Environmental Quality Analysis in School Environment by Measurements and Numerical Methods

Leonardo Guglielmi – Università degli studi G. D'Annunzio Chieti-Pescara, Italy – leonardo.guglielmi001@phd.unich.it
Samantha Di Loreto – Università degli studi G. D'Annunzio Chieti-Pescara, Italy – samantha.diloreto@unich.it
Matteo Falone – Università Politecnica delle Marche, Italy – m.falone@univpm.it
Mariano Pierantozzi – Università degli studi G. D'Annunzio Chieti-Pescara, Italy – mariano.pierantozzi@unich.it

Abstract

Energy consumption and its consequences are inevitable in modern-age human activities, particularly in the school environment.

School buildings require significant energy inputs for heating and air-conditioning, and the majority of the occupants are adolescent students, whose health and cognitive performance are vulnerable to poor indoor air quality (IAQ), thermal discomfort and acoustic noise sources.

The present study employs measurements and numerical methods to improve Indoor Environmental Quality (IEQ) and reduce energy consumption in school buildings.

Accurate measurements enable the quantification of various environmental parameters, from indoor air pollutants to temperature and relative humidity levels. These measurements form the basis for informed decision-making and interventions to improve the environment.

Numerical methods, on the other hand, offer a means to model and simulate the impact of different factors on environmental quality. Advanced computational tools allow for the assessment of scenarios, enabling stakeholders to identify optimal solutions for achieving and maintaining high standards of environmental quality in schools.

1. Introduction

Due to the SARS-CoV-2 pandemic, there has been a critical need to explore and implement novel approaches aimed to study virus airborne transport (D'Alessandro et al., 2022) and enhance indoor air quality. Several studies indicate that the risk of contagion escalates in enclosed spaces as the number of occupants and their duration of stay inside rises (Braggion et al., 2023; Dowell et al., 2022; Goodwin et al., 2021).

In Papadopoulos et al. (2022), studying IEQ is important to ensure the thermo-hygrometric comfort of occupants within a room, especially in school buildings whose classrooms are continuously occupied by a considerable number of people. In particular, assessing the variation of parameters that influence indoor air quality (IAQ) allows for increased student performance and the prevention of undesirable health effects (Amoatey et al., 2023).

The school ventilation system serves as a fundamental tool in creating a safe, comfortable, and healthy indoor environment conducive to effective learning (Calama-González et al., 2019). Beyond merely regulating temperature, proper ventilation is essential for maintaining acceptable indoor air quality (IAQ), which is vital for promoting optimal educational and health outcomes among students and staff alike (Ali et al., 2009). Thermal comfort, alongside acceptable IAQ standards, directly influences students' ability to concentrate, engage in learning activities, and perform academically (Asrani & Shah, 2019). Inadequate ventilation can lead to stuffy, stale air, which not only affects concentration levels but also increases the risk of spreading airborne contaminants, including viruses and allergens. By prioritizing effective ventilation systems within educational facilities, schools can create environments that support the physical and cognitive well-being of occupants (AiCARR, 2022; De Giuli et al., 2015; Serpilli et al., 2022). This ensures that students have

Part of
Pernigotto, G., Ballarini, I., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2025. Building simulation applications BSA 2024. bu,press.
https://doi.org/10.13124/9788860462022

the best possible conditions for learning and thriving academically, while also fostering a healthier and safer atmosphere for everyone within the school community.

This study introduces a methodological approach to studying indoor air quality in educational settings. This approach assesses the effectiveness of existing air-conditioning systems while considering the potential implementation of controlled mechanical ventilation (VMC) systems.

The methodological approach unfolds in two distinct phases. Firstly, a measurement phase is conducted wherein characteristic parameters of the target classroom are acquired using sensors deployed within a specially designed setup. Subsequently, a modeling phase follows, wherein the acquired measurement data serves as both input parameters for the model and verification benchmarks for ensuring the accuracy of simulated outcomes. The numerical model is implemented utilizing the COMSOL Multiphysics software (COMSOL), which offers a comprehensive platform for managing all aspects of the analysis within a unified study framework. This approach allows for a thorough examination of various factors influencing indoor air quality and facilitates the evaluation of potential interventions, such as the introduction of controlled mechanical ventilation systems, to enhance overall air quality and occupants' well-being within educational environments.

