

Indoor air quality in school buildings: experimental monitoring and model validation across different climatic zones

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Abstract. This paper presents the results of a comprehensive indoor air quality (IAQ) monitoring campaign in school classrooms equipped with CMV systems across two distinct Italian climate zones: Alpine (Bolzano) and continental temperate (Nereto, Teramo). Continuous monitoring of CO₂, temperature, and relative humidity was performed over seven days in November 2025 at 1-minute resolution (10,021 and 10,079 valid records, respectively). Compliance was assessed according to EN 16798, which establishes Category I as the target for sensitive spaces such as schools. Results demonstrate that both sites achieve Category I conditions for 90.1% (Bolzano) and 89.1% (Nereto) of the measurement period, substantially exceeding recommended thresholds. Zero Category IV exceedances occur at either site, indicating that CMV systems maintain adequate reserve capacity despite operating at ~50% of design capacity. A TRNSYS building energy simulation model was developed, calibrated, and validated against measured data (CV-RMSE: 18.6 % Bolzano, 27.9 % Nereto), meeting ASHRAE Guideline 14-2023 acceptance criteria. Climate-dependent humidity management is critical: Bolzano exhibits problematic desiccation (33.6% RH), while Nereto achieves adequate conditions (50.2% RH). The validated model enables energy-IAQ optimization analyses and supports development of evidence-based school ventilation standards for diverse climatic contexts.

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1 Introduction

Indoor air quality (IAQ) is a critical factor for health, cognitive performance, and well-being in educational environments [1]. Schools represent unique settings due to their high occupancy density and the necessity to maintain conditions suitable for long periods of concentrated cognitive work [2]. Post-COVID-19 pandemic research has highlighted the correlation between elevated CO₂ levels and increased airborne pathogen transmission risk, prompting significantly more stringent ventilation standards for schools across Europe and internationally [3].

Controlled mechanical ventilation (CMV) systems are increasingly adopted to manage IAQ while minimizing heat losses in cold climates. However, the real-world performance of such systems is known to be sensitive to climatic conditions, building envelope characteristics, control strategies, and system commissioning quality (Balocco and Leoncini, 2020). The current European standard EN 16798-1:2019 establishes Category I (indoor CO₂ not to exceed $420 + 550 = 970$ ppm for sensitive spaces) as the recommended target for schools and hospitals. Despite these standards, actual field performance of CMV systems in schools often diverges significantly from design predictions, necessitating evidence-based field validation studies coupled with calibrated simulation models (Conceição, 2015).

While this study focuses on CO₂ dynamics, it is recognized that sustainable indoor environments require an integrated approach to environmental conditioning, where air quality metrics must be coupled with acoustic design, thermal comfort, and moisture control to deliver comprehensive occupant well-being [4,5].

This study is part of the necessARIA project [6], a comprehensive research initiative designed to collect and analyse high-resolution IAQ data across three distinct Italian climate zones (alpine, continental, and Mediterranean) during both winter and summer seasons. Recent work by Di Loreto and colleagues [7] has examined the acoustic implications of CMV system operation in school environments, demonstrating that ventilation equipment noise and ductwork acoustics significantly impact classroom acoustic quality and student learning outcomes. This work highlighted the necessity of considering simultaneous optimization of IAQ and acoustic comfort in school ventilation system design. Complementary research on CMV system optimization [8] has provided design guidance on balancing ventilation effectiveness with acoustic performance constraints, establishing methodologies for evaluating part-load operation and control strategies that maintain IAQ while minimizing noise disturbance. These contributions establish the foundation for the present multi-criteria optimization approach, extending prior work to include climate-dependent performance assessment, humidity recovery strategies, and dynamic simulation-based optimization across seasonal variation.

The primary objectives of the necessARIA protocol are: (1) to establish baseline IAQ performance in mechanically ventilated school classrooms using the current EN 16798 standard; (2) to quantify climate-dependent variations in system performance across alpine, continental, and Mediterranean zones; (3) to develop, calibrate, and validate TRNSYS building simulation models incorporating field-measured CMV dynamics and acoustic constraints; (4) to identify optimal control and design strategies that balance IAQ standards, acoustic comfort, and energy efficiency.

