thermal insulation. Building 1 was built in the 1980s, but it was recently subjected to thermal insulation works within the framework of a program for energy efficiency improvements in public buildings. The main physical characteristics of the four classrooms are shown below (Fig. 2 and Table 1).

The four classrooms are differentiable from each other in many physical aspects, but the most obvious is the structural difference between the pairs A/B and C/D. Classrooms A and B are larger in size, have higher side walls, higher volume and floor area per occupant than C and D.

Classrooms A and B also have skylights (roof windows) whose openings are manually controlled. Its doors are arranged in parallel with the casement windows facing the outside; the doors of C and D are perpendicular to its sliding windows. The external walls are masonry double structures, with cement based coating and painted white for A and B, and with apparent brick lining for C and D. All interior walls are a bit thinner when compared with those facing the outside.

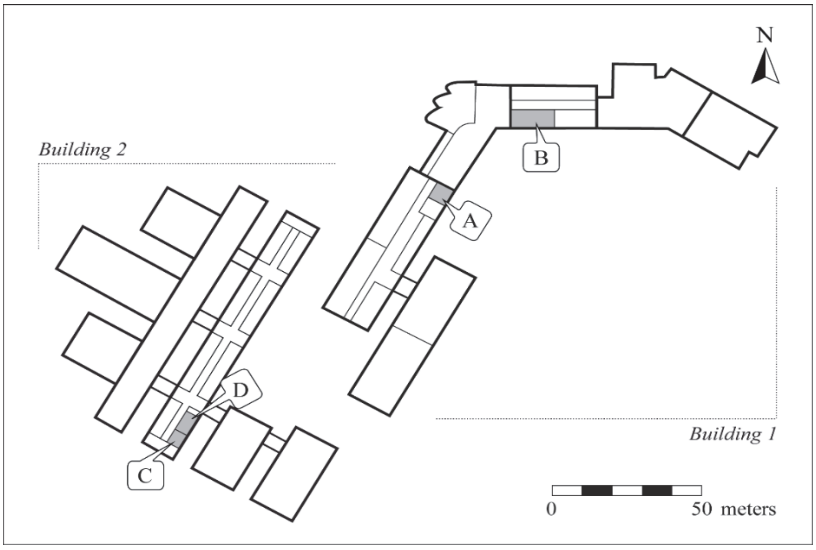

Fig. 1. Location of the classrooms in the two school buildings

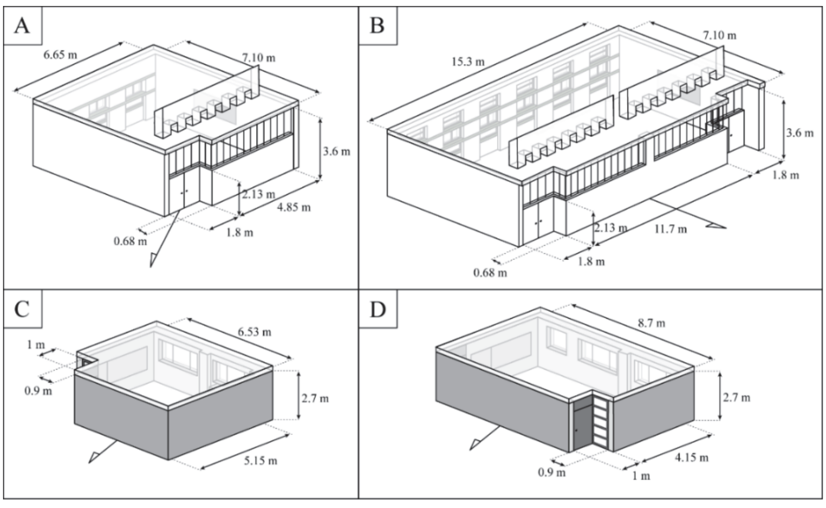

Fig. 2. 3D representation of the classrooms in the two school buildings: (A) Classroom A, (B) Classroom B are larger in size, have higher side walls, higher volume and floor area per occupant than (C) and (D) that represent Classrooms C and D

Table 1. Main physical characteristics of the selected classrooms

Parameter	***Units***	***Classrooms***			
		A	***B***	***C***	***D***
Volume	m^3	166	380	90	120
Floor area	m^2	46	106	33	44
Occupation capacity	persons	30	70	25	38
Openings Number	n.a.	8	16	5	7
Openings Type	n.a.	3 windows, 1 inner door and 4 skylights	6 windows, 2 inner doors and 8 skylights	4 windows and 1 inner door	5 windows and 2 inner doors

The inner wall for classrooms A and B is part masonry and part glass (upper) where the doors are less tight than in C and D. The entrance/exit corner for classrooms C and D is wooden made with a part holding smeared glass. Furthermore, A and B are exposed to higher wind loads than C and D whose facades are relatively protected from wind.

2.2. Experimental Description

The experiments comprised a wide range of weather conditions. CO_2 levels, air temperature and relative humidity were continuously measured for more than 3 months from 9 a.m. to 6 p.m. in each classroom for six different measuring periods, between March and May 2013:

- Classroom A: march 9th and 19th, april 5th and 20th, may 18th and 28th;
- Classroom B: march 7th and 21st, april 2nd and 18th, may 16th and 30th;
- Classroom C: march 5th and 20th, april 3rd and 16th, may 14th and 29th;
- Classroom D: march 6th and 22nd, april 4th and 17th; may 17th and 31st).

All variables aforementioned were obtained by using a GrayWolf DirectSense® IQ-610 probe with non-dispersive infrared (NDIR) detection with a range from 0 to 10,000 ppm (± 50 ppm), attached to a PDA device to store the data (Fig. 3).

The probe was placed in the middle of the classroom at 1.5 meters high to avoid the direct influence of CO_2 exhalation while the occupants were sitting.