2. Material and Methods

2.1 Indoor Environmental Parameters

To assess indoor comfort and air quality, key parameters including indoor air temperature, relative humidity, and CO_2 concentration were meticulously measured. Within enclosed spaces, such as classrooms, air quality is influenced by a spectrum of indicators and pollutants.

Elevated levels of CO_2, in particular, can detrimentally impact classroom occupants' attention, leading to symptoms such as headaches, drowsiness, and reduced concentration abilities (Braggion et al., 2023). For the measurement of air temperature and relative humidity, the technical reference standard EN ISO 7726:2002 (ISO, 2002) was adhered to, while EN ISO 16000-26:2012 (ISO, 2012) was employed for CO_2 measurement. These standards provide guidelines for assessing indoor environmental parameters.

In educational settings, adherence to specific limit values for these parameters is crucial. These values are outlined in Italian regulations DM 18/12/75 (Decreto Ministeriale, 1975) and technical standard UNI EN 16798-1:2019 (UNI, 2019), which serve as benchmark for maintaining acceptable indoor air quality levels.

2.2 Classroom Description and Measurements Equipment

In the preliminary phase of the research, which will also involve high schools at a later stage, classroom A34 at the University of Studies "G. D'Annunzio" of Chieti-Pescara is the starting point for the study. The classroom is in the "Pindaro Pole" of the Pescara campus. It is a corner classroom, positioned between the North-East and North-West sides of the ground floor near the entrance to the faculties of Engineering and Architecture (Fig. 1). Classroom A34 has a volume of 772.8 m^3, a height of 4 m, an area of 193.2 m^2 and has 4 large windows (2 on the North-East side with an area of 18.56 m^2 and 2 on the North-West side with an area of 17.6 m^2).

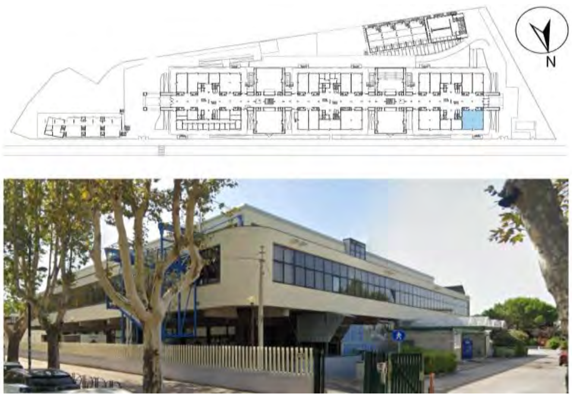

Fig. 1 – Location of classroom A34

The air-conditioning system in room A34 was recently modified. It consists of a cross-flow air handling unit that supplies the classrooms and the corridor on the north-east side of the building.

The classroom therefore has two supply channels with four vents each. The change of air is provided by 2 return vents (one on each side) and by the opening of 2 entrance doors (corridor side) and 2 emergency exits on the street side (Fig. 2).

