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Smart Healthy Schools: An IoT-enabled concept for multi-room dynamic air quality control

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ABSTRACT

Smart Healthy Schools (SHS) are a new paradigm in building engineering and infection risk control in school buildings where the disciplines of Indoor Air Quality (IAQ), IoT (Internet of Things) and Artificial Intelligence (AI) merge together. In the post-pandemic era, equipping schools with a network of smart IoT sensors has become critical to aspire for the optimal control of the IAQ and lowering the airborne infection risk of several pathogens, indirectly related to cumulated human emitted CO_2 levels over time. Thermal energy waste in winter due to improved air renewal remains of major concern but can be well monitored within a SHS monitoring architecture thanks to the flexibility of the LoRaWAN protocol able to process also a large amount of energy and climatic data at room and building scale. In this work, we report the design of the AulaSicura platform, an IoT control system co-designed by the main author and Gizero Energie to implement the SHS paradigm via clearly visible (and audible) alarm signalling in existing and new school buildings. The cloud-based LoRa system is capable of continuous and simultaneous monitoring of a variety of sensors and IAQ parameters including indoor/oudoor temperatures, rel. humidities and human-emitted excess CO_2. The multi-room monitoring concept of indoor-CO_2 levels allows centralized control of natural ventilation levels in individual classrooms and can handle (quasi)-real-time data, relevant for data post-processing and future developments in (quasi)-real-rime assessment of IAQ and infection risk levels at single room scale. The sensor network is also extensible to up to one thousand of classrooms per LoRa-node allowing centralized control of entire school districts at an urban scale. Moreover, through Modbus-LoRa I/O converters, AulaSicura can also control the same amount of mechanical ventilation units per node either in pure or hybrid mechanical ventilation modes.

1. Introduction

Over the last few years, the recent pandemic has made clear that indoor air quality (IAQ) is a critical factor for the well-being of the population. The effects of IAQ on the Quality of Life (QoL) is even more crucial for fragile and vulnerable citizens, as they are more severely affected by pollution and may facilitate the spread of new diseases and infections.

For these reasons, during the pandemic schools were considered to be one of the most critical facilities for the spreading of the virus, with several countries enforcing/encouraging closures and remote teaching solutions. Even if most of the school systems are now re-opened, it has become clear that, in order to preserve the quality and functioning of the education system, it is necessary to guarantee a safe and healthy environment for all students.

Monitoring and controlling the IAQ in schools is a challenging task, as a single school is formed by multiple rooms, each of which is densely populated for prolonged periods of time, and by several common spaces. The complexity posed by this heterogeneous scenario can only be tackled by an ad-hoc control system that may use the latest IoT (Internet of Things) results and paradigms to exploit a smart sensor and actuator network. In fact, optimal control of ventilation, air quality, and energy consumption in school buildings may significantly reduce their impact on the environment and make the economic return of such a control system

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Abbreviations: SHS, Smart Healthy Schools; IAQ, Indoor Air Quality; CAQ, Classroom Air Quality; NV, Nat. Ventilation; MV, Mech. Ventilation.

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more appealing for large scale adoption [1–3], also in the context of emerging Internet of Healthcare Things (IoHT) applications [4], although restricted to IAQ devices.

This study aims to illustrate the concept of a Smart Healthy Schools (SHS), and in particular, of SHSs equipped with wireless IoT sensors (IoT-SHS) and display units for optimal control of indoor air quality through manual airing and/or mechanical ventilation cycles.

The remainder of the paper is structured as follows: Section 2 discusses some related works; Section 3 details the possible general IoT architecture of a SHS, detailing also the characteristics of the developed prototype; Section 4 reports some preliminary results of the test campaign of such an architecture as a proof of concept, which was conducted on a limited number of classrooms (4) in a real school located in Italy, while Section 5 draws the conclusions and highlights possible future developments.

2. Related works

Over the past decade, the rise in popularity of the smart grid paradigm has led to a vast availability of controllers and intelligent systems at building and household levels, with smart control systems now in charge of managing the integration of distributed renewable sources, electric vehicle charging points/schedule and the thermal and heating systems. After the pandemic, a renovated interest has been directed towards integrating IAQ control, a functionality previously found mostly in healthcare facilities, into smart buildings. In fact, several recent studies focus on predicting and managing indoor CO_2 levels [5,6], particularly in schools with different monitoring and signalling solutions [6–9] with several commercial and public facilities integrating advanced filtration and ventilation systems to contrast the spread of diseases and in general, improve the well-being of the building's occupants [10,11]. Among public facilities, schools are of particular importance as their IAQ may have a significant impact on children's health [12] and plays a major role in the spread of diseases [7,13–15] Students' health, education [16], and well-being heavily depends on the quality of the air they breathe.

In order to improve QAC and the QoL of the students and staff, while also reducing the building's environmental impact, the control system behind an SHS has to pursue two main objectives:

1. Raise the average air volumes exchanged in classrooms, as it is a critical task for the successful mitigation of the risk of airborne contagion related to various airborne diseases, including Covid-19;
2. Contain the energy consumption of the school building, in a demand-side management and smart grid perspective.

