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The Indoor Environmental Quality in Schools in South Tyrol: Insights from the Field Measurements, and Initial Design of the Improvements

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ABSTRACT

Nowadays people spend an average of 87% of their time inside buildings. Schools are a particularly delicate type of buildings for several reasons. Firstly, their primary occupants such as children, boys and girls are more vulnerable than adults, and spend a large portion of their time in schools. Secondly, pupils, but also teachers and other school personnel have often little or no control on the indoor environmental quality (IEQ). Thirdly, school buildings are usually either old and cannot ensure an adequate IEQ (e.g. cold and leaky), or, on the other hand, recent or recently refurbished, but designed based on energy-efficiency targets only. In the latter case, buildings are very airtight, and the indoor air quality often drops unless carefully designed and commissioned (i.e. periodically tuned as the boundary conditions such as age and number of pupils vary). Thus, the aim of this study is to investigate the IEQ in schools in South Tyrol (northern Italy) and Canton Ticino (Switzerland), and to develop design solution to improve the IEQ, and hence the health and well-being of the schools' occupants. A number of case-studies has been selected in both countries including schools of all levels, and have been monitored to better evaluate the current situation. This paper presents the initial findings of the monitoring activity (including also some considerations on the complexity and limitations that are likely to occur while monitoring schools due to their young occupants) and some insights into the design solutions that are being developed to improve the IEQ in these schools. The analysis of the measured data shows that air quality in recently built schools may be considerably poorer than in older schools, being the daily average CO_2 figures above 2000ppm and the peaks above 5000ppm. Further work is needed to evaluate the levels of other contaminants such as formaldehyde, TVOCs and particulate matter, and the related implications and possible solutions.

INTRODUCTION

Nowadays people spend an average of 87% of their time inside buildings (Klepeis et al. 2001). Schools are a particularly delicate type of buildings for several reasons. Firstly, their primary occupants such as children, boys and girls are more vulnerable than adults, and spend a large portion of their time in schools (Annesi-Maesano et al. 2013).

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Secondly, pupils, but also teachers and other school personnel have often little or no control over the indoor environmental quality (IEQ). Thirdly, school buildings are usually either old and cannot ensure an adequate IEQ (e.g. cold and leaky), or, on the other hand, recent or recently refurbished, but designed based on energy-efficiency targets only. In the latter case, buildings are very airtight, and the indoor air quality often drops unless carefully designed and commissioned (i.e. periodically tuned as the boundary conditions such as age and number of pupils vary).

A large Swedish study showed that 53% of the personnel perceived the indoor air quality (IAQ) as bad or very bad (Smedje et al. 1997), while a recently published research conducted in the Helsinki area highlighted that psychosocial factors and complex relationships between and within the groups of schools' occupants (students, teachers, and others) might deteriorate the perceived IAQ (Finell et al. 2018). These findings suggest that designers should ensure the highest possible IAQ in order to minimize the chances of a poor IAQ perception, even if this negative perception enlarged by other non-technical aspects.

To characterize the IAQ in schools, several parameters were measured in previous studies such as air temperature (T), relative humidity (RH), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitric oxide (NO), nitrogen dioxide (NO_2), respirable particulate matter (PM_{10}, $PM_{2.5}$), formaldehyde (HCHO), total bacteria and fungi counts, volatile organic compounds (VOCs), other aldehydes, and radon (Godwin and Batterman 2007; Johnson et al. 2018; Lee and Chang 2000; Madureira et al. 2015, 2016; Pegas et al. 2011; Stabile et al. 2017). Depending on the context and aim of each study, a sub-set of these parameters was monitored for various length of time, from spot measurements to several weeks. However, the parameters that were recorded in almost all studies are air temperature, relative humidity, CO_2, particulate matter (PM_{10}, $PM_{2.5}$ or both), and VOCs. In certain cases, only total VOCs (TVOCs) were measured, while in others the focus was on specific VOC such as formaldehyde. It is also important to note that parameters such as CO_2 are easier to measure (more reliable measure) and hence are used as a proxy to evaluate the overall IAQ.

