Indoor Conditions in Educational Buildings: the Case of Bolzano Schools

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ABSTRACT

Indoor environmental quality in educational buildings is recognized as a crucial aspect for the achievement of the learning outcomes for students. Nevertheless, indoor school conditions are often found unsatisfactory in several European countries, including Italy, especially as regards indoor air quality IAQ. For instance, taking CO_2 concentration as IAQ indicator, the threshold of 1000 ppm is often overcome, suggesting insufficient ventilation rates. As observed in the literature, this cannot be referred to a specific type of building system or vintage: indeed, excess of CO_2 concentrations was recorded in both old and recent buildings, with either natural or mechanical ventilation systems.

In the current research, we focused on the school building stock of the city of Bolzano, Northern Italy, with the aim of monitoring the indoor conditions and defining new strategies and practices to improve the IAQ. After some preliminary measurements, we selected 5 schools, including 3 recent buildings and 2 buildings from the 70s-80s, for long-term campaigns. All educational buildings in the set rely on natural ventilation to renovate the air in the classrooms. CO_2 concentration, relative humidity and air temperature were recorded in representative classrooms during a year with a 10-minute timestep. Acquired data were analyzed according to EN 16798-1:2019, determining the share of occupied time in the different IAQ categories of the technical standard. Indoor conditions recordings were used also to assess thermal comfort according to the PMV-PPD model, and to assess the pupils' performance loss according to models available in the literature.

A diffuse problem of inadequate IAQ was highlighted in different schools, in particular during the winter season, regardless of their vintage, windows technology or students' age. Recorded temperatures were found higher than recommended, with potential implications on occupants' thermal comfort, performance and energy efficiency.

INTRODUCTION

In the past few years, under the impetus of green building initiatives, comfort, health, productivity, and satisfaction of occupants in a building have received increasing attention from the public as well as the researchers. Since students spend in schools a large part of their time, maintaining an adequate indoor environmental quality (*IEQ*) is crucial. Under the label *IEQ* are included thermal and hygrometric, visual and acoustic comfort conditions, as well as indoor air quality (*IAQ*). In particular, *IAQ* is recognised as a major contributing factor to pupils' learning performance in schools. The perceived *IAQ* is function of the accumulation of air pollutants generated by internal sources and the capability of the existing ventilation system to dilute them. In school buildings, large CO_2 concentrations are often registered because of low ventilation rates and high occupancy density, generally higher than in office and productive buildings (Clements-Croome *et al.* 2008). Low ventilation rates in classrooms have proved to reduce pupils' attention and vigilance thus negatively affecting memory and concentration (Bakó-Biró *et al.* 2012, Stafford 2015). Furthermore, high indoor CO_2 concentrations in school increase pupils' absence rate (Schendell *et al.* 2004). In addition to high indoor CO_2

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concentration, elevate temperatures causing thermal discomfort in classrooms reduce the ability of pupils to perform typical school tasks and impact performance scores (Haverinen-Shaughnessy *et al.* 2015, Porras-Salazar *et al.* 2018).
Most of the school buildings in Italy rely on natural ventilation. Moreover, occupants generally have little if no control on temperature. In the current research, we focused on the school building stock of the city of Bozen-Bolzano, Northern Italy, with the aim of monitoring the indoor conditions and defining new strategies and practices to improve the *IAQ*.
This paper presents the results of a monitoring long-term campaign on carbon dioxide concentration, relative humidity and air temperature carried on in classrooms along the school year 2018/2019. Collected data were analysed according to the current technical standards and considered as inputs to some models in the literature to determine the impact on students' performance and thus to assess potential improvement from better indoor conditions.