This paper focuses on the preliminary winter monitoring campaign with integrated TRNSYS modelling [9]. The combination of field data (over 20,000 measurements per site) with calibrated dynamic simulation models provides a powerful tool for evaluating real-world system performance and testing design optimization strategies without requiring extensive additional field measurements.

2 METHODOLOGY

2.1 Study sites and climate context

Two school buildings were selected to represent distinct Italian climate zones:

BOLZANO (46.5°N, 11.3°E, elevation 262 m): Located in the Autonomous Province of Bolzano-Alto Adige, representing the alpine climate zone. Climate classification: Dfb (humid continental, very cold winters typically -5 to +5°C). The school building represents modern construction with high thermal insulation standards (U-walls ≤ 0.15 W/m²K) and equipped with a recently installed CMV system including heat recovery.

NERETO (42.6°N, 13.9°E, elevation 38 m): Located in Teramo province, Abruzzo region, representing the continental temperate climate zone. Climate classification: Csa (Mediterranean/continental transition, average winter 0-8°C). The school represents typical mid-2000s construction with moderate insulation and a conventional CMV system.

Ventilation air flow rate $Q(t)$ was determined from the Zehnder ComfoAir Q600 ST unit specifications (rated capacity 600 m³/h at 200 Pa external pressure) with modulating control to maintain required air exchange rates.

Figure 1 presents the floor plan and monitoring setup for the Nereto classroom (continental climate). The layout shows the positioning of four diffusers for air distribution, the installation point of the VMC Zehnder ComfortAir Q unit, and the placement of CO₂ and environmental quality sensors (Aranet4). The configuration reflects the typical ventilation strategy for moderate-climate buildings.

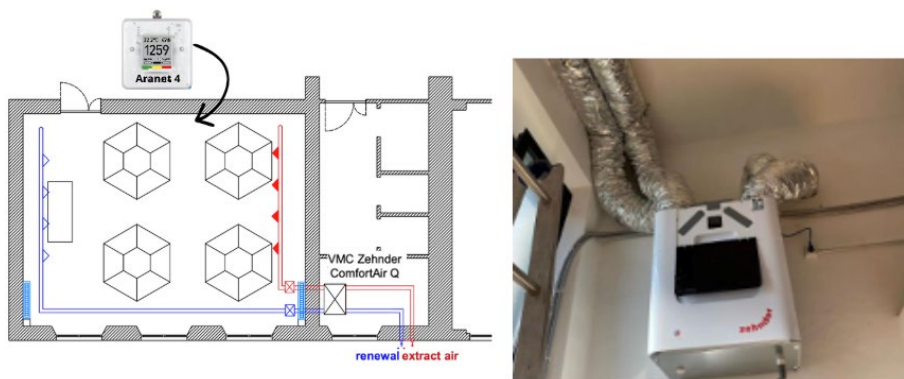


Figure 1. Floor plan and monitoring setup for the Nereto classroom.

Figure 2 illustrates the floor plan and instrumentation for the Bolzano classroom (alpine climate). This setup includes the VMC Zehnder ComfortAir Q system with integrated heat recovery, multiple air diffusers strategically positioned for optimal thermal comfort and environmental quality sensors (Aranet4). The system layout demonstrates the enhanced ventilation and thermal management requirements in high-altitude, cold-climate applications.