Based on the measured IAQ, research focused on means to improve it. Pollution sources include building location (both lithology and outdoor air), building materials (both furniture and fabric), occupants, and maintenance and cleaning activities. Evidence suggests that low IAQ is often due to poor ventilation, and also to implement source-control strategies (Madureira et al. 2015). However, while extended airing periods usually lead to lower CO_2 concentrations, research showed that a simultaneous reduction in concentration levels for all indoor pollutants might not be achieved just relying upon air permeability of the building envelope and natural ventilation (Stabile et al. 2017). Moreover, while enhancing IAQ by means of natural ventilation (which means, during the heating season, elevated air changes per hour (ACH)), thermal comfort should also be taken into account (Angelopoulos et al. 2017). However, ventilation rates are only one of the many factors influencing perceived indoor air quality and health. Other factors include building design, operation and maintenance as well as outdoor pollution and noise levels (Carrer et al. 2015; Seppänen et al. 1999).

To date, still too little is known about the current situation in schools. This applies to older buildings, but also to recently built premises. The latter case is often due to the fact that, in the last decades, design projects were mainly driven by energy demand targets. Hence, the aim of this study is to investigate the IEQ in schools in South Tyrol (northern Italy) and Canton Ticino (southern Switzerland), and to develop design solution to improve the IEQ, and hence the health and well-being of the schools' occupants. This paper presents the initial finding of the work, and it is focused on one school (in South Tyrol) that comprises an old and a recently built part.

METHODOLOGY

This study comprises two main parts, namely field studies to investigate the current situation of the schools, and design solutions to improve the IEQ in the schools by addressing the issues emerged from the field studies.

Fields studies: data collection

The school chosen for this initial analysis is located in an urban area in South Tyrol. This building was chosen as a first case study since it comprises two parts, namely an older wing and a more recently built part, and this feature eases the comparison between the IAQ in older and newer schools. Being run by the same management team, the possible differences in IAQ could be more easily and objectively explained by looking at the building characteristics only. Moreover, while no survey about occupants' satisfaction and comfort has been conducted in this study, occupants have often a perception of poor IAQ.

Two classrooms per part were selected (Figure 1), and measurements were taken in winter 2019/2020. The monitoring equipment was initially installed on a Friday afternoon in the newer part, and then moved to the older part the following Friday. Thus, both parts were monitored for a week.

In each classroom, the door and all outdoor facing openings (windows and door windows) were equipped with sensors that uses a magnetic Hall effect sensor to detect open/close events, and have a built-in radio that talks directly with low-power wide-area networking protocols. These are Boolean sensors: a "0" signal means that the sensor is "closed" (i.e. the magnet is present, so the opening is closed), while "1" means "open" (i.e. no magnet is present, so the opening is open). Signals were sent to the network gateway, and then saved in an DB server.

In each classroom, IEQ was measured with two devices: an in-house developed multi-sensors system called EQ-OX (Environmental Quality bOX) and a commercial system. EQ-OX was conceived to be a portable low-cost device that enable to measure multiple IEQ parameters such as hygro-thermal parameters, lighting level, and some IAQ parameters. The case and the board for the sensors are tailor-made, while the single sensors have been selected among those available on the market. Like the opening sensors, also EQ-OX uses a low-power wide-area networking protocol connection, and this enables to save and check the data in real time. For the analysis presented in this paper, only CO_2 measurement was considered as IAQ indicator (K-30 Sensor, range: 0-5000ppm, accuracy: ±(30ppm + 3% of reading)).

The other IAQ monitoring system was a TSI 7525 (Dual-wavelength NDIR non-dispersive infrared Sensor). As only CO_2 was used as IAQ indicator, a calibration procedure was performed before and after the measurement with three fixed concentrations of CO_2 (399ppm, 1999ppm and 3999ppm) that were injected in the TSI sensor (range: 0-5000ppm, manufacturer's accuracy: ±3.0% of reading or ±50 ppm, post-calibration accuracy: ±2%).

Figure 1 Layout of the four classrooms (older part on the left, newer on the right) including orientation and adjacent spaces. The red dot indicates the position of EQ-OX and TSI. In light blue, the outdoor-facing windows and doors (not all were openable).