Regarding the first point, the Italian National Institute of Health has recently [17] emphasized the importance of air exchange in buildings, which must be frequent and always guaranteed in order to reduce virus transmission and improve air quality. At the same time, the EU commission has been pursuing with its Green Deal initiative [18] a significant reduction of the energy consumption associated to buildings, introducing the paradigms of nearly-zero and zero energy buildings (nZEBs and ZEB). The first step towards a fully sustainable building/school is hence to introduce a smart control logic for the power management of both heating and controllable loads. In fact, several smart-home and smart-building controllers [19–21] have been designed to explicitly integrate energy storage systems and renewable sources to optimize energy management and offer ancillary services to the power grid operators. Nevertheless, energy savings and IAQ are in principle competing objectives [22], as most energy is consumed for heating and providing thermal comfort to building inhabitants which may be lowered by ventilation, when outdoor temperatures are lower than (indoor) thermal comfort temperatures, making the design of integrated systems that take into account both aspects an enabling factor for the optimal operation of the building.

In the direction of providing a flexible and scalable solution, capable of being seamlessly deployed over entire school districts and/or cities, the innovative LoRa communication protocols [23,24] may prove to be an enabling technology for SHS thanks to its long-range connectivity and very low energy consumption. Both LoRa and Narrow Band IoT (NB-IoT) devices [24] may function for prolonged periods of time (up to several years, depending on the sampling rate) allowing the placement of fully wireless sensors, but a LoRa-based solution may cover entire areas and multiple buildings with minimal setup showing excellent performances and lower costs compared to common IEEE 802.15.4 based solutions [25]. In fact, IoT sensing in schools (and in general buildings), could help assessing room-specific carbon dioxide metrics [26] and hence allow for the evaluation of room-level IAQ. We mention that both technologies can also be integrated into a 5G Multiaccess Edge Computing (5G-MEC) [27] architecture, which offers the capability of computing and deploying control decisions with extremely low latencies [28] by avoiding the need of communicating with a remote server in favour of edge computing. Given the relatively slow dynamics that characterize IAQ, in our test campaign, we opted for a cloud-based system that proved to be capable of providing an adequate control response to IAQ variations.

Fig. 1 reports a sketch of a smart school building that integrates a set of distributed IoT sensors to enable the control of IAQ by combining mechanical and natural ventilation without requiring any significant structural changes. The same system architecture, is reported, from a functional point of view, in Fig. 2.

3. Implementing the IoT smart healthy school concept: the AulaSicura approach

The system presented in this paper was named by the authors AulaSicura and was designed enhance signalling and to fully respond to the functional requirements identified to enable a SHS concept. A first campaign of tests was conducted in a real school located in Italy and this section details its general architecture and its two possible operative modalities.

3.1. IoT-enabled Smart Health Schools: general architecture

As with most smart buildings, the fundamental elements that constitute a smart IoT-SHS are:

- a distributed and connected IoT sensor network, that offers sensing and data storing capabilities in each of the classrooms, to collect and store over time instantaneous values of carbon dioxide concentrations, indoor air temperatures, and relative humidity.
- an interactive display unit, that visualyzes the feedback gathered from the sensor network and elaborated on external dedicated server (or cloud server) to compute a control action (e.g., the activation and/or speed profile of a ventilation unit, an alarm to open/close windows).
- a remote cloud platform that may conduct quasi real-time and ex-post statistical analysis on aggregated data from the sensors for a specific region/area to improve the system functioning and its control logic. We show in Fig. 3 an example of the results of the data analysis process implemented in our test campaing, while Fig. 4 displays a sketch of a possible HMI in which such data can be displayed to school staff or specialized operators.

Regarding CO_2 measurement, the typical solution involves Dual-NDIR technology and it is required for the sensors to be placed in classrooms following standard criteria such as the UNI EN ISO 16000 and UNI/PdR 122:2022.

On the contrary, a wireless, battery-operated, low-energy sensor network like that presented here may be advantageous for several reasons, including savings on electrical wiring work during retrofitting of existing buildings and the possibility of seamlessly moving the sensors to different locations.

