Impact of filter class and airflow control on the indoor airborne particles in a nursery school

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ABSTRACT

This study focuses on the impact of filtration efficiency level and airflow control, based on CO_2, on indoor air quality described by particle concentration in an urban low energy consumption nursery school during an autumn and a winter period. Measurements of indoor and outdoor particle concentrations have been carried out by using three different filter efficiency configurations in the school equipped with a balanced ventilation system with heat recovery. The tested filters are respectively classed G4, M5 and F7 according to NF EN 779 (2012). Some simulations were conducted to replicate the measurement configuration of the school equipped with G4+F7 filter configuration and to serve as a basis for the simulations with airflow control. The simulations were carried out using CONTAM multi-zone simulation tool. Measured particle concentration values have been used for the calculation of the filtration efficiency and the indoors to outdoors particle concentration ratio (I/O), the simulations boundary condition and simulations validations. The measurement results show that the efficiency on the finest particles (diameters lower than 1 μm) with G4 filter is very low, near zero, while with the G4+M5 and G4+F7 configurations the efficiency is slowly and considerably increased, at respectively about 20 to 50% and 82 to 90%, depending on the measurement day and particle diameters. For particles of diameter less than 1μm, the I/O ratio decreases as the filtration efficiency increases. But for larger particles, the I/O ratio is higher and increases when the particle size considered increases and is higher when children are present in the classrooms.

The aim of the control of airflow based on CO_2 levels is to optimize indoor air quality and energy consumption by automatically adjusting airflow according to real-time needs in the classrooms. This can help to maintain acceptable CO_2 levels and reduce airborne particle concentrations, creating a healthier environment for kindergarten occupants. Simulations using CONTAM validated the model, showing that reducing airflow by 41% increased peak CO_2 by 25% and 0.4/2.5 μm particles by 19-35%, while demand-controlled ventilation based on CO_2 maintained CO_2 levels below threshold with only a 5.7% airflow increase, reducing 2.5 μm particles by 12.4%.

This research provides useful data for optimising indoor air quality in urban nursery schools using appropriate filters and intelligent control of airflow according to CO_2 levels.

KEYWORDS

ventilation, air filtration, school, particles concentration, IAQ, CO_2, control

1 INTRODUCTION

Children spend a significant part of their time in schools, and the quality of the indoor air in these environments can have a profound impact on their health, cognitive performance, and concentration levels. Studies have consistently shown that well-ventilated spaces contribute to the reduction of airborne pollutants, leading to improved concentration and enhanced learning outcomes (Wargocki & Wyon, 2007), (Wargocki & Wyon, 2017); (Sadrizadeh, et al., 2022); (Daisey, Angell, & Apte, 2003). Traditional ventilation systems, however, can introduce pollutants from outdoor and can be energy-intensive, affecting health, operational costs, and environmental sustainability.

To address the challenges of energy consumption and indoor air quality, integrating energy-efficient ventilation solutions has become crucial (Fisk, 2000), (Emmerich & Persily, 2001). These solutions, such as demand-controlled ventilation (DCV) and energy recovery ventilation, aim to regulate airflow according to real-time demand signals. DCV strategies involve adjusting ventilation airflows based on factors such as indoor air quality (IAQ) or energy efficiency (Guyot, Sherman, & Walker, 2018), thereby reducing energy consumption for fan operation and heating/cooling compared to traditional constant air volume (CAV) systems (Merema, Delwati, Sourbron, & Breesch, 2018). In certain European school buildings, DCV systems were deployed, utilizing control systems that respond to real-time signals such as CO_2 levels or temperature. Studies have shown significant energy savings achieved through DCV compared to CAV systems. For instance, research conducted across Norwegian school buildings reported a substantial decrease in energy demand, with reductions in heating energy demand and fan usage energy (Mysen, Berntsen, Nafstad, & Schild, 2005), (Wachenfeldt, Mysen, & Schild, 2007). Similarly, in Belgian educational buildings, DCV implementation resulted in significant reductions in fan energy consumption and ventilation heat loss while maintaining comparable CO_2 levels to CAV systems (Merema, Delwati, Sourbron, & Breesch, 2018).