The technical recommendation stated by the Work Group of the Portuguese Environment Agency/Reference Laboratory for Environment regarding indoor air quality evaluation (Jardim et al., 2015) was also taken into account in our decision in using one single measuring point. This Work group establishes the need of more than one single measuring point when the building zone area is over 100 m^2. Although more than one single measuring point might increase the accuracy of measurements, main readings from preliminary tests performed by ourselves have shown us that a single measuring point would not compromise the results even in the largest room (106 m^2).

CO_2 concentrations, temperature and relative humidity were measured with an integration time set to 1 minute. To complement this data, physical information of each room was also collected such as the size of the openings, as well as information about the number of occupants, which changed along the day depending on the type, number and duration of classes.

Information regarding the height and weight of the occupants was obtained with a small survey at the end of each class. During classes, a technician conducted some ventilation tests using single or multiple manually-controlled openings. Outdoor weather information (e.g. wind speed, temperature) was also monitored in the institution campus area (10 meters high), to help analyze the ventilation rates through those openings. Outdoor CO_2 concentrations were also measured a few times for a representative period. As for outdoor parameters, the outside wind speed and temperature used as inputs in the model, as well as the relative humidity, were measured in a meteorological station installed in an open area of the campus. Wind direction in relation to facades has been taken into account in all simulations as being perpendicular, which can cause deviations especially for high speed diagonal winds.

2.3. Modeling indoor CO_2 concentrations

2.3.1. Global model description

To better understand indoor air patterns and help in managing CO_2 levels in classrooms, the indoor concentrations were simulated on a minute basis using a simple Eulerian box model. This type of model is based on the material balance of the gas inside a physical confined space, requiring information on sources, sinks and pollutant exchanges with its surroundings (Fig. 4). Furthermore, the model is based on the following assumptions: the gas concentration is homogeneous in the whole space, and source and sinks are uniformly distributed, with pollutants being mixed uniformly and instantaneously (Pepper and Carrington, 2009; You et al., 2012).

Chemical removal and/or absorption of the gas by the walls and other interior surfaces were not taken into account. The dimensions and characteristics of each classroom can affect the natural ventilation used to control CO_2 concentration and they can limit the volume of air entering in each space. The flow of fresh air into each space can, depending on wind speed and thermal difference, dilute the CO_2 concentration. Its production and outdoor levels are also main factors affecting its indoor levels.

Fig. 3. GrayWolf DirectSense® IQ-610 probe and the PDA device

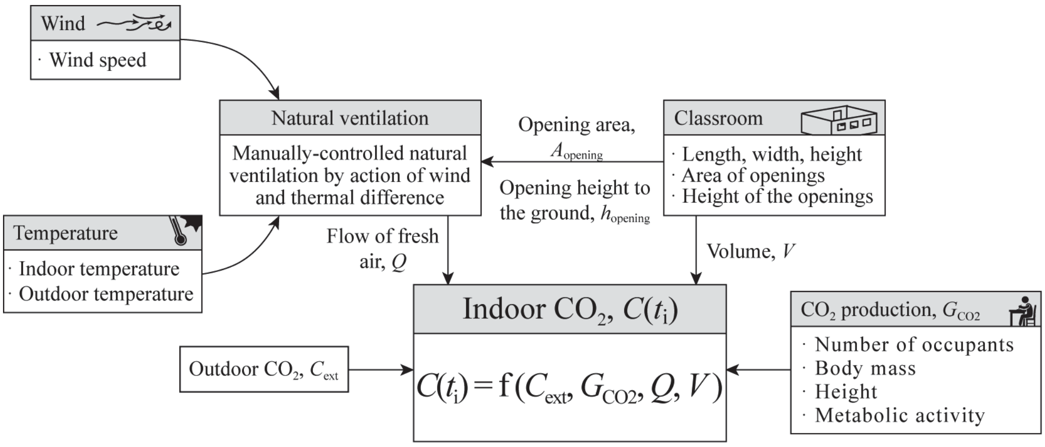

Fig. 4. Conceptual representation of the processes and parameters affecting indoor CO_2 in classrooms

Based on the previous description, temporal evolution of indoor CO_2 concentration is given as follows (CIBSE, 2005, Griffiths and Eftekhari, 2008) (Eq. 1).

$$C(t_\mathrm{i}) = C_\mathrm{ext} + (G_\mathrm{CO2}/Q) + [C(t_0) - C_\mathrm{ext} - (G_\mathrm{CO2}/Q)] \times \exp(-Q \cdot \Delta t_\mathrm{i}/V) \tag{1}$$

where: $C(t_i)$ is the indoor concentration of CO_2 (ppm) at time t_i, C_{ext} is the concentration of CO_2 (ppm) on the outside, $C(t_0)$ is the indoor concentration of CO_2 (ppm) at the beginning of the monitoring, G_{CO2} is the volume rate of CO_2 (m^3 min^{-1}) exhaled by the occupants in the classroom, Q is the fresh air flow (m^3 min^{-1}) entering or leaving the classroom, V is the classroom's volume (m^3), and t is the time interval (=1 min).

2.3.2. Modeling the CO_2 source

The release of CO_2 into the room from the metabolic processes, G_{CO2} (m^3 min^{-1}), was obtained using the expression presented by Nishi (1981), which has been used in several studies (e.g. Aglan, 2003, Meiwei et al., 2013). It is also a practice recommended by ASHRAE (2009) as part of the *Handbook of Fundamentals*. The expression was then simplified (Eq. 2) using the ASHRAE's recommended respiratory quotient of 0.83 (molar ratio between the CO_2 exhaled and the O_2 inhaled).

$$G_\mathrm{CO2} = (0.000157 \cdot A_D \cdot M_b) \cdot n \tag{2}$$

This equation requires information on the occupants' metabolic rate, M_b (met), the DuBois area, A_D (m^2) of body surface (Eq. 3) and the number of occupants, n, in each classroom. M was set to 1.2 met (1 met = 58.15 W/m^2), a value usually used for occupants performing sedentary activities. The body surface area was estimated using the DuBois area (Dubois and Dubois, 1916), which is a very common method still in use (ASHRAE, 2009; Persily, 1997; Qi et al., 2014).

$$A_D = 0.203 \cdot W^{0.425} \cdot H^{0.725} \quad (3)$$

where: H is the occupants' height, in meters, and W the weight, in kg.