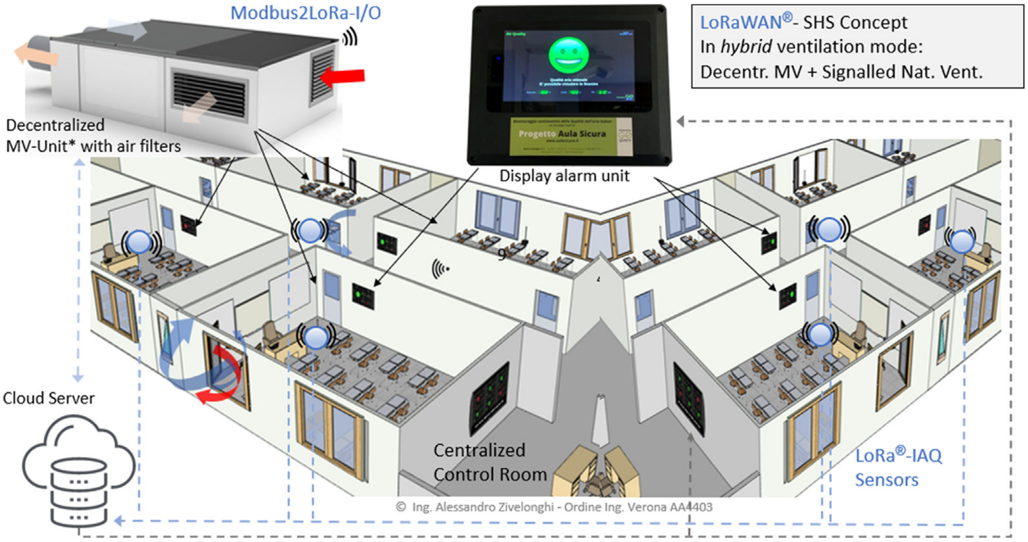


Fig. 1. Sketch of Smart Health School that integrates a distributed Indoor Air Quality Control system through a set of classroom-level sensors and controller interfaced with a centralized ventilation system, allowing both the monitoring at the building, via a dedicated Human-Machine Interface, and at classroom level thanks to ad-hod display units. *Courtesy of Helty srl (IT).

Besides CO_2/T/UR sensors, further IAQ sensors can be added to monitor a wide variety of air quality parameters of interest (e.g., VOC) as long as these sensors are IoT, i.e., permanently connectable to the Internet through a suitable protocol, e.g., LoRa or IEEE 804.15.

The proof of concept AulaSicura system relies on LoRa devices, in this case manufactured by ELSYS, that integrate miniaturized (20 × 33 × 8 mm) ultra-low-power (12 mJ/detection) CO_2 sensors with wide measurement range (0–10.000 ppm) and manufacturer's claimed accuracy of ±3 post-calibration. This device can digitally convert the measured signal with a minimum sampling interval of 20s and transmit it via LoRa radio protocol, receivable from LoRaWAN nodes located up to about 3–5 km from the device depending on the local field strength. During the test campaign, such a receiver was located approximately 1 km from the school site. The sensors mounted in the prototype are NDIR technology and use a patented self-calibration algorithm named “Automatic Baseline Correction” (ABC), which self-adjusts the CO_2 level to the background value at regular intervals (settable, normally of a few days). The ABC algorithm constantly tracks the lowest sensor reading over a preconfigured time interval and corrects any detected mid-to long-term drift from the expected background value of 400 ppm (or 0.04% vol). Fig. 5 depicts the sensor device that was employed for our testing's, while Fig. 6 shows the dedicated display unit with a touch-screen, Wi-Fi/LAN internet connection and two visual signalling modes for satisfactory and poor IAQ. In the latter, detailed instructions are also provided for windows opening with the indication of time duration and number of windows to open.

During the test campaign, it was observed that the daily carbon dioxide curve in the classrooms decayed to background levels about 2 h after the end of classes, with some deviations also due to the entry of cleaning staff. In each case, since the school building was closed after 5 p.m., it was preliminarily verified that the ambient value of 410 ppm ± 10 ppm was reached throughout the building (by pre-monitoring several

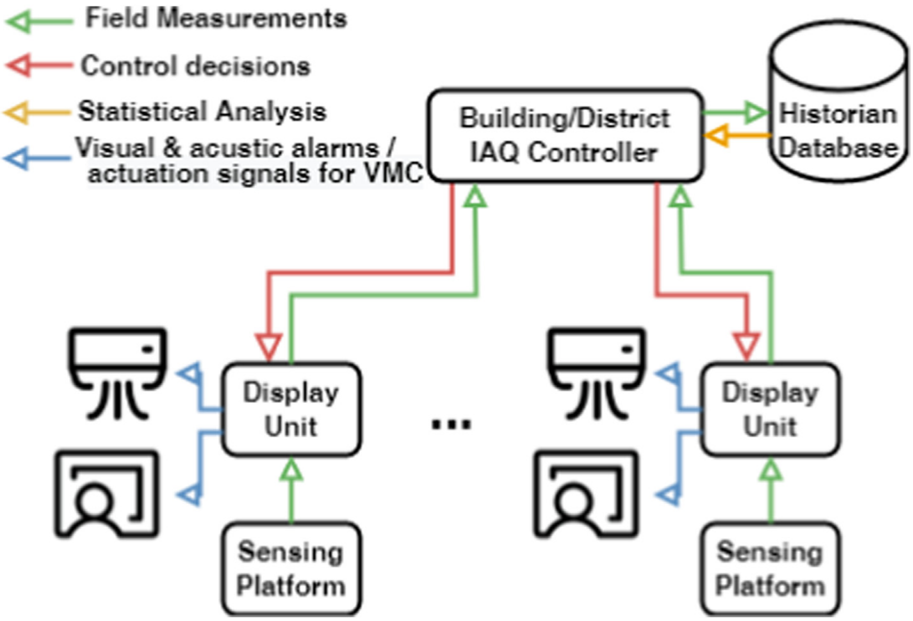


Fig. 2. Functional architecture of the control system of a Smart Healthy School with real-time feedback from IoT-IAQ sensors. In each classroom, the display units transfer the ventilation requests to the occupants or to the mechanical ventilation units on the basis of the continuous data monitoring and elaboration that takes place either in the cloud or on a dedicated server.