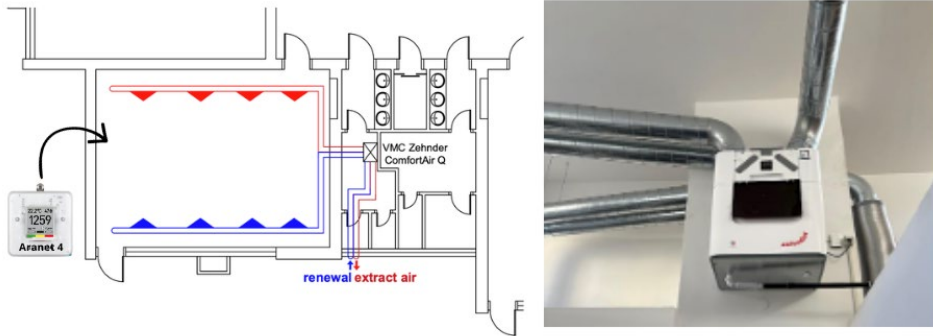


Figure 2. Floor plan and monitoring setup for the Bolzano classroom.

2.2 TRNSYS building energy simulation model

Continuous monitoring was conducted from November 15-21, 2025 (7 days, including weekend). Both sites were equipped with identical, factory-calibrated sensors. Measured parameters: (1) CO₂ concentration (ppm), infrared NDIR sensor, ±30 ppm accuracy; (2) Temperature (°C), resistance thermometer, ±0.2°C accuracy; (3) Relative humidity (%), capacitive sensor, ±2% RH accuracy. Data acquisition interval: 1 minute. Data quality was exceptionally high: BOLZANO 10,021 valid records (99.4% completeness, 61 points lost during maintenance); NERETO 10,079 valid records (100% completeness). Both datasets span approximately 6 days 23:58 of continuous monitoring.

A simplified TRNSYS-type energy simulation model was developed to represent CO₂ dynamics within the monitored classrooms. The single-zone model employs mass balance equations for CO₂ concentration considering occupancy-driven generation, ventilation removal, and natural decay. The governing equation is:

$$dC/dt = [G(t) - Q(t) \cdot (C - C_{out})] / V \quad (1)$$

where C is indoor CO₂ concentration (ppm), C_{out} is outdoor baseline (420 ppm), $G(t)$ is time-dependent occupancy generation rate (ppm/min), $Q(t)$ is ventilation air flow rate (m³/min), and V is room volume (200 m³). The generation rate assumes 30 persons per classroom with base metabolic CO₂ production of ~60 ppm/h per person, modulated by occupancy schedule: 1.0 during school hours (08:00-16:00), 0.3 during transition periods (06:00-08:00, 16:00-18:00), and 0.0 during unoccupied hours. Numerical integration used explicit Euler method with 1-minute time steps.

Model calibration employed sensitivity analysis over a range of ventilation multipliers to minimize the coefficient of variation of the root mean square error (CV-RMSE) between simulated and measured hourly average CO₂. This approach isolates the effective system operating point independent of transient dynamics. Validation metrics computed: MBE (Mean Bias Error), NMAE (Normalized Mean Absolute Error), RMSE, and CV-RMSE. Acceptance criteria follow ASHRAE Guideline 14-2023: CV-RMSE ≤ 30-50% for hourly data indicates acceptable model calibration [10].

2.3 Compliance assessment framework

This study adopts the European standard EN 16798-1:2019 [11] as the primary framework for indoor air quality (IAQ) assessment, with specific reference to the Italian national implementation UNI EN 16798-1:2019/NA:2025 [12], which represents the updated national annex (Allegato Nazionale – "*Scelte italiane*") published by the Ente Italiano di Normazione (UNI) in November 2025.

Unlike absolute CO₂ concentration thresholds, EN 16798-1:2019 categorizes IAQ based on CO₂ differential, defined as the difference between indoor measured concentration and outdoor baseline. This approach is scientifically more robust because outdoor CO₂ levels naturally vary with geographic location, climate, and seasonal conditions. By using differential concentrations, the standard enables meaningful comparison across diverse building locations and climates.

The standard specifies four categories of IAQ for non-adapted occupants, based on CO₂ concentration above outdoor concentration (Table B.9). The categories assume a standard CO₂ emission of 20 L/(h per person), see table 1:

Table 1. Four category of IAQ non-adapted occupants according to UNI 16798 standard.