So, using this model as a source, an adult person of medium size (H=1.70 m, W=70 kg) exhales about 0.34 L of CO_2 per minute considering a metabolic activity of 1.2 met and a DuBois area of 1.8 m^2.

2.3.3. Modeling natural ventilation

The air exchange in buildings using natural ventilation depends on climate, building design and human behavior, making its calculation a very complex process (Etheridge, 2011). However, taking into account the purpose of this study, a simple set of semi-empirical equations were used to predict bulk ventilation air flow rates through different types of openings - large openings (e.g. windows) and also through the building envelope openings such as cracks and interstices (air infiltration). For openings such as windows and doors air flow is driven by two different effects: pressure effect related to pressure difference between outdoor and indoor environments (pressure-driven force); and stack or buoyancy effect related to temperature difference between outdoor and indoor environments.

Although these types can be found individually, both are commonly found in naturally ventilated buildings, sometimes with one type dominating over the other. In this section both buoyancy and wind-driven natural ventilation are described individually, followed by a description of how they are defined when found together. The following equations are used for single sided ventilation since it represents the natural air flow through a single opening space in a building.

The wind-driven natural ventilation, Q_W (m^3 min^{-1}) (ASHRAE, 2009; Warren and Parkins, 1985) is influenced by several factors such as average wind speed, prevailing wind direction, seasonal and daily variation of wind speed and direction, and also terrain features (local), as described below (Eq. 4):

$$Q_W = E \cdot A_{openings} \cdot U_W \quad (4)$$

where E is the effectiveness of the openings (dimensionless), assuming values around 0.5 for perpendicular winds or between 0.25 and 0.35 for diagonal winds (ASHRAE, 2009), $A_{openings}$ (m^2) is the opening area, and U_W (m min^{-1}) is the wind speed.

The buoyancy-driven ventilation, Q_T (m^3 min^{-1}), was defined by Eq. (5) (Awbi, 1996; Van der Maas et al., 1994), which also depends on the opening area, the absolute difference between outer and inner temperatures, ΔT (ºC or K), the height of the openings from the ground, $h_{openings}$ (m), the acceleration of gravity, g (m s^{-2}), and the coefficient of discharge of the openings, C_D (dimensionless), which usually varies between 0.6 and 0.75 (Larsen, 2006, Larsen, 2008).

$$Q_T = (A_{openings}/3) \cdot C_D \cdot \sqrt{(|\Delta T|/T_{in}) \cdot h_{openings} \cdot g} \quad (5)$$

Concerning the unintentional infiltration air flow, Q_I (m^3 min^{-1}) which is the air passing through cracks and interstices, around windows and doors, and through floors and walls into a building, the ASHRAE basic model was used (ASHRAE, 2009; Colliver, 2000) (Eq. 6).

$$Q_I = 0.0283 \cdot A_L \cdot \sqrt{(C_S \cdot \Delta T) \cdot (C_W \cdot U_W^2)} \quad (6)$$

where A_L (cm^2) is the effective air leakage area (ASHRAE, 2009, Younes and Abi Shdid, 2013), ΔT (K) is the average indoor-outdoor temperature difference, U_W (m s^{-1}) is the wind speed, C_S [(L $s^{-1})^2/cm^4$ K^{-1})] the coefficient of chimney effect and C_W [(L $s^{-1})^2/cm^4$ (m s^{-1})] the wind coefficient. C_S and C_W can be found at ASHRAE (2009) and used according to certain criteria.

The simplicity of this model has made it very popular with important model assumptions being often overlooked. The total ventilation flow, Q, can be found by the following superposition technique, which is considered a robust solution to combine the estimation of several ventilation components (Eq. 7) (ASHRAE, 2009; Klems, 1983; Sherman, 1992; Walker and Wilson, 1993).

$$Q = \sqrt{Q_W^2 + Q_T^2 + Q_I^2} \quad (7)$$

3. Results and discussions

This section has been divided in three main subsections. The first one concerns the global statistics on occupancy rates and indoor air quality parameters for the whole monitoring campaign. The second one reports the temporal patterns of carbon dioxide concentrations (measured and modeled) for the distinct classrooms. The third subsection addresses the air flow rates computed from CO_2 levels. The last subsection describes the results from scenarios analysis.

3.1. Global statistics on occupancy rates and indoor air characteristics

Statistical parameters concerning occupancy rates and indoor air characteristics in the four classrooms during measuring periods (occupied and non-occupied periods) were obtained (Table 2). In general, we see that most of the measurements were performed during classes with occupancy rates below 50% of nominal capacity. Regarding the indoor air quality parameters, 1-minute average CO_2 concentrations ranged between 1100 ppm in classroom B and 2250 ppm in classroom C. As for the 1-minute maximum values, these were somehow higher and exhibited a larger amplitude, varying between 2200 ppm, in B, and over 6000 ppm, in C.

CO_2 concentrations were systematically lower in classrooms A and B than in classrooms C and D, which in part is explained by the lower volume/occupant ratio of C and D.

