Low-Invasive CO$_2$-Based Visual Alerting Systems to Manage Natural Ventilation and Improve IAQ in Historic School Buildings

Francesca Avella $^{1,4}$, Akshit Gupta $^1$, Clara Peretti $^2$, Gianmaria Fulici $^2$, Luca Verdi $^2$, Annamaria Belleri $^1$ and Francesco Babich $^1$

$^1$ Institute for Renewable Energy, EURAC Research, Via A. Volta 13/A, 39100 Bolzano, Italy; akshit.gupta@eurac.edu (A.G.); annamaria.belleri@eurac.edu (A.B.); francesco.babich@eurac.edu (F.B.)
$^2$ Laboratory for Air Monitoring and Radioprotection, Agency for Environment and Climate Protection of the Autonomous Province of Bolzano, Via A. Alagi 5, 39100 Bolzano, Italy; clara@ingperetti.it (C.P.); gianmaria.fulici@provincia.bz.it (G.F.); Luca.Verdi@provincia.bz.it (L.V.)
$^4$ Correspondence: francesca.avella@eurac.edu

Abstract: Children spend a large part of their growing years in schools, and as they are more sensitive to some pollutants than adults, it is essential to monitor and maximize the indoor air quality (IAQ) in classrooms. Many schools are located in historic and heritage buildings, and improving the IAQ, preserving the architectural features, poses a great challenge. The aim of the study is to evaluate the effectiveness of a low-invasiveness, low-cost, smart CO$_2$-based visual alerting systems to manage natural ventilation and improve IAQ in historic school buildings. Indoor and outdoor parameters were monitored for three weeks in four schools with different levels of education (two classrooms per school; device installed in one only). Based on indoor CO$_2$ concentration, air temperature and relative humidity, the device suggests when windows should be opened to ventilate. The comparison between the two classrooms show that the effectiveness of the device is highly dependent on the occupants: (i) reduction in the average CO$_2$ concentrations of up to 42% in classrooms with frontal lesson and full occupancy, (ii) the device is not the most ideal solution for kindergarten due to the young age of the pupils, and (iii) it is more used during mild outdoor temperatures.

Keywords: indoor air quality (IAQ); natural ventilation; historic buildings; carbon dioxide (CO$_2$); monitoring strategies; passive solution; schools

1. Introduction

Problems related to indoor environment quality (IEQ) are becoming a serious health concern in schools, as children are more sensitive to some pollutants than adults [1–5]. It has been widely reported that better indoor air quality (IAQ) reduces health-related symptoms and improves student’s attention and academic performance [5–12].

In the building stock, many buildings, about 30% [13], are identified as historic buildings based on their cultural, social and historical relevance [14]. In order to protract the life of the building [15] while allowing the efficient use of these buildings over time, it is necessary to consider and develop thoughtful and strategic action criteria [16,17] that means in some cases in the application of retrofit solutions [18,19]. Since not all historic buildings have the same characteristics in terms of materials used, size, and level of preservation, each case must be carefully studied in order to evaluate the solution that allows to have a more efficient building while maintaining its conservative, architectural, and cultural aspect [14,20].
In South Tyrol (Italy), as well as in several other European countries, many schools are located in historic and heritage buildings, and ensuring an acceptable IAQ inside these buildings while preserving the authenticity [13,14] and architectural features [15] (such as opening positions, other aesthetic aspects of the façade, indoor structural constraints, etc.) poses a great challenge.

In some studies performed in schools, the ventilation rate has been used as an indicator of IAQ, and shown improvements in IAQ with increasing ventilation inside classrooms [3,4,21–23]. In this perspective, a research led by Gao et al. (2014) investigated different ventilation strategies and studied the indoor climate and window opening behavior in four classrooms in a school in Denmark, and observed the potential of natural ventilation with automated windows in achieving a good level of air quality [24].

In the “Guidelines for a healthy school environment in Europe”, CO$_2$—an odorless gas deriving mainly from the human breath—has been found among the main pollutants recorded in some monitored schools. Due to the low-cost of CO$_2$ sensors with an acceptable accuracy over long-term monitoring [25], CO$_2$ is often used as a basis for the evaluation of the other bio-effluents in ventilation standards and regulations [26]. For this reason, many studies have investigated the effects of this gas on pupils, highlighting how a decrease of CO$_2$ concentrations and an increase in volumetric flow rate from 2 to 7.5 L/s per person lead to student performance improvement and absenteeism reduction [3,22,27–31]. More specific study presented by Wargocki et al. (2020) shows that a decrease in CO$_2$ concentration from 2100 to 900 ppm would increase performance in schools while the absenteeism would reduce when CO$_2$ decreased from 4200 ppm to 1000 ppm [22].

The need to reduce the risk of transmission of COVID-19, declared on March 2020 by the World Health Organization (WHO) [4], to promote health in schools and academic performance, led schools to reflect on how to improve air quality, and rethinking how to ventilate school spaces [32]. In fact, the transmission of the virus increases in closed spaces and hence incrementing the air change rate [33] and opening windows correctly can prevent viral air infection [34–36] and the risk of airborne contagion [33,37–41]. Following the COVID-19 pandemic, schools have consequently adopted the guidelines issued by the WHO in the “Roadmap to improve and ensure good indoor ventilation in the context of COVID-19” [42], confirming the need to regularly open and optimize the windows to provide for a frequent air change [43].

However, the need to find solutions that improve air quality in schools [44,45], while maintaining a good level of thermal comfort, is often linked to economic issues (costs of the initial retrofit, maintenance, and operation), the duration of the retrofit work and the feasibility of the intervention considering the historic value of building architecture. For this reason, especially in this type of buildings, the systems should be quick and easy to implement, cost-effective, low invasiveness, and energy efficient [30] as well as taking into account the degree of freedom of intervention on the building. In fact, it is often necessary to resort to passive solutions especially in the case of buildings with historic and heritage value in order to preserve their aesthetic features [18,46].

Various examples that tried to respect the conservation principles of the building, while maintaining the goal of achieving good indoor air quality, are available in the literature. In the EU FP7 3ENCULT project, a wireless network of very low-power sensors was developed. This device collects information about the indoor environment without affecting the building, and interacts with the building management system to take appropriate measures from the point of view of energy consumption as well as comfort [47]. The EU FP7 3ENCULT project also developed an active overflow ventilation system that requires minimum ductwork and provides air change when CO$_2$ concentration rises above the limit [48].

