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Indoor Air Quality monitoring in a historic school in South Tyrol, Italy

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Abstract. Children spend a large part of their growing years in schools, so it is essential to monitor and maximize the indoor air quality (IAQ) of the classrooms. In South Tyrol (northern Italy) many schools are characterised as historic and heritage buildings and improving IAQ poses a great challenge because of the need to maintain the integrity of the architectural characteristics of the structure. The aim of this paper is to provide insights into the effectiveness of a commercial low-cost smart CO_2-based visual alerting system used to improve IAQ in an urban kindergarten located in a historic building. Air temperature, relative humidity, along with indoor and outdoor air pollutants, were monitored in a classroom of 22 occupants before and after installation of the passive system. Based on high indoor CO_2 concentration and other parameters, the device alerts when to open the windows to facilitate air exchange. This research focuses on the measurements during the first few weeks after installation of the smart device. It did not show a considerable decrease in the CO_2 levels, but an improvement is desirable as the occupants become more familiar with the device. This will allow heritage buildings to guarantee a healthier environment in a simple and low-cost way.

Keywords – Indoor air quality (IAQ); Natural ventilation; Historic buildings; Carbon dioxide (CO_2); Monitoring strategies.

1. Introduction

Problems related to indoor environment quality (IEQ) are becoming a serious health concern especially in schools mainly because children have more sensitivity to some pollutants than adults [1]. It has been reported that better indoor air quality, in fact, reduces health-related symptoms and improves student's attention and academic performance [2].

In the "Guidelines for a healthy school environment in Europe", carbon dioxide (CO_2), an odourless gas deriving mainly from the human breath, has been found among the main pollutants recorded in some schools monitored [3]. Some studies show that as CO_2 concentrations decrease and ventilation rate increases, student performance improves and absenteeism at school is reduced [4][5].

The need to find solutions that improve the indoor air quality of schools is also connected in some cases to 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 in the category of historic and heritage sites in order to preserve their aesthetic features [6][7].

Various examples that try to respect the conservation principles of the building have been proposed in the literature. In the EU FP7 3ENCULT project, a wireless network of very low-power sensors, ZigBee, 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 [8].

In addition to the controlled opening of windows, there are examples of active solutions with minimal intervention. 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 [9].

In recent times, the need to ensure comfort and energy performance of buildings led to an emergence of visual signalling systems that advices the occupants when it is recommended to open the windows. Some studies affirm that their correct use is linked to multiple factors such as the place in which 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 for which it was installed, emphasizing the benefits that can be reached from its correct use [10].

In historic building, natural ventilation is likely a good solution for preserving the architectural features of the buildings. However, to ensure good IAQ for the school occupants, openings must be operated according to the rooms' pollution conditions, and smart alerting systems might be a useful support, but too little is known about their efficacy. Hence, the aim of this paper is to provide insights into the effectiveness of a commercial low-cost smart CO_2-based visual alerting system in an historic school in South Tyrol (Italy).

2. Method
The work was structured according to the following phases:

2.1. Case study
The case study analyzed in this paper is a kindergarten located in an historic building in South Tyrol dating back to 1905, chosen among the 6 schools monitored in the ongoing project Interreg ITA-CH QAES which aims at developing best practices for improving indoor air quality in regional schools.

The school selection process started with an analysis of the data available such as chemical and physical analyses conducted in previous years by the "Laboratorio Analisi aria e radioprotezione" (In English: Laboratory for air monitoring and radioprotection) meetings with public administrations and inspections with the school staff. In these occasions, they carried out short interviews to understand the management of the building and the problems related to comfort and air quality.

Among the two classrooms monitored in the school, the selection to install the passive system was made based on the high peaks of CO_2 concentration observed during the occupied hours.

