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ORIGINAL ARTICLE

Natural ventilation and indoor air quality in educational buildings: experimental assessment and improvement strategies

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Abstract Indoor environmental conditions in classrooms, in particular temperature and indoor air quality, influence students' health, attitude and performance. In recent years, several studies regarding indoor environmental quality of classrooms were published and natural ventilation proved to have great potential, particularly in southern European climate. This research aimed to evaluate indoor environmental conditions in eight schools and to assess their improvement potential by simple natural ventilation strategies. Temperature, relative humidity and carbon dioxide concentration were measured in 32 classrooms. Ventilation performance of the classrooms was characterized using two techniques, first by fan pressurization measurements of the envelope airtightness and later by tracer gas measurements of the air change rate assuming different envelope conditions. A total of 110 tracer gas measurements were made and the results validated ventilation protocols that were tested afterward. The results of the ventilation protocol implementation were encouraging and, overall, a decrease on the CO_2 concentration was observed without modifying the comfort conditions. Nevertheless, additional measurements must be performed for winter conditions.

Keywords Envelope airtightness · Air change rate · Classrooms · Indoor air quality (IAQ) · Indoor environmental quality (IEQ) · Natural ventilation

Nomenclature

H	Height of a window [cm]
max	Maximum
min	Minimum
n	Air flow exponent [−]
n_{50}	Air change rate at 50 Pa [h^{-1}]
p	Pressure [Pa]
r	Correlation [%]
w	Width of a window [cm]
wv	Wind velocity [m/s]
A	Area [m^2]
ACH	Air change rate [h^{-1}]
CO_2	Carbon dioxide
HVAC	Heating, ventilation and air conditioning
IAQ	Indoor air quality
IEQ	Indoor environmental quality
MV	Mechanical ventilation
N	Sample size
NV	Natural ventilation
NVP	No ventilation protocol
PMV	Predicted mean vote

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RH	Relative humidity [%]
T	Temperature [°C]
VP	Ventilation protocol

Greek symbols

Δ	Difference
Σ	Standard deviation
μ	Mean

Subscripts

av	Average
ext	Exterior
int	Interior
occ	Period of occupation

Introduction

In recent years, several studies evaluating the effects of the classroom environmental conditions on the learning process were published (Shendell et al. 2004; Mendell and Heath 2005; Wargocki and Wyon 2007; Bakó-Biró et al. 2012; De Giuli et al. 2012). Despite there are many methodological questions about the measurement protocol, it seems clear that indoor environmental conditions in classrooms, in particular temperature and indoor air quality (IAQ), influence students' health, attitude and performance. Knowing that children spend a large amount of their time inside school buildings and that they are more susceptible than adults to the adverse effects of indoor pollutants, since their ratio of air breathed volume versus weight is greater and their tissues and organs are still growing (Organization, W. H., 2005), school building construction and rehabilitation must be properly planned to ensure that users have the adequate conditions for carrying out their work.

Air quality and hygrothermal comfort in schools

Although not being the most important contaminant from a health perspective, in classrooms, CO_2 is the most used indicator of the ventilation efficiency, since it is a product of respiration and school buildings typically maintain high levels of occupancy during large periods of the day. Hence, CO_2 concentration is currently adopted as a key parameter for ventilation and IAQ evaluation (Al-Rashidi et al. 2012). Usually, CO_2 concentration in buildings is very low and, therefore, harmless. However, in high concentrations, which can occur in classrooms due to their high occupancy and low levels of ventilation, CO_2 has been reported to cause breathing problems, difficulty in concentration and headaches (Satish et al. 2012).

Table 1 shows the IAQ limits (outdoor air, CO_2 concentration and the corresponding air change rate (ACH)) for classrooms from some international standards and national regulations. These values were obtained considering a typical Portuguese classroom situation with 25 occupants, a floor area of 50 m^2 and an internal height of 3 m, corresponding to a volume of 150 m^3. However, the concept of typical classroom varies from country to country, which may help explain the differences in Table 1.

Several studies stated that, frequently, ventilation rate and CO_2 concentration limits are not complied with, regardless of the ventilation system. In Portugal, 76 classrooms of 11 naturally ventilated school buildings (primary and secondary) were monitored in order to evaluate any relationship between IAQ and teachers' health problems. A statistically significant correlation between central nervous system problems and CO_2 concentration levels was confirmed (Madureira et al. 2009). Haverinen-Shaughnessy et al. (2011), with a sample of 104 US schools (fifth-grade classrooms), verified that 87 of them had ventilation rates below recommended guidelines based on ASHRAE Standard 62.1 (ASHRAE 2013). Windows and doors were kept closed during the occupation period of the classrooms, and the maximum CO_2 concentration varied between 661 and 6000 ppm with a mean value of 1779 ppm. Recently, 310 schools and day-care centres distributed in all regions of France were studied (Ramalho et al. 2013). In the occupied period, the median CO_2 level was 1200 ppm in winter and 960 ppm in summer. In conclusion, the authors recommended that a minimum ventilation rate should be provided during the night to limit high level of pollutants indoors. Mydlarz et al. (2013) carried out measurements in 75 classrooms of 4 schools in the UK. It was observed that 39 % of the classrooms exceeded the recommended limit of 1500 ppm, 93 % of which were old buildings. Gaitani and Santamouris (2013) evaluated 83 classrooms of 18 schools in Greece, all naturally ventilated. With classrooms unoccupied and windows closed, the ACH varied between 0.1 and 1.9 h^{-1}. During class breaks, with most windows opened, ACH varied between 1.3 and 12.1 h^{-1}. Regarding CO_2 concentration, the 1000-ppm limit was exceeded in 61 % of the schools. Nevertheless, it is very

Table 1 IAQ requirements in classrooms

Country [standard or regulation]	Outdoor air [m^3/h]	CO_2 concentration [ppm]	ACH [h^{-1}]
Portugal [RECS (2013)]	600	1250	4.0
UK [Building Bulletin 101 (2006)]	450[a]	1500[b]	3.0
Germany [DIN1946-2 (2005)]	500	1500	3.3
Finland [National Building Code—Part D2 (2010)]	540	1200	3.6
France [Règlement Sanitaire Departmental Type (2004)]	375 to 450		2.5–3.0
USA [ASHRAE 62.1 (2013)]	558	1080[c]	3.7
Europe [EN 15251 (2007)][d]	756	880[c]	5.0

[a] Daily mean; imposes the possibility to achieve 720 m3/h. For naturally ventilated classrooms, minimum ventilation is 270 m3/h

[b] Daily mean; imposes the possibility to achieve 1000 ppm

[c] Provided in informative annexes of the standard (outdoor air concentration was assumed as 380 ppm); not defined as a requirement

[d] Value for class II (normal level of expectation—new buildings and renovations)

unlikely that the health symptoms reported in these studies are associated with the CO_2 concentration. Rather, it is much more likely that other pollutants are elevated at lower ventilation rates.