Balanced ventilation systems with heat recovery can be used in buildings to reduce energy consumption. These systems typically incorporate air filters to protect the heat exchanger (on the fresh air and exhaust air sides) and to enhance the quality of the supplied air. The selection of these filters requires careful consideration to balance air quality benefits against energy consumption due to the pressure drop associated with filter use (Liu, et al., 2017). Several studies have investigated the impact of different filter types on indoor air quality and overall system performance. Some authors (Carlsson, 2008) show that achieving optimal filtration requires adjustments in airflow rate, building envelope airtightness, and filter cassette sealing. With the 2000 construction techniques, it was challenging to exceed F7 filtration efficiency. Considering infiltration and exfiltration, an F7/MERV13 filter class is deemed necessary, while M6/MERV12 is insufficient. Additionally, research has explored filter placement strategies to optimize both air quality and energy efficiency in buildings equipped with balanced ventilation systems. In study by Ginestet et al. (Ginestet, Pugnet, & Mouradin, 2013), the performance of various air filters in balanced ventilation systems was assessed. From an energy consumption perspective, the authors emphasized the advantage of employing an F7 filter, protected by a G4 pre-filter upstream, rather than using the F7 filter alone. This configuration results in a lower pressure drop increase over time while maintaining satisfactory filtration efficiency. Ginestet et al. (Ginestet, Pugnet, & Robitu, 2015) explored the impact of filtration efficiency on particle concentration in a rural school equipped with a balanced ventilation system. Three filters (G4, F7, F9) were tested, revealing lower efficiency for G4 on particles <1 μm, whereas F7 and F9 demonstrated superior efficiency, ranging from 47 to 55% and 82 to 87% at 0.4 μm, respectively. During school occupancy, the indoor-to-outdoor (I/O) ratio remained similar as when the school was unoccupied for particles <0.5 μm but increased as the particle size increased and as the filter class decreased, sometimes exceeding 1. Overall, the use of F7 or F9 filters in the school's ventilation system effectively protects occupants from harmful and abundant outdoor particles (<1 μm) with the I/O ratio consistently below 1.

Recently, Cabovská et al. (Cabovská, Bekö, Teli, Ekberg, & Dale, 2022) studied how different ventilation strategies impact IAQ in schools. The study involved measuring thermal conditions and IAQ over 5 days in 45 primary school classrooms in Gothenburg, Sweden. Classrooms were categorized into three ventilation systems: natural/exhaust ventilation or automated window opening (A), balanced mechanical ventilation with CAV (B), and VAV (C). Both category B and C were equipped with filters class F7. Regardless of ventilation system, classrooms maintained similar temperature and humidity levels. Lower levels of CO_2, formaldehyde, PM10, and PM2.5 were obtained with categories B and C compared to A. The authors calculated the Indoor Air Pollution Index, IAPI (Sofuoglu & Moschandreas, 2003), which quantifies indoor air pollution levels from 0 (lowest) to 10 (highest) based on measured pollutant concentrations relative to minimum, maximum, and guideline limits. They found significantly higher IAPI values indicating poorer IAQ in category (A) classrooms. Despite periodic reductions in VAV system ventilation rates (category C classroom), pollutant concentrations did not substantially increase.

Alonso et al. (Alonso, Dols, & Mathisen, 2022) developed a co-simulation model, EnergyPlus-CONTAM, to assess ventilation strategies including DCV methods. The study focused on an office building in Trondheim, Norway, typically ventilated with 100% outdoor air. Results indicated that all simulated DCV strategies reduced energy consumption compared to a baseline schedule-based approach. However, CO_2-based DCV led to increased indoor particulate levels, mitigated by PM2.5 monitoring in ventilation control strategies. Overall, the study suggests that adjusting outdoor air fraction based on pollutant levels and local conditions can enhance both energy efficiency and indoor air quality.

Carbon dioxide (CO_2) concentration is commonly used to evaluate ventilation adequacy (Persily, 2015), and many DCV systems rely solely on it to assess IAQ (Fisk & De Almeida, 1998), (Gram, 2019). While CO_2 can offer a general indication of IAQ, it does not account for other potential indoor pollutants (Apte, Fisk, & Daisey, 2000). Consequently, occupants may experience poor IAQ due to these other pollutants, even when CO_2 levels are within acceptable ranges (Chao & Hu, 2004).

This study focuses on the impact of filtration efficiency level and airflow control based on CO_2 levels on indoor air quality, specifically the particle concentration, in an urban low energy consumption nursery school during autumn and winter periods. The study aims to provide valuable data for optimizing indoor air quality in urban nursery schools using appropriate filters and intelligent control of airflow according to CO_2 levels.