Fields studies: data analysis

CO_2 was chosen for this first IAQ analysis as it is a robust and widely used metric to evaluate IAQ in schools. This does not mean that if CO_2 level are below standard thresholds, then there are no IAQ issues, but it simply provides an initial useful overview and enables a comparison with several other studies.

Window sensors send a signal only when there is a change of status. For this reason, the total number of signals per sensors was initially calculated to see how often windows and doors were used. Then, to know the status of each opening at any point in time, if no signal was sent at a specific time, the latest available value was used (i.e. a window was assumed to be open until the closure signal arrived, and vice versa). However, not all outdoor-facing openings present in the four classrooms were identical as they have different size (only openable part was accounted) and opening mode (tilt or side-hung, but not both). For this reason, to calculate the total percentage of outdoor-facing openings that were open at a certain point in time, their respective normalized weight was compounded using the following equation:

$$window = \sum_{k=1}^{n} \alpha_n \cdot status\_w_n \qquad (1)$$

where:
α_n: normalized weight of opening n
$status\_w_n$: status of opening n (i.e. 1 o 0)

In classrooms "1 old" and "2 old", there are six identical windows per room (both side-hung and bottom-hung/tilt). Thus, the α_n coefficient was equal to 1/6 for all opening. In each of the other classrooms there are four openings, namely two side-hung window, one tilt window, and one door-window (side-hung). Thus, the α_n coefficient was calculated for each opening as reported in Table 1. The combined coefficient is the product of the "mode" (1.00: side-hung, 0.10: tilt) and "size" (height x width; then 1 for the largest, proportionally calculated for the others) coefficient. These combined values were then normalized so that their sum was equal to 1. Considering that the status of an opening can be 0 or 1, the use of such normalized coefficients means that "window" (in Equation 1) is equal to 1 when all openings are open. In other words, "window" equal to 1 means that 100% of the openable openings are open (i.e. there is no additional opening that could be open in the room or opening that could be open more).

Table 1. Normalized Weight Of Openings

Opening	Mode coefficient	Size coefficient	Combined coefficient	Normalized opening weight (α_n)
w1 (side-hung)	1.00	0.51	0.510	0.242
w2 (tilt)	0.10	0.85	0.085	0.040
w3 (side-hung)	1.00	0.51	0.510	0.242
w4 (door window)	1.00	1.00	1.000	0.475

Both EQ-OX and TSI provided several measurements within one minute. Firstly, recorded data was resampled calculating 10-minute average values. The analysis then focused on the comparison between CO_2 levels and status of the door and the percentage of openings ("window" factor). Considering that the classrooms are usually occupied by either students, teachers or other personnel (e.g. for cleaning purposes) from 6am to 8pm, the percentage distribution of CO_2 concentrations over time was calculated for this time interval, and then compared with values from international standards such as ASHRAE (ASHRAE 2017) and local guidelines such as "Casa Clima School" protocol (CasaClima 2020). Similarly, the statistics (e.g. average) of "window" (Equation 1) were calculated with data from 6am to 8pm. In these classrooms, students performed typical desk-based learning activities.

RESULTS AND DISCUSSION

The current situation in schools

Overall, the total number of signals received from the windows is considerably lower than those received from the doors of the classrooms, and there is no relevant difference between the different classrooms and parts of the school. In the newer part, over 4 days (Monday to Thursday) the doors sent 294 and 403 signals from classroom "1new" and "2new", respectively. Over the same period, the combined figures from all windows are 55 (19% of the door (OD)) and 112 (28% OD) (classroom "1new" and "2new", respectively). In the older part, over 4 days (Monday to Thursday) the doors sent 201 and 305 signals from classroom "1old" and "2old", while the combined figures from all windows are 23 (11% OD) and 60 (20% OD). Assuming that the usage of the door gives a measure of the usage of the room, then it seems that windows are used more in the newer part, although the difference is not wide. As shown in Table 2, the average values of the "window" parameter indicate a similar pattern, and also suggests that windows remained open for longer periods in the newer part. However, these figures should be compared with CO_2 values to better evaluate the situation.