The hygrothermal component of the indoor environmental quality (IEQ) is specified in both national and international standards and regulations. Table 2 presents the requirements for comfort in classrooms (temperature and relative humidity). It should be noted that although several international studies support adaptive comfort methodologies, these are still not included in the large majority of the national regulations.

Among European and North American countries, the idea of "low-energy", new or rehabilitated, school buildings, leading to high insulation levels, is well established (Thunshelle and Hauge 2015). However, situations of overheating might occur. This problem has been reported by several researchers (Jenkins et al. 2009; Montazami and Nicol 2013). Additionally, the latest studies show that children and adults have different perceptions of comfort. Mors et al. (2011) studied the predicted mean vote (PMV) model in three classrooms from different primary schools, located in Netherlands, all naturally ventilated. They concluded that PMV model does not accurately predict the thermal sensation of children, underestimating the thermal sensation up to 1.5 scale points. Also, it was found that children prefer lower temperatures than those predicted by adaptive models. Teli et al. (2012, 2013), through questionnaires, concluded that, out of the winter season (April to July), children prefer lower temperatures than the ones predicted in PMV and adaptive models. A literature review published by Frontczak and Wargocki (2011) on the influence of various factors on human comfort

Table 2 Hygrothermal requirements in classrooms

Country [standard or regulation]	Temperature, T [°C]		Relative humidity, RH [%]	
	Winter	Summer	Winter	Summer
Portugal [RECS (2013)]	20–25		–	–
UK [Building Bulletin 87 (2003) and 101 (2006)]	18	24 ± 4 °C[a]	–	<70[b]
Germany [DIN 1946-2 (2005)]	20–23	<26	40–60	
Finland [National Building Code—Part D2 (2010)]	21 ± 1	<25	–	–
USA [ASHRAE 62.1 (2013)][c]	–	–	≤65	
Europe [EN 15251 (2007)][d]	20	26	–	–

[a] This value can be exceeded during 80 h/year

[b] This value can be exceeded during 2 h in 12-h period

[c] Requirement to the HVAC system to be able to maintain RH under certain conditions

[d] Value for class II (normal level of expectation—new buildings and renovations)

concluded that thermal comfort is the most important parameter in IEQ evaluation and that occupants of buildings with natural ventilation revealed a more adaptive behaviour. Wargocki and Wyon (2013) published a summary of 7 experiments carried out in Denmark in 5 primary schools comprising 10 classrooms, with mechanical ventilation, involving 380 children. They concluded that high CO_2 concentrations and high temperatures are associated with a performance reduction of about 30 %. In Mediterranean climates, as a result of a favourable climate that supports the use of natural ventilation, specific adaptive models have been developed (Corgnati et al. 2009; Guedes et al. 2009; Eusébio Z. E. Conceição et al. 2012).

IEQ and students' performance

Mendell and Heath (2005) published a critical review of 30 case studies, suggesting that poor IEQ (e.g. insufficient ventilation) is common in schools and it is linked to health problems, also negatively influencing students' performance and attendance. Franchimon et al. (2009) analysed the results obtained in several studies on the relationship between students' academic performance and the ventilation rate. It was concluded that learning performance decreases for ventilation rates below 4 l/s/person and that above 10 l/s/person learning improvement is not so evident. Haverinen-Shaughnessy et al. (2011), for a set of 100 fifth-grade classrooms of different US schools, concluded that an improvement in the ventilation rate corresponds to a better academic performance (in the range 0.9–7.1 l/s/person, an increment of 1.0 l/s/person corresponds to an increase of 2.9 % in the number of students who obtained approval on standardized tests). Sundell et al. (2011) and Bakó-Biró et al. (2012) concluded that low ventilation rates are associated with absenteeism, respiratory symptoms and reduction in the attention and vigilance and negatively affect memory and concentration.

Natural ventilation in schools

In recent years, several studies regarding IEQ were published, covering schools of different levels of education with natural ventilation systems (single-sided or cross ventilation), in continuous or purge ventilation. Natural ventilation proved to have great potential, combining energy savings and occupants' satisfaction (Harvey 2009), particularly in southern European climate. However, the results, particularly in terms of thermal comfort (air temperature) and ventilation rate or levels of CO_2 concentration, have not always been satisfactory.

Coley and Beisteiner (2002, 2003) performed measurements in UK primary schools in winter and during summer, concluding that opening windows between classes—purge ventilation—has the potential to reduce CO_2, and other contaminants, levels to the recommended values. They concluded that opening windows was not commonly used due to their location (above the occupied zone) or to possible air drafts. Conceição and Lúcio (2006) monitored two unoccupied classrooms of one school in the south of Portugal with cross ventilation, using the sliding sash window opening, located above the door and main windows. An air change rate between 0.9 and 1.0 h^{-1} was obtained. CO_2 concentration in a new UK school building was measured for 1 week during heating season. The school was naturally ventilated, and it was concluded that purge ventilation during 10 min can reduce CO_2 concentration by approximately 1000 ppm without compromising thermal comfort. However, more than two periods of ventilation are required to maintain an adequate daily mean level of concentration (Griffiths and Eftekhari 2008).