METHODS

Data were recorded with a 10-minute timestep using Onset's HOBO MX1102 CO_2 logger. The main features of the sensors are reported in Table 1. The sensors were always installed on a wall, far from windows or doors and in a central position in the classroom, at a sufficient height (around 1.5 m from the floor) to avoid possible interference with direct breathing from the pupils. In order to assess the adequacy of the installation positions, preliminary tests were performed during unoccupancy time with the GrayWolf's WolfPack Modular Area Monitor, whose recordings showed limited differences between the data collected at the centre of the room volume and those on the selected position on the walls.
Acquired data were analysed according to EN 16798-1:2019, determining the share of occupied time in the different *IAQ* categories presented in the technical standard. The EN 16798-1:2019 standard identifies category II "the level normally used for the design and use" of indoor environments. Category I identifies instead the "level that should be adopted in the presence of individuals with special needs (children, elderly and disabled people)". Categories III and IV represent respectively the "level that allows to maintain the acceptable environment (introduces some risk of performance loss)" and the "level that should be adopted only for a limited part of the year, or in spaces with limited permanence".
Environmental comfort in classrooms during winter results from combination of the performance of the heating system and the ventilation effectiveness. This means that in rooms where the coordination between the controls of the heating and ventilation systems is not appropriate, thermal comfort and *IAQ* may be competing. This condition is typical in naturally ventilated rooms, where the opening of windows and doors is limited to reduce thermal discomfort caused by cold outdoor air draughts during the heating period.

Table 1. Specifications of Onset's HOBO MX1102 CO2 logger.

Temperature sensor	
Range	0 to 50 °C
Accuracy	±0.21 °C from 0 to 50 °C
Resolution	0.024 °C at 25 °C
Drift	<0.1 °C per year
Relative humidity sensor	
Range	1 % to 90 % *RH* (non-condensing)
Accuracy	±2 % from 20 % to 80 % typical to a maximum of ±4.5 % including hysteresis at 25 °C; below 20% and above 80% ±6% typical
Resolution	0.01 %
Drift	<1 % per year typical
Carbon dioxide sensor (Sensing Method: non-dispersive infrared (*NDIR*) absorption)	
Range	0 to 5000 ppm
Accuracy	±50 ppm ±5 % of reading at 25 °C, less than 90 % *RH* non-condensing and 1,013 mbar
Calibration	Auto or manual to 400 ppm
Non-linearity	<1 % of *FS*

Indoor recordings were used also as input to calculated *PMV* and *PPD* as in the technical standard EN ISO 7730:2005. The clothing value was set to 1.0 clo (typical winter clothing), sedentary activity was chosen, the air velocity was assumed to be 0.1 m/s and the mean radiant temperature was assumed equal to the air temperature. The activity level of 1.4 met was used rather than 1.2 met for sedentary activity because previous studies (ECA 1992, Pejtersen *et al.* 1991) showed that pupils in elementary schools have a metabolic rate that is about 15–20 % higher than adults.

Finally, the collected measurements allowed assessing the pupils' expected performance loss according to the works by Wargocki *et al.* (2019, 2020). In particular, the performance loss due to the thermal discomfort is assumed to be proportional to the temperature difference between the monitored valued and the comfort value (*PMV* = 0). The model of Wargocki *et al.* (2020) shows an asymptotic trend in the loss of pupils' speed or reaction time when the CO_2 concentration in the air range from 900 ppm to 2000 ppm, which are the limits of applicability of the model. In this study, for values below 900 ppm no performance loss is considered, while for values above 2000 ppm it is assumed a constant loss equal to the maximum allowable by the model (13 %). Although developed for elementary and middle school pupils, for sake of completeness the performance loss models were applied also to the two kindergartens present in the sample of monitored cases.