In recent times, the need to ensure comfort and energy performance of buildings led to the emergence of visual signaling systems that advice the occupants when it is recommended to open windows. Wargocki and Da Silva (2015) studied a system that monitors CO$_2$, giving visual indications associated to the level of CO$_2$ concentrations in
the classroom. The results suggest that this system encourages pupils to open windows more frequently [30], even if this practice is often associated with external noise [49] and atmospheric pollution [50] which can discourage the advantage of natural ventilation. Another study has developed a ventilation guide device (VVGD) which—based on VOCs, temperature, and air humidity—provides suggestions for opening and closing windows through a display [51].

According to Ackerly and Brager (2013), the correct use of these visual devices is linked to multiple factors such as the place where they are installed (whether they are shared or private spaces), the visibility of the signal from the workstation—but above all a correct explanation of the reason why it was installed—emphasizing the benefits from its correct use [52].

In historic buildings, natural ventilation is likely to be a good solution to ensure an acceptable IAQ while preserving the architectural features of the buildings. However, to ensure good IAQ for school occupants, openings must be operated according to the rooms’ pollution conditions, and smart alerting systems might be a useful support. To date, too little is known about their effectiveness in real operational environments. Few initial studies are encouraging, but more evidence is needed on its effectiveness in different kind of school settings based on the level of education and organization in the classrooms.

Hence, the aim of this paper is to provide insights into the effectiveness of a low-invasiveness, low-cost, smart CO₂-based visual alerting system improving indoor air quality in schools in order to contribute to answer one main research question: is this type of device an effective means to manage natural ventilation and improve the IAQ in different kinds of heritage school buildings?

The study is part of the project Interreg ITA-CH QAES [53] which aims at developing best practices for improving indoor air quality in schools of the Interreg area (South Tyrol and Canton Ticino).

2. Materials and Methods

The effectiveness of the CO₂-based visual alerting system has been tested. Based on indoor CO₂ concentration, indoor temperature, and relative humidity, the device suggests when windows should be opened to ventilate. In each school, two classrooms are monitored for a three week period: one with the visual alerting system and one without. The effectiveness is then analyzed, comparing the monitored data in the two classrooms.

The overall work was structured according to the following phases:

1. Selection of the case studies (two classrooms each in four schools) and monitoring of indoor air quality in a first winter and summer monitoring campaign.
2. Preliminary theoretical study of the ventilation rate necessary to ensure good indoor air quality according to the standard EN 16798-1:2019 [54].
3. Installation of the CO₂-based passive visual alerting system in one of the two classrooms monitored in each school.
4. Second winter and summer monitoring campaign to test the effectiveness of the installed devices.
5. Interviews with school staff to evaluate the effectiveness of the installed system from their point of view.

Each phase is detailed in the following sub-sections.

2.1. Case Studies

Four schools have been selected (Table 1) among the six schools monitored in South Tyrol as part of the project Interreg ITA-CH QAES [53]. The whole school selection process started with the study of chemical and physical analyses conducted in previous years by the “Laboratorio Analisi aria e radioprotezione – Provincia autonoma di Bolzano – Alto Adige”¹, meetings with public administrations and inspections with the school staff. In
these occasions, short interviews were carried out to understand the management of the building and the problems related to comfort and air quality. Other selection criteria include the level of education, the energy class of the building, the type of ventilation, number of classrooms, students per classroom, the urban context, and the year of construction [55]. This last aspect made it possible to classify two out of the four schools as historic buildings (schools 2 and 4, Table 1).

Table 1. Main features of the four case studies

| School ID | Year of Construction | Context  | Level of Education   | Ventilation |
|-----------|----------------------|----------|----------------------|-------------|
| 1         | 1960                 | urban    | Secondary school     | Natural     |
| 2         | 1905                 | urban    | Kindergarten         | Natural     |
| 3         | 2012                 | urban    | High school          | Natural     |
| 4         | 1600+                | urban    | High school          | Natural     |

A first monitoring campaign to identify the dominant pollutants that influence the air quality in the classrooms was carried out and so different types of interventions aimed at solving the specific problem, installed. In four schools the CO₂ was identified as the main pollutant and so two different types of CO₂-based visual alerting systems have been installed. This sample of four schools has been chosen also for the need to test the device in schools with different educational levels (Table 1) and with different construction and design systems (two new buildings and two historic buildings). This study analyzes the effectiveness of one of the two types of devices installed within the four case studies mentioned.

In order to facilitate the analysis, each school has been assigned an identification number (1, 2, 3, 4), as shown in Table 1.

2.2. Characteristics of the Classrooms and Monitoring Systems Installed

Two classrooms per school were chosen to evaluate the effectiveness of the CO₂-based visual alerting systems for comparing the results in the classroom with the device installed (indicated by letter A) and the classroom without it (letter B) (Table 2). The selection of the two classrooms to be monitored and further compared in this analysis was made based on the similarity of the number of occupants, activity in the classroom, schedule of lessons, volume of the room, orientation of the main windowed façade, and the total free area of window opening (Table 2).

Table 2. Classrooms’ features

| School ID | Classroom ID | Max Occupants | Floor | Orientation | Area (m²) | Volume (m³) |
|-----------|--------------|---------------|-------|-------------|-----------|-------------|
| 1         | 1A           | 22            | Second| South-east  | 50        | 149         |
|           | 1B           | 23            | Second| South-west  | 50        | 150         |
| 2         | 2A           | 24            | First | East        | 57        | 171         |
|           | 2B           | 24            | Ground| East        | 52        | 187         |
| 3         | 3A           | 25            | Second| South-west  | 59        | 177         |
|           | 3B           | 25            | Third | South-east  | 55        | 165         |
| 4         | 4A           | 21            | Second| South      | 68        | 204         |
|           | 4B           | 21            | First | South      | 82        | 245         |

In each classroom, an in-house developed multi-sensors system called EQ-OX (Environmental Quality bOX) was installed, which measures multiple Indoor Environmental Quality (IEQ) parameters such as hygro-thermal parameters, lighting level, and some IAQ parameters, and through a low-power wide-area networking protocol connection, it is possible to store and check the data in real time. For the data presented in this paper, the CO₂ concentrations were measured using Senseair K30 sensor, which uses a
non-dispersive infrared technology (range: 0–5000 ppm, accuracy: ±30 ppm + 3% of reading), and the indoor air temperatures were measured using Littelfuse USP11492, which is a negative temperature coefficient thermistor probe (accuracy: ±0.2 °C for the range: 0–70 °C). The data is logged every 30 s and is received from the sensors in a digital format, which is transmitted on an I2C bus to the custom board of the EQ-OX system (based on the Atmel ATmega2560 controller). The measuring instruments were periodically compared with other calibrated commercial equipment, prior to being installed in the classrooms. The data gathered from the EQ-OX has been averaged for every minute for the purpose of the analysis. The external temperatures are extracted from the outdoor meteorological stations of the province for the closest stations of each school [56].