It was normally occupied by 20 pupils plus 2 teachers, typically from 8am to 1pm, and since it is a kindergarten, the pupils were either sitting or playing. It is placed on the first floor of the building, east oriented, with an area of 57.20 m^2 and a volume of 201 m^3. In the classroom there are five windows on the east façade, and one window and a glass door on the south façade. They are structured as shown in Figure 1 and Table 1.
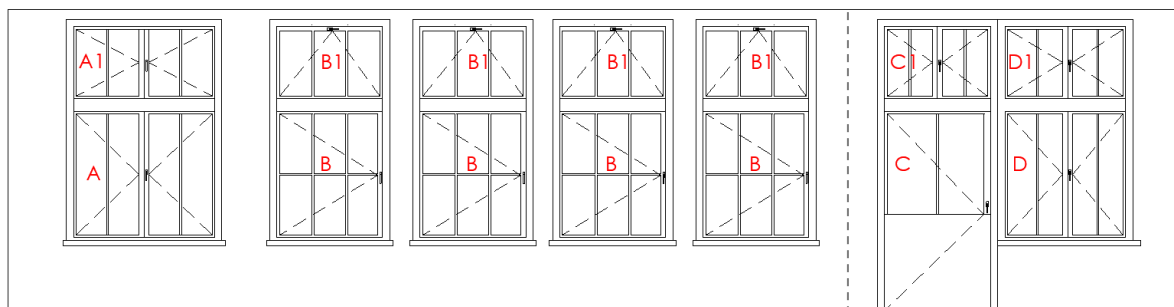

Figure 1. Shape and position of the windows in the classroom. On the left the windows on the east façade. On the right the windows on the south façade.

Table 1. Description of the windows

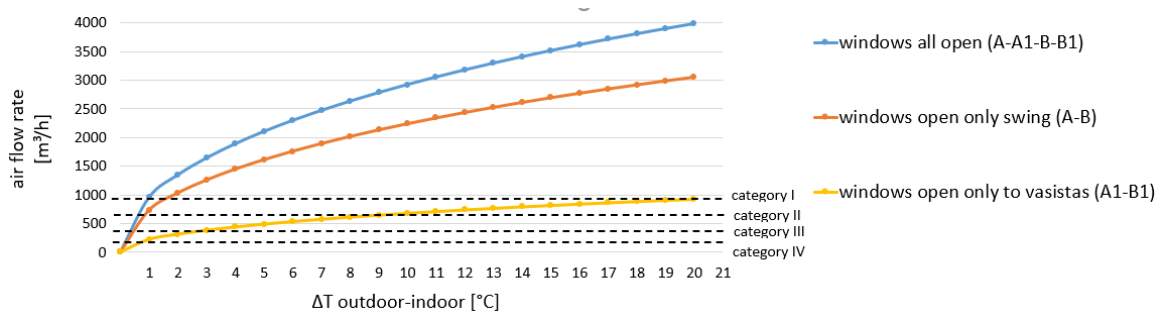| ID	Window typology	total openable surface area [m²]	total glass surface area [m²]
A	Double-wing opening window	1.760	1.500
A1	Double-wing opening window	1.000	0.820
B	Double-wing opening window	5.290	4.800
B1	Bottom hung opening window	3.000	2.640
C	Glass door	2.090	1.000

2.2. Ventilation rate required for acceptable air quality

To find the best solution to improve the indoor air quality in the school, preliminary analyzes were made according to the criteria for indoor air quality and ventilation rates suggested in the standard EN 16798-1:2019. According to this, calculation for the required ventilation air flow rates depends on the two main sources of indoor pollutants, occupancy and building materials, so that the generated pollutants can be proportionally diluted or removed.

Considering 22 occupants in a classroom of 57.20 m², Table 2 shows the total ventilation rate for the breathing zone in the four categories of quality of the buildings considering three different types of building based on the material emissions: very low-polluting building, low-polluting building, non low-polluting building (EN 16798-1:2019).

Table 2. Total ventilation rate for the breathing zone depending on occupancy density and building material

	Very low-polluting building		Low-polluting building		Non low-polluting building	
	[m³/h]	V/h	[m³/h]	V/h	[m³/h]	V/h
Category I	895	5	998	6	1204	7
Category II	626	4	699	4	843	5
Category III	358	2	399	2	482	3
Category IV	229	1	260	2	322	2

Figure 2 Calculation of single-side ventilation through windows using wind velocity and temperature difference as inputs compared with the four categories IAQ for the low polluting building.

With the aim to understand if only natural ventilation would be able to ensure the flow rates necessary for a good IAQ in accordance with EN 16798-1:2019, the air flow rate has been calculated considering only the windows on the main façade in the classroom and their opening mode (hinged, bottom hung opening or both). The calculation of the single-sided ventilation through windows using the temperature difference as inputs are done in accordance with the EN 16798-7:2017.