Santamouris et al. (2008) monitored the IAQ in 62 classrooms of 27 naturally ventilated schools of Athens. Measurements were performed in spring and fall seasons when window opening is the main ventilation procedure. Three situations were assessed: (a) empty rooms and windows closed; (b) during classes, with some windows opened; and (c) between classes, with most of the windows opened. The tracer gas method and the decay technique were used. A statistically significant relationship between the window opening and the difference in indoor–outdoor temperature was confirmed. Heudorf et al. (2009) measured the CO_2 concentration level in two mechanically ventilated primary schools in Germany during 3 weeks (in February and March). In the third week, ventilation rate was improved by including a protocol for window opening between classes. It was verified that in the third week, there was a reduction for a mean value of 1000 ppm. Mumovic et al. (2009) performed a measurement campaign in two classrooms of nine secondary schools in the UK; temperature, relative humidity and CO_2 concentration were recorded. Of the total classrooms monitored, 14 had natural ventilation (cross or single-sided ventilation), 1 hybrid ventilation and 4 mechanical ventilation. The measurements were carried out for a week in the heating season. Regarding IAQ, only six classrooms failed to meet the average 1500 ppm, all with natural ventilation. It was also found that acoustic requirements inside the rooms are possible to achieve even in schools with natural ventilation, provided that the outside noise is not excessive. De Giuli et al. (2012) evaluated seven Italian primary schools (28 classrooms), all naturally ventilated. Measurements took place in spring, and the average CO_2 concentration above the exterior concentration varied between 45 and 3635 ppm. Through surveys, it was concluded that indoor conditions strongly depend on teachers' preferences and behaviour and that windows are mainly opened during breaks. In Denmark, different ventilation strategies were tested by Gao et al. (2014) in four classrooms, including either manually operable windows or automatically operable windows (with and without an exhaust fan in operation). The classroom in which ventilation was achieved by manually operable windows had the highest air temperatures and CO_2 concentrations (air change rate was the lowest).

According to the abovementioned, various examples highlighted the potential of natural ventilation to reduce CO_2 and other contaminants levels to the recommended values, without compromising the occupants' thermal comfort. On the other hand, the practical application of too rigid ventilation protocols proved inefficient.

Research motivation

Natural ventilation, as other ventilation systems, has advantages and disadvantages. However, towards the goals of reducing energy consumption and considering the adaptive possibilities of students, our hypothesis is that in Portugal and in other southern European countries, natural ventilation in schools, both new and refurbished, has a great potential for successful implementation (Guedes et al. 2009; Ricardo M.S.F. Almeida and de Freitas 2014; Ricardo M. S. F. Almeida et al. 2016). Moreover, besides the positive impact of natural ventilation in buildings' energy efficiency, if the infiltration is controlled, the simplicity of the system must be highlighted, especially in the context of rehabilitation, where, commonly, due to architectural reasons, the introduction of mechanical systems can be a problem.

In this vein, a large research plan was prepared to experimentally assess the ventilation conditions of Portuguese classrooms, and based on the results, an improvement strategy based on a simple ventilation protocol, without modifying the comfort conditions, was tested. Classroom characterization included the IEQ evaluation, envelope airtightness measurements and air change rate determination under different boundary conditions (with emphasis on evaluating the cross ventilation potential of the classrooms). The research strategy is represented schematically in Fig. 1.

Methodology

Schools and campaigns

This paper focuses on the IAQ and thermal comfort and their relation with buildings envelope airtightness and the effect of different natural ventilation protocols in school buildings. A simplified evaluation of the thermal comfort was implemented as only the air temperature and relative humidity were considered.

The project comprises eight schools of different levels of education (from kindergarten to college) located in the town of Viseu.

School building construction is quite homogeneous. All are based on heavy construction, which provide large thermal inertia: single and double brick masonry and reinforced concrete floor slabs and roofs. The schools A, C, E, G and H have double glazed windows, while schools B, D and F have single glazed windows. Windows have aluminium frames, except school D (Table 3), which has various systems. Average ratio between glazed building envelope and floor area is 20 %. Different shading devices were identified, including fabric blinds in the interior and in the exterior PVC horizontal fixed blades (louvres) and horizontal overhangs. Regarding the envelope insulation, three periods can be defined:

- Buildings constructed before 1991 (no thermal regulation was available): No (or very low) insulation thickness was used ($U_{\text{wall}} \approx 0.90$ W/m^2 °C; Uroof ≈ 0.90 W/m^2 °C)
- Buildings constructed between 1991 and 2006 (first thermal regulation): Low insulation thickness (usually 3 cm; $U_{\text{wall}} \approx 0.60$ W/m^2 °C; Uroof ≈ 0.90 W/m^2 °C)
- Buildings constructed after 2006 (second thermal regulation): insulation thickness of approximately 6 cm ($U_{\text{wall}} \approx 0.45$ W/m^2 °C; Uroof ≈ 0.90 W/m^2 °C)

A total of 32 classrooms, installed in buildings of different types and ages and with different orientations

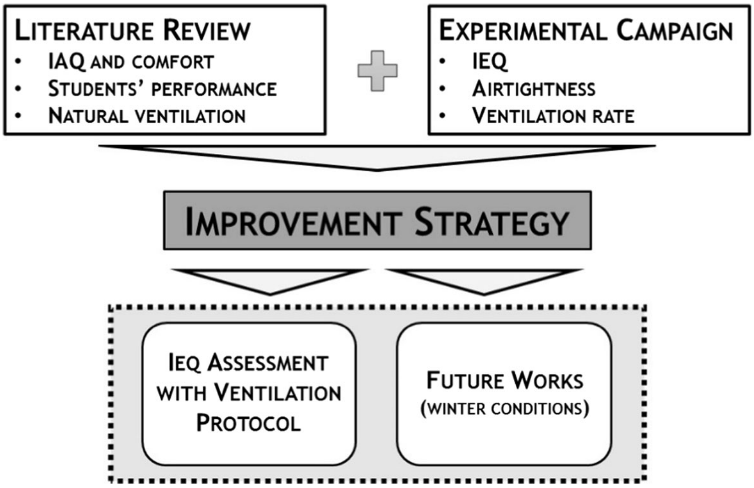


Fig. 1 Research strategy

and sun exposure, were evaluated (Table 3). Classrooms had an approximate average area of 50 m^2 and an internal height of 3 m. In each school, identical classes were selected to validate the comparison and to minimize the effect of students' absenteeism. All have bottom hung windows on the outside and several had small openings in the interior with adjoining corridors, allowing for the implementation of a cross ventilation strategy as described in "ACH measurements". Regarding heating systems, all the schools have hot water radiators, except G and H (HVAC systems). However, the use all the systems was, during most of the time, discontinuous and dependent on the school board instructions.

The exterior bottom hung windows with opening above the occupied zone allow to reduce discomfort due to drafts. The Portuguese thermal regulation (2013) only allows natural ventilation in schools if part of the windows is 1.80 m above the floor. Schools G and H have ventilation windows with an axis at a height of approximately 0.90 m but the others respect that recommendation.