2 MEASUREMENT AND SIMULATION METHODS

2.1 Measurements

Measurements with three filtration levels were performed in winter and autumn in a recent low energy consumption nursery school equipped with a mechanical ventilation system with heat recovery. The three types of filters are respectively classed G4, M5 and F7 according to NF EN 779 (2012).

The recent low energy consumption nursery school, built in 2012, is located in Villeurbanne, France, in an urban environment (see Figure 1a). It was designed to accommodate the staff and around 230 children from Monday to Friday, except Wednesday afternoons, in 8 classrooms, 2 sports rooms and 3 sleeping rooms, spread over two floors.

The school is ventilated by a balanced mechanical ventilation system with heat recovery between the incoming and outgoing air (see Figure 1b). To ensure good indoor air quality and prevent the entry of pollutants, particulates and pollen, the ventilation system is equipped with a multi-stage filtration system. Specifically, the system utilizes class G4 pleated filters and F7 V-bank filters (as per NF EN 779 (2012) standard) for the filtration of the incoming fresh air. Additionally, class G4 pleated filters are installed on the exhaust air flow to capture pollutants before the air enters in the heat recovery. The fresh air is diffused within the classrooms via ceiling diffusers and is extracted via ceiling grilles. The airflow is dynamically adjusted based on CO_2 levels measured within the classrooms.

a) b) c) d)

Figure 1: Photos of the school, AHU and filter. a) classroom, b) ventilation system, c) filter G4, b) filter F7

For this study, we conducted measurements using varying levels of filtration on the incoming air. Specifically, we tested three different filter configurations: G4, G4+M5, and G4+F7. Figure 1c and Figure 1d show the photos of the tested G4 and F7 class filters.

The measurements were carried out during autumn and winter using the same methodology as described by Ginestet et al. (Ginestet, Pugnet, & Robitu, 2015). This involved conducting measurements over a period of three consecutive days per week for three consecutive weeks in September and October 2015, as well as in January and February 2016. During these measurements, air flow was controlled and monitored periodically, with air velocity measured in straight sections of the ducts to maintain a constant air flow rate between 5000 and 5300 m^3/h (corresponding to an air exchange rate (ACH) of 1.6 to 1.7 h^{-1}). During the measurement periods, the air flow was kept constant and well balanced between supply and extract.

Particle concentrations ranging from 0.3 to 10 µm in size were measured using an optical particle counter. These measurements were conducted continuously and alternately at three key points within the ventilation system: at the inlet, representing outdoor air (O); at the outlet, within the delivered air duct, representing air being diffused indoors (S); and inside the exhaust air duct, representing air extracted from the indoor environment (I). These particle concentration values served two main purposes: first, for calculating in-situ filtration efficiency (E) by comparing particle concentrations measured in the fresh air duct (O) with those in the delivered air duct (S); and second, for determining the indoor-to-outdoor (I/O) particle concentration ratio. This ratio offers valuable insights into the extent of indoor particle pollution relative to outdoor conditions.

For each filtration level under investigation (G4, G4 + M5, and G4 + F7), measurements were taken once a week, with the day of measurement changing weekly. This resulted in three days of measurements for each filtration level studied. The filters were installed the day before the measurements, typically in the late afternoon. Normally, throughout the measurement period, the doors and windows of the school remained closed to maintain consistent testing conditions.

Additionally, prior to installation in-situ, the performance of the filters, including pressure drop and spectral efficiency in capturing DEHS (Di-Ethyl-Hexyl-Sebacat) particles, was measured in the laboratory. The test air flow rate in the laboratory was set at 3500 m^3/h.

2.2 Simulations

Simulations of air and pollutant transfers, including particles and CO_2 from outside and CO_2 emitted by occupants were conducted using multizone CONTAM software developed by the U.S. National Institute of Standards and Technology (NIST) (Dols & Polidoro, 2020).