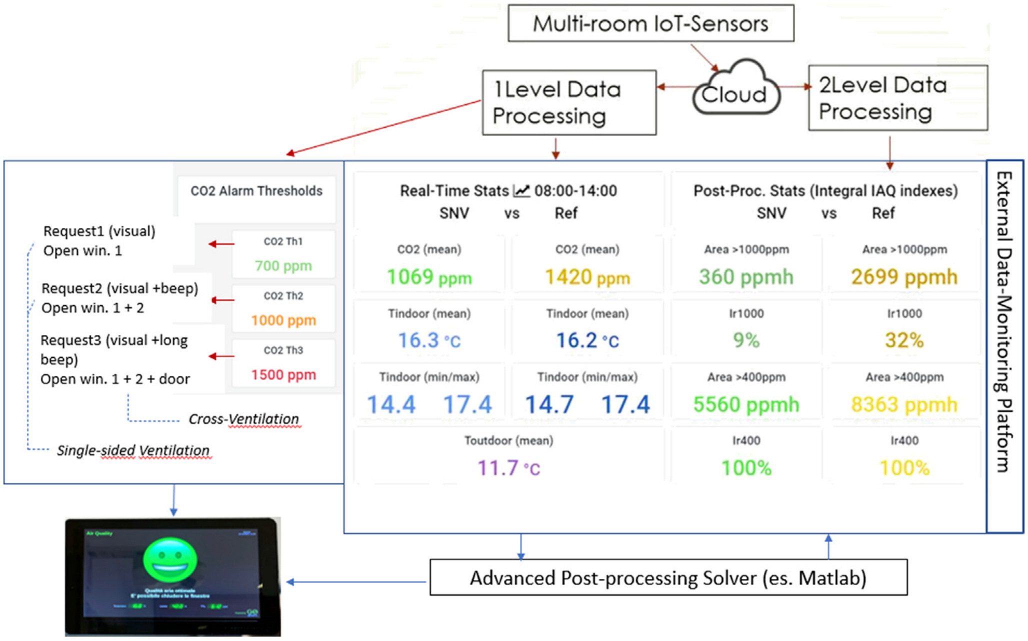


Fig. 3. Example of CAQ-dashboard, implemented in Grafana, for displaying IAQ data from the continuous monitoring of multiple rooms and two levels of data post-processing.

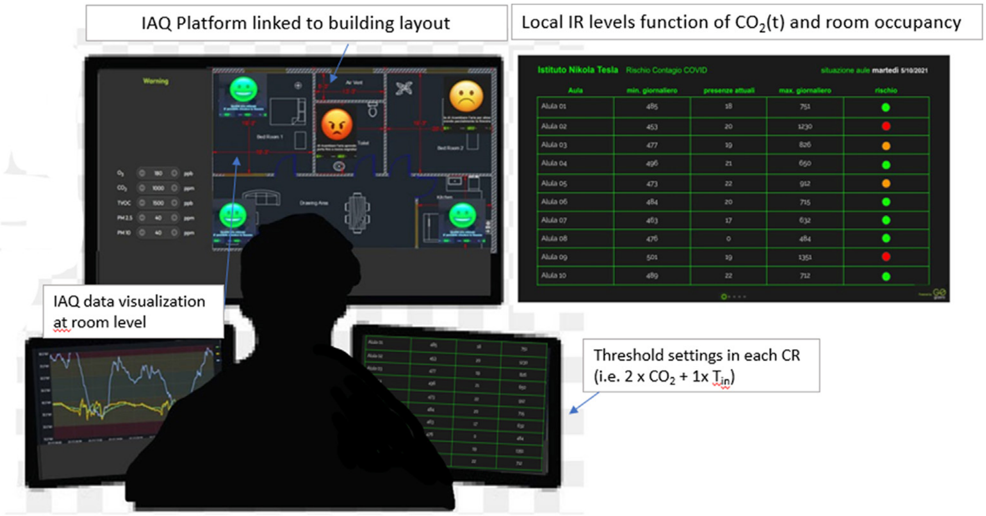


Fig. 4. Proof-of-concept for the AulaSicura IoT-IAQ platform with centralized multi-rooms control (theoretically also of IR levels) and possibility to setting locally multi-threshold alarm levels.

classrooms for a few days). During the test campaign, readings of absolute CO_2 concentration, indoor temperature and relative humidity were sampled in four classrooms of the same school building from November 2021 to May 2022 and stored on a dedicated cloud infrastructure. A low sampling frequency of about 1 in 5 min (10 μHz) was intentionally set to optimize sensor battery duration, although the employed LoRa sensors could theoretically reach 1 in 30 s (0.1 mHz). Such sampling frequencies, however, are discouraged by manufactures and system integrators due to limitations of the LoRaWAN duty-cycle during data transmission (after sampling at the edge level).

The following subsection will detail the control unit and its functioning modalities for both assisted natural ventilation and fully automated mechanical ventilation.

