Strategies for ventilation and air cleaning to control infectious respiratory particles in school classrooms

Ding, E; García-Sánchez, C; Bluyssen, P M

DOI
10.1088/1742-6596/3140/9/092006

Publication date
2025

Document Version
Final published version

Published in
Journal of Physics: Conference Series

Citation (APA)
Ding, E., García-Sánchez, C., & Bluyssen, P. M. (2025). Strategies for ventilation and air cleaning to control infectious respiratory particles in school classrooms. *Journal of Physics: Conference Series*, *3140*(9), Article 092006. https://doi.org/10.1088/1742-6596/3140/9/092006

Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

Strategies for ventilation and air cleaning to control infectious respiratory particles in school classrooms

To cite this article: E Ding *et al* 2025 *J. Phys.: Conf. Ser.* **3140** 092006

Strategies for ventilation and air cleaning to control infectious respiratory particles in school classrooms

E Ding[1*], C García-Sánchez[1], P M Bluyssen[1].

[1] Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, the Netherlands

* Corresponding author e.ding@tudelft.nl

Abstract. In response to the WHO and UN's call to ensure children's right to breathe "clean" air and the challenges posed by the COVID-19 pandemic on maintaining healthy indoor air quality (IAQ), a holistic research was conducted to explore ventilation and air cleaning strategies to control the spread of infectious respiratory particles (IRPs) in school classrooms. The study follows four key steps: (1) a literature review bridging school ventilation regimes, IRP transmission, and advanced ventilation systems; (2) a field study to evaluate real-world ventilation and thermal conditions during the pandemic; (3) an experimental investigation of performance of mobile air cleaners (MACs) followed by an in-situ validation; and (4) a combined experimental and computational study to assess personalized air cleaners (PACs) as localized exhaust for IRP removal. Findings reveal that most classrooms rely on natural ventilation, often failing to meet IAQ standards, especially when fully occupied. With windows and doors kept open, ventilation rates remained inconsistent, and thermal conditions were unsatisfactory. Hence, more controllable ventilation and air cleaning approaches are needed. MACs, when appropriately selected and positioned, offer effective protection against long-range IRP transmission at room scale, while PACs are effective at mitigating localized, short-range IRP exposure, improving IAQ at an individual level.

1. Introduction

Healthy indoor air quality (IAQ) has long been called for the surrounding environments of children to ensure their health and well-being – a priority that has engaged researchers for decades. The sudden outbreak of the Coronavirus Disease 2019 (COVID-19) pandemic, however, posed substantial challenges to this goal. Infectious respiratory particles (IRPs), transmitted via airborne pathways, can easily cause cross-infection between occupants indoors, presenting serious health threats. School classrooms, characterized by long occupancy hours and high occupant density, are hence particularly vulnerable. When the pandemic hit, the lack of effective mitigation solutions often prevented schools from fully addressing these risks, resulting in disruptions to normal educational activities. Aiming to help improve this situation, a holistic research was conducted to answer the following main research question:

Which ventilation and air cleaning strategies can be used to effectively control the spread of infectious respiratory particles in school classrooms?

This question is addressed through four steps: 1) understanding the state of the art and defining research gaps, 2) examining real-world situations to set directions for improvements, and proposing solutions at 3) room scale and 4) individual level, respectively. Corresponding to the four steps, the methods used in this study consist of four parts: (1) a literature review bridging school ventilation regimes, IRP transmission, and advanced ventilation systems; (2) a field study to evaluate real-world ventilation and thermal conditions during the pandemic; (3) an experimental investigation of performance of mobile air cleaners (MACs) followed by an in-situ validation; and (4) a combined experimental and computational study to assess personalized air cleaners (PACs) as localized exhaust for IRP removal. The schema of the research is illustrated in Figure 1. The data underlying this research can be accessed at [1].