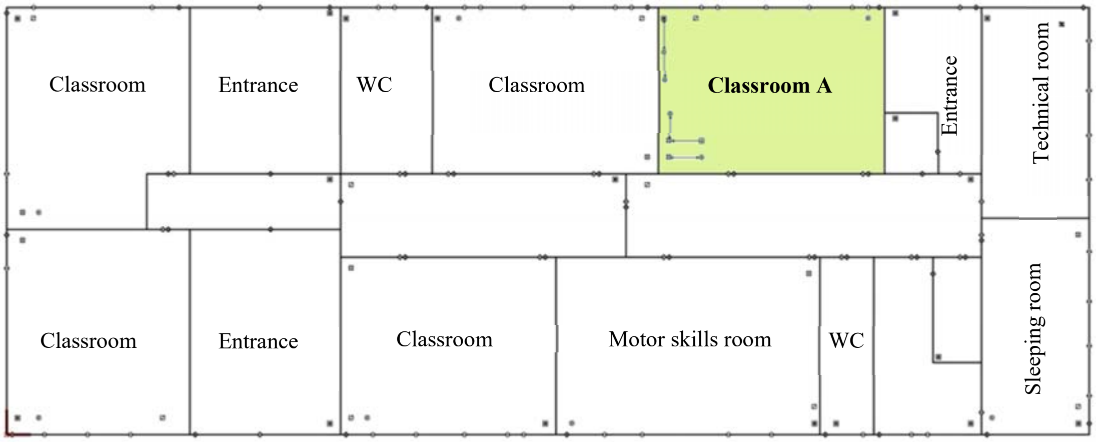


Figure 2: CONTAM model of the school floor

Modelling was conducted on one of the two floors of the school, and flow control was implemented only in classroom A, while the others are held constant. The results are presented solely for this classroom. The modelled floor (see Figure 1), covering an area of approximately 730 m^2 and a volume of around 2200 m^3, comprises 5 classrooms, 1 motor skills room, 1 rest area, and accommodates approximately 150 children. The floor is ventilated by the balanced mechanical ventilation system, with a constant ventilation rate for classroom A set at 343 m^3/h (corresponding to 5.96 L/s per person and an ACH of 1.91 h^{-1}), determined via the decay method based on CO_2 reference measurements, Tuesday, September 22. The remaining airflow, up to 3167 m^3/h, is distributed among the other rooms on the floor according to their volume. Initial simulations were based on particle and CO_2 concentration measurements conducted within the school premises. Outdoor air particle concentrations of 0.4 and 2.5 µm mean diameter, and the average filtration efficiency by particle size of the G4+F7 configuration determined from on-site measurements (80% (0.4 µm) and 90% (2.5 µm)), were used as input data. Indoor (I) and exhaust (E) air concentrations were utilized for result validation and calibration. Occupancy schedule and the number of occupants (maximum 12 children and the teacher) were retrieved from CO_2 measurements over a day. Students typically arrive in classroom at around 8:20 a.m., go out for recess twice in the morning, once at noon, and leave the classroom at around 4 p.m. Particle deposition was modelled for 0.4 and 2.5 µm particles with deposition rates of 2.50E-06 L/s and 6.00E-05 L/s respectively (Lai & Nazaroff , 2000). Resuspension was modelled using a model with a generation rate determined iteratively to match simulation results with measurement data. Significant resuspension of 0.4 µm particles was observed in the morning, potentially during cleaning and window opening before children's arrival. For 2.5 µm particles, a similar evolution with CO_2 was observed. Resuspension was modelled with a constant coefficient generation source of 0.193 µg/s weighted by presence and activity. The air temperature for both classroom A and the outdoors is considered at 20°C.

The internal and external openings include interior doors and undercutting, exterior windows, and external leakages. The doors of the classrooms are considered closed during the simulations. The external leakages simulate the infiltration between the zones and was modelled with an envelope permeability of 0.8 $m^3/(h \cdot m^2)$@4Pa. The exterior window is always closed, while the interior doors are open 1 hour to simulate class break. The ventilation system includes AHU (1), air supply (2) and extract (3) to each zone. The air handling unit is set up considering filters. The simulations are done using 12 children plus one teacher, to recreate the actual conditions. Each occupant is assigned with a CO_2 contaminant generation. The children are expected to be in medium activity (1.4 met), and between age 4-5. According to Batterman (Batterman, 2017), this group has a CO_2 averaged emission rate of 0.147 L/min.

To assess the impact on CO_2 and particle concentrations and to simulate the modulation of airflow based on CO_2, simulations were conducted with and without airflow regulation based on CO_2 levels inside classroom, A, (with an area of 60 m^2). Therefore, three simulations were performed with ventilation rates: 1) constant (cst 1) from measurements, 2) constant - minimum required and 3) modulated based on instantaneous CO_2 levels. For the case 2, the airflow rate in classroom A was assumed to be approximately equal to the minimum regulatory airflow rate in France, 200 m^3/h (15 m^3/h per occupant in kindergarten). For the case 3, the airflow rate is controlled by CO_2 levels. If $CO_2 < 800$ ppm, the airflow rate is 200 m^3/h, and if it exceeds this threshold, the rate is increased to 400 m^3/h.