3.2. IAQ control for Smart Healthy Schools: manual window management

In this setup, which is the most typical in existing schools and buildings in general, there is no system dedicated to CMV and in particular, there is no actuator able to regulate the ventilation of the various rooms. The AulaSicura prototype was tested in this condition, and relied on human intervention (e.g., the teacher's) to actuate its signals for the manual window opening. Two alarm modes were tested: pure visual mode and visual-acoustic mode, both based on a simple CO_2 threshold-based control law.

This first configuration involves visual signals (in the form of emoticons and instructions) provided to the teachers and the students through the interactive interface reported in Fig. 6 that was connected to the control unit and mounted on a wall.

In the latter case, short acoustic signals were added to the displayed emoticons, signalling different levels of air quality.

The analysis of the CO_2 excess profile showed the significant beneficial impact related to the addition of acoustic signals to visual signalling systems. This can easily be attributed to the better effectiveness in implementing the windows opening/closing requests from occupants due to more intrusive visual-acoustic signalling.

Fig. 5. Wireless LoRa sensing device (ELSYS CO2 Lite - SE) integrating a CO_2/T/UR% multi-sensor and transmitting to the centralized web-platform.

As it will be reported in the test result section, classrooms not equipped with the signalling system showed higher average CO_2 levels (in average +25% despite opening windows for about 5 min every hour) with significantly higher peaks.

It was noted, however, that the acoustic signals sometimes interfered with the lesson. Therefore, engineered acoustic patterns, such as with short beeps reserved for the first two alert levels and a long beep reserved for the highest "emergency" level were better received by occupants and motivated them to effectively open windows to maintain the safe range of 800–1000 ppm and avoid the disruption of the lecture.

In fact, the key disadvantage affecting a solution that relies on the occupants for actuating the control decisions taken by the system is related to their comfort, which also includes the thermal conditions of the room. It was observed that, during the coldest days (where the minimum temperature was recorded to be about 4 °C), the air quality significantly worsened, as the windows were not opened as instructed, despite the system implementing also a control logic aimed at minimizing the temperature discomfort of the class occupants. For this reason, a fully automatic solution in which the control unit directly governs a ventilation system is to be preferred when feasible. Fig. 7 reports a simplified sketch of the control logic employed for the assisted natural ventilation configuration, in which the target CO_2 level is tracked through a threshold-based visual/acoustic signalling system.

3.3. IAQ control for smart healthy schools: automatic ventilation and hybrid mode

The SHS IoT concept can achieve better ventilation and energy performance by managing heat recovery and controlled mechanical ventilation systems. Mechanical ventilation units, usually connected in MODBUS, are interfaced with MODBUS-LoRa conversion point devices capable of dialoguing with dedicated monitoring and control stations.

Such a system may be easily distributed so that it may differentiate on/off cycle scheduling by classroom depending on its readings and characteristics (including school spaces requiring higher ventilation rates, such as cafeterias), possibly integrating occupancy sensors that evaluate the number of occupants. A *hybrid* ventilation mode is also achievable (Fig. 1) which alternates signalled windows opening via alarm display and mechanical ventilation cycles also governed by the same sensor input.

4. Results

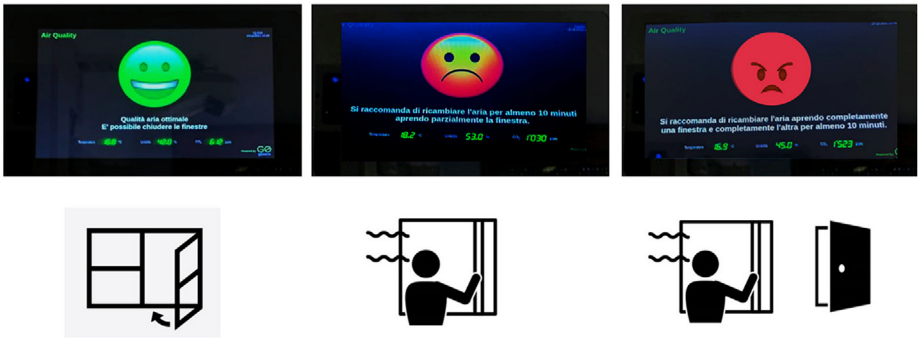
This section discusses some results from the test campaign conducted in northern Italy, in which the AulaSicura system was used to monitor and control the CAQ of a real operating school building.

4.1. Test setup

The AulaSicura platform ran its analysis on a simple, yet effective, multi-threshold control logic. When the measured CO_2 concentration exceeded certain values, poor CAQ was signalled to the room occupants through emoticons and increasingly lasting sound alarms. Such alarm CO_2 thresholds were set to the values of 700, 1100 and 1300 ppm.

The test was twofold: on the first week, the scalability and coverage of the system was evaluated on different classrooms selected in the same school building. After a week of pre-testing and provided the alarm system was running correctly together with data acquisition, the sensors and display units were seamlessly moved to two pairs of selected different classrooms for synchronous monitoring, as sketched in Fig. 8.