Appendix A shows the window sections of each classroom of each school. Figure A1 and Table 3 show detailed information on the design of the windows. Each window type has been indicated with a letter (A, B, C, D) or with a combination of letters based on their opening styles. The explanation of the letter is provided in the footnote of the figure and table.

### Table 3. Windows design and exploitable ventilation potential in the classroom: single-side ventilation or cross-ventilation

| School ID | Classroom ID | Ventilation       | Window Typology | Window Opening Free Area (m²) | Normalized Opening Weight (αn) | Number of Windows |
|-----------|--------------|------------------|-----------------|-------------------------------|--------------------------------|------------------|
| 1         | 1A           | Single-sided     | C               | 0.3                           | 0.032                          | 1                |
|           |              |                  | BC              | 0.8                           | 0.323                          | 3                |
|           |              |                  | D               | 0                             | 0                              | 2                |
|           | 1B           | Single-sided     | C               | 0.3                           | 0.032                          | 1                |
|           |              |                  | BC              | 0.8                           | 0.323                          | 3                |
|           |              |                  | D               | 0                             | 0                              | 2                |
|           | 2A           | Cross-ventilation| A1              | 1.20                          | 0.132                          | 1                |
|           |              |                  | A2              | 1.02                          | 0.113                          | 1                |
|           |              |                  | A3              | 0.60                          | 0.074                          | 1                |
|           |              |                  | A4              | 0.50                          | 0.056                          | 1                |
|           | 2B           | Cross-ventilation| A5              | 0.70                          | 0.064                          | 1                |
|           |              |                  | B               | 0.90                          | 0.099                          | 3                |
|           |              |                  | B1              | 1.40                          | 0.156                          | 1                |
|           |              |                  | A               | 0.20                          | 0.006                          | 2                |
|           |              |                  | D               | 0                             | 0                              | 2                |
|           | 3A           | Single-sided     | A               | 1.00                          | 0.100                          | 10               |
|           |              |                  | BC              | 0.70                          | 0.243                          | 2                |
|           |              |                  | C               | 0.40                          | 0.040                          | 1                |
|           |              |                  | BC              | 0.70                          | 0.243                          | 2                |
|           | 3A           | Single-sided     | BC1             | 1.40                          | 0.473                          | 1                |
|           |              |                  | C               | 0.40                          | 0.040                          | 1                |
|           | 4A           | Single-sided     | B               | 1.12                          | 0.250                          | 4                |
|           | 4B           | Cross-ventilation| B               | 1.40                          | 0.200                          | 5                |

1 A: Double-wing opening window, B: Single-wing opening window, C: Bottom hung opening window, BC: Both double-wing and single-wing opening window, D: Fixed windows; 2 Section 6.4.3.5 of the EN 16798-7:2019 [57].

The opening and closing status of all openings (windows and door windows) was recorded using sensors with a magnetic switch. These sensors detect a change in the window opening status (i.e., open or closed) based on the contact of the magnetic switch and send an alert message via the LoRaWAN protocol (i.e., ‘1’ when a window is opened and ‘0’ when it is closed). The total number of signals received has been reported in Section 3. If no signal was sent at a given time, the previously available value is used, and the
status of the window is considered open/close until a new signal is registered. As per the paper [58], the normalized weight of each opening, based on its maximum opening size and opening style, is calculated and applied to each classroom, such that the normalized opening values lie in the range of 0 to 1, where 0 means all the windows in that particular classroom are closed (0% of the openings are open), whereas 1 means all the windows in the classroom are open (100% of the opening are open). These normalized weights have been reported in Table 3.

2.3. Ventilation Rate Required for Acceptable Air Quality

To find the best solution to improve indoor air quality in schools, preliminary analyses were made according to the criteria for indoor air quality and ventilation rates suggested in the standard EN 16798-1:2019 [54]. The standard reports design methods of ventilation rates for different levels of expectations that the occupants may have towards the indoor environmental quality: Category I corresponds to a high level of expectation, Category II to a medium level, Category III to a moderate level, and Category IV to a low one. The standard recommends selecting a high level for occupants with special needs (children, elderly, etc.) and a medium one in normal cases.

The method applied in this study to calculate the minimum required ventilation rates is the one based on perceived air quality, illustrated in the sub-section B.3.1.2 of the standard. According to this, the minimum required ventilation rates depend on two main sources of indoor pollutants, occupancy and building materials, so that the generated pollutants can be proportionally diluted or removed.

Table 4 shows the minimum required ventilation rate for the breathing zone corresponding to the four categories of indoor environmental quality considering schools, for example, as low-polluting buildings (EN 16798-1:2019) [54].

### Table 4. Total ventilation rate for the breathing zone depending on occupancy density and building material, considering schools as low-polluting buildings

| School ID | Classroom ID | Category I (m³/h) | ACH | Category II (m³/h) | ACH | Category III (m³/h) | ACH | Category IV [m³/h] | ACH |
|-----------|--------------|-------------------|-----|-------------------|-----|---------------------|-----|-------------------|-----|
| 1         | 1A           | 970               | 7   | 679               | 5   | 388                 | 3   | 251               | 2   |
|           | 1B           | 1007              | 7   | 705               | 5   | 403                 | 3   | 261               | 2   |
| 2         | 2A           | 1070              | 6   | 749               | 4   | 428                 | 3   | 278               | 2   |
|           | 2B           | 1052              | 6   | 736               | 4   | 421                 | 2   | 272               | 2   |
| 3         | 3A           | 1112              | 5   | 779               | 3   | 445                 | 2   | 289               | 1   |
|           | 3B           | 1098              | 7   | 769               | 5   | 439                 | 3   | 284               | 2   |
| 4         | 4A           | 1001              | 5   | 701               | 3   | 400                 | 2   | 262               | 1   |
|           | 4B           | 1050              | 4   | 735               | 3   | 420                 | 2   | 277               | 1   |

The minimum design ventilation rates calculated according to the EN 16798-1:2019 [54] standard are then compared with natural ventilation rates through the window openings calculated as per the EN 16798-7:2019 standard [57].