3 RESULTS AND DISCUSSION

3.1 Measurement results

Figure 3 shows the filter efficiency under both laboratory (lab) and in-situ conditions. Comparisons between these two sets of data are viable as the airflow rate per filter remains similar across both testing environments. The in-situ values, as shown in Figure 3, represent an average derived from the three days measurements for each filter. The results indicate that the in-situ filtration efficiency closely aligns with that observed in laboratory settings (refer to Figure 3), suggesting proper installation within the air handling unit with minimal leaks. As expected, G4 filters exhibit notably low efficiency for particles smaller than 1 µm, nearly approaching zero. However, with the G4+M5 and G4+F7 configurations, efficiency gradually and significantly increases, reaching approximately 28 to 96% with the G4+M5 configuration and 82 to 99% with the G4+F7 configuration, depending on particle diameters.

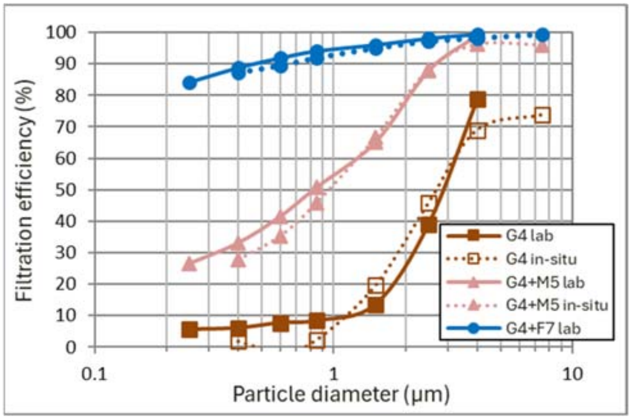
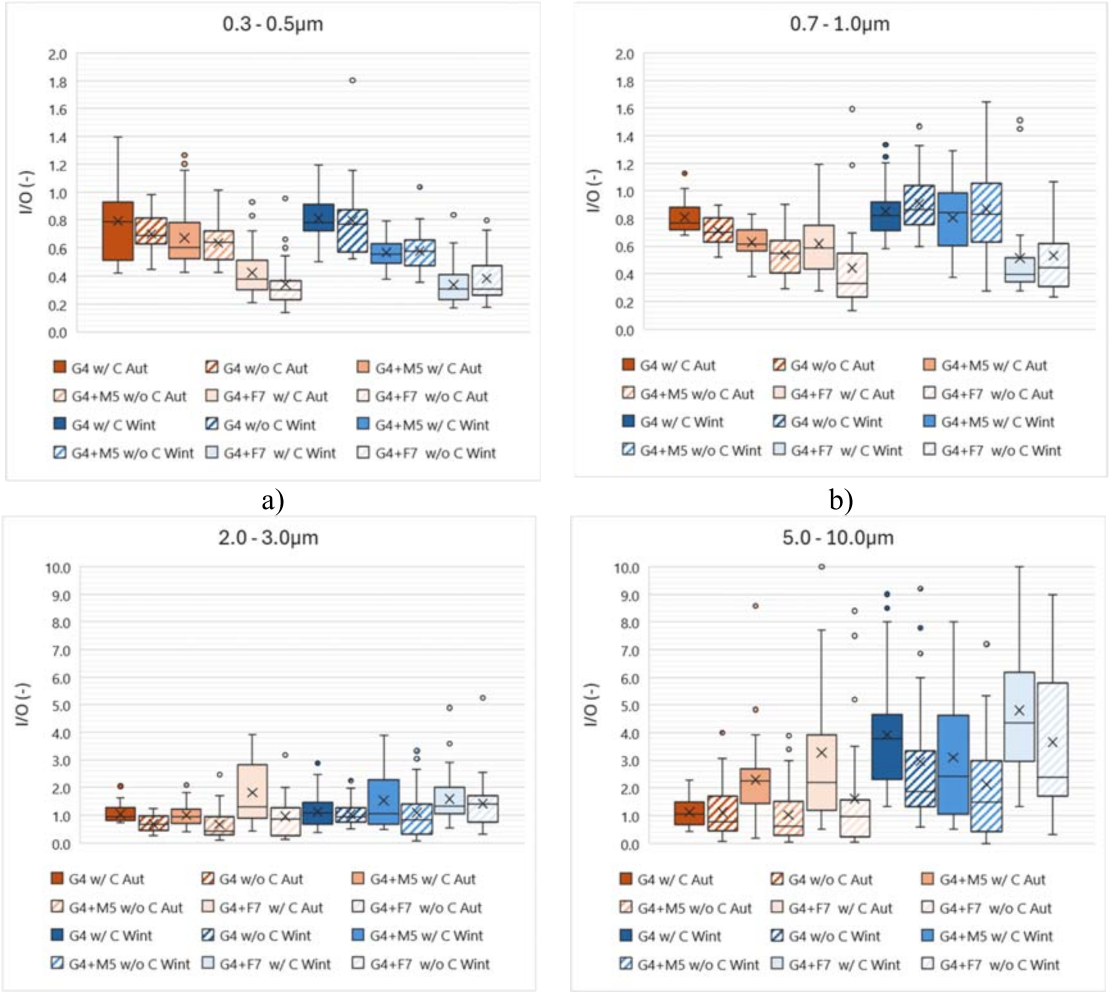