Indoor temperatures were very similar in all classrooms and exhibited a temporal pattern with low variability. During cold, mild and warm weather periods with opened windows, there were no significant changes in indoor temperature, with a few exceptions involving a combination of openings (e.g. 3 windows or 2 windows + 1 door) for about 10 minutes that resulted in temperature drops ranged between 1 and 2 ºC. Relative humidity remained within the thermal comfort interval, which according to some literature it should be between 30 and 60% (Sundell and Lindvall, 1993; Wolkoff and Kjærgaard, 2007) to avoid health symptoms (RH below 30%) and moisture problems due to the proliferation of contaminants (RH beyond 60 or 70%) (Reinikainen and Jaakkola, 2003; Toftum et al., 1998; Zhang and Yoshino, 2010). Changes in RH induced by the opening of windows were usually below 5%.

3.2. Measured and modelled temporal patterns of carbon dioxide concentrations

To have a better insight into the dynamics of the indoor CO_2, temporal patterns of occupancy and CO_2 levels (measured and modelled) were depicted together for three of the six trials carried out in each space (Fig. 5, Fig. 6). Information on ventilation openings is also shown. Simulated CO_2 levels were obtained by using the model described in the previous section. On average, CO_2 levels exhibited the lowest magnitudes, usually below 1000 ppm, during the morning hours before classes start. When those begin, CO_2 is exhaled and starts to increase, exceeding the legal threshold of 1250 ppm a few minutes later, depending particularly on the occupancy rates. In classrooms A and B, the 1-minute CO_2 levels varied between 500 ppm and 2500 ppm with the maximum values associated to periods of higher occupation and without any window or door opened. In C and D the CO_2 concentrations range from 700 ppm to around 6000 ppm.

During this period there are interruptions in CO_2 concentration while opening a window or a door during the class period. At the end of the class, when students leave the room, the CO_2 source stops until next class begins. Based on the 8-hour mean values, we see that the CO_2 standard quality was slightly exceeded in classroom A. In classroom B, CO_2 concentrations were systematically lower than the legal threshold. In classrooms C and D the situation was somehow different. CO_2 levels reached usually the quality standard around half an hour after the beginning of the first class, and from there the CO_2 levels increased to magnitudes well above the threshold limit, leading to higher and more frequent exceedances.

These two rooms were busier spaces during the monitoring periods and they have lower volumes than classrooms A and B as referred before. Furthermore, these spaces seem to be less ventilated than A and B for the same environmental conditions and similar ventilation opening areas and periods.

Table 2. Occupancy, CO_2 levels, indoor and outdoor temperature and relative humidity, for all the tests in each classroom

Parameter	***Units***	***Classrooms***			
		A	***B***	***C***	***D***
Occupancy:	%				
Mean		20	10	28	24
Maximum		70	39	92	68
Percentile 80		30	19	52	37
CO_2 concentration:	ppm				
Mean		1293	1135	2245	1949
Maximum		2853	2281	6311	5714
Percentile 80		1551	1436	3018	2512
Indoor temperature:	ºC				
Mean		20.8	21.3	21.5	21.9
Maximum		22.6	24.3	25.5	25.0
Percentile 80		22.0	22.8	23.8	23.3
Outdoor temperature:	ºC				
Mean		10.3	13.8	14.0	14.5
Maximum		18.2	22.0	24.3	25.3
Percentile 80		12.6	18.8	21.1	22.4
Indoor relative humidity:	%				
Mean		41	42	48	47
Maximum		53	59	69	67
Percentile 80		45	49	55	54
Outdoor relative humidity:	%				
Mean		58	61	64	60
Maximum		84	92	90	92
Percentile 80		72	79	87	79

The poor ventilation of these spaces is clearly evidenced by the slow and insignificant decreases in CO_2 levels during the breaks between classes. Significant decreases in CO_2 levels below the legal limit are achieved when windows were opened due to its positive effect on the wind and thermal natural ventilation rates (Fig.6, trial D2 and D3). In some situations, the success of this measure can involve the opening of a large area and hope for favorable climatic conditions. In general, the model predicts relatively well the temporal variation of CO_2 within the classrooms, although for C and D the measured values were slightly overestimated. In general, when comparing the descendent parts of both curves, during the controlled openings, the modeled curve decreases faster than the measured one. This can be explained in part because surrounding environmental conditions are probably different from those defined by the model inputs. Classrooms C and D are located in a shelter zone that seems to limit natural ventilation induced by either wind or thermal gradient between the indoor environment and the outdoor surroundings.