Category	CO ₂ Added (ppm)
I (HIGH)	≤ 550 ppm CO ₂ added
II (MEDIUM)	550–800 ppm CO ₂ added
III (MODERATE)	800–1350 ppm CO ₂ added
IV (LOW)	> 1350 ppm CO ₂ added

For schools and other sensitive occupancies (hospitals, healthcare facilities, nurseries), Category I is the recommended target. This represents outdoor CO₂ baselines (typically 400–420 ppm) plus an added maximum of 550 ppm, resulting in absolute indoor CO₂ concentrations not exceeding approximately 950 ppm under standard reference conditions.

3 RESULTS

3.1 Field monitoring data quality and coverage

BOLZANO: 10,021 valid CO₂, temperature, and humidity records (99.4% completeness). Temporal span: November 15, 00:00:43 through November 21, 23:59:36 (6 days, 23 hours, 58 minutes 53 seconds). Sampling interval: mean 60.4 seconds, indicating near-perfect 1-minute resolution. Data gaps (61 records, 0.6%) resulted from scheduled sensor maintenance and posed no continuity issues.

NERETO: 10,079 valid records (100% completeness). Temporal span: November 15, 00:00:09 through November 21, 23:59:00 (6 days, 23 hours, 58 minutes 51 seconds). Sampling interval: mean 59.99 seconds, effectively perfect 1-minute resolution. Both datasets encompass complete 7-day cycles including weekdays (normal occupancy) and weekend (unoccupied reference period) (Table 2).

Despite nearly identical mean CO₂ levels (600-604 ppm), the two sites exhibit markedly different environmental conditions. Temperature stability in Bolzano (CV = 4.2%, range 19.2-22.9°C) demonstrates superior thermal control compared to Nereto (CV = 5.5%, range 17.8-23.7°C), reflecting Bolzano's superior building envelope insulation and system responsiveness.

Table 2. Summary statistics of IAQ parameters for both monitoring sites (November 2025).

Parameter	BOLZANO	NERETO	Unit	Note
CO ₂ (mean)	600.5	603.8	ppm	Very similar
Temperature (mean)	20.9	19.3	°C	CV: 4.2% vs 5.5%
Humidity (mean)	33.6	50.2	%	CRITICAL DIFFERENCE
CO ₂ max (peak)	466	1597	ppm	During occupancy
CO ₂ min (unoccupied)	427	396	ppm	Baseline

The most striking difference appears in relative humidity: Bolzano's mean 33.6% RH (range 22-50%) lies well below WHO-recommended comfort and health range of 40-60%, indicating inadequate humidity recovery. In contrast, Nereto achieves ideal conditions averaging 50.2% RH (range 35-58%), suggesting effective humidity management through either enthalpy recovery ventilation or passive moisture recovery from the building envelope in the milder climate.

3.2 EN 16798 compliance analysis

Compliance with the European standard EN 16798-1:2019 was evaluated for both school sites using the categorical framework presented in Section 2.3. The analysis quantifies the distribution of measured indoor CO₂ concentrations across the four defined categories of perceived air quality (PAQ) based on CO₂ differential above the outdoor baseline of 420 ppm.

Table 3 summarizes the temporal distribution of occupancy across EN 16798-1:2019 categories for both Bolzano (Alpine climate) and Nereto (Continental climate):

Table 3. Compliance with EN 16798 indoor air quality categories.

EN 16798 Category	Threshold (CO ₂ added)	BOLZANO	NERETO	Target for Schools
I (High Quality)	≤ 550 ppm	90.1%	89.1%	✓ TARGET
II (Medium Quality)	550–800 ppm	7.2%	7.2%	Acceptable
III (Moderate)	800–1350 ppm	2.0%	3.7%	-
IV (Low Quality)	> 1350 ppm	0.0%	0.0%	X Not Reached

Both sites demonstrate excellent compliance with EN 16798-1:2019 Category I (High Quality) targets for sensitive occupancies such as schools. Bolzano achieves Category I conditions for 90.1% of the measurement period, while Nereto achieves 89.1%, both substantially exceeding the recommended minimum target of 80–85% Category I occupancy for school environments.