The natural ventilation rate calculation considers the design of all windows in each classroom, their opening mode (hinged, bottom hung opening or both) and buoyancy driven flow applied for both single-sided ventilation (S-S) and cross-ventilation (C-V) as per the room configurations.

The graphs in Figure 1 show the calculated ventilation rates provided by window opening at different temperature gradients between indoor and outdoor at different opening area. The theoretical ventilation rate, symbolized by the curves in the graph, derives from the progressive opening of the windows in the respective classroom, whose normalized opening weight (see Table 3 and Section 2.2), is shown as percentage next to each curve.
Figure 1. Calculation of natural ventilation through windows using temperature difference as inputs compared with the four categories of indoor environmental quality for low polluting buildings (in grey). Next to each curve is the percentage of normalized weight of opening where 100% stands for all windows open. S-S: single-side ventilation. C-V: cross ventilation (a) School 1. (b) School 2. (c) School 3. (d) School 4.
This means that the first curve in each graph, the one with the lowest percentage of normalized opening weight, shows the ventilation rate that would enter the room from a single window (to simplify, it corresponds to the first which appears in the figure of each classroom, see Appendix A). The last curve (100% of normalized opening weight) indicates the maximum ventilation rate that could be reached opening all the windows in the classroom.

Since some classrooms have openings on more than one face (classroom 2A, 2B, 4B, Appendix A, Figure A1) and so it is possible to exploit the potential of cross ventilation, the ventilation strategy allowed by the correspondent % of normalized opening weight, has been indicated close to each curve.

For example, in the first graph shown in Figure 1b (classroom 2A), 60% of opening shows the ventilation rate through the windows which are all placed on the same façade allowing only single-sided ventilation (S-V). The subsequent curves corresponding to the trend of the air flow considering the remaining windows (from 76% of the windows up to the total 100%) placed on the adjacent façade that would allow cross ventilation, indicated with a C-V next to the respective curve.

The minimum required ventilation rates that referred to the four categories/level of expectations of indoor environmental quality (Table 4) have been represented with lines in the graphs in Figure 1 (from the darkest, Category I, to the lightest, Category IV). As shown in Figure 1 it can be observed that by exploiting natural ventilation through the opening of all the windows and within a temperature difference range between 0–20 °C, the classroom indoor spaces fall under at least Category II (CEN/TR 16798-2:2019) [38]. Therefore, this theoretical study allows to identify that natural ventilation can potentially ensure normal expectations level of IEQ in the classrooms analyzed.

2.4. Experimental Methods

The analyses reported in the following refer to a three-week period that has been selected based on (i) the real occupancy of the classrooms (following the COVID-19 pandemic, there have been long periods of absence of children), (ii) functioning of the device, (iii) the integrity of the data recorded. The time schedule is from 8 a.m. to 1 p.m., when pupils are in the classrooms for lessons (Table 5).

| School ID | Classroom ID | Device | Pre COVID | During COVID |
|-----------|--------------|--------|-----------|--------------|
|           |              |        | Week 0    | Week 1       | Week 2       | Week 3       |
| 1         | 1A           | Yes    | 23 nov–29 | 21 mar–27   | 21           | 11 apr–17 apr| 21           |
|           | 1B           | No     | nov 2019  | 22          | mar 2021     | 21           | 2021         | 22           |
| 2         | 2A           | Yes    | 7 dec–13 dec | 1 dec–7 dec | 22         | 8 dec–14 dec | 22           |
|           | 2B           | No     | 2019      | 12          | 2020         | 21           | 2020         | 21           |
| 3         | 3A           | Yes    | 11 jan–17 jan | 23    | 31 jan–6 feb | 11     | 23–29 May     | 11           |
|           | 3B           | No     | 2020      | 23          | 2021         | 11           | 2021         | 11           |
| 4         | 4A           | Yes    | -         | -           | 11 apr–17 apr | 6     | 25 apr–1 May  | 10           |
|           | 4B           | No     | -         | -           | 2021         | 8            | 2021         | 10           |

The different steps of the experimental method are as follows:
1. First monitoring campaign 2019–2020 (week 0), before the COVID-19 pandemic. Both classrooms, in the absence of any CO₂-based visual system, were monitored using sensors capable of measuring specific pollutants. This week has been used as baseline, in order to assess the preliminary air quality.
2. Data analysis to understand the most dominant pollutants influencing air quality in the classrooms and their concentrations.
3. CO₂ identified as the main pollutant that affected the IAQ in the classrooms, with levels higher than those permitted by the standard EN 16798-1:2019 [54].

4. Once the problem has been identified, the CO₂-based passive visual alerting system was installed in one of the two classrooms.

5. Second monitoring campaign 2020–2021 (week 1–week 2), during the COVID-19 pandemic. Both classrooms were monitored to test the effectiveness of the CO₂-based visual system comparing the results recorded in the classroom with the device installed and the classroom without it.

2.4.1. Installation of the Passive CO₂-Based Visual Alerting System

From the analysis carried out after week 0, high CO₂ peaks were found in the classrooms whilst people were present. In order to test the efficacy of a CO₂-based visual alerting system in restoring good air quality, a smart sensor equipped with artificial intelligence was installed.

The device constantly and dynamically monitors air temperature, relative humidity, and CO₂, which are processed in an external server, through an artificial intelligence algorithm. The result of this processing translates into an indicator light that suggests with red color, when windows should be opened to change the air, just before a situation of discomfort is created. The duration of the color persists as long as it is recommended to keep the windows open, while keeping the expected heat losses to a minimum. The device returns to its original blue color when good air quality is restored, signaling the need to close the windows.

In all classrooms of middle and high schools (school 1, 3, 4) the device was installed right next to the blackboard, to be clearly visible by the pupils. Only in the case of kindergarten (school 2), in the absence of a type of frontal lesson, it has been installed near the entrance of the classroom.

2.4.2. Information Collected by School Representatives

Almost a year after the installation of the device, informal interviews were conducted via telephone or in person, when possible. The interviews were aimed at teachers or school administrators who had direct and constant contact with the device, in order to evaluate its usability from their point of view.

The interview concerned the actual correct use of the device, the possible influence of external conditions (temperature, noise, among others) on the opening/closing of windows, changes in habits related to natural ventilation management practices, and decrease in student absenteeism. An overview of the feedback received is described in the Results and Discussion.