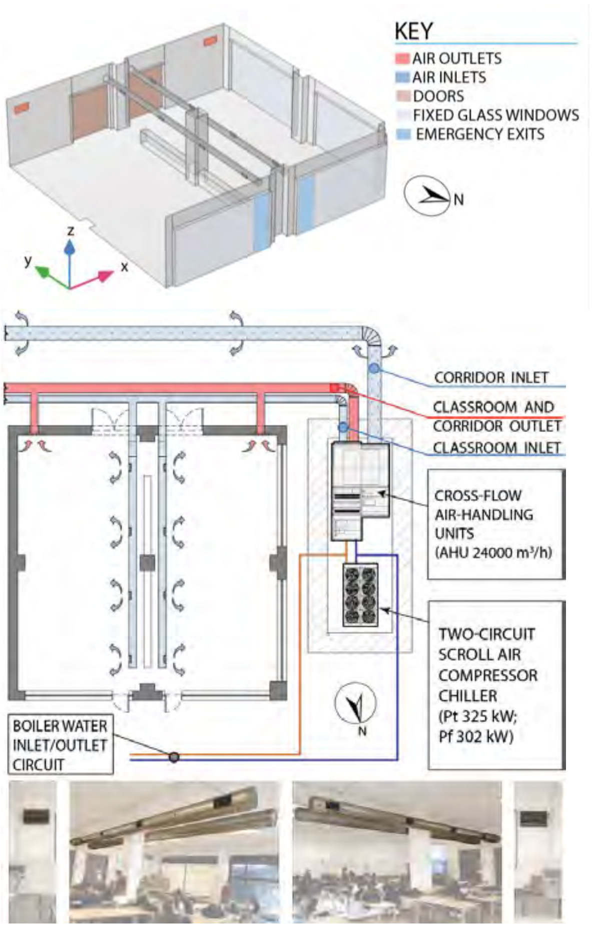

Fig. 2 – Description of air-conditioning system in Classroom 34

The measuring system consists of several sensors placed on a stand. The aluminum support is designed to allow the sensors to be positioned so that they do not clash with each other. It allows the sensors to be handled in a compact position on an easy-to-transport telescopic tripod. Fig. 3 shows the mounted sensors and their position within the measurement set-up.

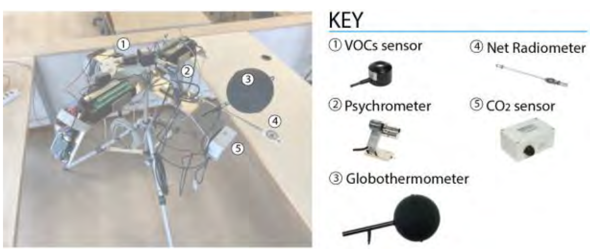

Fig. 3 – Measurement set-up

The sensors involved are a VOCs sensor, a psychrometer, a geothermometer, a net radiometer and a CO_2 sensor. The measured quantities and measuring range from each sensor are shown in Table 1. The acquisition system, also mounted on the cross-mount, consists of two E-log terminal blocks with slave function and one alpha-log in master function. Both devices are supplied by LSI LASTEM. The alpha-log device is connected via Ethernet cable to a PC and then controlled via the 3Dom software.

Table 1 – Measuring range of each sensor

Transducer	Measures	Measuring Range
1) VOCs sensor	VOCs	0 [ppm] – 2000 [ppm]
2) Psychrometer	Temperature	-5 [°C] – 60 [°C]
	Relative Humidity	0 [%] – 100 [%]
3) Globo thermometer	Globe Temperature	-30[°C] – 70 [°C]
4) Net Radiometer	Radiation Net	-1500 [W/m²] – 1500 [W/m²]
5) CO_2 sensor	CO_2	0 [ppm] – 5000 [ppm]

In the measurement phase, the position of the instrument was chosen so as not to interfere with normal classroom activities (Fig. 4).

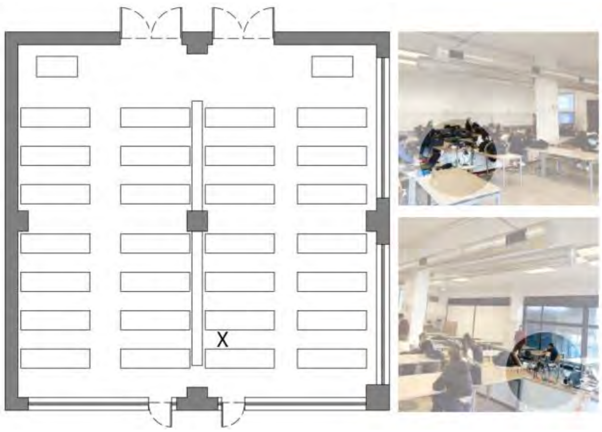

Fig. 4 – Position of the instrument within the classroom

The measurements were carried out continuously over five days, from Monday 4 March 2024 to Friday 8 March 2024 during both the night period and during lessons and daily activities. During the daytime period, three students monitored the proper functioning of the system and transcribed observations such as the number of occupants and their location, as well as the duration of air changes if present.

2.3 Numerical Simulation

The numerical model of classroom A34 was created with version 6.1 of the COMSOL Multiphysics software.