The research was developed in three campaigns:

- Spring 2013 (March–May): Measurements were performed during four consecutive days in each school in occupied classrooms; hygrothermal performance (T and RH) and IAQ (CO_2) were evaluated.
- Summer 2013 (July–September): ACH rate measurements were performed using the tracer gas method—decay technique—in unoccupied classrooms and according to various conditions concerning window and door positions; classrooms airtightness, including the influence of windows and other openings, was determined using the fan pressurization method (blower door).
- Autumn 2013 (September–October): Same parameters as for the first campaign were measured during 2–4 days. However, in each school, two classrooms were selected with specific conditions for single-sided or cross ventilation and a ventilation protocol was imposed. The other two classrooms had no control on the window opening.

Tests and equipment

Research included temperature, relative humidity and CO_2 concentration continuous measurements with 1-min sampling interval. Existing international recommendations were accomplished (WHO European Centre for Environment and Health 2011; Materials 2012; ISO 2001), in particular, for sensor location, avoiding windows and heater proximity. The sensors are in line with the requirements of the standard ISO 7726 (ISO 2001). Generally, sensors were positioned next to the teacher desk (at an approximate height of 0.70 m), protected from direct breathing into the sensor. The following equipment was used: one indoor air quality measurement device that records temperature, relative humidity and CO_2 concentration (temperature accuracy ±0.5 °C; relative humidity accuracy ±2 %; CO_2 concentration accuracy 2.75 % + 75 ppm), three data loggers for temperature and relative humidity (temperature accuracy ±0.35 °C; relative humidity accuracy ±2.5 %) and three infrared dispersive measurement devices

Table 3 School building characterization

School								
Designation	Year Built	Level of education	Designation	Area [m^2]	Building floor	Orientation	Window type[a]	Ventilation system[b]
A	1993	College	A1	53	0	S	TT + BH	MV off
			A2	51	0	S/W		
			A3	62	1	S		
			A4	60	1	S/W		
B	1991	Lower secondary	B1	59	0	NE	S + BH	NV
			B2	64	0	SW		
			B3	48	1	NE		
			B4	49	1	SW		
C	2004	Kindergarten	C1	51	0	SE	BH	NV
			C2	51	0	NW		
		Primary	C3	51	1	SE		
			C4	51	1	NW		
D	1968	Lower secondary	D1	53	−1	S	SH + BH	NV
			D2	53	1	S		
			D3	54	1	S		
			D4	38	−1	S / E	S	
E	1996	Primary	E1	50	0	E	SH + BH	NV
		Lower secondary	E2	63	0	S / E		
			E3	48	1	E		
			E4	63	1	W / S		
F	1958	Primary	F1	48	0	S / N	S + BH	NV
			F2	48	1	S / N		
			F3	48	0	S / N		
			F4	48	1	S / N		
G	2011	Kindergarten	G1	48	0	E	TT + BH	HVAC
			G2	44	0	W		
		Primary	G3	48	1	S		
			G4	44	1	S		
H	2011	Kindergarten	H1	51	0	E	SH + BH	HVAC
			H2	50	0	W		
		Primary	H3	50	1	W		
			H4	51	−1	E		

[a] *TT* tilt and turn, *BH* bottom hung (tilting), *SH* side hung (casement), *S* sliding (horizontal sash)

[b] *MV* mechanical ventilation, *NV* natural ventilation, *HVAC* heating, ventilation, and air conditioning

for CO_2 concentration (±50 ppm or ±5 % of the reading, whichever is greater). All the sensors used in this project were calibrated by the manufacturers and by an independent governmental entity.

Ventilation rate (ACH) measurements were performed according to ASTM E741: 2011 (ASTM 2011). A photoacoustic detection equipment with a repeatability of 1 % of the measured value and the SF_6 tracer gas were used. According to this standard, the test's uncertainty is 10 %.

Regarding envelope airtightness assessment, the fan pressurization methodology proposed in EN 13829: 2001 (CEN 2001) was used. The test allows the determination of n_{50}, which corresponds to the air change rate at a pressure difference of 50 Pa. A blower door was used with an accuracy of the gauge of ±1 Pa or ±2 %, whichever is greater. The average uncertainty of the tests was 8.9 %, determined according to the procedure detailed in the standard annex.

Exterior climate conditions were assessed (temperature, relative humidity and wind direction and velocity) by the use of a local meteorological station. During the ventilation rates and airtightness tests, the average air temperature was 20 °C and the average wind velocity was 1.2 m/s.

Portugal has a temperate Mediterranean climate, however, with differences between north and south and distance to Atlantic Ocean. Viseu, located in the center of Portugal, is characterized by lower rainfall and higher annual temperature range. However, as can be seen in Table 4, the external temperature, except for a few winter months, allows the use of natural ventilation, while avoiding the risk of discomfort due to drafts. In buildings where ventilation rate is highly dependent on the window opening, the importance of exterior temperature becomes crucial. Similarly, in the months of June and September, outside temperatures are moderate allowing cross ventilation for indoor cooling. During the winter period, special attention should be paid as natural ventilation (trickle ventilation) can only be used together with a heating system that compensates the air temperature. The introduction of light sensors indicating periods of high CO_2 concentration can also be an interesting option. The Portuguese thermal regulation (2013) indicates, for the town of Viseu, approximately 1700 heating degree days (base 18 °C).

IEQ assessment

Classroom IEQ was evaluated according to the previously described methodology. Descriptive statistical analysis of the results is presented in Table 5, which includes information about indoor temperature, relative humidity and CO_2 concentration, during the period of occupation and the correspondent weather conditions, temperature and relative humidity, both daily (T_{ext} and RH_{ext}) and only considering the period of occupation (T_{occ} and RH_{occ}). Normal distribution of the data sets was tested (Shapiro-Wilk test; $p < 0.05$).

Table 4 Monthly weather variables in the town of Viseu (2012)—period between 8:00 and 18:00

	T_{av} [°C]	HR_{av} [%]	wv_{av} [m/s]
January	8.7	68.1	3.2
February	8.5	44.7	3.9
March	14.2	44.9	3.7
April	9.5	77.0	3.6
May	17.8	60.7	3.3
Jun	19.5	61.7	3.0
September	21.7	47.5	4.0
October	15.2	70.9	2.8
November	9.8	78.2	3.6
December	8.9	81.3	3.1

A clear distinction between the hygrothermal and the IAQ results must be made. Temperature and relative humidity results revealed a performance within the comfort zone according to the Portuguese regulation: average temperature above 20.0 °C (the only exception is school B with 19.7 °C), with a relatively small dispersion of results (standard deviation below 2.0 °C, the only exception being school C with 2.1 °C); the maximum temperature was observed in school E with 26.1 °C and the minimum temperature was 16.6 °C in schools A, B and C; relative humidity mean values varied between 46 and 64 %, and the overall oscillation is limited to the range 30–77 %, usually considered as adequate indoor conditions (CEN 2006); the maximum relative humidity was registered in school B (76.5 %) and the minimum one in school D (30.0 %). When analysing the temperature only considering the period of occupation, the effect of exterior temperature becomes clear.