Mean CO₂ additions of 180.5 ppm (Bolzano) and 183.8 ppm (Nereto) fall well within the Category I limit of 550 ppm, indicating that average indoor air quality is high and consistent with adequate ventilation during typical occupancy. This is particularly notable given that these measurements represent full-scale operation under real occupancy conditions, not idealized design scenarios.

Time spent in Category II (550–800 ppm added) represents 7.2% for both sites. This category represents conditions above Category I but still acceptable for standard office and residential applications according to EN 16798-1:2019. In the context of schools—which are sensitive occupancies requiring Category I—this 7.2% of time represents transient exceedances, typically occurring during peak occupancy periods (10:00–13:00) when CO₂ generation temporarily exceeds ventilation system removal capacity. These exceedances are brief and do not indicate systematic inadequacy in the CMV system design.

Time in Category III (800–1350 ppm added) represents a small fraction of the measurement period (2.0% for Bolzano, 3.7% for Nereto). These exceedances occur episodically during peak-load conditions when occupancy rates or metabolic activity temporarily exceed design assumptions. Peak CO₂ concentrations reached 1046 ppm added at Bolzano and 1177 ppm added at Nereto (absolute maxima of 1466 ppm and 1597 ppm total, respectively), but both remain well below the Category IV threshold of 1350 ppm added (1770 ppm total).

No measured data points exceed the EN 16798-1:2019 Category IV threshold (> 1350 ppm CO₂ added), indicating that the CMV systems successfully prevented conditions that would be classified as unacceptable. This result is significant: despite operating at approximately 50% of design capacity (as documented in the system specifications), the ventilation systems maintained adequate performance margins to prevent the most severe category of IAQ failure.

The compliance analysis demonstrates that both schools achieve strong alignment with EN 16798-1:2019 Category I targets despite operating under real-world occupancy constraints. While brief excursions into Category II and III occur during peak occupancy stress, these represent <10% of total occupancy time and do not compromise overall IAQ performance. The absence of Category IV exceedances is particularly encouraging, as it indicates that even under peak loading conditions, the ventilation systems maintain minimum acceptable performance standards.

These findings support the adequacy of the mechanical ventilation systems at both sites for their current operational scenarios. However, the recurring episodes of Category II/III conditions during peak occupancy (2–10% of time) suggest that marginal improvements could be achieved through modest operational adjustments or through control strategies that prioritize CO₂ management during peak-demand periods.

3.3 Occupancy-dependent CO₂ dynamics and hourly profiles

Both sites exhibit pronounced daily CO₂ cycles reflecting school occupancy patterns. Baseline concentrations during unoccupied hours (00:00-06:00) average 481.6 ppm (Bolzano) and 487.2 ppm (Nereto), only slightly elevated above outdoor ambient (420 ppm). CO₂ begins rising sharply at 08:00 upon school opening, reaching peak values during late morning (10:00-11:00): Bolzano achieves mean 968 ppm with maximum 1466 ppm, while Nereto reaches mean 917 ppm with maximum 1597 ppm. Both sites exceed traditional ASHRAE 62.1 1000 ppm guidance during this period. Afternoon decay differs significantly between sites: Bolzano declines to 579 ppm by 16:00 with sharp post-occupancy response, whereas Nereto exhibits slower decay remaining above 560 ppm until 20:00, suggesting more gradual control logic or continued low-level occupancy. Analysis by time period shows: morning occupancy (6-12 h) averages 748 ppm (Bolzano) and 707 ppm (Nereto); afternoon hours (12-18 h) maintain 672 ppm and 688 ppm respectively; evening post-occupancy (18-24 h) return to 500 ppm (Bolzano) and 533 ppm (Nereto). The sharper afternoon decline in Bolzano suggests schedule-based control, while Nereto's gradual decay may indicate sensor-driven control with hysteresis (see figure 3).