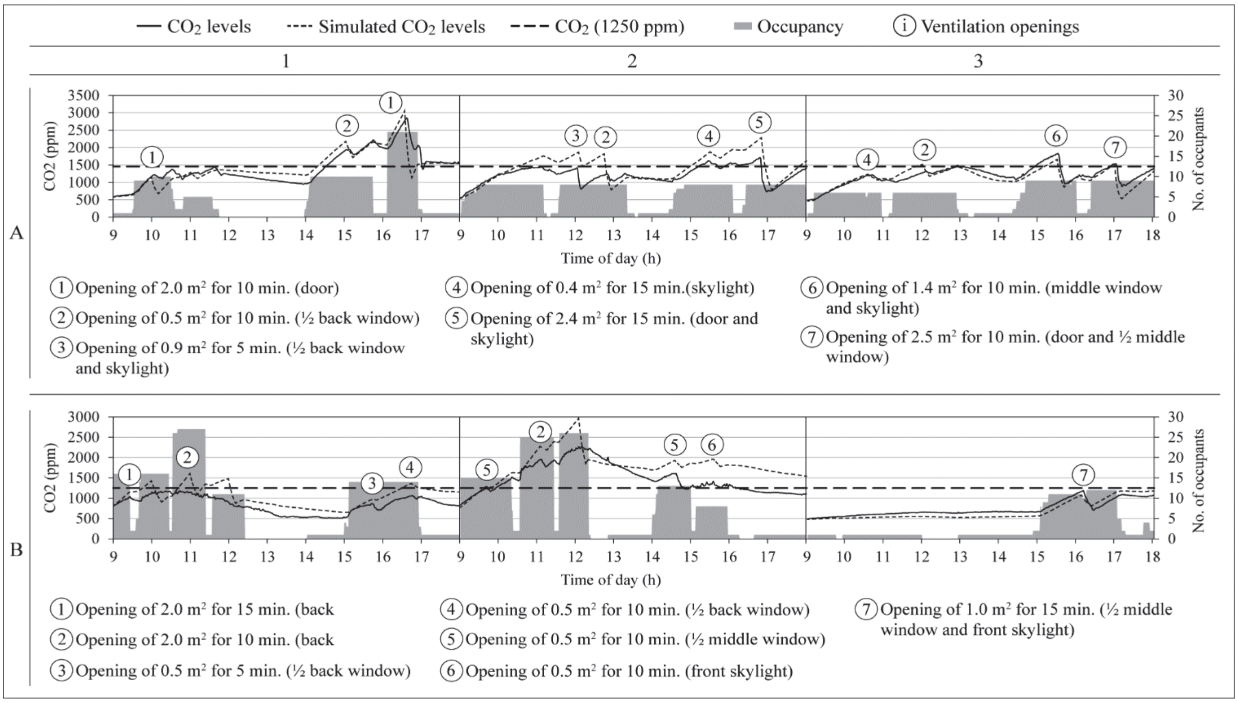

Fig. 5. Temporal variation of measured and simulated CO_2 levels for classrooms (A) and (B)

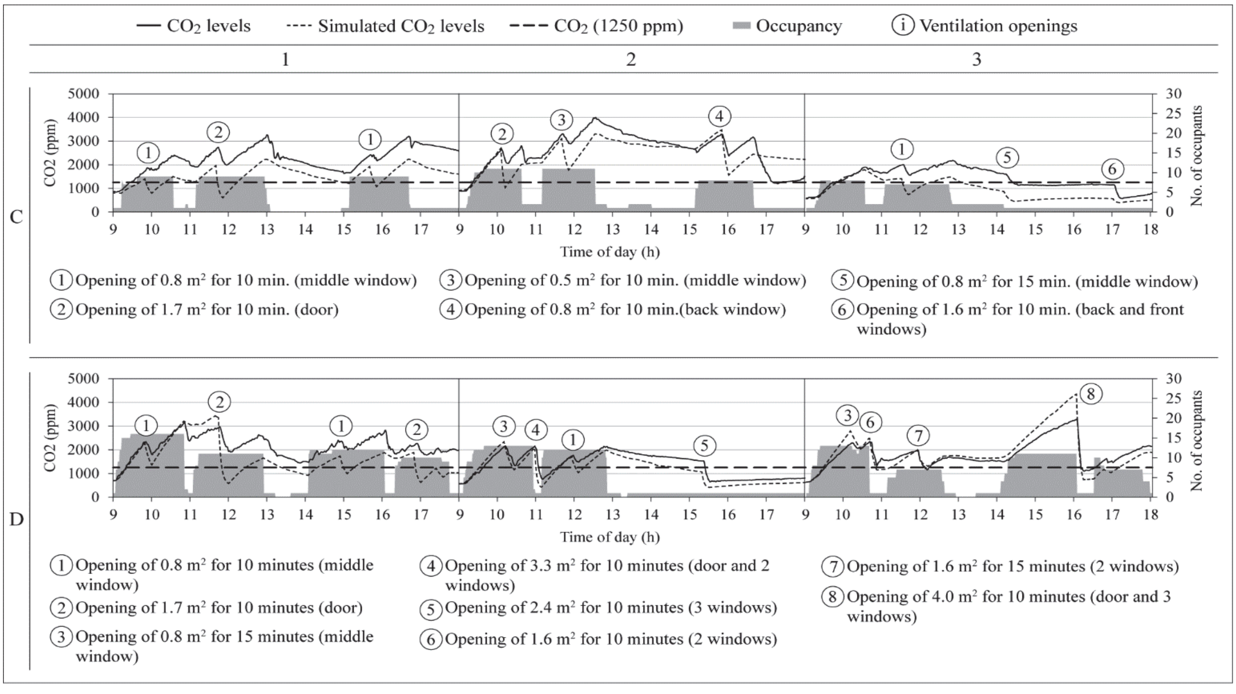

Fig. 6. Temporal variation of measured and simulated CO_2 levels for classrooms C and D

The quality of the simulated values was assessed by using some statistical parameters, which are commonly applied in the evaluation of models performance (Borrego et al., 2008; Hanna et al., 1993; Kumar et al., 2006): correlation coefficient (r), geometric mean bias (MG), geometric mean variance (VG) and index of agreement (d) (Table 3). In general, those parameters show the ability of the model for simulating the dynamics of CO_2 in closed spaces. The correlation coefficient values show a good linearity between simulated and measured data for classrooms A, B and C. For classroom D, the linearity was lower maybe induced by both shadowing caused by surrounding trees or other buildings, and wind turbulence, generating distinct meteorological conditions from those resembled by data collected at 10 meters high. Geometric mean bias and the geometric mean variance indicates that for all classrooms the model predicts the CO_2 levels relatively well, but with some under or overestimation. The index of agreement shows a good association between the variables, which also reinforce the information provided by the correlation coefficient. Further, the index of agreement shows that the variables fluctuate in a very similar way. It is evident that the model predicted well every opening for ventilation, as well as class breaks and ends.