The reference set of classrooms was chosen so that they were all geometrically similar, hence assuring a fair benchmark for the subsequent testings. Test classrooms were equipped with both a sensor and a control unit, and their teachers and students were instructed to follow the visual-acoustic alarms (including texted messages) regarding the opening of the windows. The remaining pair of classrooms followed only the general, open-loop, guidelines suggested by the school institute for air quality management (e.g., opening the windows for 10 min after every class). This dual setup, simultaneously monitored, allows for a comparison between a controlled and an uncontrolled case under similar aeration conditions, so that it is possible to isolate and quantitively assess the contribution of the AulaSicura system, since exogenous factors (e.g., external temperature, background CO_2 level) although variable, were almost identical in paired classrooms and measured by a dedicated outdoor sensor.



Qualità aria ottimale
E' possibile chiudere le finestre

Si raccomanda di ricambiare l'aria per almeno 10 minuti aprendo parzialmente la finestra.

Si raccomanda di ricambiare l'aria aprendo completamente una finestra e completamente l'altra per almeno 10 minuti.

Fig. 6. Visual signals examples as displayed on the AulaSicura control unit and related requested actions.

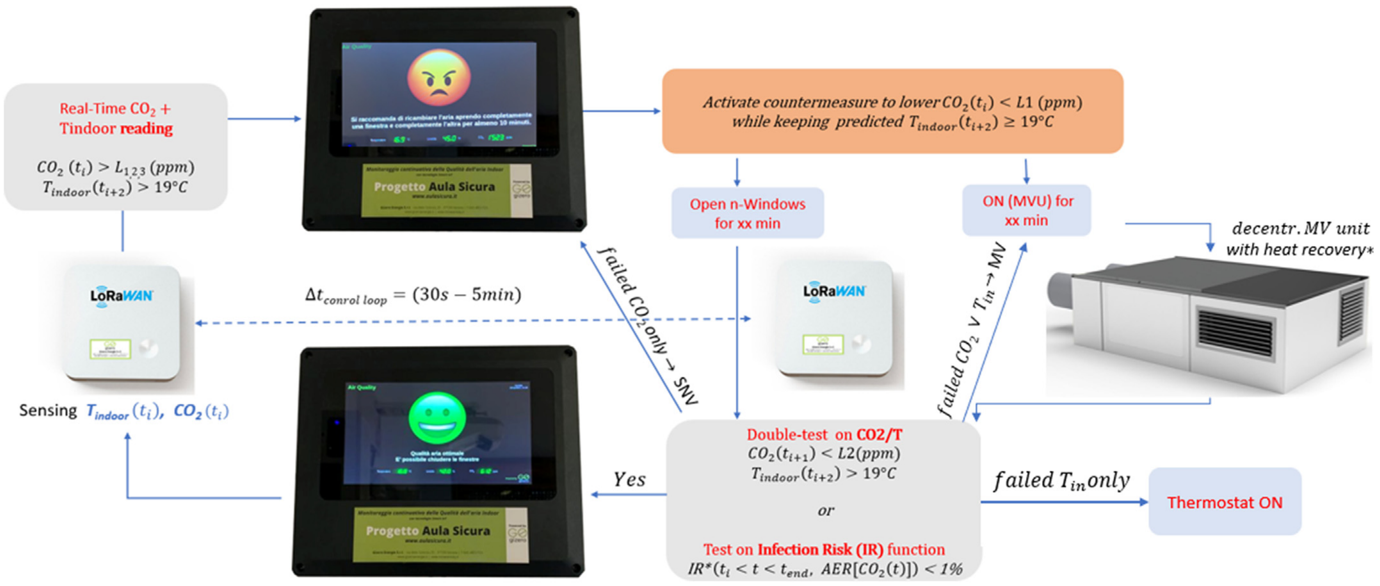


Fig. 7. AulaSicura sensing + display platform and dynamic control loop for hybrid ventilation (simplified) to keep CO_2 levels in a single room below assigned thresholds (i.e. 1000 ppm) or, alternatively, to keep a more complex probabilistic Infection Risk (IR) function (related to integrated CO_2 levels over time) below a given IR threshold (e.g. 1%, see, for instance, recently revised box models based on the Rudnick-Milton hyphotesis [29–31]). Courtesy of Helty srl (IT).

The full testing campaign was carried out spanning a total period of five months and three winter months (with a one-month interruption due to excessively cold conditions), collecting and storing measurements on a 5-min basis.

4.2. Results

Here only some of the most significative testing results are shown to illustrate the AulaSicura concept and the Smart-Healthy-School proof-of-concept (SHS-PoC).

From our testing, we observed that our IoT-alarm system in SNV mode allowed for a reduction of the average CO_2 concentration level, measured over the entirety of the monitoring campaign, of about 25%, with human-group related variations and also very significant daily-peak attenuation up to 85% during some days. In fact, the overall average value of CO_2 concentration, measured between 8:00 a.m. and 2:00 p.m., was about 927 ppm for the classrooms equipped with the signalling unit, whereas the reference classrooms reached an average concentration of about 1283 ppm. As expected, some impact was observed on the thermal comfort, particularly in December (Fig. 9), as the temperature measured in the classrooms showed an average difference of about 1 °C.

4.3. Advanced functionalities and more complex control logics

The proposed control logic proved to be effective, but it was designed to cope with the limited flexibility offered by an old school building. In fact, as the building was not equipped with a mechanical ventilation system, the AulaSicura controller had to resort to human intervention to actuate its com-mands, meaning that a continuous control law (e.g., a signal obtained with a standard PID controller) or cycled feedback-control logic (as suggested in Ref. [32] was impractical, although the temporal granularity of the measurements would in principle allow for more complex computations and logics.