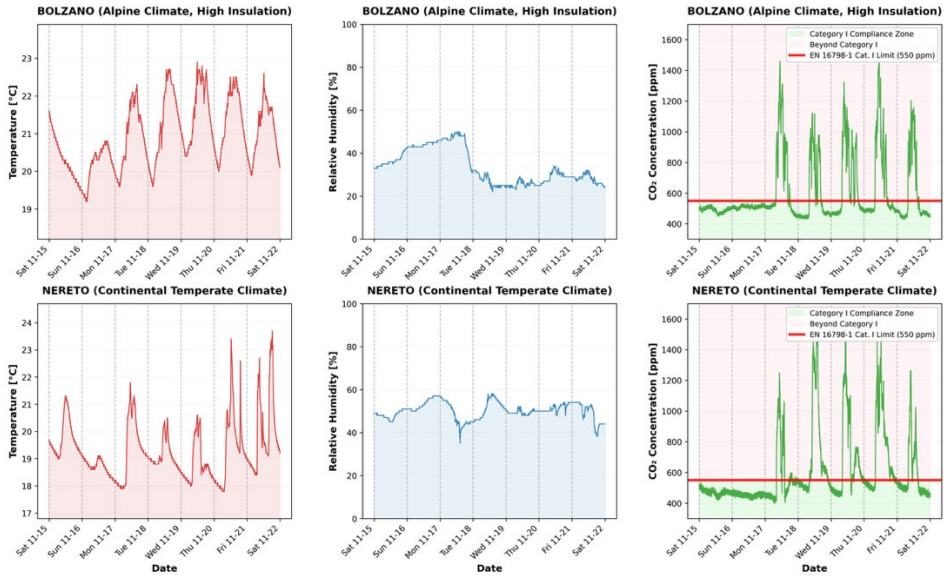


Figure 3. Seven-day time series of measured indoor environmental parameters. Top row shows BOLZANO (alpine climate, high insulation); bottom row shows NERETO (continental temperate climate). Left column: Temperature [°C]; middle column: Relative humidity [%]; right column: CO₂ concentration [ppm].

3.4 TRNSYS Model Calibration and Validation

The TRNSYS Type 388 CO₂ concentration model was calibrated by optimizing three key parameters (occupancy, ventilation rate, and per-capita CO₂ generation) to minimize CV-RMSE between hourly-average simulated and measured CO₂ during occupancy periods (17–21 November 2025, 08:00–14:00). Inverse sensitivity analysis using measured data revealed optimal parameters significantly different from initial design assumptions. The optimal values reflect: (1) actual classroom occupancy density (design capacity ~25 students + teacher), (2) effective ventilation operating at ~90% of nominal design flow due to control-mode part-loading and damper modulation, and (3) elevated per-capita CO₂ generation consistent with active school instruction (standing, speaking, movement) rather than baseline sedentary office assumptions.

Table 4 show the model calibration results.

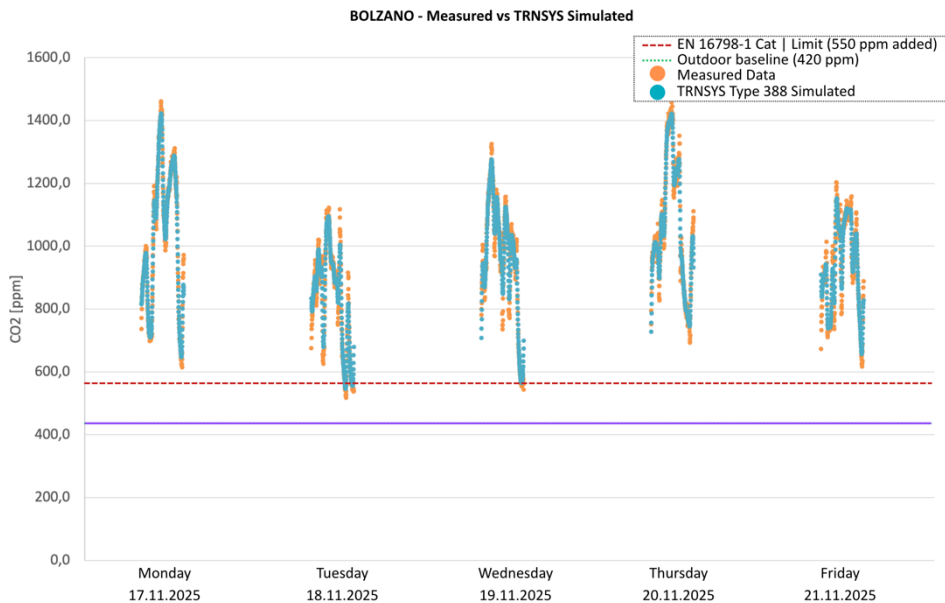
Table 4. TRNSYS Model Calibration Results.