Figure 3: Filter efficiency determined in laboratory (lab) and in-situ

Figure 4 shows the results obtained throughout the 9-days measurement campaign, highlighting the ratio between indoor and outdoor particle concentration (I/O) as a function of inlet filter configurations (G4, G4+M5, G4+F7), the presence of children (with and without children), season (autumn and winter) and particle size ranging from 0.3 to 10 µm. The results show that the filter configuration significantly influences the I/O ratio. Typically, the I/O ratio decreases as filtration efficiency increases, particularly for particles smaller than 2 µm in diameter. Specifically, with G4 filters, without children the mean ratio ranges from 0.7 to 0.8, while with G4 +M5 filters, it improves to 0.54 to 0.67, and with G4 +F7 filters, it further improves to 0.34 to 0.62 for particles smaller than 2 µm. However, for larger particles where indoor and outdoor particle levels are low, no clear relationship is observed. For particles of 2-3 µm and 5-10 µm, the I/O ratio almost remains around 1 and increases at 4.8 respectively.



a) b) c) d)

Figure 4: Indoor-to-outdoor (I/O) particle concentration ratio based on averages during occupied/unoccupied time (w/ C / w/o C) with different inlet filter configurations (G4, G4+M5 and G4+F7), seasons (autumn and winter) and particle size a) 0.3-0.5 µm, b) 0.7-1.0 µm, c) 2.0-3.0 µm, d) 5.0-10 µm.

Occupancy significantly influenced the indoor-to-outdoor (I/O) ratio especially for the largest particles. Scenarios with children (w/ C) generally displayed higher I/O ratios, ranging from 0.42 to 3.28, compared to scenarios without children (w/o C), which ranged from 0.34 to 1.61. This indicates that the presence of children intensifies indoor activity and pollutant generation, resulting in poorer indoor air quality.

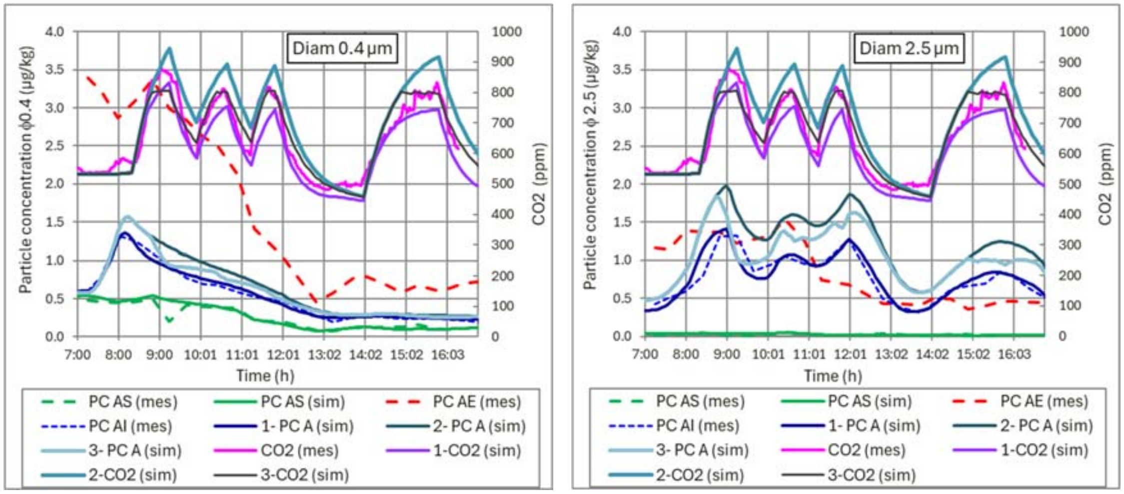
The seasonal impact on the indoor-to-outdoor (I/O) particle ratio is moderate, with minor differences between autumn and winter. However, a consistent trend emerges: in winter, slightly higher mean I/O ratios (w/o C, ranging from 0.38 to 3.65) are typically observed across all filter configurations and particle size fractions compared to autumn (w/o C, ranging from