On the indoor air quality evaluation, a completely different scenario was observed with high CO_2 concentrations being identified, with a magnitude that, in some situations, should be a matter of concern for the building administration. This kind of situation is not new, even in countries with different climate conditions, since several previous studies reported similar problems in classrooms throughout the World (Jenkins et al. 2009; Despoina Teli et al. 2011; Montazami et al. 2012; Ricardo M.S.F. Almeida and de Freitas 2014). Maximum values were above 3000 ppm in all school buildings, and in four of them, they have increased up to 4000 ppm. Considering average values for the all period, only schools G and H presented concentrations below 1250 ppm (the Portuguese regulation concentration limit); in six buildings, the mean value was higher than 1500 ppm and in two of them it was higher than 2000 ppm. For our sample, the best performing schools were G and H. On the other hand, the worst scenarios were observed in schools A and F. These findings might be related to the external conditions as, for instance, average external temperature during monitoring: for school A was 9.3 °C and for school H was 20.3 °C (enhancing the window opening). High

Table 5 IEQ results (spring 2013)

School	T_{int} [°C]			RH_{int} [%]			CO_2 [ppm]		T_{ext} [°C]	T_{occ} [°C]	RH_{ext} [%]	RH_{occ} [%]
	$\mu \pm \sigma$	Max	Min	$\mu \pm \sigma$	Max	Min	$\mu \pm \sigma$	Max	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$	$\mu \pm \sigma$
A	20.9 ± 1.8	25.5	16.6	58.1 ± 4.5	65.8	42.3	2318 ± 666	3708	9.3 ± 2.6	11.0 ± 2.6	66.4 ± 16.5	59.0 ± 17.4
B	19.7 ± 1.1	22.1	16.6	64.3 ± 5.3	76.5	47.2	1820 ± 787	4270	10.6 ± 2.5	12.4 ± 2.2	73.1 ± 12.0	68.9 ± 13.5
C	20.2 ± 2.1	24.3	16.6	61.8 ± 6.5	75.3	33.6	1490 ± 724	4038	14.9 ± 5.3	19.1 ± 3.9	57.5 ± 21.2	42.4 ± 14.3
D	21.4 ± 1.9	25.6	16.9	45.7 ± 5.4	56.4	30.0	1711 ± 686	3456	13.3 ± 5.9	15.9 ± 6.0	49.8 ± 15.5	41.8 ± 15.0
E	23.5 ± 1.3	26.1	18.4	50.6 ± 6.2	62.6	33.7	1606 ± 654	4028	16.9 ± 5.4	20.5 ± 5.0	49.7 ± 18.7	38.7 ± 14.3
F	22.1 ± 1.3	24.4	17.9	62.1 ± 6.2	73.1	39.9	2513 ± 893	4032	14.6 ± 4.3	16.7 ± 4.6	65.5 ± 17.9	58.2 ± 19.4
G	21.6 ± 1.5	25.4	17.5	46.2 ± 6.8	62.5	32.6	945 ± 520	3052	15.9 ± 6.4	20.7 ± 4.1	54.9 ± 22.0	36.8 ± 10.3
H	22.0 ± 1.1	25.1	18.2	46.3 ± 7.3	65.8	30.8	1210 ± 578	3136	20.3 ± 6.3	24.2 ± 4.6	62.3 ± 18.9	50.2 ± 16.1

standard deviation values also indicate a large spreading on the results (Fig. 2).

The importance of improving classroom ventilation arises from results of first campaign. The next step, in the study, was to evaluate the ventilation conditions of the classrooms, including the potential to improve ventilation rates by simple adjustments based on a ventilation protocol that must be implemented in such a manner that classroom comfort conditions are not neglected.

Classroom airtightness: blower door measurements

Envelope airtightness was the first assessed ventilation parameter which is essential for the air infiltration and, therefore, affecting both the energy efficiency of the building and the IAQ. Classroom airtightness was evaluated by the fan pressurization method according to the experimental procedure referred in "Methodology". Tests were performed on one classroom of five schools (the schools/classrooms Id. is the same as presented in Table 3).

The followed methodology allowed the evaluation of the individual contribution of the envelope elements for the classroom airtightness. Therefore, several experimental setups were analysed in each classroom: the first corresponding to the "in use scenario" where nothing was sealed; then the construction elements that have a higher contribution to the air leakage of the classroom (external and internal windows and other openings) were individually and consecutively sealed. The individual contribution was then computed by the difference between consecutive tests. All the remaining boundary conditions were kept unchanged. Therefore, the "nothing sealed" scenario includes leakage from the neighbouring classrooms and is a measure of internal building leakage corresponding to typical use conditions (method A of EN 13829: 2001(CEN 2001). This procedure resulted in a total of 34 blower door tests (17 for pressurization and 17 for depressurization). Table 6 summarizes the results, including the setup description, the ratio window to floor area, the air change rate at a pressure difference of 50 Pa (n_{50}) and the air flow exponent (n) of the corresponding permeability law. Figure 3 presents the maximum differences of n_{50} (maximum and minimum value).

Obtained results showed large differences between schools. The construction characteristics, including materials and technical solutions adopted (e.g. ventilation