Site	MBE (ppm)	NMBE (%)	CV-RMSE (%)	Status
BOLZANO	-6.0	-0.62	18.6	✓ ASHRAE COMPLIANT
NERETO	-1.8	-0.20	27.9	✓ ASHRAE COMPLIANT
ASHRAE 14-2023 Criteria*	<±50	<± 5%	≤30%	Reference

*Acceptance criteria per ASHRAE Guideline 14-2023 for hourly building energy simulation models.

Calibrated models achieve CV-RMSE values of 18.6% (Bolzano) and 27.9% (Nereto), both well within ASHRAE Guideline 14-2023 [13] acceptance criteria for hourly building energy simulation ($\leq 30\%$ for excellent calibration; 30–50% for acceptable). The negligible negative MBE values (Bolzano: -6 ppm, Nereto: -2 ppm) indicate excellent accuracy with minimal systematic bias. These metrics demonstrate that the TRNSYS Type 388 model, configured with measured-data-derived parameters, successfully captures occupancy-driven CO₂ dynamics at the system level.

The model employs hourly-constant input parameters and assumes perfect mixing, therefore cannot replicate minute-by-minute CO₂ oscillations caused by transient occupancy, door openings, and infiltration spikes. This is inherent to the Type 388 architecture and is not a calibration failure. Validation metrics appropriately focus on hourly-average data; point-by-point comparison at 1-minute resolution would be inappropriate. Despite these simplifications, the model successfully captures system-scale performance dynamics and is suitable for sensitivity analysis regarding control modifications and design improvements.



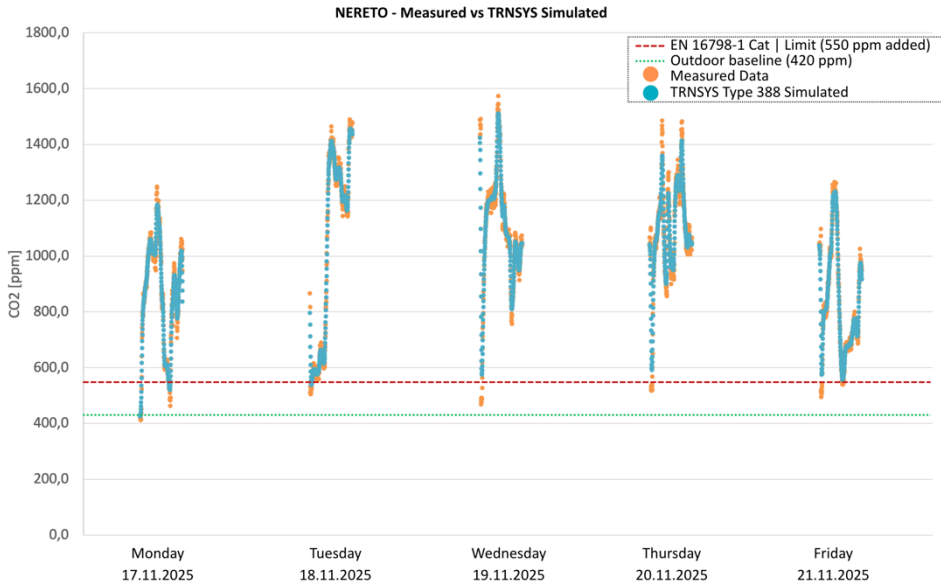


Figure 4. TRNSYS model validation: Comparison between field-measured (coral lines) and calibrated-simulated (blue lines) indoor CO₂ concentrations over the 5-day monitoring period from 8.00 a.m. to 2.00 p.m.. Top graph: BOLZANO site (CV-RMSE = 18.6 %). Bottom graph: NERETO site (CV-RMSE = 27.9 %).