0.34 to 1.61). This suggests that during winter, increased indoor time for children may contribute to elevated indoor air pollution levels due to particle generation or resuspension. Interestingly, the trend is reversed for the G4+F7 filter configuration when considering particles smaller than 5 µm, with children present. This could be attributed to the potential opening of windows during the occupancy period.

3.2 Simulations results

Figure 5a and Figure 5b show the evolution of measured (mes) and simulated (sim) particle concentrations (PC) for 0.4 µm and 2.7 µm mean diameters respectively and CO_2 using CONTAM for the three ventilation strategies (1-, 2-, 3-). The results demonstrate a good correlation between concentrations measured and simulated in the supplied air (AS) and indoor air (AI) with room (A). Figure 5b shows a strong correlation between measured AI values and CO_2 levels, indicating that the finest particles (diameter less than 0.7 µm) primarily originate from outdoors, while larger particles (diameter greater than 0.7 µm) are generated indoors (due to the presence of people and activities).

The airborne particle concentration within the school (measured and simulated AI) is quite close to that of the supplied air (AS), with a positive deviation resulting from the influx of outdoor particles through envelope leakages and generated by the occupants and activities.



a) b)

Figure 5: Measured (mes) and simulated (sim) particle concentrations (PC) for a) 0.4 µm and b) 2.7 µm mean diameters respectively and CO2 for the three ventilation strategies (1-, 2-, 3-)

The simulation results with the three ventilation strategies show that reducing the airflow rate by approximately 41% (strategy 1- to 2-) leads to an increase at peak times of around 25% for CO_2, 19% and 35% for 0.4 µm and 2.5 µm particles respectively. With demand-controlled ventilation based on CO_2 levels (strategy 3-), the CO_2 concentrations are maintained below the set threshold, while the airflow rate has been increased by approximately 5.7% above the minimum required (strategy 2-). Particle levels have decreased, particularly for 2.5 µm particles by 12.4%. For 0.4 µm particles, a slight decrease is noted.

4 CONCLUSIONS

This study provides valuable insights into optimizing indoor air quality in urban low energy consumption nursery school through appropriate filtration and intelligent airflow control based on CO_2 levels. The results demonstrate that increasing filtration efficiency, particularly for particles smaller than 2 µm, significantly reduces the indoor-to-outdoor particle concentration ratio. Specifically, using G4+F7 filters improved the ratio from 0.7-0.8 with G4 filters to 0.34-0.62 for sub-2 µm particles. The presence of children and seasonal variations also impact indoor air quality, with higher particle levels observed during occupancy and winter months.

Simulations using CONTAM software accurately correlated measured and simulated particle and CO_2 concentrations, validating the model. Reducing airflow by 41% led to 25% higher peak CO_2 levels and 19-35% increases in 0.4 µm and 2.5 µm particle concentrations. In contrast, demand-controlled ventilation based on CO_2 maintained levels below the threshold while increasing airflow by only 5.7% above the minimum. This strategy reduced 2.5 µm particle levels by 12.4% and slightly decreased 0.4 µm particles. These findings highlight the importance of optimizing ventilation strategies and filtration to balance energy efficiency and indoor air quality in kindergartens. Demand-controlled ventilation based on CO_2 levels, combined with high-efficiency particulate filters, offers a promising approach to maintain healthy indoor environments while minimizing energy consumption.

Further research is needed to assess the long-term impacts and cost-effectiveness of these strategies in real-world settings.

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6 REFERENCES

Alonso, J., Dols, W., & Mathisen, H. (2022). Using Co-simulation between EnergyPlus and CONTAM to evaluate recirculation-based, demand-controlled ventilation strategies in an office building. *Building and Environment, 211*.