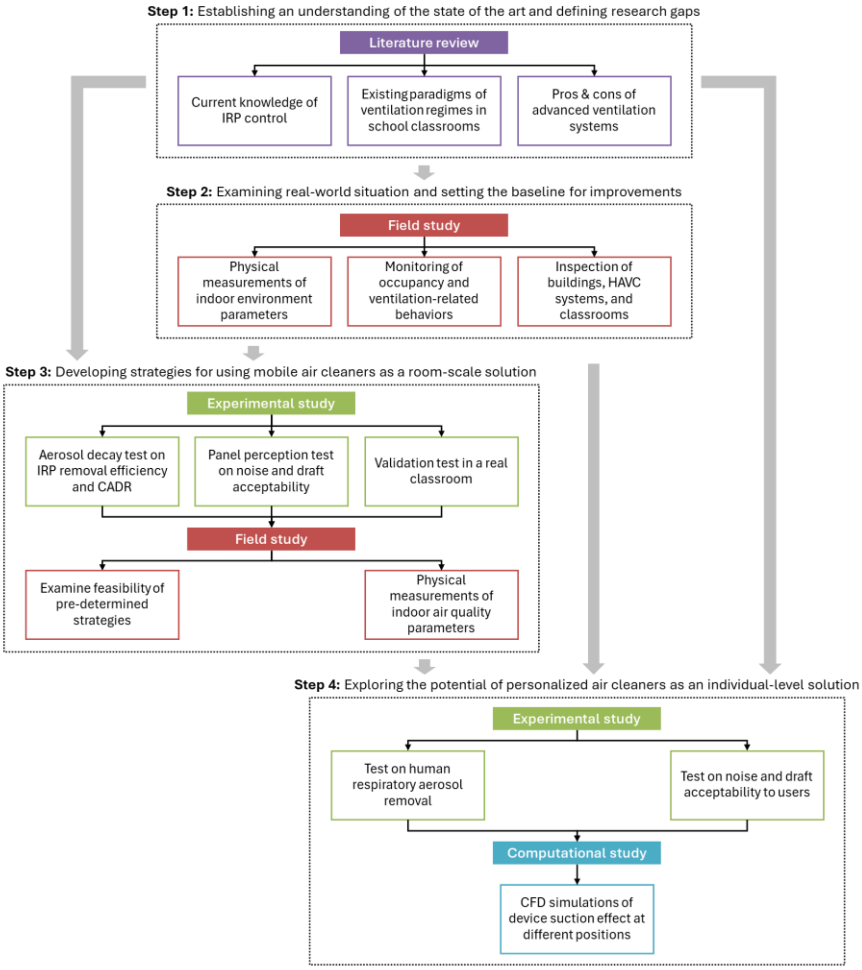

Figure 1. Schema of the research.

2. Step 1: Establishing an understanding of the state of the art and defining research gaps

To start, a systematic literature search using a large combination of keywords was performed, which formed three main topics regarding the focus of the research: 1) the current situation of ventilation strategies and IAQ conditions in school classrooms; 2) features and control of airborne transmission of IRPs; and 3) performance and feasibility of advanced ventilation systems. By including 94 research papers, eight standards and guidelines, and five reports, a deep understanding of each topic and the connections among them were obtained. The detailed summary of the literature search and screening criteria can be found in [2].

The results of the literature review are summarized in [2]. Airborne transmission of IRPs plays a critical role in spreading respiratory diseases like COVID-19. These particles, produced through breathing, speaking, sneezing, and coughing, can be transmitted through both short-range and long-range pathways. Short-range transmission occurs within close proximity, while long-range transmission involves particles remaining suspended in the air and traveling further distances.

Long-range transmission can be controlled via conventional ventilation regimes, either natural or mechanical. However, their effectiveness in non-hospital settings, particularly in schools, remains uncertain due to unclear guidelines on optimal airflow rates and distribution patterns. Additionally, these systems operate under assumptions such as steady-state conditions and well-mixed air, which do not accurately reflect the transient and dynamic nature of short-range transmission.