The graph in Figure 2 shows the air flow rates necessary for good indoor air quality, considering, for example, the school as a low polluting building. Taking advantage of single-sided ventilation through the opening of the windows of the east facade, the building falls at least into Category II, that means in a medium level of expectation (CEN/TR 16798-2:2019)

2.3. Experimental methods
The different steps of the experimental method are as follows:

- First monitoring campaign to assess indoor air quality in the classroom using sensors capable of measuring specific pollutants.
- Data analysis to understand the most dominant pollutants influencing the air quality in the classroom and their concentrations.
- CO_2 identified as the main pollutant that affected the IAQ in the classroom, with levels higher than those permitted by the standard.
- Installation of the CO_2 -based passive visual alerting system.
- Second monitoring campaign to test the effectiveness of the installed device.

2.3.1 First winter campaign (2019) and second winter campaign (2020)
The two monitoring campaigns were carried out in the same winter period one year apart, both lasting 7 days. Table 3 presents in detail the main aspects and parameters monitored.

Table 3. First winter campaign (2019) and second winter campaign (2020).

	2019	2020
Start of monitoring	10 Dec 2019 (Tuesday)	1 Dec 2020 (Tuesday)
End of monitoring	16 Dec 2019 (Monday)	7 Dec 2020 (Monday)
Parameters measured	Air temperature, Relative humidity, Carbon dioxide, Nitrogen dioxide, Ozone, PM 2.5, PM 10, Carbon monoxide, status of the windows	Air temperature, Relative humidity, Carbon dioxide, status of the windows
Average n° of pupils/day	~ 20 + 2 teachers	~ 17 + 2 teachers
Schedule when pupils are present in class	8am – 1pm (except 12 Dec 2019, 8am – 11am)	8am – 1pm

The opening and closing status of the windows was recorded using sensors with a magnetic switch, that sends an alert message via the LoRaWAN protocol when a window is opened or closed. Preliminary analysis showed irregularities in this data. Moreover, it was not possible to determine the effective area of the windows opening. Future studies could foresee the use of more reliable sensors to evaluate the actual air change rate in the classrooms from each window.

2.3.2 Installation of the passive CO_2-based visual alerting system
From the analyzes carried out after the first winter monitoring campaign, high CO_2 peaks were found in the classroom during the occupied hours. Restoring good air quality inside the room is imperative and for this reason a smart sensor, equipped with artificial intelligence, has been installed.

The device constantly and dynamically monitors air temperature, humidity, and CO_2, 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 colour, when it is time to open the windows to change the air, just before a situation of discomfort is created. The duration of the colour persists as long as it is recommended to keep the windows open, while keep the expected heat losses to the minimum. The device returns to its original blue color when good air quality is restored, signaling the need to close the windows.

3. Results and discussion

The study presented in this paper aims to verify the effectiveness of a commercial low-cost smart CO_2-based system which alerts when to open the windows and for how long to restore a good indoor air quality, avoiding heat losses.

Considering a threshold level of 1200 ppm (EN 16798-1:2019), CO_2 concentrations as high as 1800 ppm were observed in the first monitoring campaign, as evident in figure 3.

In view of improving the indoor air quality in the classroom, the passive system has been installed and a second monitoring campaign in 2020 was carried out to evaluate its effectiveness. For the purpose to assess the quality of air in the occupied hours, the following analyses will focus only on the time range in which pupils are present in the classroom (8am – 1pm).
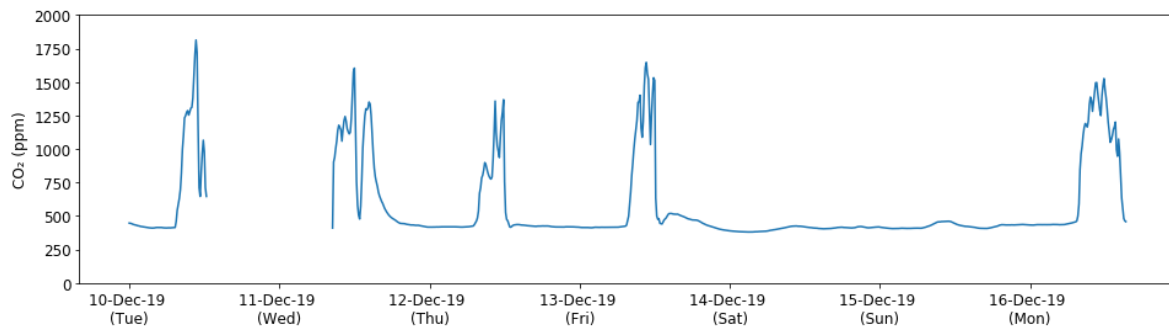