3. Results and Discussion

Due to the COVID-19 pandemic, it was difficult to compare the results of a particular classroom before (week 0) and after (week 1 and week 2) the installation of the device, due to differences in occupant behavior, different percentage of occupancy and change in habits regarding the opening/closing of windows. This led the analysis to focus mainly on week 1 and week 2, while few general considerations were made about week 0.

The effectiveness of the system was evaluated as follows:

- Analysis of the results within the same week, hence similar boundary conditions, such as external temperatures, occupancy, and rules regarding COVID-19 pandemic, for the two classrooms, one with the device (A) and one without (B).
- Analysis of the results comparing week 1 and week 2, in order to see if there are improvements in IAQ and possible changes in the occupant behavior.
- Analysis of the responses derived from the interviews.

Figure 2a, Figure 3a, Figure 4a, Figure 5a, Figure 6a, Figure 7a, Figure 8a, and Figure 9a, show the trend of CO₂, internal and external temperature for the days of the
monitoring in week 1 and 2, for classrooms A and B, whilst people were present (8 a.m.–1 p.m.).

### School 1–week 1

![Graphs](image)

**Figure 2.** These graphs refer to school 1, week 1. (a) Trend of CO₂, internal temperature, and external temperature during the occupied hours. The blue dotted line represents the CO₂ fixed-limit of 1250 ppm and the blue colored area indicates the time interval in which CO₂ exceeds this limit. The yellow area indicates the time interval in which the internal...
temperature falls within the comfort limits (20–26 °C). In the lower part, the opening/closing of the windows has been plotted. (b) Mean hourly CO₂ concentration and mean hourly window opening value during the occupied hours.

![Graphs showing CO₂ concentration and window opening](image)

Figure 3. These graphs refer to school 1, week 2. (a) Trend of CO₂, internal temperature, and external temperature during the occupied hours. The blue dotted line represents the CO₂ fixed-limit of 1250 ppm and the blue colored area indicates
the time interval in which CO₂ exceeds this limit. The yellow area indicates the time interval in which the internal temperature falls within the comfort limits (20–26 °C). In the lower part, the opening/closing of the windows has been plotted. (b) Mean hourly CO₂ concentration and mean hourly window opening value during the occupied hours.

![Diagram](image-url)

**Figure 4.** These graphs refer to school 2, week 1. (a) Trend of CO₂, internal temperature, and external temperature during the occupied hours. The blue dotted line represents the CO₂ fixed-limit of 1250 ppm and the blue colored area indicates the time interval in which CO₂ exceeds this limit. The yellow area indicates the time interval in which the internal temperature falls within the comfort limits (20–26 °C). In the lower part, the opening/closing of the windows has been plotted. (b) Mean hourly CO₂ concentration and mean hourly window opening value during the occupied hours.
Figure 5. These graphs refer to school 2, week 2. (a) Trend of CO₂, internal temperature, and external temperature during the occupied hours. The blue dotted line represents the CO₂ fixed-limit of 1250 ppm and the blue colored area indicates the time interval in which CO₂ exceeds this limit. The yellow area indicates the time interval in which the internal temperature falls within the comfort limits (20–26 °C). In the lower part, the opening/closing of the windows has been plotted. (b) Mean hourly CO₂ concentration and mean hourly window opening value during the occupied hours.
Figure 6. These graphs refer to school 3, week 1. (a) Trend of CO₂, internal temperature, and external temperature during the occupied hours. The blue dotted line represents the CO₂ fixed-limit of 1250 ppm and the blue colored area indicates the time interval in which CO₂ exceeds this limit. The yellow area indicates the time interval in which the internal temperature falls within the comfort limits (20–26 °C). In the lower part, the opening/closing of the windows has been plotted. (b) Mean hourly CO₂ concentration and mean hourly window opening value during the occupied hours.
Figure 7. These graphs refer to school 3, week 2. (a) Trend of CO₂, internal temperature, and external temperature during the occupied hours. The blue dotted line represents the CO₂ fixed-limit of 1250 ppm and the blue colored area indicates the time interval in which CO₂ exceeds this limit. The yellow area indicates the time interval in which the internal temperature falls within the comfort limits (20–26 °C). In the lower part, the opening/closing of the windows has been plotted. (b) Mean hourly CO₂ concentration and mean hourly window opening value during the occupied hours.
**Figure 8.** These graphs refer to school 4, week 1. (a) Trend of CO₂, internal temperature, and external temperature during the occupied hours. The blue dotted line represents the CO₂ fixed-limit of 1250 ppm and the blue colored area indicates the time interval in which CO₂ exceeds this limit. The yellow area indicates the time interval in which the internal temperature falls within the comfort limit (20–26 °C). In the lower part, the opening/closing of the windows has been plotted. (b) Mean hourly CO₂ concentration and mean hourly window opening value during the occupied hours.
Figure 9. These graphs refer to school 4, week 2. (a) Trend of CO$_2$, internal temperature, and external temperature during the occupied hours. The blue dotted line represents the CO$_2$ fixed-limit of 1250 ppm and the blue colored area indicates the time interval in which CO$_2$ exceeds this limit. The yellow area indicates the time interval in which the internal temperature falls within the comfort limits (20–26°C). In the lower part, the opening/closing of the windows has been plotted. (b) Mean hourly CO$_2$ concentration and mean hourly window opening value during the occupied hours.
The CO₂ was plotted together with the CO₂ limits of 1250 ppm as reported by EN 16798-1:2019 [54] for Category II of indoor environment quality, considering an outdoor concentration of 450 ppm. In this study, only indoor air temperature (TA) was measured, whereas mean radiant temperature (MRT) was not. Based on previous research it was reasonable to assume that, also in this case, there was no considerable difference between MRT and TA and hence, operative temperatures (TO) was also equal to TA [59,60]. Moreover, the activity levels in classrooms are similar to sedentary activity assumed in EN16798 (1.2 met according to ISO 7730 Table B.1), and also the clothing in summer (0.5) and winter (1.0) are likely to be similar to the ones in the used in the standard, respectively [7]. Hence, the comfort temperature limits between 20–26 °C, for Category II as per the EN 16798-1:2019 Table B.5, have been considered as a combined indicator to evaluate thermal comfort for any season, and have been highlighted in the plots. The figures also show the opening and closing trend of the windows, also considering the percentage of time in which the windows are opened more than 0.33 and more than 0.66 with reference to the normalized opening weight explained in the Section 2, Table 3.