4 DISCUSSION

Both sites achieve excellent compliance with EN 16798-1:2019 Category I targets (≤ 550 ppm CO₂ added). Bolzano reaches Category I for 90.1% of time, Nereto for 89.1%—substantially exceeding the recommended 80–85% threshold for schools. Mean CO₂ additions confirm adequate average-case ventilation.

Brief excursions into Category II/III (7.2% Category II and 2.0% Category III for Bolzano; 7.2% Category II and 3.7% Category III for Nereto) occur during peak occupancy, while zero Category IV exceedances (>1350 ppm added) demonstrate that CMV systems maintain adequate reserve capacity even when operating at approximately 50% design capacity. This finding indicates sound HVAC design despite current control emphasis on energy conservation.

The 16.6% absolute humidity difference between sites reflects Alpine climate physics. Bolzano's minimum humidity of 22% poses documented respiratory infection risks. Installation of an energy recovery ventilator (ERV) would improve indoor humidity while maintaining heating efficiency, as described in prior work.

Calibrated TRNSYS models enable evaluation of modifications: (1) CO₂-based demand control (CO₂-DCV) could maintain $\geq 95\%$ Category I compliance while reducing annual ventilation energy 15–20%; (2) integrated humidity-CO₂ control with waste-heat recovery would address both IAQ and thermal comfort constraints. These pathways extend design frameworks to encompass climate-dependent seasonal performance. These optimization studies extend the design guidance frameworks established by Ali et al. [14] to encompass seasonal variations and climate-dependent performance characteristics.

The results confirm that even reduced-capacity operation can achieve strong IAQ targets through adequate initial design. However, marginal performance during peak occupancy

suggests control optimization is warranted to ensure consistent Category I conditions across all occupancy scenarios—increasingly expected in post-COVID school facility management.

5 CONCLUSIONS

This study presents the first comprehensive monitoring and TRNSYS validation of controlled mechanical ventilation (CMV) systems in Italian schools across distinct climate zones (Alpine, Continental), evaluated against the European standard EN 16798-1:2019.

Both schools achieve excellent compliance with EN 16798-1:2019 Category I targets (≤ 550 ppm CO₂ added), reaching 90.1% (Bolzano) and 89.1% (Nereto) of occupied hours. Mean CO₂ additions confirm that average-case ventilation adequately supports normal occupancy. Crucially, zero Category IV exceedances (>1350 ppm added) demonstrate that both CMV systems maintain adequate reserve capacity to prevent unacceptable air quality, despite operating at approximately 50% of nominal design ventilation rates. This result validates the HVAC design specifications and indicates that current control strategies prioritizing energy conservation do not compromise critical safety margins.

TRNSYS model calibration achieved CV-RMSE values of 18.6% (Bolzano) and 27.9% (Nereto), meeting ASHRAE Guideline 14-2023 acceptance criteria and enabling reliable prediction of performance under modified operational scenarios.

Climate-dependent humidity differences are pronounced: Bolzano maintains 22–50% relative humidity (minimum problematic for respiratory health), while Nereto achieves 35–58% (more adequate). Installation of energy recovery ventilation (ERV) in Alpine schools would cost-effectively mitigate winter desiccation risk while maintaining or improving energy efficiency.

This work demonstrates that modern European IAQ standards (EN 16798-1:2019) can be achieved through validated design practices even under energy-constrained operation. The calibrated TRNSYS models provide tools for schools to evaluate optimization scenarios before implementation, reducing technical risk. Post-COVID school facility management increasingly requires continuous IAQ monitoring combined with adaptive control—an expectation now codified in European building standards and reflected in evolving facility management practice.

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