Current school ventilation standards primarily focus on perceived air quality and energy efficiency rather than infection control. CO_2 concentration is often used as an indicator of air quality, but it does not reliably reflect IRP levels. Many school classrooms fail to meet even existing ventilation requirements, leading to poor IAQ that negatively impacts student health, comfort, and academic performance. To improve infection control, ventilation strategies must shift from a comfort-based approach to a health-focused one.

Personalized ventilation (PV) systems, including personalized air supply (PS) for delivering clean air and personalized air exhaust (PE) for removing exhaled contaminants, offer a promising solution for reducing short-range transmission. These systems have been effective in high-risk environments such as hospitals and aircraft but require adaptation for school settings due to differences in spatial layout, occupancy patterns, and classroom activities.

3. Step 2: Examining real-world situations and setting the baseline for improvements

Following the literature study, a field study was carried out to investigate the real-world ventilation and thermal conditions in school classrooms during the COVID-19 pandemic. In total, 31 classrooms across 11 Dutch secondary schools were involved, with students aged 12 to 18. The selection of schools for this study considered a variety of factors, including the types of secondary education, urban or rural locations, and year of construction. Within each school, classrooms were chosen to represent different ventilation regimes. To track the evolution of conditions in the classrooms at different stages of the COVID-19 pandemic, as various levels of control and prevention measures were implemented, each school was visited twice: once before and once after a national lockdown, namely from October to December, 2020, and from March to June, 2021, respectively. Each school visit lasted for one day, where the indoor and outdoor CO_2 concentration and air temperature were monitored, and the occupancy and occupants' behaviours were observed. The CO_2 concentrations measured during the occupied hours were then used to calculated the ventilation rate per person in the classrooms, for which generalized estimating equations (GEE) were adopted to compare and analyze the difference between the two visits. The detailed description of the study design and data anaylises are presented in [3].

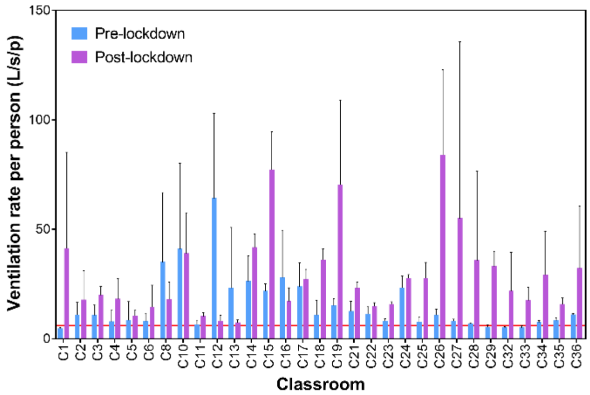

Figure 2. Ventilation rate per person in the classrooms. Note: the red line denotes the minimum ventilation rate person required by Dutch Fresh Schools guideline [4].

The results of the field study are summarized in [3]. The first thing to be noted is that, during the field study, most schools opted to keep classroom windows and doors open throughout the day to maximize outdoor air supply, a practice recommended in the media as an important pandemic control measure. This practice, which exposed indoor environments to uncontrollable outdoor conditions, caused mechanical ventilation systems, particularly mechanical air supply and balanced mixing ventilation in some classrooms, to not operate as designed. As a result, these classrooms were essentially relying on natural ventilation alone. The results of ventilation rate per person and CO_2 concentration are presented in Figures 2 and 3.

Before the lockdown, classrooms operated at normal student occupancy levels (average 17 persons). Results showed that they struggled to meet the required ventilation rate, as prescribed by the Dutch Fresh Schools guideline [4]. This was evidenced by unacceptably high indoor CO_2 concentrations observed during occupied hours, namely above level C (800 ppm above outdoor level [4]). After the lockdown, reduced student occupancy (average 10 persons) due to social distancing requirements resulted in lower indoor CO_2 concentrations and higher ventilation rates per person. However, the GEE analysis revealed that this improvement was mainly due to the reduction in occupancy rather than changes in ventilation practices.