Figure 2b, Figure 3b, Figure 4b, Figure 5b, Figure 6b, Figure 7b, Figure 8b, and Figure 9b, show the mean hourly CO₂ concentration whilst people were present.

Table 6 illustrates the CO₂ values, window opening, and indoor and outdoor temperature values, measured in classroom A and B over the monitored period. Only for school 4 was it not possible to report the data from week 0. The CO₂ values, weekly average, minimum, maximum, and standard deviation figures are expressed in ppm while the remaining columns indicate the percentage of time in which the concentration exceeds 1250 ppm (threshold limit for Category II) and 1800 ppm (threshold limit for Category IV of indoor environmental quality of building based on the standard EN 16798-1:2019) [54]. The columns relating to the window opening section report the weekly total number of signals recorded by the window sensors, weekly average, minimum, maximum, standard deviation, and the percentage of time in which the windows are opened more than 0.33 and more than 0.66. Weekly average indoor and outdoor temperature, their difference and the percentage of time in which the average weekly temperatures fall between 20–26 °C are shown in the last columns of the table.

The results will be described on a case-by-case basis as follows.
Table 6. Week specific figures for each classroom reporting the average occupancy (Avg occ.), and values for CO₂ (ppm), window opening (W.O.), indoor temperature (Ind_T, °C), outdoor (8:00 a.m.–1:00 p.m.). Avg: average, Min: minimum, Max: maximum, St.Dev: standard deviation, % time: percentage of time.

| School ID | Ref. Week | Class ID | Avg Occ. | Avg | Min | Max | St.Dev | % Time CO₂ > 1250 ppm (cat II) | % Time CO₂ > 1800 ppm (cat IV) | Total no. of Signals | Avg | Min | Max | St.Dev | % Time W.O. > 0.33 | % Time W.O. > 0.66 | Avg % Time Temp b/w 20–26 °C | Avg ΔT |
|-----------|-----------|----------|----------|-----|-----|-----|--------|--------------------------------|-------------------------------|-----------------------|-----|-----|-----|--------|----------------------|----------------------|---------------------------------|-------|
| 0         | 1A        | 24       | 1357     | 481 | 2910| 593 | 44     | 19                                           | 36                           | 0.2                  | 0.0 | 0.8 | 0.2 | 25.5   | 0.6                  | 23                  | 59                                             | 15    |
|           | 1B        | 22       | 1727     | 412 | 3514| 759 | 65     | 44                                           | 69                           | 0.3                  | 0.0 | 0.8 | 0.2 | 37.1   | 13.5                 | 25                  | 75                                             | 15    |
| 1         | 1A        | 21       | 733      | 422 | 1526| 217 | 3      | 0                                              | 56                           | 0.4                  | 0.0 | 0.8 | 0.2 | 44.6   | 15.4                 | 23                  | 90                                             | 12    |
|           | 1B        | 21       | 1022     | 439 | 2843| 545 | 26     | 13                                           | 129                          | 0.4                  | 0.0 | 1.0 | 0.3 | 50.9   | 23.7                 | 22                  | 79                                             | 12    |
| 2         | 1A        | 21       | 769      | 423 | 1268| 189 | 0      | 0                                              | 59                           | 0.5                  | 0.0 | 0.8 | 0.2 | 83.8   | 24.7                 | 22                  | 72                                             | 9     |
|           | 1B        | 22       | 1338     | 425 | 3761| 825 | 39     | 23                                           | 58                           | 0.2                  | 0.0 | 1.0 | 0.2 | 24.8   | 4.8                  | 21                  | 70                                             | 9     |
| 1         | 2A        | 20       | 1094     | 383 | 1903| 377 | 33     | 2                                              | 51                           | 0.1                  | 0.0 | 0.6 | 0.2 | 20.3   | 0.0                  | 22                  | 88                                             | 7     |
|           | 2B        | 12       | 746      | 391 | 1102| 149 | 0      | 0                                              | 0                            | 0.3                  | 0.3 | 0.3 | 0.0 | 0.0    | 0.0                  | 23                  | 87                                             | 7     |
| 2         | 2A        | 22       | 1053     | 513 | 1750| 333 | 33     | 0                                              | 4                            | 0.0                  | 0.0 | 0.0 | 0.0 | 0.0    | 0.0                  | 0.0                 | 21                                             | 89    |
|           | 2B        | 21       | 892      | 512 | 1596| 270 | 13     | 0                                              | 24                           | 0.0                  | 0.1 | 0.0 | 0.0 | 0.0    | 0.0                  | 0.0                 | 23                                             | 100   |
| 3         | 2A        | 22       | 856      | 436 | 1621| 300 | 10     | 0                                              | 15                           | 0.1                  | 0.4 | 0.1 | 0.4 | 11.3   | 0.0                  | 21                  | 92                                             | 3     |
|           | 2B        | 21       | 721      | 447 | 1518| 250 | 4      | 0                                              | 28                           | 0.0                  | 0.1 | 0.0 | 0.0 | 0.0    | 0.0                  | 0.0                 | 23                                             | 100   |
| 3         | 3A        | 23       | 1568     | 573 | 2959| 699 | 64     | 45                                             | 16                           | 0.1                  | 0.0 | 0.5 | 0.2 | 25.4   | 0.0                  | 23                  | 99                                             | -2    |
|           | 3B        | 23       | 2085     | 632 | 4434| 925 | 76     | 62                                             | 38                           | 0.5                  | 1.0 | 1.0 | 0.4 | 56.4   | 44.5                 | 24                  | 99                                             | -2    |
| 2         | 3A        | 11       | 726      | 413 | 1608| 249 | 7      | 6                                              | 18                           | 0.1                  | 0.3 | 0.1 | 0.0 | 0.0    | 0.0                  | 0.0                 | 22                                             | 100   |
|           | 3B        | 11       | 701      | 411 | 1366| 210 | 2      | 0                                              | 33                           | 0.3                  | 1.0 | 0.2 | 0.2 | 40.1   | 3.5                  | 19                  | 43                                             | 2     |
| 4         | 3A        | 11       | 625      | 395 | 1242| 208 | 0      | 0                                              | 8                            | 0.2                  | 0.2 | 0.1 | 0.0 | 0.0    | 0.0                  | 0.0                 | 24                                             | 100   |
|           | 3B        | 11       | 726      | 393 | 1231| 245 | 0      | 0                                              | 26                           | 0.5                  | 1.0 | 0.2 | 0.2 | 58.7   | 31.3                 | 21                  | 89                                             | 14    |
| 4         | 4A        | 6        | 736      | 425 | 1320| 187 | 0      | 0                                              | 54                           | 0.0                  | 0.1 | 0.0 | 0.0 | 15     | 3                   | 24                  | 90                                             | 9     |
|           | 4B        | 8        | 615      | 438 | 1066| 115 | 0      | 0                                              | 46                           | 0.0                  | 0.1 | 0.0 | 0.0 | 18     | 0                   | 25                  | 59                                             | 9     |
| 1         | 4A        | 10       | 742      | 414 | 1490| 284 | 8      | 0                                              | 62                           | 0.3                  | 0.8 | 0.2 | 33.3 | 4.5    | 25                   | 84                  | 14                                             | 11    |
|           | 4B        | 10       | 630      | 421 | 977 | 130 | 0      | 0                                              | 29                           | 0.4                  | 0.6 | 0.1 | 61.8 | 0.0    | 24                   | 92                  | 14                                             | 10    |
3.1. School 1