Figure 3. Mean hourly CO_2 concentration in the considered days in 2019.

In Figure 4, a comparison has been shown between the same days of the week of 2019 and those of 2020, in order to maintain the daily schedule of the lessons. As evident, there is no considerable difference between the values recorded in the two different monitoring campaign, but boundary conditions need to be studied further. Parameters like indoor-outdoor temperature difference, wind velocity, relative humidity, sunlight exposure, can highly influence the amount of wind velocity entering through an open window. Figure 4 shows that there are similar ranges of CO_2 concentration on all the days during occupied hours, except for Monday 2019 whose CO_2 values are concentrated in a more restricted range (750 ppm – 1600 ppm) compared to the same day of the week of 2020 whose values are spread over a wider range. A similar behaviour in comparison with the other days of the week is also found in terms of internal temperatures (Figure 5). A more significant difference in terms of CO_2 is instead recorded in the median values which are lower during the week of 2020 (represented by the white dot in Figure 4).
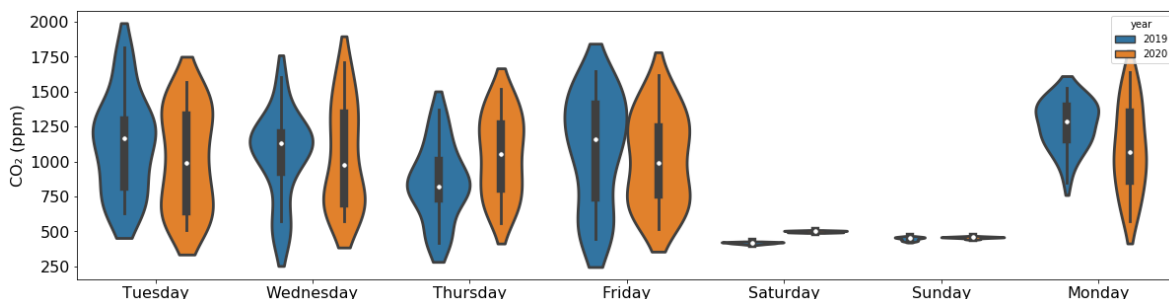

Figure 4. Violin plots showing fitted distribution and range of CO_2 concentration in 2019 and 2020 during occupied hours.
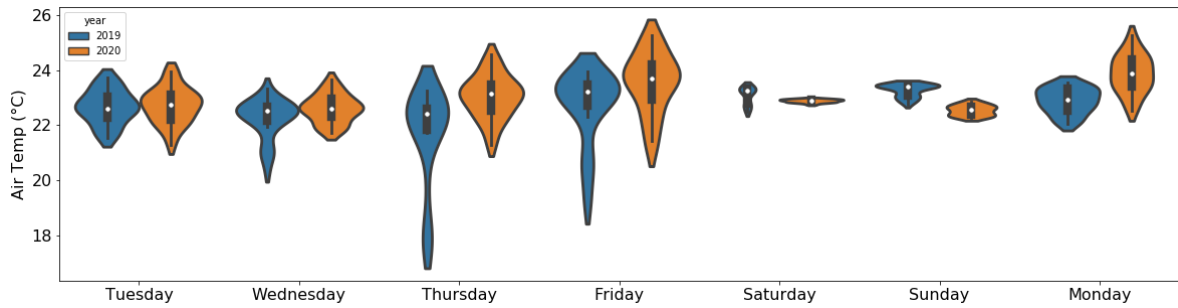
Figure 5. Violin plots showing fitted distribution and range of indoor temperatures in 2019 and 2020 during occupied hours.