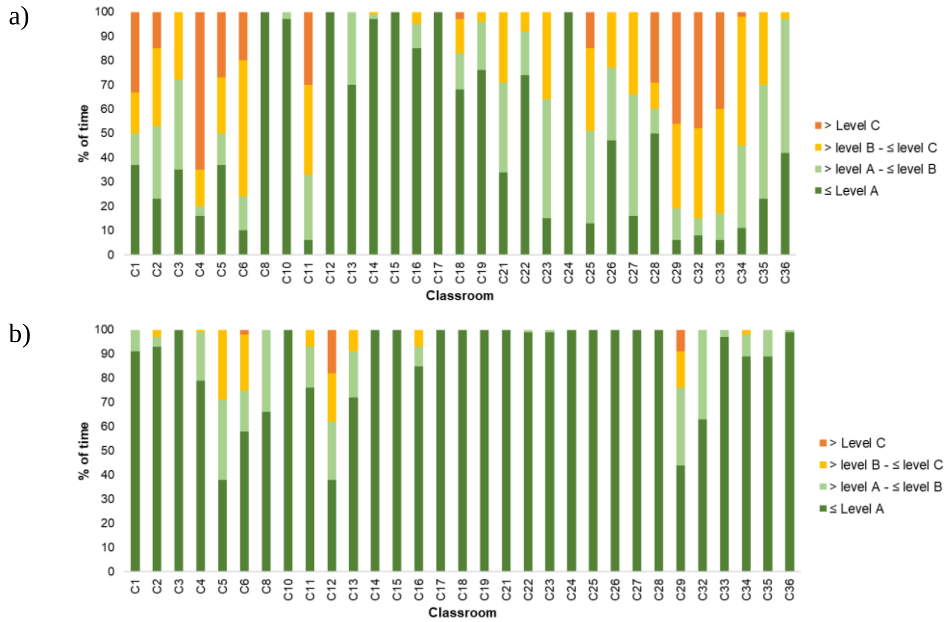

Figure 3. Time distributions of CO_2 concentration during occupied hours in the classrooms among different categories of Dutch Fresh Schools guideline [4]: (a) pre-lockdown; (b) post-lockdown.

Additionally, thermal conditions in the classrooms were unsatisfactory both before and after the lockdown, failing to meet the desired levels [4]. Before the lockdown, school visits took place during the heating season, and classroom temperatures were generally cold, likely because windows and doors were kept open. After the lockdown, indoor temperatures increased with the season, but several classrooms still experienced unacceptable temperature extremes, which can lead to discomfort for students.

4. Step 3: Developing strategies for using mobile air cleaners as a room-scale solution

For controlling long-range airborne transmission of IRPs, mobile air cleaners (MACs) were proposed, considering their flexibility and affordability. Given the large variety of MACs available, first, a set of criteria to guide the selection process, considering both technical and economic factors, as illustrated by Figure 4. Accordingly, eight small- and medium-sized floor-standing MACs were selected, of which seven were assessed via laboratory experiments. The detailed information on the tested MACs are summaried in [5].

The MACs were first tested in the Experience room of the SenseLab at Delft University of Technology, with an interior of a classroom setting [6]. The assessments included 1) an aerosol decay test using an artificial aerosol generator to determine the aerosol removal rate and clean air delivery rate (CADR) and 2) a panel perception test with human subjects to examine occupants' perception of the noise and draft caused by the MACs. Based on the results, the optimal condition for each type of MAC was determined and then validated in a university lecture room with a similar size to a real-world primary/secondary school classroom. The detailed methods are presented in [5].