Table 2. "window" value statistics

Classroom	Average	Minimum	Maximum	Standard deviation
1new	0.16	0.00	0.96	0.22
2new	0.25	0.00	1.00	0.19
1old	0.01	0.00	0.33	0.04
2old	0.03	0.00	0.50	0.08

Tables 3 to 6 illustrate the CO_2 values measured in the four classrooms over 4 days (Monday to Thursday, same periods used for the calculation of the factor "window"). Daily average, minimum, maximum and standard deviation figures are expressed in ppm, while the remaining columns indicate the percentage of the time in which the concentration was above the threshold indicated in the table (in ppm). For each day, both EQ-OX (E) and TSI (T) data are reported. In Table 5 and 6, there is no EQ-OX data for day 21 due to a technical problem with the network gateway. Moreover, as the full-scale of both devices is 5000ppm, the column "Above 5000" should be read as the percentage of time in which values were above the full-scale.

Table 3. CO_2 daily figures – classroom "1 new"

Day (device)	CO_2 avg	CO_2 min	CO_2 max	CO_2 std	Above 1000	Above 2000	Above 3000	Above 4000	Above 5000
13 (E)	1481	824	2382	424	81%	13%	0%	0%	0%
13 (T)	1773	424	2983	614	88%	39%	0%	0%	0%
14 (E)	1213	683	2035	402	64%	2%	0%	0%	0%
14 (T)	1414	620	2265	450	85%	12%	0%	0%	0%
15 (E)	2078	977	3750	744	98%	52%	12%	0%	0%
15 (T)	2397	518	4133	940	87%	69%	28%	2%	0%
16 (E)	1246	702	2876	483	62%	10%	0%	0%	0%
16 (T)	1229	612	3195	620	52%	9%	1%	0%	0%

Table 4. CO_2 daily figures – classroom "2 new"

Day (device)	CO_2 avg	CO_2 min	CO_2 max	CO_2 std	Above 1000	Above 2000	Above 3000	Above 4000	Above 5000
13 (E)	1893	1005	4562	1068	100%	36%	18%	7%	0%
13 (T)	2323	451	5100	1289	88%	54%	32%	13%	4%
14 (E)	874	605	2297	288	14%	1%	0%	0%	0%
14 (T)	1454	663	4500	960	47%	21%	11%	2%	0%
15 (E)	1942	560	5041	1329	46%	44%	24%	11%	1%
15 (T)	2454	591	5697	1495	64%	56%	40%	16%	5%
16 (E)	1302	596	3083	549	89%	14%	2%	0%	0%
16 (T)	1624	607	3490	786	85%	27%	9%	0%	0%

EQ-OX figures are generally lower that TSI values, but the trends and distributions over time are in reasonable agreement. Both devices show that CO_2 values are considerably more elevated in the newer part of the school. In classroom "1new", for most of the time, the figures are above 1000ppm. On day 15, the daily average is above 2000ppm, and CO_2 is above 3000pm in over a quarter of the time. Data from classroom "2new" (Figure 2) also exceeds 1000ppm for most of the time, and are above 4000ppm for more than 10% of the time in two out of four days. There is a smaller percentage of time in which CO_2 rises even above 5000ppm, which is the full-scale of both EQ-OX and TSI.

Table 5. CO_2 daily figures – classroom "1 old"

Day (device)	CO_2 avg	CO_2 min	CO_2 max	CO_2 std	Above 1000	Above 2000	Above 3000	Above 4000	Above 5000
20 (E)	1397	833	2524	442	34%	5%	0%	0%	0%
20 (T)	1350	418	3034	644	71%	18%	1%	0%	0%
21 (E)	-	-	-	-	-	-	-	-	-
21 (T)	1525	463	3215	745	68%	26%	2%	0%	0%
22 (E)	968	523	2470	491	34%	4%	0%	0%	0%
22 (T)	1149	514	2778	552	54%	8%	0%	0%	0%
23 (E)	1629	643	3096	773	69%	38%	4%	0%	0%
23 (T)	1869	493	3477	864	85%	46%	12%	0%	0%

Table 6. CO_2 daily figures – classroom "2 old"