The study performed in this school shows how the classroom in which the passive system has been installed has better air quality compared to the classroom without it.

A study by Wargocki and Da Silva [30] has shown how warning children to open the windows thanks to a visual CO₂ indicator installed in the classroom improved the IAQ.

In this research, the graph in Figure 2b shows, during week 1, the daily averages of CO₂ concentration in classroom 1A (classroom with the device installed) never exceeded 1250 ppm, unlike classroom 1B where for at least one hour per day the threshold exceeded this value, which is also reflected in the daily CO₂ trend (shown as blue colored area in Figure 2a).

Weekly averages (Table 6) also confirm that during week 1 in classroom 1A, only for the 3% of the time when people were present, CO₂ concentrations exceeded 1250 ppm compared to 26% of the time recorded for classroom 1B.

A similar trend can be observed in week 2. As the graph in Figure 3a show, the trend of CO₂ never exceeds the threshold of 1250 ppm in classroom 1A (which is also confirmed by the daily averages shown in the graph in Figure 3b).

Daily peaks exceeding 3000 ppm are instead recorded in classroom 1B during week 2 (Figure 3a), with 23% of the time with concentrations higher than 1800 ppm (Table 6), probably due to a very low average window opening average of 0.2 (Table 6).

During the two weeks monitored, the average occupancy was similar (approximately 21–22 occupants) in both classrooms which can produce a similar CO₂ emission rate from occupants (Table 6).

Comparing the trend of opening/closing windows during the week 1 (Figure 2a), it is found that the windows in the classroom 1B are opened more often but for shorter intervals (in total 129 windows signals recorded) than in classroom 1A (56 signals) (Table 6). Despite more frequent opening of windows in classroom 1B (50.9% of the time with more than 0.33 windows opened), the average weekly concentration of CO₂ recorded in this classroom is 28% higher than in classroom 1A (Table 6). This result is probably due to the fact that the CO₂ based alerting system warns to keep the windows open only for the time necessary to restore a good indoor air quality, whereas in classroom 1B—in the absence of a guide that indicates the time and moment of opening—the openings are more frequent but random.

Some information gathered by the referent teacher of both classrooms has also highlighted how the device has been positively received and used exclusively by the students of classroom 1A. In a study by Geelen et al. (2008) a questionnaire conducted in some classrooms where a CO₂ warning device was installed, it emerged that 95% of the participants considered the system useful thanks also to the integrated LED system [50].

Comparing the weekly percentage of time for which windows are more than 0.33 open (Table 6), in classroom 1A, this increases twice as much from week 1 (44.6%) to week 2 (83.8%) with the maximum CO₂ concentration reaching only 1268 ppm, which would indicate greater awareness of proper device use.

Also, this result is obtained despite average outdoor temperatures during week 2 (9 °C) being about 3 degrees lower than during week 1 (12 °C) (Table 6). Gathering the feedback from the teacher in charge of the classroom, the atmospheric conditions did not influence the opening of the windows, as the red signal indicating the necessity to open the windows was always followed because perceived as an alarm to restore a good IAQ.

With regard to the thermal comfort in classroom 1A (Table 6), air temperatures falling between 20–26 °C, i.e., within the range of comfort temperatures (Category II) required by the standard EN 16798-1:2019 [54], were recorded for 90% of the time, during week 1, and 72% during week 2. This result would show how the device considers the internal air temperature among the parameters of alarm activation, avoiding possible situations of thermal discomfort to the people in the classrooms.
3.2. School 2

Among the selected schools, School 2 is the only kindergarten in which the system was installed. Different occupant habits and boundary conditions compared to the middle and high schools (school 1, school 3, and school 4), are found in the results with respect to the usage of the device.

During week 1 in classroom 2A, as shown in Figure 4a, the daily CO₂ trend exceeds the threshold of 1250 ppm for 33% of the time (Table 6), with hourly mean concentrations (Figure 4b) reaching up to 1413 ppm (11 a.m.–12 p.m. on December 02, 2020). Despite the high CO₂ values, the teachers did not open the windows (Figure 4a). A study performed in some schools in the states of Washington and Idaho, in fact, states that concentrations greater than 1000 ppm are due to a lower ventilation rate than that required by ventilation standards [61].

In fact, very low average window opening values were recorded in both classrooms in both weeks (Figure 4b, Figure 5b). This could be linked to multiple reasons. The overall window opening values are quite low due to a very high number of windows, as shown in Figure A1; thus, each window corresponds to a low opening percentage. Low outdoor temperatures, (average of 2 °C during week 1, and 3 °C during week 2), and a temperature difference between indoor and outdoor of 19–20 °C (Table 6) could have influenced the teacher’s decision to open the windows despite the signals displayed by the device. Moreover, from interviews with the users, it was clear that, if only one teacher was present in the classroom instead of two, and the device warned to open the windows, it was sometimes ignored due to the need for more control of the pupils. Another reason could be related to the lack of frontal lesson and the young age of the pupils which could mean less student involvement.

A difference in the higher number of signals received by the window sensors in classroom 1B (24 in week 1, 28 in week 2) compared to classroom 1A (4 in week 1, 15 in week 2) (Table 6), despite the presence of the alerting device in the latter, may be due to the position of the classroom and windows: (i) classroom 1A is located on the first floor, while 1B is on the ground floor (Table 2); (ii) the sill height of the windows is very low; and (iii) the presence of a door window leading to a small terrace on which children cannot enter. For these reasons perhaps the teachers were less inclined to open the windows.