Due to the classroom configuration and the imbalance in vents mass flow rate, the entire geometry was analysed considering the presence of people and closed doors and windows.

The adopted approach relies on continuity and Reynolds-Averaged Navier-Stokes (RANS) equations in their steady, incompressible form as follow:

$$\rho \boldsymbol{\nabla} \cdot \boldsymbol{u} = 0 \quad (1)$$

$$\rho(\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} = \boldsymbol{\nabla} \cdot [-p\boldsymbol{I} + \boldsymbol{K}] + \boldsymbol{F} + \rho \boldsymbol{g} \quad (2)$$

with

$$\boldsymbol{K} = (\mu + \mu_T)(\boldsymbol{\nabla u} + (\boldsymbol{\nabla u})^T) \quad (3)$$

In the above equations, standard constitutive relations for Newtonian fluid were considered. Moreover, Boussinesq's approximation was employed to consider the buoyancy, and the system closure was guaranteed by k-ε turbulence model, here not reported for sake of compactness.

Furthermore, the energy equation was considered:

$$\rho C_p \boldsymbol{u} \cdot \boldsymbol{\nabla} T + \boldsymbol{\nabla} \cdot \boldsymbol{q} = Q + Q_p + Q_{vd} \quad (4)$$

in which Fourier's law was introduced to describe the heat thermal flux:

$$\boldsymbol{q} = -k\boldsymbol{\nabla} T \quad (5)$$

Finally, Fick's law describes vapour (v) and carbon dioxide (CO_2) diffusion in ambient air as follows:

$$M_v \boldsymbol{u} \cdot \boldsymbol{\nabla} c_v + \boldsymbol{\nabla} \cdot (-M_v D \boldsymbol{\nabla} c_v) = G \quad (6)$$

$$\boldsymbol{u} \cdot \boldsymbol{\nabla} c_{co_2} + \boldsymbol{\nabla} \cdot (-D_{co_2} \boldsymbol{\nabla} c_{co_2}) = R_{co_2} \quad (7)$$

The acquired measurement data was used as input parameters for the computations such as the vents inlet and outlet air velocity and the external surfaces temperature.

3. Results and Discussion

In the following Table 2, the average values for thermal comfort parameters, together with CO_2 concentration, for A34 room, are presented.

Table 2 – Operative condition of A34 classroom divided into three period of observation

Time	Type of Measure	Avg	Number of people	Observation
From 8:00 to 9:00 a.m.	Temperature [°C] Relative Humidity [%] CO_2 [ppm]	19.0 49.6 487.4	0	System On
From 1:00 to 3:00 p.m.	Temperature [°C] Relative Humidity [%] CO_2 [ppm]	21.8 44.6 612.4	49	System On All Door-windows open
From 6:00 to 7:00 p.m.	Temperature [°C] Relative Humidity [%] CO_2 [ppm]	21.4 43.8 926.9	70	System On All Door-windows closed

The values presented refer to the average indication of all sensors for the periods the classroom was crowded and not; these periods, including the number of students.

In Fig. 5 the air temperature, relative humidity and CO_2 concentration of the 6th of March from 8:00 to 9:00 a.m. (empty classroom), from 1:00 to 2:00 p.m. (occupied classroom with open door), from 18:00 to 19:00 p.m. (occupied classroom), are presented.