In this direction, one could employ a system-identification based methodology to estimate a model for the air dynamics in order to predict the CO_2 concentration evolution in response to window openings and/or ventilation commands.

Another promising approach, that may better capture the specific class-room characteristics, would be to consider a data-driven and Deep Learning-based regressor system to estimate the Air Exchange Rates (AERs, also known in the IAQ literature as ACH, Air Changes per Hour) to be expected, given the current room occupants, internal and external temperatures and ventilation levels. Moreover, integration of Model Predictive Control (MPC) algorithms for predictive energy management, as the one proposed by the authors for Energy Management System of an nZEB - see Ref. [21] - could be easily extended for energy optimized infection risk control (provided that an adequate model for the ventilation dynamics is available to the controller.

Independently from the nature of the underlying prediction system, the design of a predictive optimization controller would be compliant with the proposed IoT architecture, as the required computations may be carried out by a dedicated server and then be actuated though LoRa communications.

4.4. SHS equipped with mechanical ventilation units

After the Covid-19 pandemic, new school buildings are highly recommended and, in some countries, obliged (cfr. the recent Italian regulations “Criteri Ambientali Minimi”) to install mechanical ventilation systems to ensure constant and more controllable air renewal rates while minimizing at the same time thermal waste in winter. Mechanical ventilation systems, on the other hand, are much more capital-costly solutions than assistive signalling systems for manual airing (5–10 times higher cost/classroom) and found financial barriers to large-scale diffusion particularly in retrofitting a large amount of existing school buildings, so that a limited (although increasing) number of best-practices can be found. It is also said that mechanical ventilation systems can be further differentiated between centralized MV systems with air handling units - AHU - able to also actively control the thermal comfort to be found in most advanced recent constructions (usually embedded in complex HVAC systems with active air heating systems) or distributed MV systems ideal for retrofitting existing school buildings, with one dedicated unit per classroom devoted to air renewal control with heat recovery, also wall-integrable. A real-case example of the first kind is the primary school “Silvio Pellico in Sona”, VR, an italian best-practice case (winner of the CasaClima Award) equipped with centralized AHU before the pandemic in early 2019, whereas an interesting case of the second type, with full MV-retrofit with wall integration involving 58 classrooms, is that of the secondary school in Fontaniva, Province of Padua, operative since 2021. Another relevant best practice case is to be found in Italy region “Marche” where about 300 over

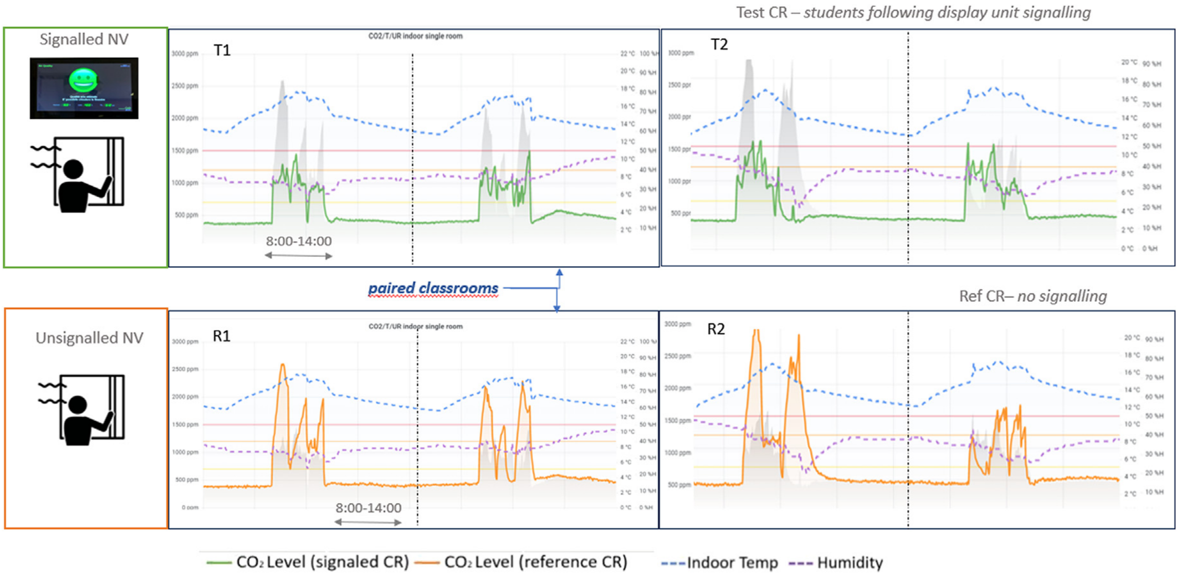
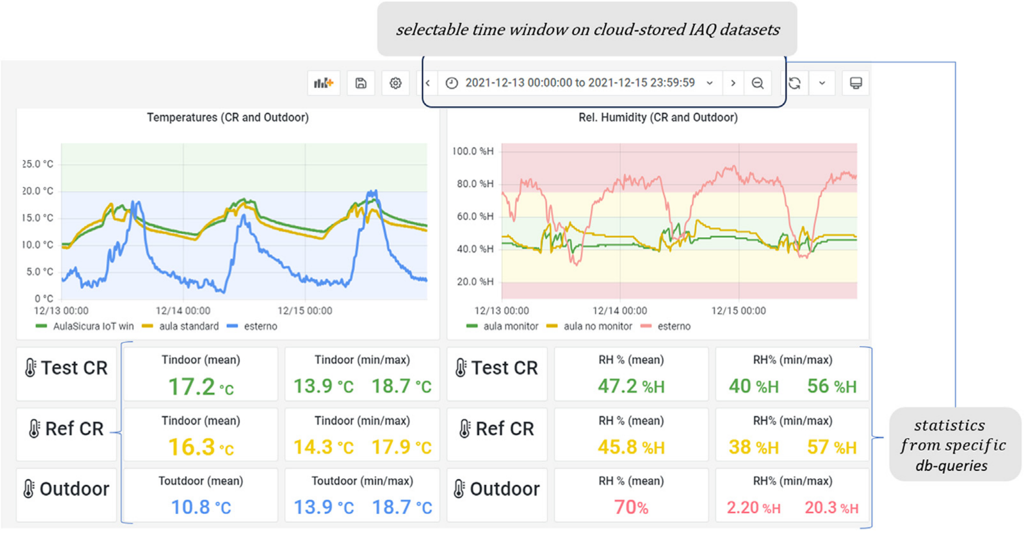