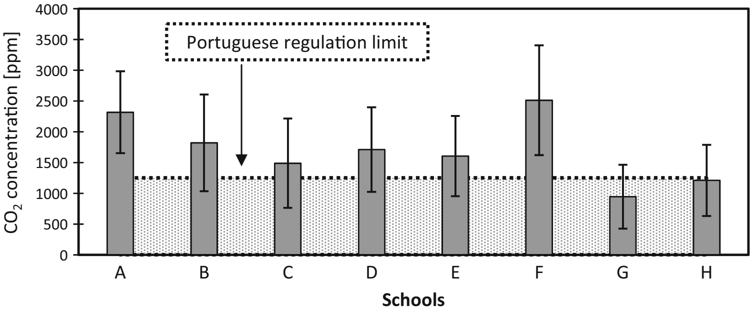


Fig. 2 CO_2 concentration average and standard deviation

Table 6 Measured airtightness and related parameters

School/ classroom	Setup	$A_{\mathrm{window}}/A_{\mathrm{floor}}$ [−]	n_{50} [h^{-1}]	n [−]	r [−]
A/A1	NS	0.27	21.3	0.534	99.9
	VGS		14.1	0.535	99.9
	VGS + DS		6.1	0.577	99.8
	VGS + DS + EWS		5.8	0.593	99.8
B/B4	NS	0.17	11.2	0.595	99.9
	VGS		5.1	0.629	99.9
	VGS + IWS		4.5	0.596	99.7
	VGS + IWS + EWS		2.1	0.689	98.7
C/C2	NS	0.25	1.7	0.652	99.9
	IWS		1.7	0.669	99.9
	IWS + EWS		1.6	0.668	99.9
D/D2	NS	0.26	10.4	0.617	99.9
	IWS		6.8	0.563	99.8
	IWS + EWS		3.5	0.614	99.3
E/E1	NS	0.16	5.0	0.584	99.9
	SEWS		4.5	0.575	99.9
	SEWS + TEWS		4.3	0.582	99.9

NS nothing sealed, *VGS* ventilation grilles sealed, *DS* door sealed, *EWS* external windows sealed, *IWS* interior windows sealed, *SEWS* sliding exterior windows sealed, *TEWS* top-hung exterior window sealed

system and aperture mode of the windows) and also the buildings' age, are decisive for the envelope airtightness. The largest reduction was observed in school B (81 %) with the most important contributions from the ventilation grilles and exterior window frame. Reductions of 73 and 66 % were obtained in schools A and D, respectively. All these constructions have more than 20 years. On the contrary, lower airtightness was detected in schools C and E. Even for the "in use" condition (nothing sealed), the average airtightness at Δp = 50 Pa was 1.7 and 5.0, respectively. School C windows are bottom hung, very airtight and most of the glazed area is fixed, which might help to explain the lower values.

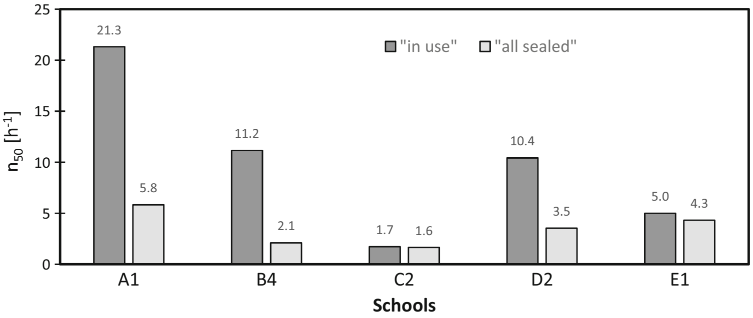
Envelope airtightness is closely linked with infiltration and, therefore, it can assume an important role on the building ventilation, particularly in naturally ventilated buildings. However, despite having a positive impact on the classrooms' IAQ, being "uncontrolled" ventilation, it should be minimized because it will be responsible for large energy losses during the winter season, negatively affecting the building energy efficiency. Therefore, infiltration should be minimized and the focus must be on "controlled" natural ventilation.

ACH measurements

ACH measurements were made on unoccupied classrooms, during summer break (August), using the tracer gas method—decay technique. According to the specific conditions of each classroom, such as window type and position, several experimental setups were assessed in order to evaluate the different possibilities for natural ventilation: everything closed (only infiltration), single-sided ventilation, cross ventilation and with and without door opened (Fig. 4).

A total of 110 measurements were performed on the 32 classrooms under study. All the measurements were made with moderate wind conditions (average velocity of 4.1 m/s). The experimental procedure time length varied between 30 min and 5 h, depending on the ventilation rate (longest duration for lower ventilation rate) and according to the specified on ASTM E741: 2011 (ASTM 2011). The sampling point was located on the centre of the classroom at a height of 1.2 m; two fans were used to mix and to distribute the tracer gas uniformly in the zone, and

Fig. 3 Average airtightness at Δp = 50 Pa



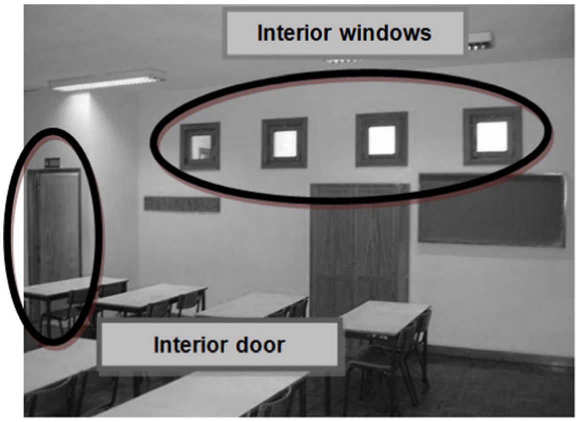


Fig. 4 Example of interior openings used for the ACH determination

data was collected with a 40-s interval (in average). The regression method was used to determine the ACH. The tracer gas was injected only inside the classroom under evaluation, and the room was highly ventilated between tests to rule out contamination. When testing with open door, the decay is also due to air flow with the adjacent compartments, which may result in overestimating the ACH.

Natural ventilation potential was assessed in the following conditions:

- Everything closed or "in use" position (ex. permanent openings above the entrance door): It is intended to simulate the current conditions of natural ventilation achieved by infiltration only
- Single-sided ventilation: It was used when classrooms did not have interior windows or other openings and two exterior windows were opened
- Cross-ventilation: It was used when classrooms had exterior and interior openings (interior openings adjacent to the corridor) and two exterior and two interior windows were opened
- Cross-ventilation and door opened: Identical to the previous setup but with the entrance door opened ($\approx 0.8 \times 2.0$ m^2)

Table 7 details the classrooms windows characteristics.

Figure 5 shows the cross ventilation strategy, highlighting the bottom hung window's system and the axis position.

Table 8 summarizes the results in each school, including the number of samples (N).