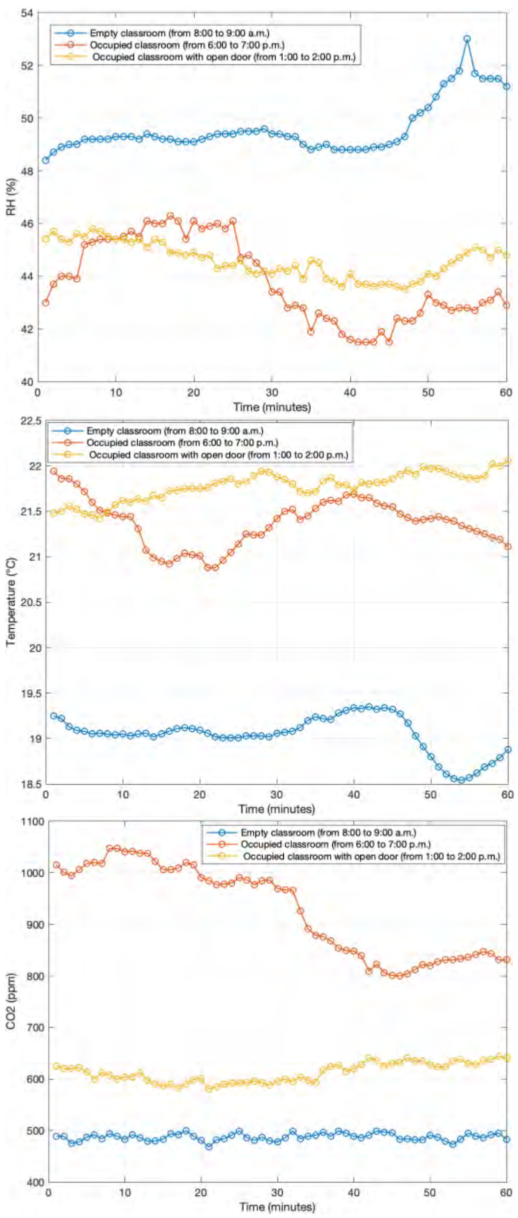

Fig. 5 – Air temperature, relative humidity, and CO2 concentration during the measurement period

Fig. 6 shows the results of the calculated variables on selected section planes. Sections A and B were made at the inlets, while section C at the outlet in the left side of the room.

These results were calculated by imposing the conditions for 6th March from 6:00 pm to 7:00 pm.

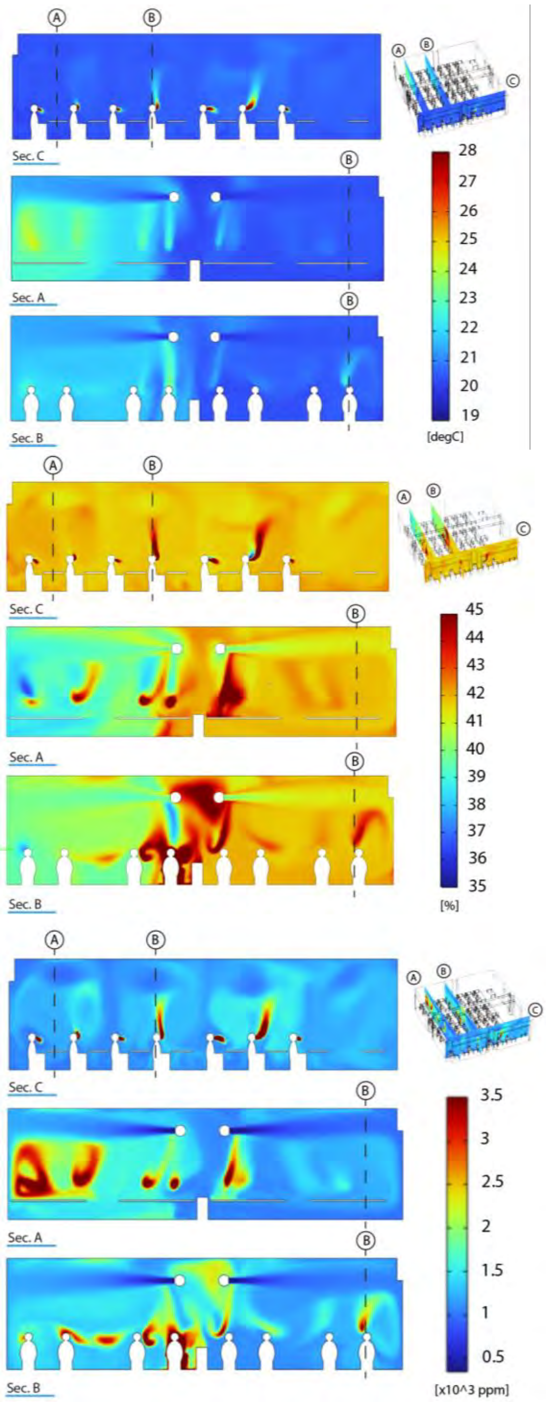

Fig. 6 – Air temperature, relative humidity, and CO2 concentration calculated by COMSOL Multiphysics

The results were consistent with the set boundary conditions.