Fig. 8. Configuration of the experiment conducted in a school building located in northern Italy. A total of four similar but physically different classrooms in the same building were simultaneously monitored to prove multi-room data acquisition (2 with alarm unit AulaSicura and 2 without). The experimental plots show the proof of concept of a SHS requiring monitoring in multiple classrooms with a scalable number of rooms, here limited to 4, but easily extendable to hundreds and up to one thousand per LoRa node, depending on the total dataflow amount. It is noted - as also shown in Di Gilio at al. (2021) [8] that classrooms equipped with a signalling alarm unit performed remarkably better in terms of lower CO_2 levels cumulated in classrooms over time (cfr green vs orange signals). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).



Test CR	Tindoor (mean) 17.2 °C	Tindoor (min/max) 13.9 °C 18.7 °C	Test CR	RH % (mean) 47.2 %H	RH% (min/max) 40 %H 56 %H
Ref CR	Tindoor (mean) 16.3 °C	Tindoor (min/max) 14.3 °C 17.9 °C	Ref CR	RH % (mean) 45.8 %H	RH% (min/max) 38 %H 57 %H
Outdoor	Toutdoor (mean) 10.8 °C	Toutdoor (min/max) 13.9 °C 18.7 °C	Outdoor	RH % (mean) 70%	RH% (min/max) 2.20 %H 20.3 %H

Fig. 9. Grafana visualization interface for quasi-realtime and ex-post stats on climatic data. Daily evolution of temperature and humidity data over multiple winter days in test and reference classrooms.

10.000 classrooms (3%) have been equipped with decentralized MV-units for a total investment cost of 9 Mil. € [33].

Making these interventions real SHS best-practice, however, would further require dedicated centralized data management systems able to collect operational data of distributed MV-systems in real-time, also in the perspective of maintenance and life-cycle of a large amount of electromechanical devices as MV systems in fact are. In this sense the present IoT-based architecture and data acquisition system extensible to a large number of wireless sensors has shown the potential for future integration with distributed MV-systems, also in case such systems have been already installed in a school building. In fact, retrofitting an IoT sensor infrastructure like the one we have shown for the AulaSicura system would require almost no installation costs due to absence of cable works and durability due to long-term battery duration of the LoRa sensors with optimized data-transmission.

5. Conclusions and future works

This paper presented the design process and main functionalities of the AulaSicura system, a prototype platform for Indoor Air Quality (IAQ) monitoring and control specifically designed to self-control the Classroom Air Quality (CAQ) in schools and public buildings. The proposed system, composed by a custom alarm display for signalling visual and audio alarms, a sensing platform able to measure various quantities related to the CAQ including CO_2 concentration, and a cloud-server feeded by a LoRa sensor-network, allows for the continuous and precise monitoring of individual classrooms in school buildings, showing the potential of deployment for entire school districts.

The prototype of the system was tested in a real working environment in SNV mode, consisting in an operating school located in northern Italy, over a period of 4 months. From this testing campaign it was observed how, even if deployed in its simplest configuration that relies on teachers and students to actuate its window opening commands, the AulaSicura system contributed to reduce the CO_2 concentration significantly via signalled natural ventilation and so improving an important parameter of the CAQ. Future works are related to the integration of predictive-based optimization systems into the platform and the testing of the system in a setting in which it can be interfaced with the control system of a mechanical ventilation system, so that it may oversee the functioning of both the thermal and IAQ controllers, as well as the testing of (quasi)-real-time infection risk models.

Declaration of competing interest

The authors declare that at the time the paper has been published they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The work was entirely self-funded. An indirectly related patent is pending (IT202100023255).

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