Figure 6, Figure 7, Figure 9, Figure 10 show the hourly average of each day of the week monitored, the CO_2 concentration and the outdoor temperatures in 2019 and 2020 during the occupied hours. In the graph of Figure 8 the two monitoring campaigns are compared in terms of percentage difference with respect to the first campaign, and it can be deduced that there is no clear decay or increase in the concentration. However, some substantial changes are discussed below.

Comparing, for example, in Figure 6, the day of Tuesday at 11am and 12pm in 2019 with that of 2020, in Figure 7, an increase in the CO_2 concentration of 30% and 55% was recorded (Figure 8). This is probably due to higher outside temperature values recorded in 2020 (Figure 9) than those monitored in 2019 (Figure 10) which could have induced occupants to open windows more frequently.

The increase of more than 100% in the CO_2 concentration (Figure 8) recorded at 12pm and 1pm on December 3, 2020 (Figure 7) compared to the values recorded in 2019 (Figure 6) in the same time slot, is perhaps due to the absence of pupils in classroom. As Figure 6 and Figure 7 show, the same concentration results around 400 ppm – 500 ppm, in fact, were recorded only during the weekend when the school remains closed.
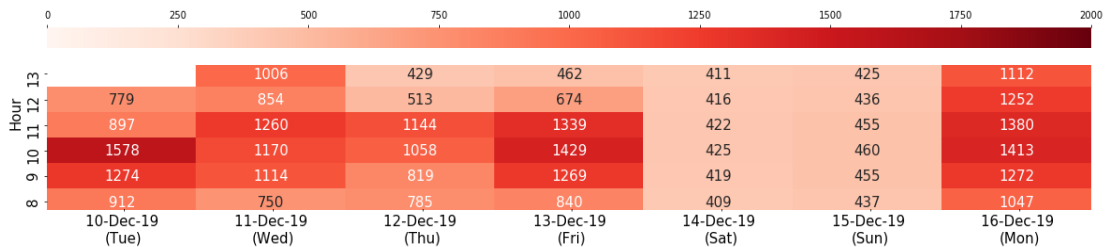

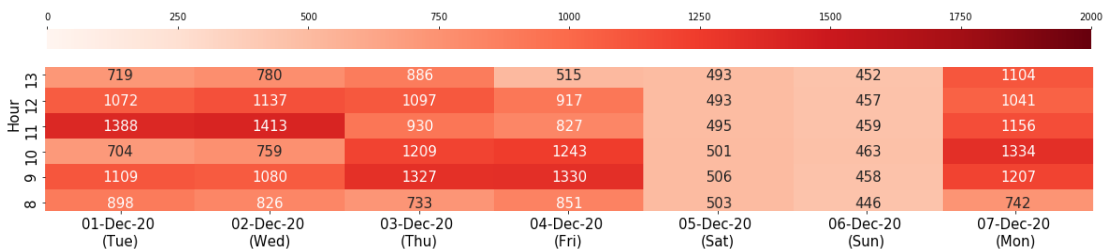**Figure 6.** Mean hourly CO_2 concentration in the week of 2019 during the occupied hours.

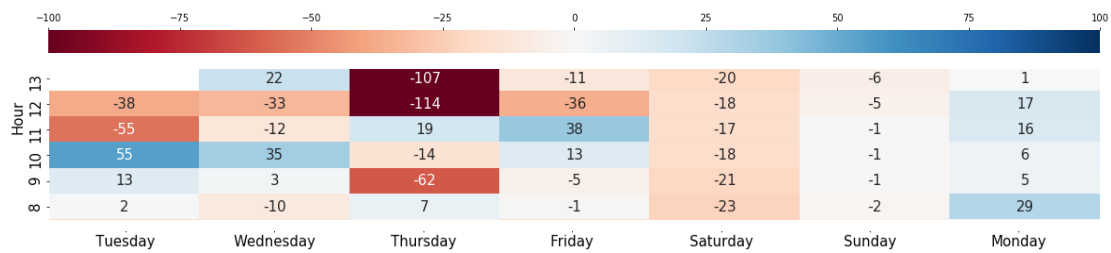**Figure 7.** Mean hourly CO_2 concentration in the week of 2020 during the occupied hours.