In particular, in section C, the variables are changed in concentration due to convective motions driven by the air-conditioning system.

In fact, when the inputs are at the occupant's head (position B), the trend is upward. However, when the vent is placed at a certain distance from the oc-

cupant (position A), the trend is downward.
In addition, on the left side of sections A and B, there is a high concentration of parameters caused by poor air circulation. In fact, measurements of the air velocity coming out of the vents on the left side of the room show that the system is unbalanced on that side.
A correct comparison with the experimental data can be made by taking the average of the data for the first half-hour of acquisition. Indeed, in this period, the data do not undergo great fluctuations and are comparable with steady-state simulations.
The air temperature, relative humidity and CO_2 concentration evaluated in the simulation at the points corresponding to the position of the sensors are presented in Table 3.

Table 3 – Conditions evaluated in the simulation at the points corresponding to the position of the sensors.

Time	Number of people	Type of Measure	Avg (first half-hour)	Comsol point
6th of March from 6:00 to 7:00 p.m.	70	Temperature [°C]	21.3	20.5
		Relative Humidity [%]	45.1	41.8
		CO2 [ppm]	1006.9	1150.9

The temperature and relative humidity values deviated little from the average values measured. Respectively 0.8° C less and 3.3% more for the realized model. This deviation is probably due to the imposition of the regulatory intake values of 20 °C and 40%. As far as CO_2 concentration is concerned, the deviation is higher. In fact, the model shows 144 ppm more than the measured data. This deviation can be attributed to the fact that the model assumes that each occupant emits the same amount of CO_2 at the same instant.
In addition, a second simulation was implemented as a further verification of the results.
The interval taken into consideration was the time between 4:00 a.m. and 5:00 p.m. on 8 March. During this time, all doors and windows were closed, and the classroom was occupied by 43 people.

Table 4 shows the actual values referring to the first half-hour of measurement and the simulation results evaluated at the points already mentioned.

Table 4 – Conditions evaluated in the simulation at the points corresponding to the position of the sensors

Time	Number of people	Type of Measure	Avg (first half-hour)	Comsol point
8th of March from 4:00 to 5:00 p.m.	43	Temperature [°C]	21.4	20.2
		Relative Humidity [%]	43.4	40.3
		CO2 [ppm]	693.4	583.5

In the latter case, the simulated temperature is 1.2 °C lower, the simulated relative humidity is 3.1% lower and the simulated CO_2 concentration is 109.9 ppm lower.
In general, the percentage deviation between measured and simulated data is 4%-5% for temperature and 7% for relative humidity and 14%-16% for CO_2 concentration.
Nevertheless, the quite good agreement between the measured and computed data highlights the potential of the proposed approach.

4. Conclusion

In conclusion, the thorough analyses conducted through in-situ measurements and advanced modeling techniques have yielded valuable insights into indoor environmental quality within educational settings, notably in room A34. The favourable outcomes observed underscore the effectiveness of existing ventilation systems and environmental control measures in upholding conducive learning environments.
Looking ahead, there are exciting opportunities for further advancements in this field. A key focus lies in integrating advanced sensor technologies and real-time monitoring systems to proactively manage indoor environmental conditions. By leveraging transient simulations, educational institutions can enhance precision in optimizing indoor air quality

and thermal comfort while concurrently reducing energy consumption.

Furthermore, there is a growing emphasis on sustainable building design and operation, recognizing the intricate relationship between indoor environmental quality, energy efficiency, and occupant well-being. Future endeavors may entail the adoption of energy-efficient ventilation systems, the incorporation of renewable energy sources, and the infusion of biophilic design principles to foster healthier and more productive learning environments.

Funding

This research was funded by the project "necessARIA - Need for efficient strategies of air exchange for health of occupants in school buildings"; PNC - National Plan complementary to the PNRR - PNC Ministry of Health - E.1 Health-environment-biodiversity-climate, by Ministry of Health

References

AiCARR. 2022. "52nd International Conference on HVAC and Health, Comfort, Environment - Equipments and Design for IEQ and Sustainability".