Case studies

The experimental analysis was performed considering 5 representative public schools located in Bolzano (Northern Italy), identified by the letters from A to E (Table 2). Two classrooms have been monitored for schools A, D and E, and 1 for schools B and C. The average floor area of the monitored classrooms is around 50 m². Schools B, C and E are recent buildings whereas A and D are from the '80s. All classrooms in the set rely on natural ventilation to renovate the internal air, by manually opening and closing windows and doors. In all classrooms, access doors are on the opposite side with respect to the windows. The access doors connect the classrooms with internal corridors/atriums. The kindergarten classrooms on the ground floor (S.B and S.E-C.1) have also doors to the inner courtyard on the window side. According to the schools' policies, these doors are not used to ventilate the classrooms during the occupancy period. No school considered in this study is close to heavily trafficked streets or placed in their vicinity. In the internal and external proximity of the windows there are no obstacles that could restrict the natural flow of air. The heating of the building is entrusted to central heating system for all the cases considered with no possibility for the occupants to adjust the temperature setpoint.

In school A (a middle school) the age of pupils ranges between 10-13 years, whereas in schools C and D (elementary schools) pupils' age is 6-10 years. School B and E are kindergartens with pupils in the age 3-6 years.

The climate in Bolzano is semi-continental, with cold winters and hot summers. The city is located in a valley, around 250 m above sea level. The average hourly wind speed (at 10 m above ground) in the municipality territory does not change significantly during the year, and is typically lower than 5 km/h. On the contrary, the main wind direction is not constant and varies throughout the year. The daily temperature excursion is generally quite large, so in winter night frosts often occur, while in summer, although it can be very hot during the day, the nights and the early mornings generally remain cool.

As regards the weather conditions during the experimental campaign, the average temperature ranged from 1.2 °C in January 2019 to 21.1 °C in June 2019 (PAB 2019a, 2019b). It should be noted that May 2019 was characterized by average temperatures remarkably lower than average and, therefore, the Municipality of Bolzano has exceptionally extended the heating period until 26.05.2019 (well beyond the conventional limit for this climate zone set at 15.04.2019).

Table 2. Characteristics of the monitored schools.

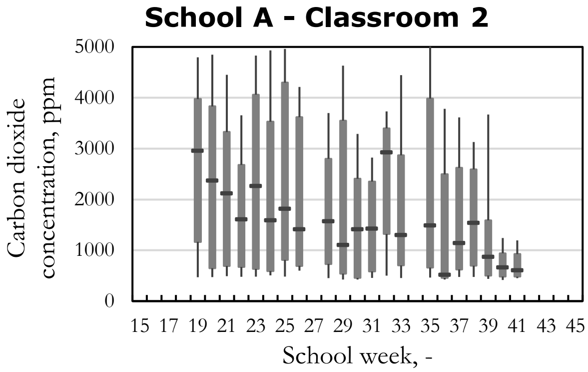
School (S) - Classroom (C)	School type	Construction Year	Floor	Type of windows	Windows orientation
S.A – C.1	Middle	1987	2^{nd}	Sash windows	West
S.A – C.2			3^{rd}	Sash windows	South
S.B	Kindergarten	2012	ground floor	Tilt and turn windows and doors	South
S.C	Elementary	2014	2^{nd}	Tilt and turn	South-East
S.D – C.1	Elementary	1985	3^{rd}	Tilt and turn	South
S.D – C.2			4^{th}	Tilt and turn	West
S.E – C.1	Kindergarten	2009	ground floor	Tilt and turn windows and doors	West/South
S.E – C.2			1^{st} floor	Tilt and turn windows	West

RESULTS AND DISCUSSION

In order to characterize the air permeability of the classroom envelope, a CO_2 decay test method similar to that adopted in the work by Stabile *et al.* (2016) has been used. The CO_2 concentration decay in the classroom was analysed as soon as the students left for 6 hours, with windows and doors kept closed. Since the EN 16798-1 method to assess perceived *IAQ* according to pollutants concentration considers categories determined in terms of differential concentrations, an equivalent and average external CO_2 concentration of 400 ppm is considered, which accounts for the outdoor level and the concentration of CO_2 in the spaces adjacent to the monitored classrooms. The infiltration rate in the school A, C and D ranged between 0.30 h^{-1} and 0.45 h^{-1}, while for the school B and E it was between 0.09 h^{-1} and 0.17 h^{-1}, indicating a better building airtightness (recent buildings).