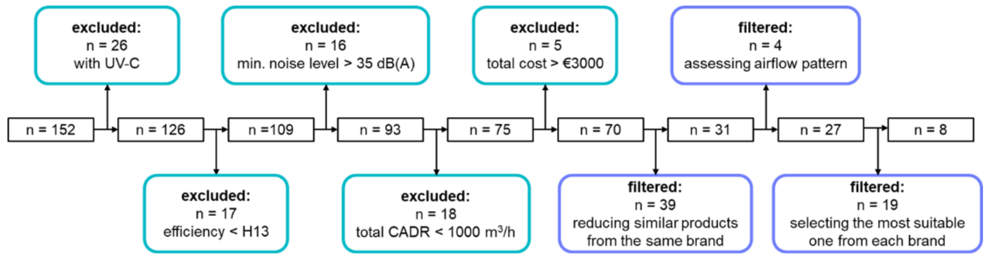

Figure 4. Selection process of the tested mobile air cleaners.

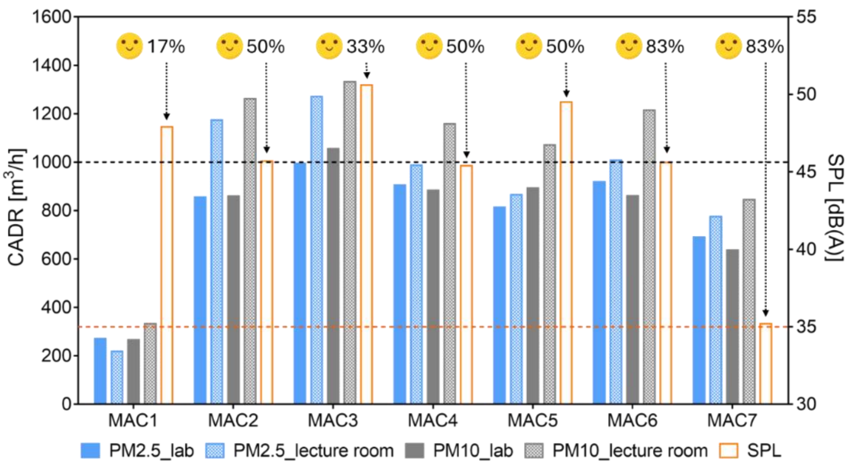

Figure 5. CADR of $PM_{2.5}$ and PM_{10} in the lab/lecture room, and sound pressure level (SPL). The black dashed line indicates the desired amount of CADR for 30 students per classroom (1000 m^3/h). The orange dashed line indicates the limit of noise level in classrooms (35 dB(A)) [4].

The results of the laboratory study are summarized in [5] and illustrated in Figure 5. It is indicated that MACs equipped with high-efficiency filters (H13) were effective at removing IRPs in a classroom setting. In general, CADR should be at least 1000 m^3/s for classrooms with 30 students to ensure the necessary airflow rate of 8.5-10 L/s per person. The most important factor in achieving a satisfactory CADR was the airflow pattern of the MAC, particularly how contaminated air is drawn in and clean air is expelled. MACs with upward airflow (either vertical or angled) proved more effective at distributing clean air throughout the room compared to those with horizontal airflow. Additionally, the placement of the MACs was crucial, as directing airflow toward the occupied zone maximized efficiency.

Further testing in a university classroom confirmed the laboratory findings. It was revealed that as the room size increased, multiple MACs became necessary to maintain optimal air delivery. The integration of MACs with mechanical ventilation systems provided even better results, achieving higher CADR compared to laboratory tests that lacked background ventilation. However, followup research is required to determine the optimal configuration for combining ventilation systems and air cleaning devices to maximize performance.

Besides, noise and draft are important factors for using MACs in school classrooms. At higher settings required for sufficient CADR, the noise levels often exceeded the prescribed threshold. However, panel assessments varied across different MACs and conditions, as shown in Figure 5. Despite this, the air velocities generally met the requirements for avoiding draft discomfort, and positive feedback was received regarding overall comfort. This emphasizes the importance of balancing MAC performance with occupant comfort and considering user feedback in optimizing MAC usage.