In line with previous studies (Ricardo M.S.F. Almeida and de Freitas 2014), results exposed airtight enclosures. For the scenario of windows closed (Cl), the ACH average ranged from 0.04 h^{-1} in school C to 0.5 h^{-1} in school B, with exception of school D that presented 1.5 h^{-1}. In fact, school D is a special case since the wood on the window frames is deteriorated and in a very poor condition, allowing uncontrolled airflow. Another interesting conclusion is that, when available, cross-ventilation (CV) has a great potential. In this condition, results varied between 1.6 and 7.6 h^{-1}. Regarding the single-sided (SS) ventilation, results were more

Table 7 Windows characteristics

School	Exterior windows				Interior windows			
	Type	Area of 1 window: $w \times h$ [cm^2]	Opening at the top[a] [cm]	Height to floor [m]	Type	Area of 1 window: $w \times h$ [cm^2]	Opening at the top[a] [cm]	Height to floor[b] [m]
A	BH	110 × 60	25	2.46	–	–	–	–
B	BH	54 × 43	19	2.24	BH	73 × 45	25	2.10
C	BH	168 × 56	27	1.70	–	–	–	–
D	BH	79 × 42	15	2.50	L	90 × 51	–	2.78
E	BH	92 × 71	14	2.34	L	86 × 42	–	2.50
F	BH	121 × 42	26	2.23	–	–	–	–
G	BH	100 × 197	10	0.72	BH	47 × 82	7	1.89
H	BH	157 × 136	14	0.90	–	–	–	–

BH bottom hung (tilting), *L* louvred

[a] Horizontal distance between movable and fixed frame

[b] Axis height in Fig. 2

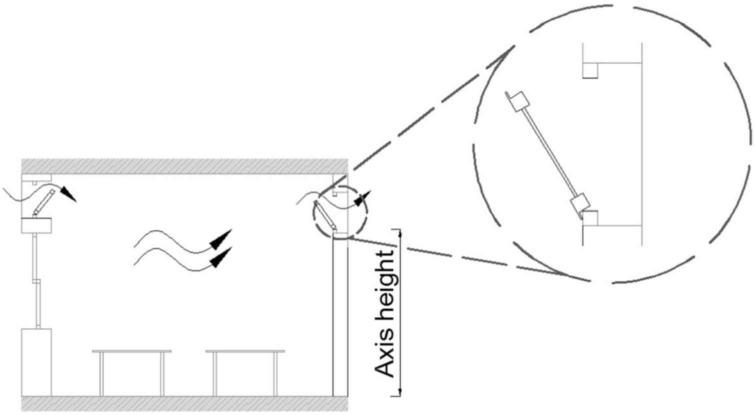


Fig. 5 Cross-ventilation scheme and axis position

modest, ranging from 0.6 to 2.9 h^{-1}, although still being an interesting approach to improve the IAQ.

The variability of the results was also analysed. Figure 6 presents the results box-plot.

Envelope airtightness, which corresponds to the situation of windows closed, is the one that presents less variability, the other scenarios having a wider range of results. For this situation, median ACH was 0.2 h^{-1} clearly confirming that infiltration is not sufficient to control and dilute the CO_2 internal production as well as all the other air contaminants. Therefore, additional ventilation must be provided. For that purpose, results revealed that the two ventilation modes that can be implemented during classes (CV and SS) should significantly improve the IAQ. A median ACH of 2.8 and 1.0 h^{-1} was found for CV and SS, respectively. As it would be expected, CV has a higher potential according to the reference values presented in Table 1 for the Portuguese case. The ventilation mode CV + door, which can be implemented during breaks, presents the higher median value, 3.4 h^{-1}, and can provide an

Table 8 Statistical analysis of the ACH tests in each school and setup

School		Setup			
		Cl	CV	CV + door	SS
A	*N*	4	2	5	4
	$\mu \pm \sigma$	0.2 ± 0.1	5.7 ± 1.7	6.4 ± 3.5	1.8 ± 0.8
B	*N*	3	4	4	1
	$\mu \pm \sigma$	0.5 ± 0.2	2.3 ± 0.7	3.3 ± 1.0	1.1 ± 0.0
C	*N*	4	–	5	5
	$\mu \pm \sigma$	0.04 ± 0.03	–	7.2 ± 4.6	2.0 ± 1.4
D	*N*	4	3	4	1
	$\mu \pm \sigma$	1.5 ± 0.1	3.9 ± 1.0	4.3 ± 2.8	2.9 ± 0.0
E	*N*	4	3	4	1
	$\mu \pm \sigma$	0.2 ± 0.1	1.6 ± 0.7	2.0 ± 0.4	0.6 ± 0.0
F	*N*	4	–	4	7
	$\mu \pm \sigma$	0.1 ± 0.03	–	2.7 ± 0.8	0.7 ± 0.7
G	*N*	4	2	6	4
	$\mu \pm \sigma$	0.3 ± 0.1	7.6 ± 1.0	5.0 ± 4.9	0.9 ± 0.7
H	*N*	4	–	5	5
	$\mu \pm \sigma$	0.2 ± 0.04	–	3.9 ± 1.4	1.1 ± 0.5

Cl windows closed, *CV* cross ventilation, *CV + door* cross ventilation + door, *SS* single-sided ventilation

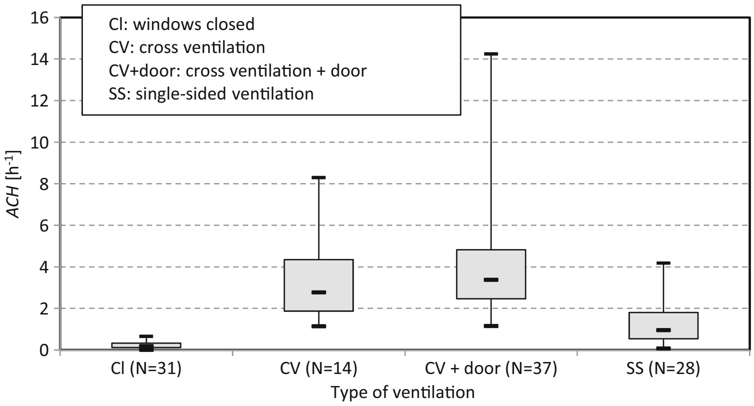


Fig. 6 Box-plot of the results of the ACH measurements

important contribution for the control of CO_2 concentration. CV modes are the ones that present higher variability with maximum values up to 8.3 and 14.2 h^{-1} for CV and CV + door, respectively.

The ACH obtained with tracer gas and the blower door results can be compared. The relation $n_{50}/20$ is typically used for low precision estimations of the ACH value through infiltration (Max 1986). Yet, this rule of thumb, though useful, is based on experience in single family homes, not individual classrooms, and the results must be analysed taking this limitation into account. Table 9 compares the results obtained using both methods. In classrooms B4, C2 and E1, a good agreement can be found. Yet, it is important to notice that ACH results are median values obtained in different classrooms, which may also explain the differences obtained in classrooms A1 and D2. Two important ideas arise from these results. On the one hand, no clear relation between blower door and tracer gas measurements was found in the context of classrooms and additional research is required in this area. Climatic conditions, such as the wind speed and direction and the indoor/outdoor temperature gradient, can help to explain the differences and their importance must be investigated. On the other hand, once again, it was confirmed that these are airtight classrooms.