Apte, M., Fisk, W., & Daisey, J. (2000). Associations between indoor CO2 concentrations and sick building syndrome symptoms in U.S. office buildings: An analysis of the 1994-1996 BASE study data. *Indoor Air, 10*(2), 246–257. doi:https://doi.org/10.1034/j.1600-0668.2000.010004246.x

Batterman, S. (2017). Review and Extension of CO□-Based Methods to Determine Ventilation Rates with Application to School Classrooms. *Int J Environ Res Public Health, 14*(2).

Cabovská, B., Bekö, B., Teli, G., Ekberg, D., & Dale, L. (2022). Ventilation strategies and indoor air quality in Swedish primary school classrooms. *Building and Environment, 226*.

Carlsson, T. (2008). Air filtration: Choosing the right filter class for HVAC systems. *Filtration & Separation, 45*(9), 36-38.

Chao, C., & Hu, J. (2004). Development of a dual-mode demand control ventilation strategy for indoor air quality control and energy saving. *Building and Environment, 39*(4), 385–397. doi:https://doi.org/10.1016/j.buildenv.2003.09.007

Daisey, J., Angell, W., & Apte, M. (2003). Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. *Indoor air, 13*(1), 53-64.

Dols, W., & Polidoro, B. (2020). *CONTAM User Guide and Program Documentation Version 3.4.* Technical Note 1887, NIST.

Emmerich, S., & Persily, A. (2001). *State-of-the-art review of CO2 demand controlled ventilation technology and application.* Internal Report, NIST Interagency.

Fisk, W. (2000). Health and productivity gains from better indoor environments and their relationship with building energy efficiency. *Annual Review of Energy and the Environment, 25*(1), 537-566.

Fisk, W., & De Almeida, A. (1998). Sensor-based demand-controlled ventilation: a review. *Energy and Buildings, 21*(1), 35-45.

Ginestet, A., Pugnet, D., & Mouradin, L. (2013). Air filtration: Air filters for balanced ventilation systems. *Filtration and Separation, 50*(1), 30-33.

Ginestet, A., Pugnet, D., & Robitu, M. (2015). How the filtration of the incoming air decreases the particle concentration within a school equipped with a balanced ventilation system. *36th AIVC Conference : Effective ventilation in high performance buildings*, (p. 8). Madrid, Spain.

Gram, O. (2019). *Use of low cost pollutant sensors for developing healthy demand controlled ventilation strategies.* Master's thesis, Norwegian University of Science and Technology, Trondheim, Norvege.

Guyot, G., Sherman, M., & Walker, I. (2018). Smart ventilation energy and indoor air quality. *Energy and Buildings, 165*, 416-430.

Lai, A., & Nazaroff , W. (2000). Modeling indoor particle deposition from turbulent flow onto smooth surfaces. *Journal of Aerosol Science, 31*(4), 463-476.

Liu, X., Xiao, M., Zhang, X., Gal, C., Chen, X., Liu, L., . . . Clements-Croome, D. (2017). A review of air filtration technologies for sustainable and healthy building ventilation. *Sustainable Cities and Society, 32*, 375-396.

Merema, B., Delwati, M., Sourbron, M., & Breesch, H. (2018). Demand controlled ventilation (DCV) in school and office buildings: Lessons learnt from case studies. *Energy and Buildings, 172*, 349-360.

Mysen, M., Berntsen, S., Nafstad, P., & Schild, P. (2005). Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools. *Energy and Buildings, 37*(12), 1234-1240.

Persily, A. (2015). Indoor Carbon Dioxide Concentrations in Ventilation and Indoor Air Quality Standards. *36th AIVC: Effective ventilation in high performance buildings*, (pp. 810-819). Madrid, Spain.

Sadrizadeh, S., Yao, R., Yuan, F., Awbi, H., Bahnfleth, W., Bi, Y., . . . Li, B. (2022). Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment. *Building Engineering, 57*.

Sofuoglu, S., & Moschandreas, D. (2003). The link between symptoms of office building occupants and in-office air pollution: the Indoor Air Pollution Index. *Indoor Air, 13*(4), 332-343.

Wachenfeldt, B., Mysen, M., & Schild, P. (2007). Air flow rates and energy saving potential in schools with demand-controlled displacement ventilation. *Energy and Buildings, 39*(10), 1073-1079.

Wargocki, P., & Wyon, D. (2007). The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children: ASHRAE 1257-RP. *HVAC&R Res., 13*(2), 165-191.

Wargocki, P., & Wyon, D. (2017). Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork. *Building and Environment, 112*, 359-366.