Ali H.H., H.M. Almomani, M. Hindeih. 2009. "Evaluating indoor environmental quality of public school buildings in Jordan" *Indoor and Built Environment* 18: 66–76. https://doi.org/10.1177/1420326X08100760

Amoatey P., K. Al-Jabri, S. Al-Saadi, I. Al-Harthy, M. Al-Khuzairi. 2023. "Impact of Indoor Environmental Quality on Students' Comfort in High School Buildings during the Summer Season in an Extreme Climate" *Journal of Architectural Engineering* 29. https://doi.org/10.1061/JAEIED.AEENG-1468

Asrani S., D. Shah. 2019. "Assessing the indoor environmental quality of municipal schools in Ahmedabad". Proceedings of Technologies for Sustainable Development - 7th Nirma University International Conference on Engineering, NUICONE 2019, pp. 73–78.

Braggion A., A. Dugerdil, O. Wilson, F. Hovagemyan, A. Flahault. 2023. "Indoor Air Quality and COVID-19: A Scoping Review" *Public Health Reviews* 44. https://doi.org/10.3389/phrs.2023.1605803

Calama-González C.M., R. Suárez, Á.L. León-Rodríguez, S. Ferrari. 2019. "Assessment of indoor environmental quality for retrofitting classrooms with an egg-crate shading device in a hot climate" *Sustainability* 11. https://doi.org/10.3390/su11041078.

COMSOL - Software for Multiphysics Simulation. https://www.comsol.com/

De Giuli V., R. Zecchin, L. Corain, L. Salmaso. 2015. "Measurements of indoor environmental conditions in Italian classrooms and their impact on childrens comfort" *Indoor and Built Environment* 24: 689–712. https://doi.org/10.1177/1420326X14530586

Dowell D., W.G. Lindsley, J.T. Brooks. 2022. Reducing SARS-CoV-2 in Shared Indoor Air, *JAMA* 328 (2022) 141–142. https://doi.org/10.1001/jama.2022.9970.

Goodwin L., T. Hayward, P. Krishan, G. Nolan, M. Nundy, K. Ostrishko, A. Attili, S.B. Cárceles, E.I. Epelle, R. Gabl, E.J. Pappa, M. Stajuda, S. Zen, M. Dozier, N. Anderson, I.M. Viola, R. McQuillan. 2021. "Which factors influence the extent of indoor transmission of SARSCoV-2? A rapid evidence review" *Journal of Global Health* 11: 1–26. https://doi.org/10.7189/JOGH.11.10002

ISO 16000-26:2012. 2012. "Indoor air Part 26: Sampling strategy for carbon dioxide (CO2)". ISO: Geneva, Switzerland.

Italian Government. 1975. Decreto Ministeriale 18 dicembre 1975, Norme tecniche aggiornate relative all'edilizia scolastica, ivi compresi gli indici di funzionalità didattica, edilizia ed urbanistica, da osservarsi nella esecuzione di opere di edilizia scolastica.

Papadopoulos G., E.I. Tolis, G. Panaras. 2022. "IEQ assessment in free-running university classrooms" *Science and Technology for the Built Environment* 28: 823–842. https://doi.org/10.1080/23744731.2022.2052519

Serpilli F., S. Di Loreto, V. Lori, C. Di Perna. 2022. "The impact of mechanical ventilation systems on acoustic quality in school environments". Proceedings of the 52nd AiCARR International Conference "HVAC and Health, Comfort, Environment - Equipments and Design for IEQ and Sustainability”. https://doi.org/10.1051/e3sconf/202234305002

UNI EN ISO 7726:2002. 2022. "Ergonomia degli ambienti termici - Strumenti per la misurazione delle grandezze fisiche".

UNI EN 16798-1:2019. 2019. "Prestazione energetica degli edifici - Ventilazione per gli edifici - Parte 1: Parametri di ingresso dell’ambiente interno per la progettazione e la valutazione della prestazione energetica degli edifici in relazione alla qualità dell’aria interna, all’ambiente termico, all’illuminazione e all’acustica - Modulo M1-6". UNI: Milan, Italy.