Table 9 Comparison between blower door and ACH tests, respectively, in each classroom and school

Classroom	$n_{50}/20$[a]	ACH[b]	n_{50}/ACH
A1	1.07	0.20	107
B4	0.56	0.50	22
C2	0.09	0.04	45
D2	0.52	1.50	7
E1	0.25	0.20	25

[a] Nothing sealed

[b] Cl windows closed; median of three or four classrooms

IEQ assessment with ventilation protocol

The first campaign results enhance the importance of improving classroom ventilation. After the individual analysis of the classrooms airtightness, described in "Classrooms airtightness: blower door measurements" and "ACH measurements", the following step on this investigation was then to improve the ventilation rates by simple adjustments based on a ventilation protocol, which should be implemented in such a manner that classrooms' comfort conditions are not neglected. The measurements were monitored by at least one research team member to guarantee that the protocol has been followed. Nevertheless, the users' ability to interact with building, changing the boundary conditions to meet their expectations, was also encouraged.

Therefore, in the last measurement campaign (September–October), the parameters of the first campaign were measured during 2–4 days. However, in each school, there were two classrooms where specific conditions for cross and single-sided ventilation were imposed (ventilation protocol—VP). The other two classrooms, carefully selected as identical to the previous, had no control on the window opening (NVP) as the users could change the conditions according to their sensations. In the classrooms with VP, exterior and interior (adjacent to the corridor) bottom hung windows were opened in the beginning of the day (Fig. 4). Throughout the day, users had the possibility to close them, if they felt

Table 10 Air temperature, relative humidity and CO_2 concentration (VP and NVP)

School	T_{int} [°C] $\mu \pm \sigma$		RH_{int} [%] $\mu \pm \sigma$		CO_2 [ppm] $\mu \pm \sigma$		
	VP	NVP	VP	NVP	VP	NVP	Δ %
A	24.1 ± 1.2	24.7 ± 1.4	67 ± 5.1	70 ± 5.8	978 ± 536	1436 ± 635	32
B	27.7 ± 1.8	26.6 ± 1.7	46 ± 4.7	53 ± 5.1	788 ± 312	1279 ± 683	38
C	26.6 ± 2.1	27.0 ± 1.9	45 ± 5.3	45 ± 4.6	1611 ± 633	1222 ± 696	–32
D	23.0 ± 1.2	24.0 ± 1.2	67 ± 6.1	66 ± 5.9	1059 ± 588	1576 ± 648	33
E	26.5 ± 1.4	26.6 ± 1.5	54 ± 5.6	57 ± 5.5	768 ± 364	949 ± 486	20
F	24.4 ± 1.3	24.2 ± 1.6	48 ± 5.0	51 ± 5.3	954 ± 425	1316 ± 577	28
H	24.3 ± 1.7	22.9 ± 1.5	52 ± 5.8	64 ± 6.4	1370 ± 598	2485 ± 857	47

uncomfortable. Moreover, teachers were encouraged to maintain the door opened during breaks. Hence, the idea was to test a simple and feasible protocol, which afterwards could easily be implemented on day by day basis and that meet the user's expectations by enabling them to adjust the environment.

Table 10 shows the average values of air temperature, relative humidity and CO_2 concentration separately for scenarios with and without ventilation protocol. The percent improvement in terms of CO_2 concentration is also indicated, with positive values corresponding to a reduction in concentration.

The introduction of a ventilation protocol resulted on an improvement of the CO_2 concentration in six schools. The only exception was school building C, probably because users (teachers) had the possibility to reject the protocol if they felt uncomfortable, and in this school, window opening axis is inside occupied zone (situation that does not occur in the other schools) making it easier to operate. Apart from this particular situation, the implementation of the ventilation protocol was positive: the most interesting performance was obtained in school H with a reduction of 47 % in the CO_2 concentration, and even for the less efficient scenario (school E), an improvement of 20 % was obtained. Another important result that must be underlined is that the comfort conditions were not neglected with this protocol since no significant difference of temperature between VP and NVP classrooms was found (Kruskal-Wallis test; $p > 0.05$). However, it is important to refer that these results were obtained during autumn. When compared to the spring measurements (Table 5), the interior air temperature and relative humidity are similar, pointing to the potential of the methodology during that period. Nevertheless, additional measurements must be performed for winter conditions to validate the strategy.

Conclusions

On the first campaign, the IEQ of 32 classrooms was assessed and the following conclusions can be stated: temperature and relative humidity results revealed a performance within the comfort zone with an average temperature above 20.0 °C and a small dispersion and relative humidity mean values varied between 45 and 65 %; IAQ measurements exposed a different situation. Maximum values of CO_2 concentration above 3000 ppm were recorded in the eight school buildings, and in four of them, this value increased up to 4000 ppm. Regarding the average values, only two schools presented a concentration below the limit of 1250 ppm, and in six buildings, the mean value was higher than 1500 ppm and in two higher than 2000 ppm; and from these results, the importance of improving classroom ventilation arises.

The airtightness tests allowed to conclude that the construction characteristics, including the materials and the technical solutions adopted, namely the ventilation system and aperture mode of the windows, and the buildings' age are decisive for the envelope airtightness.

Natural ventilation potential was also evaluated through tracer gas measurements of the ACH. The results revealed airtight enclosures and, therefore, additional ventilation must be provided. For that purpose, results suggested that both cross and single-sided ventilation have great potential. The choice of opening windows and their location are both important in the design of the school facade as this affects the effectiveness of natural ventilation.

The application of the ventilation protocol, based on a cross and single-sided ventilation strategy, shows a decrease on the CO_2 concentration without modifying the comfort conditions. Yet, results in school C reveal that sometimes protocol implementation is not straightforward and that this strategy should continue to be explored and validated for winter conditions. Maintaining the interior door opened during breaks is a very simple measure whose potential will be tested in the future. Additionally, in the winter period, trickle ventilation can also be an alternative, together with heating systems that compensate the air temperature. Finally, the introduction of light sensors indicating periods of high CO_2 concentration can also be tested.

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Compliance with ethical standards

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