5. Step 4: Exploring the potential of personalized air cleaner as an individual-level solution

For controlling short-range airborne transmission of IRPs, personalized air cleaners (PACs) were proposed to be used as a localized exhaust, leveraging the advantages of both PE systems and mobile air cleaners. This study tested a PAC with a high-efficiency H13 electrostatic filter, which was appropriately sized for individual use. Via experimental tests with human subjects, the perceptual assessments of the PAC's noise and draft were first conducted, followed by the evaluation of its respiratory aerosol removal efficiency with subjects breathing into a box. Then, computational fluid dynamics (CFD) simulations were performed to assess the impact of various positioning on the PAC's suction effect. The detailed setup of the experimental tests and the CFD simulations are described in [7].

The results of the experimental and computational study on a PAC are summarized in [7] and illustrated in Figure 6. User perception, particularly regarding noise and draft, plays a crucial role in the feasibility of PACs. The panel of subjects found that the PAC's higher noise levels were unacceptable, so only the lower setting was evaluated in the following stages. The aerosol removal test demonstrated that at this setting, the PAC reduced exhaled particle concentrations by 40% to 51%, with higher efficiency for smaller particles. However, results were influenced by air recirculation within the PAC's box.

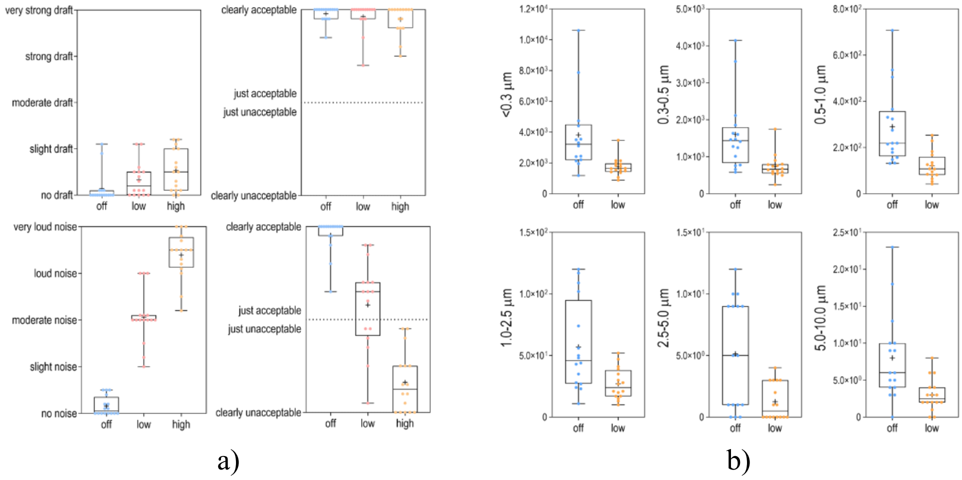

Figure 6. Perceptual assessments of the PAC (a) and respiratory aerosol reduction by the PAC (b).

The results of the CFD simulations, visualized as the velocity contour, are shown in Figure 7. Six positions were simulated to compare the suction area of the PAC, with the central vertical position providing the best results. In real-life, this setup may also benefit from the upward movement of exhaled particles caused by the thermal plume of the human body, enhancing the PAC's ability to capture IRPs. Nonetheless, the PAC's suction effect is in general limited, possibly due to the low airflow rate. Alternatives like increasing suction airflow rate, expanding the suction surface area, or reducing the distance to the user may improve efficiency, but could need to be carefully configured.