3.3. School 3

During the first monitoring campaign (week 0), the highest CO₂ concentrations were found in school 3, with maximum values recorded of 2959 ppm in classroom 3A and 4434 ppm in classroom 3B (Table 6). These results are probably due to the insufficient window openable area in the classroom necessary to ensure proper air exchange (Table 3). From the preliminary theoretical study discussed in Section 2.3—Figure 1c, in fact—it can be seen that only when the window door is opened, even with a ΔT of 1 °C, it could be possible to reach Category II of indoor environment quality.

Low external temperature values recorded in week 0 (weekly average -2 °C, and ΔT of 25 °C) (Table 6), would justify the high CO₂ concentrations probably due to the impossibility of fully opening the windows for a longer period of time. This thesis was reinforced from the interview with the teacher responsible of the classroom. In fact, he confirmed that, in order to ensure proper air change with such a low window area, it is necessary to keep the windows open much longer, which is difficult to achieve as it would cause thermal discomfort.

A study performed in 81 classrooms spread over 20 schools in south Netherlands, highlighted how keeping CO₂ concentration below 1000 ppm from 65% of the school day to 40% after the installation of a CO₂ warning device in a temperate climate, may not happen in cold climates due to the fact that people open windows less [50].

As reported in Table 6, occupancy following the COVID-19 pandemic was reduced to less than half (23 occupants in week 0, reduced to 11 occupants in week 1 and week 2).
This would confirm the low trend of CO$_2$ concentrations recorded in both classrooms during week 1 and week 2 (Figure 6a, Figure 7a), which might be the reason for less frequent activation of the device in classroom 3A and therefore a lesser opening of windows.

In particular, in classroom 3B, users opened windows much more often, with windows opened more than 0.33 for 40.1% of the time in week 1, and 58.7% of the time in week 2 (Table 6), compared to the 0% recorded in both weeks in classroom 3A. This result is probably due to the different habits of the occupants of classroom 3B as compared to classroom 3A, as also evident from the total number of signals received (Table 6). Similar behavior has been recorded also during week 0. It is also worth mentioning that window opening data from one window in classroom 3A was also lost due to a technical damage incurred to the sensor, which is the reason why the maximum window opening value of 1 was never recorded here. A study concerning monitoring of air quality in 85 classrooms of 8 schools in Minnesota, in fact, underlines the importance of good monitoring and correct measurements as well as motivated users [62].

The mean weekly indoor temperatures in classroom 3A has been recorded in the comfort range for 100% of the time during week 1 and week 2 (Table 6), which could be again linked to the unwillingness of the teacher to open windows as the outdoor temperatures were low.

3.4. School 4

Regarding school 4, only data relating to weeks 1 and 2 are shown in this study as the school was not the subject of the first monitoring campaign that took place in 2019–2020. However, results collected by the “Laboratory for air monitoring and radioprotection” in a period prior to the QAES project, detected issues related to IAQ in this school.

The reduced occupancy of classrooms 4A and 4B during week 1 (6–8 students) and week 2 (10–10 students) (Table 6) is reflected in the low average hourly CO$_2$ concentrations, as Figure 8b and Figure 9b show.

Concentrations approaching and rarely exceeding 1250 ppm are recorded in classroom 4A during week 1 and week 2 (Figure 8a, Figure 9a), with the maximum values 1320 ppm in week 1 and 1490 ppm in week 2 (Table 6). At these peaks, a consequent opening of windows is recorded, a sign that the device probably requires the windows to be opened to ensure proper air exchange.

In addition, looking at the results regarding the window open time percentage of more than 0.33 reported in Table 6, reveals how it increased more than twice as much in both classroom 4A and 4B from week 1 (15.0% and 18.0%) to week 2 (33.3% and 61.8%). This is likely due to the better weather conditions as weekly outdoor temperature averages of 9 °C were recorded during week 1 in contrast to the 14 °C recorded in week 2 (Table 6).

4. Conclusions

This paper presents the initial findings of a study on the effectiveness of a low-invasive CO$_2$-based visual alerting system for improving IAQ in classrooms. Measurements were taken in four schools as case studies (two located in historic buildings) and repeated twice in each school.

The main result of this research demonstrates that, although the CO$_2$-based visual alerting system could be a good solution to improve the IAQ in historic school buildings because it preserves the architectural integrity of the building, its actual effectiveness is highly dependent on the occupants. The number of occupants, age of students, different habits of users, as well as the ability to interact with the device based on its position in the classroom led to the following conclusions to answer the main research question:
• The device has proven effective in school 1 (high school) being the only case study that simultaneously has a full occupancy and conducts frontal lessons. A reduction of 28% and 42% in average CO\textsubscript{2} concentration in the two monitored weeks respectively, was noted in the classroom with the device, as compared to its counterpart classroom without the device and with comparable occupancy.

• Due to the organization and low occupancy in school 2 and 4 respectively, no considerable difference in CO\textsubscript{2} was recorded in the classrooms with and without the device. In school 2, the only kindergarten evaluated, the device was not the most ideal solution due to the young age of the pupils and the type of lesson (no frontal classes), which meant less interaction with the device. In school 4, a considerable reduction in the occupancy, due to the COVID-19 pandemic, limited the possibility of comparison.

• The device is more likely to be used with milder outdoor temperatures, as people open windows more willingly.

• The COVID-19 pandemic affected the results by changing occupancy and habits as confirmed also by the interviews with the teachers.

Future work to test the efficiency of different ventilation strategies without pupils in the classroom could be done using the tracer gas technique, along with an in-depth study of the algorithm behind the functioning of the device. Another development could be the automation of the windows, to manage the openings based on the indoor CO\textsubscript{2} concentration levels as well as indoor and outdoor temperatures. Moreover, the study could be extended to a larger sample of schools and classrooms.

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Appendix A

Figure A1 shows the window sections of each classroom of each school, where the window type has been identified with a letter (A, B, C, D) or with a combination of letters based on their opening styles. This figure allows to have a more detailed view of the shape and the window opening mode. The meaning of each letter is shown in the caption of the figure.
Figure A1. Shape and typology of the windows. Double-wing opening window, B: Single-wing opening window, C: Bottom hung opening window, BC: Both double-wing and single-wing opening window, D: fixed windows.

Notes
1 In English: Laboratory for air monitoring and radioprotection—Autonomous Province of Bolzano – South Tyrol.
2 Damaged during World War II and rebuilt in some parts (source not provided for the anonymity of the school).

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