Figure 8. Percentage difference between the CO_2 concentration in the week of 2019 and 2020 during the occupied hours.
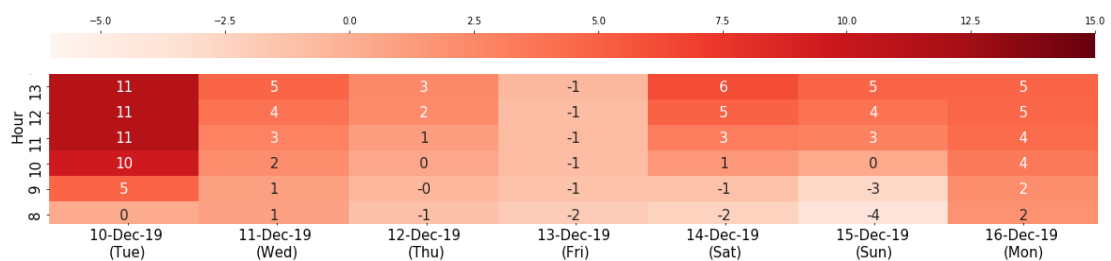

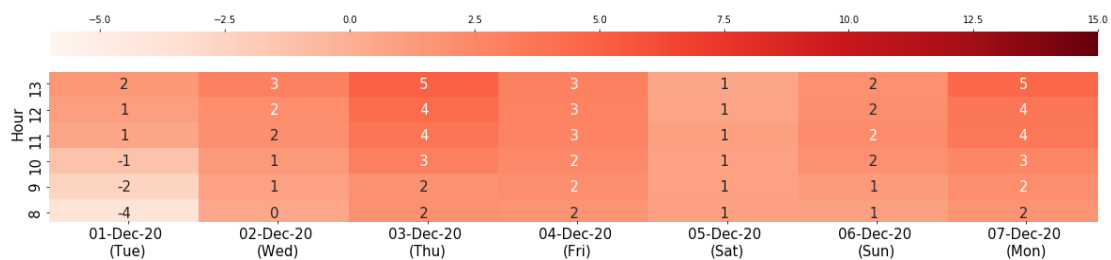**Figure 9.** Mean hourly outside temperature in week of 2019 during the occupied hours.

Figure 10. Mean hourly outside temperature in the week of 2020 during the occupied hours.

Among the different conditions that could influence the correct usage of the device can affect the teachers' behaviour, who may not be the same from one year to another. For this reason, they could have different understanding and approach towards opening the windows for air change and/or thermal comfort. Also, the on-going COVID-19 situation during the 2020 monitoring campaign may have influenced the behaviour of the teacher and the school management staff leading them to open the windows more frequently regardless of the signals displayed by the device.

4. Conclusion

The aim of this study was to investigate the effectiveness of a commercial low-cost smart CO_2-based visual alerting system installed in a kindergarten classroom located in a historic building in South Tyrol.

Based on the indoor CO_2, temperature, and relative humidity and thanks to a visual display system, this device alerted when the windows should be opened to facilitate air exchange. The classroom is on the first floor of the school and was monitored during the heating season. The first monitoring campaign was conducted to assess the air quality in the classroom, while the second aimed to evaluate the efficiency of the installed system.

As a result of the study, it seems that there is no considerable difference between the CO_2 values recorded in the first and second monitoring campaign. This is probably due to the unfamiliarity of the occupants with the device and to the different boundary conditions such as:

- Different outside temperatures. High external temperatures can positively affect the opening of windows.
- Different number of pupils and maybe dissimilar types of activities carried out in the classroom.
- Different teachers from one year to another, with different skills or notions.
- COVID-19 situation which could lead to more frequent opening of the windows to ensure abundant ventilation in the classroom.

Preliminary studies carried out on the number and shape of existing windows show that there is potential for the single-side ventilation to ensure the air exchange necessary to ensure a good indoor air quality. This will allow heritage buildings to guarantee a healthier environment without having to resort to additional strategies.

As the paper shows, significant results have not yet been achieved but the system will be tested during an entire academic year, cross-referencing the data with the information about the opening and closing of the windows and the impressions collected by teachers. Further future investigations in order to test the efficiency of different ventilation strategies without pupils in the classroom, could be done using the tracer gas technique as indicated in the study [11].

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