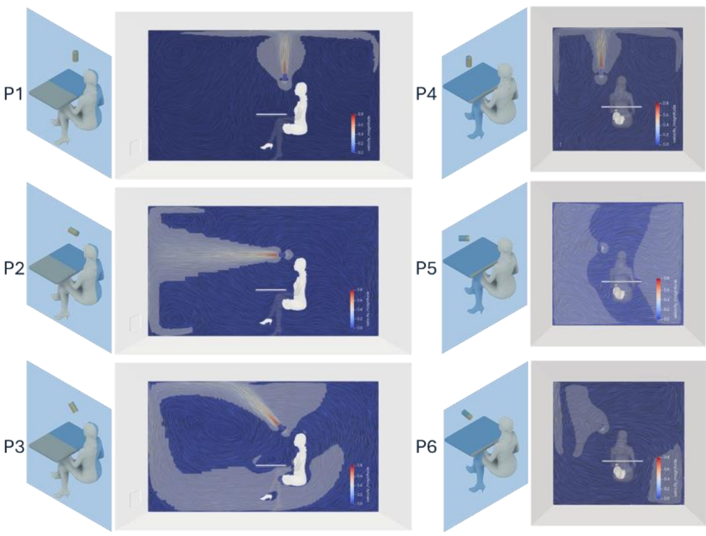

Figure 7. Simulated geometries and velocity contours of the PAC as a localized exhaust at different positions.

6. Conclusions

To conclude, this research demonstrated that currently, the ventilation in school classrooms (mostly relying on window-based natural ventilation) often falls short of meeting existing requirements, and thus is likely insufficient to control the spread of IRPs. Therefore, more controllable ventilation approaches, namely mechanical ventilation systems, are needed, alongside complementary interventions like MACs and PACs. The findings reveal that MACs, when appropriately selected and positioned, offer room-scale protection against long-range IRP transmission, while PACs are effective in managing localized, short-range IRP exposure, particularly where seating arrangements or class activities increase close contact. Together, these solutions offer a comprehensive framework for managing IRPs in classroom settings.

Acknowledgements

This research was partly funded by ZonMw and Dutch Ministry of Education, Culture and Science.

References

[1] Ding, E., García-Sánchez, C., Bluyssen, P.M. (2024): Data underlying the PhD dissertation: "Healthy air for children: Strategies for ventilation and air cleaning to control infectious respiratory particles in school classrooms". 4TU.ResearchData. Available at: https://doi.org/10.4121/88542bc3-ff1d-4163-b977-9c28d2d88fc4.v2

[2] Ding, E., Zhang, D., & Bluyssen, P.M. (2022). Ventilation regimes of school classrooms against airborne transmission of infectious respiratory droplets: A review. *Building and Environment*, *207*, 108484.

[3] Ding, E., Zhang, D., Hamida, A., García-Sánchez, C., Jonker, L., De Boer, A.R., Bruijning, P.C.J.L., Linde, K.J., Wouters, I.M., & Bluyssen, P.M. (2023). Ventilation and thermal conditions in secondary schools in the Netherlands: Effects of COVID-19 pandemic control and prevention measures. *Building and Environment*, *229*, 109922.

[4] The Netherlands Enterprise Agency (RVO). (2021). *Program of requirements – Fresh schools 2021* (in Dutch). (Accessed on 1 July 2021). Available at: https://www.rvo.nl/sites/default/files/2021/06/PvE-Frisse-Scholen-2021.pdf

[5] Ding, E., Giri, A., Gaillard, A., Bonn, D., & Bluyssen, P.M. (2024). Using mobile air cleaners in school classrooms for aerosol removal: Which, where and how. *Indoor and Built Environment*, *33*(10), 1964–1987.

[6] Bluyssen, P.M., van Zeist, F., Kurvers, S., Tenpierik, M., Pont, S., Wolters, B., van Hulst, L., & Meertins, D. (2018). The creation of SenseLab: a laboratory for testing and experiencing single and combinations of indoor environmental conditions. *Intelligent Buildings International*, *10*(1), 5–18.

[7] Ding, E., Giri, A., García-Sánchez, C., & Bluyssen, P.M. (2024). Feasibility of a personalized air cleaner as a localized exhaust for short-range respiratory aerosol removal in classroom settings: A pilot study. (under review)