3.3. Natural ventilation air flow rates

As seen in the previous section, ventilation has a great influence on indoor CO_2. To better understand this relationship, measured concentrations of CO_2 were used to estimate the fresh air flow (Q) over time, under transient conditions (Batterman, 2017). This assessment also involved the calculation of CO_2 emission rates as described in section 2.3.2. The calculation of ventilation rates used the Newton-Raphson method (Boyer et al., 1999; Verbeke and Cools, 1995) to solve the governing mass balance equation (Eq. 1). Air exchange rates expressed in changes per hour (CPH, h^{-1}) were also obtained for each classroom, dividing the flow of fresh air, Q (m^3 min^{-1}), by the volume, V (m^3), of the classroom and then converting the time from minutes to hours. The CPH corresponds to the number of times the indoor air of a given space is replaced with fresh air per hour. The ventilation air flow rate per occupant was also calculated for comparison purposes. Both parameters are common indicators found in literature to report the performance of spaces regarding ventilation capability (Bakó-Biró et al., 2012; Santamouris et al., 2008).

Mean CPH values and fresh air flow rates per person are shown below (Table 4). Occupancy rates are also shown for all the classrooms. The analysis was also performed for two different ventilation conditions: non-controlled (ventilation occurring just through infiltration) and controlled natural ventilation (involving ventilation through large openings).

CPH values associated to uncontrolled natural ventilation conditions (without ventilation openings) ranged on average from 0.5 h^{-1} and 0.7 h^{-1}, with building 1 exhibiting CPH values slightly lower than those estimated for building 2. This magnitude is in line with the ventilation air flows observed for several buildings in some European countries (Dimitroulopoulou, 2012), but for classrooms these rates are incompatible with the desired quality standards, being considered a very poor ventilation ability for this type of spaces (You et al., 2012).

Under conditions of controlled natural ventilation, CPH values were much higher, ranging on average between 1.8 h^{-1} and 3.1 h^{-1}. However, values as high as 5 h^{-1} can be obtained for opening areas around 2 m^2 and opening periods of about 15 minutes per hour, under favorable meteorological conditions. This means that keeping the same opening for one hour, CPH values can increase to about 20 h^{-1}.

A comparison between non-controlled and manually controlled natural ventilation conditions for each classroom based on the fresh air flow per person was performed (Fig. 7). This analysis was based on the mean occupancy registered during testing and the nominal occupation capacity of each classroom.

Table 3. Results of the statistical parameters used to evaluate the simulated CO_2 concentration against the measured values

Parameter	***Formula***	***Range of acceptable values***	***Ideal value***	***Classrooms***			
				A	***B***	***C***	***D***
m	n.a.	n.a.	n.a.	3240	3240	3240	3123
Correlation coefficient	$r = \frac{\sum_{i=1}^{N}(M_i - \bar{M}) \cdot (S_i - \bar{S})}{\sqrt{\sigma_M \cdot \sigma_S}}$	0 – 1	1.0	0.77	0.81	0.72	0.65
Geometric mean bias	$MG = \exp(\overline{\ln M} - \overline{\ln S})$	> 0.0	1.0	1.07	0.82	1.11	1.08
Geometric mean variance	$VG = \exp[\overline{(\ln M - \ln S)^2}]$	> 0.0	1.0	1.00	1.04	1.01	1.01
Index of agreement	$d = 1 - \frac{\sum_{i=1}^{N}(S_i - M_i)^2}{\sum_{i=1}^{N}(\lvert S_i - \bar{M}\rvert + \lvert M_i - \bar{M}\rvert)^2}$	0 – 1	1.0	0.87	0.78	0.83	0.77

M_i and S_i represent the indoor CO_2 concentration, measured and simulated, for time = I; M and S represent the average indoor CO_2 concentration, measured and simulated; σ_M e σ_S represent the standard deviation of the indoor CO_2 concentration, measured and simulated

Table 4. Average fresh air flow per person and CPH for each classroom, with and without ventilation openings

Parameter	***Units***	***Classrooms***			
		A	***B***	***C***	***D***
Volume	m^3	166	380	90	120
Occupancy:	No.				
mean		5.7 ± 1.5	6.6 ± 2.3	7.3 ± 3.5	8.8 ± 2.6
maximum		30	70	25	38
With ventilation openings:					
Avg. opening area	m^2	1.11 ± 0.27	1.19 ± 0.28	0.93 ± 0.23	1.37 ± 0.35
Total opening time	min	283	392	441	399
Fresh air flow per opening area	$L\ s^{-1}m^{-2}$	124.34 ± 32.26	223.09 ± 118.08	103.78 ± 86.17	85.33 ± 35.93
Fresh air flow per person:	$L\ s^{-1}$				
at mean occupancy		21.42 ± 9.93	37.96 ± 36.33	12.05 ± 7.96	13.63 ± 10.86
at maximum occupancy		3.78 ± 1.45	2.78 ± 1.27	0.78 ± 0.19	2.73 ± 1.4
Average CPH	h^{-1}	2.46 ± 0.94	1.84 ± 0.84	2.82 ± 0.69	3.11 ± 1.60
Without ventilation openings:					
Fresh air flow per person:	$L\ s^{-1}$				
at mean occupancy		5.09 ± 0.88	7.79 ± 3.52	2.66 ± 1.09	2.64 ± 1.03
at maximum occupancy		0.94 ± 0.21	0.72 ± 0.46	0.19 ± 0.04	0.6 ± 0.25
Average CPH	h^{-1}	0.61 ± 0.13	0.48 ± 0.31	0.67 ± 0.13	0.68 ± 0.29