Indoor air quality

In Figure 1, two boxplots charts for the weekly CO_2 concentration during occupancy time in two classrooms are reported as representative of the situation in elementary schools (A, C and D) and kindergartens (B and E). The CO_2 concentrations measured in the Classroom 1 of the School E is much lower than those recorded in the classrooms of the School A, with median values always below category II (1200 ppm) and maximum values that rarely exceed category IV (> 1750 ppm). Similar considerations can be made for the other classrooms monitored in the School B and School E (not shown in Figure 1). In addition to architectural and structural differences, the differences in CO_2 distributions in kindergartens and elementary schools can be explained by the lower number of occupants per classroom, the lower age of the occupants and the diversification of activities compared to those allowed in elementary and middle schools, which can significantly influence the ventilation balance in the rooms. It is excluded that these differences are due to greater air infiltration since kindergartens display the lower average air change rate during non-occupancy time.
A marked difference can be detected in the concentration distribution trends between classrooms in the elementary school. These differences can be caused by different external and adjacent internal environment as well as different behavioural habits regarding the opening of doors and windows. However, it appears that the median concentration values for elementary schools are for mostly above the limit associated with category I (950 ppm) and with peaks well above the maximum limit of category III (1750 ppm).



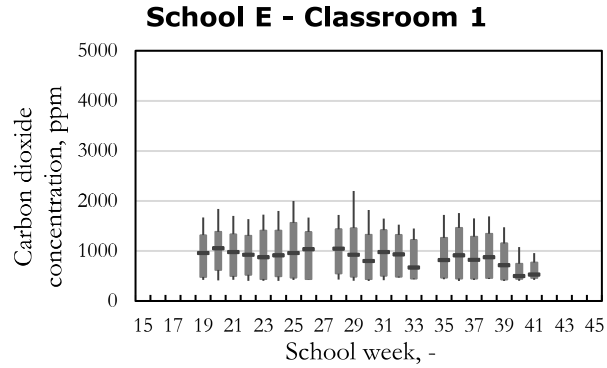


Figure 1. Boxplots representing the weekly carbon dioxide concentration in ppm during occupancy time in two classrooms.

These trends indicate that air changes through infiltration and through doors and windows openings are not sufficient to dilute the CO_2 generated by the occupants. The cause of this may lie in design deficiencies for the ventilation of the building, overcrowding of the room in question (not proportionate to the openings present) and the lack or insufficient opening of windows. This last point may be due to several reasons, such as the presence of physical obstacles to the opening of windows (blocking, malfunction), excessive thermal or acoustic discomfort due to the opening of doors/windows, non-simultaneous opening of doors and windows due to excessive draught air-flows or related to activities conducted in the classroom. These considerations are confirmed by the trends shown in Figure 2, reporting the percentage distributions of the occupancy time in which the CO_2 concentration is within a given class of the technical standard EN 16798-1:2019. The results have been distinguished into heating and non-heating periods. It should be mentioned that due to the exceptional extension of the heating period until the end of May 2019, most of the presented data (90 %) refer to this period.

From the data shown in Figure 2, the differences between kindergartens and elementary and middle schools is confirmed, with the former having higher occurrences in category I and II. The indoor air quality during heating period for elementary schools (A, C and D) is often unsatisfactory. A general improvement in the air quality is observed during the non-heating period. This is probably due to the increase in the duration and frequency of door and window openings allowed by the improvement of outdoor conditions (increased external temperature). Only in two cases (S.C and S.D-C.1) the percentage of occupancy time in category I is lower than 80 % during the non-heating period, however these classrooms also show a great improvement compared to the heating period.