Day (device)	CO_2 avg	CO_2 min	CO_2 max	CO_2 std	Above 1000	Above 2000	Above 3000	Above 4000	Above 5000
20 (E)	1039	638	1789	287	22%	0%	0%	0%	0%
20 (T)	985	424	2141	473	38%	5%	0%	0%	0%
21 (E)	-	-	-	-	-	-	-	-	-
21 (T)	1110	453	2441	512	52%	9%	0%	0%	0%
22 (E)	656	481	1034	128	2%	0%	0%	0%	0%
22 (T)	811	453	1771	335	20%	0%	0%	0%	0%
23 (E)	818	531	1883	276	16%	0%	0%	0%	0%
23 (T)	978	456	2283	422	29%	5%	0%	0%	0%

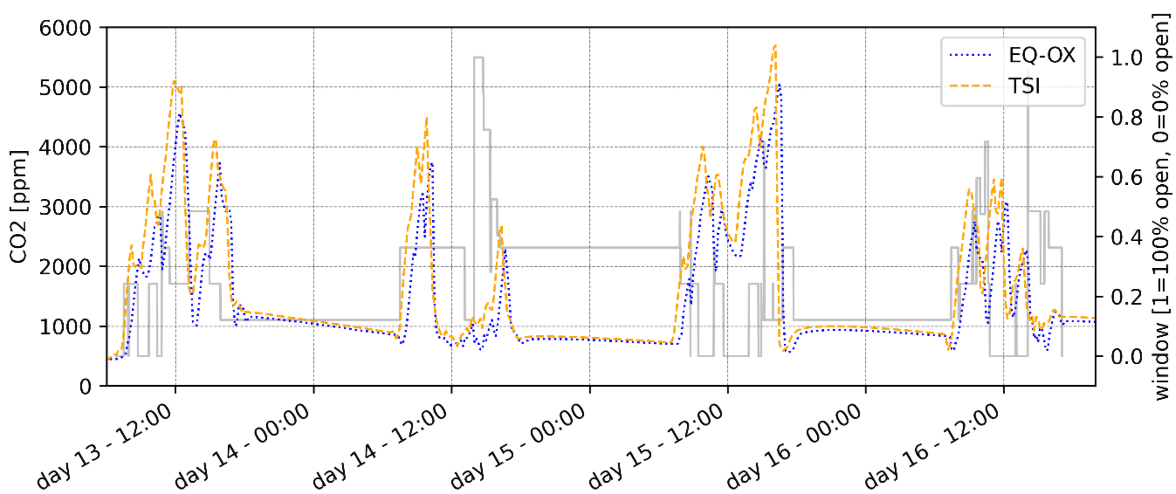

Figure 2 CO_2 levels in classroom "2new" measured with EQ-OX and TSI. In grey, the "window" factor.

On the other hand, in the older part, CO_2 figures in classroom "2old" are low as the large majority of the data is below 1000ppm, most of the remaining values are below 2000ppm, and no value above 3000ppm was recorded. In classroom "1old" the figures are higher (Figure 3), but the majority of the values are still below 2000ppm, and no value is above 4000ppm. In certain days, there is a considerable number of values between 2000ppm and 3000ppm.

Considering that 1000ppm is the most widely used threshold for CO_2 in schools, measured data highlights that IAQ is acceptable only in one out of four classes, while is clearly not acceptable in two classrooms. The fact that the average "window" factor in these two classes (i.e. "1new" and "2new") is higher suggests at least three important points. Firstly, occupants seem to perceive this poor IAQ as they open the windows more often than those in the other classrooms. However, secondly, such ventilation does not seem to be effective as the CO_2 levels remain well above any recommended limit. Hence, while in the older part a better use of the windows is very likely to ensure to keep CO2 below 1000ppm, a deeper analysis is required for the newer part. Thirdly, the fact that the doors of the two classrooms in the newer part face another classroom (a so-called "open classroom", see Figure 1), and not a traditional unoccupied corridor, further limits the possibility to decrease CO_2 levels.