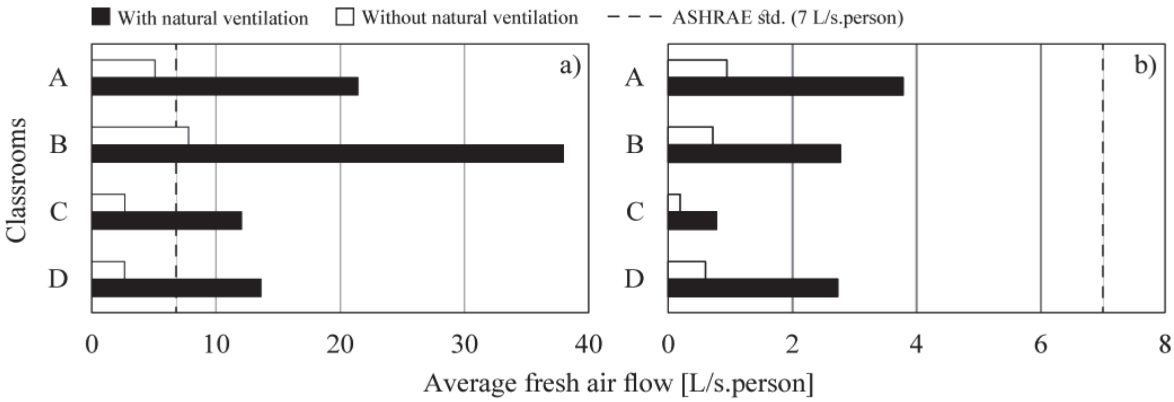

Fig. 7. Average fresh air flow per person, with and without natural controlled ventilation, a) for mean occupancy during testing and b) for maximum occupancy of each classroom

Results show that classroom B provided more fresh air per occupant under uncontrolled ventilation through building cracks and interstices. On average, the room provides fresh air slightly above the recommended value (≈ 7 L s^{-1} $person^{-1}$), but that was not always true, especially when occupancy increased. Higher amounts of fresh air are required to fulfill the ventilation quality criterion. Using data gathered at the time of the openings it was possible to see that the fresh air flowing into the rooms was enough for all the occupants. Taking into account the maximum occupation capacity, results show that the fresh air flow per person was below the ASHRAE recommended value (7 L s^{-1} $person^{-1}$), for controlled and uncontrolled natural ventilation.

To meet that standard, higher ventilation rates are required, and those can be achieved by increasing the opening ventilation area, period or a combination of both. Factors such as outdoor temperature, relative humidity and wind affect the ventilation periods, simply because they are time-dependent variables. The information gathered about these parameters allowed us to understand that they have different patterns during the day, the week and the season

3.4. Scenario analysis

Different scenarios were defined and simulated to evaluate the influence of a window opening strategy on the CO_2 levels for different environmental conditions. Simulations were performed for a classroom with fixed dimensions, different occupation rates and distinct ventilation opening areas and periods, with the purpose of providing generic information, easily understandable and applicable by school staff, teachers or students in managing CO_2 levels in classrooms.

The space tested in these different scenarios was a classroom with a volume of 120 m^3 and with a capacity of 30 persons. Outdoor conditions taken into account in our simulations resemble different Mediterranean climate conditions: cold (4 –10 ºC; 2 –

5 m s^{-1}), mild (10 – 20 ºC; <2 m s^{-1}) and warm (20 – 25º C; <2 m s^{-1}). Room temperature was set to 20 ºC for all scenarios. The initial value of CO_2 was defined as 550 ppm based on background measurements carried out indoors. Sedentary conditions were used to resemble the type of activity performed in most classes.

The base scenario corresponds to what normally occurs during classes. Three additional scenarios were considered, based on realistic conditions/practices, mainly focusing on opening the classroom windows, which could be implemented by school staff or teachers, involving 10 minutes openings during classes and 10 or 20 minutes between classes. During the lunch break the rooms were unoccupied during 90 minutes.

Simulation results (Fig. 8) show that it is possible to maintain CO_2 levels around or below 1250 ppm during a daily period of classes just by opening a very small window a few times along the day.

For the base scenario the occupants will be potentially exposed to unsafe indoor air quality, for the three different environmental studied conditions. The other three scenarios show average CO_2 levels below 1500 ppm regarding cold conditions. When conditions change to mild or warm, only the scenarios with permanent opening (from 9 a.m. to 6 p.m.) and with two openings (during class and break) are close to be a good option for ventilation (average CO_2 below 2000 ppm).

4. Final considerations

This study provides a detailed snapshot on the dynamics of indoor CO_2 in common naturally ventilated (i.e. ventilation based on the simple window-opening strategies) classrooms of school buildings and gives useful orientations for the planning and management of indoor air quality in these spaces. Although it has been based on a case study carried out in the north of Portugal, the main findings can be easily transferable to other worldwide geographical realities, especially for those with a temperate climate with dry and temperate summer.

Our results show clearly that classrooms are systematically under-ventilated, leading to high levels of CO_2 and possibly other pollutants. Indoor CO_2 levels show that under uncontrolled natural ventilation the quality standard is easily exceeded a few tens of minutes after the beginning of the first class of the day. With all windows and doors closed, CO_2 values usually grow up to magnitudes of several thousand ppm, causing a detrimental effect upon the comfort and health of the occupants. These discomfort and health risk conditions can be more critical under cold or windy climate conditions since these environmental conditions prompt school staff, teachers and students to keep all outdoor openings closed over very long periods. This generalized behavior reduces heat losses, assures a better thermal comfort, but can cause a silent negative effect in the occupants.

This reality can be found in many other developed countries and to reverse it, behavioral changes are needed so that efficient and low cost solutions can be implemented, such as setting daily routines for opening external windows for a few minutes many times throughout a workday. For the success of this procedure, it is important that users have control over the ventilation and understand how to manage it. Several tests performed along the present study demonstrated to be possible to provide healthy indoor air to the occupants by opening windows for a few minutes and at least once an hour. It was also evident that for high occupancy rates, sufficient fresh air can be supplied to all occupants, by adopting the simple window-opening ventilation strategy.