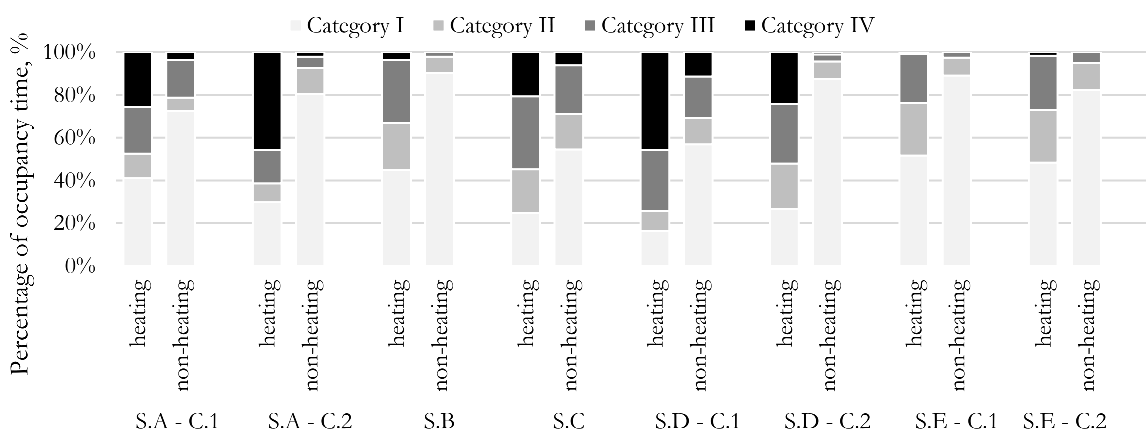


Figure 2. Indoor air quality categories distribution (based on CO_2 concentration) during occupancy time. For each classroom, the columns refer to heating and non-heating periods.

Indoor thermal comfort

Figure 3 shows the weekly distributions of internal temperatures and PMV during the heating period for the two classrooms, respectively representing a building constructed during the 1980s (School A) and a more recently constructed building (School E). The boxes delimit the range between the 10th and the 90th percentiles, the horizontal lines indicate the medians and the upper and lower whiskers are the maximum and minimum values, respectively.