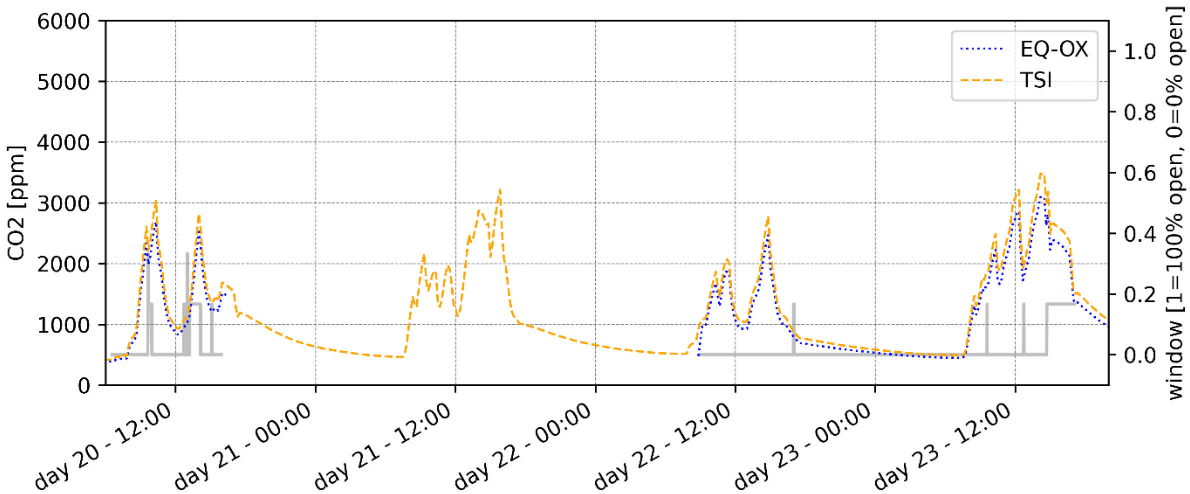

Figure 3 CO_2 levels in classroom "1old" measured with EQ-OX and TSI. In grey, the "window" factor.

The possible design improvements

Several drivers were identified in order to select optimal retrofit solutions to improve IAQ in schools: time of installation, ease of maintenance, economic feasibility, low aesthetical impact, low acoustic impact and energy efficiency, as well as replicability in other school buildings. Design outdoor air volume flows recommended by the standard EN 16798-1: 2019 to provide indoor air quality range between 370m^3/h and 1300m^3/h for classrooms such as those presented in this paper. The design volume flow rate depends on the level of contaminants emitted by building materials and on the target level of expectations (high, normal or acceptable).

Theoretically, natural ventilation provided by window opening under winter conditions (ΔT > 10K) could ensure more than 1800m^3/h in the classroom in the newer part and 2000m^3/h in the classroom in the older part. However, window design in the two classrooms is quite different and influences the way students operate them. Although the older part classrooms have lower window-to-wall ratio (16%) compared to the newer part classroom (35%), the opening area-floor surface ratio is 10-11 % in both cases. Due to different openings design, windows are not accessible in the same way and drafts can be perceived differently. Solutions under evaluation for the classrooms in the older part include window replacement with enhanced thermal performance and opening design to exploit natural ventilation reducing draft risk.

A decentralized ventilation system is proposed for the classrooms in the newer part where glazed components are far away from their end of lifetime and still have elevated thermal performance. The decentralized ventilation solution allows for demand-based ventilation up to 600m^3/h airflow, heat recovery and simple set up and control.

CONCLUSIONS

The aim of this study was to investigate the indoor air quality in schools in South Tyrol, and to identify possible design solution to improve the current situation where required.

The main conclusions are as follows:

- The initial CO_2 analysis shows that the levels in more recently built schools may be considerably worse than those measured in older schools. Daily average values above 2000ppm and peaks above 5000ppm were found.

- In newer and more air tight buildings, elevated CO2 concentrations are likely to be due to a combination of factors, namely undersized openings, lack of unoccupied corridors that could compensate the insufficient openings, and a too limited capability of the occupants of using the available openings.
- Possible improvements include window replacement with enhanced opening design and installation of a decentralized mechanical ventilation unit.

Further work is needed to extend the analysis to a larger sample of schools and classrooms, and to evaluate the levels of other contaminants such as formaldehyde, TVOCs and particulate matter, and the related implications and possible solutions.

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