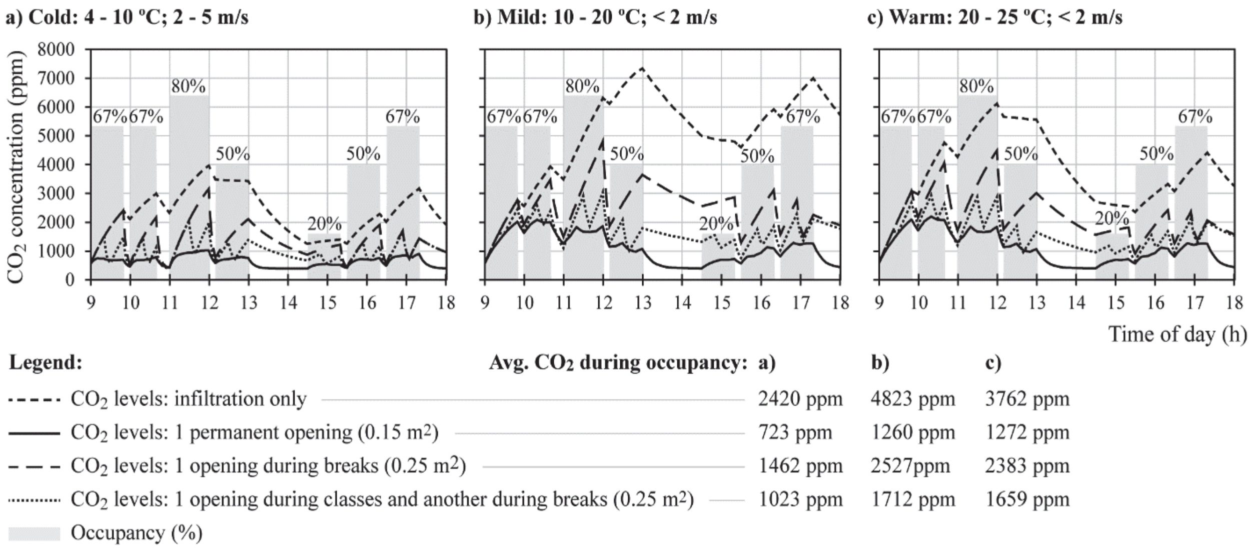

Fig. 8. Simulated CO_2 levels for a daily period of classes regarding four different scenarios, for cold (a), mild (b) and warm (c) weather conditions

However, to meet this healthy quality standard in such conditions, large opening areas and long opening periods may be required causing thermal discomfort sensation to the occupants. Alternatively, automatically controlled opening/closing window systems can be implemented according to the prescribed set points for a given health, hygienic or thermal comfort parameter. If these solutions are not easy to implement, it is recommended to have a more spaced classroom occupation throughout the day or adopt modern top-down natural ventilation as part of a well-designed natural ventilation strategy.

The methodology adopted in this study provided some insight on what can happen to IAQ in naturally ventilated classrooms. Based on the outcomes and observations made during our research, daily routines involving opening of windows can be established as a measure to improve indoor air quality.

Although this way of acting may seem outdated, we should emphasize that the investment and maintenance costs associated to HVAC systems are prohibitive for many institutions leaving them with preferences focused on low cost measures based on simple ventilation systems, manually or automatically controlled.

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Nomenclature

A_D	DuBois area of body surface	m^2
A_L	Effective air leakage area	cm^2
$A_{openings}$	Area of openings of a classroom	m^2
$C(t_0)$	Indoor concentration of CO_2 at the beginning of the monitoring	ppm
$C(t_i)$	Indoor concentration of CO_2 at time t_i	ppm
C_D	Coefficient of discharge of the openings	---
C_{ext}	Outdoor concentration of CO_2	ppm
CO_2	Carbon dioxide	---
CPH	Air exchange rates expressed in changes per hour	h^{-1}
C_S	Coefficient of chimney effect	$[(L\ s^{-1})^2/cm^4\ K^{-1})]$
C_W	Wind coefficient	$[(L\ s^{-1})^2/cm^4\ (m\ s^{-1})]$
d	Index of agreement	
E	Effectiveness of the openings	---
g	Acceleration of gravity	$m\ s^{-2}$
G_{CO2}	Volume rate of CO_2 exhaled by the occupants in the classroom	$m^3\ min^{-1}$
H	Height of the occupants	m
$h_{openings}$	Height of the openings from the ground	m
M_b	Metabolic rate of the occupants	met (1 met = 58.15 W/m^2)
m	Number of comparisons	---
M	Average concentration of CO_2 measured indoors	ppm
MG	Geometric mean bias	---
M_i	Measured indoor CO_2 concentration for time t_i	ppm
n	Number of occupants in a classroom	---
Q	Fresh air flow entering or leaving a classroom	$m^3\ min^{-1}$
Q_I	Infiltration air flow	$m^3\ min^{-1}$
Q_T	Buoyancy-driven ventilation	$m^3\ min^{-1}$
Q_W	Wind-driven natural ventilation	$m^3\ min^{-1}$
r	Correlation coefficient	---
RH	Relative Humidity	%
S	Average concentration of CO_2 simulated indoors	ppm
S_i	Simulated indoor CO_2 concentration for time t_i	ppm
σ_M	Standard deviation of the indoor CO_2 concentration (measured)	ppm
σ_S	Standard deviation of the indoor CO_2 concentration (simulated)	ppm
t_i	Time	min
T_{in}	Indoor temperature	ºC or K
ΔT	Difference between outer and inner temperatures	ºC or K
U_W	Wind speed	$m\ min^{-1}$
V	Volume of the classroom	m^3
VG	Geometric mean variance	---
TVOC	Total volatile organic compounds	---
W	Weight of the occupants	kg

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