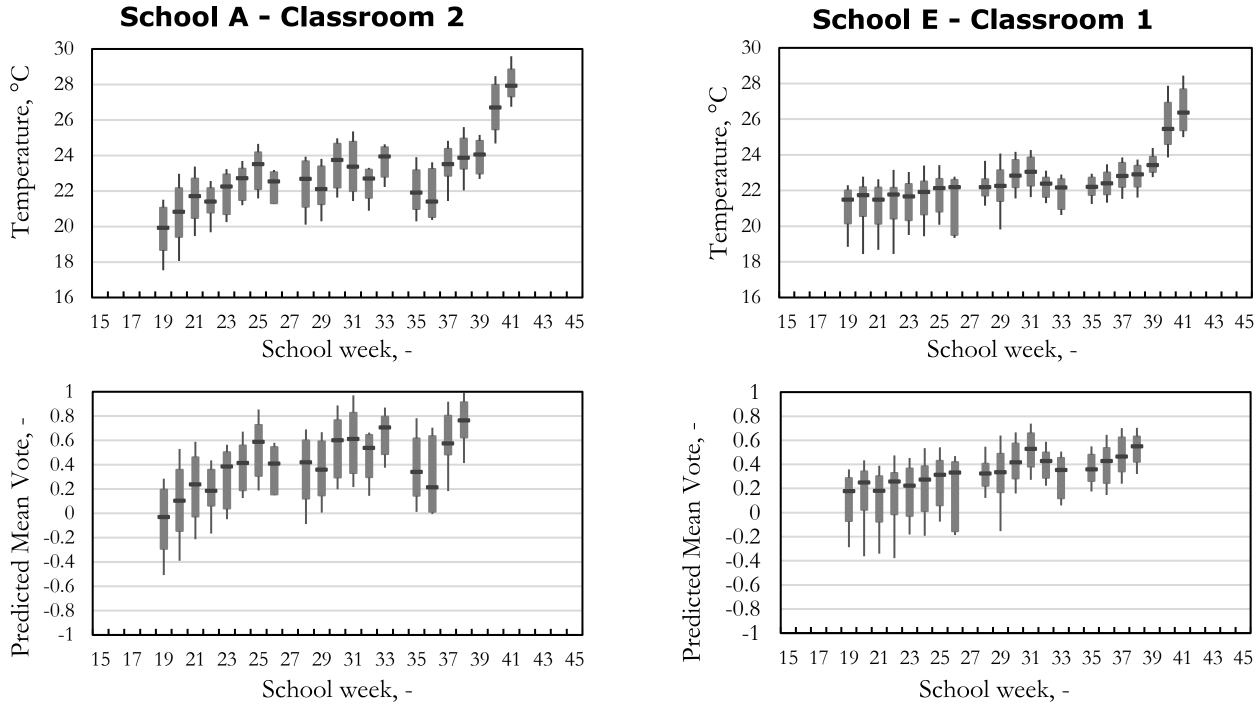


Figure 3. Boxplots representing weekly indoor temperature (top) and PMV (bottom) during occupancy time in two classrooms.

The Classroom 2 of School A displays a high variability in the average indoor air temperature, which results strongly influenced by the outdoor temperature. This variability can also be observed in the *PMV* distribution. The set point of the heating system is adequate only for the first period of analysis, in which the lowest outdoor temperatures are observed. For the rest of the monitored period, the indoor environment is too warm for the planned activities. In the case of school E - classroom 1, the weekly average indoor temperature in the classroom is almost always between 21 °C and 24 °C with maximum deviations of around 3 °C. The outside temperature has little influence on indoor conditions, which indicates a good insulation of the building envelope. Observing the *PMV* distribution, it can be observed that throughout the heating period, children are exposed to an environment that is slightly too warm, even during the coldest period. The cause of this may be an inadequate control of the heating system or the overheating occurred because of other heat internal gains not considered during the design. In the latter case, the ventilation may be suspected to be inadequate to remove the excess of heat without causing local discomfort and therefore the opening of windows/doors may be limited.

The graph in Figure 4 shows the share of occupancy time during the heating period in each of the thermal comfort categories provided by EN 16798-1:2019. All the classrooms, except the elementary School C during the occupation periods are mostly in category I or II. Category IV occurs for more than 10 % of the time only in 3 cases. This indicates that almost all the schools considered in this study have satisfactory thermal conditions, although the increased share of category II suggests that the setpoint of the classrooms could be lowered, which would be beneficial also for energy consumption.

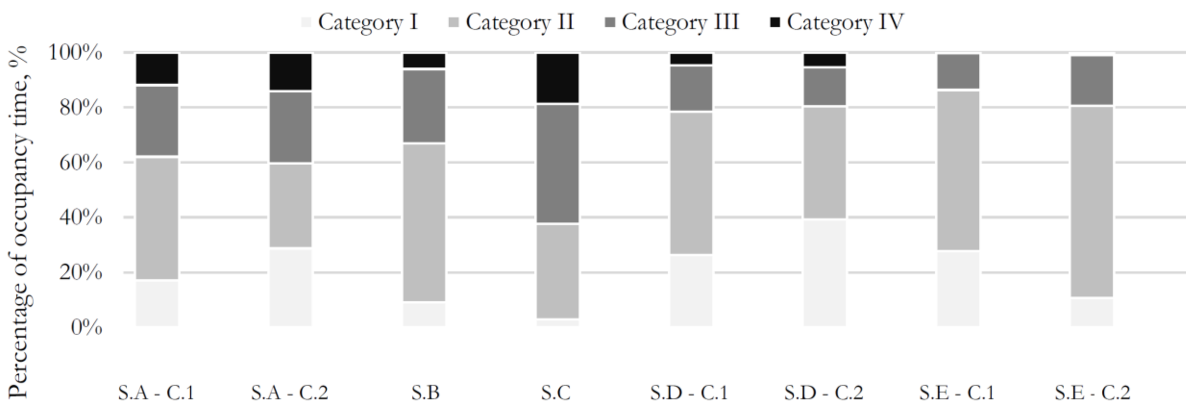


Figure 4. Indoor thermal comfort categories distribution during occupancy time (heating period).

Pupils' performance

Figure 5 shows the distribution of the pupils' relative performance during occupancy time related to the *PMV* (limited to heating period) and indoor CO_2 concentration using the models by Wargocki *et al.* (2019, 2020). The performance loss due to the thermal discomfort is proportional to the temperature difference between the monitored valued and the comfort value. Its distribution is similar in all the considered classroom and reflects the tendency to have temperatures higher than necessary. The average performance loss results between 15 % and 17 %. The performance loss referred to *IAQ* follows the CO_2 distributions. In kindergartens, loss of performance is limited, with median values practically equal to the minimum. For elementary schools, on the other hand, average losses range between 5 % and 11 %.

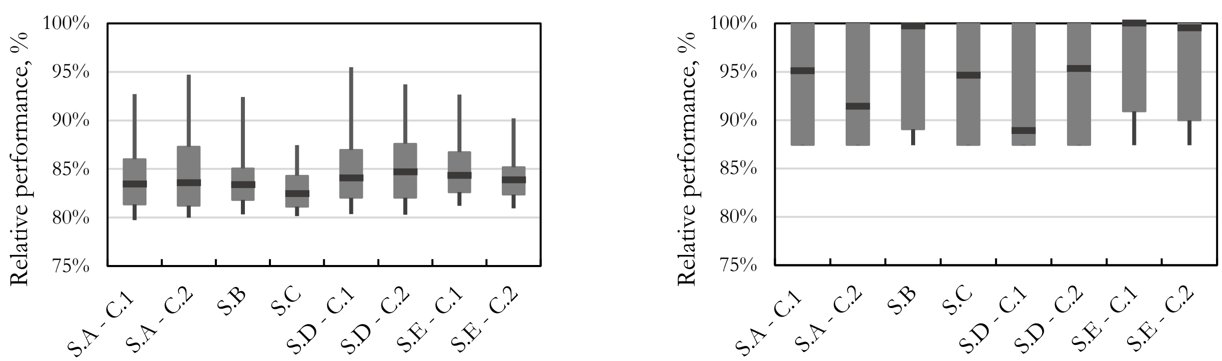


Figure 5. Boxplots representing the relative performance during total occupancy time related to the calculated *PMV* (left) and Carbon dioxide concentration according to Wargocki *et al.* (2019, 2020).

CONCLUSION

In this paper, the indoor conditions of eight natural ventilated classrooms belonging to the school building stock of the city of Bolzano have been monitored in a long-term campaign. The thermal comfort was mostly acceptable even if temperatures tended to be slightly too high. The monitoring results showed that the air quality was unsatisfactory for most of the period of occupation. The issue affects both recent and older buildings. Although not always satisfactory, the quality in kindergartens was better than in elementary schools. Results show that air quality tends to improve after the heating period, which may indicate an increase in the natural ventilation rate of buildings. According to the applied models from the literature, the main performance loss of the pupils is due by the thermal discomfort due to the high temperature in the classrooms.

The CO_2 concentration values shown in kindergartens and all the schools after the end of the heating period suggest that even just by adopting good window/door opening strategies there is room to improve the *IAQ*; possible solution may be to establish ventilation routines or install visual sensors to increase the awareness of occupants. Nevertheless, it must be considered that it will be necessary to carefully assess its impact on the heating energy consumption and the possible occurrence of local discomfort. Furthermore, the adoption of local thermostat could improve the control of the room temperature with positive effects on the energy consumption and pupil's performance. In conclusion, a better integrated control of heating system and natural ventilation system could be helpful to further improve the environmental and energy performance of new and existing natural ventilated educational building.

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